DOE Solar Energy Technologies Program Peer Review

Electro-Optical Characterization Team

NREL

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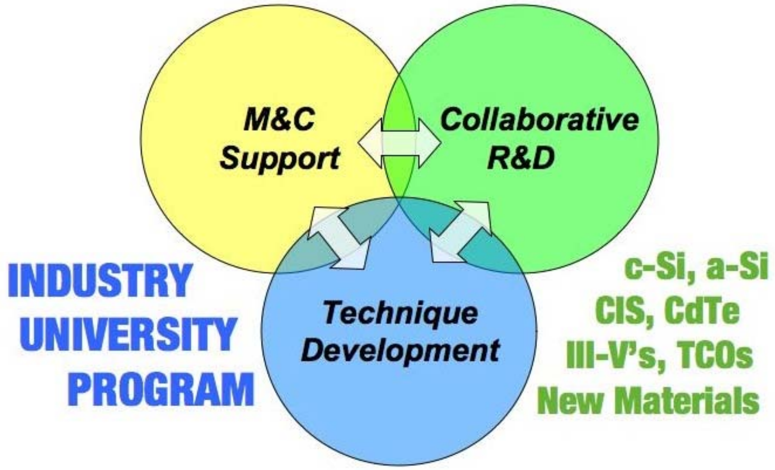
Relevance/Objective



- **The primary objective of the electro-optical characterization team is to help our partners and stakeholders in industry, university, and NREL reach their goals by establishing a clear link between material properties, device processing; and the device efficiency, reliability, and cost.**
- **Most of our techniques are rapid and non-contact, providing characterization at every stage of processing, and making them ideal for in-line and *in situ* applications**

Summary of Activities

Electro-Optical Characterization Team capabilities

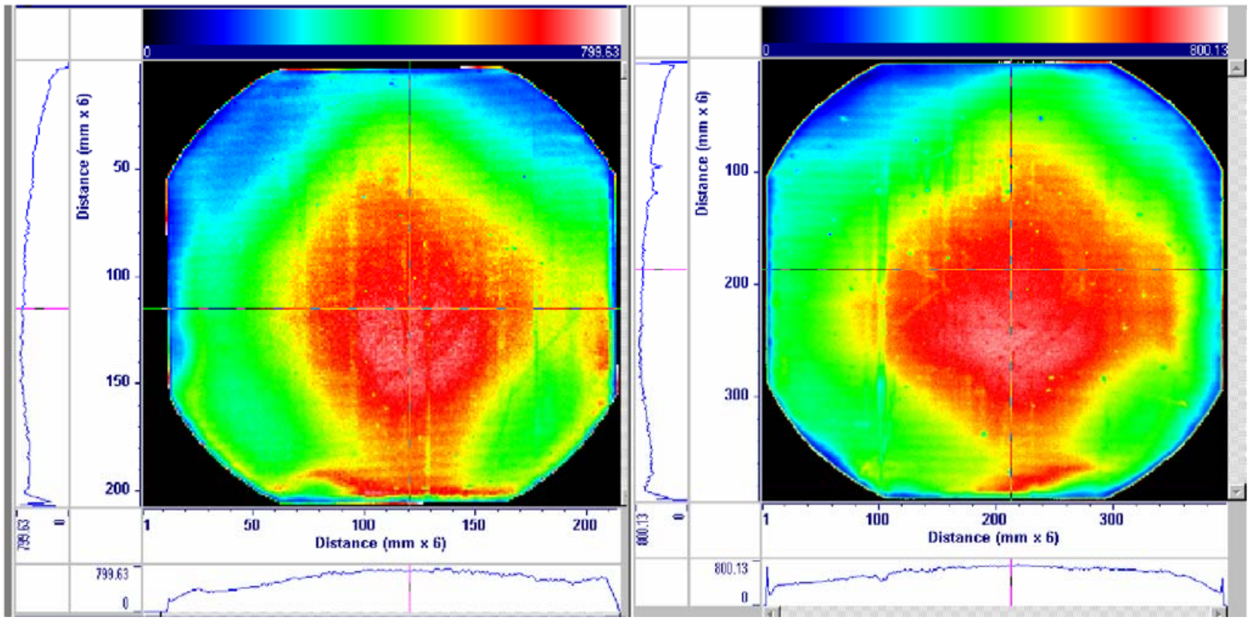
Technique or capability	Typical Applications	Materials/Technologies supported
Photoluminescence spectroscopy (PL)	Electronic structure of materials, bandgap, defect identities, material quality	Silicon, poly thin films, organics, new materials
Minority-carrier lifetime spectroscopy	Time-resolved measure of photoexcited carrier population, detailed studies of recombination processes	Silicon, poly thin films, organics, new materials
Fourier Transform infrared (FTIR) and Raman spectroscopy	Probes molecular vibrational modes and free-carrier effects, providing information on composition, impurity concentration, local chemical environment, and carrier concentration	Silicon, poly thin films, organics, new materials
Spectroscopic ellipsometry	Rapid, non-contact optical probe capable of determining film thickness, crystallinity, roughness, composition, and electronic properties. Particularly well-suited to in-line or *in situ* measurements.	Silicon, poly thin films, organics, new materials
Capacitance techniques (C-V and DLTS)	Measure flow of electrons within a material in response to changes in applied bias, to determine free-carrier concentration and defect-state parameters	Silicon, poly thin films, organics, new materials

Summary of Activities

Electro-Optical Characterization Team capabilities

Technique or capability	Typical Applications	Materials/Technologies supported
Scanning defect mapping	Uses a scanning laser and an integrating sphere to provide detailed maps of grain boundaries and dislocations in silicon solar cells	Silicon, poly thin films
Reflectance spectroscopy	Uses broadband reflectance of a solar cell to provide detailed maps of physical parameters including surface roughness and texture, AR coating thickness, metallization area and height, and backside metallization properties.	Silicon, poly thin films
Computational modeling	Advanced 2D modeling allows us to simulate electro-optical experiments and solar cell devices	Silicon, poly thin films, organics, new materials
Technique development	We apply our existing knowledge and expertise to the advancement of existing experimental techniques and the creation of new techniques	Silicon, poly thin films, organics, new materials

Reflectometry quickly characterizes Si PV cell properties



Thickness maps of AR coating on two textured commercial PV-Si wafers showing variations in the thickness pattern in one production run.

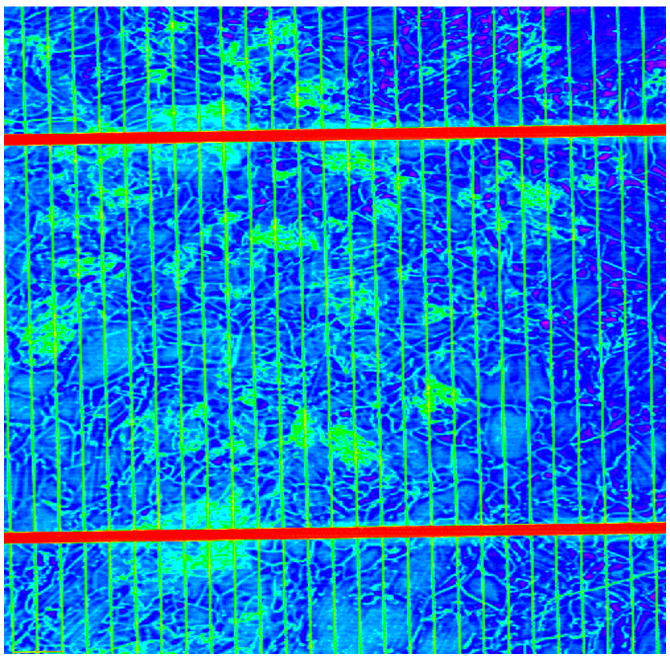
<u>Reflectance spectroscopy mode</u>

surface roughness or quality of texture
Thickness of AR coating
Height and area of front metallization
Thickness of the wafer
Back surface reflectance

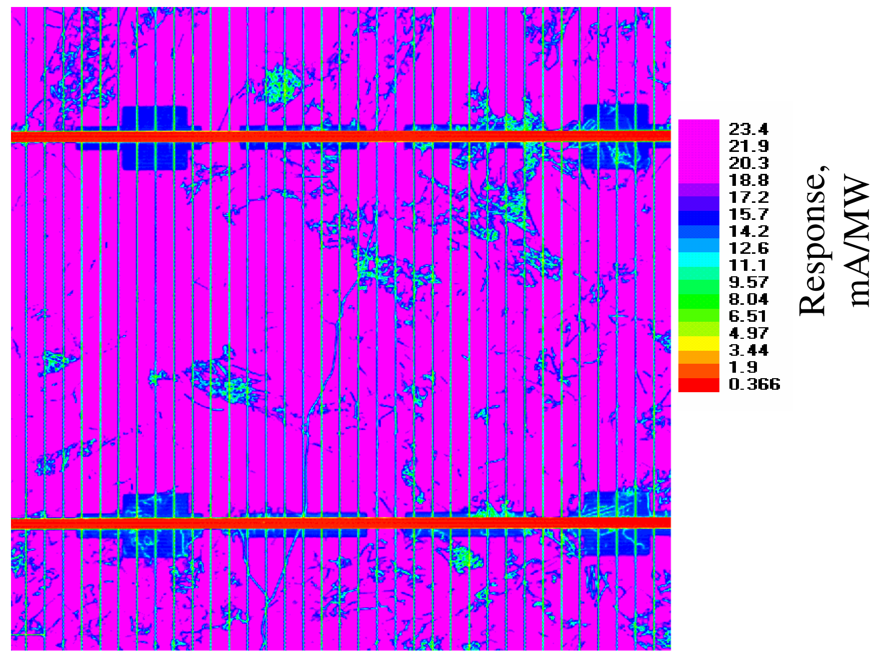
<u>Imaging mode</u>

spatial maps of these parameters.

Laser beam induced current map reveals location of defect clusters



<LBIC> = 16.3 mA/cm^2
V_{OC} = 581.2 mV, J_{SC} = 23.84 mA/cm^2,
FF = 72.8.



<LBIC> = 23.07 mA/cm^2
V_{OC} = 604.7 mV, J_{SC} = 30.304 mA/cm^2,
FF = 70.05

Summary of Activities

FTIR-reflection maps the properties of combinatorial-IZO films

Typical TCO Behavior

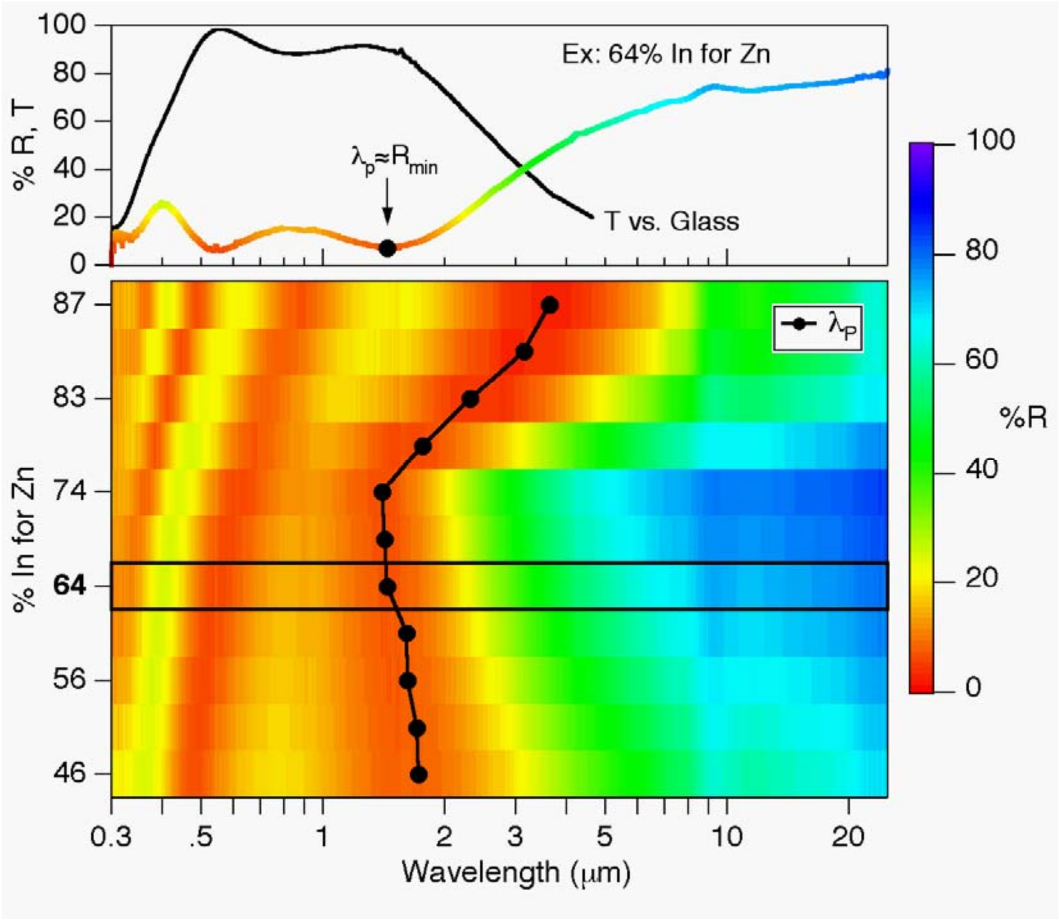
High IR Reflectivity

1.5µm < λ

Plasma Wavelength

$\lambda_p \sim R_{min}$

$\lambda_p \sim N^{-1/2}$



FTIR mapping capabilities

- R&T
- photoluminescence
- Raman scattering

Reflection Image Map

Summary of Activities

Multiple techniques are being developed for Si material quality evaluation using carrier lifetime measurements

- Our group has pioneered development of photoconductive decay techniques (RCPCD) for characterization of photoexcited carrier lifetime and material quality in c-Si and px-Si for PV.

- We have recently developed and tested 1-D and 2-D mapping of lifetime using RCPCD.

- We are currently studying the relationship between PL intensity and lifetime for PL lifetime mapping in Si wafers.

- We are examining the accuracy of microwave reflectivity lifetime measurements, as well as pump-probe free-carrier absorption techniques

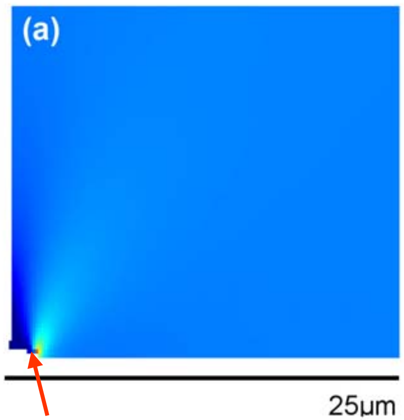
- NREL research-fellow emeritus Richard Ahrenkiel recently completed a 6 month study of lifetime measurement needs of the Si PV industry, which will guide our technique development work in this area.

Budget History

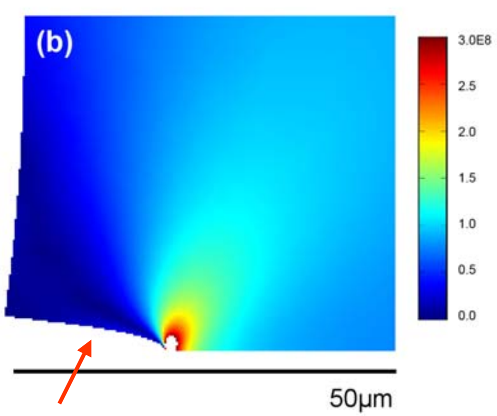
Project Task(s)	Total Value
PVA6.3101	1,692,000
PVB6.6131	200,000
PVA7.3101	340,850
Grand Total	2,232,850

Service contracts, equipment repair & calibration are not included. FY07 task list amount available on continuing resolution

Advanced the understanding of crack propagation and wafer breakage in Si wafers



2 µm microcrack



20 µm microcrack

- We have developed a new technique for screening wafers that have fatal cracks. In this technique, controlled stresses (representative of those experienced by a wafer during cell fabrication) are applied to a wafer to determine the propensity of the wafer for breakage.

- Because wafer breakage is directly related to the kinetics of microcrack propagation, we are developing a theoretical model, which can be used to investigate propagation of microcracks under various stress distributions that are prevalent in solar cell processing.

- The end result of this project will be a methodology that the PV industry can use to minimize wafer breakage.

Accomplishments

Metallization Firing and SiN:H Studies

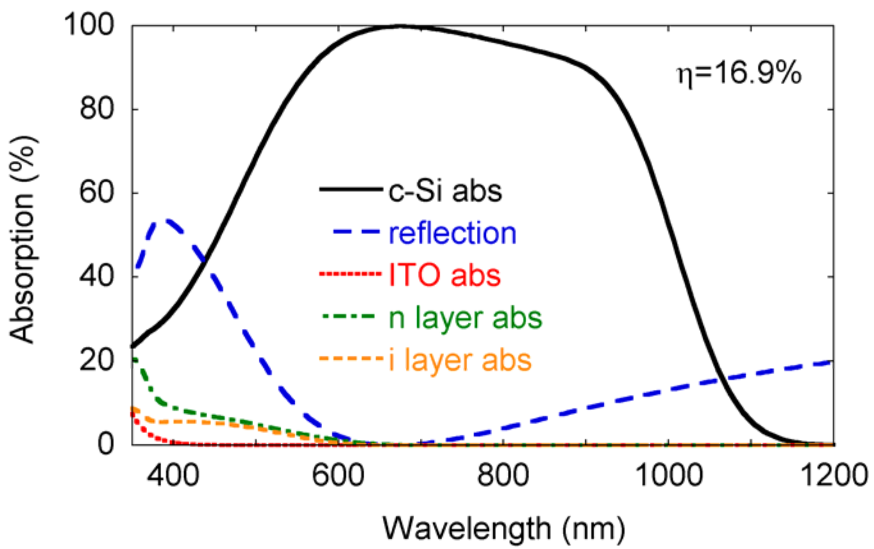
(in collaboration with BP Solar, Ferro, and Applied Materials).

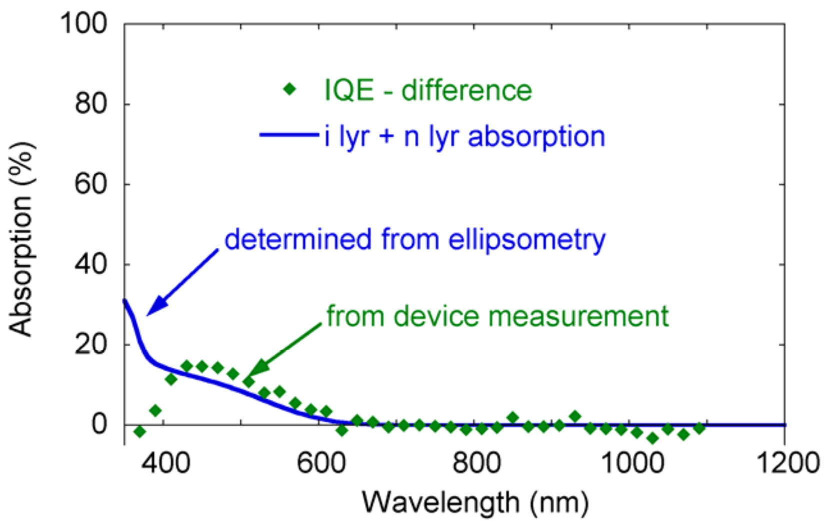
- We have built an optical processing furnace with a capability to exhaust effluent, monitor the temperature distribution of the entire solar cell using multiple thermocouples attached to the cell itself, and control the entire process cycle.
- Two important findings are:
  - For a given optical flux, screen-printed cells exhibit a large temperature difference between regions with and without front metallization. (812 °C, away from the buss bar, 786 °C under the buss-bar)
  - These temperatures are far below the eutectic point of Ag-Si (835^{o}C) and the melting point of Ag (961.9^{o}C), yet they yield low-resistance ohmic contacts.

Accomplishments

Helped to increase the efficiency of SHJ solar cells through use of SE for materials and device optimization

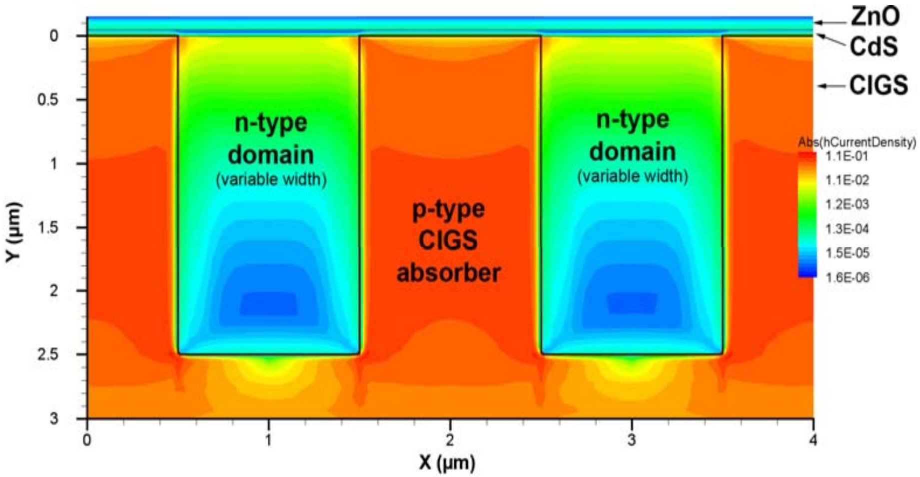
- In FY06 NREL's silicon materials and devices team achieved 18.2% efficiency on a p-type FZ wafer
- SHJ's present significant challenges for characterization because a-Si:H layers are so thin 3-5 nm, and properties are thickness- and substrate-dependent.
- We have used *in situ* and *ex situ* SE to study the growth process and characterize the optical and electronic properties of a-Si:H layers, providing input on optimizing device growth and processing.





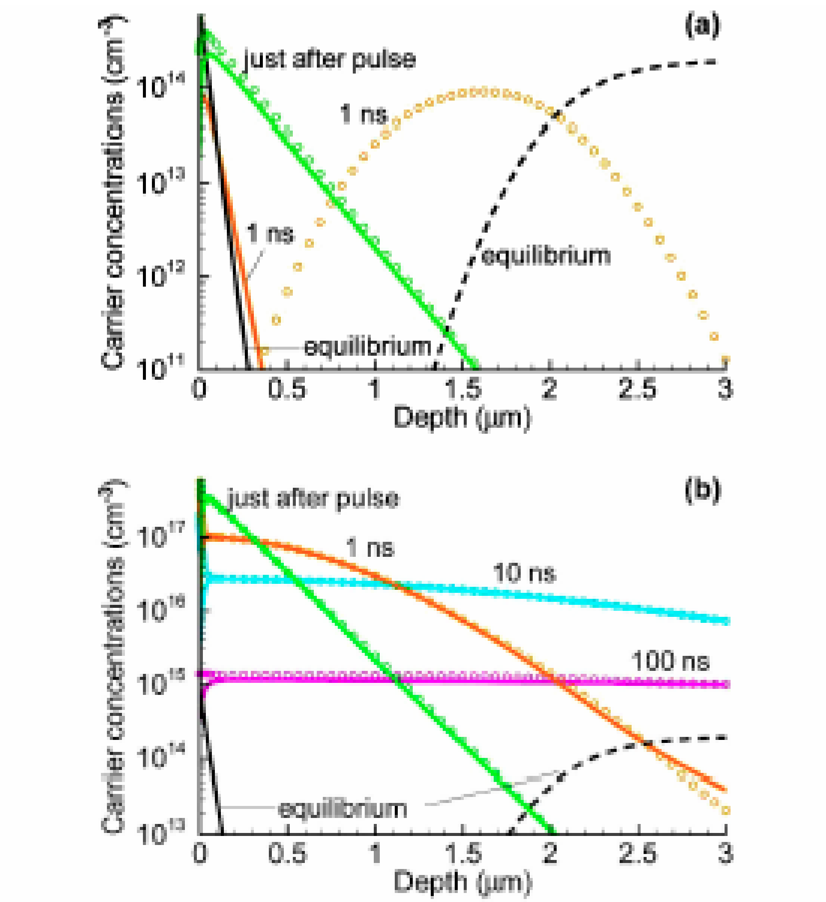
Accomplishments

Developed 2-D solar cell device models to elucidate limitations in crystalline and px- PV devices



• Researchers have recently proposed that nanodomains in CuInGaSe2 solar cells may form a three-dimensional network of p-n regions that separate charge, alter solar cell operation, and possibly improve device efficiency. We have constructed a 2D model of CIGS solar cells to investigate the implications of this theory.

Developed 2-D solar cell device models to elucidate limitations in crystalline and px- PV devices



- A 2D model of CdS/CdTe polycrystalline device has been used to track the complex carrier dynamics following a short laser pulse into a junction and indicates how lifetime measurements are affected by grain boundaries and surface recombination, and conversely, to what degree lifetime measurements can resolve the impact of these different recombination mechanisms on device performance.

Organized the 16th Workshop on Crystalline Silicon Solar Cell & Modules: Materials and Processes

- The Silicon Workshop helps the Si-PV industry by (1) bringing together the industry, research, and academic communities, (2) disseminating scientific and technical information, and (3) providing feedback to NREL/DOE on important research tasks, as perceived by the PV community.

- The workshop was attended by 157 scientists and engineers from 39 research institutions, DOE GO and HQ offices, and 34 international PV and semiconductor companies.

- This year's sessions reviewed recent advances in crystal growth technologies, impurities and defects in semiconductors, feedstock issues, solar cell processing, thin-film Si and heterojunction devices, solar cell metallization, and module reliability issues. The theme of the workshop—"**Getting More (Watts) for Less ($i)**"—reflected the growing need for maximizing the use of silicon to obtain the largest amount of PV energy.

Schedule of Major Events/Milestones

- **4/07 – Develop and implement a plan to support the TPP awardees that can be met with available resources.**
- **9/07 – Organize the 17th Workshop on Crystalline Silicon Solar Cell Materials and Processes; identify priority R&D issues for the Si PV industry**
- **9/07 – Establish a multi-dimensional computer model for mc-Si devices; assess value and limitation of model output.**
- **9/07 – Complete the study of the kinetics of micro-crack propagation and improve our understanding of how thermal profiling and mechanical stresses, associated with conventional processing, impact propagation.**
- **9/07 – Assess the technical shortcomings of minority-carrier lifetime measurement techniques used to determine material quality of mc-Si; apply improved understanding to facilitate better measurements of material quality for the PV industry; publish internal report.**
- **9/07 – Develop an *in situ* spectroscopic ellipsometry measurement and analysis capability for the TCO sputtering tool in the PDIL.**

Future Directions

- **Establish on-going collaborative R&D relationships with SAI TPP partners.**
  - **Working together is much more effective than 'sample in, sample out'**
- **Develop advanced multi-dimensional models for 1st, 2nd, and 3rd generation PV technologies**
- **Develop new measurement and characterization techniques in response to needs of the PV industry.**
  - **Electro-optical techniques are well-suited for in-line and *in situ***
- **Advance the science and understanding of lifetime measurement techniques for Si PV applications**
- **Develop *in situ* and in-line applications of spectroscopic ellipsometry**

Thank you for your attention