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Steve Johnston, Fei Yan, Mowafak Al-Jassim
National Renewable Energy Laboratory

Katherine Zaunbrecher
National Renewable Energy Laboratory and Colorado State University

Omar Sidelkheir and Kamel Ounadjela
Calisolar

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Quality Characterization of Silicon Bricks using Photoluminescence Imaging and Photoconductive Decay

Steve Johnston,[1] Fei Yan,[1] Katherine Zaunbrecher,[1,2] Mowafak Al-Jassim,[1] Omar Sidelkheir,[3] and Kamel Ounadjela[3]

[1]National Renewable Energy Laboratory; 15013 Denver West Parkway; Golden, CO 80401, USA
[2]Colorado State University; Fort Collins, CO 80526, USA
[3]Calisolar; 985 Almanor Ave.; Sunnyvale, CA 94085, USA

***Abstract* — Imaging techniques can be applied to multicrystalline silicon solar cells throughout the production process, which includes as early as when the bricks are cut from the cast ingot. Photoluminescence (PL) imaging of the band-to-band radiative recombination is used to characterize silicon quality and defects regions within the brick. PL images of the brick surfaces are compared to minority-carrier lifetimes measured by resonant-coupled photoconductive decay (RCPCD). RCPCD is a transient photoconductive decay technique that monitors the recombination of excess carriers using a frequency of about 420 MHz. Carriers are excited by nanosecond laser pulses of long-wavelength light in the range of 1150 nm. The low frequency and long penetration depth of light promote measurement of carriers away from the surface such that lifetimes of up to 100 μs are measured in upgraded-metallurgical-grade silicon, and up to 200 μs in electronic-grade silicon bricks. PL intensity shows correlation to lifetime in addition to the valuable spatial information from top to bottom of the brick and defect regions throughout the brick.**

***Index Terms* — photoluminescence, imaging, infrared imaging, charge-carrier lifetime, photoconductivity, photovoltaic cells, silicon, impurities.**

I. Introduction

Imaging techniques can rapidly characterize material quality and defect density. Photoluminescence (PL) imaging can be applied to silicon from the brick level to all wafer process steps [1–11]. At the brick level, material thickness allows for measurement and correlation to lifetime where surface recombination effects are minimized [6–7]. PL images of the brick can be used to calculate lifetime [7, 10], or separate lifetime measurements can be performed. The lifetime can be mapped to give some spatial resolution, or the lifetime can be correlated at limited points to the PL image to generate a high-resolution lifetime image in minimal time [7, 11].

II. Experiment

Band-to-band PL imaging is collected using a Princeton Instruments Pixis 1024BR Si charge-coupled-device (CCD) camera cooled to about -50°C. The light source is composed of four 30-W, 810-nm laser diodes with engineered diffusers to spread out the light over the brick's area. The intensity is near that of one sun, or ~100 mW/cm^2. Figure 1 shows the PL imaging system configured to collect an image on the side of a multicrystalline Si brick.

Fig. 1. Photograph of the PL imaging system showing the camera, four laser diode outputs for optical excitation, and a Si brick as the subject of the imaging.

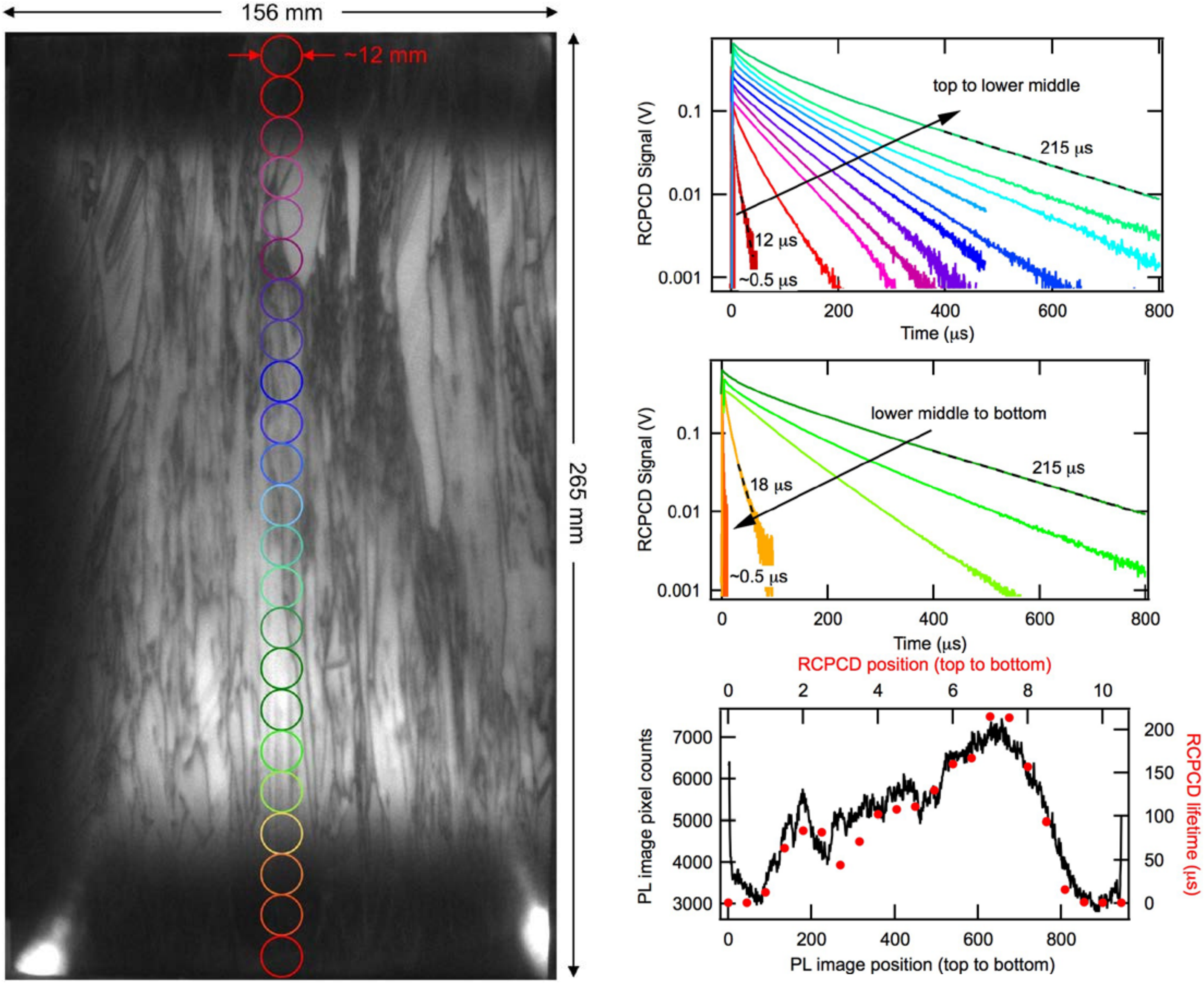

Fig. 2. PL imaging of a brick face (left image). Lifetime decay curves are shown in the right column.

We have collected PL images on multicrystalline silicon bricks that are 156 mm x 156 mm and roughly 27 cm tall. No surface-passivation treatment is applied for either the imaging or lifetime measurements. An example of a brick PL image is shown in Fig. 2. This brick is from the corner of a cast ingot, and the image is of the face where the left edge is an outside edge of the ingot. The image shows how PL intensity decreases at the bottom, side, and top regions due to impurities diffusing into the silicon from the crucible and impurities segregating to the top during cooling. The network of dark lines within the bulk of the brick correspond to dislocation networks and grain boundaries that propagate during the casting process. These defect clusters contain extended defects that can accumulate impurities and form precipitates. All of these dark defect regions have low PL emission due to the high recombination of carriers through other non-radiative defect states. The image shows two bright streaks from the bottom corners that extend toward the center due to strong reflections of the excitation light. These artifacts of the imaging could likely be reduced or eliminated with improved excitation lighting configuration.

The PL image of the brick surface is compared to minority-carrier lifetimes measured by resonant-coupled photoconductive decay (RCPCD) [12]. RCPCD is a transient photoconductive decay technique that monitors the recombination of excess carriers using a frequency of about 420 MHz. A photograph of the RCPCD excitation coil near the silicon brick is shown in Fig. 3. Carriers are excited by nanosecond laser pulses of long-wavelength light near 1150 nm. The light travels through the hole in the box and through the coil, which is positioned roughly 1 mm from the brick. The low frequency and long penetration depth of light promote

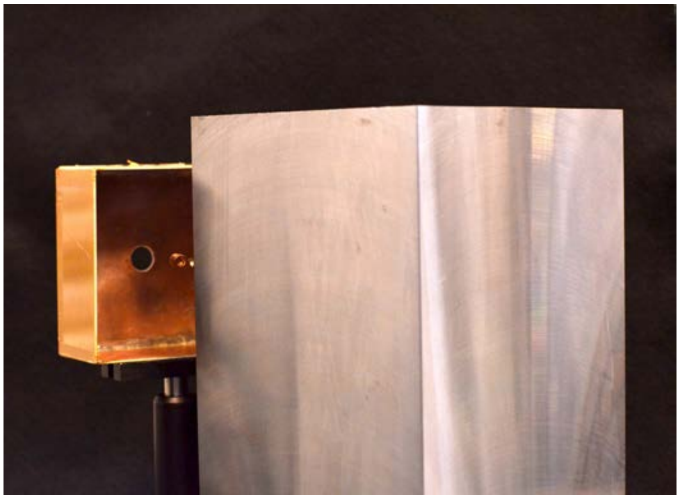

Fig. 3. Photograph of the RCPCD coil antenna near a silicon brick.

measurement of carriers away from the surface such that lifetimes are dominated by bulk recombination after initial surface recombination takes place. Absorption of 1150-nm wavelength light in silicon and penetration of 420-MHz radiation into typical 10^{16} cm^{-3} doping give a measurement depth of 3 to 5 mm from the surface of the brick. The measurement carrier frequency has adequate bandwidth to resolve decay rates down to about 50 ns.

On the brick image shown in Fig. 2, colored circles indicate the RCPCD measurement area (12-mm diameter spot) and steps of 12 mm from top to bottom. The photoconductive decay curves are plotted on a logarithmic scale such that a linear fit of slope is the exponential decay time constant, or carrier lifetime. This transient decay gives a direct measurement of lifetime that does not require assumptions about photo-generation or measurement of light intensity, as do techniques based on measured photoconductivity [13]. The plots of Fig. 2 show various decay curves from top to bottom of the brick. The fits are made at lower injection levels after initial surface recombination no longer dominates the decay curve. At the top edge, the decay times are very short, leading to lifetimes less than 1 µs. The top plot shows how lifetimes increase from the top edge toward the center of the brick. The middle plot then shows how lifetimes, after reaching their peak in the lower middle portion of the brick, then become shorter again toward the bottom edge of the brick. Lifetimes of up to ~200 µs are measured in this electronic-grade silicon brick, whereas lifetimes of up to ~100 µs are more typical for upgraded metallurgical-grade, or solar-grade, silicon. In the bottom plot of Fig. 2, the PL intensity down the center of the brick is plotted on the left axis, while the measured carrier lifetime values are plotted on the right axis. The scales of each axis are adjusted to show correlation and account for background counts in the image. Using the axes scales, a linear factor can be calculated and used to convert the PL image to a minority-carrier lifetime image, as shown in Fig. 4. This results in a high-resolution lifetime image [6–7] that can be acquired quickly based on 1-minute or less PL exposure times and a few seconds for RCPCD measurement points to correlate the image to lifetime. Large variations of doping may need to be accounted for separately, because the PL, in addition to excess carrier density, is also proportional to doping [9, 11]. Overall, PL intensity shows correlation to lifetime and provides valuable spatial information from top to bottom of the brick and for defect regions seen throughout the surfaces of the brick.

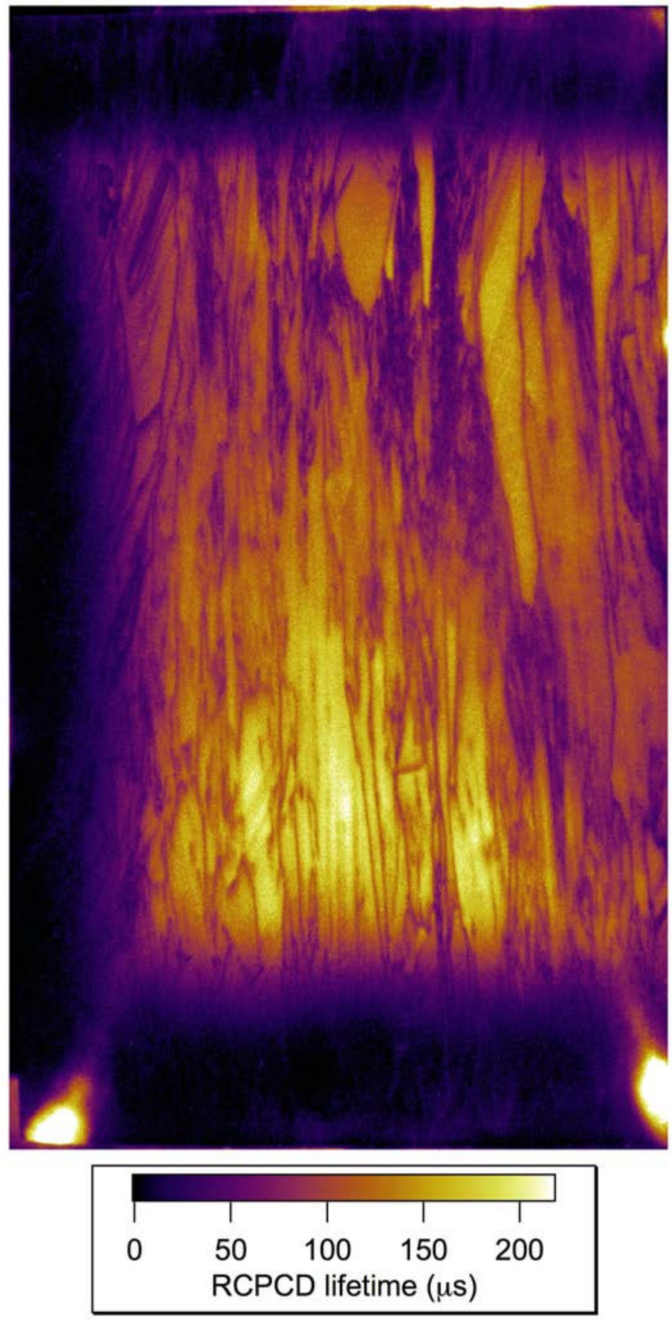

Fig. 4. The PL image is converted to a lifetime image through correlation to RCPCD-measured minority-carrier lifetimes.

Another example of characterizing Si brick lifetimes by imaging and mapping is shown in Fig. 5. This brick is from the edge of an ingot where one side has increased impurities due to diffusion from the crucible during casting. The bottom quarter had been cropped off due to poor quality, but the pieces were placed back together for the imaging and mapping measurements. The top row shows PL images of each face of the brick, and each face was also scanned to measure RCPCD along the center line as was shown in Fig. 2. The color scale indicates values of lifetime as measured by RCPCD and correlated to the PL. Lifetime values of up to 70–80 μs were measured by RCPCD. This brick is 265 mm tall, and so, with the camera's 1024 x 1024 CCD array, the resolution is roughly 260 μm per pixel. Artifacts of strong reflections are shown at the bottom corners, as were seen in Fig. 2.

The middle row of Fig. 5 shows microwave-reflection photoconductive decay (μ-PCD) lifetime maps measured on a Semilab system. The Semilab system uses a carrier frequency of 10 GHz and an excitation wavelength of 950 nm, so the depth of measurement is only about 0.5 mm from the surface into the brick. The small excitation spot size of about 1-mm diameter provides for fairly good spatial resolution. Using 0.5-mm steps, the lifetime mapping requires about 45 minutes

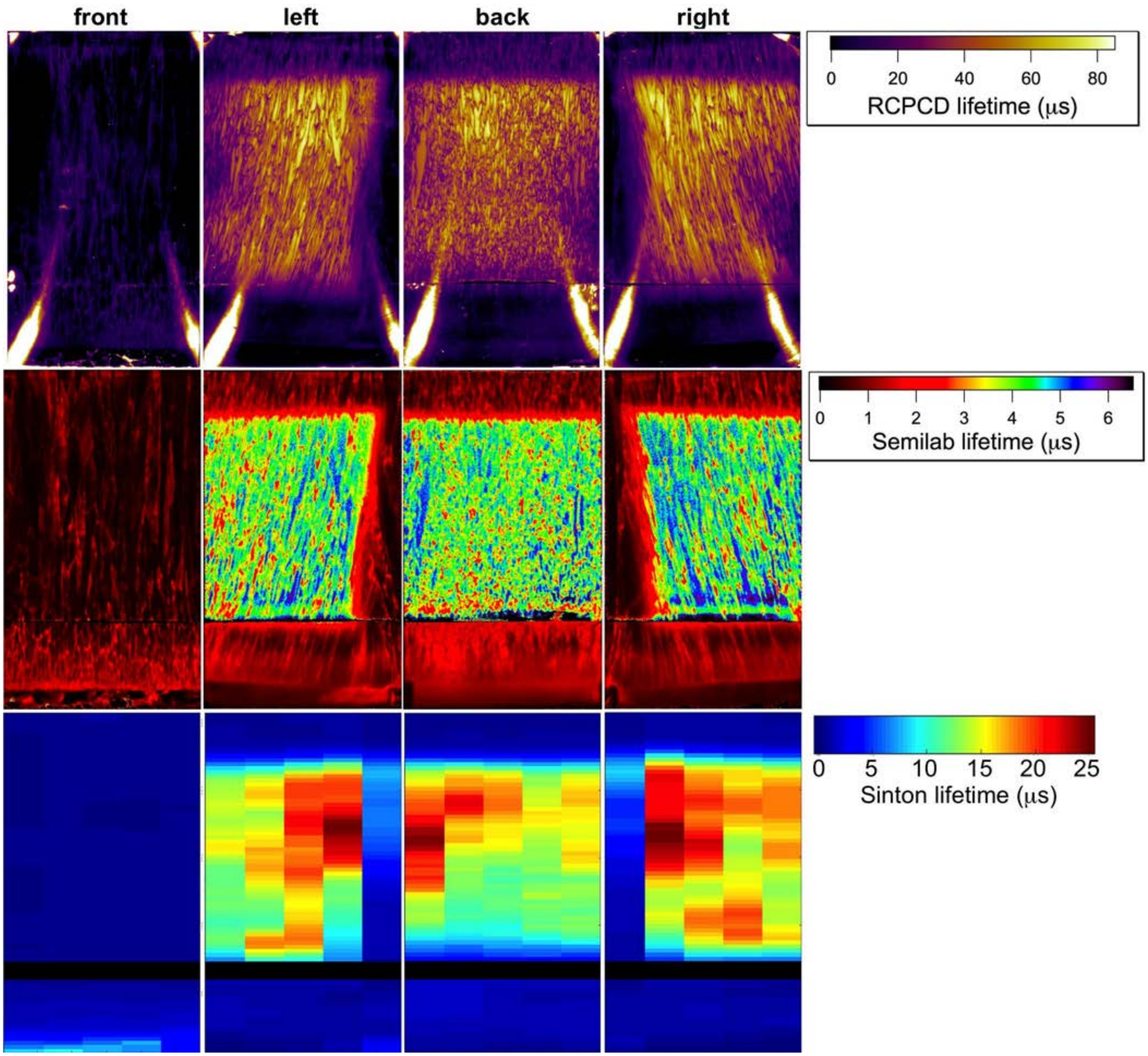

Fig. 5. Lifetime maps of the four side-faces of a Si brick. The top row shows PL imaging that is converted to lifetime values through correlation to RCPCD lifetime scans down the center of each face. The middle row shows lifetime maps acquired using a Semilab microwave reflection photoconductive decay system. The bottom row shows lifetime maps from a Sinton Instruments brick lifetime measurement system.

for each side. However, because the penetration depth of the measurement is lower, the recombination of carriers is greatly affected by the surface, and the measured, or effective, carrier lifetimes are shorter [11]. The highest lifetimes on this brick reported by the Semilab tool are about 6 μs.

The bottom row of Fig. 5 shows lifetime maps acquired from a Sinton Instruments brick lifetime measurement system using the quasi-steady-state photoconductance (QSSPC) measurement technique [13]. This system uses a sensor with a 4 mm x 30 mm coil to define the measurement area, and the entire brick was scanned with five sweeps. The Sinton system uses filtered light so that it is predominantly in the infrared, and it has a depth sensitivity of about 2.5 mm. Although this depth sensitivity of QSSPC exceeds that of the Semilab μ-PCD, unpassivated surfaces are reported to still have a strong effect on the measurement results [13]. The maximum measured lifetimes of about 25 μs are lower than those of 70–80 μs measured by the transient-based RCPCD technique. This is a similar result to a brick lifetime comparison of QSSPC and transient modes reported previously [13].

III. Conclusion

Photoluminescence images on silicon bricks can be correlated to lifetime measured by photoconductive decay and could be used for high-resolution characterization of material before wafers are cut. The RCPCD technique has shown the longest lifetimes of any of the lifetime measurement techniques we have applied to the bricks. RCPCD benefits from the low-frequency and long-excitation wavelengths used. In addition, RCPCD is a transient technique that directly monitors the decay rate of photoconductivity and does not rely on models or calculations for lifetime. The measured lifetimes over brick surfaces have shown strong correlations to the PL image intensities; therefore, this correlation could then be used to transform the PL image into a high-resolution lifetime map.

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