Evaluation of Four Imaging Techniques for the Electrical Characterization of Solar Cells

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Outline

• Introduction – development of techniques

• Minority-Carrier Lifetime
  • Photoconductive Decay
    1) Photoluminescence (PL) Imaging
    2) Carrier Density Imaging (CDI)

• Diffusion Length – Finished Cells
  3) Electroluminescence (EL) Imaging

• Shunt Detection – Finished Cells
  4) Dark Lock-In Thermography (DLIT)

• Summary
Development of mapping & imaging

**Microwave Conductivity Decay** (lifetime in Ge; 1959)

_Semiconductor Physics Laboratory, Inc. (Semilab)_ 1989, >700 systems.

**Quasi-Steady-State Photoconductance**


**Photoluminescence in Si**


Then imaging, T. Trupke, R. Bardos, et al. ~2006.

_BT Imaging_, 2008

**Carrier Density Imaging:** S. Glunz, W. Warta, et al. first mapping with detector since mid-1990s, then camera imaging, M. Bail et al. in 2000.

_AESCUSOFT GmbH Automation_, 2002; with alliance partner: Fraunhofer Institute for Solar Energy Systems

**Electroluminescence Imaging:** T. Fuyuki et al. 2005

**Shunt Imaging:** Breitenstein, O. since mid-1990s

_AESCUSOFT GmbH Automation_, 2002
Lifetime Measurements by μ-PCD

• A pulse of laser light creates excess carriers

• The increased carriers change the conductivity of the semiconductor

• Microwave reflection is dependent on the conductivity of the semiconductor

• Measure the time constant of the decay in conductivity

\[ R = - \frac{d\delta n}{dt} = \frac{\delta n}{\tau} \]
\[ \delta n = \delta n_0 e^{-t/\tau} \]
Photoconductive decay transients on silicon sample

Excitation wavelength ≈ 1000 nm
Injection level ≈ 10^{16} \text{ cm}^{-3}
Semilab Lifetime Mapping
Photoluminescence (PL) Imaging

• Excite excess carriers with light, $h\nu > E_g$ (810 nm), use filters to block reflections.
• Measure PL, i.e. portion of recombination that is radiative recombination, $h\nu \sim E_g$ (~1150 nm).
• Si CCD camera cooled to -75°C.
• 1024 x 1024 array of 13 $\mu$m square pixels.
p-type CZ Si, 200 Ω-cm, ~6x10^{13} \text{ cm}^{-3}, 310 \ \mu\text{m} \ \text{thick}

Image acquired in as little as 1 second, longer for shorter lifetimes and poor surface passivation
mc-Si with thermal oxide

Semilab map

PL image
n-type, CZ, 1-10 Ω-cm, \(\sim 10^{15} \text{ cm}^{-3}\), 500μm, both sides polished
Carrier Density Imaging

- InSb infrared camera cooled to ~76 K
- Spectral response from 3.6 to 5.1 μm
- 640 x 512 array of 15 μm square pixels
- 100 Hz frame rate
- Lock-in detection, similar to averaged subtractions of dark background image from lit absorption image

- Free carrier absorption or emission of infrared radiation
- For absorption, hot plate is black body source:
  - high emissivity with flat black high-temperature paint,
  - ~50° to 100°C
  - Square pulse 1-30 Hz
  - ~30 W of 810nm laser diode excitation
p-type CZ Si, 200 $\Omega$-cm, $\sim 6 \times 10^{13}$ cm$^{-3}$, 310 $\mu$m thick

Image acquired in approximately 15 seconds, ($\sim$ 1 sun intensity of light turned on and off at $\sim$ 20 Hz, camera: 100 frames per second), longer acquisition time for shorter lifetimes and poor surface passivation

PL image

CDI (IR) image
n-type, CZ, 1-10 Ω-cm, ~10^{15} \text{ cm}^{-3}, 500 \mu\text{m}, \text{both sides polished}

Semilab lifetime map

Lifetime to CDI correlation

Carrier Density Image (IR camera)
Electroluminescence Imaging

- Si CCD camera cooled to -75°C
- 1024 x 1024 array of 13 μm square pixels
- Collect PL when forward biasing the cell
- With sample and camera in dark, and no filters, EL data collection in ~1 sec.
EL – diffusion length comparison

Electroluminescence, 1 s exposure time

Semilab – LBIC scan, ~12 hour scan time, collect reflection, IQE data, too
EL and LBIC comparison

Electroluminescence: 700mV forward bias

Semilab: LBIC

Efficiency

- ~13%
- ~14%
- ~15%
Dark Lock-in Thermography

Sense heat due to current flowing in shunts

- InSb infrared camera cooled to ~76 K
- Spectral response from 3.6 to 5.1 μm
- 640 x 512 array of 15 μm square pixels
- 100 Hz frame rate
- Lock-in detection, similar to averaged subtractions of dark, no-bias background image from biased image
- Use ~1 to 30 Hz for bias pulses
- Total acquisition time of few to ~30 s
- Varying bias for shunt characterization
  - Ohmic-type, Schottky-type, pre-breakdown, and recombination-induced
DLIT for shunting characterization

Characterize shunts using varying voltage and frequency

Zoom in using telescope lens with ~5 μm resolution
Process-Induced Cracking
Schottky-Type Shunts

SEM images
Aluminum Particles

SEM images
Summary

• **Photoluminescence Imaging** uses Si CCD camera
• **Infrared Carrier Density Imaging** uses IR camera
  - Both show good correlation to Semilab microwave reflection lifetime
• **Electroluminescence** compares to LBIC diffusion length maps
• IR camera for **shunt detection** and cell characterization
• Industry has shown interest in these imaging techniques due to their fast measurement speed for characterization and possibly in-line process control.

![Diagram](image.png)

- wafer
- Lifetime image
- surface passivation
- annealing
- Lifetime image
- cell
- Lifetime image

~150mm x 150mm