Solar cell inspection via photoluminescence imaging in the NIR/SWIR

Introduction

The use of photoluminescence (PL) imaging to inspect solar cells is a rapidly growing area of interest in the field of energy research. Recently, leading-edge groups in the United States, Germany, Japan, Australia, and Singapore have begun exploring the advantages of utilizing InGaAs focal plane arrays (FPAs) to characterize multicrystalline silicon (mc-Si) solar cells via PL imaging in the near infrared (NIR) and shortwave infrared (SWIR) spectral regions.

Unlike electroluminescence (EL) imaging, which relies on the detection of relatively bright signals and can only be employed at the final stage of solar cell manufacturing, low-signal PL imaging can be implemented throughout the entire manufacturing process.[1–3] See Figure 1.

PL imaging has great potential as an in-line monitoring tool. The ability to utilize this highly sensitive imaging technique during the early stages of the manufacturing process has significant ramifications, as PL images of ingots, bricks, and as-cut wafers can be predictive of final solar cell efficiency.

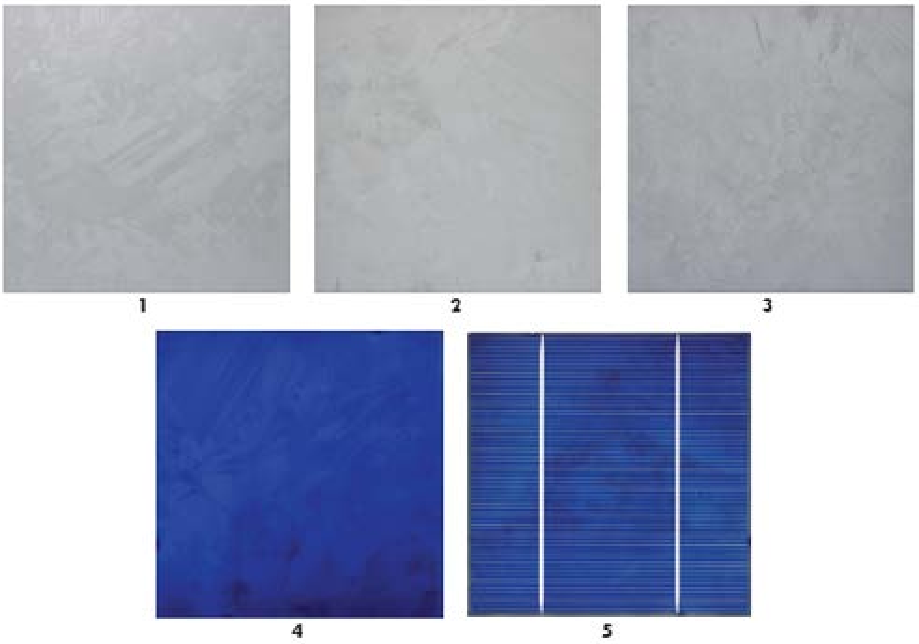


Figure 1.
PL imaging can be used to detect defects throughout the entire mc-Si solar cell manufacturing process. This series of wafer images, for instance,was acquired at the following stages: (1) as-cut, (2) after texturing, (3) after emitter diffusion, (4) after antireflective coatings deposition, and (5) after metallization.

PL imaging of mc-Si wafers

When 800 nm excitation light is applied to mc-Si wafers, electron-hole pairs generated by light photons recombine, causing photoluminescence emission. In the band-to-band (~1000 – 1200 nm) wavelength range for these wafers, the photoluminescence associated with defects (i.e., impurities or anomalous material compositions) is weaker due to the recombination of relatively fewer electron-hole pairs in the flawed regions. Therefore, defects are perceived as darker in band-to-band PL images (see Figure 2).

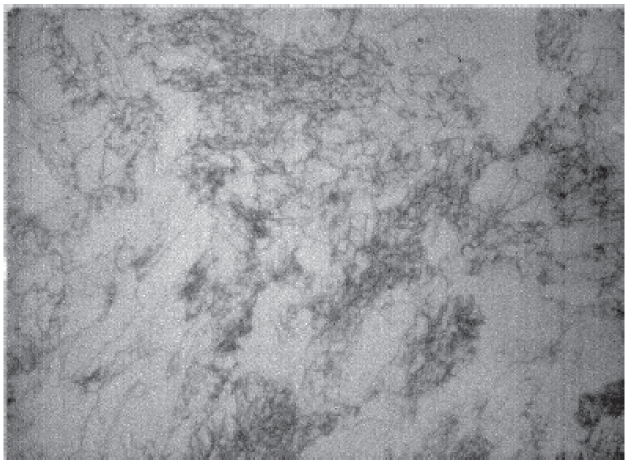


Figure 2.
Defects are visible as darker regions in band-to-band PL images of mc-Si wafers. Image acquired with a Princeton Instruments NIRvana:640 InGaAs FPA camera.

In the defect-band (~1300 – 1600 nm) wavelength range, however, the defect-related sub-bandgap emissions are stronger. Therefore, defects are easier to observe in defect-band PL images (see Figure 3).

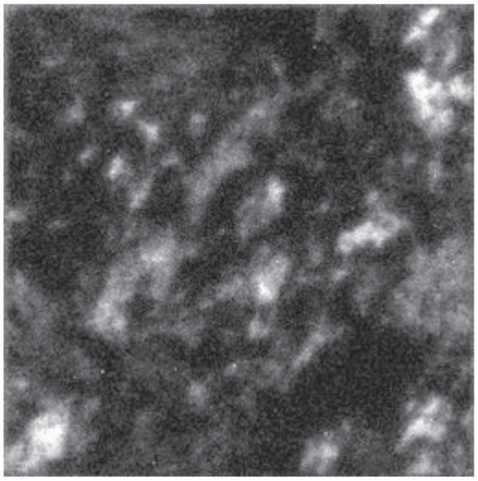


Figure 3.
In defect-band PL images of mc-Si wafers, the defects are visible as high-intensity regions. Image acquired with a Princeton Instruments NIRvana:640 InGaAs FPA camera.

www.princetoninstruments.com info@princetoninstruments.com
TOLL-FREE +1.877.474.2286 | PHONE +1 609.587.9797
Visit the Princeton Instruments website to find a dealer in your area.

PL imaging in the defect-band wavelength range holds great promise for better localization and identification of specific defects in mc-Si wafers.

InGaAs FPA and Si-CCD cameras

Scientific-grade cameras with silicon CCDs specially designed to boost sensitivity at NIR wavelengths, such as the Princeton Instruments PIXIS:1024BR (see Figure 4), are often utilized for broadband imaging of low-light-level photoluminescence in research labs. Over the past few years, back-illuminated, deep-depletion silicon CCD cameras have become the preferred tool for in-line PL imaging of mc-Si wafers due to the cameras' high resolution, relatively inexpensive cost, and acceptable – albeit less than ideal – quantum efficiency in the NIR.

Figure 4.
The PIXIS:1024BR from Princeton Instruments utilizes a backilluminated, deep-depletion silicon CCD with megapixel resolution to improve sensitivity in the NIR region of the spectrum. This camera system is particularly useful for PL imaging of mc-Si wafers.

Although Si-CCD camera systems are currently used for offline and in-line inspection, their "low to no" quantum efficiency in the band-to-band wavelength range necessitates long exposure times for defect detection. To overcome this inherent technology limitation, a number of research labs have begun using camera systems featuring InGaAs FPAs to perform PL imaging of mc-Si ingots, bricks, wafers, and solar cells. InGaAs FPAs deliver quantum efficiency superior to that of Si-CCDs at wavelengths above 900 nm (see Figure 5).

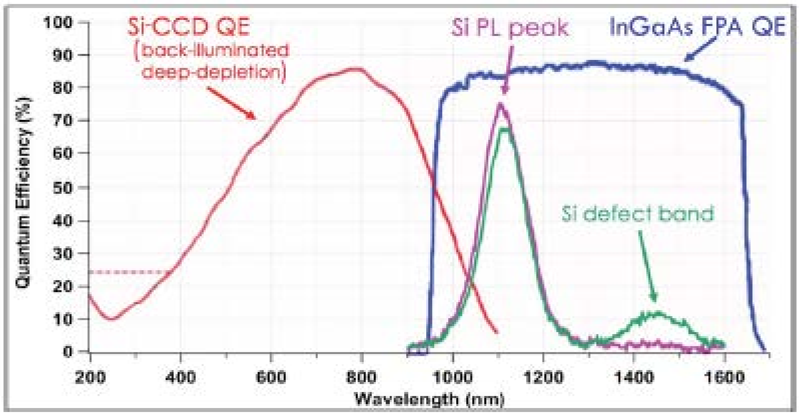


Figure 5.
This graph presents relevant photoluminescence emission wavelengths as well as the quantum efficiencies of both an InGaAs FPA and a back-illuminated, deep-depletion silicon CCD.

www.princetoninstruments.com info@princetoninstruments.com
TOLL-FREE +1.877.474.2286 | PHONE +1 609.587.9797
Visit the Princeton Instruments website to find a dealer in your area.

Table 1.

(Above)The utility of InGaAs FPA cameras and back-illuminated, deep-depletion silicon CCD cameras for photoluminescence imaging is compared across several key parameters.

Scientific-grade InGaAs FPA cameras offer ideal response characteristics above 900 nm for PL imaging of mc-Si. These cameras can allow defects to be detected during early stages of the manufacturing process (e.g., via PL imaging of as-cut wafers or NIR/SWIR transmission imaging of ingots) while also increasing the speed at which inspection is performed (i.e., by cutting the required length of exposure times). See Table 1.

InGaAs FPA vs. Back-Illuminated, Deep-Depletion Silicon CCD Cameras for Photoluminescence Imaging									
	QE	R&D Work <1100	Ingot Imaging	Off-Line Inspection	In-Line Inspection	As-Cut Wafer Imaging		Cost	Dark Current
	>800 nm - <1100 nm					Band-to-Band	Defect Band		
InGaAs FPA	High	Ideal	Ideal	Ideal	Ideal	Excellent	Excellent	High	Adequate
Si-CCD	Adequate	Adequate	Not Suitable	Adequate	Adequate	Adequate	Not Suitable	Low	Ideal

Dr. Steven Johnston, a research scientist at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, continues to use a PIXIS:1024BR Si-CCD camera for band-to-band PL imaging in order to characterize solar cells for quality, but has also started utilizing the superb NIR/SWIR quantum efficiency of an InGaAs FPA camera system in his lab (see Figure 6).

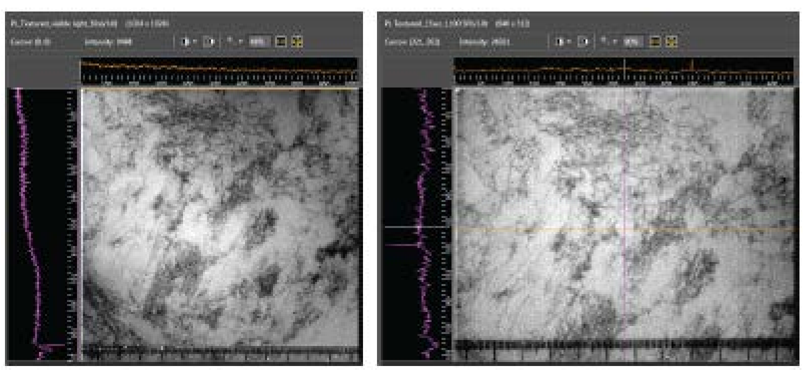


Figure 6.

(Right) Band-to-band PL images of mc-Si wafers utilizing a Princeton Instruments PIXIS:1024BR back-illuminated, deep-depletion silicon CCD camera (left) and a Princeton Instruments NIRvana:640 InGaAs FPA camera (right).

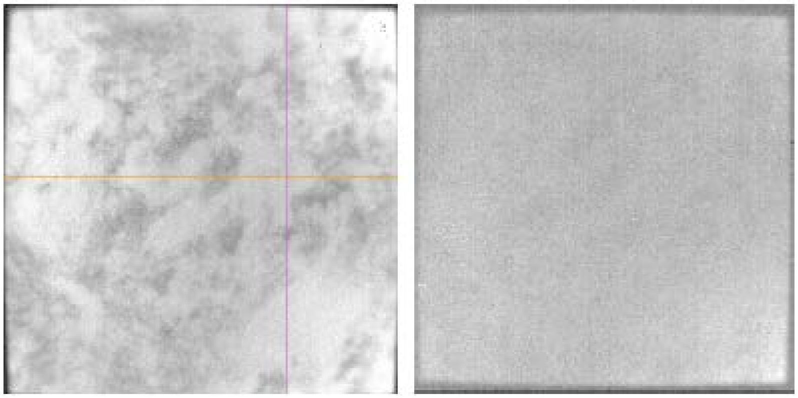
www.princetoninstruments.com info@princetoninstruments.com
TOLL-FREE +1.877.474.2286 | PHONE +1 609.587.9797
Visit the Princeton Instruments website to find a dealer in your area.

Figure 7.
The Princeton Instruments NIRvana:640 is a new InGaAs camera that features a 640 x 512 FPA cooled to -85°C.

InGaAs FPA cameras, such as the new Princeton Instruments NIRvana:640*, will play a key role in PL imaging within the defect-band wavelength range (see Figure 3). As the world's first scientific-grade, deep-cooled, large-format InGaAs camera system for low-light-level NIR/SWIR imaging and spectroscopy applications, the NIRvana™ (see Figure 7) features a 640 x 512 InGaAs FPA with response up to 1.7 µm.

The NIRvana:640 camera's InGaAs FPA is Peltier cooled to -85°C to minimize thermally generated noise (dark noise), thus providing higher signal-to-noise ratios (see Figure 8). Its outstanding sensitivity in the NIR/SWIR also shortens the exposure times required for PL imaging, which is critical for achieving optimal throughput in the manufacturing process.

Figure 8.
The PL image on the left was acquired using a deep-cooled Princeton Instruments NIRvana:640 InGaAs FPA camera system, which enables flexible exposure times up to 60 sec. The PL image on the right was acquired using a video-rate InGaAs FPA camera system without cooling, which limits exposure times to tens of milliseconds.



Most important, Dr. Johnston explains that his lab has observed linear correlations between defect-band PL images from as-cut wafers (as well as from wafers after several other processing stages) and final solar cell efficiencies. By using a technique in which the count of image pixels above an established threshold is compared to the total number of pixels in the PL image, the group is able to derive a defect area fraction for each wafer. The resultant defect percentage from each stage demonstrates a linear correlation with the finished solar cell's efficiency.

Not only can defect-band PL imaging at early stages of the manufacturing process predict final solar cell efficiency, Dr. Johnston notes, the data can also be utilized to sort incoming wafers and direct them to various specially designed processing lines in order to optimize the finished solar cells' performance.

www.princetoninstruments.com info@princetoninstruments.com
TOLL-FREE +1.877.474.2286 | PHONE +1 609.587.9797
Visit the Princeton Instruments website to find a dealer in your area.

To further facilitate the accurate determination of defect specifics, Dr. Johnston intends to use narrowband filters at 50 nm increments from 1300 to 1600 nm, an approach discussed by Dr. Michio Tajima (ISAS/JAXA, Japan) at a recent conference.[4] He adds that another possible experimental protocol, namely, cooling mc-Si wafers for testing purposes, may also yield enhanced information concerning individual defects.

Conclusion

Newly available scientific-grade, deep-cooled, large-format InGaAs FPA cameras such as the NIRvana from Princeton Instruments will enable researchers to observe photoluminescence emission at longer (i.e., SWIR) wavelengths and rapidly obtain more detailed information about defects within multicrystalline silicon solar cells.

The ability to quickly acquire PL imaging data in the defect band between 1300 and 1600 nm at any stage of the manufacturing process is expected to aid in the clearer identification of a specific defect's material composition or impurity. This data could also be utilized to better inform process modifications aimed at eliminating defects and improving the efficiency of individual solar cells.

In this way, PL imaging in the NIR/SWIR via state-of-the-art InGaAs FPA cameras can help increase yield as well as reduce manufacturing costs.

Back-illuminated, deep-depletion silicon CCD cameras such as the Princeton Instruments PIXIS:1024BR, meanwhile, continue to offer superb resolution and sufficient quantum efficiency for cost-effective PL imaging at shorter NIR wavelengths.

Princeton Instruments is the only company that provides both deep-cooled InGaAs FPA and silicon CCD cameras suitable for advanced PL imaging applications in the research lab and on the manufacturing floor.

www.princetoninstruments.com info@princetoninstruments.com
TOLL-FREE +1.877.474.2286 | PHONE +1 609.587.9797
Visit the Princeton Instruments website to find a dealer in your area.

References

1. S. Johnston, F. Yan, M. Al-Jassim, K. Zaunbrecher, O. Sidelkheir, and A. Blosse, “Imaging study of multi-crystalline silicon wafers throughout the manufacturing process”, Preprint, Presented at the 37th IEEE Photovoltaic Specialists Conference (PVSC 37), Seattle, Washington, June 19-24, 2011.

2. F. Yan, S. Johnston, M. Al-Jassim, K. Zaunbrecher, O. Sidelkheir, and A. Blosse, “Defect-band emission photoluminescence imaging on multicrystalline Si solar cells”, Preprint, Presented at the 37th IEEE Photovoltaic Specialists Conference (PVSC 37), Seattle, Washington, June 19-24, 2011.

3. T. Trupke and W. McMillan, “Photovoltaics: Photoluminescence imaging speeds solar cell inspection”, Laser Focus World, December 2010.

4. M. Tajima, T. Iwai, Y. Iwata, F. Okayama, K. Tanaka, and H. Toyota, “Impurity and defect analysis in solar cell Si by photoluminescence spectroscopy and topography”, Presented at the MRS Technology Development Workshop: Photovoltaic Materials and Manufacturing Issues II, Denver, Colorado, October 4-7, 2011.

Resources

For more information about InGaAs FPA and silicon CCD cameras from Princeton Instruments, please visit www.princetoninstruments.com.

www.princetoninstruments.com info@princetoninstruments.com
TOLL-FREE +1.877.474.2286 | PHONE +1 609.587.9797
Visit the Princeton Instruments website to find a dealer in your area.

Princeton Instruments