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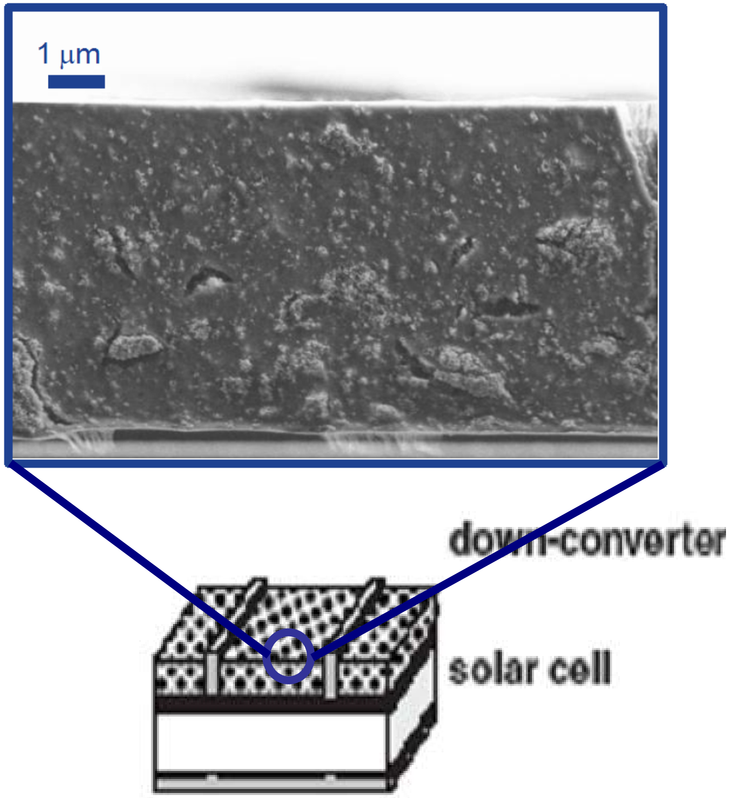

GOAL: Development of a low cost layer, which will down-convert high energy solar photons to useful low energy photons, with high efficiency

Efficiency Enhancing Layers for Photovoltaic Modules

Program Team – PV
DE-EE0000568

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Overview

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Timeline

- Project start date: 8/1/2009
- Project end date: 7/31/2011
- Percent complete: 38%

Budget

- Total project funding: $2.4M
  - DOE share: 50%
  - GE cost share: 50%
- Funding received in FY09
  - $125,069
- Funding for FY10
  - $841,123

Barriers

- Efficiency:
  - >5% relative gain
- Design & Packaging
  - New coatings
- Manufacturing:
  - deployment on large-scale modules

Partners

- Rensselaer Polytechnic Institute
  - Next generation PV and optics model
- University of Georgia
  - Down conversion optical characterization

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Challenges, Barriers or Problems

- Efficiency
  - Today's thin film PV modules limited in efficiency
  - Use down-shifting (DS) layers to boost efficiency of virtually any PV module
- Design of modules
  - DS layers allow greater flexibility in design of PV modules
- Manufacturing
  - Low cost DS layers allow for easy integration into the manufacturing process of any PV module

Impact

- Increased PV deployment in US
- US based PV module manufacturing

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Relevance: Pathways to High Efficiency

There are various pathways to high efficiency:

- Multijunction solar cells
  - In production (high cost)
- Multiple absorption path solar cells (impact ionization, multiple exciton generation)
- Multiple energy level solar cells (localized levels or intermediate bands)
- Multiple temperature solar cells (utilization of hot carriers)
- Dilute II-VI oxide semiconductor cells (ZnMnOTe)
- Solar Thermophotovoltaics (TPX)

⇒ **Our approach: D*own conversion of photons* for *Multiple spectrum solar cells***

- **All these approaches have theoretical efficiency limits > 31%**
- ***Many technical challenges that require fundamental scientific research***
- ***Up/down conversion most practical approach today for boosting efficiency of terrestrial flat-plate PV***

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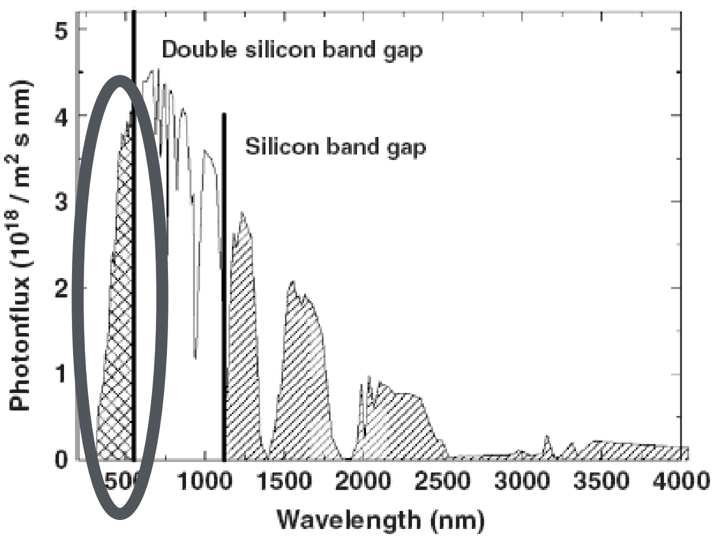
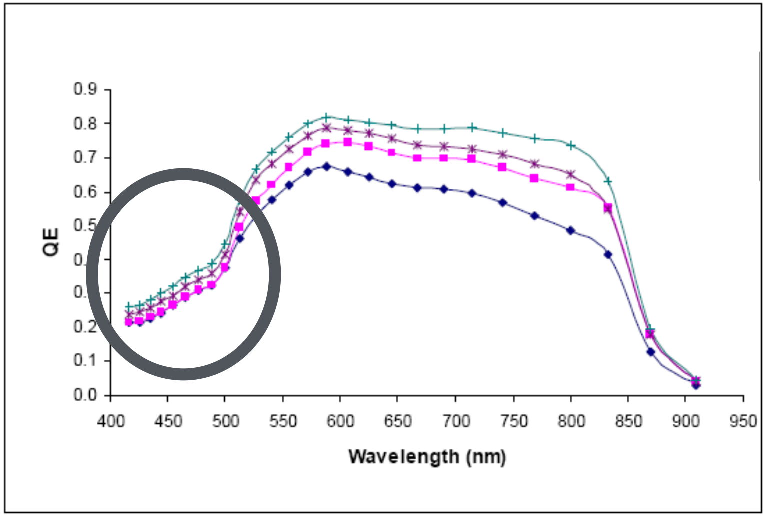
Relevance: Increase PV Efficiency

- 2 fundamental efficiency loss mechanisms in solar cells:
  - High energy (short wavelength) photons: thermalization
  - Low energy: transmission
- Thin film cells:
  - Absorption loss in window layers





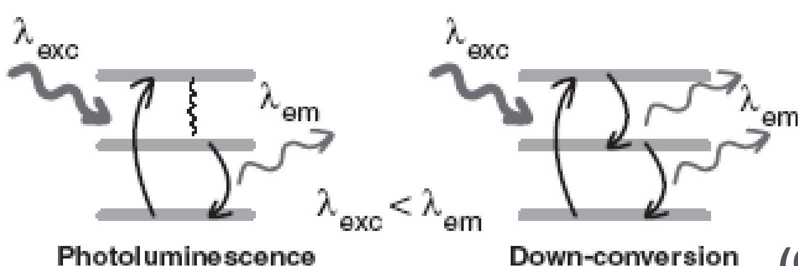
Thin film solar cells [Gupta, et al., MRS (2001)]

Approach

Convert high energy light to useful lower energy light

- Photoluminescent/down-converting converting layers can be applied to front of a standard solar cell without significant modification in the process
- Increases efficiency with minimal capital expenditure and cost
    - Potential for < $5/m2
- Can also be applied at module level

Strumpel, et al., Solar Ener. Mater. Sol. Cell (2007)



(Quantum splitting)

1 photon in, 1 photon out

QE = 100%

1 photon in, 2 photons out

QE = 200%)

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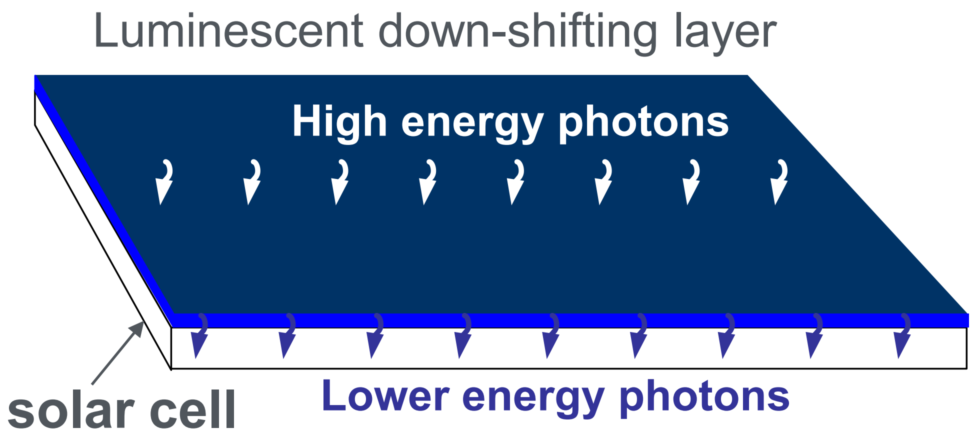
Functional Layers on PV Modules



- PL and down-conversion
  - 0.5-8% absolute efficiency gain
  - thin film PV modules with PCE >15%
- Scalable, low-cost processes (<$0.05/W)
- Gain demonstration on cells and mini-modules
- Go/No-Go Metrics
  - Design with > 1% gain
  - DS materials with high QE (>70%)
  - DS Films with high QE (> 40%)
  - Process flow for scalable integration

Task 1 - Modeling

Modeling Approach

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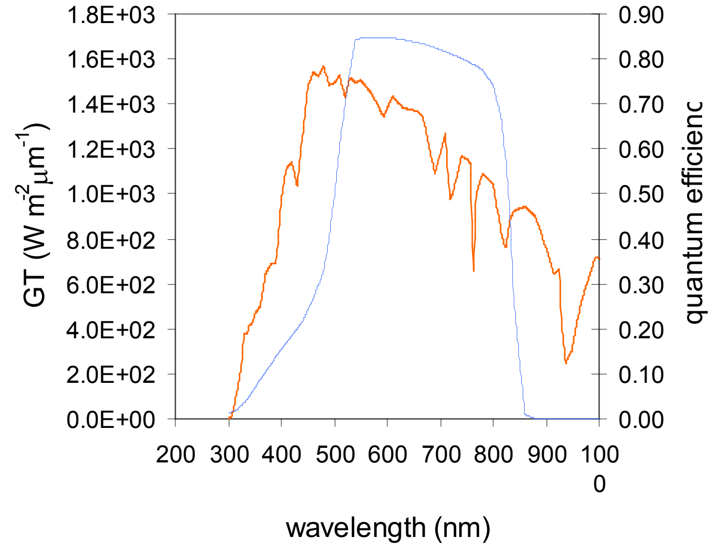
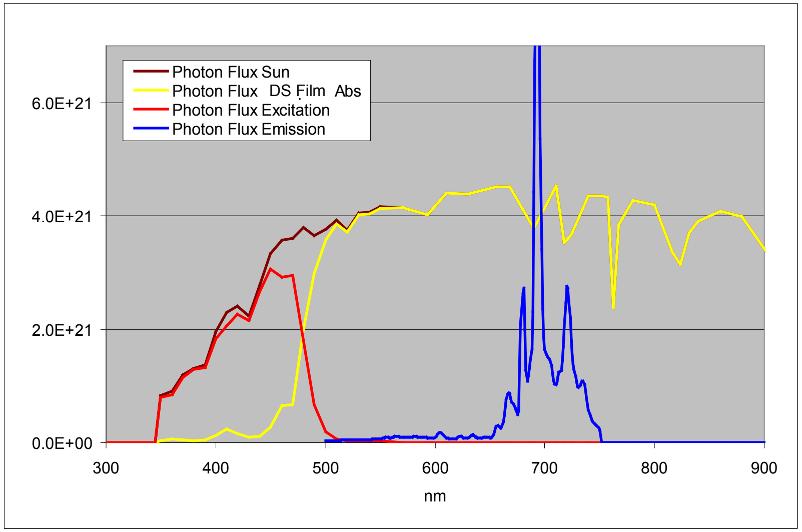
- Entitlement
  - Module QE and solar spectrum (AM1.5G)
  - DS film excitation and emission spectra
  - Calculate modified solar spectrum
- Optical modeling
  - Thin film (ray tracing)
  - Radiative transport theory





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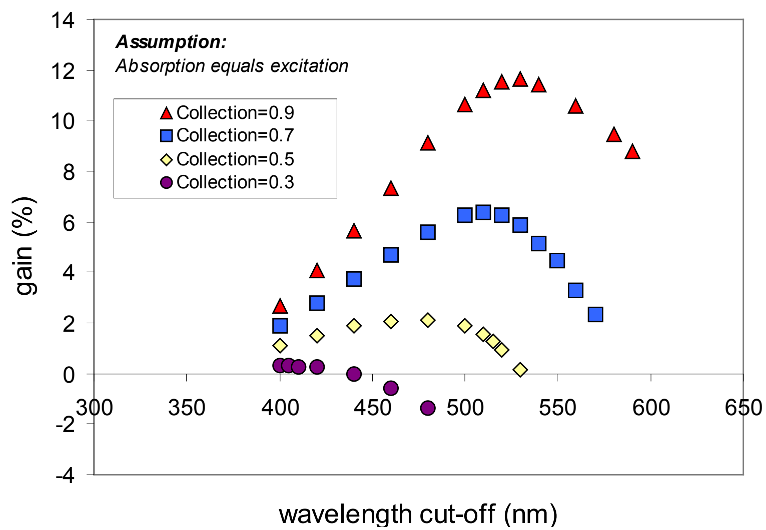
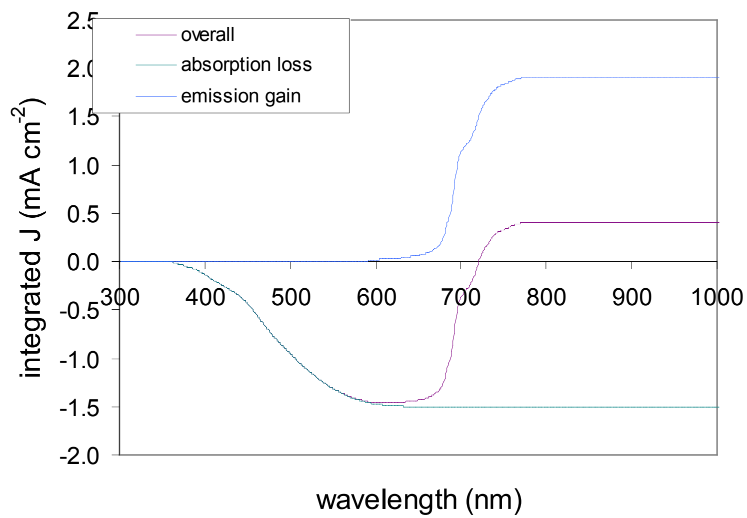
Summary of Modeling Results

- Gain calculated for various PV technologies (thin film, Si) technologies
  - Assumed idealized (box-like) excitation and emission spectra
  - Assumed QE of 0.85
  - **Gain as high as 12% possible (DS)**
  - Higher gain for DC/QS
- Gain depends strongly on DS film parameters
- Calculated light collection factor
  - Higher than 50%
- Evaluated gain for over 30 GE compositions
  - Down-selected to 2 leading materials systems
- Established thickness range and optical losses using optical model





Novel optical designs (RPI)

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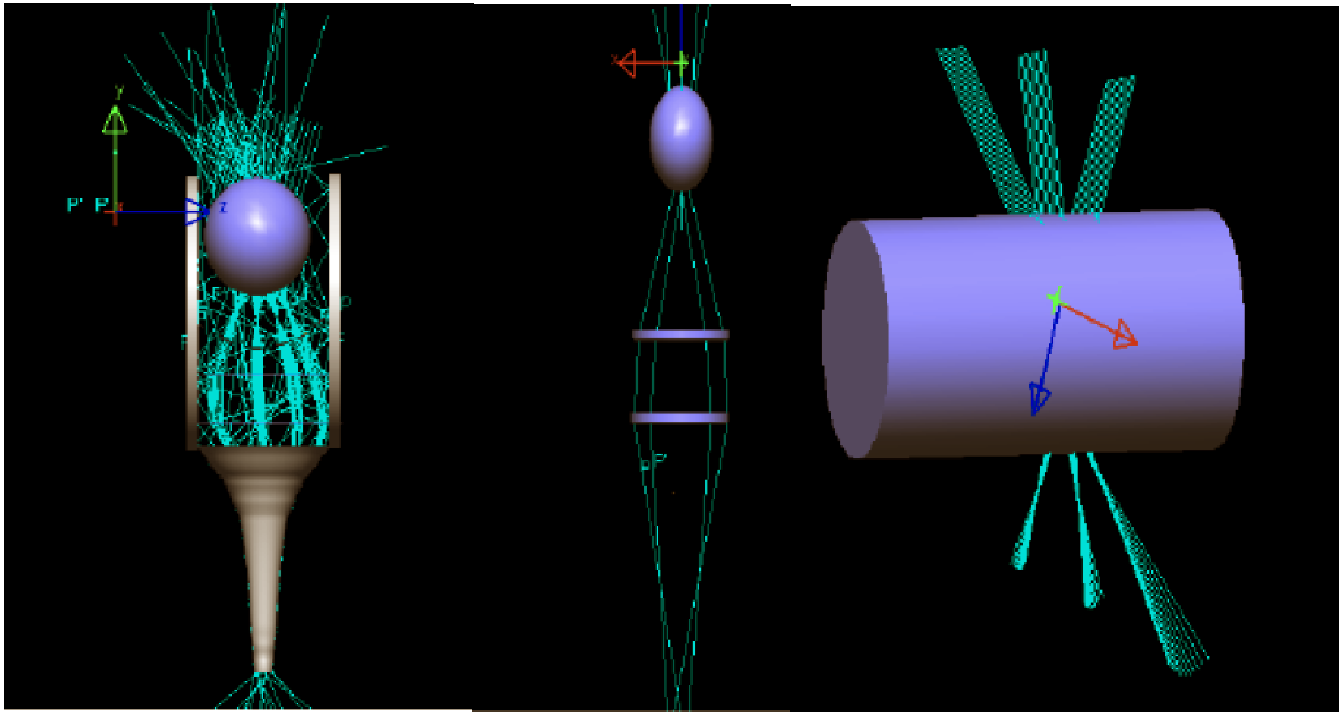

- Working with RPI to develop novel module-level optical designs that incorporate efficiency enhancing layers

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Task 2 – Down Shifting Materials

DS Materials Synthesis

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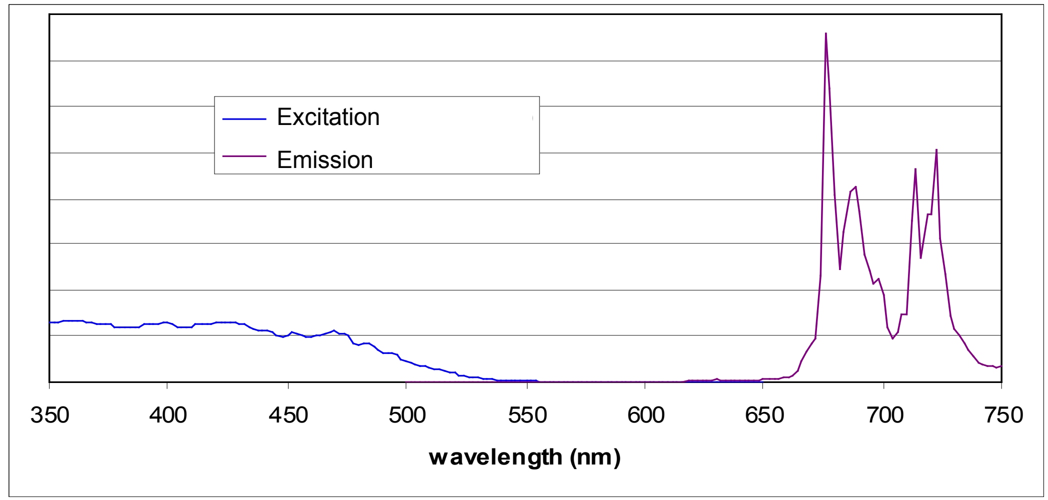
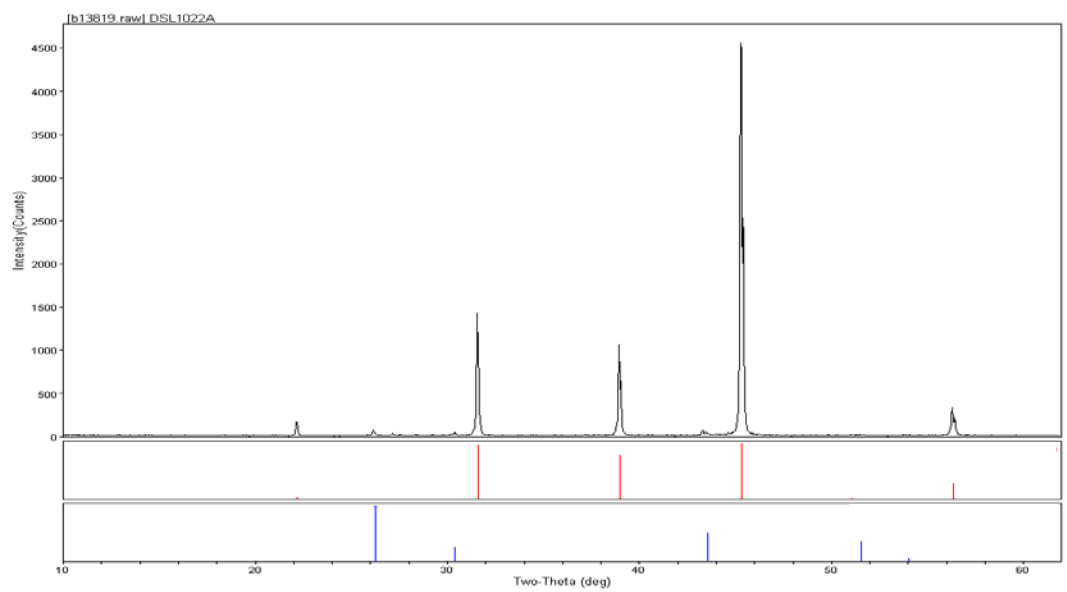
- Fabricated DS materials with
  - well separated excitation and emission
  - Highly crystalline with minimal second phases
- Optical properties
  - Quantum efficiency ~ 90%
  - Absorption(@490 nm) =75%





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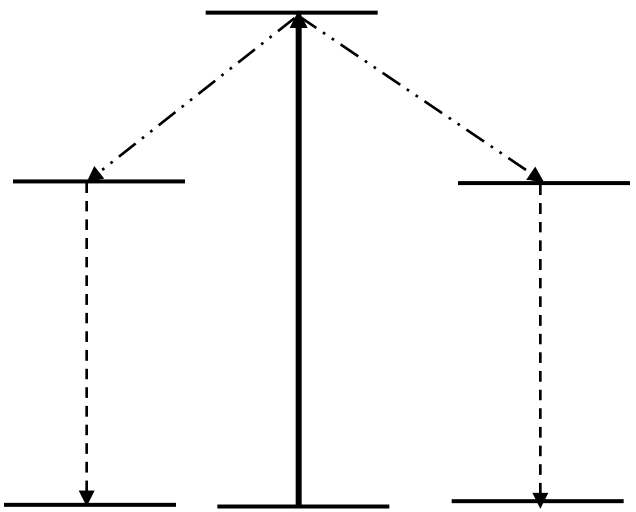
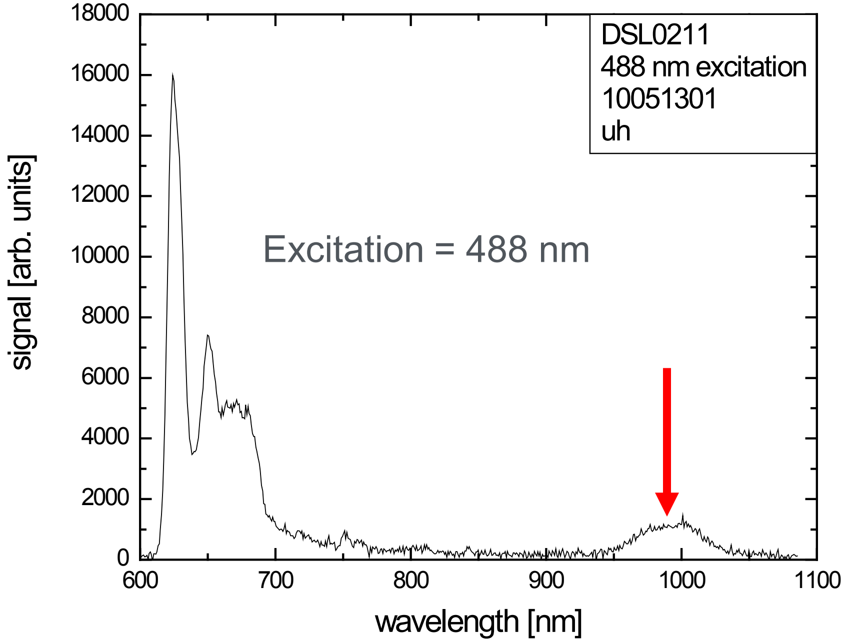
Down-conversion/quantum splitting (UGA)

- We have successfully detected quantum splitting in the near-IR





- This result validates the team's approach and gives direct experimental evidence of the "two-for-one" downconversion process.

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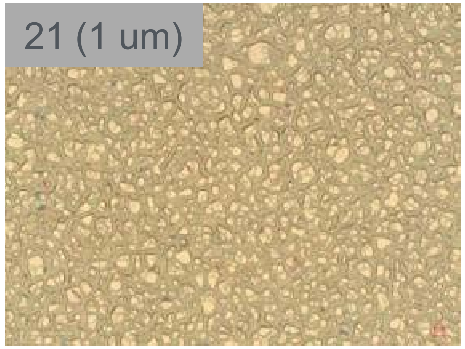
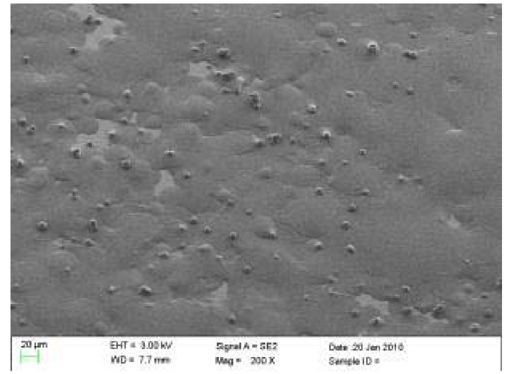
Task 3 – Down Shifting Films

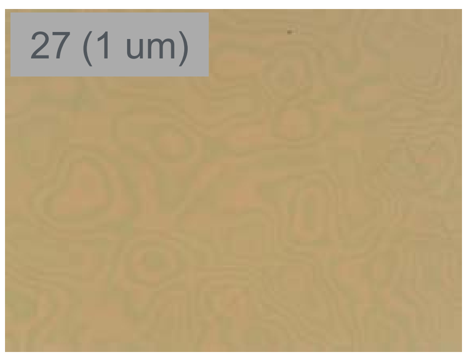
Processed DS Films

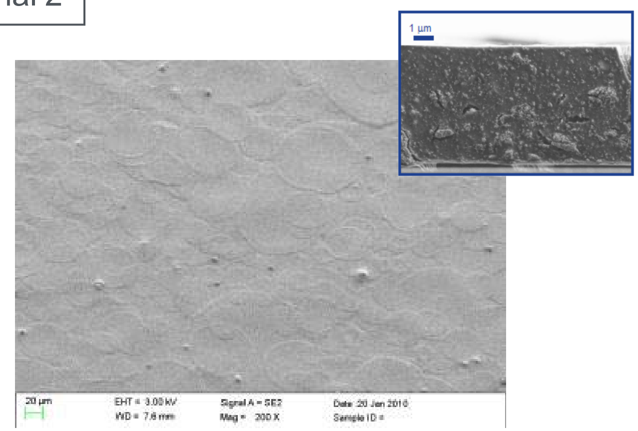
Material 1





Material 2





- Fabricated DS films with improved morphology using manufacturable process
- Performed detailed analysis of potential low-cost processes

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DS Film Excitation/Emission Spectra

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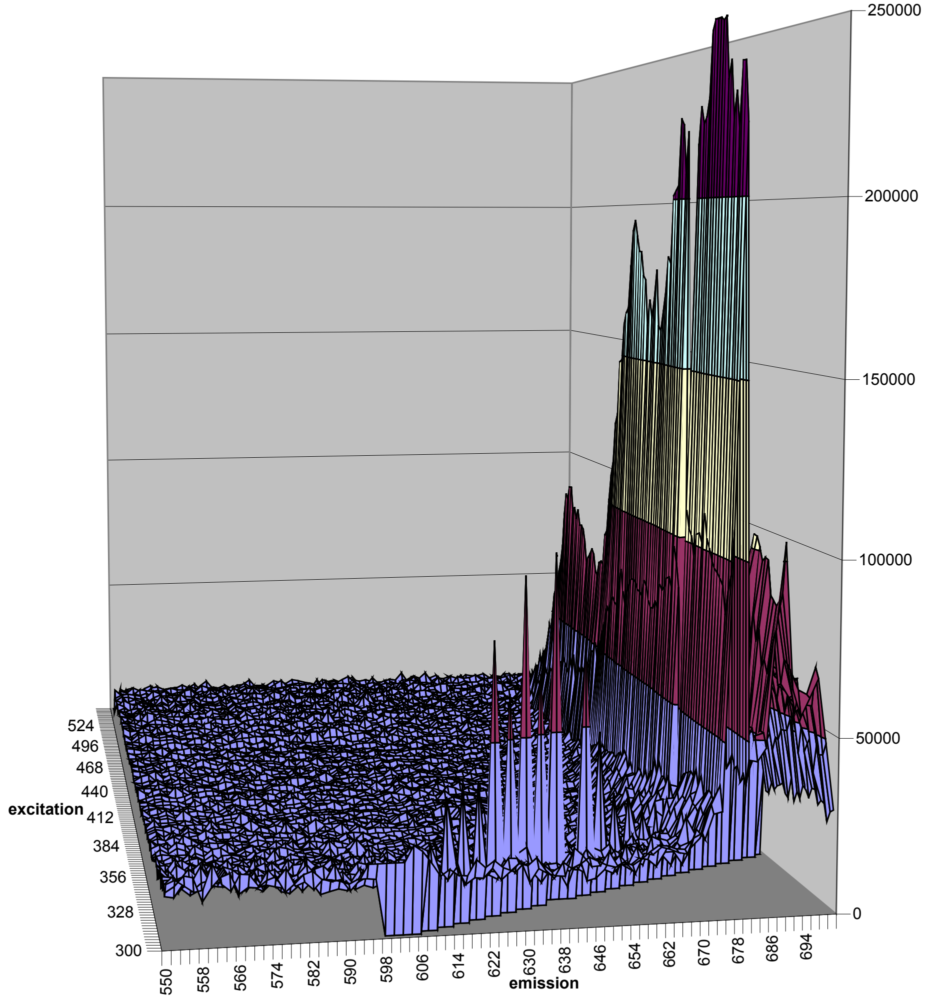

- Measured excitation/ emission spectra from DS films using integrating sphere
- Preliminary QE values low – addressing via analysis and optimization

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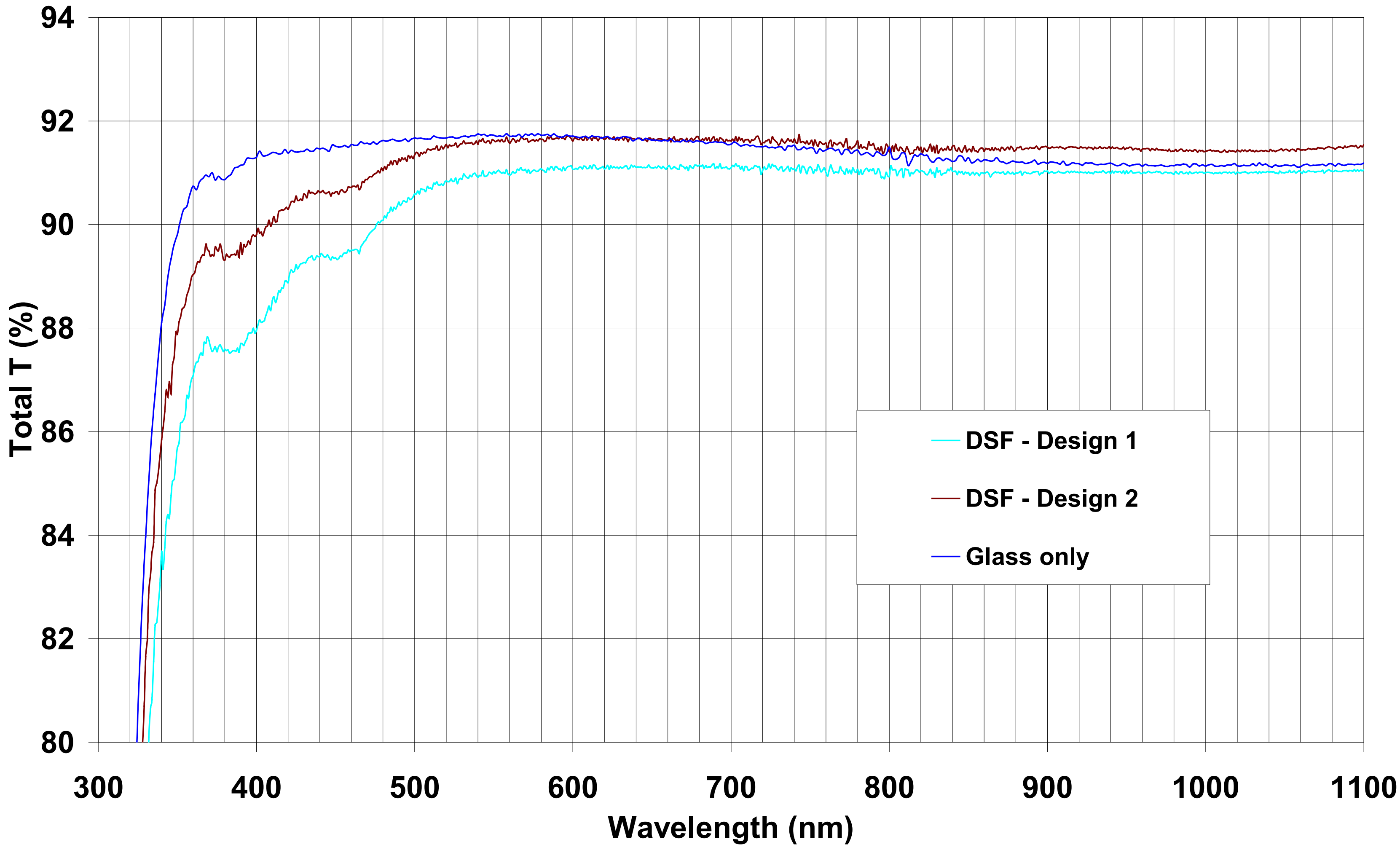
Long Wavelength Optical Loss



- DS films show promising optical transmission relative to controls

Task 4 – DSF Integration with PV Modules

Preliminary DS Film Data

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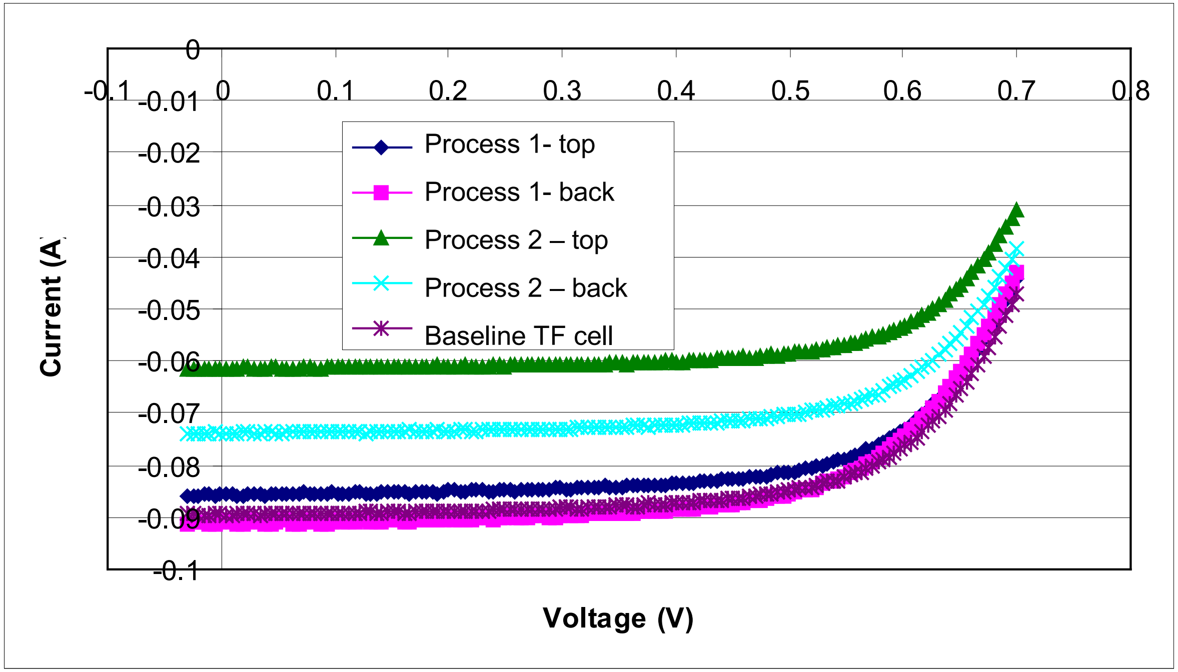
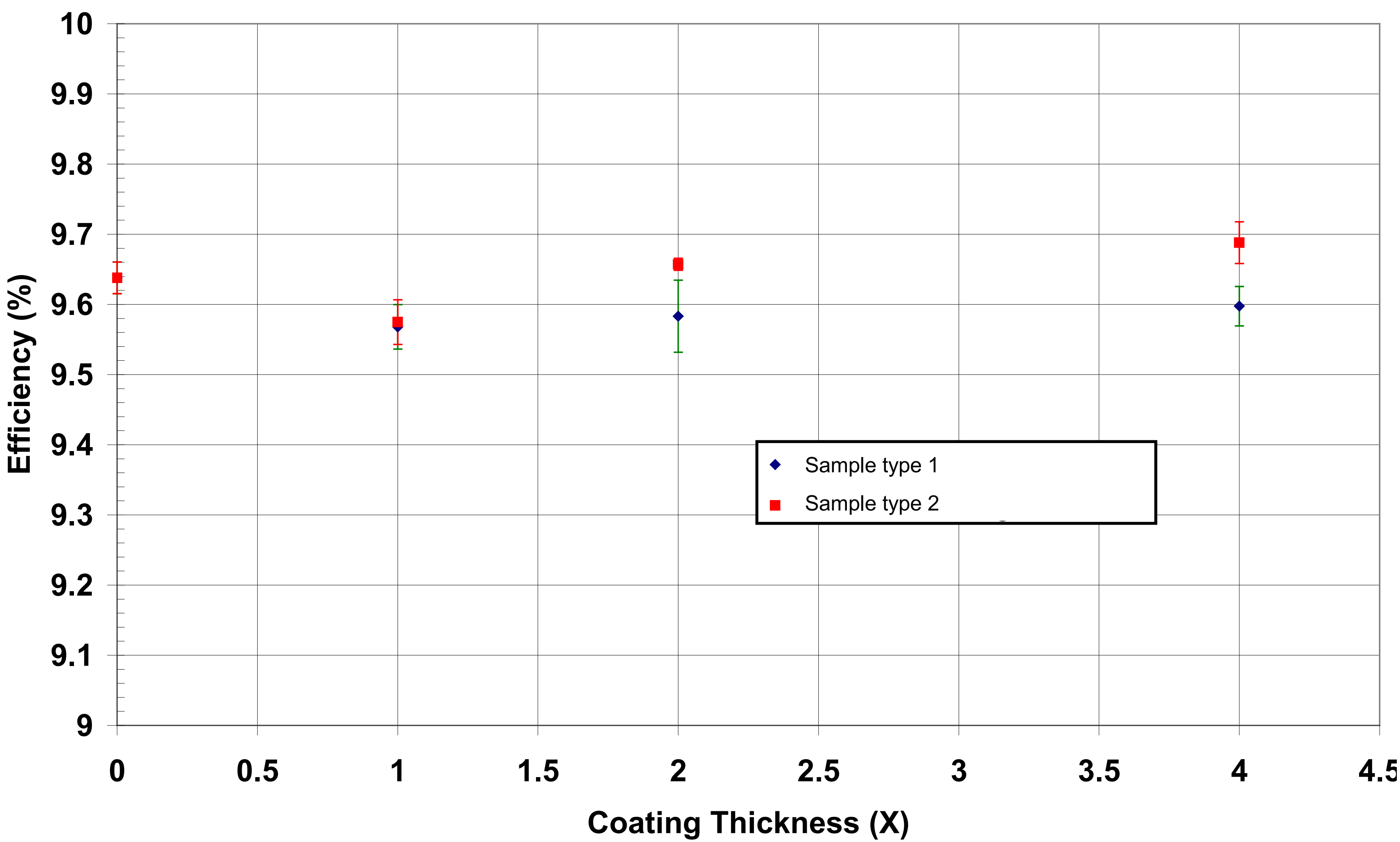


	Jsc	Efficiency
Baseline	2.32E-02	11.9957
Process 1 – top	2.23E-02	11.4354
Process 1 - bottom	2.36E-02	11.7809
Process 2 - top	1.60E-02	8.3151
Process 2 - bottom	1.92E-02	9.9604

- Pre-award work
- Showed less-than-expected reductions in PV efficiency
- Suggested there is a path to improved efficiency

Thin Film Solar Cell Testing



First PV cell tests: no loss in efficiency

Future Plans (FY 2011 and beyond)

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- Task 1:
  - iterative design with input from experimental results
- Task 2:
  - Optimization of leading DS materials system
  - Pursue demonstration of DC materials system with broadband excitation
- Task 3:
  - Improve QE of DS films to > 40% (***Key Go-No Go Metric***)
- Task 4:
  - Develop process flow for integration with PV modules (***Key Go-No Go Metric***)
  - Demonstrate gain on solar cells and mini-modules

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Collaborations

- Rennselaer Polytechnic Institute
  - Relationship: sub
  - University
  - Within the DOE Solar Program
  - Monthly meetings

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- University of Georgia
  - Relationship: sub
  - University
  - Within the DOE Solar Program
  - Monthly meetings, exchange of samples and data

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Summary

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- Modeled DS film impact on multiple PV technologies
- Showed designs with > 10% relative gain
- Evaluated over 30 DS compositions and down-selected to 2 leading materials
- Model shows practical thickness of 2-50 μm
- Fabricated DS materials with >90 QE
- Demonstrated quantum splitting mechanism with excitation energies applicable to the solar spectrum
- Fabricated prototype DS films using manufacturable processes and measured excitation/emission
- DS films show promising optical properties
- Demonstrated DS films do not reduce efficiency of thin film solar cells
  - Net gain expected with subsequent optimization

Performance Metric or property	Prototype/ Component /Material	Status in FY09	Result in FY10	Notes
Design > 1% absolute	Model	-	>1% design shown	Requires advance optics
DS QE > 70%	Material	-	>90% demonstrated	Relative to a standard
DS film QE >40%	Component	-	<20%	Optimizing DS film structure
PV cell efficiency > 5% relative	Prototype	-	0%	Losses equal gains; optimizing DS films

Acknowledgements

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Danielle Merfeld, Kelly Fletcher, Jim LeBlanc, Jerry Trant, Paul Diconza, John Freer, Bob Shalvoy, Tom McNulty

Partha Dutta

Uwe Happek

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