BUILDING TECHNOLOGIES PROGRAM
LIGHTING RESEARCH AND DEVELOPMENT

2009 PROJECT PORTFOLIO: SOLID-STATE LIGHTING

U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

January 2009

2009 Project Portfolio:
Solid-State Lighting

The U.S. Department of Energy (DOE) partners with industry, universities, and national laboratories to accelerate improvements in solid state lighting (SSL) technology. These collaborative, cost-shared efforts focus on developing an energy-efficient, full spectrum, white light source for general illumination. DOE supports SSL research in six key areas: quantum efficiency, longevity, stability and control, packaging, infrastructure, and cost reduction.

The *2009 Project Portfolio: Solid-State Lighting* provides an overview of SSL projects currently funded by DOE, and those completed from 2003 through 2008. Each profile includes a brief technical description, as well as information about project partners, funding, and research period. The *Portfolio* is a living document and will be updated periodically.

Projects are organized throughout the *Portfolio* in alphabetical order by technology, funding source, and then performing organization.

Prepared by
D&R International, Ltd.
January 2009

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Epitaxial Growth of GaN Based LED Structures on Sacrificial Substrates

Investigating Organization
Georgia Institute of Technology

Principal Investigator(s)
Ian Ferguson

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $756,050
Contractor Share: $277,639

Contract Period
10/01/06 - 12/31/09

Technology
Light Emitting Diodes

Project Summary

The objective of this work is to develop high efficiency LED devices that will lead to higher external quantum efficiency performance, better electrostatic discharge durability, simple low cost fabrication, high product yield with high brightness, and better heat management. A sacrificial substrate will be used for device growth that can easily be removed using a wet chemical etchant leaving only the GaN epi-layer and possibly a very thin (~1mm) intermediate substrate. This will require development of growth techniques for substrates other than sapphire, such as Si or ZnO. After substrate removal, the GaN LED chip can then be mounted in several different ways to a metal heatsink/reflector. Then light extraction techniques can be applied to the chip such as surface roughening, wave-guiding, or others and compared for performance.

Low-Cost Substrates for High Performance Nanorod Array LEDs

Investigating Organization
Purdue University

Principal Investigator(s)
Timothy D. Sands

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $899,948
Contractor Share: $225,195

Contract Period
05/01/06 - 04/30/09

Technology
Light Emitting Diodes

Project Summary

The primary emphasis is aimed at improving the internal quantum efficiency (IQE) of GaN-based LEDs has been on reducing the threading dislocation density, these approaches including epitaxial lateral overgrowth, bulk GaN substrates and bulk SiC substrates - inevitably increase the materials or manufacturing costs markedly. This project is designed to exploit the relief of lattice mismatch strain and the expulsion of dislocations that are characteristic of nanoheteroepitaxy in the growth of heteroepitaxial device structures on nanoscale substrates to expand the spectral range of efficient GaN-based LEDs to include the entire visible spectrum, thereby eliminating the efficiency losses associated with phosphor down-conversion. The investigators have demonstrated the fabrication of uniform arrays of GaN nanorods using a low-cost process that does not involve foreign catalysts or direct-write nanolithography.

High Performance Green LEDs by Homoepitaxial MOVPE

Investigating Organization
Rensselaer Polytechnic Institute

Principal Investigator(s)
Christian Wetzel

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,830,075
Contractor Share: $1,137,057

Contract Period
08/22/06 - 08/23/09

Technology
Light Emitting Diodes

Project Summary

The objective of this work is the development of processes to double or triple the light output power from green and deep green AlGaInN light emitting diode (LED) dies within 3 years in reference to the Lumileds Luxeon II. Lumileds Luxeon II dies and lamps have been identified by the Department of Energy as the uniform reference of current performance levels and therefore will be used in our performance comparisons. This project will pay particular effort to all aspects of the internal generation efficiency of light. LEDs in this spectral region show the highest potential for significant performance boosts. The results will be high output green and deep green (525 - 555 nm) LED chips as part of high efficacy red-green-blue LED modules. Such modules will perform at and outperform the efficacy target projections for white-light LED systems in the Department of Energy's accelerated roadmap of the SSL initiative.

Photoluminescent Nanofibers for High Efficiency Solid State Lighting Phosphors

Investigating Organization
Research Triangle Institute

Principal Investigator(s)
Lynn Davis

Subcontractor
Donaldson Company
Evident Technologies

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,509,903
Contractor Share: $377,475

Contract Period
09/01/06 - 03/31/10

Technology
Light Emitting Diodes

Project Summary

The overall objective of this project is to develop and validate advanced photoluminescent nanofibers (PLN) containing quantum dots (QDs) that improve the external quantum efficiency (EQE) of Solid State Lighting (SSL) devices. This will be done in conjunction with an evaluation of manufacturing options for the technology. The PLNs are intended for use as secondary emitters in advanced, high efficiency SSL devices. This proposed program will seek to demonstrate that PLNs offer several advantages over existing technologies, including the following: Higher luminous intensity and lumens per lamp; Increased phosphor luminous efficacy and improved EQE; Greater control over the quality of the emission spectrum; Longer operational lifetime; and Easier-to-handle format that is likely amenable to large-scale manufacturing.

Innovative Strain-Engineered InGaN Materials of High Efficiency Green Light Emission

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Michael Coltrin

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,797,000

Contract Period
10/01/06 - 09/30/09

Technology
Light Emitting Diodes

Project Summary

The objective is to develop high-efficiency deep-green (= 540 nm) light emitters based on strain-engineered InGaN materials. This objective is crucial for success of the multi-chip approach to energy-efficient solid-state lighting, which combines output from red, green, and blue (RGB) LEDs to produce white light.

The team plans to improve internal quantum efficiency (IQE) by developing thick, strain-relaxed InGaN templates for growth of deep-green active regions. These novel templates will enable active-region quantum wells (QWs) with much lower strain than is currently possible using GaN templates. Reduced strain lowers the piezoelectric field in the QWs, resulting in improved light-emission efficiency. Since strain fundamentally limits indium incorporation during InGaN growth, reduced strain also raises the attainable indium composition at a given growth temperature, making longer emission wavelengths possible without suffering from enhanced defect formation at lower growth temperatures. P-n junction structures will be fabricated and tested to quantify the IQE of these improved materials, with a final project goal of demonstrating an IQE at 545 nm that is at least 2.5X greater than that of current-state-of-the-art deepgreen LEDs.

High-Efficiency Nitride-Based Photonic Crystal Light Sources

Investigating Organization
University of California, Santa Barbara

Principal Investigator(s)
James S. Speck

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,200,000
Contractor Share: $300,000

Contract Period
08/01/06 - 07/31/09

Technology
Light Emitting Diodes

Project Summary

The University of California, Santa Barbara is focusing on the maximization of light extraction efficiency and total light output from light engines driven by Gallium Nitride (GaN)-based LEDs. The objectives of this project center on the development of novel GaN-based LED structures for use in advanced solid-state light engines which are suitable for general illumination. The target specifications for such light engines include a luminous efficacy of greater than 154 lm/W, a total flux of 1,500 lumens, a color rendering index of greater than 80 at a corrected color temperature of 3000K, and a projected lifetime of greater than 74,000 hours at 70% lumen maintenance.

An Integrated Solid-State LED Luminaire for General Lighting

Investigating Organization
Color Kinetics Incorporated

Principal Investigator(s)
Mr. Kevin Dowling

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,741,444
Contractor Share: $581,942

Contract Period
10/01/06 - 03/31/09

Technology
Light Emitting Diodes

Project Summary

The objective is to develop a novel hybrid-LED source, which generates the white emission by combining the light from direct emission LEDs with the emission from down-conversion phosphors. The goal is the development of a warm white solid-state lamp product by 2008 with a source efficacy of 80 LPW at 2800K color temperature and 92+ CRI. The team will target a lamp equivalence that is suitable as replacement for 60W incandescent lamps. The proposed lamp will have a total flux of 800 Lumens.

Phosphor Systems for Illumination Quality Solid State Lighting Products

Investigating Organization
General Electric Global Research

Principal Investigator(s)
Anant Setlur

Subcontractor
GE Lumination
University of Georgia

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,495,774
Contractor Share: $1,343,878

Contract Period
10/01/06 - 09/30/09

Technology
Light Emitting Diodes

Project Summary

The objective will focus upon phosphor development for violet LED (max=405 nm) + phosphor downconversion (violet pcLED) lamps. The target will be to replace incandescent lamps with the LED lamps with the following characteristics:CCTs (2700-3100 K); Minimal device-to-device color variation; No detectable change in the lamp color point over 50,000 hr lifetime; 96 lm/W at CCT~3000 K and CRI>80;71 lm/W at CCT<3100 K and CRI~95;Estimated end-user price of $40/klm at 2009.

Novel Heterostructure Designs for Increased Internal Quantum Efficiencies in Nitride LEDs

Investigating Organization
Carnegie Melon University

Principal Investigator(s)
Professor Robert Davis

Subcontractor
Univeristy of Michigan

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,426,184
Contractor Share: $363,638

Contract Period
10/01/07 - 09/30/10

Technology
Light Emitting Diodes

Project Summary

The objectives of this interdisciplinary program of collaborative research are the conduct of research concerned with theoretical experimental investigations regarding the influence on the density of non-radiative channels and IQE of (a) graded and relaxed InGaN buffer layers having the final composition of the InGaN quantum well (QW) to suppress any negative aspects of polar fields in the action region, (b) dislocations and their reduction in the InGaN buffer layers and the QWs, (c) number of quantum wells and the dependence of the efficiency as a function of injection into these wells, (d) enhanced polarization-based p-type doping and hole injection levels at Ohmic contacts and (e) the use of novel heterostructure design to funnel carriers into the active region for enhanced recombination efficiency and elimination of diffusion beyond this region and (f) the fabrication and characterization of blue and green LEDs with enhanced IQE.

High-Efficiency Non-Polar GaN-Based LEDs

Investigating Organization
Inlustra Coporation

Principal Investigator(s)
Dr. Paul T. Fini

Subcontractor
University of California, Santa Barbara

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,440,000
Contractor Share: $360,000

Contract Period
10/01/07 - 11/30/10

Technology
Light Emitting Diodes

Project Summary

This is a comprehensive research program focusing on better understanding the factors that affect III-nitride LED internal quantum efficiency (IQE), and maximizing IQE in blue and green HB-LEDs based on non-polar (Al,In)GaN films. The objectives of this project center on the development of HB-LED active regions with high internal quantum efficiency, for immediate application in advanced solid-state light engines that are suitable for general illumination.

The target specifications for the proposed HB-LEDs include internal quantum efficiency of at least 90% for blue LEDs, greater than 60% for green LEDs, and packaged LED power at 20 mA greater than 10 mW.

Unlike conventional III-V semiconductors, GaN-based optoelectronic devices have strong (>1 MV/cm) built-in electrical polarization fields, which are oriented in the [0001] c-direction. The proposed project intends to dramatically increase the IQE of blue and green InGaN HB-LEDs via the use of quantum heterostructures fabricated on the non-polar a- and m-planes. Another principal objective is to develop a practical means of quantitatively measuring IQE via electroluminescence from actual HB-LED device structures.

Improved InGaN Epitaxial Quality by Optimizing Growth Chemistry

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Dr. J. Randall Creighton

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $785,000

Contract Period
08/01/07 - 08/31/09

Technology
Light Emitting Diodes

Project Summary

The goal of the Sandia National Laboratory is to develop high-efficiency green (530 nm) light emitters based on improvement in InGaN epitaxial material quality. High indium compositions needed for green emission are very difficult to obtain. Limited thermodynamic stability and unwanted parasitic chemical reactions are two fundamental roadblocks to controllable and efficient epitaxial growth. This proposal addresses improvement of InGaN active regions. Improved growth efficiency and control of indium incorporation will also enable better LED manufacturability.

Parasitic gas-phase reactions during film growth have been shown to form unwanted gas-phase nanoparticles during GaN, AlN, and AlGaN growth. For Al containing films, these nanoparticles are responsible for a loss of up to 80% of the input Al, resulting in growth inefficiency and poorly controlled alloy composition. Preliminary experiments showed that nanoparticles are also formed during InGaN growth. It is thus important to characterize and understand the complex parasitic gas-phase chemistry in InGaN growth. In situ laser light scattering will be used to examine InGaN nanoparticle formation in detail, with particular emphasis on the role of the carrier gas composition, V/III ratio, residence time, and temperature. A thermophoretic sampling technique and ex situ transmission electron microscopy will be used to examine InGaN nanoparticle structure and composition. A variety of experimental methods, including in situ FTIR, will be employed to determine the exact role that hydrogen (versus nitrogen) carrier gas plays in the InGaN growth process.

Thermodynamic and surface kinetic effects also limit In-incorporation. The InGaN film growth chemistry and alloy stability will be studied as a function of growth conditions. A large database of InGaN growth rates and composition over a wide range of MOCVD conditions will be generated, followed by the measurement of the InGaN film desorption (or evaporation) rates using in situ reflectometry. These measurements will quantitatively determine the thermodynamic or kinetic stability of InGaN films as a function of temperature and gas-phase composition. Using the knowledge gained, a quantitative and predictive reactor-scale model of the combined (parasitic) gas-phase chemistry and thin-film growth process will be developed and used to optimize In-incorporation. The ultimate goal will be improved InGaN quantum well internal quantum efficiency (IQE) through higher-temperature growth of high In-content films. Using optimized growth conditions (e.g. higher temperature) a 2X improvement in IQE for standard 530 nm InGaN multiquantum well (MQW) structure will be demonstrated.

Multicolor, High Efficiency, Nanotextures LEDs

Investigating Organization
Yale University

Principal Investigator(s)
Dr. Jung Han

Subcontractor
Brown University

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $900,000
Contractor Share: $225,153

Contract Period
10/01/07 - 09/30/10

Technology
Light Emitting Diodes

Project Summary

The goal of this project is to create a new class of active medium with an amplified radiation effiency capable of near-unity electron-to-photon conversion for solid state lighting applications. The target is to reach 120 lm/W luminous efficacy of at least 550 nm and produce intellectual impacts to the SSL technology based on three innovative concepts:

1) Self-assembled synthesis of textured arrays of 1D InGaN nanorods for enhanced quantum confinement and radiation cross section,

2) Near-field resonant enhancement of spotaneous and stimulated emission in eliciting maximum photon generation, and

3) Concurrent nanoscale growth of InGaN on polar, non-polar, and semi-polar planes for enhanced multicolor emission.

The objective in Phase I is to achieve mechanistic understanding of nanphotonic enhancement and nanoscale synthesis science in order to consolidate experience and success pertaining to SSL. The objective of Phase II is to achieve near-unity IQE from self-assembled nanorod arrays on non-polar surfaces. The incorporation of such nanostructures active medium into electrically injected device, with above 120 lm/W lumnous efficacy, will be the ultimate goal in Phase III.

The proposed research seeks to explore and integrate unique nanoscale phenomena peratining to SSL applications, including nanostructure induced carrier confinement, enhanced sub-wavelength scattering and light extraction, single-crystalline dislocation-free synthesis of active medium, and simultaneous nano-epitaxy on polar, semi-polar, and non-polar templates.

LED Chips and Packaging for 120 LPW SSL Component

Investigating Organization
Cree, Inc.

Principal Investigator(s)
James Ibbetson

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,231,877
Contractor Share: $410,624

Contract Period
10/01/07 - 09/30/09

Technology
Light Emitting Diodes

Project Summary

Cree proposes to develop a high-efficiency, low cost lamp module that will target commercial luminaire applications and is capable of replacing standard, halogen, fluorescent and metal halide lamps based on the total Cost-of-Light. Cree proposes to achieve the required efficiency gains developing photonic-crystal LEDs and improving packaging concepts. This development will build on Cree's expertise in thin-film LED products and packaged LEDs. The focus of the photonic crystal development is to improve the light extraction efficiency compared to conventional LEDs. Cree will perform the work to deliver by the end of a focused two-year effort 120 LPW lamp modules that emit at 4,100K. These modules will be integrated into 1400 Lumen luminaires.

GaN-Ready Aluminum Nitride Substrates for Cost-Effective, Very Low Dislocation Density III-Nitride LEDs

Investigating Organization
Crystal IS, Inc.

Principal Investigator(s)
Leo J. Schowalter

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,029,343
Contractor Share: $257,337

Contract Period
05/01/08 – 04/30/10

Technology
Light Emitting Diodes

Project Summary

The objective of this project will be to develop and then demonstrate the efficacy of a cost-effective approach for a low defect density substrate on which AlInGaN LEDs can be fabricated. The efficacy of this "GaN-ready" substrate will then be tested by growing high efficiency, long lifetime $In_xGa_{1-x}N$ blue LEDs.

The approach used to meet the project objectives is to start with low dislocation density AlN single-crystal substrates and grow graded $Al_xGa_{1-x}N$ layers on top. The $Al_xGa_{1-x}N$ layer will be graded all the way to pure GaN and will be grown thick enough so that all lattice mismatch strain is completely relaxed to produce a "GaN-ready" substrate. The efficacy of these substrates will be evaluated through the growth and fabrication of blue LEDs. The LEDs fabricated with low threading dislocation densities (TDDs) will also be benched marked against state-of-the-art LEDs fabricated on sapphire substrates. These sapphire based LEDs typically have TDD > 108 cm^{-2} and we anticipate developing LEDs under this program with TDD < 106 cm^{-2}. Finally, LED structures will be optimized for light extraction efficiency.

Fundamental Studies of Higher Efficiency III-N LEDs for High-Efficiency High-Power Solid-State Lighting

Investigating Organization
Georgia Institute of Technology

Principal Investigator(s)
Russell Dupuis

Subcontractor
Arizona State University
Luminus

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,503,626
Contractor Share: $698,473

Contract Period
09/01/08 - 08/30/11

Technology
Light Emitting Diodes

Project Summary

The goal of this project is to understand in a fundamental way the impact of strain, defects, polarization, Stokes loss, and unique device active region designs upon the internal quantum efficiency (IQE) of III-N LEDs and to employ this understanding in the design and growth of high-efficiency LEDs. This information will be the underpinning used to provide advanced device designs that lead to improved device performance at high current densities. This new understanding will be applied to the development of prototype III-N LEDs in green spectral region with IQE that exceed current-generation production devices by a factor of higher than 2 (from <25% to >45% at 525nm and <10% to >25% at 540nm) with the ultimate goal of achieving visible LEDs having IQE values of ~90% by 2025.

High Extraction Luminescent Materials for Solid State Lighting

Investigating Organization
Phosphortech Corporation

Principal Investigator(s)
Chris Summers

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,404,645
Contractor Share: $351,277

Contract Period
06/01/08 - 05/31/11

Technology
Light Emitting Diodes

Project Summary

The main objective of this program is to develop high extraction phosphor systems. The approach for achieving the high efficiency goals is based on maximizing the extraction and quantum efficiencies of the phosphor materials at the LED operating temperatures. This is a comprehensive program for the refinement of its patented sulfoselenide systems as well as the development of new bulk and nanocrystalline derivatives with improved QY, thermal and chemical stability.

Novel Defect Spectroscopy of InGaN Materials for Improved Green LEDs

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Andrew Armstrong

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,340,000

Contract Period
04/01/08 - 03/31/11

Technology
Light Emitting Diodes

Project Summary

The goal of this research is to develop a novel quantitative, nanoscale depth-resolved deep level defect spectroscopy methodology applicable to InGaN thin films like those found in the active regions of InGaN/GaN green LEDs and to LEDs themselves. By monitoring defect incorporation as a function of systematically varied growth conditions, optimized growth of InGaN films with minimized defect concentration will be demonstrated. Using the optimized growth conditions, QWs and LEDs will be characterized to demonstrate improvements in IQE and EQE, respectively. Also, defect spectroscopy directly applicable to LEDs will be developed to determine any impact that defects have on efficiency roll-off at high current density. The enhanced understanding and mitigation of the impact of defects on LED performance is anticipated to enable more efficient green LEDs and advance SSL technology.

Efficient White SSL Component for General Illumination

Investigating Organization
Cree Inc.

Principal Investigator(s)
James P. Ibbetson

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,995,988
Contractor Share: $562,971

Contract Period
04/01/08 - 03/31/10

Technology
Light Emitting Diodes

Project Summary

Cree is developing to a novel 100 lumens per watt (LPW) solid-state lighting (SSL) component suitable for insertion into SSL luminaries for commercial lighting. To achieve this objective, Cree is building on its high brightness white light emitting diode (LED) platforms to boost the warm white LED efficacy. Improvements to the LED wall plug efficiency, phosphor efficiency, and package system efficiency are being addressed. New phosphor materials are being developed and integrated along with LED chips into a package designed for optimum color mixing and efficacy. Cree will perform the work to deliver 100 LPW lamp modules that emit white light with a color temperature of 3000K by the end of a focused two-year effort. These modules will be integrated into 1250 lumen proof-of-concept luminaires.

Affordable High-Efficiency Solid-State Downlight Luminaires with Novel Cooling

Investigating Organization
General Electric Global Research

Principal Investigator(s)
Mehmet Arik

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,164,530
Contractor Share: $721,510

Contract Period
07/15/08 - 04/30/10

Technology
Light Emitting Diodes

Project Summary

The objective of this program is to develop an illumination quality solid-state lighting (SSL) luminaire based on LED cooling using synthetic jets combined with optimized system packaging and electronics. Upon completion, the team will deliver 1500 lumen luminaries with:

- > 75 lm/W efficacy
- $51 end-user price
- 50,000 h lifetime
- Manufacturing and marketing plan
- Physics-of-failure-based LED luminaire reliability models

The performance and reliability of future LED lighting systems are driven by the thermal management solution of the system. Systems using passive heat sinks will require a larger size compared to conventional lighting systems, potentially limiting their implementation. This project is developing thermal management solutions based upon synthetic jets that will be integrated into compact lighting fixtures. Synthetic jets create high-speed turbulence coolant streams that can provide >5X cooling versus natural convection cooling. Although this technology is still under development, initial results show the potential to shrink the size of the thermal management solution as well as the ability to run LEDs at higher driving currents, potentially reducing overall system cost.

Enhancement of Radiative Efficiency with Staggered InGaN Quantum Well Light Emitting Diodes

Investigating Organization
Lehigh University

Principal Investigator(s)
Nelson Tansu

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $598,445
Contractor Share: $150,481

Contract Period
06/01/08 – 05/31/11

Technology
Light Emitting Diodes

Project Summary

The objective of the proposed research is to improve the intrinsic quantum efficiency of InGaN-based LEDs for the green spectral region, in particular addressing issues due to the poor wave function overlap from the existence of polarization fields inside the quantum well (QW) active regions. For this goal, the team is investigating the use of staggered InGaN QWs as improved active region, which consists of two or three InGaN layers with different In-contents forming the QW system. They are addressing the serious performance-limiting issue presented by the existence of polarization fields in III-Nitride active regions, namely the low electron-hole wave function overlap that becomes a severe problem for structures with higher In-content. To circumvent this problem they are using staggered InGaN which will improve the overlap and will lead to increased radiative recombination rate and higher radiative efficiency. They are addressing this challenge in three phases:

1) Phase I: proof-of-concept of polarization engineering via staggered InGaN QW for enhanced radiative efficiency
2) Phase II: comprehensive recombination analysis and optical characterizations (NSOM, and time-resolved PL) for understanding the recombination mechanisms in InGaN QW
3) Phase III: MOCVD and device optimization of staggered InGaN QW for achieving high radiative efficiency LEDs emitting at 550-nm with radiative efficiency > 40%.

Several components that will be addressed as part of the proposed works are:
- Device physics and numerical design of staggered InGaN QW for enhanced radiative recombination rate
- MOCVD epitaxy and device fabrication of staggered InGaN QW LEDs
- Recombination analysis, NSOM and time-resolved PL of staggered InGaN QW
- Device optimization for III-Nitride LEDs with high internal quantum efficiency

High Quality Down Lighting Luminaire with 73% Overall System Efficiency

Investigating Organization
OSRAM SYLVANIA Development Inc.

Principal Investigator(s)
Robert Harrison

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $873,526
Contractor Share: $218,381

Contract Period
07/01/08 - 06/30/10

Technology
Light Emitting Diodes

Project Summary

The goal of this project is to develop a highly efficient luminaire by optimizing the optical, thermal and electronic efficiencies to achieve an overall 73% efficiency in the luminaire. This means 73% of the luminous flux generated by the LED devices instant-on will be maintained in the complete LED system luminaire under steady-state conditions. The light will be mixed from multiple blue LED sources in the remote phosphor layer which emits uniform, highly efficient white light in a hemispherical lambertian emission pattern. In a second step a reflector + lens/ diffuser concept is used to redirect the light into a 60 degree emission pattern. Thermally the objective is to design a chip on board light engine using blue chips and a remote phosphor layer closely coupled to a heat sink to provide us with a 5-6 K/W system thermal impedance. Electrically the objective is to design a driver with 90% efficiency and 50 khrs lifetime matching the lifetime of the LED light engine.

100 Lumen per Watt 800 Lumen Warm White LED for Illumination

Investigating Organization
Philips Lumileds Lighting, LLC

Principal Investigator(s)
Decai Sun

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,649,900
Contractor Share: $2,649,900

Contract Period
09/15/08 - 09/14/10

Technology
Light Emitting Diodes

Project Summary

Philips Lumileds Lighting Company is developing a high power LED capable of producing 800 lm of Warm White light with Color Correlated Temperature(CCT) in the range of 2800 K to 3500 K, Color Rendering Index(CRI) >90 and LED efficiency of over 100 LPW. The development effort will focus on pump LED device electrical injection efficiency and optical extraction efficiency improvement, high power LED package design and reduction in package thermal resistance and improvement in phosphor system efficiency and CCT control. The complete program will be executed on Philips Lumileds high power LED Luxeon K2® platform which gives a robust fast path for turning pre-production prototypes delivered by this program into high volume production LEDs that can have a direct impact on energy savings and reduction in carbon emission.

This program will integrate the resulting LED into a PAR38 light bulb with driver and optics to demonstrate feasibility in target application. Reliability testing will be done throughout the program to ensure that the approach taken meets the requirement for long life and consistent color expected from solid state lighting solutions.

Sintered Conductive Adhesives for HB-LED Thermal Management

Investigating Organization
Aguila Technologies, Inc.

Principal Investigator(s)
Dr. Matthew Wrosch

Subcontractor
None

Funding Source
Small Business Research R&D, Phase I

Award
DOE Share: $99,889

Contract Period
06/01/08 - 01/30/09

Technology
Light Emitting Diodes

Project Summary

Continuous improvements in high brightness light emitting diode (HB LED) technologies open up the possibility for utilization of these devices for general illumination. However, before HB LEDs can replace traditional lighting sources, improvements to their thermal management schemes, particularly the bonding technologies that hold the device components together, must be developed to ensure consistent color quality and competitive operational lifetimes. Conductive adhesives are typically used for low cost assembly, but these materials represent the weakest point in the thermal path. To address this issue, sintered conductive adhesives which form metallurgical bonds with the device components can provide an order of magnitude or better thermal performance than existing adhesive technologies.

Thermal Management for High-Brightness LEDs

Investigating Organization
Aqwest LLC

Principal Investigator(s)
Dr. John Vetrovec

Subcontractor
None

Funding Source
Small Business Research R&D, Phase I

Award
DOE Share: $99,358

Contract Period
08/29/08 - 03/30/09

Technology
Light Emitting Diodes

Project Summary

High-brightness (HB) light emitting diodes (LEDs) have demonstrated promise for general illumination in commercial and household applications, and offer up to 75% savings in electric power consumption over conventional lighting systems. Realizing the full potential of this new and highly efficient light source requires major improvements in cooling the LED chip and the LED package to prevent early degradation in light output and catastrophic failures.

This project will develop and demonstrate a novel "active heat spreader" (AHS) which efficiently removes heat for LED and allows the diode junction to operate at reduced, safer temperature, thereby extending LED lifespan and reliability. Integrated HB-LED assemblies with AHS aimed at specific product types will be developed for early introduction on the market.

Innovative AHS developed by this project offers LED life extension by a factor of 2 or more while enabling at least 10% higher LED light output. Availability of this high-performance thermal management device promises to accelerate replacement of inefficient incandescent lights (especially in recessed light applications) by LED-based lighting and, thereby, potentially save $5.3 billion or more in electricity costs.

Built-In Electrofluidic Thermo-Management of Solid-State Illumination Arrays

Investigating Organization
Physical Optics Corporation

Principal Investigator(s)
Mr. Michael Reznikov

Subcontractor
None

Funding Source
Small Business Research R&D, Phase I

Award
DOE Share: $99,992

Contract Period
06/01/08 - 01/30/09

Technology
Light Emitting Diodes

Project Summary

The unavailability of adequate thermal management solutions for high brightness light emitting diodes (HB LED's) limits the use of their superior advantages, such as high energy efficiency, low-temperature operation, robustness, digital control, low-voltage operation, and long life. The unresolved heat causes the LED junction temperature to rise, which limits the life of the light source and also causes color shifts. Solving the thermal issue is a large step in the direction of creating a market shift toward LED's for general illumination, which will save large amounts of energy globally.

Based on electrohydrodynamic atomization, electrostatically-controlled liquid and vapor transport, and an electrostatically-assisted convective heat sink, the proposed system uses electrostatically-enhanced, two-phase thermal transporters embedded into the epoxy casing of multiple HB LEDs to provide a thermal resistance near 4°C/W between the LED junction and the ambient environment. The transporters of the proposed system will efficiently extract heat from each LED junction and direct it to an ultra-compact system heat sink, which is convectively cooled by a cluster of ion-driven air microjets.

By creating a practical means for cooling HB LED arrays, the proposed system will allow the conventional light bulb to become LED-based. Consequently, because of their high energy efficiency and extreme longevity, significant energy savings will be realized globally and the production of waste will be reduced, thus extending the life of landfills. The core technology of the proposed system will have tremendous marketability since technological growth in a number of industries has recently been limited by insufficient thermal management solutions, i.e., scaled-down conventional cooling systems have been unable to meet intensified heat flux demands.

High Efficiency Long Lifetime OLEDs with Stable Cathode Nanostructures

Investigating Organization
Lawrence Berkley National Laboratory

Principal Investigator(s)
Samuel S. Mao

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $600,000

Contract Period
06/15/06 - 06/14/09

Technology
Organic Light Emitting Diodes

Project Summary

The objective is to develop nanostructured OLEDs by implementing a cathode-organic layer interface that has improved electron injection efficiency and is environmentally stable for ease of manufacturing and long product life. This approach represents a fundamental shift in design of OLED cathode materials and structures. The primary benefit is the expected development of patterned OLED cathodes that are less sensitive to the environment thus reducing the need for vacuum processing and packaging. A secondary benefit of the proposed technology is the potential of scale-up patterning of cathode into photonic structures that can effectively out-couple light that is otherwise unavailable with conventional planar geometry.

High Quality Low Cost Transparent Conductive Oxides

Investigating Organization
Los Alamos National Laboratory

Principal Investigator(s)
Anthony Burrell

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,650,000

Contract Period
08/01/06 - 07/31/09

Technology
Organic Light Emitting Diodes

Project Summary

The overall object of this program is to develop cost effective routes to transparent conductors suitable for organic light emitting diode devices. LBNL will approach this problem in three ways. Initially, they will examine known transparent conductors using the PAD system and evaluate there feasibility for cost effect production and material quality. They will also focus on the production of doped zinc oxide as a transparent conductor and develop methodologies suitable for producing this transparent conductor on glass (i.e. low temperature methods). Finally they will develop a combinatorial approach to materials development, using PAD, to search for new and better transparent conductors.

Novel High Work Function Transparent Conductive Oxides for Organic Solid-State Lighting Using Combinatorial Techniques

Investigating Organization
Pacific Northwest National Laboratory and National Renewable Energy Laboratory

Principal Investigator(s)
Daniel Gaspar

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,200,000

Contract Period
10/01/06 - 09/30/09

Technology
Organic Light Emitting Diodes

Project Summary

The overall objective is to develop new indium-free transparent conductive oxides with high work function and stability in organic light emitting device configurations. The team will accelerate the discovery of novel TCO materials for solid state lighting by using a set of unique combinatorial deposition and analysis techniques which are capable of generating a wide range of related TCO compositions on a single substrate. These combinatorial films will be created and characterized at DOE's National Renewable Energy Laboratory (NREL) and integrated with small molecule OLEDs at DOE's Pacific Northwest National Laboratory (PNNL). As improved TCOs are discovered, facilities at PNNL will also allow for production of limited prototype quantities on larger scale glass for testing by lighting and OLED manufacturers.

The primary goal is a TCO with equivalent or better transparency and sheet resistance to those of ITO. However, success could also be achieved even if the transparency and sheet resistance of the new TCO is too low by depositing a thin layer of it on top of commercial ITO, thereby raising its work function and chemically isolating the In-containing oxide from the active organic layers. A further goal will be a more stable TCO material that can withstand operating environment of the OLED for the anticipated operating lifetime of a solid state lighting source. We will focus on materials which are processible at low (< 200°C) temperatures so as to allow deposition on plastic substrates for high volume scale-up or roll-to-roll manufacturing.

High Efficiency Microcavity OLED Devices with Down-Conversion Phosphors

Investigating Organization
University of Florida

Principal Investigator(s)
Franky So

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,200,000
Contractor Share: $300,000

Contract Period
06/01/06 - 08/31/09

Technology
Organic Light Emitting Diodes

Project Summary

The overall objective of this project is to demonstrate high efficiency white emitting OLED devices with luminous efficiency between 100 lm/W and 150 lm/W with integrated microcavity structure and down conversion phosphors. To achieve this device performance, the main focus of this work will be on three areas, namely (1) demonstration of a 2X reduction in OLED device operating voltage by employing the appropriate dopants in the carrier transporting layers, (2) demonstration of a 3X light out-coupling efficiency enhancement by incorporating microcavity structure in the OLED devices and (3) demonstration of a 2X down-conversion efficiency (from blue to white) using phosphors.

Multi-Faceted Scientific Strategies Toward Better SSL of Phosphorescent OLEDs

Investigating Organization
University of North Texas

Principal Investigator(s)
Mohammad Omary

Subcontractor
University of Texas at Dallas

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,569,868
Contractor Share: $699,228

Contract Period
10/01/06 - 01/15/10

Technology
Organic Light Emitting Diodes

Project Summary

The objective of this project is to advance phosphorescent OLEDs through: (1) a targeted synthesis of emitters designed to exhibit efficient phosphorescence in the solid state, and (2) construction and optimizing the performance of monochromatic and white OLEDs on glass and flexible substrates. The emitters are screened candidates among the large variety of recently synthesized and newly designed molecular and macromolecular metal-containing phosphors. The emitters and devices will be optimized to quantitatively harvest triplet excitons, maximize the charge transport properties to warrant efficient injection of carriers into the emissive layer, assess and improve the long-term durability of the various emitters and device types, and reduce the manufacturing cost both by constructing thinner and more efficient devices and by seeking less expensive device components.

OLED Lighting Device Architecture

Investigating Organization
Eastman Kodak

Principal Investigator(s)
Dr. Yuan-Sheng Tyan

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,167,283
Contractor Share: $778,190

Contract Period
10/01/06 - 03/31/09

Technology
Organic Light Emitting Diodes

Project Summary

This project takes a systems approach to develop and co-optimize four key technologies in parallel to bring about a significant advancement in the power efficiency and lifetime of OLED based white-light illumination devices. The four key technologies areas are; light extraction efficiency enhancement, low operating voltage materials and structures, high quantum efficiency and stable white emitters, and stacked-architecture.

The project leverages the extensive OLED materials and device expertise in Kodak Research Laboratories and Kodak Display Business Units. It combines extensive modeling and experimental work. It is expected that at the end of the two-year project we will deliver an OLED device architecture having over 50 lm/W power efficiency and 10,000 hours lifetime at 1000 cd/m^2. The device will be suitable for development into successful commercial products.

Investigation of Long-Term OLED Device Stability via Transmission Electron Microscopy Imaging of Cross-Sectioned OLED Devices

Investigating Organization
Lawrence Berkley National Laboratory

Principal Investigator(s)
Gao Liu

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $825,000

Contract Period
08/01/07 - 09/15/10

Technology
Organic Light Emitting Diodes

Project Summary

The objective is to improve OLED lifetime and functionality by combining novel fabrication and state of the art characterization techniques to understand the origins of device degradation in white light OLEDs. The research focuses on the interfacial evolution at different stages of device lifetime to provide a comprehensive understanding of the interface degradation and resulting device characteristics to design more stable interfaces by controlling the light emitting polymer this film morphology for improved lifetime.

The research combines the advanced transmission electron microscopy imaging techniques with polymer morphology control to correlate the structure and interface changes to the device degradation process. Techniques that better control the morphology of the light-emitting layer are to be developed. The ability to control the morphology of this layer will allow for optimization of the device for the desired performance attributes of improved efficiency and brightness. Upon analysis, the morphologies that give the best long-term performance will be identified, along with the processes leading to these morphologies. The approaches to stabilize the morphology and interface will also be studied in this work.

High Stability Organic Molecular Dopants for Maximum Power Efficiency OLEDs

Investigating Organization
Pacific Northwest National Laboratory

Principal Investigator(s)
Daniel Gaspar

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,733,122

Contract Period
07/30/07 - 07/29/10

Technology
Organic Light Emitting Diodes

Project Summary

Researchers at the Pacific Northwest National Laboratory are developing a new set of molecular dopants for bright, long lived OLEDs by tethering high electron affinity moieties to stable, vacuum-sublimable anchor molecules. In this manner, they are introducing charge into the OLED layers in a spatially controllable manner more analogous to an inorganic semiconductor dopant. In addition to improving the stability of doped OLEDs, the ability to control doping in fixed positions relative to the electrodes and organic interfaced will allow separation of interfacial and bulk effects for creating compositionally graded layers leading to optimization of both voltage and efficiency in bright, long lived OLEDs for solid state lighting.

High Quantum Efficiency OLED Lighting Systems

Investigating Organization
General Electric Global Research

Principal Investigator(s)
Dr. Joseph Shiang

Subcontractor
M.I.T.
Stanford University

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,697,422
Contractor Share: $1,200,586

Contract Period
10/01/07 - 12/31/10

Technology
Organic Light Emitting Diodes

Project Summary

GE, Stanford, and MIT will team together to overcome the limitations in current technology by delivering to DOE a >75LPW illumination quality white light device (2800-6500 CCT, >85 CRI, >7000 hour life) that has a luminous output comparable to a 60W incandescent lamp (900 lumens). The proposed lighting systems feature optimized multiple color, high IQE OLEDs that are arranged on a common substrate. A synergistic combination of the light management film and OLED structure will form the basis of the Light Extraction Architexture (LEA). The OLED elements will be optimized using electrode texturing and "extra-fluorescence" to amplify the effect of the LEA. The OLED will be powered by a simple power supply that can be operated from standard line voltages and will require minimum additional luminaire structures, thus minimuzing driver and luminaire losses. When all technologies in this program are fully developed, the expected EQE entitlement will exceed 75%. As a result, a key roadblock to OLED technology development and commercialization for the lighting market will be removed.

Low Cost, High Efficiency Polymer OLEDs Based on Stable p-i-n Device Architecture

Investigating Organization
Add-Vision Inc.

Principal Investigator(s)
Devin MacKenzie

Subcontractor
UCLA
University of California, Santa Cruz

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,569,728
Contractor Share: $442,746

Contract Period
10/01/08 - 09/30/11

Technology
Organic Light Emitting Diodes

Project Summary

The objective of the proposed research is to synthesize new conjugated polymers and photocurable electrolytes that allow the formation of a static p-i-n junction in polymer thin films and the development of low cost fully printable P-OLED lamps for SSL with a target performance of 40 Lm/W at 800 cds/m2 and >5,000 hour lifetime, that can be fabricated over larger-areas on flexible plastic substrates using a printable air-stable electrode. The research will involve polymer synthesis, nanoscale polymer composition, thin-film processing, and the characterization of electrical, optical, and electrochemical properties. This work intends to optimize targeted material sets, identify the barriers to performance relevant for SSL lamp applications, optimize processing towards the performance requirements of SSL P-OLED, and demonstrate the p-i-n P- OLED lamp technology as a large-area, ultra-low cost solution for US manufacturing.

Charge Balance in Blue Electrophosphorescent Devices

Investigating Organization
Pacific Northwest National Laboratory

Principal Investigator(s)
Asanga B. Padmaperuma

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,782,638

Contract Period
04/01/08 - 03/31/11

Technology
Organic Light Emitting Diodes

Project Summary

The objective of this project is to develop new ambipolar phosphine oxide host materials to improve charge balance in blue phosphorescent OLEDs, a necessary component of efficient white OLEDs. Developing compatible host and blocking materials for blue phosphorescent dopants is challenging because triplet exciton energies higher than the dopant are required for all materials while reasonable charge transport rates must be maintained to ensure injection of charge into the emissive layer. In conjunction with their phosphine oxide electron transporting / hole blocking materials, new phosphine oxide host materials incorporating hole transporting capability will provide appropriate energy level alignments to optimize the injection and transport of both electrons and holes into the emission layer. This will be accomplished while still maintaining the high triplet exciton energy necessary to achieve efficient energy transfer to the phosphorescent dopant. Achieving charge balance in the recombination region of the OLED will maximize the luminescence efficiency, as well as improve device stability by preventing charge accumulation at the interfaces.

Application of Developed APCVD Transparent Conducting Oxides and Undercoat Technologies for Economical OLED Lighting

Investigating Organization
Arkema, Inc.

Principal Investigator(s)
Gary Stephen Silverman

Subcontractor
Philips Lighting

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,101,305
Contractor Share: $525,326

Contract Period
09/03/08 - 09/02/10

Technology
Organic Light Emitting Diodes

Project Summary

The project focuses on using a suitable alternative for tin doped indium oxide (ITO) as a transparent conducting oxide (TCO) on glass substrates. Doped ZnO, has been developed by Arkema and its partners for application in the fenestration (window) market. Subsequently, this project is focused on using technology from the fenstration industry and applying it to the OLED lighting market. This represents a necessary economical step for OLED lighting by shifting the “Substrate “ cost from expensive ITO Flat Pannel Display glass to doped ZnO on residential window glass. The key deliverable at the end of the two year project is a 1 square foot OLED prototype suitable for market testing.

Development of High Efficacy, Low Cost Phopshorescent OLED Lighting Ceiling Luminaire System

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Mike Hack

Subcontractor
University of Michigan
University of Southern California
Armstrong World Industries

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,918,878
Contractor Share: $760,375

Contract Period
07/10/08 – 07/09/10

Technology
Organic Light Emitting Diodes

Project Summary

The objective of the project is to develop and deliver high efficiency OLED lighting luminaires that exceed the Department of Energy (DOE) 2010 performance projections. Specifically, the project team plans to deliver two prototype OLED lighting luminaires, each consisting of four individual OLED lighting panels integrated into Armstrong's TechZone novel open architecture ceiling systems. Each system is anticipated to produce over 300 lumens, have an overall efficiency of 55 lm/W, a CRI = 85 and a > 10,000 hour projected lifetime to 70% of initial luminance, and designed for low cost manufacturing with a projected panel cost of less than $50 per klm. In addition, the team anticipates delivery of one 6" x 6" lighting panel fabricated on a flexible metal foil substrate, demonstrating the possibility of a range of form factors.

Materials Degradation Analysis and Development to Enable Ultra Low Cost, Web-Processed White P-OLED for SSL (Phase II)

Investigating Organization
Add-Vision Inc.

Principal Investigator(s)
Devin MacKenzie

Subcontractor
LBNL

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $748,258

Contract Period
08/15/08 - 08/14/10

Technology
Organic Light Emitting Diodes

Project Summary

AVI and the Lawrence Berkeley National Laboratory uncovered efficiency degradation mechanisms for doped polymer organic light emitting devices in Phase-I, and will develop a next generation set of materials and processing using this analysis to create high efficiency, longer lifetime printed devices with flexible encapsulation produced in a low cost, air printing process. Upon achievement of the performance and lifetime improvements, Phase-II and III emphasize product demonstration, process scale-up and pilot manufacture with continuous engagement with our manufacturing licensee(s) and product development customers.

High Efficiency Organic Light Emitting Devices for General Illumination (Phase II)

Investigating Organization
Physical Optics Corporation

Principal Investigator(s)
Paul Shnitser

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $745,000

Contract Period
08/08/07 - 08/07/09

Technology
Organic Light Emitting Diodes

Project Summary

The goal of this project is to develop a novel architecture and fabrication technology for OLED substrates that will enhance light extraction efficiency and improve the uniformity and color perceptive of OLEDs, while being suitable for mass fabrication at low cost. The Phase II work will include further optimization of substrate layers, optimization of the parameters of the surface relief structure, development of technology for inexpensive roll-to-roll fabrication of OLED substrates on a flexible polymer base, and development of a set of crucial substrate parameters and the methods to control them to optimize the manufacturing process.

New Low Work Function, Transparent Electrodes for Robust Inverted-Design OLEDs

Investigating Organization
Tda Research, Inc.

Principal Investigator(s)
Dr. Shawn A. Sapp

Subcontractor
STTR – Colorado State University, Dept. of Chemistry, Professor C. Michael Elliott

Funding Source
Small Business Research R&D, Phase I

Award
DOE Share: $100,000

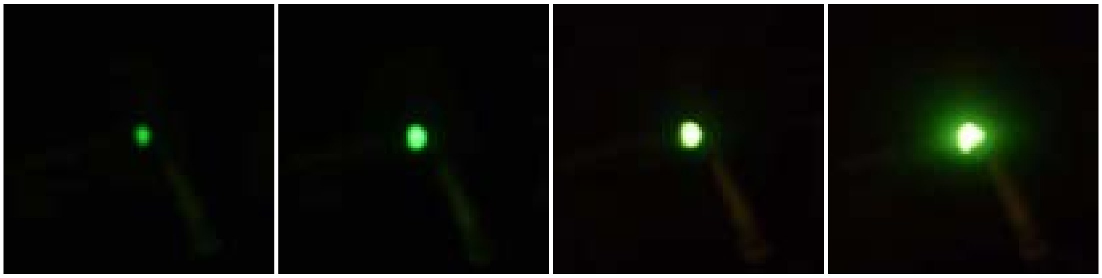
Contract Period
06/30/08 - 03/29/09

Technology
Organic Light Emitting Diodes

Project Summary

Approximately 20% of US energy consumption comes from illumination alone; this usage can be halved by emerging OLED lighting technologies. However, materials stability issues have lowered the operating life of these OLEDs, and one of the main culprits is the use of indium-tin oxide as a transparent electrode. The goal of this project is the fabrication and testing of new inverted OLED prototypes incorporating new materials as the transparent electrodes to improve efficiency, stability, and lifetime.

TDA Research, Inc. (TDA) has been developing specialty conducting polymer materials for the last six years for use in OLEDs, solar cells, flat screen displays, printed electronics, sensors, and RFID applications. This research has led to a line of commercial products available from Sigma-Aldrich since August 2004. Recently, we discovered a low work function, transparent version of our conducting polymer that can be processed from solvent dispersion. During this project we have thus far produced a variety of our transparent, low work function conducting polymers and confirmed their electronic and optical properties. With the help of CSU, we have streamlined our OLED fabrication process with highly efficient, standard design OLEDs (see figure below). Our next step will be to use our conducting polymers with a low work function transparent conducting oxide as the cathode in inverted OLED prototypes. This inverted device structure eliminates the need to use ITO as the transparent conductor and simultaneously eliminates the need for a reactive metal cathode. Together this will lead us to highly efficient inverted OLEDs that have the necessary stability and lifetime to enter the lighting market.



5V 10V 15V 20V

Efficient Large Area WOLED Lighting (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Rui-Qing (Ray) Ma

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
08/20/08 - 08/19/10

Technology
Organic Light Emitting Diodes

Project Summary

Improvements in the overall efficiency and lifetime of these OLED devices are required before they become commercially viable products. The objective of this project is to enable the demonstration of an efficient, novel OLED illumination system with 150 lm/W power efficacy. Phase I demonstrated a non-stacked white phosphorescent OLED with 6 organic materials. The device exhibited extremely long lifetime (LT_{50} >200,000 hrs) at an initial luminance of 1,000 cd/m^2. Phase II will involve the design and fabrication of a prototype warm white OLED that achieves 75 lm/W with LT_{70} > 35,000 hours at an initial luminance of 1,000 cd/m^2.

Enhanced Light Outcoupling in WOLEDs

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Rui-Qing (Ray) Ma

Subcontractor
None

Funding Source
Small Business Research R&D, Phase I

Award
DOE Share: $99,919

Contract Period
06/01/08 - 01/30/09

Technology
Organic Light Emitting Diodes

Project Summary

In 2001, lighting is estimated to consume 8.2 quads (approximately 762 TWh), or about 22% of the total electricity generated in the U.S., so new high-efficiency solid-state light sources, such as light emitting diodes (LEDS) and organic LEDs (OLEDs), are needed to help reduce the ever increasing demand for energy. An OLED is potentially an inexpensive diffuse source that may compete most directly with and offer a ‘green’ alternative to conventional incandescent light sources; however, improvements in the overall efficiency of these devices are still required before they become commercially viable products and attain expected goals in terms of cost ($3 per 1000 lumens) and performance (150 lumens per watt).

This proposed research will utilize novel outcoupling enhancement features in OLEDs architectures to enable highly efficient, organic, solid-state, lighting sources to replace short lifetime 12 lm/W incandescent sources, and hence reduce overall energy consumption in the U.S. Additionally, the research will support future work to attain OLEDs having 150 lm/W power efficacy.

Today, OLED technology is the leading emerging technology for flat panel displays (FPDs), with recent product introductions in cell phones. Many of these features that are desired for FPDs are also making OLED technology of great interest to the solid-state lighting community. For example, OLEDs are bright and colorful lambertian emitters with excellent power efficiency at low voltages. In addition, OLEDs are thin-film devices that provide thin form factors especially when built on flexible substrates. Moreover, OLEDs require less materials, have fewer processing steps, and may be less capital intensive than today's dominant liquid crystal displays (LCDs).

High Efficacy Phosphorescent SOLED Lighting (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Vadim Adamovich

Subcontractor
University of Southern California
University of Michigan

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $749,981

Contract Period
08/20/08 - 08/19/10

Technology
Organic Light Emitting Diodes

Project Summary

New, high-efficiency, solid-state light sources, such as organic light emitting diodes (OLEDs), are needed to help reduce the ever increasing demand for energy. Improvements in the overall efficiency and lifetime of OLED devices are required before they become commercially viable products. The objective of this project is to design, characterize and build a stacked OLED (SOLED) that will provide the research necessary to achieve the performance required for commercial products. This will require analytical study of the device physics to increase the stability of WOLEDs developed in Phase I, improving the device total power efficacy to >75 lm/W. One key aspect of the work will target the understanding and fabrication of organic junctions that electrically connect vertically SOLEDs. Once having established firm design parameters, UDC will then design, build, and characterize SOLED 2" × 2" panels.

WOLEDs Containing Two Broad Emitters (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Vadim Adamovich

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
08/08/07 - 08/07/09

Technology
Organic Light Emitting Diodes

Project Summary

The proposed research will utilize novel OLED fixtures enabling highly efficient stable, organic, solid-state lighting sources to replace short lifetime 12 lm/W incandescent sources, and hence reduce overall energy consumption in the U.S. Additionally, the research will support future work to attain OLEDs having 150 lm/W power efficacies.

In Phase I, a white OLED containing only two phosphorescent emitters was demonstrated with an efficacy of 24 lm/W at a forward luminance of 800 cd/m^2. The device had a CIE = (0.38, 0.37), a CRI of 71, and a correlated color temperature of 3,900K and met the targets of the Phase I program.

During Phase II, white OLEDs with a simple architecture containing only two phosphorescent emitters and/or as few organic materials as necessary will be developed to enable low-cost white OLED lighting sources. These devices will have color rendering indexes (CRI) of >75, and efficacy of 60 lm/W at 1,000 cd/m^2.

Blue/UV LEDs with Very High Photon Conversion and Extraction Efficiency for White Lighting

Investigating Organization
Boston University

Principal Investigator(s)
Professor Theodore Moustakas

Subcontractor
SAIC - Spilios Riyopolous

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $959,993
Contractor Share: $242,700

Contract Period
09/24/04 - 11/30/07

Technology
Light Emitting Diodes

Project Summary

This project is studying a unique approach to growing GaN-based LEDs on thick textured GaN quasi-substrates, using Hydride Vapor Phase Epitaxy (HVPE) instead of more costly Metal-Organic Chemical Vapor Deposition (MOCVD). It is anticipated that the work will demonstrate vastly improved device efficiencies. This is due to the substantial reduction in defect densities normally associated with nitride devices grown on materials of differing lattice constants, such as sapphire. In addition to exploring the potential for large increases in internal quantum efficiency due to the defect density reduction, significant increases in external quantum efficiencies are also possible due to the reduction in natural wave guiding that generally occurs at material interfaces. This imaginative work will address a number of issues plaguing the performance of nitride systems and may enable future breakthroughs in device efficiency and light management.

Nanostructured High-Performance Ultraviolet and Blue LEDs

Investigating Organization
Brown University

Principal Investigator(s)
Dr. Arto Nurmikko

Subcontractor
Yale University

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $900,000
Contractor Share: $229,033

Contract Period
09/23/03 - 03/31/07

Technology
Light Emitting Diodes

Project Summary

In this project, nanomaterial science is synergized with fundamental optical physics concepts pertaining to light-matter interaction. The goal is to develop a new class of high-performance light emitting diodes in the blue and near ultraviolet for solid state lighting applications, covering the spectral regime of approximately 370-480 nm. The overall mission is to implement novel, highly adaptable device concepts that enable flexible use, and match the broad spectrum of requirements posed by contemporary solid state lighting approaches. The light emitters are based on nanostructured gallium nitride and related semiconductors, which were encased by engineered nano-optical photonic confinement structures. The researchers aim to reach the goal of a highly wall-plug-efficient, high-power optical device (> 100 lm/W) by concentrating on two specific, highly interrelated elements within the LED.

Development of Advanced LED Phosphors by Spray-Based Processes for Solid State Lighting Applications

Investigating Organization
Cabot Superior MicroPowders

Principal Investigator(s)
Mr. Klaus Kunze

Subcontractor
Sandia National Laboratories (SNL)

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,287,383
Contractor Share: $779,315

Contract Period
10/01/04 - 04/01/07

Technology
Light Emitting Diodes

Project Summary

The goal of the project is to develop luminescent materials using aerosol processes for making improved LED devices for solid state lighting applications. This will be accomplished by selecting suitable phosphor materials that are generated by liquid or gas to particle conversion in micron to submicron ranges (0.1 - 1 micron) with defined spherical morphology and various particle size distributions, coated or uncoated, and applying them by appropriate mixing with or without extra layer components such as glass particles into thin phosphor layers to create more optically efficient LED devices. The specific technical objectives of the proposed work are as follows:

- Demonstrate the feasibility of spherical micron and submicron sized phosphor materials with homogeneous dopant distribution and various particle sizes and particle size distribution obtained by spray pyrolysis to create LED phosphors with improved luminescence efficiency.
- Develop phosphor particles in the range around 100nm to demonstrate the feasibility of more efficient luminescent centers with strongly reduced optical scattering.
- Incorporate these phosphor powders into organic or inorganic layer structures to understand and evaluate the effect of morphology and spread of the size distribution on phosphor layer efficiency.

- Produce multiple phosphor compositions for blended layers to investigate the effect of matched morphology, particle size and spread of particle size distribution on phosphor layer efficiency.
- Incorporate low melting glass particles to test for improved layer optical characteristics and thermal stability.
- Develop coated phosphors for incorporation into more temperature robust and less humidity sensitive layers.

Phosphor-Free Solid State Lighting Sources

Investigating Organization
Cermet Inc.

Principal Investigator(s)
Mr. Jeff Nause

Subcontractor
Georgia Tech

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $3,840,370
Contractor Share: $971,239

Contract Period
09/30/03 - 02/28/07

Technology
Light Emitting Diodes

Project Summary

Cermet's work focuses on growing conventional materials on novel substrates that possess unique physical properties with less internal strain. This process has the potential to increase efficiency; have emissions that can be adjusted by carefully applying potentials across the substrate; and can be made to behave like a phosphor, absorbing photons of one color and emitting new ones that are of a different color.

The goal of Cermet's effort is to implement large-area zinc oxide fluorescent substrate technology and state-of-the-art, lattice-matched nitride epitaxy technology to address substrate, epitaxy, and device limitations in the high growth area of solid state lighting. Cermet, in collaboration with researchers at Georgia Institute of Technology, will bring several technological innovations to the marketplace, including the following:

1. Truly lattice matched, low defect density (as low as 104 cm^2) nitride emitter structures resulting in significantly reduced non-radiative recombination centers. This goal will be achieved by combining molecular beam epitaxy (MBE) and metallorganic chemical vapor deposition (MOCVD) with a ZnO substrate that is lattice matched to nitride LEDs in the wavelength range of 330 to 420 nm. Shorter wavelength designs are also possible using strain compensated layer growth.

2. White light emission via a self-fluorescing mechanism in the ZnO substrate. This will be accomplished by doping the ZnO substrates to yield emission in the vision spectrum. Optical pumping of the substrate will be achieved with the integrated nitride emitter.

3. Ability to adjust the color content of the white light. This will be achieved by adjusting the doping concentration of the substrate.

High-Efficiency LED Lamp for Solid State Lighting

Investigating Organization
Cree, Inc.

Principal Investigator(s)
Mr. James Ibbetson

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,419,584
Contractor Share: $473,194

Contract Period
09/1203 - 12/31/06

Technology
Light Emitting Diodes

Project Summary

Cree SBTC is working to develop LED chip and package technology that will enable high-efficiency, cost-effective LED lamps for solid state lighting. Although the energy efficiency of state-of-the-art LED technology now exceeds that of conventional incandescent lamps, significant improvements in the cost performance – measured in dollars per kiloLumen – are crucial to realizing substantial energy savings from solid state lighting in the near future. The objective of the program is to demonstrate the potential for solid state lamps to become available at a fraction of today's cost by substantially increasing the operating current density and energy efficiency of the white LEDs used as the lamp "filaments," compared to white LEDs available today.

In this research, Cree will leverage its highly efficient Gallium Indium Nitride on Silicon Carbide (GaInN/SiC) emitter technology, and its low thermal resistance surface mount packaging technology. The program goals will be achieved by combining innovative approaches in (a) GaInN-based materials technology, (b) LED device fabrication, and (c) solid state lamp packaging. GaN-based materials and LED chip design will be optimized to enable very high current density operation of LEDs. Advanced chip designs and fabrication techniques will be developed with improved energy efficiency by reducing the optical and electrical losses that typically occur. Packaging technology will be developed that allows an increase in the power dissipation from a given footprint and makes more efficient use of the light emitted from the LED chips. Together, the improvements will allow the delivery of a lot more light per LED chip unit area, thus driving down the overall lamp cost.

The project has increased the quantum efficiency of a 1 x 1 mm^2 blue LED chip to 49% (after packaging) when operated at a drive current of 350 mA. With the addition of a phosphor, this translates into a white LED with an efficacy of 86 lumens per watt. At 700 mA, or twice the current density, blue LED quantum efficiency of 43% and white LED efficacy of 68 lumens per watt have been demonstrated.

Small-Area Array-Based LED Luminaire Design

Investigating Organization
Cree, Inc.

Principal Investigator(s)
Thomas Yuan

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,651,867
Contractor Share: $616,461

Contract Period
01/04/05 - 01/09/08

Technology
Light Emitting Diodes

Project Summary

Cree Inc. Santa Barbara Technology Center (SBTC) is designing and developing a compact light emitting diode (LED) based luminaire that could enable the replacement of a significant portion of the current incandescent market. Specifically, the program targets a BR/PAR-style integrated reflector luminaire suitable for low-cost insertion into existing commercial and residential lighting fixtures.

Since performance alone will not be the sole metric determining eventual wide acceptance of LED-based lighting into commercial markets, Cree will utilize a rapidly growing foundation of commercial LED and LED package manufacturing experience to ensure cost effective, manufacturable solutions are implemented in an integrated luminaire suitable for high-efficiency, drop-in replacement of existing incandescent light sources.

Cree achieved white LED arrays with an efficacy of 78 lumens per watt at 350 mA. A thermal resistance of 8^{o}C/W from junction to board has been realized. These arrays will be the basis of the luminaire.

White Light Emitting Diode Development for General Illumination Applications

Investigating Organization
Cree

Principal Investigator(s)
James Ibbetson

Subcontractor
Lawrence Berkeley National Laboratory

Funding Source
BT/NETL SSL

Award
DOE Share: $2,247,250
Contractor Share: $750,000

Contract Period
09/30/00 - 10/31/04

Technology
Light Emitting Diodes

Project Summary

In this completed program (October 2004), Cree SBTC and LBNL developed high-efficiency, high-radiance LED and packaging technology to push white LED brightness into the 50-60 lumens-per-watt range. At such levels, novel solid state lamps using a few LED "filaments" should be capable of replacing less energy-efficient lighting technologies. Potential benefits include lamp dimability, efficiency, consistent lifelong color, extended lamp life, and the absence of toxic materials.

By the end of the program, Cree demonstrated white lamps with output of 67 lumens at 57 lumens per watt using a single LED chip, and compact lamp prototypes with output up to 1200 lumens at >40 lumens per watt using multiple LEDs.

In this research, Cree leveraged its highly efficient Gallium Indium Nitride on Silicon Carbide (GaInN/SiC) emitter technology. Advanced chip designs and fabrication techniques were developed to increase the energy efficiency of the LED chip by reducing the optical and electrical losses that typically occur. The development process used a combination of optical modeling, device simulation, fabrication, and characterization of device prototypes to assess the impact of various design modifications on chip performance. LED chip efficiency nearly tripled over the course of the program.

In addition, novel solid state lamp package technology was developed with LBNL to ensure that light emitted from the LED chip can be used efficiently in actual lighting applications. This work included thermal and optical modeling to establish package design constraints, and the use of high-reliability materials for very long-lived LEDs. Lamp prototypes were built and evaluated to see how various materials and design geometries affected heat dissipation and light output from a compact LED source. One such demonstrator was a narrow viewing angle (±30) light source with the same optical source size as a conventional MR16 lamp. In this case, the LED lamp output 800 lumens with an efficacy of 40 lumens per watt, or roughly the same amount of light as a commercial halogen reflector lamp at more than twice the energy efficiency.

Quantum-Dot Light Emitting Diode

Investigating Organization
Eastman Kodak

Principal Investigator(s)
Keith Kahen

Subcontractor
Cornell University
University of Rochester

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $616,329
Contractor Share: $410,886

Contract Period
08/01/06 - 07/31/08

Technology
Light Emitting Diodes

Project Summary

Eastman Kodak is creating low cost inorganic quantum dot light emitting diodes (QD-LEDs), composed of quantum dot emitters and inorganic nanoparticles, which have the potential for efficiencies equivalent to that of LEDs and OLEDs and lifetime, brightness, and environmental stability between that of LEDs and OLEDs. Both the quantum dot emitters and the inorganic nanoparticles will be formed by colloidal chemistry processes.

Specific program objectives are: 1) Understand the device physics of transport and recombination processes in the QD-LEDs; 2) Create a suite of measurement tools for characterizing the properties of the nanocrystals, such as, size, shape, compositional profile, quantum yield, and the effectiveness of the surface passivation; 3) Optimize simultaneously the conduction, injection, and recombination processes in the QD-LED emitter layer; 4) Create n- and p-type transport layers composed of nanoparticles whose resistivities are less than 100 ohm-cm; 5) Form low resistance ohmic contacts (~1 ohm-cm^2) to the QD-LED; and 6) Create a green-yellow emitting QD-LED with a brightness greater than 300 cd/m^2, an external quantum efficiency of ~3 lumens/W and a device operational lifetime (50%) of more than 1000 hours.

Novel Approaches to High-Efficiency III-V Nitride Heterostructure Emitters for Next-Generation Lighting Applications

Investigating Organization
Georgia Institute of Technology

Principal Investigator(s)
Mr. Russell Dupuis

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $428,632
Contractor Share: $152,097

Contract Period
09/30/03 - 06/30/07

Technology
Light Emitting Diodes

Project Summary

Georgia Tech Research Corporation is working to produce new knowledge of the roles various materials have on LED properties and efficiencies and a more detailed understanding of the fundamental chemical process behind light production. The university's goal is to assimilate new information that enables the possibility of developing more efficient green LEDs that could, in turn, produce a new LED device capable of complete color-spectrum white light.

The Georgia Tech research program will develop technologies for the growth and fabrication of high-quality green light-emitting devices in the wide-bandgap III-V nitride InAlGaN materials system. The group's research will include four components. Part One will make use of advanced equipment for the metal organic chemical vapor deposition (MOCVD) growth of III-nitride films and the characterization of these materials. Part Two focuses on the development of innovative growth technologies for high-quality green light-emitting diodes. Part Three will involve the study of strain effects and piezoelectric and polarization effects upon the LED performance. Part Four will focus on the design, fabrication, and testing of nitride LEDs.

Tasks 1 and 2: Focuses on studying the growth and characteristics of our standard blue LED structures which are based on growth condition optimizations for the GaN-based LED structures that were developed in this program. These LED performance characteristics are used for a reference for comparison purposes with green LED performance characteristics that are currently under study. The device structure consists of an n-type GaN:Si cladding layer, InGaN/GaN MQW, p-type AlGaN:Mg electron blocking layer, p-type GaN:Mg cladding layer, and GaN:Mg p-contact layer (from sapphire substrate to top). The team explored the use of various p-type layers for growth of InGaN-GaN MQW LEDs and have shown significant improvement for InGaN:Mg p-type contact layers in place of the standard GaN:Mg p-type contact layer.

Tasks 3 and 4: Focuses on developing a 1-dimensional mode for the diode active region incorporating the piezoelectric and polarization fields in order to examine the influence of LED performance on the quantum-well and barrier alloy compositions and thicknesses. For measurement of device output and I-V characteristics, the team performed wafer-level quick-test mapping as well as measurement of fully processed devices (unpackaged die form). For device fabrication, the mesa is defined and n-type and p-type contacts are formed by employing Ni/Au and Ti/Al/Ti/Au metal scheme, respectively.

SCALING UP: KiloLumen Solid State Lighting Exceeding 100 LPW via Remote Phosphor

Investigating Organization
Light Prescriptions Innovators, LLC

Principal Investigator(s)
Mr. Waqidi Falicoff

Subcontractor
OSRAM Opto Semiconductors, OSRAM Opto Semiconductors, Inc.
University of California, Merced-Center for Nonimaging Optics
Lawrence Berkeley National Laboratory- Lighting Research Group
Fisk University
LPI Precision Optics LTD.
L&L Optical Services
Northeast Photosciences

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,156,644
Contractor Share: $291,829

Contract Period
04/11/05 - 09/15/08

Technology
Light Emitting Diodes

Project Summary

Light Prescriptions Innovators, LLC (LPI) of Irvine, California, a nonimaging optics R&D company with wide experience in LED lighting optical design, proposes to team with LED chip-making giant OSRAM Opto Semiconductors, Lawrence Berkeley National Laboratory, University of California, Merced, and Fisk University, in a collaborative project applying for DOE funding. The project objective is to apply new technologies to fabricate a prototype that can prove that mass-produced high-flux LED modules can compete with fluorescent, incandescent and halogen lighting in efficacy, flux, and cost/watt.

LPI and OSRAM plan to break through the limits formerly holding back makers of LEDs (Light Emitting Diodes) seeking to create general illumination sources using white Solid-State Lighting (SSL). The most popular method being used today is by coating a blue LED with a phosphor coating. When the blue light hits the phosphor, it glows white.

Some of the drawbacks with this method are that the LED heats up and can damage the longevity of the phosphor conversion and, therefore, the life of the LED. Also, the efficiency of the LED suffers because half of the phosphor's omni directional emission goes back toward the LED chip. Much of this light gets trapped in the LED package and is reabsorbed by the chip, causing it to heat up even more than it did by the initial blue light production.

There is a further inefficiency in the conventional set-up, one that is also suffered by single-color LEDs. That is, if you try to gang several adjacent LEDs to act as a single light source, the great heat load is difficult to remove. This, in turn, prevents the higher currents possible with one chip alone.

What is proposed by the LPI/OSRAM team is to optically unite a number of separate, top-emitting OSRAM ThinGaN blue LEDs, using LPI's patent pending “combiner” optics that feed an exit aperture coated with phosphor. This avoids the separated chips heating each other. Also, the phosphor is far removed from the source of the heat that can reduce its efficiency, or even damage it. Further, part of the white light that tries to go back to the source will be recycled by special optics, which increases efficacy and alleviates overheating of the LED chip. The result is that the chip can now be driven harder and generate more light. A side benefit is that the proposed optics homogenizes the light, so that variations of phosphor brightness and color are minimized, in the case of flux reductions, or even a total failure, of an LED in the array.

Development of Key Technologies for White Lighting Based on LEDs

Investigating Organization
LumiLeds Lighting U.S., LLC

Principal Investigator(s)
Mike Krames
Robert M. Biefeld

Subcontractor
Sandia National Laboratories

Funding Source
BT/NETL SSL

Award
DOE Share: $1,377,000
Contractor Share: $562,500

Contract Period
09/20/01 - 03/31/04

Technology
Light Emitting Diodes

Project Summary

In a two-and-a-half year program ending in Spring 2004, Lumileds Lighting worked with Sandia National Laboratories (SNL) to understand how and why certain physical and chemical processes affect the performance of InGaN/GaN compound semiconductor LEDs. The project had three research areas: 1) the study of performance impacts caused by different kinds of material dislocations and defects and ways to reduce these for LED structures grown on sapphire substrates; 2) the direct measurement of various physical properties of different semiconductor layers during reactor growth; and 3) the feasibility of using semiconductor nanoparticles for the efficient conversion of blue or ultraviolet light to broad spectrum, high-quality, white light.

In the first area, a cantilever epitaxy (CE) process developed at SNL was employed to reduce dislocation density in GaN. CE is a simplified approach to low dislocation density GaN that requires only a single substrate etch before a single GaN-based growth sequence for the full device strucure. CE has achieved low dislocation density GaN in layers only a few microns thick, and the effect of CE on high power InGaN/GaN LED performance was measured. In the second area, the team developed advanced tools and measurement techniques for use in reactors under the extreme conditions necessary to grow these compound semiconductor films. These measurements demonstrated the possibility to exert much more precise control over important physical parameters that establish the electrical and optical properties of products made in these reactors. In particular, they demonstrated improved process control over critical temperatures at key growth steps, improving run-to-run color targeting for green LEDs by several factors. The team has also used advanced chromatographic techniques to monitor gas compositions at critical intervals. Using these methods, the quality and uniformity of the films can be improved dramatically.

In the third area, the researchers investigated the use of sophisticated, tiny semiconductor structures (nanoparticles, or "quantum dots") to convert the monochrome emission characteristic of inorganic compound semiconductor LEDs to more useful broadband emissions, such as white light. The team produced samples to determine their performance attributes and achieved record high quantum efficiencies for certain quantum dot materials. It also investigated means for incorporating the quantum dots into thin films that can be applied to high power LED chips to produce white LED lamps based solely on semiconductors. The team identified several challenges that need to be overcome before devices like these can eventually may be made on a commercial scale, providing an important step forward in DOE's quest of vastly increased efficiency in LEDs.

White LED with High Package Extraction Efficiency

Investigating Organization
Osram Sylvania Product Inc.

Principal Investigator(s)
Matthew Stough

Subcontractor
Alfred University

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $482,964
Contractor Share: $120,741

Contract Period
10/01/06 - 09/30/08

Technology
Light Emitting Diodes

Project Summary

Osram Sylvania Product Inc. is attempting to develop a high efficient phosphor converting white LED product through increased extraction efficiency of the LED package. A multi-layer thin film coating is applied between LED chip and phosphors to reflect the inward yellow emission, increasing their probability of forward escape. Additionally, a transparent monolithic phosphor may replace the powdered phosphor to reduce the back scattering blue light caused by phosphor powders. The researchers are testing three different coating and phosphor configurations to improve the extraction efficiency of the phosphors-based LED, with a goal of 80 lm/W.

An Efficient LED System-in-Module for General Lighting Applications

Investigating Organization
Philips Electronics North America Corporation

Principal Investigator(s)
Mr. Jim Gaines

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,562,998
Contractor Share: $1,041,999

Contract Period
04/11/05 - 09/14/08

Technology
Light Emitting Diodes

Project Summary

Philips Lighting - Lighting Electronics NA, together with Philips Semiconductors and the Philips Corporate Calibration and Standards Lab, propose to develop multi-colored LED sources in which a single integrated package, containing multiple high power LED die, serves as a self-contained lamp module generating feedback-controlled light of user-selectable color and intensity. In addition to the LED die, the package will include first-stage optics for color mixing, optical and thermal feedback sensors, structures for thermal management, and drive and control electronics. The LED die will be close together to promote color mixing and to provide a compact source so that the package will deliver about as many lumens as current luminaires of the same exit surface area. The user will supply, via an intuitive interface, a control signal to specify lamp color and intensity. The user will not have to understand the intricacies of feedback control systems in order to use the resulting lighting system. The proposed system will be equipped to accept wireless links to remote controls and/or remote sensor signals (such as those from daylight sensors). Philips refers to this integrated LED multi-chip source system as an LED system-in-module (LED-SIM) and believe, based on their extensive manufacturing and commercial experience in lighting, that such an integrated system is critical for early market acceptance. Developing this technology will require capabilities in optics, thermal management, electronics, silicon integration and system architecture. They expect the LED-SIM modular approach (and the general principles that will be derived) to provide a direct path to lamp systems useful in the majority of commercial lighting applications and some residential applications. However, for the purpose of this project, they limit the carrier to be LED-SIMs intended specifically for general lighting applications (non-accent), equivalent to reflector PAR (flood) systems and recessed CFL systems. The project is organized in three phases. Two of these are stages of increasing integration, and the last is to build the resulting LED-SIM into a flood lamp demonstrator.In the first phase, experimental RGBA white-light LED-SIMs will be designed and built with integrated LEDs, sensors, drive and control electronics, first stage optics, and thermal management. The electronics will be integrated in modules (e.g. controller, driver, memory chips, passive components, and user interface electronics). Minimization of lamp size is not a priority in this phase. The goal is to make a self-contained lamp module generating feedback-controlled light of user-selectable color and intensity, and requiring only line voltage input power and a signal defining the light color and intensity. In the second phase, building on the first phase, the LED-SIM design will be finalized, by integrating the electronic functional blocks fully, incorporating optimized thermal management designs and incorporating improved optics. The size of the module will be minimized. A general output from this phase is a methodology for designing LED-SIMs that will be useable for various applications. In the third phase, a prototype lamp system, sized to retrofit a PAR38 lamp, will be made, based on the LED-SIMs. The ultimate deliverable and the result of the third phase is a flood lamp with an intuitive user interface for color and intensity selection.

Development of Bulk Gallium Nitride Growth Technique for Low Defect Density Large Area Native Subs

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Karen Waldrip

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $497,800

Contract Period
06/01/06 - 05/31/08

Technology
Light Emitting Diodes

Project Summary

Bulk gallium nitride is difficult to grow from the melt due to a low solubility of nitrogen in liquid gallium, which forces the use of high temperatures and high nitrogen gas overpressures. Here, the recipient uses alternative molten-salt-based solvents in which the solubility of nitrogen may be intrinsically higher, and in which there is the opportunity to produce nitrogen directly through electrochemical methods. Their preliminary experiments have shown that nitrogen gas can be continuously electrochemically reduced to N^{-3} in a molten chloride salt (a lithium-chloride/potassium-chloride eutectic) at 450°C and atmospheric pressure, and that bulk GaN crystals of mm-scale sizes could be grown in an afternoon using this technique.

Development of White LEDs Using Nanophosphor-InP Blends

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Lauren Shea Rohwer

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $599,757

Contract Period
09/18/06 - 06/01/08

Technology
Light Emitting Diodes

Project Summary

This objective is to develop blends of oxide nanophosphors and semiconductor quantum dots (QDs) in encapsulants to produce high conversion efficiency white-emitting blends with a variety of correlated color temperatures and good color rendering index. The ultimate goal of this research is to produce white LEDs containing encapsulated nanophosphor-QD blends that are superior to LEDs made with QDs or traditional phosphors alone.

The approach is to select from the best available phosphors those that can be synthesized in nanoscale form. Several oxide phosphors with high quantum yield (QY) and strong absorption in the near-UV/blue spectral region were targeted. The main challenge was to synthesize these phosphors as nanoparticles, and maintain their high QY at the nanoscale.

Improved InGaN Epitaxy Yield by Precise Temperature Measurement

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Mr. J. Randall Creighton

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $425,000

Contract Period
09/30/04 - 11/30/06

Technology
Light Emitting Diodes

Project Summary

The objective of this project is to develop and refine a precise and absolute temperature measurement technique to be used on production class (i.e. multiwafer) InGaN MOCVD reactors. The Recipient shall develop and test "state-of-the-art" pyrometers on production class MOCVD systems that measure thermal radiation at wavelengths where the wafer and/or epilayer are opaque. This work will draw upon and extend previous research (funded by DOE) that developed emissivity correcting pyrometers (ECP) based on the high-temperature GaN opacity near 400 nm (the ultraviolet-violet range, or UVV), and the sapphire opacity in the mid-IR (MIR) near 7.5 microns. The improved temperature control will greatly increase the yield of InGaN epitaxial material; thereby significantly lowering the cost of the final LED products.

Investigation of Surface Plasmon Mediated Emission From InGaN LEDs Using Nano-Patterned Films

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Arthur Fischer

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $795,000

Contract Period
09/11/06 - 09/30/08

Technology
Light Emitting Diodes

Project Summary

This project proposes to develop a high efficiency LED structure taking advantage of surface plasmons. Surface plasmons are electromagnetic waves at the interface between a metal and dielectric (semiconductor) which have been shown to improve light emission by as much as 90 times in specialized, optically pumped LED structures. This project aims to develop electrically injected devices which benefit from the plasmon effect.

Nanostructural Engineering of Nitride Nucleation Layers for GaN Substrate Dislocation Reduction

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Daniel D. Koleske

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $605,000

Contract Period
09/18/06 - 04/30/08

Technology
Light Emitting Diodes

Project Summary

The goal of the project is to develop MOCVD growth methods to further reduce GaN dislocation densities on sapphire which inhibit device efficiencies. The study establishes a correlation between the nuclei density and dislocation density. Methods to reduce the nuclei density while still maintaining the ability to fully coalesce the GaN films were investigated.

Nanowire Templated Lateral Epitaxial Growth of Low Dislocation Density GaN

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
George T. Wang

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $616,000

Contract Period
09/18/06 - 04/30/08

Technology
Light Emitting Diodes

Project Summary

This project proposed to develop inexpensive and low defect density GaN substrates enabling higher efficiency LED devices. This goal was to be accomplished by developing growth techniques for GaN nanowires which are then induced to grow laterally and coalesce into a high quality planar film.

Novel ScGaN and YGaN alloys for High Efficiency Light Emitters

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Daniel D. Koleske

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $320,000

Contract Period
06/15/06 - 06/30/08

Technology
Light Emitting Diodes

Project Summary

The objective of this research is to add scandium (Sc) and yttrium (Y) to the InGaN-based LEDs to increase the operating wavelength while maintaining the high IQE currently observed in blue InGaN-based LEDs.

Ultrahigh-Efficiency Microcavity Photonic Crystal LEDs

Investigating Organization
Sandia National Laboratories

Principal Investigator(s)
Mr. Arthur Fischer

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,200,000

Contract Period
09/01/04 - 12/31/06

Technology
Light Emitting Diodes

Project Summary

The objective of this work is to design, fabricate and test 400 nm - 460 nm InGaN microcavity photonic crystal (PX) LEDs. Enhanced light extraction will be achieved through the use of a planar cavity based on a conducting GaN/AlGaN epitaxial distributed Bragg reflector in conjunction with a two-dimensional photonic lattice. The objective of phase I is to demonstrate improved brightness of top-emitting microcavity PX-LEDs compared to planar control LEDs. The objective of phase II is to demonstrate a flip chip microcavity PX-LED with an external quantum efficiency 2x greater than planar control LEDs.

Ultra High p-Doping Materials Research for GaN Based Light Emitters

Investigating Organization
Technolgies and Devices International

Principal Investigator(s)
Vladimir Dmitriev

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $600,000
Contractor Share: $150,000

Contract Period
06/26/06 - 06/30/07

Technology
Light Emitting Diodes

Project Summary

The objective is to develop novel technology of ultra highly doped (hole concentration at room temperature, p >1019 cm^{-3}) p-type GaN layers and AlGaN/GaN heterostructures for lighting applications. Highly doped p-type GaN-based materials with low electrical resistivity and abrupt doping profiles are of great importance for efficient light emitters for solid state lighting (SSL) applications. High p-type doping is required to improve (i) carrier injection efficiency in light emitting pn junctions, (ii) current spreading in light emitting structures, and (iii) parameters of ohmic contacts to reduce operating voltage and tolerate higher forward currents needed for the high output power operation of light emitters. Highly doped p-type GaN layers and AlGaN/GaN heterostructures with low electrical resistivity will lead to novel device and contact metallization designs for high power high efficiency GaN-based light emitters. The project is focused on material research for highly doped p-type GaN materials and device structures for applications in high efficiency light emitters for general illumination.

Development of White-Light Emitting Active Layers in Nitride-Based Heterostructures for Phosphorless Solid State Lighting

Investigating Organization
University of California, San Diego

Principal Investigator(s)
Ms. Jan Talbot, Dr. Kailash Mishra

Subcontractor
OSRAM Sylvania

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $955,656
Contractor Share: $245,273

Contract Period
09/28/04 - 12/31/07

Technology
Light Emitting Diodes

Project Summary

The main objective of this collaboration between UC San Diego (PI: Prof. Jan Talbot) and OSRAM SYLVANIA (Dr. K. Mishra) was to develop a new LED architecture using thin films of nitride-based luminescent semiconductor alloys of GaN, AlN, and InN, and suitably chosen activator ions to produce white light. The activator ions consisted of one or two types of ions that, together and with band edge emission from the alloy, will yield a superposition of emission spectra from the individual activator ions and lead to a white-light emitter with high efficacy and color rendering index.

ZnO PN Junctions for Highly Efficient, Low-Cost Light Emitting Diodes

Investigating Organization
University of Florida

Principal Investigator(s)
Dr. David Norton

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $912,089
Contractor Share: $241,094

Contract Period
09/02/04 - 09/30/07

Technology
Light Emitting Diodes

Project Summary

This project aims to demonstrate a viable method of synthesizing novel II-VI compound semiconductors based on Zn with Mg (and other) metallic dopants. Intended to demonstrate much better materials properties, such as increased p-type concentrations and mobility, enhanced heterojunction constructs, and other effects thought to increase internal quantum efficiency, this project will determine if indeed such a system is a practical alternative to the defect-prone III-V system (currently manufactured, but of limited efficacy). Traditionally, these materials were thought to be too brittle and too easily contaminated by environmental constituents, such as, water to be of value as LEDs. The researchers are working to overcome these limitations using unique alloying technologies.

The overall objective of this research will be formation of light-emitting ZnO-based pn junctions. The focus will be on three issues most pertinent to realizing a ZnO-based solid state lighting technology, namely: 1) achieving high p-type carrier concentrations in epitaxial (Zn,Mg)O thin films; 2) realizing band edge emission from a ZnO-based pn homojunction; and 3) achieving band edge emission for ZnO-based pn heterojunctions that are designed to yield efficient light emission. Related objectives include understanding the doping behavior of phosphors and nitrogen in ZnO and ZnMgO, identifying the potential and limitations of ZnO pn junction LED performance, and achieving electroluminescence in polycrystalline ZnO-based pn junctions fabricated on glass.

Innovative Development of Next-Generation and Energy-Efficient Solid State Light Sources for General Illumination

Investigating Organization
Georgia Institute of Technology

Principal Investigator(s)
Mr. Ian Ferguson

Subcontractor
None

Funding Source
EE Science Initiative

Award
DOE Share: $500,000
Contractor Share: $125,000

Contract Period
09/30/03 - 07/31/06

Technology
Light Emitting Diodes

Project Summary

GaN and InGaN, the base materials for light emitting diodes in the blue and UV parts of the spectrum, were grown on ZnO substrates using MOCVD. These materials are currently being characterized via several techniques, including X-ray diffraction, secondary ion mass spectroscopy, and etch pit density in conjunction with atomic force microscopy. Baseline GaN was already measured with respect to defect density, which was 3-5x10^8 cm^{-2}. In situ substrate removal has not yet been successful. Other alternative substrates (e.g., $NdGaO_3$) will be tested over the coming year, and we expect to obtain defect densities of the materials grown on ZnO shortly. In addition, progress has been made on reducing the 1100°C process temperature through the use of alternative nitrogen sources such as an atomic nitrogen plasma or dimethylhydrazine to replace ammonia. Reduction of the process temperature allows use of many other alternative substrates.

Phosphors were made from SrS and $SrGa_2S_4$ activated with Eu. We expect to have similar materials using Ce as the active material over the coming year. The SrS and $SrGa_2S_4$ doped with Eu were made into nanoparticles that enhanced their emission efficiency. The emission measured by photoluminescence peaked at 616nm (orange/red). Light emitting diodes were fabricated using metal-organic chemical vapor deposition of GaN and InGaN multiple quantum wells. These diodes were optimized for emission at

400nm. A second round of diodes has already been fabricated, one year ahead of schedule, with dual wavelength emissions at 418nm and 481nm. These diodes are being incorporated as pump sources with the phosphors mentioned above (SrS:Eu,Ce and $SrGa_2S_4$:Eu, Ce as nanoparticles) for measurement of equivalent lumen output. We anticipate measuring the lumen output of the integrated dual wavelength LED driving the phosphors before the new year.

Development of Photonic-Crystal LEDs for Solid State Lighting

Investigating Organization
Sandia National Laboratory

Principal Investigator(s)
Mr. Robert M. Biefeld

Subcontractor
University of New Mexico

Funding Source
EE Science Initiative

Award
DOE Share: $350,000

Contract Period
10/01/03 - 06/15/05

Technology
Light Emitting Diodes

Project Summary

Sandia National Laboratories, working together with Lumileds Lighting, a major U.S. manufacturer of high power LEDs, and the University of New Mexico, are developing photonic lattices for improving the efficiency of blue LEDs based on indium gallium nitride (InGaN) emissive layers. Photonic crystals have the potential to couple substantially more of the light internally generated within the active layers of an LED into external, usable radiation than is possible with simple planar surfaces. The light output from planar surfaces is limited by a classical optical effect known as total internal reflection, which allows only a small fraction of the internally generated light to escape from the high refractive-index LED materials. Photonic crystals, with periods comparable to the optical wavelength within the LED, employ diffractive effects to couple out light that is otherwise unavailable, enhancing the overall efficiency of the LED is an important step toward realizing commercial lighting applications. The photonic lattices being developed in this project are two-dimensional photonic crystals. These photonic crystals can improve the efficiency of LEDs through two different mechanisms: improvement of the radiative efficiency of the device and improvement of the extraction efficiency. Extensive process development is being performed to fabricate the extremely fine, nano-scale features necessary for the production of a photonic crystal using electron beam, nano-imprint, and interferometric lithography. Detailed theoretical calculations are also being performed to design photonic lattices for improved LED efficiency. Characterization of photonic lattices with emissive layers is being done on processed wafers in order to confirm theoretical calculations and provide design guidelines. Finally,

complete LEDs are being fabricated using various photonic lattice designs and the emission efficiency is being determined. The project has a goal of doubling the external quantum efficiency of InGaN LEDs.

Sandia National Laboratories' Joel Wendt has developed an optimized process for the electron beam patterning of photonic crystals onto GaN LEDs. This process is dependent on the details of the photonic lattice being patterned as well as the mask material being used. The process was developed by exposing a large variety of test patterns and characterizing the resulting patterns. A large number of photonic crystal LEDs have been successfully patterned. The patterned LEDs are either sent to Lumileds or retained at Sandia National Laboratories for etching and characterization.

Sandia National Laboratories has also been exploring the development of a nano-imprinting process to enable the rapid patterning of large areas. This type of inexpensive, large-area patterning process will be necessary for the production of LEDs using photonic lattices. Sandia is currently exploring imprinting features using commercially available resists.

Professor Steven Brueck of the University of New Mexico (UNM) has been contracted by Sandia National Laboratories to explore the development of interferometric lithography for use in the patterning of large-area photonic crystals on GaN LEDs. Interferometric lithography is the use of the interference between a small number of coherent optical beams to create small-scale periodic patterns in a single, parallel, large-area exposure. A 360-nm period pattern was used as an etch mask to fabricate photonic crystal LEDs. This pattern was written over an area (~ 2.5×2.5 cm2) much larger than that of a single LED in only a few seconds with a pair of two-beam interferometric lithography exposures. The pattern was generated at UNM on a partially fabricated III-nitride LED wafer. After completion of the fabrication, this LED yielded uniform light emission from the largest-area (1x1 mm2) III-nitride photonic crystal ever demonstrated. Efforts are currently underway to evaluate the impact of this structure on the quantum efficiency of this device, and to optimize the photonic crystal structure.

This achievement has both scientific and technological implications. Large-area devices are important for verifying the extraction efficiency gains available with photonic crystals and for enabling a systematic optimization of the photonic-crystal parameters. Edge effects in small devices (10's to 100's of microns) can mask the important physics that becomes evident at larger areas. The process is very facile, allowing rapid and inexpensive changes in the pattern period, the dimensions of the pattern features, and the pattern symmetry. The interferometric lithography process creates a much larger area pattern than was used in this experiment. UNM is already patterning an area of ~ 2.5×2.5 cm2 in a single exposure. Extension to a more highly engineered, full-wafer patterning tool, necessary for the ultimate goal of low-cost, high-volume manufacturing, is an important future direction.

Sandia National Laboratories' Ron Hadley has developed a three-dimensional semivectorial finite-difference time-domain (FDTD) computer code to evaluate the impact of the photonic crystal on the LED efficiency. He has compared the predictions of this code to actual planar LED output characteristics and achieved good agreement. This code is now being used to predict the output from a variety of photonic-crystal LED designs. The code's predictions are being benchmarked against experimental photonic-crystal LED results. The development of this code should enable the team to predict the optimum photonic crystal for use with a particular LED in a much shorter time than would be required for a purely Edisonian approach.

Sandia National Laboratories has performed preliminary time resolved photoluminescence measurements on unetched quantum well wafers . This process is necessary in order to develop a baseline measurement process for extracting non-radiative lifetime information from unetched samples. These measurements will be extended to include a comparison of samples etched under a variety of conditions to establish etching procedures that will minimize damage to the active region in the LEDs. This may be necessary to optimize the performance of the photonic crystal LEDs.

Improving the Efficiency of Solid State Light Sources

Investigating Organization
University of California - San Diego

Principal Investigator(s)
Joanna McKittrick

Subcontractor
Lawrence Berkeley National Laboratory
University of California, Berkeley

Funding Source
EE Science Initiative

Award
DOE Share: $439,814
Contractor Share: $24,113

Contract Period
09/30/01 - 03/31/02

Technology
Light Emitting Diodes

Project Summary

There are two possible structures for a white LED. The first option is to develop an efficient white-emitting material that can replace the red-, green-, and blue-emitting materials in the classic LED heterostructure.

The second option is to embed a single composition, white-emitting material or three-phosphor blend (red, green, and blue) into the epoxy dome that surrounds the UV-emitting LED heterostructure. Existing white LEDs use a blue-emitting diode that excites a yellow-emitting phosphor embedded in the epoxy dome. The combination of blue and yellow makes a white-emitting LED.

The University of California-San Diego has discovered and developed a single composition white-emitting phosphor that is a terbium activated and cerium co-activated oxide. Cerium efficiently transfers energy to terbium, which mainly has a green emission with blue and red satellite peaks. Cerium-activated oxides have a saturated blue emission, but a long emission tail that extends into the green and red regions of the visual spectra. By enhancing the green and red emission from this phosphor using terbium, an efficient, long UV-excited white-emitting phosphor may be achieved. In addition, a tri-blend phosphor mixture has been discovered.

High-Efficiency Nitride-Based Solid State Lighting

Investigating Organization
University of California, Santa Barbara

Principal Investigator(s)
Shuji Nakamura

Subcontractor
Lighting Research Center at Rensselaer Polytechnic Institute

Funding Source
EE Science Initiative

Award
DOE Share: $2,995,155

Contract Period
09/28/01 - 04/30/05

Technology
Light Emitting Diodes

Project Summary

This project is focused on developing efficient white-light-emitting luminaires via a combination of novel GaN-based blue light emitting diodes (LEDs) and conventional YAG:Ce-based yellow phosphors. The blue LEDs ‘pump’ the yellow phosphor, and white light results from proper color mixing.

Typical (In,Al)GaN LEDs are composed of thin (< 0.1 micron) stacked layers with varying composition and doping (i.e., electrical conductivity), which are processed in a cleanroom to etch a defined mesa structure and deposit metal contacts. Unfortunately, due to the relatively high index of fraction of these materials, only a little light (< 8% per face), generated within the chip, escapes from it. Thus, a significant enhancement in light extraction (and, therefore, overall efficiency) is needed.

The novel LEDs studied in this project are termed Microcavity LEDs (MC-LEDs), whose total thickness is a fraction of a conventional LED. This reduced cavity thickness (ideally about 0.5 micron or less) causes the formation of optical modes within the structure and their accompanying directional emission from the structure. This directional emission is calculated to lead to high light extraction efficiency (> 40 %), given that we can carefully control the thickness and composition of the various device layers, which, in the case of a quantum well are, as thin as 10 nanometers. In addition, microcavity formation requires precise control of device thinning after the as-grown film has been detached from its substrate. Lastly, the electrical contacts and mirror(s) on either side of the structure need to be properly formed, both requiring significant processing optimization.

We are also developing luminaire designs that are tailored for directional emission from MC-LEDs. These luminaires must first be designed using ray-tracing and other optical modeling software, since the internal and external geometry of an ‘optimal’ luminaire design is often not inherently obvious. In addition, the placement of the yellow phosphor and the composition/refractive index of its medium must be properly chosen, since they directly affect overall luminaire efficacy. Once these factors have been considered and a prototype is constructed, we place an MC-LED in the luminaire to experimentally verify the efficiency and uniformity of light emission.

Development of UV-LED Phosphor Coatings for High-Efficiency Solid State Lighting

Investigating Organization
University of Georgia

Principal Investigator(s)
Mr. Uwe Happek

Subcontractor
GE Global Research

Funding Source
EE Science Initiative

Award
DOE Share: $418,049
Contractor Share: $104,533

Contract Period
1/23/04 - 05/15/06

Technology
Light Emitting Diodes

Project Summary

The objective of this work is to develop highly efficient solid state lighting sources based upon UV-LED + phosphor combinations. This will be done by focusing on the improvement of the phosphor coating conversion efficiency in UV-LEDs, where the fundamental quenching mechanisms for phosphor coatings will be determined and quantified. This information will aid designers in developing LED packages that will minimize or even eliminate many of the phosphor quenching pathways. Higher efficacy LED packages will be demonstrated at the end of this program.

Resulting from the research, the team successfully demonstrated a 1.5-2x increase in phosphor conversion efficiency over the initial baseline phosphor. The project also allowed the discovery and quantification of critical phosphor quenching mechanisms within LED packages.

An Advanced Nanophosphor Technology for General Illumination (Phase I)

Investigating Organization
Boston Applied Technology

Principal Investigator(s)
Ms. Xiaomei Guo

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
6/27/05 - 3/26/06

Technology
Light Emitting Diodes

Project Summary

Conventional phosphors are in micrometer scale, light scattering at grain boundaries is strong and decreases light output. Conventional phosphors obtained by solid state sintering method has lower concentration quenching threshold due to non-uniform doping. The cost of conventional the sol-gel method to produce nano-phosphors is too high, due to low solubility of metal alkoxides. Salted sol-gel method (SSG) can prepare nano-phosphors in size from tens to hundreds of nanometers that are smaller than the light wavelength and can reduce scattering. SSG can improve uniformity of doping and lift the concentration quenching threshold. SSG is capable for massive production at low cost. We plan to make high energy-efficient nanophosphors, such as conventional YAG:Ce, and novel R2O3:Ce.

Efficient phosphors for lighting applications have been a long standing goal for researchers. The nano-phosphors generated over the contract period will greatly improve the energy efficiency for varies of lighting sources. They will be the next generation of phosphors. The SSG technology will also generate a broad impact on nano-particle fabrication. Its potential application will not be limited.

Ultraviolet LEDs for Solid State Lighting

Investigating Organization
Cermet

Principal Investigator(s)
Jeff Nause

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,694

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

Two approaches are emerging as viable techniques for the production of solid state white light: visible wavelength LEDs coupled with modified phosphor compositions and UV emitters coupled with traditional, highly efficient YAG phosphors. The latter approach has the advantage of producing light with familiar color temperatures (warmth), which will greatly enhance the adoption rate of the light source by the public. However, UV (340 nm and 280 nm) semiconductor emitters with sufficient power required to stimulate YAG phosphors are not available.

The goal of this program was to develop the technology necessary to enable commercial production of high-quality (In,Al,Ga)N epitaxial materials and high-performance UV LEDs on AlN substrates for solid state lighting applications. Three major areas were targeted for a successful program through a Phase II effort: 1) development of production grade bulk AlN wafers using Cermet's Vapor Growth Process; 2) development of better quality materials, which include p- and n-type doped AlGaN and InAlGaN-based multi-quantum wells; 3) and introduction of novel LED device structures.

Project Results
In the nine-month Phase I program, Cermet and Georgia Tech's efforts focused on two of the three major technological barriers in the development of UV emitters.

The first effort focuses on development of high-quality, bulk AlN crystals to eliminate dislocations, which can be a major contributor to efficiency roll-off at high drive current densities. Bulk AlN minimizes thermal expansion cracking in high Al-content emitters. Aluminum nitride substrates are transparent in the UV portion of the spectrum, allowing through-wafer emitter designs into the deep UV. Lastly, AlN has a significant thermal conductivity, enabling effective power management of large area power (>0.5 watt) LEDs for SSL needs.

Two-inch-diameter bulk AlN was grown using Cermet's process. The materials exhibited an etch pit density of 1 x 10 5 cm-2 and X-ray peak widths as low as 76 arc seconds. Polished surfaces of 5.8 angstroms (rms) were achieved on this material. The second effort focused on development of high n-type doping level in AlxGa1-xN alloys. Initial AlGaN layers and multiple quantum wells were grown on AlN substrates, with excellent structural results obtained.

Novel Active Layer Nanostructures for White Light Emitting Diodes (Phase I)

Investigating Organization
Dot Metrics Technologies

Principal Investigator(s)
Mr. Mike Ahrens

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase 1

Award
DOE Share: $100,000

Contract Period
7/13/04 - 4/13/05

Technology
Light Emitting Diodes

Project Summary

The most efficient solid state white lights developed to date typically use a bright blue light emitting diode, as a blue source, and, simultaneously, to optically excite an inorganic downconverter, converting a fraction of the blue light to yellow. The yellow light is mixed with the leftover blue to be perceived by the human eye as white. The energy efficiency of such a “white light emitting diode” is limited because the photonic downconversion process suffers from a fundamental energy loss (“Stokes shift") as higher energy blue photons are converted to yellow. Also, the color uniformity in the illuminated region is not ideal, because the geometry of the blue source (a chip) is different than the source geometry of the yellow source (a layer atop the chip). Recent results on InGaN LEDs have highlighted the positive effect of nanostructure on LED efficiency (O'Donnell, Martin et al. 1999). Dot Metrics Technologies and UNC Charlotte are working to incorporate multicolor nanostructured active layers into light emitting devices, to achieve the same advantages with more color flexibility. In Phase I, we are formulating mixtures of various sizes of semiconductor quantum dots and integrating them into quantum dot composite structures. The color of the peak luminescence of a semiconductor quantum dot is dictated by the quantum size effect when the particle size is small compared to the Bohr-exciton radius (Brus 1984). Deposited quantum dot samples are analyzed with fluorescence microoscopy and scanning probe microscopy. A preliminary LED design has been developed and LED devices are currently being fabricated in a designed experiment to determine optimum conditions for high-efficiency white light emission.

References:

Brus, L. E. (1984). "Electron–electron and electron-hole interactions in small semiconductor crystallites: The size dependence of the lowest excited electronic state." Journal of Chemical Physics 80(9): 4403-4409.

O'Donnell, K. P., R. W. Martin, et al. (1999). "Origin of luminescence from InGaN diodes." Physical Review Letters 82: 237-240."

A Novel Growth Technique for Large Diameter AlN Single Crystals (Phase I)

Investigating Organization
Fairfield Crystal Technology, LLC

Principal Investigator(s)
Dr. Shaoping Wang

Subcontractor
Suny at Stony Brook, under the direction of Professor Michael Dudley

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,586

Contract Period
6/27/05 - 3/26/06

Technology
Light Emitting Diodes

Project Summary

III-V nitride-based high brightness UV and visible LEDs are of a great interest for general illumination, but the light output efficiencies of current high brightness LEDs are still inadequate. A key material issue preventing achieving higher light output efficiency in LEDs is the poor crystalline quality of the nitride epilayers resulted from lattice-mismatched substrates. AlN single crystal is the best substrate material, apart from GaN, that is suitable for III-V nitride epitaxy, particularly for UV LED epilayers with high Al contents. Fairfield Crystal Technology proposes to use a novel physical vapor transport technique to grow large diameter, high-quality AlN bulk single crystals. These AlN single crystals can be used as substrates for growth of high-quality nitride LED epilayers. In this proposed Phase I effort, a novel physical vapor transport technique for AlN single crystal growth will be studied extensively. The focus of the study is to understand the effect of the growth setups used for the physical vapor transport growth on the quality of AlN crystal boules.

A Novel Growth Technique for Large Diameter AlN Single Crystal Substrates (Phase II)

Investigating Organization
Fairfield Crystal Technology, LLC

Principal Investigator(s)
Dr. Shaoping Wang

Subcontractor
SUNY at Stony Brook, under the direction of Professor Michael Dudley
Yale University, under the direction of Professor Jung Han

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000
Contractor Share: $200,000

Contract Period
10/01/06 - 11/06/08

Technology
Light Emitting Diodes

Project Summary

III-V nitride-based high brightness UV and visible LEDs are of a great interest for general illumination, but the light output efficiencies of current high brightness LEDs are still inadequate. A key material issue preventing achieving higher light output efficiency in LEDs is the poor crystalline quality of the nitride epilayers resulted from lattice-mismatched substrates. AlN single crystal is the best substrate material, apart from GaN, that is suitable for III-V nitride epitaxy, particularly for UV LED epilayers with high Al contents. Fairfield Crystal Technology will use a novel physical vapor transport technique to grow large diameter, high-quality AlN bulk single crystals. These AlN single crystals can be used as substrates for growth of high-quality nitride LED epilayers. In this Phase II SBIR project, Fairfield will develop aluminum nitride single crystal substrates that enable fabrication of highly efficient light emitting devices for solid-state lighting.

Development of Silicon Nanocrystals as High-Efficiency White Phosphors

Investigating Organization
InnovaLight

Principal Investigator(s)
David Jurbergs

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

Silicon nanocrystals produced and capped in the sub-10nm regime are efficient light emitters in the visible range due to quantum confinement effects. The specific color of emission is dictated by the size of the particle. As such, an ordered distribution of nanocrystals can be used to produce white light. This characteristic, coupled with nanocrystalline silicon's inherent stability and efficiency, makes these materials appropriate for use as phosphors with blue or near-UV high brightness light emitting diodes (HB-LEDs) in producing efficient white light for the general illumination market– a large and compelling market opportunity.

Silicon holds great promise in this application. First, silicon is capable of high efficiencies. Researchers have shown efficiencies approaching 90% from photo-excited silicon nanoparticles prior to any attempt to optimize emission. Second, the inherent stability of silicon, firmly substantiated over its 30 years as the fabric of modern day electronics, uniquely enables long lifetimes. Color stability is also achieved using a single material solution to reach all of the colors of the visible spectrum. This avoids the differential aging characteristic of other approaches that require multiple materials to do the same thing. Third, these novel materials can be tuned to achieve a high-quality white light by simply controlling the size distribution. Lastly, the surface passivation of the particles enable them to be suspended in a variety of solutions that, in turn, enable a number of efficient and well-understood, solution-based deposition schemes, such as ink

jet printing. This is an important issue for manufacturability, and for successful commercialization. The combination of these advantages makes silicon a compelling option for HB-LED phosphors for white light emission.

InnovaLight has already produced unique size-controlled silicon nanocrystals with a variety of emission colors (color being a function of size). These materials have demonstrated high initial efficiencies. During the course of this grant, improvements to the photoluminescent quantum efficiency and color tunability was attempted through synthetic process control, particularly in the area of surface passivation. In addition, optimization of the color quality of white light emission was to have been conducted had high-efficiency emission been obtained.

The objective of this grant was to determine the capability of nanocrystalline silicon to function as a phosphor for use with high-brightness LED's. When this proposal was drafted, InnovaLight had demonstrated that relatively efficient photoluminescence in the visible region was obtained from colloidal silicon nanocrystals. They had also demonstrated color tunability in this material system, which offered potentially great benefits for achieving a phosphor with a high color-rendering index (CRI). Although Innovalight was successful in producing soluble silicon nanocrystals by surface derivatization, work is still being done on optimization of the surface properties of these novel materials. It is anticipated that significant improvements in efficiency could be achieved through improved surface passivation. Over the course of this project, significant improvements in passivation were achieved in that higher band-gap materials (yellow- and green-emissive silicon nanocrystals) were stabilized. In addition, proof-of-concept devices were fabricated utilizing silicon nanocrystals as phosphor materials in combination with blue-emitting high-brightness LED's. These proof-of-concept devices, although not yet optimized for optimal color-rendering, proved that white emission was possible by using silicon nanocrystal light emitters as phosphors. At the conclusion of this study, a large range of organic passivation methods had been attempted. However, all of these attempts were incapable of producing nanocrystalline silicon with higher photoluminescent quantum efficiency than unpassivated material. Although attainment of high quantum yield material remains a challenge to commercialization, Innovalight is continuing to explore new schemes to achieve high-efficiency, color-tunable silicon nanocrystal materials. Based upon discoveries made after the conclusion of the grant, it is expected that these new processes will improve the quantum efficiency of these materials to a level that is needed for the commercialization of these materials as phosphors. Continued effort will then be needed to optimize the use of these materials to achieve high CRI with conventional HB-LEDs.

General Illumination Using Dye-Doped Polymer LEDs

Investigating Organization
Intelligent Optical Systems

Principal Investigator(s)
Steven Cordero

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,998

Contract Period
7/1/02 - 6/30/03

Technology
Light Emitting Diodes

Project Summary

New illumination technologies should be cost effective and have an acceptable color-rendering index (CRI). OLEDs, as broadband white light sources, are one such technology. A major advancement in the development of OLEDs has been the implementation of phosphorescent dyes as the emitting species, which has prompted large device enhancements to both monochrome and broadband OLED systems.

These advances have also created opportunities to enhance lighting efficiency by mating electro-phosphorescence with novel polymers. Intelligent Optical Systems (IOS) is pursuing this pathway, which is expected to result in easy-to-process polymer materials. These materials have exceptional properties, and are an inexpensive and efficient general illumination lighting source. This methodology will allow polymer light emitting devices (PLEDs) to obtain the outstanding efficiencies of small molecule-based devices.

IOS has successfully demonstrated a white light source for general illumination that uses the triplet emission from one or more dyes embedded in a novel polymer matrix. Using this approach, the devices maximize the conversion of charge-to-light. The methodology is unique because the polymer matrix allows the use of highly efficient phosphorescent dyes as emitters within the device architecture. The researchers expect that external device efficiencies will be greater than 4%, while maintaining excellent color rendering quality and high brightness.

In the first phase of the project, IOS demonstrated the feasibility of producing PLEDs significantly more efficient than existing fluorescent-based white devices. Future research will involve strengthening and enhancing the PLED technology by studying performance degradation issues. Material purity, device fabrication pathways, and device structural design will be researched. This research will be instrumental in improving the device fabrication capabilities, material analysis, and overall lighting knowledge needed for this technology to improve solid state lighting efficiency.

Advanced Materials for Thermal Management in III-Nitride LEDS (Phase I)

Investigating Organization
K Technology Corporation

Principal Investigator(s)
Mr. Mark J. Montesano

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
06/28/06 - 03/27/07

Technology
Light Emitting Diodes

Project Summary

Light emitting diodes (LEDs) require about 1/10th the power of regular (incadescent) bulbs. By developing advanced materials that can extract heat from the LEDs, the LEDs will be able to emit higher intensity light thereby making them viable for independent light sources such as room lighting. Over 200 billion killowatts are used in the US yearly for incandescent lighting, the saving on power consumption could be dramatic and help lessen dependence on foreign oil. kTC is developing a highly conductive printed wiring board material that will integrate the thermal managemnt and electrical interconnects of the packaged LEDs. The Phase I program will verify the feasibility of this material concept.

Gallium Nitride Substrates for Improved Solid State Lighting

Investigating Organization
Kyma Technologies

Principal Investigator(s)
Mark Williams

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

Device cost and limitations in GaN materials technology, manifested by the lack of a large, native-nitride substrate, currently holds back the incorporation of GaN-based devices into solid state light sources. The use of GaN substrates will address these issues by reducing the number of performance-hindering defects in devices and by achieving lower costs because of fabricating devices with higher yields. Kyma Technologies has developed a process for fabricating 50 mm GaN substrates, enabling the realization of high-efficiency blue-green and UV LEDs.

The availability of freestanding GaN substrates should significantly simplify the growth of GaN since lattice and thermal issues will no longer be relevant. Homoepitaxy growth decreases the average GaN threading dislocation density, thus improving the electrical properties of the material. The accomplishment of low-dislocation-density GaN material will increase lifetime and brightness in optoelectronic devices. Moreover, lower defect levels should also increase thermal conductivity of the GaN, which will be beneficial for device operation. Wafer cracking and/or bowing will be minimized because the coefficient of thermal expansion between the GaN epitaxial layer and the substrate will be the same.

Kyma Technologies and Georgia Tech are developing a process for production of LED device structures with low defect densities on gallium nitride substrates. The nitride MOVPE growth process is being used to grow gallium nitride epitaxial layers on this substrate material. The program will determine the optimal growth conditions for MOCVD growth of GaN on GaN substrates. The GaN substrate has structural and thermal properties that will improve gallium nitride and AlGaN layers in the device structure. The electrical and optical characteristics and defect density of GaN epitaxial layers on GaN substrates will also be characterized.

Kyma Technologies has completed the Phase I SBIR and demonstrated the feasibility of producing LEDs on gallium nitride substrates. The Phase I development effort focused on GaN substrate characterization, demonstration of growth of GaN epitaxial films, and fabrication of a SQW LED device. The blue LEDs fabricated on gallium nitride substrates operated with a forward voltage (Vf) of 3.0 – 3.5 V at 20 mA for a LED emitting at a wavelength of 450 nm. This represented an improvement over the same device fabricated on a sapphire substrate.

Enhanced Optical Efficiency Package Incorporating Nanotechnology Based Downconverter and High Refractive Index Encapsulant for AlInGaN High Flux White LED Lamp with High Luminous Efficiency LED Phosphor Performance (Phase I)

Investigating Organization
Nanocrystals Technology

Principal Investigator(s)
Rameshwar Bhargava

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,933

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

Nanocrystals Technology LP (NCT) has developed unique nanotechnology-based materials that will cost-effectively enhance performance of white LED lamps for general illumination applications. These innovations include optically non-scattering efficient downconverter Nanophosphors and high refractive index (HRI) Nanocomposites that enhance both the Package Optical Efficiency (POE) and Light Extraction Efficiency (LEE) of white LED lamp at the package level.

Today in white LEDs, blue-to-white light conversion is exclusively achieved by using YAG:Ce 3+, an efficient broad-band, yellow-green phosphor. One of the drawbacks of this system is that the mixing of blue/yellow color not only produces halo effect, but also yields inferior color rendering. Absorption process in phosphors such as YAG:Ce 3+, involve impurity states of rare-earth (RE) emission that have low absorption coefficient of about 40 cm-1 in the region of interest. The low absorption in RE systems requires larger size particles and increased scattering to enhance the net absorption. Nanocrystals has demonstrated that in nanophosphors, the absorption coefficient associated within intra-atomic states of the RE-activator is enhanced by two orders of magnitude. These nanophosphors ,when optimized, would eliminate the required scattering conditions and the halo effect.

NCT has developed nanocomposites of refractive index of 1.8 . This was achieved by incorporating TiO_2 nanoparticles with proprietary coating that are dispersed uniformly to yield optically transparent nanocomposites. The HRI encapsulants were used to demonstrate >25% improvement in efficiency of green and red LEDs. Furthermore, we have incorporated YAG:Ce 3+ bulk phosphor of refractive index 1.85 in nanocomposite encapsulant of refractive index 1.8. The matched refractive indices render the downconverter nanocomposite optically transparent. These optically transparent HRI nanocomposites containing bulk YAG-phosphor increase the efficiency of white LEDs by 40% over the current LEDs that use the same YAG-phosphor and encapsulant of refractive index of 1.5.

Projected 50% enhancement in POE due to the optically non-scattering downconverter, when combined with an additional ~40% enhancement in LEE due to HRI encapsulant, would lead to a good color-quality, high-luminous efficacy white LED lamp with ~ 95 lm/W using present AlInGaN blue LED die/chip with wall-plug-efficiency of 25%. With improved LED chip efficiency in the future, the use of HRI nanocomposites and nanophosphors will allow us to achieve luminous efficacy of 200 lm/W.

Improved Light Extraction Efficiencies of White pc-LEDs for SSL by Using Non-Toxic, Non-Scattering, Bright, and Stable Doped ZnSe Quantum Dot Nanophosphors (Phase I)

Investigating Organization
Nanomaterials & Nanofabrication Laboratories (NN-Labs, LLC)

Principal Investigator(s)
David Goorskey

Subcontractor
University of Arkansas

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,636

Contract Period
6/20/07 - 3/19/08

Technology
Light Emitting Diodes

Project Summary

The most common and cheapest type of white LED consists of a yellow-emitting phosphor powder surrounding a blue-emitting LED die. One serious challenge is improving the light extraction efficiency (LEE), often referred to as “package efficiency”, of pc-LEDs. This proposal specifically addresses the LEE issue to improve the overall efficiency of white LEDs allowing them to compete with conventional (and toxic) mercury-vapor fluorescent lamps. Specific impacts would include providing massive energy savings worldwide, reducing the amount of mercury release into the environment, and providing an economic boost to US LED manufacturers while allowing them to retain technocal superiority over foreign corporations.

Specifically, this SBIR Phase I project will incorporate high quantum efficiency doped nanocrystal quantum dots (D-dots™) into high-index TiO2 using sol-gel techniques to form scatter-free nanophosphor composites for white phosphor conversion light emitting diodes (pc-LEDs) which are presently limited by poor light escape efficency at the die-encapsulant interface (due to poor refractive index matching) and back-scattering from the bulk phosphor layer. Nanophosphors are too small to scatter light and if embedded into a high-index material, can achieve near index matching with the LED die, thereby solving both of these current problems. D-dots™, a new class of nanocrystal light emitting materials, do not suffer from parasitic reabsorption associated with “intrinsic” quantum dots, are highly stable up to 300^{o}C, and are immune to photo-oxidation under intense UV irradiation making them ideal candidates for replacing bulk phosphors in white pc-LEDs. The high performance D-dots™ newly invented by this SBIR team are free of toxic heavy metals such as cadmium in CdSe and CdS quantum dots which have been the traditional workhorses for intrinsic nanocrystal emitters.

Phase I will focus primarily on integrating yellow-emitting Mn-doped ZnSe D-dots™ into TiO2 sol-get matrices deposited on near-UV/blue LED dies whereas Phase II will develop additional D-dot™ nanophosphors to improve the color rendering index and luminous afficacy of white LEDs.

High-Efficiency Nanocomposite White Light Phosphors (Phase I)

Investigating Organization
Nanosys, Inc.

Principal Investigator(s)
Dr. Erik Scher

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,891

Contract Period
7/13/04 - 4/12/05

Technology
Light Emitting Diodes

Project Summary

The objective of the proposed program is the development of a down-converting system based on engineered nanocomposite materials that will improve the overall cost, performance, and efficiency of solid-state white light.

The Phase I project focuses on determining the feasibility of utilizing engineered nanocomposite down-conversion layers for white light illumination and demonstrating the potential benefits from a perfectly color-matched, non-scattering, index-matched, high-quantum yield, thin-film phosphor layer technology. This project will increase an understanding of the various loss mechanisms occurring within the complete system and is directed at: 1) fabricating optimum nanocomposite mixtures based on theoretical predictions; 2) demonstrating the effect of controlling index of refraction and scattering in the phosphor layer; and 3) projecting eventual performance improvements upon further materials optimization and device design in Phase II.

The proposed technology has the potential to produce solid state white light exceeding the best traditional fluorescent and incandescent bus, with rendering of greater than 80, color temperature of 4,000K, and luminous efficiency of greater than 200 lm/W, while at a cost of less than $1/klm.

High-Efficiency Nanocomposite White Light Phosphors (Phase II)

Investigating Organization
Nanosys, Inc.

Principal Investigator(s)
Jian Chen

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $749,414

Contract Period
08/01/05 - 07/10/06

Technology
Light Emitting Diodes

Project Summary

The objective of the proposed program is the development of a revolutionary and innovative down-converting system based on engineered nanocomposite materials that will dramatically improve the overall cost, performance and efficiency of solid-state white light. This is more than a new phosphor, but rather a complete down-converting system that will impact all aspects of SSWL. The proposed technology has the potential to produce solid-state white light exceed the best traditional fluorescent and incandescent bulbs, with color rendering of greater than 80, color temperature of 4,000K, and luminous efficiency of greater than 200 lm/W while at a cost of less than $1/klm.

New, Efficient Nano-Phase Materials for Blue and Deep Green Light Emitting Diodes (Phase I)

Investigating Organization
Nomadics

Principal Investigator(s)
Mr. Wei Chen

Subcontractor
Oklahoma State University

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/1/04 - 4/1/05

Technology
Light Emitting Diodes

Project Summary

Scientists at Nomadics have invented several nanomaterials exhibiting strong emissions in blue (435 nm) and deep green (555-585 nm). These new materials will complement, and possibly replace, the existing GaN-based and InP(As) based materials for illumination and full-color displays.

Phase I will involve the demonstration of a new type of blue emission material with a high photoluminescence quantum yield (>40%), high stability and low cost that is promising for blue LEDs. It will involve the demonstration of II-VI semiconductor nanoparticle LEDs with efficient deep grain emission (555-585 nm), low power, and high stability. Phase I will also demonstrate the concept of all-inorganic semiconductor nanoparticle LEDs with much better performance in electroluminescence efficiency, brightness, stability, and longevity than organic/inorganic nanoparticle LEDs.

The application of LEDs are ubiquitous and include indicator lights, numeric displays on consumer electronic devices, flat panel displays, general illumination, biological/ biomedical imaging and detection, and bacterial disinfection.

The goal of this project is to fabricate efficient nanoparticle LEDs with emission wavelengths in the range of 555- 585 nm. To meet the overall goal of fabricating deep green LEDs, this project will focus on the following objectives in Phase I:

1. Synthesis of silica-coated CdTe, CdSe, and CdSe/CdS solid nanoparticles with emission wavelengths in the range of 555-585 nm and photoluminescence quantum efficiency greater than 50%.

2. Demonstration of efficiency enhancement and lifetime improvement by PLD fabrication of nanoparticle/PPV LEDs in high vacuum.

3. Demonstration of high-efficiency electroluminescence and good stability from all-inorganic nanoparticle LEDs by sandwiching nanoparticle monolayers between p-type (SiC, ZnTe) and n-type (Si) semiconductor layers. All-inorganic nanoparticle LEDs should exhibit low operation power and voltage and high longevity.

4. Improvement of recipes for making blue nanoparticles with narrow-size distribution and high (40%) efficiency.

Successful accomplishment of these objectives will serve as proof-of-principle and will warrant continuation of the research into Phase II with a focus on demonstrating viable nanoparticle LEDs with external quantum efficiency of 25-30%, brightness of 2000 cd/cm2, and lifetime of 5000 hours.

At this point, we have successfully made nanoparticle with deep green emission with high efficiency (Figure 1) and have observed electroluminescence from our nanoparticle LEDs. Light emitting diode performance is affected by the thickness of the hole and electron transport layers. By optimizing the thickness of these layers, we have successfully confined the carriers within the nanoparticle emitting layer and observed strong luminescence from the nanoparticles.

Efficient Hybrid Phosphors for Blue Solid State LEDs

Investigating Organization
PhosphorTech Corporation

Principal Investigator(s)
Hisham Menkara

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,984

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

PhosphorTech is pursuing the development of high-performance fluorescent materials for next generation lighting application using solid state lamps. The novel phosphor materials and lighting devices will be based on hybrid organic/inorganic systems with superior color rendering and power conversion efficiencies to the current state-of-the-art technology. These materials will be fabricated using controlled synthesis techniques. Existing UV-efficient silicate phosphors will be modified to allow blue light absorption and broadband emission in the yellow-green. The goal of Phase I is a white LED having a luminous efficiency of 30 lm/W (2 times that of incandescent bulbs) and a color rendering index over 80. The goal of Phase II is a white LED having a luminous efficiency > 50 lm/W and a CRI > 90.

The availability of efficient white LEDs will open up a number of exciting new application markets, such as white light sources replacing traditional incandescent and fluorescent light bulbs and efficient low-voltage backlights for portable electronics. The down-converting hybrid phosphor materials could also be used to make pixelated screens for full-color photonically driven displays (using RGB filters), and even in maintenance-free LED-based traffic lights.

High-Extraction Luminescent Material Structures for Solid State Light Emitting Diodes (Phase I)

Investigating Organization
PhosphorTech Corporation

Principal Investigator(s)
Hisham Menkara

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,976

Contract Period
7/1/04 - 4/1/05

Technology
Light Emitting Diodes

Project Summary

In Phase I, PhosphorTech successfully demonstrated novel high-performance fluorescent materials for next generation lighting application using solid state lamps. The novel phosphor materials and lighting devices were based on hybrid organic/inorganic systems with superior color rendering and power conversion efficiencies to the current state-of-the-art technology. These materials were fabricated using controlled solid state synthesis techniques and were derived from existing UV-efficient phosphors that were modified to allow blue light absorption and broadband emission in the yellow-green (550-580 nm) and yellow-orange (580-610 nm) part of the visible spectrum.

Novel non-garnet materials were successfully demonstrated with luminous efficiencies exceeding those of commercial cerium-doped yttrium aluminum garnet phosphors (YAG:Ce). During Phase I, various compositions of the SrxBa(1-x)SiO4:Eu phosphor system have been successfully synthesized by solid state reactions using SrCO3, BaCO3, and SiO2 as precursors. In addition, ZnSexS(1-x):Cu phosphors were successfully produced using a copper-doped mixture of ZnS and ZnSe precursors. The organic materials used in the study were commercially available fluorescent pigments based on rhodamine and auramine molecular compounds. Using the phosphor materials with a blue LED, hybrid solid state sources were demonstrated with luminous efficiencies exceeding those of YAG-based LEDs. Two hybrid approaches were demonstrated: (1) Blue LED using an inorganic-organic phosphor system; and (2) Blue/Red LEDs using an inorganic phosphor. Stability tests were conducted on the new hybrid materials and new lamp designs were developed to minimize thermal aging for high-power applications.

Future improvement of the phosphors' quantum efficiencies along with improved LED performance and luminaire designs are expected to yield luminous performance exceeding that of fluorescent lamps. Various illumination architectures will need to be evaluated and built in order to maximize the light extraction from the solid state lamp system while maintaining high-longevity at high power levels. Commercialization of some of the new non-garnet materials is currently being pursued by PhosphorTech, and at least two patent applications were filed with the U.S. Patent Office on inventions that were derived, in part, from Phase I research.

Manufacturing Process for Novel State Lighting Phosphors (Phase I)

Investigating Organization
PhosphorTech Corporation

Principal Investigator(s)
Hisham M. Menkara

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,997

Contract Period
6/27/05 - 3/26/06

Technology
Light Emitting Diodes

Project Summary

Solid state lighting (SSL) is rapidly gaining momentum as a highly energy-efficient replacement technology for traditional lamps. However, current solid state LED devices still suffer from low efficiencies partly due to optical mismatch between the LED and phosphor materials. PhosphorTech has developed a new class of high index material with superior optical performance to the current state of the art. These patent-pending phosphors were optically designed to maximize LED light outcoupling through careful control of their optical properties (such as, refractive index, scattering, absorption, luminescence efficiency, etc.). During the Phase I project, PhosphorTech proposes to demonstrate the feasibility of large-scale production of these new phosphor materials. Phase II goal will be to mass produce these materials at the levels demanded by the future SSL market.

Microporous Alumina Confined Nanowire Inorganic Phosphor Film for Solid State Lighting (Phase I)

Investigating Organization
Physical Optics Corporation

Principal Investigator(s)
Dr. Alexander Parfenov

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,973
Contractor Share:

Contract Period
06/28/06 - 03/27/07

Technology
Light Emitting Diodes

Project Summary

This project proposes a new advanced phosphor to combine with a light-emitting diode to create a pure white solid-state lighting device that is at least 20% more efficient than current ones. In addition, the technology of the phosphor helps to create long-lived devices with fewer environmental hazards in both processing and use of the device. Currently, several phosphors are prepared and characterized for micro Raman, photoluminescence, and electron microscopy. A demonstration LED device is being prepared with new color phosphors.

Sliding Mode Pulsed Current IC Drivers for High Brightness Light Emitting Diodes

Investigating Organization
SynDiTec, Inc.

Principal Investigator(s)
Anatoly Shteynberg

Subcontractor
Northeastern University

Funding Source
Small Businesss Technology Transfer

Award
DOE Share: $99,994
Contractor Share:

Contract Period
6/27/05 - 3/26/06

Technology
Light Emitting Diodes

Project Summary

The goal of this project is to derive models to state space the dynamic behavior of a High Brightness - LED (HB-LED) arrays through hysteretic pulse current averaging techniques.

To date, we have:
1. Synthesized mathematical models and derived algorithms for pulse current averaging control.

2. Modeled and simulated the new hysteretic controller for HB-LEDs. Unusual to hysteretic control, the new SynDiTec “pulsed current averaged” controllers restrict the amount that a duty ratio in a DC-DC converter can increase each switching time cycle.

3. Simulated the SynDiTec actual controllers for a boost converter using two separate software packages. Using these simulations, we have created: time domain simulations, phase plane analysis, and sensitivity simulations to model uncertainties.

4. Developed a system block diagram with pin connections for a next generation driver IC primarily designed for driving white LEDs.

5. Built a prototype of the LED driver IC with FPGA and have experimentally verified that the pulsed current averaging algorithms work effectively.

Overall, we demonstrated that the SynDiTec pulse current averaging hysteretic control works to drive HB LED's. Further, the method is simple, low cost, and feasible for driving HB LED's. Some other advantages of this method appear to be:

- Inherent pulse-by-pulse current limiting, making the power converter nearly immune to damage from overload.
- No external compensation needed.
- Fast response of the inductor current.

The SynDiTec controller with unique rate limiter is able to stabilize and control the LED current in the boost converter configuration and stabilizes to approximately 20mA, while the boost inductor current remains in DCM with peak value of 120mA. On the other hand, if traditional hysteretic control is used without the SynDiTec rate limiter, the controller does not work. That is, although the LED current stabilizes around 20mA, the inductor current never reaches steady state, and eventually ramps to theoretically infinity. Thus, the SynDiTec controller appears to maintain the simplicity of hysteretic control, but because of the unique algorithm, is applicable to HB LED systems that previously could not be directly applied with traditional hysteretic control.

Novel Low-Cost Technology for Solid State Lighting (Phase I)

Investigating Organization
Technologies and Devices International

Principal Investigator(s)
A. Usikov

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,976

Contract Period
7/1/03 - 4/30/04

Technology
Light Emitting Diodes

Project Summary

The work of Technologies and Devices International focuses on demonstrating a novel epitaxial technology with substantially reduced process cost for fabrication group-III nitride epitaxial structures for white light emitting diodes. The technology is based on hydride vapor phase epitaxy (HVPE) of AlGaN/GaN light emitting structures.

For group-III nitride semiconductors, HVPE is known to be a low-cost method for fabrication of thick quasi-bulk GaN materials, GaN-on-sapphire, and AlN-on-sapphire templates used as substrates for device fabrication. The Phase I objective is to extend HVPE cost-effective epitaxial technology for the fabrication of white light emitting devices. Al(In)GaN-based blue ultra violet emitters fabricated by HVPE technology for lighting applications will be demonstrated.

This technology will also provide a number of technological advantages for the growth of high-efficient blue and UV light-emitting structures. General lighting devices will be fabricated by packaging the blue or UV LEDs with a white light conversion phosphor blend. Potential applications include residential general illumination, aviation, and hazard indicators.

The researchers have also designed light emitting structures and investigated material deposition HVPE technology. A novel HVPE method has grown two sets of epitaxial materials. Grown samples are under characterization. The next step will be to grow p-type AlGaN layers, and to fabricate structures for blue-UV LED dies processing and delivery of pn structures for phosphorous deposition.

Novel Low-Cost Technology for Solid State Lighting (Phase II)

Investigating Organization
Technologies and Devices International

Principal Investigator(s)
Dr. Alexander Usikov

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $749,953

Contract Period
08/01/05 - 08/01/06

Technology
Light Emitting Diodes

Project Summary

The main technical objective of this program is to demonstrate an alternative cost-effective epitaxial technology for fabrication of GaN-based light emitting devices for white lighting applications, and to investigate these novel light-emitting semiconductor structures.

1. Investigate GaN-based materials produced by novel epitaxial technology for LED applications including high conductivity p-type GaN and AlGaN materials and light emitting materials with increased quantum efficiency of radiative recombination.

2. Reduce defect density and impurity background concentration in light emitting epitaxial structures to improved lifetime and operation stability of the devices.

3. Develop low defect lattice matched substrate materials for high-efficiency GaN-based LED structures. GaN and AlGaN templates will be developed and tested for LED fabrication.

For group III nitride semiconductors, HVPE technology is known to be a low-cost method for the fabrication of thick quasi-bulk GaN materials. Phase I demonstrated feasibility of this technical approach for fabrication of GaN and AlGaN templates (composite substrates) for GaN-based light emitting devices and producing white light emitting structures.

In Phase II, TDI will focus on the development of cost-effective manufacturing technology for Al(In)GaN-based structures and improvement efficiency of violet, UV, and white LED lamps. The target brightness of white LEDs is 100 lm/W.

GaN-on-sapphire, AlN-on-sapphire, and AlGaN-on-sapphire template substrates for blue LEDs have been fabricated by HVPE technology and characterized. Crystal structure, optical, and electrical properties of grown materials are measured. Dislocation densities are estimated using results of X-ray material characterization. P-type Mg- and Zn-doped single- and multi-layer GaN and AlGaN structures have been grown by HVPE technology. The structures are under investigation.

Development of cost-effective epitaxial technology for high-efficient white LEDs will speed up penetration of solid-state lighting into the illumination market and improve LED performance. It is anticiapted that as a result of this Phase II SBIR program, high-efficiency high brightness GaN-based light emitting devices will be demonstrated using novel cost effective epitaxial technology. Novel substrate materials for advanced GaN-based devices will be developed and tested. Defect density in the structures will be decreased leading to better device performance. Efficiency of radiation recombination in GaN-based materials will be increased and carrier injection efficiency into light emitting regions of LED structures will be improved.

GaN, AlGaN, and AlN layers and multi-layer structures are grown employing multi-wafer growth equipment developed at TDI. Sapphire wafers used as substrate materials. The growth performed in temperature range from 1000 to 1100oC. Magnesium, zinc, and silane are used for doping. The gas flow rates are varied to control GaN (AlGaN) growth rates in the range form of 0.2 to 3.0 mm/min. The layers and the structures are characterized by X-ray diffraction, optical and scanning electron microscopy, atomic force microscopy, photoluminescence, UV transmission, and capacitance-voltage (C-V) measurements.

High-Efficiency ZnO-Based LEDs on Conductive ZnO Substrates for General Illumination (Phase I)

Investigating Organization
ZN Technology

Principal Investigator(s)
Mr. Gene Cantwell

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/3/04 - 4/12/05

Technology
Light Emitting Diodes

Project Summary

High-efficiency, white light LEDs will be fabricated from alloys of ZnO on conductive ZnO substrates utilizing a phosphor(s) to convert the nearly monochromatic, blue or near UV light of the LED to white light. The method for p-type doping patented by the PI along with the growth of high-quality ZnO substrated in-house, will enable the project to proceed rapidly. The inherent luminous efficiency of ZnO, along with the ability to construct totally vertical devices due to the conductive substrate and the lower cost of the basic materials, will result in increased efficiency and lower cost than the current technology.

ZnO-based LED structures will be fabricated and characterized during Phase I. Initially, a simple pn device will be made and fully characterized for electrical and electro-optic characteristics. Subsequently, a single quantum well LED will be constructed using a CdZnO alloy as the quantum well and MgZnO as the barriers. The LED structure will be fully characterized and the data used to project efficiency of an optimized LED device based on these compounds. Selection of a phosphor(s) for conversion to white light and their impact on the overall efficiency will be projected.

Development of this technology will result in high-efficiency, low-cost, white light LEDs for general illumination. In addition, it will also result in high-brightness blue and ultra violet LEDs for application in displays, backlighting, and other applications. The technology for high-efficiency diode lasers will derive from the LED technology. These lasers will have application in the high density optical storage industry (DVDs, etc.), in the printing industry, (i.e., direct computer writing to printing plates), a in other areas requiring a highly compact, high efficiency laser source in the blue or ultra violet.

Next Generation Hole Injection/Transport Nano-Composites for High Efficiency OLED Development

Investigating Organization
Agiltron Inc.

Principal Investigator(s)
Dr. King Wang

Subcontractor
Penn State University
University of California, Los Angeles

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $360,925
Contractor Share: $90,231

Contract Period
08/01/06 - 07/31/07

Technology
Organic Light Emitting Diodes

Project Summary

This proposal seeks to improve the electrical efficiency of OLEDs through the use of a novel nano-composite coating material for the anode coating/hole transport layer. The specific objective of this proposed research is an OLED with 60-80 lm/W with a CRI above 90 that lasts more than 10,000 hours.

Low Cost Transparent Conducting Nanoparticle Networks for OLED Electrodes

Investigating Organization
Argonne National Laboratory

Principal Investigator(s)
Jeffrey W. Elam

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $956,100

Contract Period
09/11/06 - 03/12/08

Technology
Organic Light Emitting Diodes

Project Summary

Development of transparent conductive oxides (TCOs) is critical for OLED device efficiency. This project proposes an innovative transparent conducting layer consisting of a self assembled network of conducting particles whose nanometer dimensions and large open area ratios make them much more transparent for a given electrical conductivity than conventional TCOs.

Thin Film Packaging Solutions for High-Efficiency OLED Lighting Products

Investigating Organization
Dow Corning Corporation

Principal Investigator(s)
Ken Weidner

Subcontractor
Philips Lighting

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,414,300
Contractor Share: $2,348,673

Contract Period
11/30/04 - 06/30/08

Technology
Organic Light Emitting Diodes

Project Summary

The objective of the project is to develop and demonstrate thin film packaging materials and low cost substrates for application to high efficiency PhOLED devices as required for general illumination and in particular high value lighting in store displays. The packaging approach taken is based on thin film SiC PECVD coating materials previously demonstrated for application to microelectronics. These materials and processes will be adapted to lower temperatures, larger areas, and different substrates. Silicone based interfacial layers will be considered to reduce interlayer defects, reduce stresses, and improve adhesion. These thin film coatings will be optimized for use as OLED encapsulation, moisture and oxygen barriers on plastic films, and ion diffusion barriers on glass substrates. Composite substrates will be formed using available low cost glass and plastic substrates with applied smoothing layers to reduce surface roughness and barriers to extend life. High efficiency phosphorescent small molecule OLED devices will be used to evaluate device level performance. Test articles will be fabricated of increasing size and performance ultimately resulting in a 2ft x 2ft sq module.

During the conduct of the project, the project team completed and delivered the following achievements:
• A three-year marketing effort that characterized the near-term and longer-term OLED market, identified customer and consumer lighting needs, and suggested prototype

product concepts and niche OLED lighting applications that will give rise to broader market acceptance as a source for wide area illumination and energy conservation.

• A thin film encapsulation technology with a lifetime of nearly 15,000 hours, tested by calcium coupons, while stored at 16°C and 40% relative humidity ("RH"). This encapsulation technology was characterized as having less than 10% change in transmission during the 15,000 hour test period.

• Demonstrated thin film encapsulation of a phosphorescent OLED device with 1,500 hours of lifetime at 60°C and 80% RH.

• Demonstrated that a thin film laminate encapsulation, in addition to the direct thin film deposition process, of a polymer OLED device was another feasible packaging strategy for OLED lighting. The thin film laminate strategy was developed to mitigate defects, demonstrate roll-to-roll process capability for high volume throughput (reduce costs) and to support a potential commercial pathway that is less dependent upon integrated manufacturing since the laminate could be sold as a rolled good.

• Demonstrated that low cost "blue" glass substrates could be coated with a siloxane barrier layer for planarization and ion-protection and used in the fabrication of a polymer OLED lighting device. This study further demonstrated that the substrate cost has potential for huge cost reductions from the white borosilicate glass substrate currently used by the OLED lighting industry.

• Delivered four-square feet of white phosphorescent OLED technology, including novel high efficiency devices with 82 CRI, greater than 50 lm/W efficiency, and more than 1,000 hours lifetime in a product concept model shelf.

• Presented and or published more than twenty internal studies (for private use), three external presentations (OLED workshop – for public use), and five technology-related external presentations (industry conferences – for public use).

• Issued five patent applications, which are in various maturity stages at time of publication.

High-Efficiency, Illumination Quality White OLEDs for Lighting

Investigating Organization
General Electric Global Research

Principal Investigator(s)
Mr. Joseph Shiang

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,860,785
Contractor Share: $1,226,050

Contract Period
12/21/04 - 03/31/08

Technology
Organic Light Emitting Diodes

Project Summary

GE is developing a novel organic device design and corresponding materials set that will directly result in white OLEDs capable of producing >45 LPW by th end of the program. To achieve the program goal, the team will expand the existing library of materials and designs, and develop the necessary processing expertise to produce OLED devices in which all of the spin-state and charge transport pathways are tightly controlled to convert 100% of the injected charge into a light suitable for use in a white light source.

In the program, GE developed several routes to the fabrication of multilayer devices. In addition, GE developed new chemistries for polymer materials and emissive dopants. By using these chemistries and multilayer technology, polymer OLEDs with different colors and external quantum efficiencies of >10% were built, and the fundamental feasability of the device concept demonstrated. In addition, devices that exhibit peak energy efficiencies of >8% w/w (optical power divided by electrical power) were demonstrated for both red and blue solution processed OLED devices.

OLED Durability and Performance

Investigating Organization
General Electric Global Research

Principal Investigator(s)
Anil Duggal

Subcontractor
None

Funding Source
BT/NETL SSL

Award
DOE Share: $2,951,064

Contract Period
9/1/00 - 11/15/03

Technology
Organic Light Emitting Diodes

Project Summary

GE Global Research conducted a three-year program to reduce the long-term technical risks that are keeping the lighting industry from embracing and developing OLEDs. The specific goal was a demonstration light panel that delivers white light with brightness and light quality comparable to a fluorescent source and with an efficacy better than that of an incandescent source. This required significant advances in three areas: 1) improvement in OLED energy efficiency at high brightness; 2) improvement of white light quality for illumination; and 3) the development of cost-effective, large-area fabrication techniques.

The technical effort was divided into three main technical phases designed to achieve a significant milestone at the end of each year. In Phase I, GE developed a small area-efficient white light device. This task involved sourcing available blue polymers and using these to fabricate and evaluate device performance. One polymer was chosen for white device development. The key outcome of this phase was the first demonstration that high-illumination-quality white light could be generated using OLED technology.

Phase II focused on scaling up the white device manufacturer to a device measuring 36 square inches. In order to do this, new area-scalable device designs were developed to allow the development of large area OLEDs using low-cost techniques. The key outcome of this phase was the invention of a novel device design that is tolerant to manufacturing defects and scalable to large areas.

Phase III was devoted to improving the underlying OLED device efficiency and developing the technology and system optimization required to build a 2 ft. x 2 ft. demonstration panel for white-light illumination. The key outcome of this phase was a final 2 ft x 2ft OLED deliverable panel with the following "world-record" specifications:

Color Temperature: 4000 K Efficacy: 15 Lumen/Watt
Color Rendering: 88 CRI Light Output: 1200 Lumens

This project was successful both in meeting its technical objectives and in demonstrating to the lighting community that OLEDs are a potentially viable solid state lighting source. This is evidenced by the healthy quantity and variety of OLED lighting projects currently being funded by DOE.

Hybrid Nanoparticle/Organic Semiconductors for Efficient Solid State Lighting

Investigating Organization
Los Alamos National Laboratory

Principal Investigator(s)
Darryl Smith

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $800,000

Contract Period
10/01/06 - 03/31/08

Technology
Organic Light Emitting Diodes

Project Summary

The objective of this project is to establish a new class of high efficiency, low-voltage, stable hybrid OLEDs for general illumination. This new class of hybrid OLEDs will be fabricated from organic/inorganic nanoparticle composite semiconductors.

Material and Device Designs for Practical Organic Lighting

Investigating Organization
Los Alamos National Laboratory

Principal Investigator(s)
Mr. Darryl Smith

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,018,369

Contract Period
10/01/04 - 09/30/07

Technology
Organic Light Emitting Diodes

Project Summary

This project will combine theoretical and experimental approaches to methodically address key material challenges for OLED use in general illumination applications. The project will systematically advance the physical and chemical understanding of how materials-related phenomena can be altered to make very high efficiency, low voltage, stable, inexpensive, and reliable devices. The fundamental knowledge gained from this work will contribute to product development.

To establish high efficiency, low-voltage, stable materials for practical, organic light emitting diode based general illumination applications, it is necessary to simultaneously ensure that: essentially all electrons and holes injected into the structure form excitons; the excitons recombine radiatively with high probability; the minimum drive voltage is required to establish a given current density in the device; and the material and device are stable under continuous operation. The project applied a tightly knit theory/fabrication/ measurement approach to understand and optimize four essential material and device elements necessary for satisfying these requirements: 1) charge injection, 2) carrier mobility, 3) organic/organic heterojunctions, and 4) exciton processes. Because of the many material and device options available, we will develop general methods of achieving the device requirements in these four areas.

Low-Cost Nano-Engineered Transparent Electrodes for Highly Efficient OLED Lighting

Investigating Organization
Oak Ridge National Laboratory

Principal Investigator(s)
David Geohegan

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $600,000

Contract Period
12/01/06 - 06/30/08

Technology
Organic Light Emitting Diodes

Project Summary

This project addresses two challenges whose solution is crucial to improve the efficiency of organic-LEDs: enhanced internal quantum efficiency via control over the singlet/triplet ratio, and enhanced carrier transport through poorly conducting organic materials by using carbon nano-tubes as low-cost transparent electrodes.

Polymer OLED White Light Development Program

Investigating Organization
OSRAM Opto Semiconductors

Principal Investigator(s)
Alfred Felder

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,031,310
Contractor Share: $2,031,310

Contract Period
2/5/04 - 1/31/07

Technology
Organic Light Emitting Diodes

Project Summary

OSRAM Opto Semiconductors (OSRAM) successfully completed development, fabrication and characterization of the large area, polymer based white light OLED prototype at their OLED Research and Development (R&D) facility in San Jose, CA. The program, funded by the Department of Energy (DOE), consisted of three key objectives:
* Develop new polymer materials and device architectures – in order to improve the performance of organic light emitters.
* Develop processing techniques – in order to demonstrate and enable the manufacturing of large area, white light and color tunable, solid state light sources.
* Develop new electronics and driving schemes for organic light sources, including colortunable light sources.

A world record efficiency of 25 lm/W was established for the solution processed white organic device from the significant improvements made during the project. However, the challenges to transfer this technology from an R&D level to a large tile format such as, the robustness of the device and the coating uniformity of large area panels, remain. In this regard, the purity and the blend nature of the materials are two factors that need to be addressed in future work.

Novel Organic Molecules for High-Efficiency Blue Organic ElectroLuminescence

Investigating Organization
Pacific Northwest National Laboratory

Principal Investigator(s)
Mr. Paul Burrows

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,400,000

Contract Period
10/01/04 - 10/31/07

Technology
Organic Light Emitting Diodes

Project Summary

This project explores using state-of-the-art phosphorescent organic light emitters to dramatically increase the power efficiency of blue organic light emitting devices by incorporating them in novel, electron-transporting host layers. Blue is thought by many to be the color that limits the efficacy of white OLED devices, as well as full-color organic light emitting displays. Typically, organic phosphors are doped into a conductive host matrix and emission results from energy transfer from the host to the triplet state of the phosphor. Development of efficient blue OLEDs based on this technology has been particularly challenging because the host material must exhibit triplet level emission > 450 nm without sacrificing charge transporting properties. Current host materials do not meet these requirements because there is a tradeoff between increasing the bandgap of the material and decreasing the p-aromatic system, which adversely affects charge transport properties. Deeper blue phosphors have only been demonstrated in insulating, wide bandgap host materials with charge transport occurring via hopping between adjacent dopant molecules. This leads to high voltage and ,therefore, less efficient devices.

An alternative route for achieving blue shifted emission energies is to replace the nitrogen heteroatoms with phosphorus. For example, aromatic diphosphine oxides are stable compounds that exhibit electroluminescence in the ultraviolet spectral region (335 nm for one example already tested) while extended electronic states in the phosphorus

atom give rise to good electron transport at low voltages. Thus, it is possible to widen the bandgap without eliminating the aromatic backbone of the molecule, which makes these materials excellent hosts for high-efficiency blue phosphors, as well as longer wavelength OLEDs.

Cavity Light Emitting Diode for Durable, High Brightness and High-Efficiency Lighting Applications

Investigating Organization
SRI International

Principal Investigator(s)
Yijian Shi

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $690,456
Contractor Share: $186,436

Contract Period
09/30/06 - 09/30/07

Technology
Organic Light Emitting Diodes

Project Summary

The overall objective of this work is to produce highly efficient white OLED devices using a novel device structure, the CLED structure, which will lead to a path for achieving the DOE goals of 100 LPW efficiency and 50,000 hours lifetime at 850 cd/m^2. The proposed product development research project includes a two-phase effort that will be completed within 36 months. The Phase I objective is to develop a reliable process for production of the CLED with desired specifications that will demonstrate approximately 5 times higher efficiency than a conventional OLED at 1000 cd/m^2. The objective of Phase II is to produce white CLED device with 1000-3000 lm/device light output, 100 LPW efficiency, and 10,000-hour lifetime (at 850 cd/m^2). We expect this study to identify a path of achieving >100 LPW efficiency and 50,000-hour lifetime.

Novel Low-Cost Organic Vapor Jet Printing of Striped High-Efficiency Phosphorescent OLEDs for White Lighting

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Mike Hack

Subcontractor
Michigan University

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $2,400,000
Contractor Share: $1,600,000

Contract Period
09/23/04 - 12/31/08

Technology
Organic Light Emitting Diodes

Project Summary

The overall objective of this work is to produce highly efficient white OLED devices using a novel device structure, the CLED structure, which will lead to a path for achieving the DOE goals of 100 LPW efficiency and 50,000 hours lifetime at 850 cd/m^2. The proposed product development research project includes a two-phase effort that will be completed within 36 months. The Phase I objective is to develop a reliable process for production of the CLED with desired specifications that will demonstrate approximately 5 times higher efficiency than a conventional OLED at 1000 cd/m^2. The objective of Phase II is to produce white CLED device with 1000-3000 lm/device light output, 100 LPW efficiency, and 10,000-hour lifetime (at 850 cd/m^2). We expect this study to identify a path of achieving >100 LPW efficiency and 50,000-hour lifetime.

Surface Plasmon Enhanced Phosphorescent Organic Light Emitting Diodes

Investigating Organization
University of California, Santa Barbara

Principal Investigator(s)
Mr. Guillermo Bazan

Subcontractor
None

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $854,860
Contractor Share: $213,382

Contract Period
09/28/04 - 08/01/08

Technology
Organic Light Emitting Diodes

Project Summary

Work by leading OLED researchers has repeatedly demonstrated that phosphorescent OLED performance is not limited to 25% of the relaxation pathways that produce photonic emissions, owing to statistical spin of excited states normally associated with singlets. Phosphorescence is routinely used in the laboratory to fabricate phosphorescent OLEDs with performance surpassing 80%. This project will explore novel radiative decay control techniques to harness the energy of triplet states that are chemically and quantum-mechanically different, but functionally similar to currently accepted phosphorescent methods. The three-year project will systematically explore blending of chromophores and different plasmon structures to achieve better efficiencies via enhanced triplet annihilation and utilization.

Novel Materials for High-Efficiency White Phosphorescent OLEDs

Investigating Organization
University of Southern California

Principal Investigator(s)
Dr. Mark Thompson

Subcontractor
Princeton University
Universal Display Corp.

Funding Source
Building Technologies Program/NETL

Award
DOE Share: $1,350,000
Contractor Share: $494,068

Contract Period
09/30/04 - 03/31/08

Technology
Organic Light Emitting Diodes

Project Summary

This project involves a materials synthesis effort, in which large families of materials will be generated, intended for use in each of the different parts of the OLED. Each of the materials will be prepared with a specific device concept in mind, which involves resonant injection of carriers into the emissive layer. The materials to be prepared and examined here include carrier transporting/injecting materials, host materials for the doped emissive layer, and phosphorescent dopants, in a range of colors as well as broadband emitters. All of these materials will be extensively screened for chemical and thermal stability before being incorporated into OLEDs. OLED testing will be done in both monochromatic and white OLED structures. Many of the materials being prepared in this program will be useful in a range of different OLED structures and could be adopted by other research groups and programs to enhance the efficiency and stability of their devices.

The device architecture used in this program will rely on several specific design criteria to achieve high efficiency and long lifetime. The use of phosphorescent dopants will be necessary in any OLED structure to meet the DOE's performance goals. The emissive materials are all phosphorescent complexes, which have demonstrated long device lifetimes and high efficiencies in monochromatic devices, which are expected to carry over to properly designed white devices. The weak link in these materials is the blue

phosphorescent dopant. These materials will be specifically targeted, and have a sound strategy to solve the blue reliability problems. In addition to designing the optimal monochromatic and broadband phosphors for the devices, a controlled energetic alignment for the devices will be relied upon, which will minimize drive voltage and increase the exciton formation efficiency. The carrier-injecting materials will be chosen to match the HOMO and LUMO levels in the emissive dopant exactly, such that the carriers are injected into the phosphorescent dopant in a resonant process. The phosphor will be doped into a wide gap host material, which will prevent host-carrier interactions, keeping the carriers and excitons exclusively localized on the phosphors.

Materials Degradation Analysis and Development to Enable Ultra Low Cost, Web-Processed White P-OLED (Phase I)

Investigating Organization
Add-Vision, Inc.

Principal Investigator(s)
J. Devin MacKenzie

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $98,855

Contract Period
6/20/07 - 3/19/08

Technology
Organic Light Emitting Diodes

Project Summary

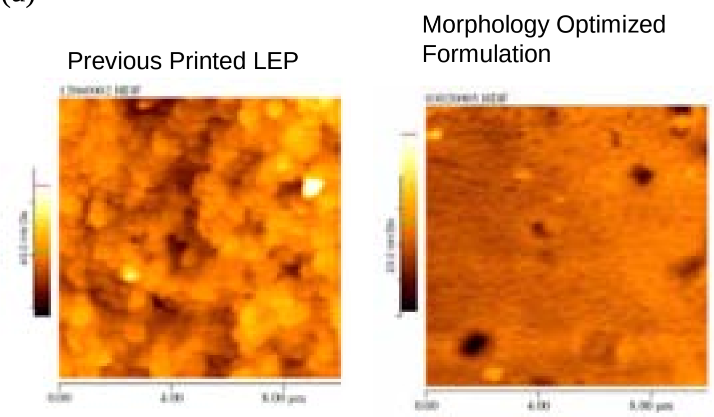
Add-Vision ("AVI") has developed a path for specialty SSL using a doped Polymer Light-Emitting Diode (POLED) device structure, enabling printing of devices with low capital equipment and operating costs. Devices made with AVI's approach are efficient, thin, flexible, and robust and AVI has plans with licensing partners to commercialize this technology in entry level specialty SSL applications. However, additional performance improvements, which would be made possible through the degradation analysis and material and process development proposed in the early stages of this STTR program would enable commercialization of this technology in a broader range of applications of interest to DOE and their licensees for interior buildings, safety and night lighting.

AVI will combine its expertise in printed POLED devices, materials, processing and electrical characterization with the materials analysis and synthetic capabilities of Lawrence Berkeley National Laboratory to identify the primary efficiency degradation mechanisms for doped POLED devices (Phase-I), then develop a next generation materials set based on this analysis for high efficiency, longer lifetime printed devices. Upon achievement of the performance and lifetime improvements, Phase-II and III emphasize product demonstration, process scale-up and pilot manufacture with continuous engagement with their manufacturing licensee(s) and product development customers.

AVI's POLEDs are anticipated to accelerate the early adoption of POLED technology in SSL and improve energy savings and overall product performance in future building applications, including electronic signage, architectural lighting, safety lighting, emergency and portable lighting, and other specialty lighting products. The print-based manufacturing approach of this OLED technology has inherently low cost capital equipment and operating adoption, product start-up, and large scale web manufacture of SSL that could leverage the resources of the U. S. 's more than 40,000 printing operations.

Since the beginning of the project, Add-Vision has seen substantial improvements in device performance through morphology improvements, formulation optimization of LEP materials, and improved encapsulation technology. We have now repeatedly demonstrated fully air printed P-OLED devices of >1000 hrs lifetime with 100 Cd/m^2 maximum luminance, meeting our initial brightness lifetime goals. Work is ongoing to improve operating voltages and further elucidate the next limiting degradation issue. This includes ongoing work with purified organic materials and microscopy work made available by LBNL.

(a)



(b)

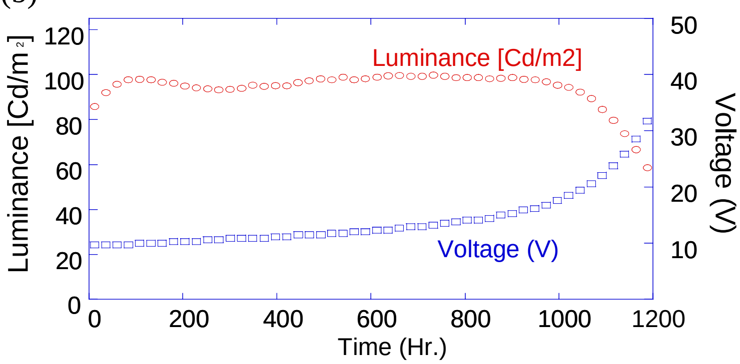


Figure 1. (a) Atomic force micrographs showing the improvements in surface morphology that have been achieved through printed LEP formulations development [right] as compared to the previous formulations [left] Note that the X and Y scales are 8 microns and the z height scales are 40nm per division on the left and 20 nm per division on the right. The lifetime test data for an encapsulated part made from these formulations is shown in (b) demonstrating 1000 hrs operation in air under constant current driving conditions.

Enhancing Charge Injection and Device Integrity in Organic LEDs (Phase I)

Investigating Organization
Agiltron Inc.

Principal Investigator(s)
Mr. King Wang

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/13/04 - 4/12/05

Technology
Organic Light Emitting Diodes

Project Summary

Organic lighting emitting diode (OLED) based sold state lighting is a candidate technology that offers significant gains in power efficiency, color quality, and life time at lower cost and less environmental impact than traditional incandescent and fluorescent lighting. However, current achievements in OLED devices have not yet realized the power efficiency and lifetime requirements for general lighting applications. Two important factors limiting performance are on-efficiency and non-balanced charge injection leading to poor device stability.

The goal of this program is to develop innovative, low cost OLED anode surface modification technology, which will increase device energy efficiency by 5 to10 times while also significantly improving device stability and lifetime simultaneously. OLED anode (ITO) modification using an ultra-thin cross-linked hole transporting layer is planned by means of a low-cost self assembly approach. Cross-linkable, high hole transporting molecules will be synthesized and application methods commensurate with automated processing will be developed.

Air-stable, cross-linkable, high mobility hole transporting molecules have been synthesized with a high yield. These molecules are being spin-coated on conventional ITO substrates, on which multilayer OLED structures will be fabricated. Improvements in device energy efficiency and lifetime by the novel ITO surface modification layer will be evaluated and compared with OLED devices built on bare ITO substrates and substrates coated with other ITO modification agents. The coating process will be scaled to coat large-area rigid or flexible ITO substrates under an ambient environment using low-cost automated dip-coating or roll-to-roll coating processes, which are under development.

High performance OLEDs will be extremely beneficial for solid state lighting, high brightness image displays, sign indicators, automobile displays, and wearable electronics.

Enhancing Charge Injection and Device Integrity in Organic LEDs (Phase II)

Investigating Organization
Agiltron, Inc

Principal Investigator(s)
Dr. King Wang

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $749,942

Contract Period
08/01/05 - 07/10/07

Technology
Organic Light Emitting Diodes

Project Summary

Agiltron is developing an innovative, low-cost anode surface modification technology for OLEDs, designed to significantly increase device efficiency and improve device stability and lifetime as well. Researchers have developed stable, high-yield, high hole transporting molecules that can cross-link to form ultrathin coatings. These coatings will be used to modify the surface of the indium tin oxide (ITO) anode of the OLED to enhance the injection of holes into the active area and increase device stability. Significantly, and in parallel, Agiltron is also developing a low-cost mist deposition approach for OLED fabrication that is scalable into a continuous mass production manufacturing technique. Development efforts will continue in Phase II that were begun in Phase I, where the feasibility was demonstrated through a continuous optimization and scale-up of air-stable and cross-linkable HTL materials synthesis and development of low-cost, large-scale mist deposition processes for polymer OLED fabrication. Agiltron's hole transport materials have been evaluated with promising results in a real device environment by GE's Solid State Lighting Group. The test results show Agiltron materials are more robust at high brightness conditions than current industry standard PEDOT, which indicates that more stable devices and longer device a lifetimes can be expected. Agiltron's approach represents an unparalleled opportunity to contribute to the OLED performance target goal of 100 lumens per watt and lifetime of 50,000 hours, and the cost target goal of $3.00 per 1000 lumens.

Flexible Environmental Barrier Technology for OLEDs (Phase I)

Investigating Organization
Alameda Applied Sciences Corp.

Principal Investigator(s)
Jason Wright

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
6/20/07 - 3/19/08

Technology
Organic Light Emitting Diodes

Project Summary

Protecting OLEDs from moisture and oxygen remains the key technical challenge for fabricating flexible solid-state lighting displays with acceptable service lifetimes. OLED-based displays on flexible PET polymer substrate have been demonstrated; however, they exhibited poor operating lifetimes due to atmospheric exposure. Alameda Applied Sciences Corporation (AASC) proposes to develop a high-throughput, low-temperature thin film environmental barrier technology on PET polymer substrates to lower costs and reduce permeation rates.

In Phase I, AASC will use its energetic thin film deposition process to demonstrate the feasibility of producing low defect density ceramic barrier films suitable for OLED devices on PET substrates. The goal is to produce ceramic/PET single-layer barriers with defect densities $<1.0 mm^{-2}$ and $<5x10^{-3}$ $g{\cdot}m^{-2}{\cdot}day^{-1}$ water vapor transmission rate (WVTR) at 100% RH and 40°C. Phase-II will focus on further optimization of barrier properties to $<10^{-6}$ $g{\cdot}m^{-2}{\cdot}day^{-1}$ WVTR and $<10^{-5}$ $cc{\cdot}m^{-2}{\cdot}day^{-1}$ oxygen transmission rate (OTR), accelerated environmental testing of encapsulated OLED devices, and integrating their barriers into the context of a production scale setting.

Low-cost high throughput roll-to-roll deposition of effective thin film moisture barriers would represent a key enabling technology for increasing lifetimes of OLED-based lighting. The public benefits of a viable OLED display industry are due to the revolutionary transformation in energy efficiency as the U.S. gradually shifts to LED and

OLED-based lighting. To give an idea of the magnitude of the opportunity, in 2001, 30% of U.S. buildings site electricity consumption (total: 2390 terawatt hours) was due to lighting.

High-Performance, Silicon Nanocrystal-Enhanced Organic Light Emitting Diodes for General Lighting (Phase I)

Investigating Organization
InnovaLight

Principal Investigator(s)
Mr. Fred Mikulec

Subcontractor
University of Texas at Austin

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/15/04 - 4/15/05

Technology
Organic Light Emitting Diodes

Project Summary

Silicon nanoparticles hold great promise toward enabling highly efficient, color tunable, and cost-effective white light emitting devices capable of meeting the high standards of the general illumination market. While silicon, in its usual bulk form, does not emit light, when the particle size is reduced below five nanometers, these silicon nanoparticles, can display very bright photoluminescence. Single, particle spectroscopy research has shown that quantum efficiencies approaching 100% are technically possible. Depending upon the size of the nanoparticle, this emission is tunable throughout most of the visible spectrum and into the IR. Precise variation of size and size distribution provides a simple, yet powerful, means of controlling emission quality. Also, since the emitter is the same silicon material in all cases, we do not anticipate differential aging problems that would tend to degrade emission quality over time.

The objective of this Phase I grant proposal is to develop a novel core-shell passivation scheme to stabilize silicon nanocrystal photoluminescence and, ultimately, achieve the theoretically predicted 100% quantum efficiency. InnovaLight is currently well on the way toward achieving this milestone. In Phase I, silicon nanocrystals will be treated using an innovative passivation scheme that coats them with novel inorganic shells. Two different core-shell combinations will be explored and proof-of-concept devices will be made. The resultant materials will be analyzed for both their physical and emissive properties. The goal is to have well-characterized, light emitting particles ready for device optimization work in Phase II, a project we anticipate will focus on employing the stabilized nanocrystals in novel hybrid organic light emitting devices.

Numerous other high-value market opportunities exist for the proposed technology as well, including flat panel displays, specialty lighting, biological sensors, quantum dot lasers, and novel floating gate memory structures. There is much commercial value in furthering research into this fundamental scientific area.

New Stable Cathode Materials for OLEDs (Phase I)

Investigating Organization
International Technology Exchange

Principal Investigator(s)
Terje Skotheim

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,800

Contract Period
08/01/04 - 08/01/06

Technology
Organic Light Emitting Diodes

Project Summary

NAC (nanostructured amorphous carbon) materials can be made electroactive by "doping" with a wide range of elements and compounds. The materials are deposited in a vacuum using plasma-enhanced chemical vapor deposition (PECVD) with the substrate at or near room temperature. The films can be deposited on a wide range of substrates, including polymeric and other organic substrates.

NAC films are dense and can be made pinhole-free at a thickness below 1 mm. They have excellent properties as corrosion protection coatings, implying that these films are effective barriers to water and oxygen. The work function can be varied by doping with elements with different electronegativities.

During Phase I, OLEDs were fabricated with a 100 nm thick emitter layer of Alq_3 and a PEDOT:PSS hole conducting layer on ITO. The top layer was an Al-doped NAC cathode layer. The performance of these OLEDs were compared with that of OLEDs made with evaporated Al metal films as cathodes. Additionally, OLEDs were made in the reverse order with the emitter layer deposited on top of the NAC cathodes and with a thin, semi-transparent Au film as anode. The results fulfilled the objective of demonstrating the proof-of-principle that NAC coatings can be used as cathode materials. The Al-NAC cathodes had a turn-on voltage of ~8V vs. ~4V for cells with evaporated Al metal cathodes.

In addition, atomic force microscopy of the NAC coatings revealed that the ~1mm coatings that were used were atomically smooth and free of pinholes.

New Stable Cathode Materials for OLEDs (Phase II)

Investigating Organization
International Technology Exchange

Principal Investigator(s)
Dr. Terje Skotheim

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $749,824

Contract Period
7/14/04 - 7/13/06

Technology
Organic Light Emitting Diodes

Project Summary

Many of the cathode materials currently in use in Organic Light Emitting Diodes (OLEDs), both for display and general lighting applications, are highly reactive metals, such as Mg, Li and, Ca and alloys, which are unstable and prone to oxidation. This complicates manufacturing and requires complex encapsulation techniques. It has led to reduced lifetimes of the devices. There is a need to develop cathode materials that have low work function for efficient electron injection, can be coated over large areas with a robust deposition process, and possess a higher degree of environmental stability against oxidation than cathode materials currently in use. This project will develop a new class of nanostructured amorphous carbon cathode coatings that satisfies those criteria. The materials can be coated on a variety of substrates, as thin films using plasma enhance chemical vapor deposition (PECVD), allow tailoring of the work function over a wide range and are dense to resist the penetation of both oxygen and water. During Phase I, the first examples of this new class of cathode coatings were produced that demonstrated the principle. OLED devices incorporating the nanocomposite films as cathodes were made and tested, and areas for optimization of the composition and deposition conditions were identified. During the first year of the two-year Phase II project, a specially designed PECVD tool has been be constructed for the deposition of nanocomposite cathode films. In the second year, deposition conditions are being optimized to provide films with varying and controllable work function and efficient electron injection into the organic emitter layer. The films will be analyzed with TEM, X-ray, and photoelectron

spectroscopy to determine structure and work function, and tested as cathodes in OLED devices.

Solid state lighting based on OLED devices have the potential to provide highly energy-efficient general lighting. This could effect very substantial energy savings, as much as 10% of the nation's total energy use by some estimates. This technology represents an industry of the future where the U.S. still maintains a technological lead, substantially due to the efficacy of the DOE-funded program. The coatings developed under this Phase II project will become an important enabling technology to realize the potential of OLED-based general lighting. Other applications include OLEDs for displays, particularly displays on flexible substrates.

Zinc Oxide-Based Light Emitting Diodes (Phase I)

Investigating Organization
Materials Modification, Inc.

Principal Investigator(s)
Dr. R. Radhakrishnan

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/14/2004 - 4/14/05

Technology
Organic Light Emitting Diodes

Project Summary

In order to improve the cost and efficiency of OLEDS for solid state lighting, an alternate transparent conducting oxide (TCO) electrode has been proposed. This TCO will be prepared as a sputtering target and coated on glass substrates. These will be converted into fully functional OLEDS for evaluation. An alternate to ITO will provide for lower cost and potentially higher performance OLEDs, flat panel displays, electrochromic mirrors and windows, and defrosting windows.

A selectively doped TCO has been synthesized and pressed into a sputtering target. The TCO has been deposited onto a glass substrate at various sputtering conditions to obtain films of various resistivities and transmittance. The substrates will be used for the construction of OLED for testing and evaluation at Universal Display Corporation.

Zinc Oxide-Based Light Emitting Diodes (Phase II)

Investigating Organization
Materials Modification, Inc.

Principal Investigator(s)
Dr. Ramachandran Radhakrishnan

Subcontractor
General Atomics Display Systems, San Diego, CA

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
08/01/05 - 01/31/08

Technology
Organic Light Emitting Diodes

Project Summary

Indium Tin oxide, currently used as the transparent conducting oxide electrode in OLED construction, is very expensive. It is desirable to lower the cost and resistivity of the electrode material and increase its optical transmissivity. In order to improve the cost and efficiency of OLEDs for solid-state lighting, this project is studying alternate transparent conducting oxide materials. In the Phase I effort, selectively-doped conducting oxides were deposited on polished glass substrates. Transparent films with low resistivity (<20 ohms/sq) and optical transparency (>85%) were obtained. In the Phase II effort, these conducting oxides are being deposited on glass substrates for fabrication of green colored exit signs. The signs will be developed to meet ENERGY STAR requirements.

New Solid State Lighting Materials (Phase I)

Investigating Organization
Maxdem

Principal Investigator(s)
Matther Marrocco

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,957

Contract Period
7/1/02 - 6/30/03

Technology
Organic Light Emitting Diodes

Project Summary

Maxdem is currently working to extend Phase I results to a three-color system. In addition, more economically efficient methods of synthesis of the new phosphors are being developed. In the first quarter of Phase II, new monomers and phosphors have been prepared. These will be tested in OLEDs when all three (blue, green, red) phosphors have been fully characterized.

Maxdem will work to develop white-emitting electroluminescent materials and devices. A concept to control energy flow within the emitting layer will be used to prepare and evaluate a large number of polymers and blends. Optimization of material and device structures will result in phosphors meeting solid state lighting system performance and cost requirements.

The goal is to enable broad lighting applications primarily in the commercial and military sectors. The proposed concepts may also have utility in other photonic applications such as displays, lasers, sensors, and photovoltaic devices.

New Solid State Lighting Materials (Phase II)

Investigating Organization
Maxdem

Principal Investigator(s)
Dr. Matthew Marroca

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $749,813

Contract Period
6/1/03 - 6/1/05

Technology
Organic Light Emitting Diodes

Project Summary

Maxdem is currently working to extend Phase I results to a three-color system. In addition, more economically efficient methods of synthesis of the new phosphors are being developed. In the first half of Phase II, new monomers and phosphors have been prepared. New polymerization methods were applied to obtain very precise control over the charge carrier transport properties and other physical properties of the Maxdem phosphors. Red, blue and green phosphors with a range of electron and hole mobilities have been prepared. Device fabrication and testing is now in progress.

Maxdem will work to develop white-emitting electroluminescent materials and devices. A concept to control energy flow within the emitting layer will be used to prepare and evaluate a large number of polymers and blends. Optimization of material and device structures will result in phosphors meeting solid state lighting system performance and cost requirements.

The goal is to enable broad lighting applications primarily in the commercial and military sectors. The proposed concepts may also have utility in other photonic applications such as displays, lasers, sensors, and photovoltaic devices.

Efficient Nanotube OLEDs (Phase I)

Investigating Organization
NanoTex Corporation

Principal Investigator(s)
Dr. L.P. Felipe Chibante

Subcontractor
Lawrence Berkeley National Laboratory

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
9/22/04 - 4/12/05

Technology
Organic Light Emitting Diodes

Project Summary

Polymer-based OLED is recognized as an ideal source for area lighting application for the potential large area production and approaching the required efficiency and unit brightness, and color rendering effects. In order to achieve low cost and high efficiency, it is crucial to have an air stale cathode with efficient electron injection properties.

Carbon nanotube (CNT) has been demonstrated as a viable electron injection material for OLED application, with the need to increase solubility and dispersion to improve performance.

In Phase 1, NanoTex proposes to use purified single wall type of CNT, combined with surfactant conductive polymer, to develop a stable solvent processible cathode for OLED applications.

Highly Efficient Organic Light-Emitting Devices for General Illumination (Phase I)

Investigating Organization
Physical Optics Corporation

Principal Investigator(s)
Dr. Paul Shnitser

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $99,997

Contract Period
06/28/06 - 03/27/07

Technology
Organic Light Emitting Diodes

Project Summary

Physical Optics Corporation has developed a new technology for fabricating low-cost organic light emitting devices suitable for general illumination with improved energy efficiency. The technology is relatively inexpensive and well-suited for mass production. In Phase I, several experimental devices have been fabricated and tested.

Polymer White Light Emitting Devices (Phase I)

Investigating Organization
Reveo

Principal Investigator(s)
Jaujeng Lin

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $99,800

Contract Period
7/1/03 - 4/30/04

Technology
Organic Light Emitting Diodes

Project Summary

The goals of Phase 1 are to demonstrate the functionality of Reveo's new material technology for light-emitting electrochemical cells (LECs) with frozen p-i-n junctions, and to demonstrate the applicability of the materials to organic electroluminescent devices. Devices fabricated with the new materials will be tested for white light quality, high efficiency, high brightness, low operating voltage, and insensitivity to electrode materials and film thickness. Success developing this material may lead to improved solid-state lighting performance for general illumination.

The feasibility of the frozen junction approach was successfully demonstrated in Reveo's recent research for single color light emitting devices and showed great potential in flat panel color displays.

The characteristics of the frozen junction LECs make it possible to fabricate high efficiency, high power output and long lasting light emitting devices at low cost. Because balanced charge injection in LECs is insensitive to the band gap and ionization potentials of semiconducting polymers, frozen-junction LECs provide an approach to fabricating high quality white lights

There are three main methods that have been proposed to produce white OLED devices using polymers or organic small molecules: 1) The first one is to dope the single host emissive layer with some laser dyes that emit at different color ranges from the host material or blending two different emissive materials; 2) An alternative one is to use a microcavity structure to get two or three emissions simultaneously from one emissive layer; 3) The third one is to use a multi-layered device structure to get different color emission at the same time from different emissive layers

Since LECs utilize single layer organic materials, the first method is the most suitable for LECs to generate white light. In Phase I, organic emitting materials used in white OLEDs will be used in LECs to demonstrate the feasibility of producing white light. In phase II, organic light emitting materials will be specially designed and synthesized for LEC devices to generate high-efficiency, high-power, long-lasting, and low-cost white light.

The simplest solid electrolyte system was chosen in Phase I to prove the concept of Reveo's innovation. Commercially available poly(ethylene oxide), PEO, will be used as the ion transport material. Organic salts will be synthesized bearing vinyl polymerizable functionality. The new electrolyte system and commercially available emitters will be used to fabricate LECs with frozen p-i-n junctions. Devices will be made and tested for unipolar light emission, fast response, high brightness, low operating voltage and insensitivity to electrode materials and film thickness.

End uses include a wide range of OEL display and general lighting applications, including both mini-size and wall-size displays, and single-color to full-color OEL displays and light sources. The Phase I work will validate the proposed material design and device fabrication concept. The results of Phase I will provide a solid foundation for a Phase II program in which Reveo will further improve and refine the material design and device fabrication strategy. The result will be high-quality and high-performance LECs.

Polymer Composite Barrier System for Encapsulating LEDs (Phase I)

Investigating Organization
T/J Technologies, Inc.

Principal Investigator(s)
Dr. Suresh Mani

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
6/27/03 - 6/25/05

Technology
Organic Light Emitting Diodes

Project Summary

Organic light emitting devices (OLEDs) may find widespread application as replacements for fluorescent lighting, small displays, and general indoor/outdoor illumination. However, advanced packaging materials are needed to improve their lifetime and durability. This project will develop a transparent, high-barrier polymer composite system for encapsulating OLEDs. The composite materials, comprised of a high barrier polymer and highly dispersed nanoscale additives, will extend the operational lifetime of OLEDs to over 10,000 hours. Dramatic improvements in the moisture and oxygen barrier properties of transparent polymers will be achieved by tailoring the processing and microstructure of the nanocomposite systems. Phase I will produce polymer nanocomposites comprised of a high barrier polymer and a range of selected additives that can be oriented to reduce gas and vapor permeation. In addition, solution-based processing will be utilized to improve additive dispersion and the ability to orient the additive. The materials will be screened for optical clarity and moisture/oxygen transmission rates.

In this program, T/J Technologies and Michigan State University will co-develop a transparent, high barrier polymer composite system for encapsulating OLEDs. The composite materials, comprised of high barrier polymer and highly disperse nanoscale additive will extend the operational lifetime of OLEDs to >10,000 hours. Dramatic improvement in moisture and oxygen barrier properties of transparent polymers will be achieved by tailoring the processing and microstructure and nanocomposite systems.

In Phase I, polymer nanocomposites comprised of high barrier polymer and a range of selected additives that can be oriented to reduce gas and vapor permeation will be produced. Solution-based processing will be utilized to improve additive dispersion and the ability to orient the additive. The materials will be screened for optical clarity and moisture/oxygen transmission rates.

The target application for this technology is polymer based encapsulants for low cost OLEDs. It is anticipated that OLEDs will find application as replacement for fluorescent lighting, small displays, decorative lighting, glowing wallpaper and general indoor/outdoor illumination. Additional market opportunities for low cost, transparent, high impact plastics with significantly increased moisture and oxygen barrier properties include lightweight replacement of glass n structured applications, lenses, coatings for electronic packaging and flexible packaging films for food and non-food applications to replace existing metallized and laminate films.

High-Efficiency White Phosphorescent OLEDs (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Brian W. D'Andrade

Subcontractor
Princeton University under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $98,894

Contract Period
6/27/05 - 3/26/06

Technology
Organic Light Emitting Diodes

Project Summary

Universal Display Corporation (UDC), in collaboration with Professor Mark Thompson from the University of Southern California (USC) and Professor Stephen Forrest from Princeton University, propose to improve the efficiency of white phosphorescent OLEDs (PHOLEDä) using novel emissive region doping profiles that further enhance the light outcoupling efficiency and the carrier recombination efficiency of PHOLEDs by 30% over that of conventional uniformly doped PHOLEDs.

Varying and optimizing the doping profile within the emissive layer may improve the recombination efficiency in PHOLEDs, and hence increase the external quantum efficiency (EQE). In addition, the novel structures, such as mesh layers, that we are investigating in this program, could also improve the outcoupling efficiency by aligning the molecular transition dipole moments parallel to the substrate, which would then further increase the EQE.

At the end of this Phase I, we hope to demonstrate a white PHOLED having >30 lm/W at 800 nits, with correlated color temperature between 2,800 K and 6,000K, and color rendering >75.

High Efficiency White TOLED Devices for Lighting Applications

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Vadim Adamovich

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
7/13/04 - 4/12/05

Technology
Organic Light Emitting Diodes

Project Summary

The objective of this work is to demonstrate the technical feasibility of increasing the optical extraction efficiency of a white OLED light source using transparent OLED (TOLED) technology.

In Phase I, optimized white transparent phosphorescent OLEDS (T-PHOLED) designed specifically for general illumination sources will be simulated. This will lead to the demonstration of an approximate 1 cm2 white T-PHOLED light source on a glass substrate, optically coupled to an external reflector t provide a greater than 20% enhanced optical extraction over a similar conventional bottom emission device.

The objective of this work is to demonstrate the technical feasibility of increasing the optical extraction efficiency of a white OLED light source using transparent OLED (TOLED) technology.

The ultimate outcome of this work is to develop a novel energy efficiency, long lived, solid state white lighting source based on phosphorescent organic light-emitting device (PHOLED) technology. This novel light source may find application in diffuse lighting application in the commercial, residential and industrial sectors. Based on novel features that include its thin, lightweight form and transparency, this product may also be used in novel architectural, automotive and wearable electronic applications.

High-Recombination Efficiency White Phosphorescent Organic Light Emitting Devices (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Brian W. D'Andrade

Subcontractor
Princeton University under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $98,894

Contract Period
6/27/05 - 3/26/06

Technology
Organic Light Emitting Diodes

Project Summary

Universal Display Corporation (UDC), in collaboration with Professor Mark Thompson from the University of Southern California (USC) and Professor Stephen Forrest from Princeton University, propose to improve the efficiency of white phosphorescent OLEDs (PHOLEDä) using novel emissive region doping profiles that further enhance the light outcoupling efficiency and the carrier recombination efficiency of PHOLEDs by 30% over that of conventional uniformly doped PHOLEDs.

Varying and optimizing the doping profile within the emissive layer may improve the recombination efficiency in PHOLEDs, and hence increase the external quantum efficiency (EQE). In addition, the novel structures, such as mesh layers, that we are investigating in this program, could also improve the outcoupling efficiency by aligning the molecular transition dipole moments parallel to the substrate, which would then further increase the EQE.

At the end of this Phase I, we hope to demonstrate a white PHOLED having >30 lm/W at 800 nits, with correlated color temperature between 2,800 K and 6,000K, and color rendering >75.

High-Recombination Efficiency White Phosphorescent Organic Light Emitting Devices (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Brian W. D'Andrade

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000
Contractor Share: $150,000

Contract Period
08/07/06 - 08/06/08

Technology
Organic Light Emitting Diodes

Project Summary

The objective is to develop novel low-cost, high-efficiency solid-state organic light-emitting devices (OLEDs) for general illumination. The project seeks to optimize the recombination efficiency of white OLEDs (WOLED™) such that electrons and holes generate a desired ratio of red, green and blue excitons leading to an unsaturated white emission enabling a WOLED with color rendering index (CRI) of >75, and efficacy of 40 lm/W at 800 cd/m^2. This proposed optimization will be effectively accomplished using an organic vapor phase deposition (OVPD) system that is capable of producing novel doping profiles within the emissive regions of an OLED.

High Stability White SOLEDs (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Brian W. D'Andrade

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
6/20/07 - 3/19/08

Technology
Organic Light Emitting Diodes

Project Summary

Universal Display Corporation proposes to increase the lifetime and power efficacy of WOLEDs by vertically stacking multiple OLEDs in series. They will develop a white phosphorescent stacked OLED (SOLED) with a lifetime of >5,000 hrs from an initial average luminance of 1,000 cd/m^2, and having a warm white color with correlated color temperatures between 2,500 K – 3,500 K and color rendering index >70.

Good WOLED longevity, together with other efficiency-enhancing device developments will enable the commercialization of organic solid-state lighting sources that attain power efficiency of 150 lm/W at luminance of 1,000 cd/m^2 by 2025. This program takes another significant and critical step towards this efficiency goal by exploring methods to improve the longevity of high brightness WOLEDs by vertically stacking phosphorescent OLED devices in series.

The stacked WOLED architecture enables the use of less current to generate the same amount of luminance as a single WOLED, thereby increasing device lifetime. The reduction in drive current has additional efficiency improving benefits as resistive heating and voltage losses in a lighting panel can effectively be reduced, and the SOLED power efficacy at a given luminance can be higher than a single OLED because OLED efficacy increases with decreasing drive current.

Low-Voltage, High-Efficiency White Phosphorescent OLEDs for Lighting Applications (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Brian W. D'Andrade

Subcontractor
Princeton University, under the direction of Prof. Stephen R. Forrest
University of Southern California

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
07/14/04 - 07/13/06

Technology
Organic Light Emitting Diodes

Project Summary

The approach taken in this project is to combine novel low-voltage dopants, world record efficient phosphorescent OLED emission layers, and a stacked PHOLED architecture, to demonstrate a high-power efficiency >50 lm/W organic light source.

In Phase I, the goals were met and a white PHOLED, based on red, green, and blue phosphorescent emitters, was demonstrated to have a world record power efficiency of 20 lm/W at a luminance of 800 cd/m2. This device was reported at the 2004 Society for Information Display conference in Seattle, Washington. The overall excellent performance was accomplished without the use of outcoupling enhancement, so there remains significant potential to increase the power efficiency of low voltage PHOLEDs by a factor of more than 1.5.

In Phase II, UDC, Princeton University, and USC are further exploring new materials and device architectures that will be used by UDC in the fabrication of high-efficiency prototype lighting panels. The anticipated benefits of this work will be to demonstrate a new path for highly efficient white light sources by introducing a new dimension to the device design, such as high power, thereby significantly reducing the size of the substrate necessary for devices to produce optical power (>800 lumens) for room lighting.

The stacked PHOLED (SOLED™) is based on red, green, and blue (R-G-B) or white sub-pixel elements that are vertically stacked on top of each other versus sub-pixel elements that are laterally spaced. This is possible because these sub-pixels employ transparent p- and n-doped organic layers enabling R, G, or B light to be emitted coaxially through the contacts, the adjacent sub-pixels, and the substrate. The area of the device can easily be halved if two PHOLEDs are stacked, and hence the substrate cost savings and device manufacturability would both significantly improve by a factor of at least two, and improvements would scale with the number of PHOLEDs stacked on each other.

At the end of Phase II, we will deliver a 6”X6” prototype lighting panel based on low-voltage, high-power-density PHOLED lighting sources that are >25 lm/W efficient, have CRI >75, and CIE coordinates similar to that of a blackbody radiator at a temperature between 2,500 K and 6,000 K.

Monomer-Excimer Phosphorescent OLEDs for General Lighting (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Mike Weaver

Subcontractor
None

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/1/02 - 6/30/03

Technology
Organic Light Emitting Diodes

Project Summary

Based on its research in phosphorescent OLED (PHOLED™) technology, the project team has demonstrated OLEDs that are up to four times more power efficient than previously thought possible. Under two DOE SBIR awards, Universal Display Corporation, Princeton University, and the University of Southern California pursued a novel approach to broadband white light generation based on this highly efficient PHOLED technology.

Fabricating a white OLED light source from a series of striped PHOLEDs has the potential to provide a tunable, white lighting source with the requisite performance for CIE and color rendering. So far, the team has demonstrated the feasibility of using this approach for flat-panel displays.

The aim of this Phase 1 study was to demonstrate a striped white light PHOLED light source. UDC has successfully completed and achieved all 3 of the goals set to demonstrate this task. We successfully fabricated 1" striped white PHOLED sources with CIE co-ordinates of (0.32, 0.39) and a CRI of 86 (15% higher than the program goal) and demonstrated a power efficiency of 5.5 Lm/W at 800 cd/m2 exceeding the program goal by 10%. Finally a preliminary study was made to determine the minimum stripe resolution necessary for a 3 color white light source to appear uniform to the eye. This work demonstrates the feasibility of the striped PHOLED color source approach to enable next generation flat panel general illumination sources.

Recently, UDC was awarded a phase II contract to continue the development of a general illumination source using PHOLEDs. In Phase II, UDC plans to demonstrate a white PHOLED light source on a glass substrate with an efficiency of 20 lm/W at a luminance of 800 cd/m2. Additionally, UDC plans the demonstration and delivery of 6” ´ 6” prototype lighting panels based on PHOLED lighting sources, based on tiling four 3” ´ 3” sub-panels. This will involve the mechanical and electrical design of the panels, with particular focus on the manner in which individual light sources are interconnected, design and fabrication of drive electronics, mask layout for the component sub-panels, along with their fabrication and characterization.

The successful completion of this Phase 2 work will significantly accelerate the use of PHOLED devices as commercial lighting sources. The integration of these parallel efforts with the strategies developed in this proposal will enable PHOLEDs to become a viable source of general illumination.

Novel High Efficiency High CRI Phosphorescent OLED Lighting Containing Two Broad Emitters (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Brian W. D'Andrade

Subcontractor

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Technology
Organic Light Emitting Diodes

Project Summary

For phosphorescent organic light emitting devices, this project will further increase the conversion efficiency of electrical energy into light energy and reduce manufacturing costs, such that these white solid state devices can replace conventional incandescent and fluorescent lighting sources.

Novel High-Performance OLED Sources (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Brian W. D'Andrade

Subcontractor
Princeton University
under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
6/27/03 - 6/25/05

Technology
Organic Light Emitting Diodes

Project Summary

Based on its research in phosphorescent OLED (PHOLED) technology, the project team has demonstrated OLEDs that are up to four times more power efficient than previously thought possible. In this Phase 2 program, Universal Display Corporation, Princeton University, and the University of Southern California are further pursuing two novel approaches to further increase the efficiency of broadband white light generation building on the successful feasibility studies of highly efficient white PHOLED technology demonstrated in our two previous DOE SBIR Phase 1 awards.

Novel Striped Design for White OLED Illumination Sources. Here the Team is investigating the use of PHOLEDs in a striped-pattern R-G-B configuration to demonstrate very-efficient white light generation. In this configuration, each stripe contains one of three colors, red, green and blue, or red, yellow and blue. Fabricating white OLED light sources in this manner offers a number of potential advantages and benefits. These include 1) very high power efficiency, 2) long lifetime, 3) excellent CIE and CRI, 4) full color tunability, and 5) color correction for differential aging.

Monomer-Excimer White OLED Illumination Sources While there are a number of possible approaches to produce white OLED (WOLED) lighting; USC and Princeton University recently demonstrated a novel approach using high-efficiency phosphorescent excimers. In addition to offering a power efficient approach, this approach also offers provides opportunities to reduce both the number of dopants and the number of discrete emissive layers, simplifying the device structure, the fabrication process and the resulting manufacturing costs. Our approach to reduce the number of dopants and structural heterogeneities inherent in the preceding architectures is to employ a lumophore that forms a broadly emitting state, such as an excimer or exciplex (i.e. an excited state whose wavefunction extends over two identical or dissimilar molecules, respectively).

Recently, the team has accomplished the following: New platinum functionalized random copolymers for use in solution processable white organic light emitting devices were synthesized and evaluated. A record 100% internal quantum efficiency green [CIE (0.30, 0.64)] device was fabricated. This device had EQE = 20% and a luminous efficiency = 75 cd/A at 100 cd/m2. A new record efficiency blue device has been developed. Blue [CIE (0.14, 0.21)] devices were fabricated with a luminous efficiency of 19 cd/A and an external quantum efficiency of 12% at 100cd/m2. This is a much higher efficiency than can be achieved from fluorescent emitters, and is a 60% improvement over previous blue device reports provided by UDC. Developed a model to predict the ability of an end-user to differentiate between the various colored striped lines.

In Phase 2, the team will demonstrate white OLEDs with greater than 20 lm/W efficiency at 800 cd/m2, and deliver 6” x 6” prototype lighting panels, based on tiling four 3” x 3” sub-panels. This work will then be coupled with parallel development programs focusing on improving PHOLED performances through new materials development, device optimization, lifetime improvement, and novel approaches to enhance the optical extraction efficiency. The successful completion of this Phase 2 program will significantly accelerate the use of OLED devices as commercial sources of general illumination.

Novel Light Extraction Enhancements for White Phosphorescent OLEDs (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Brian W. D'Andrade

Subcontractor
Princeton University
under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/21/03 - 4/20/04

Technology
Organic Light Emitting Diodes

Project Summary

In Phase 1, Universal Display Corporation, a developer of OLED technologies for flat panel displays, lighting and other opto-electronic applications, is working to demonstrate innovative techniques to improve OLED power efficiencies, a critical performance attribute for the general lighting industry. Universal Display and its research partners at Princeton University and the University of Southern California are developing several novel approaches for producing highly efficient white light using the Company's phosphorescent OLED (PHOLED™) technology.

In addition to the use of this highly efficient PHOLED technology, better light extraction techniques are required to achieve the power efficiency targets of the general lighting market, as in a conventional OLED only approximately 25% of the generated photons are emitted from the device. In this program, Universal Display and Princeton University demonstrated the feasibility of using specialized designs, such as lens arrays, on an OLED device to enhance the amount of generated light that is captured or extracted from the device as useful light.

Specifically, two key objectives of Phase 1 were: Demonstrate and deliver a white PHOLED light source on a glass substrate, with an attached flattened lens array to provide enhanced optical extraction over a similar device without an attached lens.

Characterize the above white light sources and demonstrate > 15 lm/W at 800 nits luminance.

During Phase I of this program, the team accomplished several key goals: developed a process for producing different microlens silicon molds, demonstrated device performance characteristics that met expectations, and explored new outcoupling schemes based on models of outcoupling enhancement using aperiodic gratings.

Silicon molds for forming microlenses from poly-di-methyl-siloxane (PDMS), a thermal curable elastomer, were fabricated. The ability to control the dimensions and shape of the silicon mold is important since these factors affect the outcoupling efficiency. Our work demonstrated that we have the capability to optimize the silicon molds to further enhance the outcoupling efficiency by adjusting the period and size of the array elements.

Both sets of microlenses formed from the molds improved the outcoupling efficiency by ~22%. The improvement in efficiency was found by comparing the total forward emission from devices with and without the microlens array attached to the glass substrate. The total forward emission was found by using an integrating sphere, such that all forward emitted light was collected in the sphere. The efficiency of a white device operating at 6.3 V and 20 lm/W having CIE (0.39, 0.40) at 800 cd/m2 was improved such that the same device with microlenses operated at 6.3 V and 24 lm/W at 1000 cd/m2, which met our goals.

Novel Light Extraction Enhancements for White Phosphorescent OLEDs (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Brian W. D'Andrade

Subcontractor
Princeton University under the direction of Prof. Stephen R. Forrest

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
07/14/04 - 07/13/06

Technology
Organic Light Emitting Diodes

Project Summary

The goal of this project is to realize an innovative approach to low-cost solid-state white light sources by applying two novel outcoupling schemes to our high-efficiency phosphorescent OLEDs (PHOLED™) to achieve power efficiencies >60 lm/W.

The Phase I goals were exceeded by fabricating white PHOLEDs with microlenses having 24 lm/W at a luminance of 1,000 cd/m^2. The efficiency improvement was obtained by increasing the outcoupling efficiency by 22%. The total forward emission for devices with and without the lens arrays were measured with an integrating sphere, such that all forward-emitted light was collected in the sphere. Currently, we have made green, red, and blue-striped white 6"×6" lighting panels having a maximum efficiency of 30 lm/W, and are continuing to develop PHOLEDs that emit 500-800 lumens for room lighting.

In Phase II, UDC and Princeton University will demonstrate high-power-efficiency white PHOLED lighting panels. The team will build on their successful Phase I program to demonstrate white PHOLEDs that have improved outcoupling efficiency through the attachment of microlens arrays, in addition to incorporating OLED luminaires that increase the total PHOLED outcoupling efficiency by at least 50%.

Novel Lower-Voltage OLEDs for High-Efficiency Lighting (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Brian W. D'Andrade

Subcontractor
Princeton University
University of Southern California

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/1/03 - 4/30/04

Technology
Organic Light Emitting Diodes

Project Summary

The team led by Universal Display Corporation with their university partners at Princeton University and the University of Southern California is focusing on the development of novel, low-voltage phosphorescent light emitting structures to enable OLEDs with power efficiency >20 lm/W at a brightness of 800 cd/m2. The power efficient OLEDs will result from the development of innovative, highly conductive hole and electron transport systems in conjunction with high-efficiency triplet emitters.

Triplet emitters contain a heavy metal atom that facilitates the mixing of singlet and triplet states, allowing singlet to triplet energy transfer through intersystem crossing. This leads to highly efficient devices where 100% of the excitons can potentially produce optical emission, in contrast to only approximately 25% in conventional fluorescent devices. The high conductivity hole and electron transport systems will be achieved by selecting p- and n-type dopants along with the appropriate organic buffer layers. The resulting structure will be a p-i-n type device. The team has already identified several candidate material systems and is currently working to improve their stability.

The novel structures will also have potential use in energy-efficient, long-lived, solid state white OLED applications in general illumination, automotive, and wearable electronics. The team is already exploring two approaches for generating white light in a parallel Phase 1 SBIR effort. The first approach is based on a simple striped R-G-B configuration, and the second on using a phosphorescent monomer-excimer emission layer. P-i-n doping can be incorporated into both of these approaches.

The purpose of this Phase 1 was to demonstrate and deliver to DOE a white light phosphorescent OLED (PHOLEDä) light source, employing p- and n-type conductivity dopants, having a power efficiency close to 20 lm/W at a luminance of 800 cd/m2. The key tasks were:

Specifically, the key objectives of Phase 1 were:

1. Demonstrate and deliver a white PHOLED light source on a glass substrate with a drive voltage close to 3V at 800 cd/m2 luminance through the use of conductivity doped p-type and n-type transport layers.

2. Investigate the use of ion implantation to improve the efficiency of the doping process.

3. Develop organic dopants for n-type organic transport layers.

4. Characterize the above white light sources and demonstrate > 20 lm/W at 800 nits brightness for a CIE of (0.33, 0.33) and CRI > 75.

During Phase I of the pin PHOLED program, the team met the Phase 1 goal and developed a low voltage, 20 lm/W white PHOLED as well as explored strategies to improve device stability. These efforts led to an 6.3 V, 19.7 lm/W white device with CIE (0.39, 0.40) at 800 cd/m2, a 7.0 V, 17.1 lm/W green PHOLED with a lifetime of 35 h under an accelerated constant current drive of 40 mA/cm2, and a novel n-type dopant with reduced diffusivity.

Novel Plastic Substrates for Very High Efficiency OLED Lighting (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Brian W. D'Andrade

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
06/28/06 - 03/27/07

Technology
Organic Light Emitting Diodes

Project Summary

Of the three OLED characteristics that determine overall power efficacy (outcoupling efficiency, internal quantum efficiency, and drive voltage), outcoupling efficiency is the only parameter that has not achieved maximum efficiency. Typically, 60% of the optical energy generated in an OLED is unavailable, because it cannot escape the device, so increasing the outcoupling efficiency is required to achieve an overall OLED efficacy of 150 lm/W.

During this Phase I program, Universal Display Corporation (UDC) will try to increase the total light outcoupling efficiency of phosphorescent light emitting devices from 40% to 50% by reducing the refractive index contrast between OLED active layers and the device substrate. With 100% internal quantum efficiency from phosphorescence, 50% outcoupling efficiency, and 3.5 V operating voltage, white phosphorescent OLEDs should be capable of 150 lm/W efficacy.

Stable, Efficient, Large Area WOLED (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Brian W. D'Andrade

Subcontractor
None

Funding Source
Small Business Innovation R&D, Phase I

Award
DOE Share: $100,000

Contract Period
6/20/07 - 3/19/08

Technology
Organic Light Emitting Diodes

Project Summary

Universal Display Corporation (UDC) proposes to increase the lifetime of large-area (25 cm^2) phosphorescent white OLEDs (WOLEDs) by improving the currect distribution throughout the active area of the WOLED. The target is to ensure less than 30% change in luminance across the OLED active region, and a lifetime of >1,000hrs from an initial total flux of 8 lm, which corresponds to an average luminance of 1,000 cd/m^2. The reduction of voltage losses across large area WOLEDs will enable these devices to both achieve long lifetimes and improved efficacies similar to small area WOLEDs.

High Efficiency White TOLED Devices for Lighting Applications (Phase II)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Michael Lu

Subcontractor
Princeton University

Funding Source
Small Business Innovation R&D, Phase II

Award
DOE Share: $750,000

Contract Period
07/13/05 - 07/10/07

Technology
Organic Light Emitting Diodes

Project Summary

In Phase II of this SBIR, UDC and Princeton University will demonstrate high-power-efficiency white transparent OLED (TOLED) lighting panels. The team will continue to develop white TOLEDs focusing on maximizing efficiency and transparency through less absorbing organic and conducting oxide layers. In addition, the team will optimize monolithically encapsulated TOLEDs.

The reason for implementing monolithic thin film encapsulation is to reduce the optical loss at the OLED-to-air interface. UDC will demonstrate the potential for stacking TOLED/OLED and TOLED/TOLED together to create high luminous intensity lighting panels or transparent lighting panels. All of these activities are working toward realizing a 20% increase in optical outcoupling. We believe that Phase I results have clearly demonstrated that the approach of using a TOLED within an optical reflector has the potential to achieve enhanced optical outcoupling for white light sources. Specific technical issues identified during Phase I included that the efficiency of the TOLED device could be increased through better engineered cathodes, and that further development of the overall design of the TOLED within the reflector cavity is required to fully assess the potential for using white TOLEDs for general illumination.

Specifically, the key objectives of Phase II are:

1. Demonstrate improved TOLED device performance by using IZO (replacing ITO) as the transparent conducting oxide in the transparent cathode.
2. Demonstrate a combined efficiency transparency product by improved TOLED layer designs.
3. Implement a monolithic thin film TOLED encapsulation to enhance light extraction.
4. Optimize the thickness of all the layers in the TOLED to maximize light output by microcavity modeling.
5. Demonstrate high luminous output stacked TOLED/OLED or TOLED/OLED with appropriate index-matching gel/adhesive.
6. Stimulate, design, and fabricate a TOLED/OLED with a parabolic dish reflector lamp.
7. Fabricate deliverable: a 6x6 white TOLED lighting prototype CRI>75, CIE coordinates similar to that of a blackbody radiator at a color temperature between 2,500 K and 6,000 K, and power efficiency > 25 lm/W at lighting luminance levels of 1,000 cd/m^2.

White Illumination Sources Using Striped Phosphorescent OLEDs (Phase I)

Investigating Organization
Universal Display Corporation

Principal Investigator(s)
Dr. Brian W. D'Andrade

Subcontractor
Princeton University
University of Southern California

Funding Source
Small Business Innovation Research

Award
DOE Share: $100,000

Contract Period
7/1/02 - 6/30/03

Technology
Organic Light Emitting Diodes

Project Summary

Based on its research in phosphorescent OLED (PHOLED™) technology, the project team has demonstrated OLEDs that are up to four times more power efficient than previously thought possible. Under two DOE SBIR awards, Universal Display Corporation, Princeton University, and the University of Southern California pursued a novel approach to broadband white light generation based on this highly efficient PHOLED technology.

Fabricating a white OLED light source from a series of striped PHOLEDs has the potential to provide a tunable, white lighting source with the requisite performance for CIE and color rendering. So far, the team has demonstrated the feasibility of using this approach for flat-panel displays.

The aim of this Phase 1 study was to demonstrate a striped white light PHOLED light source. UDC has successfully completed and achieved all 3 of the goals set to demonstrate this task. We successfully fabricated 1” striped white PHOLED sources with CIE co-ordinates of (0.32, 0.39) and a CRI of 86 (15% higher than the program goal) and demonstrated a power efficiency of 5.5 Lm/W at 800 cd/m2 exceeding the program goal by 10%. Finally a preliminary study was made to determine the minimum stripe resolution necessary for a 3 color white light source to appear uniform to the eye. This work demonstrates the feasibility of the striped PHOLED color source approach to enable next generation flat panel general illumination sources.

Recently, UDC was awarded a phase II contract to continue the development of a general illumination source using PHOLEDs. In Phase II, UDC plans to demonstrate a white PHOLED light source on a glass substrate with an efficiency of 20 lm/W at a luminance of 800 cd/m2. Additionally, UDC plans the demonstration and delivery of 6” ´ 6” prototype lighting panels based on PHOLED lighting sources, based on tiling four 3” ´ 3” sub-panels. This will involve the mechanical and electrical design of the panels, with particular focus on the manner in which individual light sources are interconnected, design and fabrication of drive electronics, mask layout for the component sub-panels, along with their fabrication and characterization.

The successful completion of this Phase 2 work will significantly accelerate the use of PHOLED devices as commercial lighting sources. The integration of these parallel efforts with the strategies developed in this proposal will enable PHOLEDs to become a viable source of general illumination.