Sputtered II-VI Alloys and Structures for Tandem PV

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ABSTRACT

This project focuses primarily on the development and optimization of two II-VI alloy materials for top cells (CdMnTe and CdMgTe) and HgCdTe for bottom cells of tandem PV devices. These are being explored both in two-terminal and four-terminal configurations. Spectroscopic ellipsometry is being developed for real-time analysis and deposition control. Parallel effort addresses the development and optimization of transparent back contacts (TBCs) for top cells and for interconnect junctions (IJs). Cell efficiencies with alloys of E_g>1.6 eV have been limited. Narrow-gap HgCdTe alloys show more promising performance. Prototype two-terminal and four-terminal devices have been prepared with good performance from the TBC or IJ.

1. Objectives

The overall project objective is to develop the foundations of a polycrystalline thin-film technology leading to tandem cells reaching 25% efficiency at AM1.5. The U. of Toledo CdTe group is developing II-VI ternary wide-band-gap alloys $Cd_{1-x}Mn_xTe$ and $Cd_{1-x}Mg_xTe$, as well as thin CdTe in the high performance configuration, e.g., with appropriate current matching to bottom cells of copper-indium diselenide (CIS)-based materials or the low-band-gap II-VI ternary $Hg_{1-x}Cd_xTe$, ZnO:Al, In_2O_3:Sn (ITO). ZnTe:N and ZnTe:Cu are being explored to meet the need for transparent back contacts and low resistance interconnects in monolithic two-terminal structures. Additional objectives involve the development of a knowledge base to facilitate rational materials and device optimization with an emphasis on spectroscopic ellipsometry. Optical modeling, using the determined optical functions of the individual components, is being performed with thickness and composition as variables to establish optimum optical collection. *In situ*, real-time and post-deposition optical characterization methodologies are being established to serve as a model for the analysis of polycrystalline thin films.

2. Technical Approach

After our initial studies of sputtered CdZnTe films and cells, we have focused our efforts on optimizing the properties of CdTe alloys with Mn and Mg. To reach E_g=1.7 eV, the Mn and Mg alloys require only about 15% alloying in contrast to more than 40% for Zn. These two alloys also have smaller lattice contraction with x-value than does Zn. These two advantages are balanced somewhat by the greater sensitivity of the alloys of Mn and Mg to oxygen and water vapor. Thus a major effort is placed on studies of possible post-deposition treatments in vapors containing chlorine.

Another technical approach for the fabrication of two-terminal tandem structures relaxes the 1.7 eV constraint on the top-cell band gap and utilizes a thin 1.5 eV CdTe layer. The UT group has demonstrated that sputter deposition yields CdTe cells with good performance down to a CdTe thickness of 0.7 μm.

A third technical approach involves the sputter-deposition of narrow-gap alloys based on $Hg_xCd_{1-x}Te$ for the bottom cell of the two-terminal tandems.

Additional efforts are directed toward improved top and back contacts and recombination junctions, including modeling performance of heavily doped n/p bilayers with large defect densities.

A significant emphasis is placed on spectroscopic ellipsometry and the construction of a database of optical properties of these alloys that will facilitate real-time optical diagnostics in support of better understanding and control of thin-film growth and post-deposition treatments.

3. Results and Accomplishments

3.1 Optical properties of CdMnTe and CdMgTe from spectroscopic ellipsometry

A rotating compensator multichannel spectroscopic ellipsometer with a spectral range from 0.7 to 6.5 eV is being used to obtain real-time spectroscopy during film growth with monolayer sensitivity. The lower photon energy data are used to track the overall thickness of the film versus time and the bulk optical properties associated with free carriers, whereas the high energy data are used to track the near-surface optical properties due to interband transitions and hence the alloy composition of the growing film. See Table 1. Further detail on recent SE results is given in a separate poster in this meeting.

Table 1 Band gap and critical point energies and widths for the as-deposited and $CdCl_2$-treated $Cd_{1-x}Mg_xTe$ of Fig. 1 in comparison with CdTe results.

	CdTe as-dep.	CdTe $CdCl_2$-treat.	CdMgTe as-dep.	CdMgTe $CdCl_2$-treat.
E_0 (eV)	1.497	1.499	1.615	1.633
E_1 (eV)	3.274	3.331	3.354	3.303
$\Gamma(E_1)$ (eV)	0.411	0.200	0.480	0.216
$E_1+\Delta_1$ (eV)	3.844	3.883	3.901	3.878
$\Gamma(E_1+\Delta_1)$ (eV)	0.484	0.368	0.520	0.309
E_2 (eV)	5.193	5.208	5.179	5.197
$\Gamma(E_2)$ (eV)	0.993	0.796	1.252	0.879

3.2 Top cells with transparent back contacts

We have fabricated sputtered CdS/CdTe cells with a variety of transparent back contacts. The most promising devices had contacts consisting of either (a) ZnTe:N/ITO or (b) ZnTe/Cu/ITO, where the ZnTe:N was reactively sputtered and the indium tin oxide (ITO) was also sputtered. The copper was evaporated. Best cell parameters were:

(a) V_{OC}=643 mV, J_{SC}=21.9, FF=65%, and η=9.1%, and
(b) V_{OC}=699 mV, J_{SC}=19.2, FF=52%, and η=7.0%.

The substrate was Pilkington TEC-7 with CdS (0.13 μm) and CdTe (1.8μm). The ZnTe and ITO were 100 nm and Cu 3 nm thick. All layers were sputtered. The thicknesses of the transparent back contact layers were not carefully optimized to achieve anti-reflection conditions. In structure (b) the ZnTe layer was added before the 3 nm of Cu to prevent excessive diffusion of Cu into the CdTe. Cells with CdTe as thin as 0.68μm finished with contact (a) yielded 6% efficiency but with lower V_{OC} and FF. We are optimistic this type of structure might be suitable for four-terminal tandems in conjunction with CIGS. In fact we have recently fabricated such a device and delivered to NREL. The QE responses of the top and bottom cells are shown in Fig. 1.

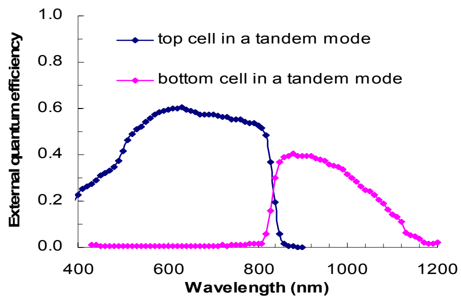

Fig. 1 QE response of CdTe top cell with contact structure (a) and CIGS bottom cell.

3.3 Progress with Mg alloys of CdTe

$Cd_{1-x}Mg_xTe$ films have been prepared by magnetron sputtering from commercial sintered targets prepared with 20% and 40% MgTe by weight. These have resulted in alloy films with x ≈ 5% and x≈20% with excellent density and p-type characteristics. (Slightly higher x-values were obtained when Ne was used as the sputter gas rather than Ar, as expected from momentum transfer considerations. However, the sputtering rate decreased, so most of our work has used Ar.)

For CdS/$Cd_{1-x}Mg_xTe$ cells, we found that some post-deposition treatment in vapors containing Cl significantly improved efficiencies, similar to the case of CdTe. We believe this treatment helps passivate grain boundaries in these alloys. Best results were obtained with a two-step anneal, first in an inert atmosphere and then for 5-10 minutes at 390 ^oC in vapors of $CdCl_2$. Best cell performance to date has been achieved with 5% Mg yielding 3.4% efficiency. The QE onset was 1.58 eV.

3.4 Progress with Hg alloys of CdTe

$Hg_{1-x}Cd_xTe$ alloy films have been prepared by sputtering from targets sintered from the mixed binary alloys with excellent characteristics. Dense single-phase films were obtained with deposition at ~100 ^oC where the as-deposited x-value was ~80% and E_g≈1.1 eV. Again cell performance improved significantly with activation anneal treatments in Cl vapors but with less tendency to lose initial stoichiometry.

The structure of the superstrate, monolithic (2-terminal) tandem is shown in Fig. 2 in comparison with the four terminal device using CIGS for the bottom cell.

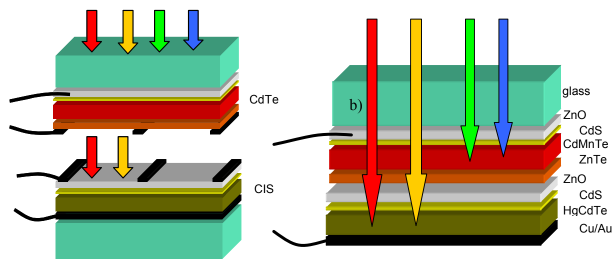

Fig. 2 Structure of 4- and 2-terminal cells based on a II-VI top cell and either CIGS or HgCdTe bottom cells similar to those realized in this project.

4. Conclusions

Our most promising results for tandem cell preparation have been with very thin CdTe top cells. This work indicates promise for a sputtered, superstrate-structure top cell with CdTe thickness below 0.8 μm followed with a sputtered interconnect junction of ZnTe:N/ITO and a CdS/HgCdTe bottom cell. Although some progress has been made, post-deposition activation treatments seem to be necessary for the wide-band-gap alloys and these remain challenging. The Hg alloy films are more stable in post-deposition processing.

ACKNOWLEDGEMENTS

We are indebted to NREL for support under the High Performance PV Program through subcontract XAT-4-33624-06.

SELECTED 2006/2007 PUBLICATIONS

1. A. Gupta, V. Parikh, A.D. Compaan, “High efficiency ultra-thin sputtered CdTe solar cells” Solar Energy Materials & Solar Cells, 90, 2263-2271 (2006)
2. X. Mathew, J. Drayton, V. Parikh, and A.D. Compaan, “Sputtered $Cd_{1-x}Mg_xTe$ Films for Top Cells in Tandem Devices,” 2006 IEEE 4th World Conference on PVEC-Proc. pp. 327-331.
3. V. Y. Parikh, J. Chen, S.X. Marsillac, and A.D. Compaan, “Transparent back contacts and interconnect junctions for CdTe top cells,” 2006 WCPEC pp. 321-326.

OUTSIDE THE TWO-PAGE LIMIT—

MORE PUBLICATIONS

4. V.Y. Parikh, J. Drayton, S.L. Wang, A. Gupta, and A.D. Compaan, “Polycrystalline thin-film tandem solar cells cascaded by ZnTe/ZnO interconnects,” -2005, 430-433, IEEE Piscataway, N.J. 2005.
5. X. Mathew, J. Drayton, V. Parikh, and A.D. Compaan, “Sputtered $Cd_{1-x}Mg_xTe$ Films for Top Cells in Tandem Devices,” 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion-Proceedings (IEEE Piscataway, N.J. 2006) pp. 321-326.
6. V. Y. Parikh, J. Chen, S.X. Marsillac, and A.D. Compaan, “Transparent back contacts and interconnect junctions for CdTe top cells,” 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion-Proceedings (IEEE Piscataway, N.J. 2006) pp. 321-326.
7. S. Wang, J. Chen, J. Li, A. Gupta, R.W. Collins, and A.D. Compaan, “Ellipsometry studies of $CdCl_2$ treated CdTe and related ternary alloy films for solar cell applications,” Mater. Res. Soc. Symp. Proc. **865,** F5.29 (2005).

PROJECT HISTORY & RELATIONSHIPS

This project is an offshoot of a long-running research thrust on CdTe-based solar cells initiated at UT in 1990 with a three-year subcontract from the Solar Energy Research Institute (SERI) and having Solar Cells Inc, as a lower-tier subcontractor. Although the UT and SCI funding was separated after the first year, we have continued with frequent collaborations. SERI/NREL support for the UT effort has continued since that time, evolving into Thin Film Photovoltaics Partnership Program support for research on CdTe-based solar cell structure and fabrication, cell modeling and characterization of materials and devices. Professor Xunming Deng joined the funded research in 1998, bringing expertise in amorphous silicon-based solar cells and broad cell processing knowledge. Professor Dean M. Giolando brought expertise in thin films of metal oxides to the group in 2000. Professor Victor Karpov joined the funded research in 2001, bringing theoretical expertise in semiconductor and device physics. Professor Robert Collins joined these efforts in 2004, bringing expertise in optical physics and real-time analysis. Sylvain Marsillac, an expert in chalcopyrites, joined the group UT PV in the fall of 2005.

As an NREL subcontractor the UT PV group places particular emphasis on collaborations with industries related to the PV field and for the training of students and postdoctoral associates for contributing to the PV-related industries. The UT PV group has been awarded several NREL contracts jointly with industrial partners (as sub-contractor to Solar Cells, First Solar, and ISET and as sub-contractor for First Solar and ITN) as well as direct grants from industrial sponsors to UT. Other collaborations are developing with newer companies in the Toledo area such as McMaster Energy Enterprises, Midwest OptoElectronics (MWOE) and Innovative Thin Films (ITF). Both graduate and undergraduate students and postdoctoral associates have been and are employed as interns and as full employees of First Solar, MWOE and ITF.

The extensive research on sputtered CdTe-based thin film solar cells provided a unique opportunity for UT to respond effectively to the NREL solicitation “High Performance Photovoltaics Program, Phase IA -- Identifying Critical Pathways”. With the resulting award, the UT research project on II-VI ternary alloys entitled "Polycrystalline Thin-Film II-VI Top Cells for Tandem Photovoltaics" was initiated using the versatile and scalable low-temperature sputtering method to prepare ternary alloys with wider and narrower gaps than CdTe, which enable development of the tandem devices. Low deposition temperatures are likely to be key to depositing a good second cell without damaging the first. The following accomplishments were achieved within the two-year Phase IA research program:

- High quality as-deposited films of $Cd_{1-x}Zn_xTe$ and $Cd_{1-x}Mn_xTe$ with band gaps of 1.6 to 1.8 eV were obtained from unreacted targets composed of mixed binary compounds;
- Optimized post-deposition $CdCl_2$ treatments on the best sputtered $CdS/Cd_{1-x}Zn_xTe$ solar cells gave reasonably good performance (V_{oc}=0.74 V, J_{sc}=19 mA/cm^2, FF = 0.51); however, the $CdS/Cd_{1-x}Mn_xTe$ cells were much poorer (V_{oc}=0.58 V, J_{sc}=5.6 mA/cm^2, FF = 0.31);
- High quality as-deposited films of $Hg_xCd_{1-x}Te$ with a band gap of 1.0 eV were successfully deposited, and good reproducibility in x could be obtained by controlling substrate temperature and gas pressure;
- Post-deposition $CdCl_2$ treatment of $Hg_xCd_{1-x}Te$ improved structural and electronic properties as indicated by an increase in conductivity by three orders and in grain size by a factor of three;
- Recombination junction structures were fabricated from ZnTe:N/ZnO bilayers with contact resistance of ~1.5 Ω-cm^2 and utilized in some prototype cell structures and transparent back-contacted devices.
- Two-terminal tandem cells were fabricated with CdTe (d=2.0 μm, E_g=1.5 eV) top and $Hg_xCd_{1-x}Te$ (d=1.2 μm, E_g=1.1 eV) bottom cells. Although an improved V_{oc} of the tandem (V_{oc}=0.96 V) was obtained over single junction devices, the efficiency (1.2%) was reduced due to the low current (2.0 mA/cm^2) which was limited by the bottom cell.

The new NREL project under "Phase IB -- Exploring and Accelerating Ultimate Pathways", entitled "Sputtered II-VI Alloys and Structures for Tandem PV", which is the focus of the present review will extend the initial progress into new ternary alloy fabrication, post-processing optimized for these alloys, further tandem device development, and more advanced characterization and device and optical physics.

COMMERCIALIZATION PLANS

Over the past eighteen months the CdTe PV group, together with the amorphous and nanocrystalline silicon group and the CIGS group at The University of Toledo, has actively engaged with PV-related companies in Ohio to establish the Wright Center on Photovoltaics Innovation and Commercialization (PVIC). This center involves collaboration also with The Ohio State University and Bowling Green State University and is partially funded by the Ohio Department of Development. The PVIC brings together three major Ohio universities, 13 PV-related companies, federal laboratories and not-for-profit organizations in Ohio to tackle issues related to lowering the cost of installed solar products and to stimulate PV-related entrepreneurship.

PVIC was formed as a means of coupling the strong PV research base at the University of Toledo with a core competency of advanced manufacturing in Ohio. Innovation and commercialization activities revolve around eliminating market barriers currently facing companies in the PV sector. Companies active in the PV industry, from those researching advanced materials development to those deploying energy producing devices, advise and coordinate experts in Ohio universities and Battelle in their PVIC contributions. Ultimately, PVIC consists of an internationally recognized group of PV fabricators with an infrastructure attractive to companies that are already successfully marketing and to researchers of the future generations of PV. These activities bring together established companies and researchers, at the forefront of developments in the PV industry, and seed the formation of new startup companies. For maximum impact on increasing production efficiency and lowering costs, PVIC takes a vertically integrated approach from research in advanced materials to the fabrication of production-scale modules, to issues related to installation, and finally to aspects of customer acceptance. Consequently, PVIC consists of academic, industrial, and federal laboratory members as experts in semiconductors or as suppliers to PV fabricators. Collaborators in PVIC possess knowledge of how to overcome real-life problems arising in connecting a module to the electric grid and how to obtain customer support for building-integrated PV designs. Companies along the entire value chain have been brought into PVIC, and each has identified its current market status relative to shipping products or providing services to customers. Each company identified what commercialization barriers exist between their current positions and where they need to be in order to satisfy customer demands. Based on the collective expertise of the personnel in PVIC, equipment, instruments, and techniques were identified that can help to eliminate commercialization barriers faced by each of the companies involved in the Center.

In addition to helping established industries in the full value chain of the PV market, members of the UT PV group have founded companies to assist in the commercialization efforts. By way of example faculty investigator, Dean M. Giolando, co-founded Innovative Thin Films, employing a chemical spray technique to deposit a number of metal oxides, which can be inserted into the TCO/CdS/CdTe PV stack to provide an enhancement in overall power output. While working with the PV fabricator, Solar Fields, the coatings allow a thinning of the CdS layer and an increase of one to two percent in the efficiency of large-area devices. The PVIC structure allows for acceleration in commercializing these findings because it brings together substrate producers such as Pilkington NA and PV fabricators such as Solar Fields to exploit intellectual property developed under this contract at UT.

PRINCIPAL PROJECT PERSONNEL

(FOLLOWING PAGES)

Alvin D. Compaan, Principal Investigator – Professor of Physics
(Percentage of time on this project 23%)

Degrees: A.B., Calvin College, 1965
M.S., University of Chicago, 1966
Ph.D., University of Chicago, 1971

Experience:

Research Associate, New York University, 1971-1973
Assistant Professor, Kansas State University, 1973-1977
Associate Professor, Kansas State University, 1977-1981
Professor, Kansas State University 1981-1987
Alexander von Humboldt Fellow, Max Planck Institute für Fkf 1982-1983
Professor of Physics, The Univ. of Toledo 1987-
Director, Center for Materials Science and Engineering, U. of Toledo, 1996-
Chair, Dept of Physics and Astronomy 7/1/2004-

Patents awarded/applications filed:

"Process for RF Sputtering of Cadmium Telluride Photovoltaic Cell," patent No. 5,393,675 *awarded on Feb. 28, 1995*, to Alvin D. Compaan, assigned to The Univ. of Toledo.

"Semiconductor having group II-group VI compounds doped with nitrogen," inventors: Alvin D. Compaan, Kent J. Price, Xianda Ma, and Konstantin Makhratchev, S/N 09/815,958, *filed 3/26/01*.

Graduate student/postdoc advising: 17 M.S., 10 Ph.D., 10 postdoctoral

Recent related refereed publications (out of ~200 total):

- V.G. Karpov, A.D. Compaan, and Diana Shvydka, "Effects of nonuniformity in thin-film photovoltaics," Appl. Phys. Lett. **80**, 4256 (2002).
- Diana Shvydka, V.G. Karpov, and A.D. Compaan, "Low-light divergence in photovoltaic parameter fluctuations," Appl. Phys. Ltrs, **82**, 2157 (2003).
- Alvin D. Compaan, "Magnetron sputtering for low-temperature deposition of CdTe-based Photovoltaics," Mat. Res. Soc. Symp. Proc. **763,** 145-154 (2003)
- Y. Roussilon, D.M. Giolando, Diana Shvydka, A.D. Compaan, and V.G. Karpov, "Blocking thin film nonuniformities: photovoltaic self-healing," Appl. Phys. Ltrs., **84**, 616 (2004))
- V. G. Karpov, A. D. Compaan, and Diana Shvydka, "Random diode arrays and mesoscale physics of large-area semiconductor devices," Phys. Rev. B **69**, 045325 (2004)
- A.D. Compaan, A. Gupta, J. Drayton, and S-H. Lee, and S. Wang, "14% sputtered thin-film solar cells based on CdTe," Phys. Stat. Sol. (b), **241**, 779-782 (2004).
- Xiangxin Liu, A.D. Compaan, and Jeff Terry, "Cu K-Edge X-ray Fine Structure Changes In CdTe With $CdCl_2$ Processing," Xiangxin Liu, Alvin D. Compaan and Jeff Terry, , 2004 European MRS meeting, Strasbourg, *Thin Solid Films* **480-481**, 95-8, (2005).
- S.H. Lee, A. Gupta, SL Wang, A.D. Compaan, and B. McCandless, "Sputtered CdZnTe films for top junctions in tandem solar cells," *Solar Energy Materials and Solar Cells*, **86**, 551-563 (2005).
- J. Drayton, A. Vasko, A. Gupta, and A.D. Compaan, "Magnetron Sputtered CdTe Solar Cells on Flexible Substrates," *Proc. 31st IEEE Photovoltaic Specialists Conference-2005*, 406-409, IEEE Piscataway, N.J. 2005.
- Alvin Compaan, "Photovoltaics: clean electricity for the 21st century," *APS News* (an invited contribution in the Physics and Technology Forefronts series). April 2005, p. 6. [available on line at http://www.aps.org/apsnews/0405/040514.cfm]
- X. Liu , A.D. Compaan, and J. Terry, "Cu K-edge EXAFS studies of $CdCl_2$ effects on CdTe solar cells," Mater. Res. Soc. Symp. Proc. **865,** F4.2 (2005).
- X. Liu and A.D. Compaan, "Photoluminescence from ion implanted CdTe crystals," Mater. Res. Soc. Symp. Proc. **865,** F5.25 (2005)
- Gupta and A.D. Compaan, "High efficiency, 0.8 micron CdS/CdTe solar cells," Mater. Res. Soc. Symp. Proc. **865,** F14.33 (2005).
- Y. Roussillon, D. M. Giolando, V. G. Karpov, Diana Shvydka, and A. D. Compaan, "Reach-through band bending in semiconductor thin films," Appl. Phys. Lett., **85**, 3617-19 (2004).
- Y. Roussillon, V. G. Karpov, Diana Shvydka, J. Drayton, and A. D. Compaan, "Back contact and reach-through diode effects in thin-film photovoltaics," J. Appl. Phys. **96**, 9283-8 (2004).

Victor G. Karpov, co-Principal Investigator, Professor of Physics
(Percentage of time on this project 19%)

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PRINCIPAL AREAS:

Condensed Matter Theory, Semiconductors, Photovoltaics, Non-crystalline materials and thin films, Phase transformations, Radiation effects.

EDUCATION: Dr. of Sciences - Institute for Nuclear Physics, Academy of Science USSR (1986).
Ph.D. - Leningrad Polytechnic Institute, 1979.

EMPLOYMENT RECORD:

2001 – present	Professor, University of Toledo
1999 – 2001	Senior Scientist at First Solar, LLC, Toledo OH
1997 – 1999	Senior Scientist at the Higher Dimension Research, Inc.; St. Paul, MN;
1995 – 1997	Visiting Scholar at The University of Chicago, Chicago, IL;
1992 --1993	Visiting Scientist at the Argonne National Lab., Argonne, IL;
1973 – 1995	Professor at St. Petersburg State Technical University (Russia).

RELEVANT PUBLICATIONS:

1. *Back contact and reach-through diode effects in thin-film photovoltaics*, Y. Roussillon, V. G. Karpov, D. Shvydka, J. Drayton, and A. D. Compaan, J. Appl. Phys., **96**, 7283 (2004)
2. *Reach-through band bending in semiconductor thin films*, Y. Roussillon, D. Giolando, Diana Shvydka, A. D. Compaan, and V. G. Karpov, Appl. Phys. Lett. **85**, 3617 (2004)
3. *E^2 phase transitions: thin-film breakdown and Schottky barrier suppression*, V. G. Karpov, D. Shvydka, and Y. Roussillon, Phys. Rev**. B70**, 155332 (2004)
4. *Critical disorder and phase transition in random diode arrays*. V. G. Karpov, Phys. Rev. Lett., **91**, 226806 (2003) .
5. *Random diode arrays and mesoscale physics of large-area semiconductor devices*, V. G. Karpov, A. D. Compaan, and Diana Shvydka, Phys. Rev B **69**, 45325 (2004).
6. *Blocking thin film nonuniformities: photovoltaic self-healing*, Y. Roussillon, D. Giolando, Diana Shvydka, A. D. Compaan, and V. G. Karpov, Appl.Phys.Lett. **84***,*2004, pp.616-618.
7. *Admittance spectroscopy revisited: Single defect admittance and displacement current*, V. G. Karpov, Diana Shvydka, U. Jayamaha and A. D. Compaan, J. Appl. Phys., **94**, 2003, pp. 5809-5813.
8. *Photoluminescence Fatigue and Related Degradation in Thin-Film Photovoltaics*, Diana Shvydka, C. Verzella , V. G. Karpov and A. D. Compaan, J. Appl. Phys. **94**, 2003, pp. 3901-3906.
9. *Electron-beam induced degradation in CdTe photovoltaics.* R. Harju, V. G. Karpov, D. Grecu, G. Dorer J. Appl. Phys., **88**, p. 1794 (2000).
10. Shunt screening and size dependent effects in thin-film photovoltaics V. G. Karpov, G. Rich, A. V. Subashiev, G. Dorer, J. Appl. Phys. **89**, 4975 (2001)

Robert W. Collins, co-Principal Investigator, Professor of Physics

(Percentage of time on this project 19%)

Jan 2004 - NEG Endowed Chair of Silicate and Materials Science and Professor of Physics, Department of Physics and Astronomy, University of Toledo, Toledo OH

Education

1977-1982 Harvard University, Division of Applied Sciences, Cambridge, MA
M. S. in Applied Physics received in 1979
Ph. D. in Applied Physics received in 1982

1973-1977 Clark University, Worcester, MA
A. B. with honors in Physics, summa cum laude; member □BK

Previous Positions

1992 – 2004 The Pennsylvania State University, Univ. Park, PA
Professor of Physics and Materials Research,

1988-1992 The Pennsylvania State University, University Park, PA
Associate Professor of Physics and Materials Research.

1982-1988 BP America/Standard Oil Co., Warrensville Heights, OH
Senior Research Physicist

1979-1982 Harvard University, Division of Applied Sciences, Cambridge, MA
Research Assistant

Affiliations

American Physical Society and Materials Research Society

Overview of Publication List

About 300 articles have been published and 80 invited presentations have been given on: optical and electronic analysis of semiconductors and photovoltaic devices; optical properties of thin films; optical instrumentation design for ellipsometry, and Stokes vector and Mueller matrix spectroscopies; real time spectroscopic ellipsometry characterization of materials and device preparation and processing; thin film nucleation and microstructural evolution. Materials studied include: amorphous, nanocrystalline, and microcrystalline semiconductors, diamond and amorphous carbon; metal, conducting oxide, conducting polymer, and electrochromic thin films; and III-V and II-VI semiconductors and dielectrics. Devices studied include solar cells and electrochromic structures.

Graduate Student and Post-doctoral Scholar Advising

Ph.D. students receiving degrees: 16; Post-doctoral scholars employed: 26.

Selected Relevant Publications

1. "Spectroellipsometry for Characterization of $Zn_{1-x}Cd_xSe$ Multilayered Structures on GaAs", Joungchel Lee, R.W. Collins, A.R. Heyd, F. Flack, and N. Samarth, *Applied Physics Letters* **69**, 2273-2275 (1996).
2. "Optical Depth Profiling of Band Gap Engineered Interfaces in Amorphous Silicon Solar Cells at Monolayer Resolution", H. Fujiwara, Joohyun Koh, C.R. Wronski, R.W. Collins, and J.S. Burnham, *Applied Physics Letters* **72**, 2993-2995 (1998).
3. "Rotating Compensator Multichannel Ellipsometry: Applications for Real Time Stokes Vector Spectroscopy of Thin Film Growth", Joungchel Lee, P.I. Rovira, Ilsin An, and R.W. Collins, *Review of Scientific Instruments* **69**, 1800-1810 (1998).
4. "Analysis of Specular and Textured SnO_2:F Films by High Speed Four-Parameter Stokes Vector Spectroscopy", P.I. Rovira and R.W. Collins, *Journal of Applied Physics* **85**, 2015-2024 (1999).
5. "Ellipsometry in Analysis of Surfaces and Thin Films", R. W. Collins, in: *Encyclopedia of Analytical Chemistry*, edited by R. A. Myers, (Wiley, West Sussex UK, 2000) pp. 9120-9162.

Dean M. Giolando: co-Investigator, Professor of Chemistry
(Percentage of time on this project 19%)

Education: Ph.D., University of Illinois, Urbana, IL, 1987
B.S., Rochester Institute of Technology, Rochester, NY, 1981

Professional Experience:
Founder, Innovative Thin Films, LLC, 6/1/02-present
Senior Scientist, First Solar, LLC, 5/15/00 – 8/15/00
Professor of Chemistry, University of Toledo, 6/01-
Associate Professor of Chemistry, University of Toledo, 9/94-6/01
Assistant Professor of Chemistry, University of Toledo, 9/88-9/94

Postdoctoral Research Associate, University of Texas, 9/86-8/88

Consulting: CVD Precursors for Semiconductors and Ceramics
- Libbey-Owens-Ford Company, 7/89-present
- Solar Cells, Inc., 1996, 1998-2002
- Engineered Glass Products, 2000-present

Research Interests: Synthetic, structural and reactivity studies on compounds containing the main group elements; coordination complexes containing thiolate ligands; organometallic compounds. Molecular precursors to solid state materials; fabrication and characterization of ultramicroelectrodes (ca. 10 µm).

RESEARCH FUNDING

Libbey-Owens-Ford Company. "Organoindium Precursors for Indium Tin Oxide" (Giolando PI, 12/1992 to 6/2004).
First Solar, LLC. "Molecular Precursors for CVD Materials", (Giolando PI, Jan. 1999 to Dec. 2002).
Engineering Glass Products. "Analysis of material from EGP", (Giolando PI, May 2000 to June 2000).

PUBLICATIONS (1980 to present): 52 in peer-reviewed journals

Yann Roussillon, Dean Giolando, Diana Shvydka, Alvin D. Compaan, and Viktor G. Karpov "Blocking Thin Film Nonuniformities: Photovoltaic Self-healing", Applied Physics Letters, **2004**, *84*, 616-8.
Dean M. Giolando, Jon R. Kirchhoff, Holger Mueller, Phu Q. Nguyen and Ihab N. Odeh, "Fabrication and Characterization of Alumina-Coated Carbon Fiber and Silicon Carbide Fibers Ultramicroelectrodes by Chemical Vapor Deposition", *Chem. Vap. Deposition*, **2002**, *8*, 93-98.
D. Rose, R. Powell, U. Jayamaha, M. Maltby, D. Giolando, A. McMaster, K. Kormanyos, G. Faykosh, G. Dorer "R & D OF CDTE PV CELLS, MODULES, AND MANUFACTURING EQUIPMENT: PLAN AND PROGRESS TO 100 MW/YR" *Conf. Rec. IEEE Photovoltaic Spec. Conf.* **2000**, 28th, 428-431.

PROFESSIONAL PRESENTATIONS: 58, national and international meetings

Dean M. Giolando, Ahmad Taha, Samia Al-Qaisi, Xunming Deng, Al Compaan, "Application of Spray Pyrolysis Metal Oxide Thin Films for Photovoltaic Applications" presented at the International Energy Conversion Engineering Conference, Providence, RI, August, **2004.**
Dean M. Giolando, Alan McMaster, Micheal Maltby, U. Jayamaha "Commercialization of TCO materials by APCVD techniques" presented at the MRS Workshop on TCO materials, Denver, CO, June, **2000**.

PATENT APPLICATIONS: 9

Dean M. Giolando, Alan McMaster and Samia Al-Qaisi, "Coating Substrates by Spray Pyrolysis", *US Patent*, filed July 2005.