National Renewable Energy Laboratory
Innovation for Our Energy Future

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

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Steve Johnston
Greg Berman
Nathan Call
Richard Ahrenkiel

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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

Sinton Consulting, Inc. 1992, >200 systems.

Photoluminescence in Si

First mapping: S. Ostapenko, I. Tarasov, J. Kalejs, et al., 1999; M. Tajima et al. 2004;

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

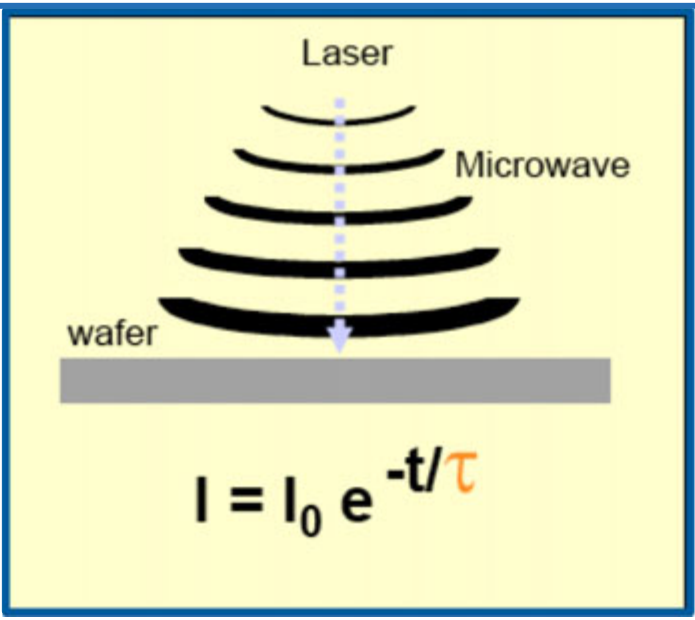
Lifetime Measurements by μ-PCD

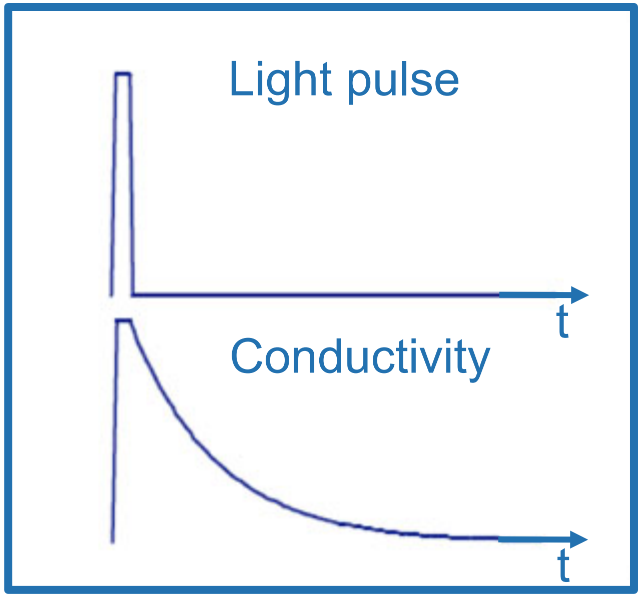
- A pulse of laser light creates excess carriers

- 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

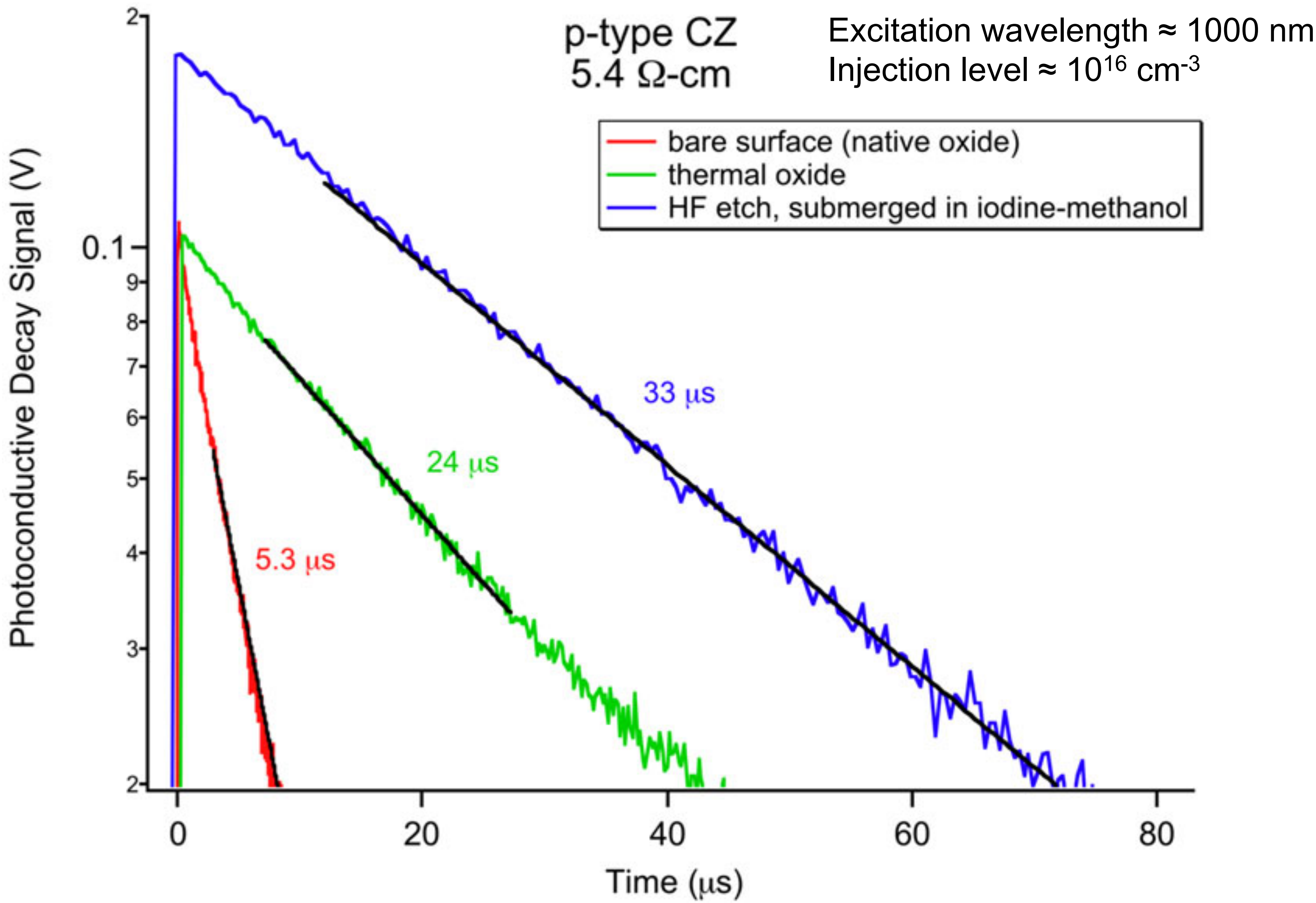




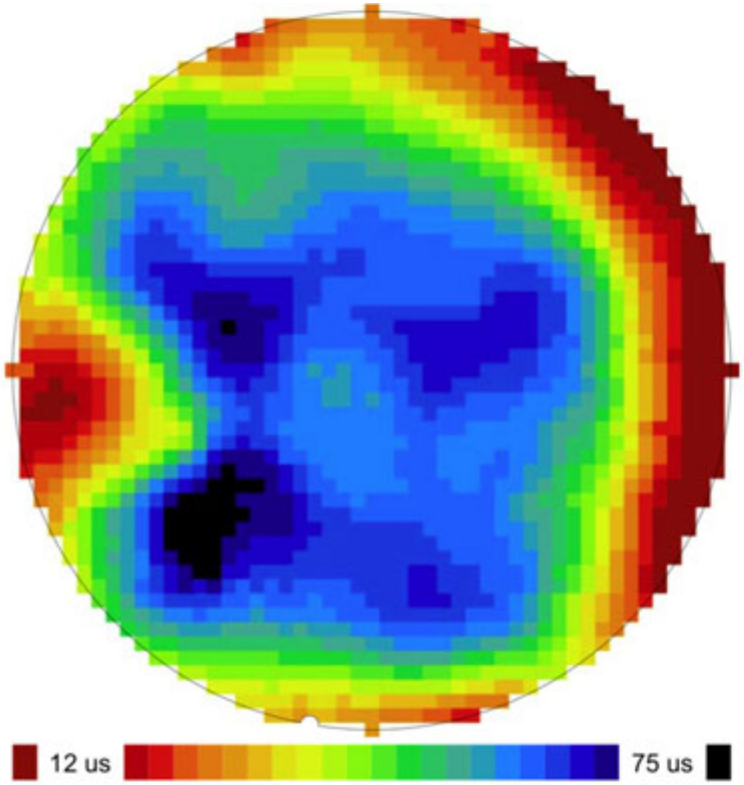
$$R = -\frac{d\delta n}{dt} = \frac{\delta n}{\tau}$$

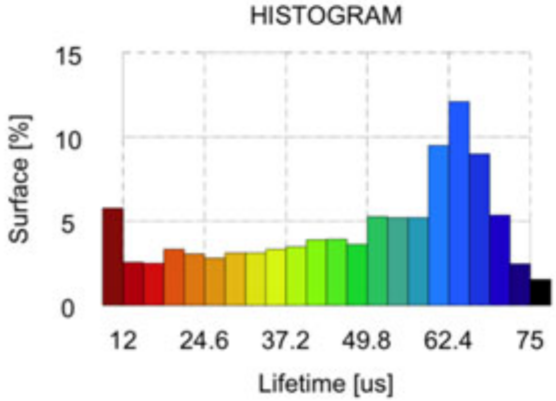
$$\delta n = \delta n_o e^{-t/\tau}$$

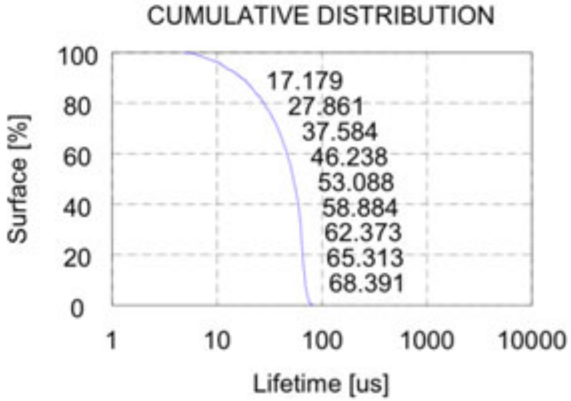
Photoconductive decay transients on silicon sample



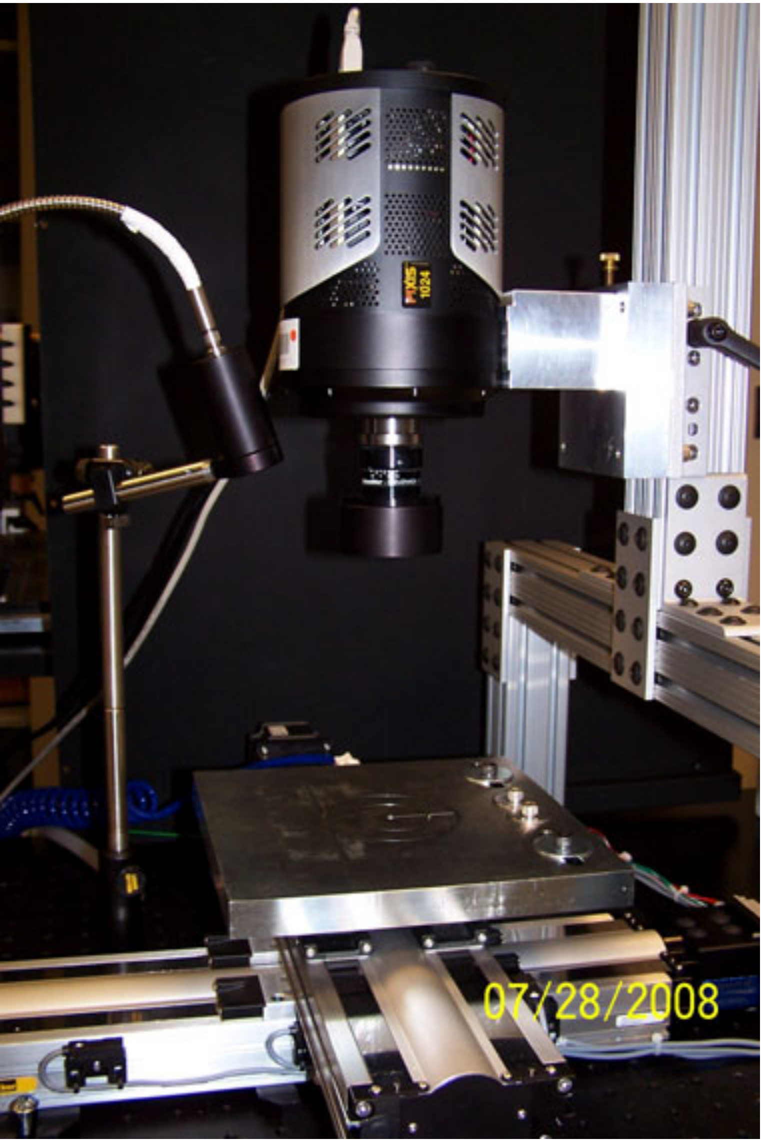
Semilab Lifetime Mapping



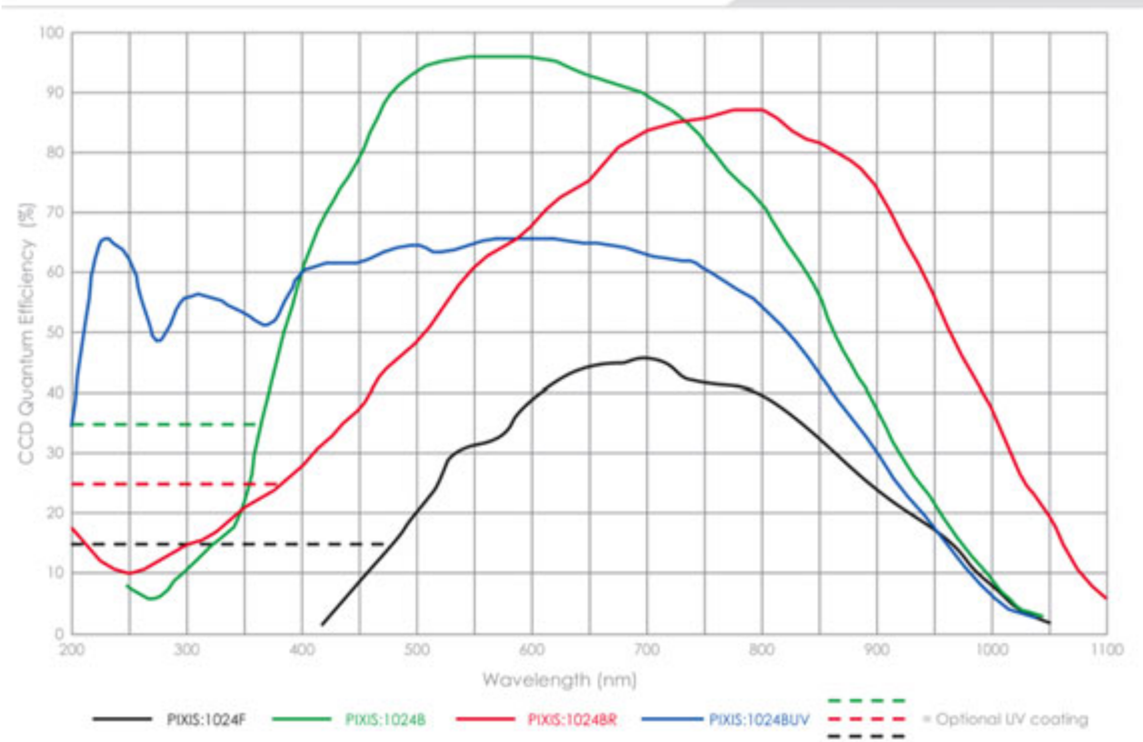




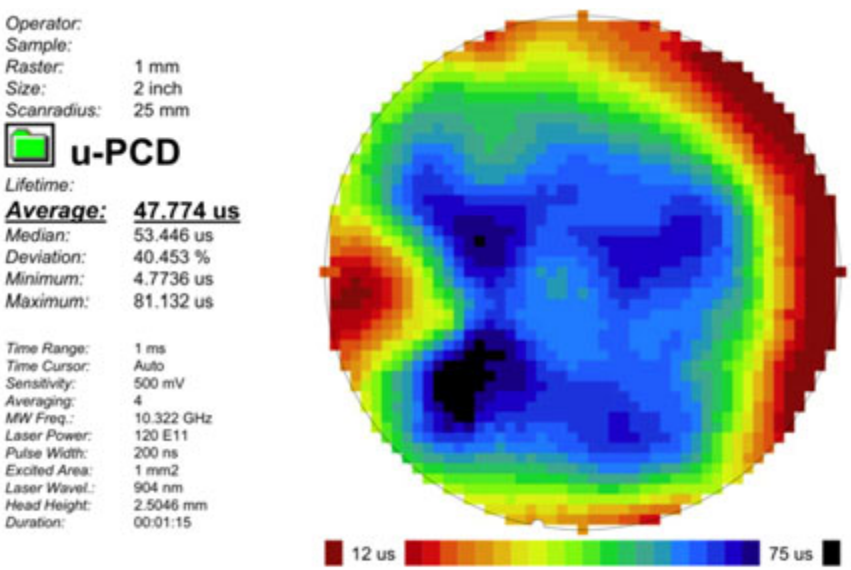
Photoluminescence (PL) Imaging



- 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 μm square pixels.



p-type CZ Si, 200 Ω-cm, ~6×10^{13} cm^{-3}, 310 μm thick



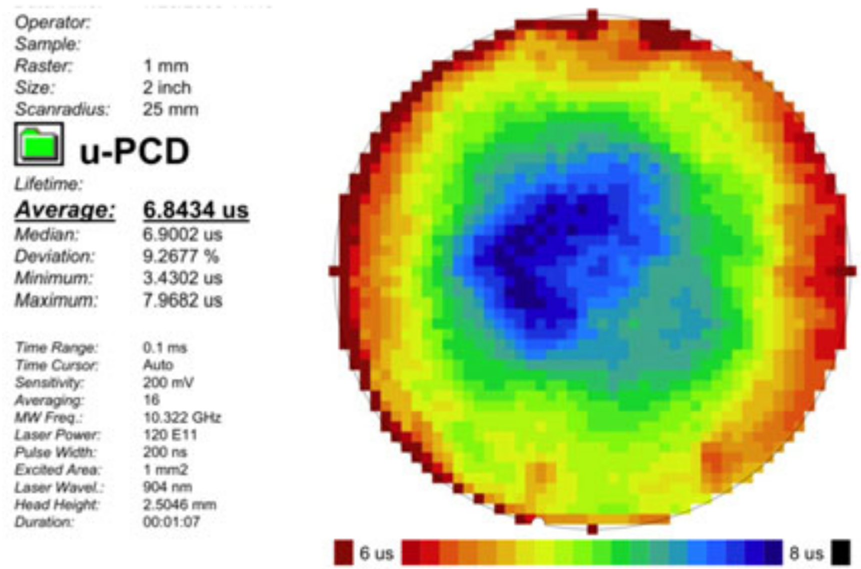
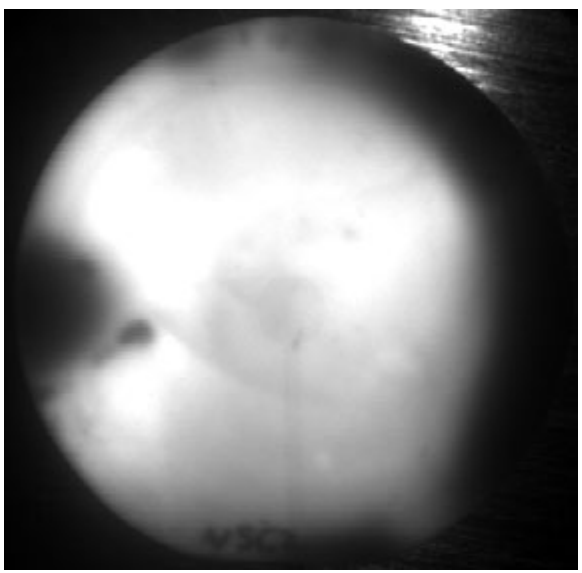
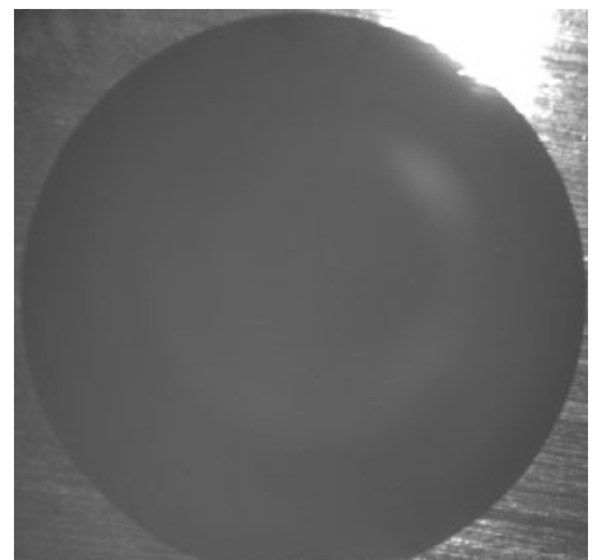


Image acquired in as little as **1 second**, longer for shorter lifetimes and poor surface passivation



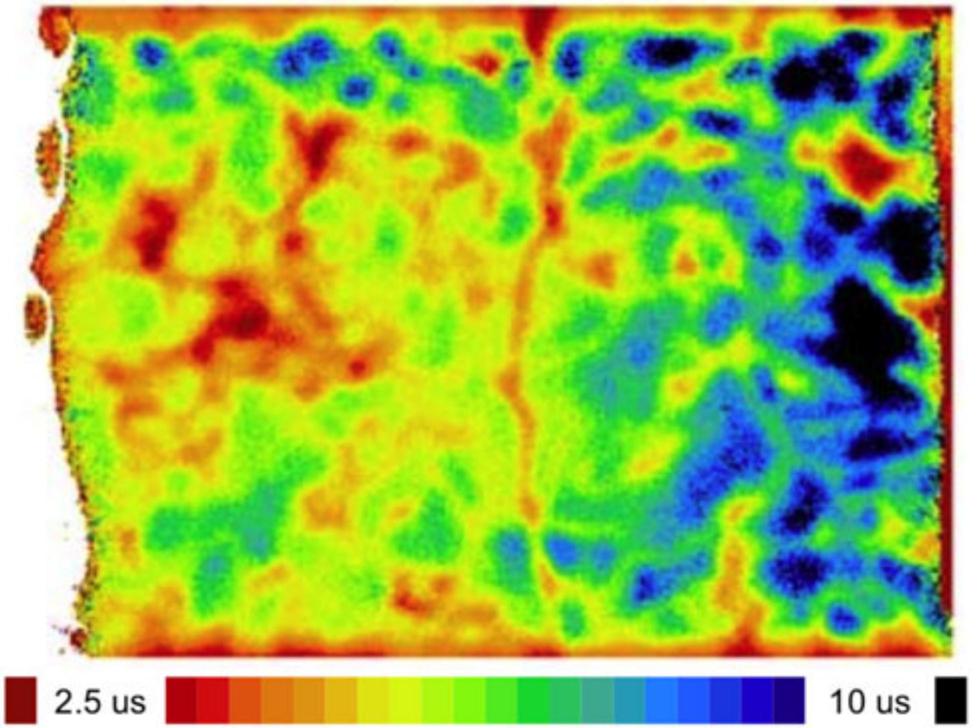
With oxide

No oxide

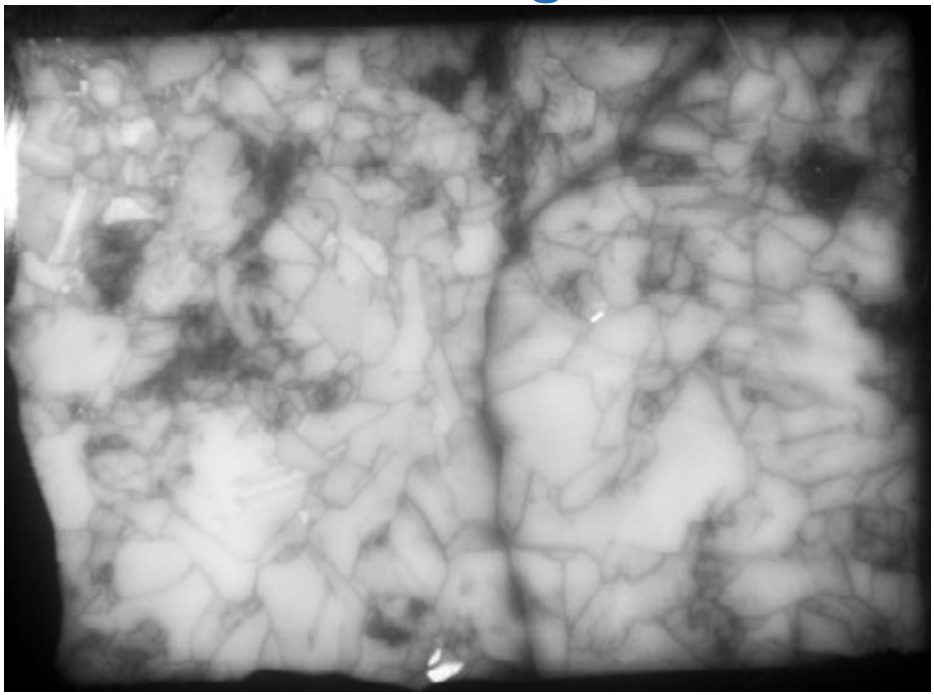


mc-Si with thermal oxide

Semilab map

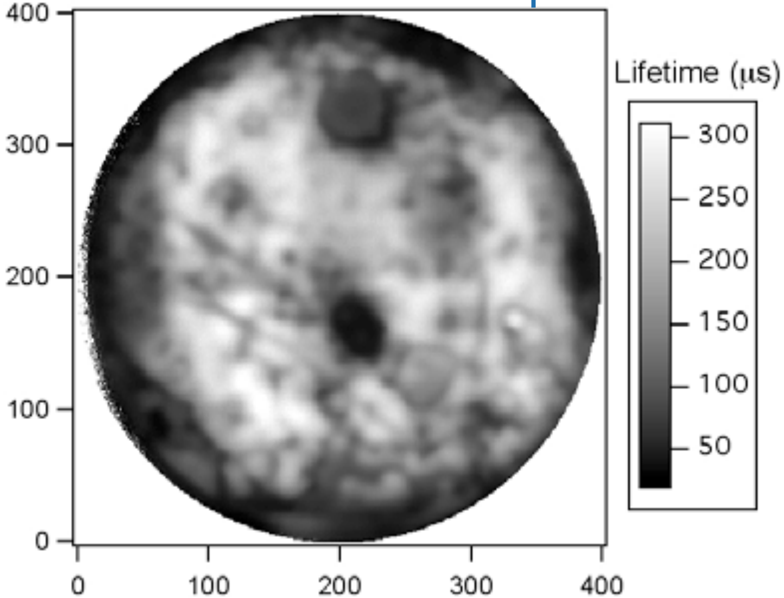


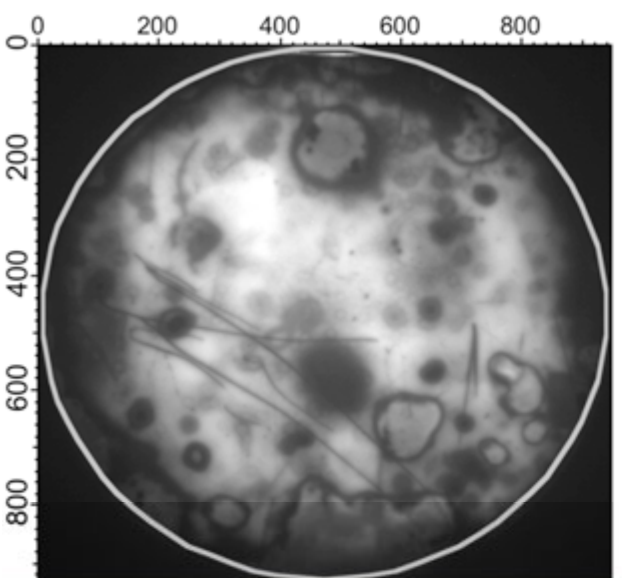
PL image



n-type, CZ, 1-10 Ω-cm, ~10^{15} cm^{-3}, 500μm, both sides polished

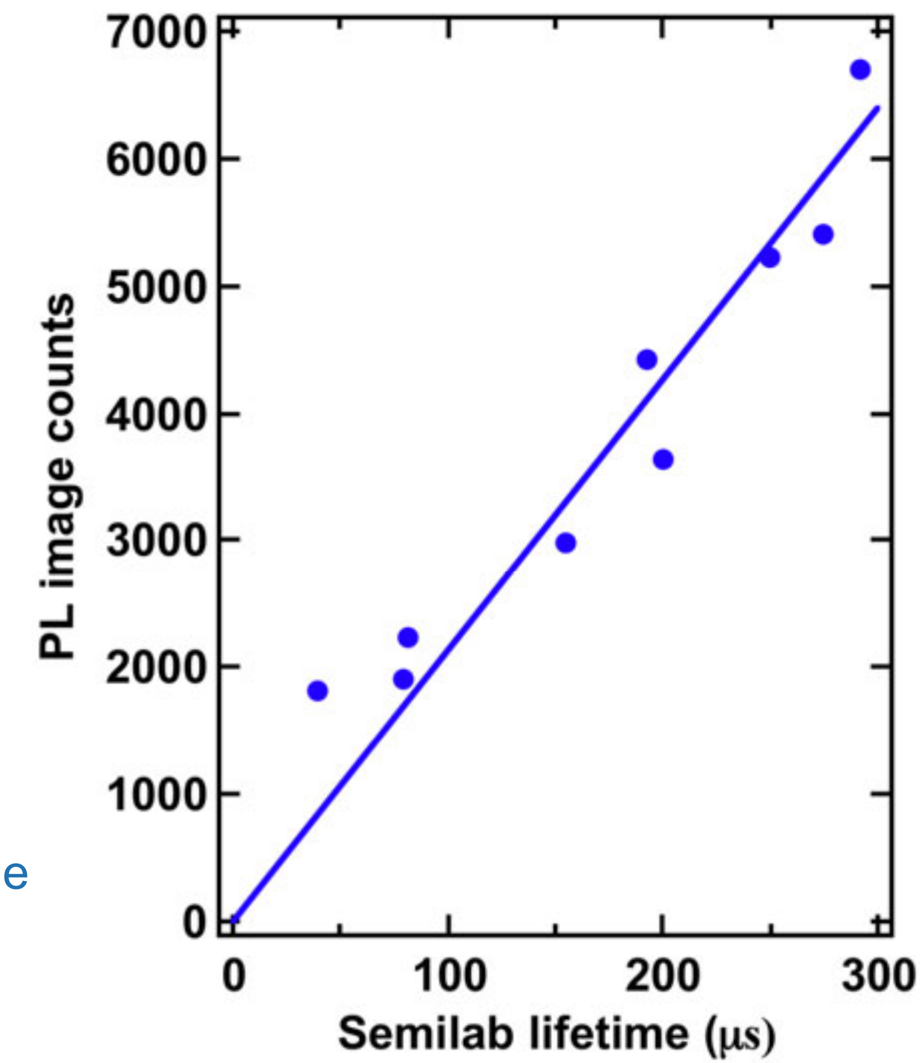
Semilab lifetime map



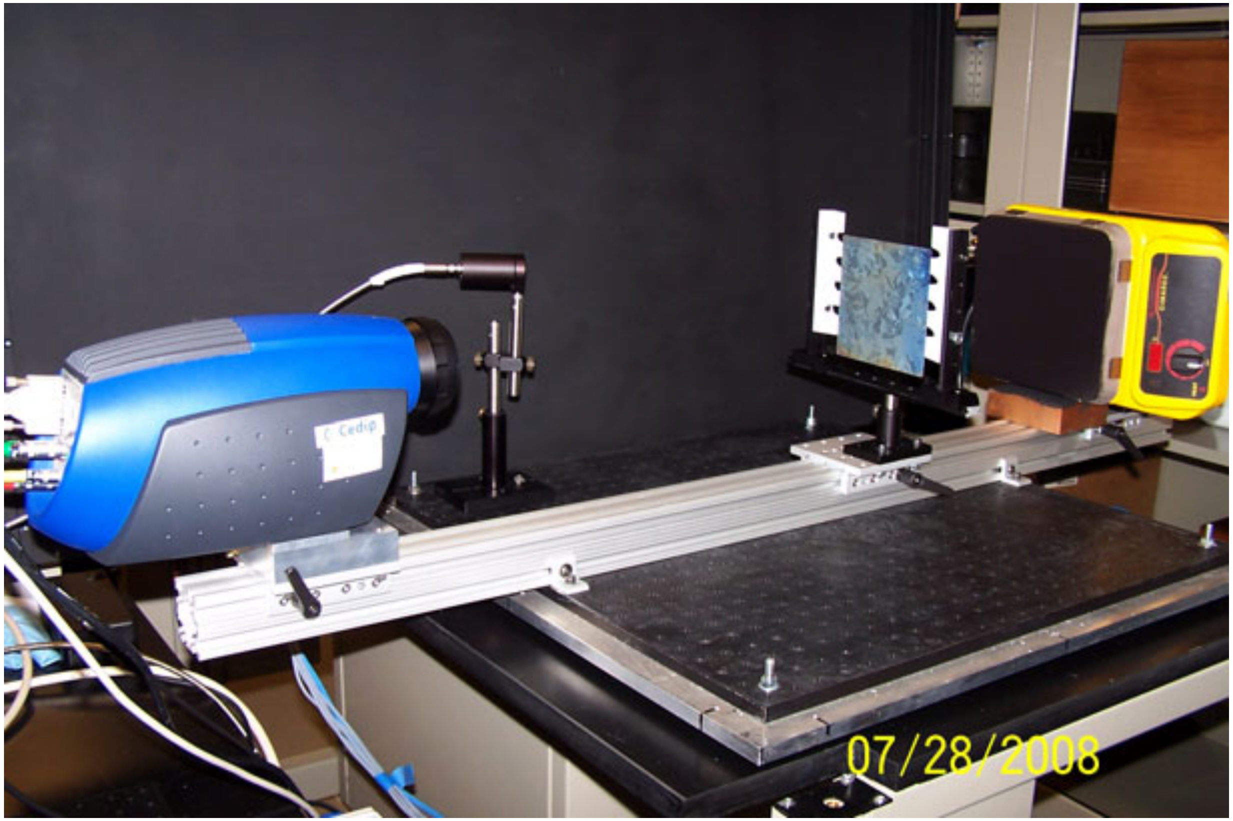


PL image

Lifetime to PL correlation



Carrier Density Imaging



- 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

- 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

p-type CZ Si, 200 Ω-cm, ~6×10^{13} cm^{-3}, 310 µm thick

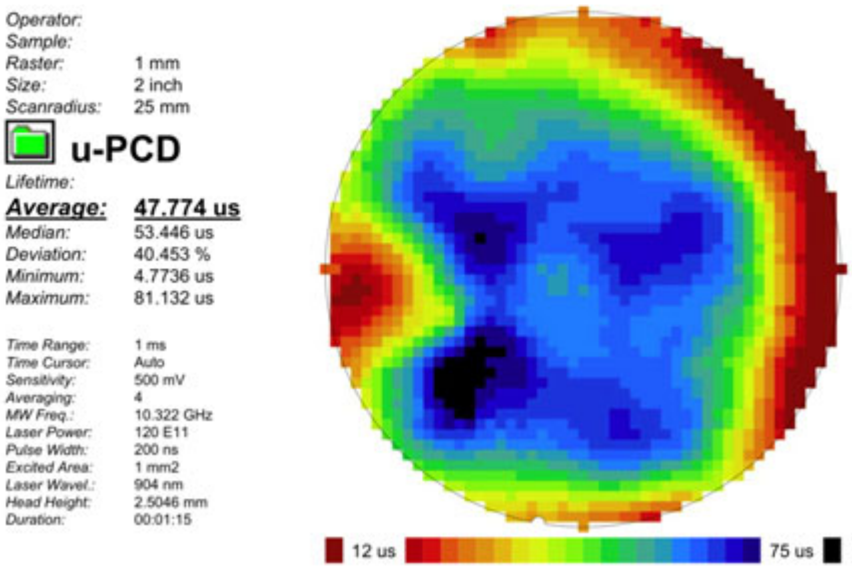
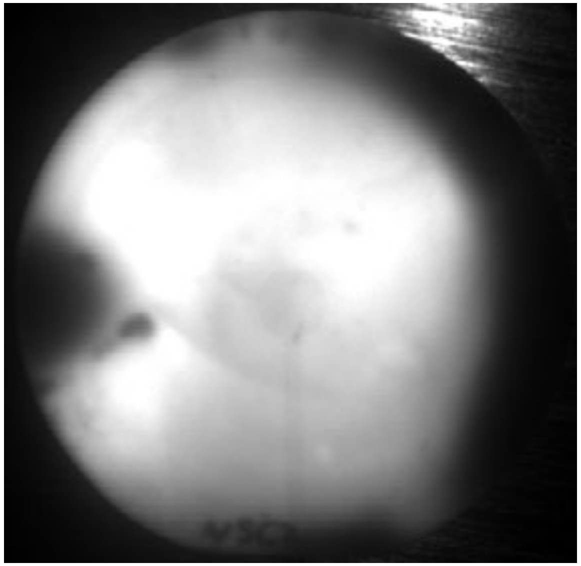
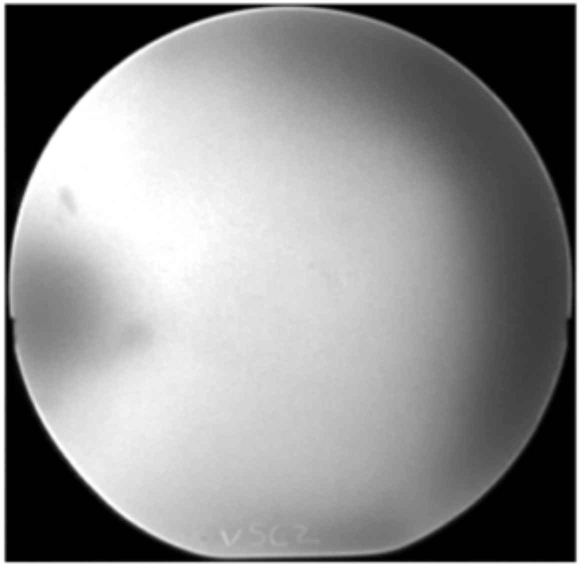


Image acquired in approximately **15 seconds**, (~1 sun intensity of light turned on and off at ~20 Hz, camera: 100 frames per second), longer acquisition time for shorter lifetimes and poor surface passivation

PL image

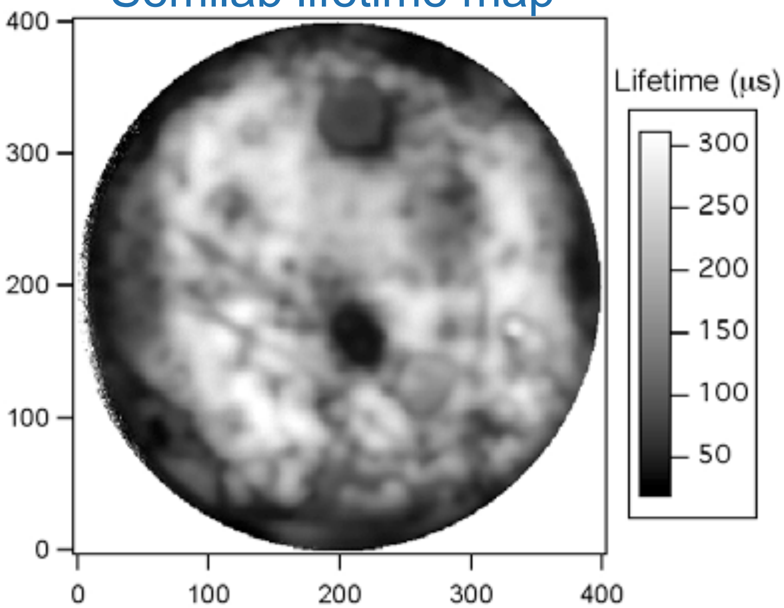


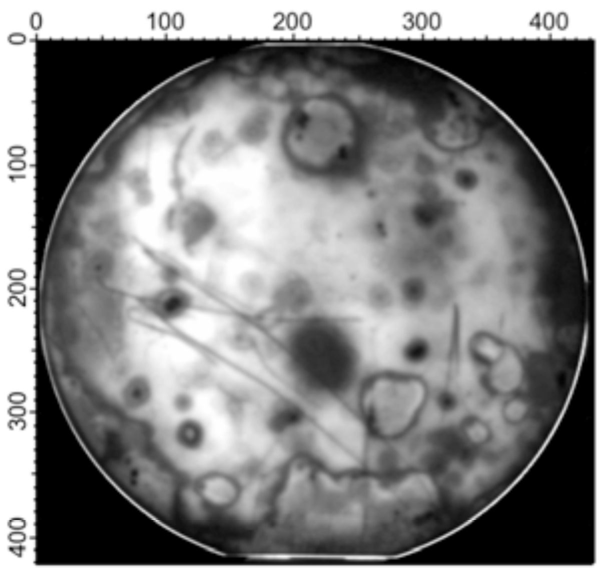


CDI (IR) image

n-type, CZ, 1-10 Ω-cm, ~10^{15} cm^{-3}, 500μm, both sides polished

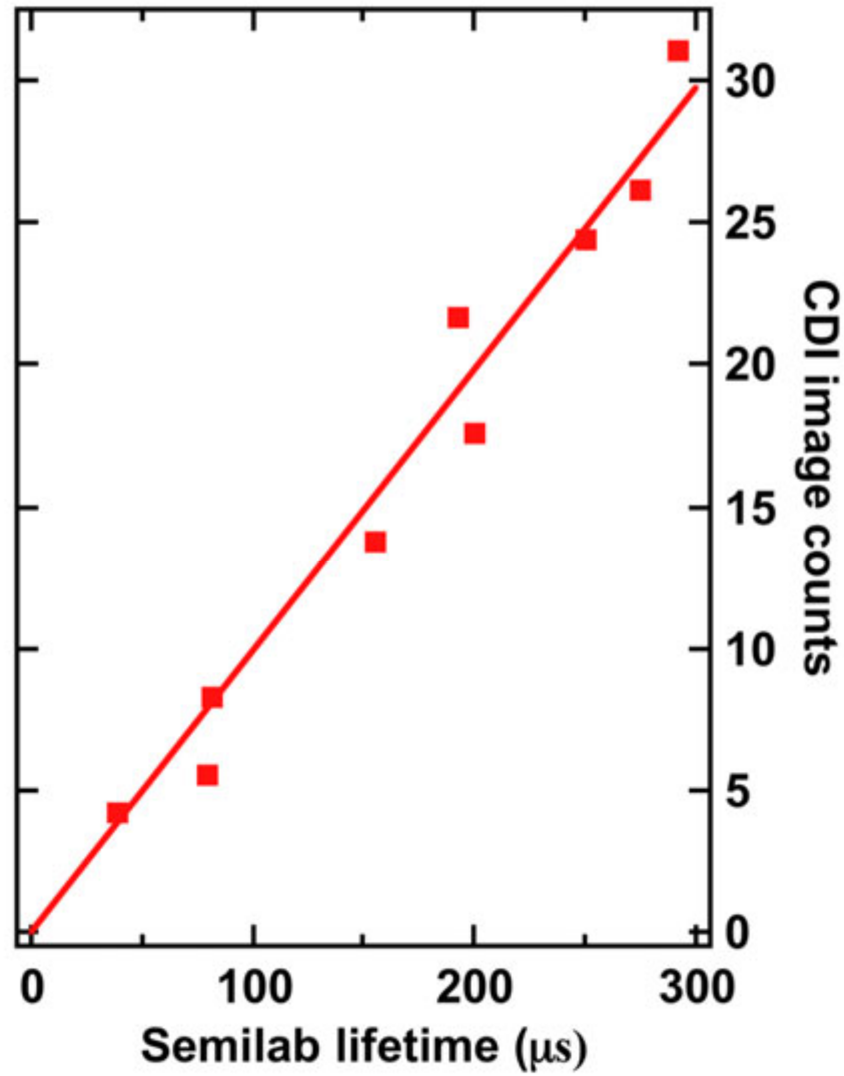
Semilab lifetime map



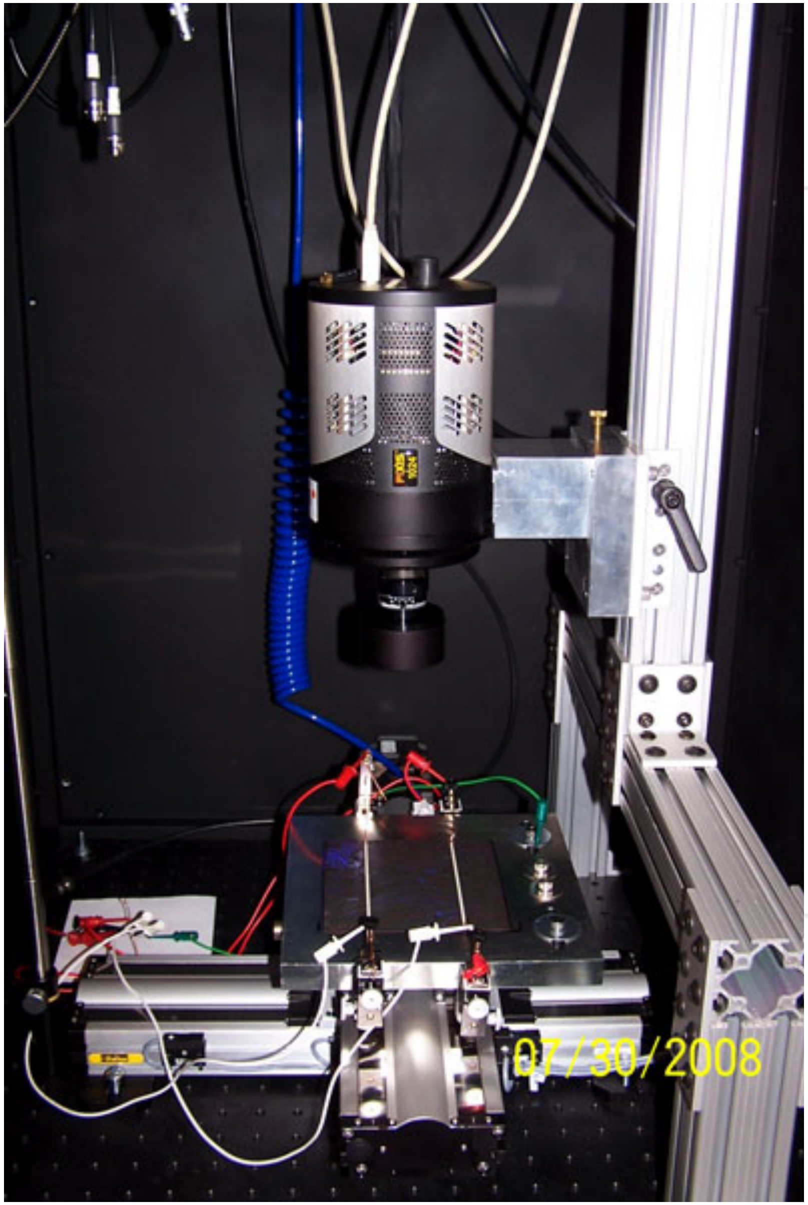


Carrier Density Image (IR camera)

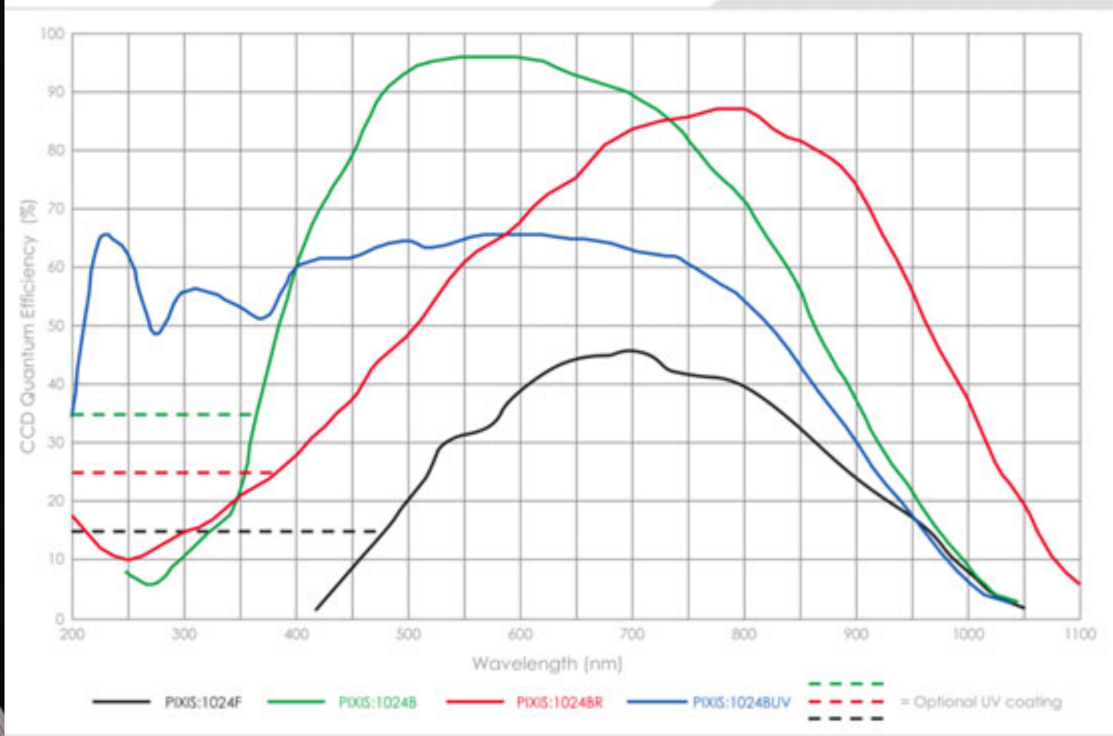
Lifetime to CDI correlation



Electroluminescence Imaging



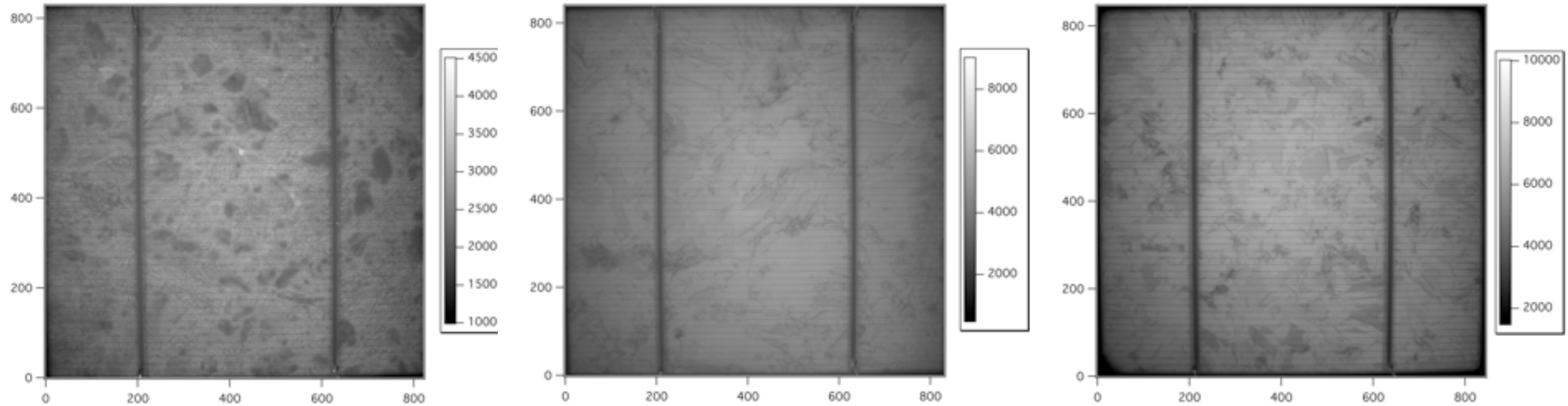
- Si CCD camera cooled to -75°C
- 1024 x 1024 array of 13 μm square pixels



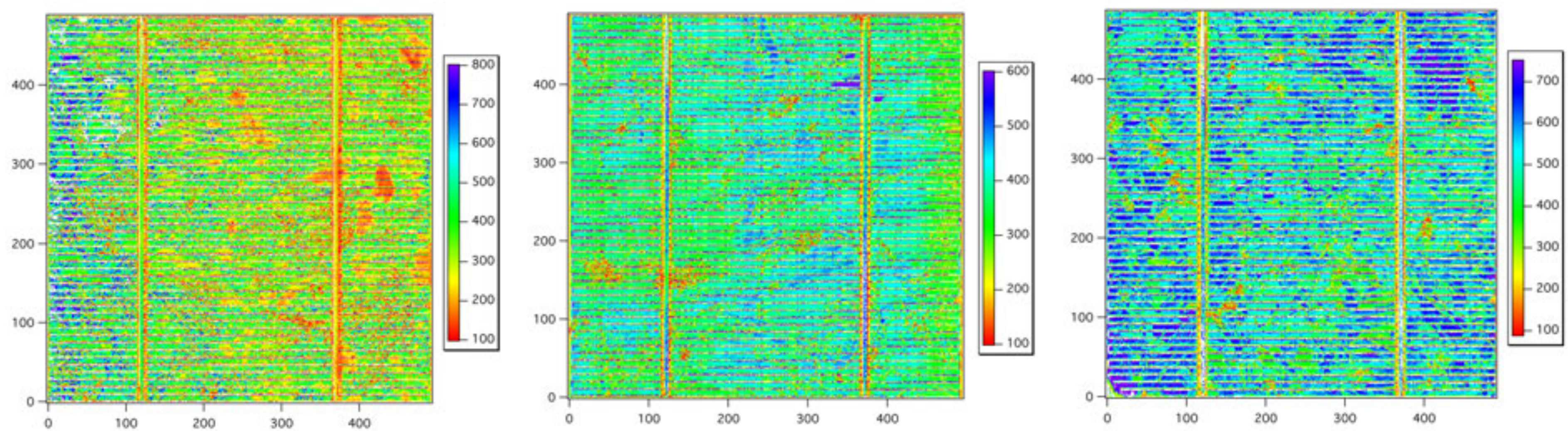
- Collect PL when forward biasing the cell
- With sample and camera in dark, and no filters, EL data collection in ~1 sec.

EL – diffusion length comparison

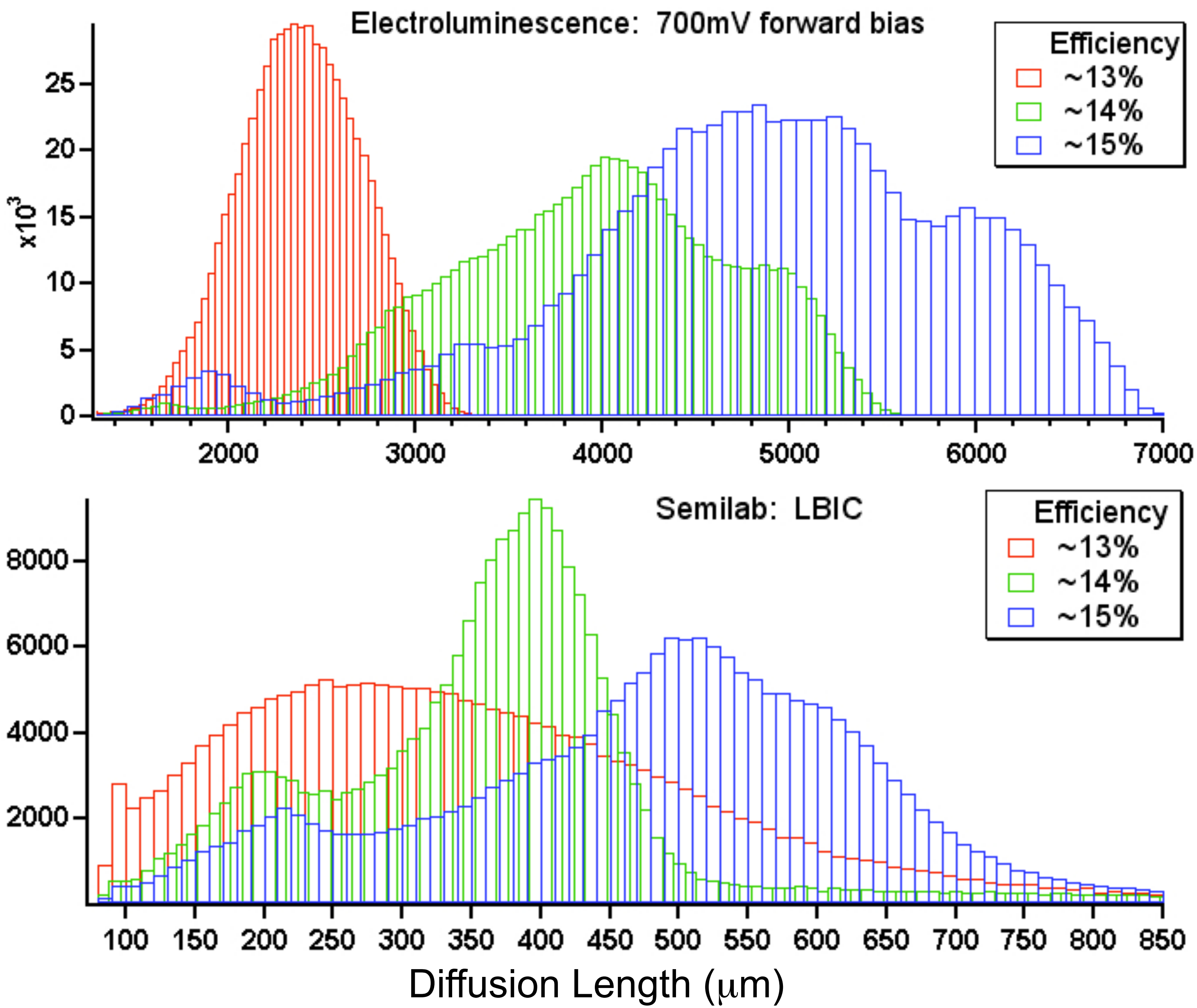
Electroluminescence, 1 s exposure time



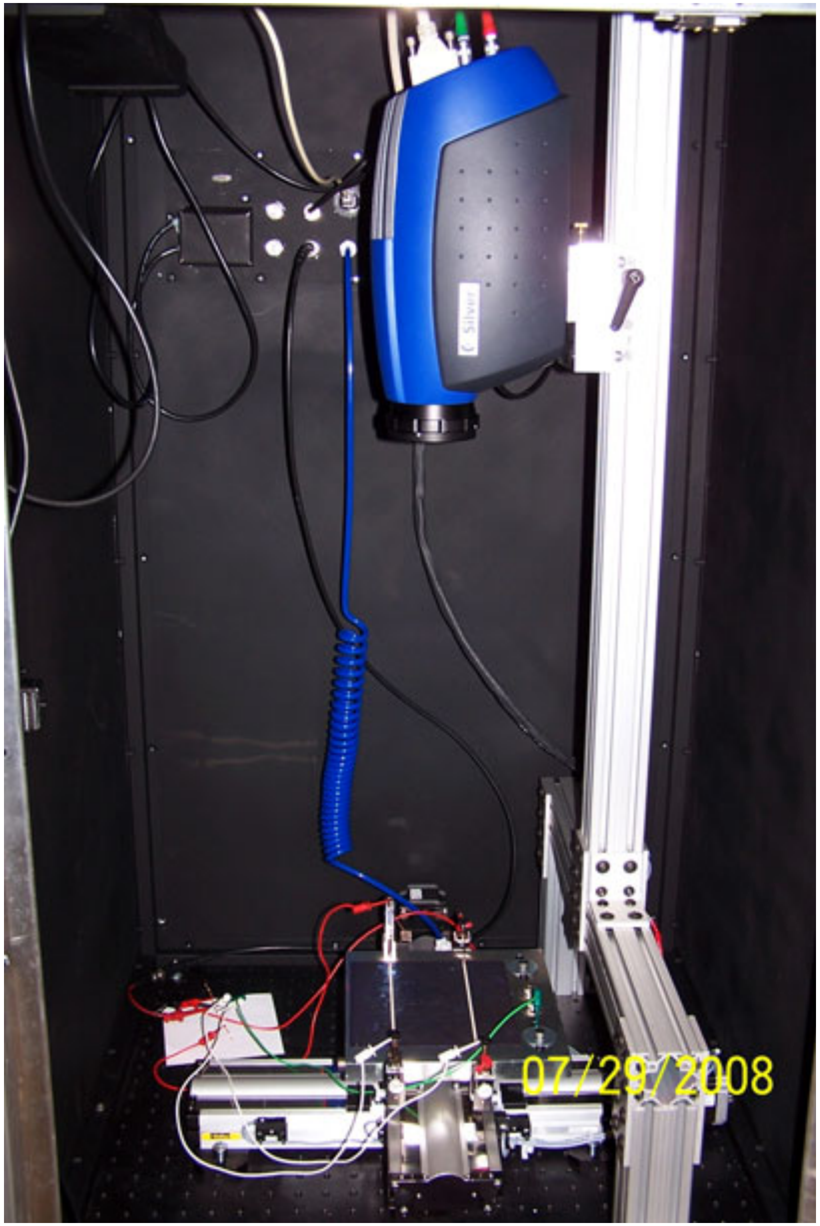
Semilab – LBIC scan, ~12 hour scan time, collect reflection, IQE data, too



EL and LBIC comparison



Dark Lock-in Thermography

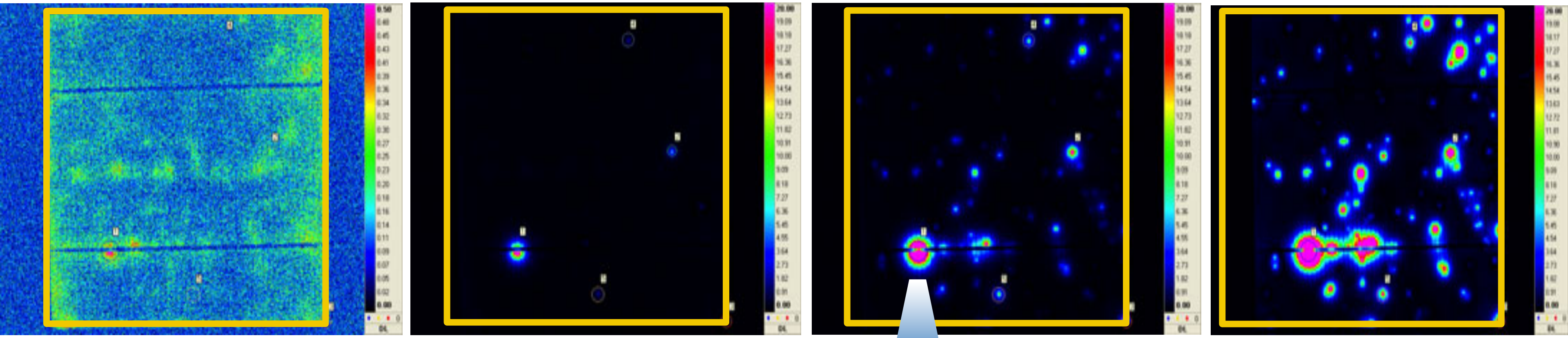


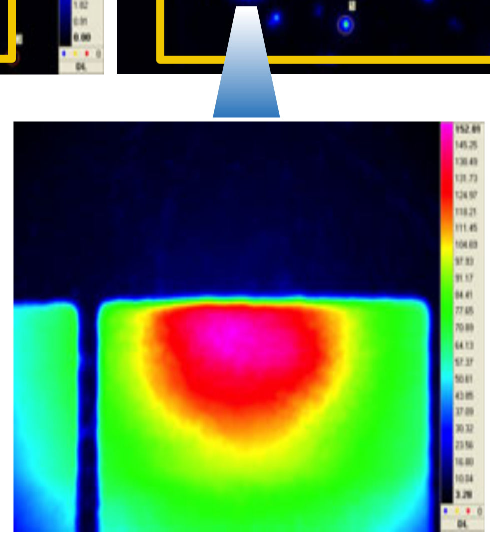
Sense heat due to current flowing in shunts

- 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

0.6 V_F | 2 V_R | 4 V_R | 6 V_R

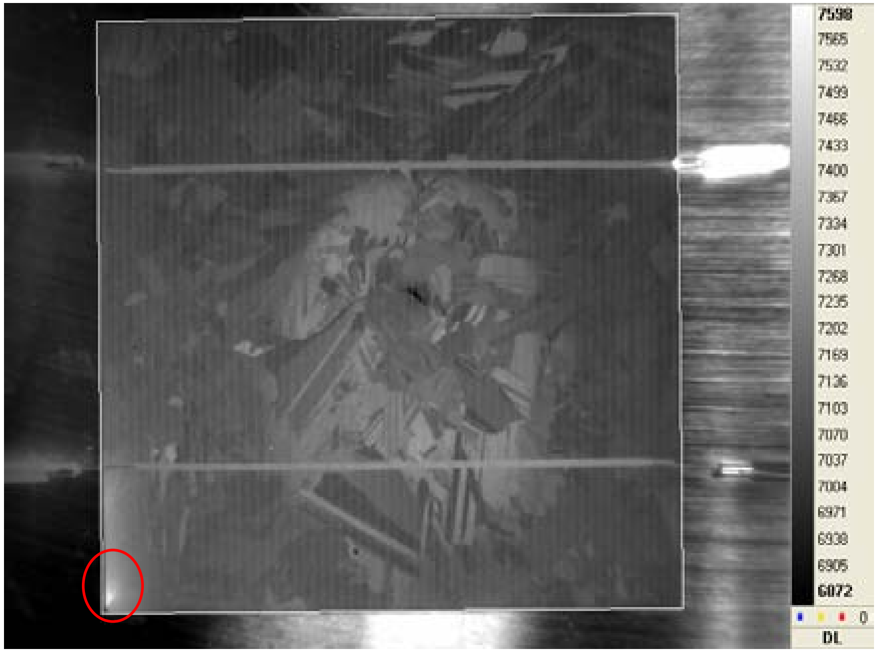


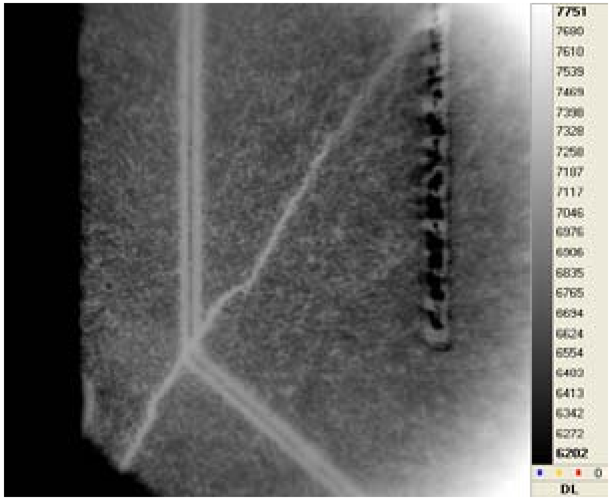


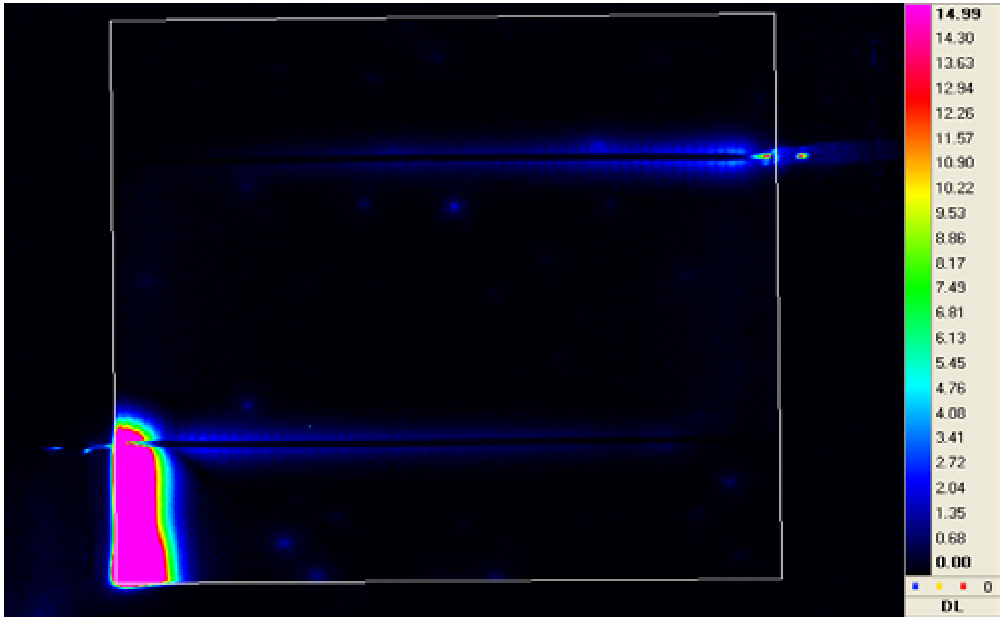
Characterize shunts using varying voltage and frequency

Zoom in using telescope lens with ~5 μm resolution

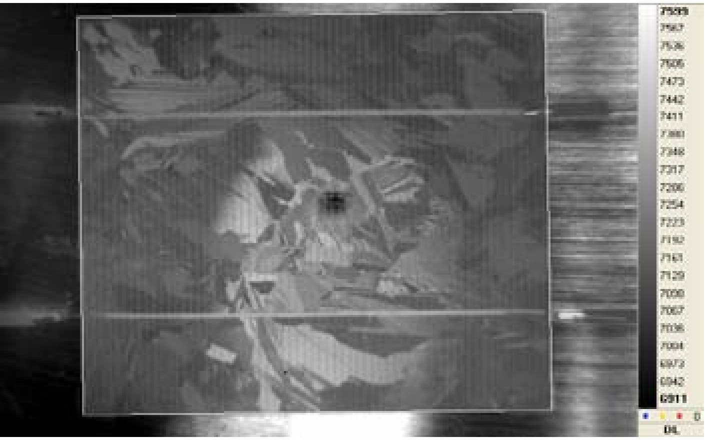
Process-Induced Cracking

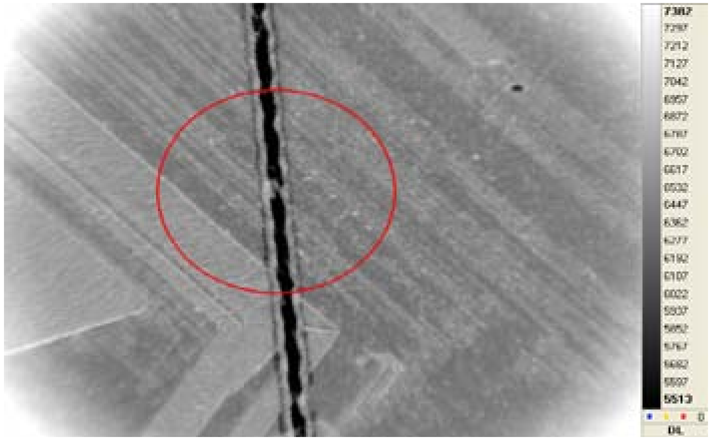


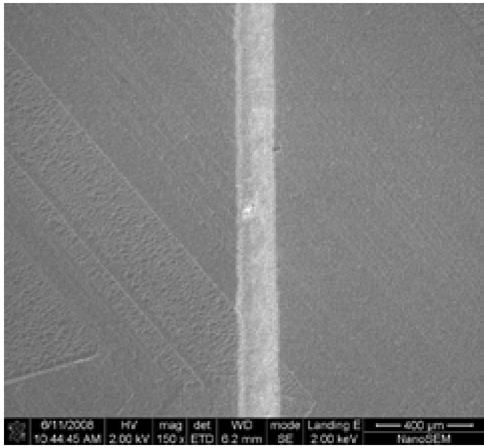


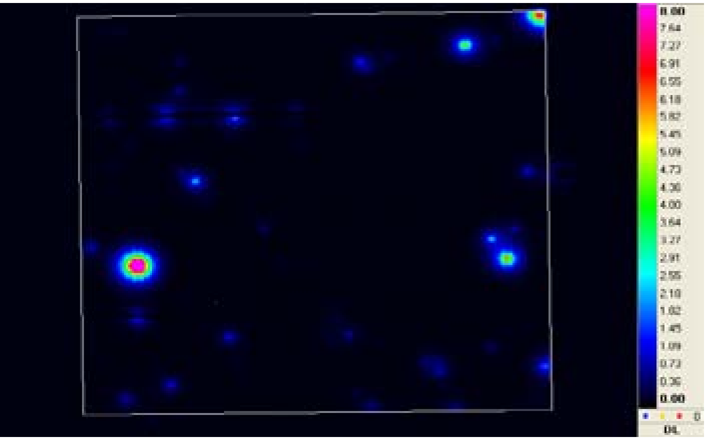


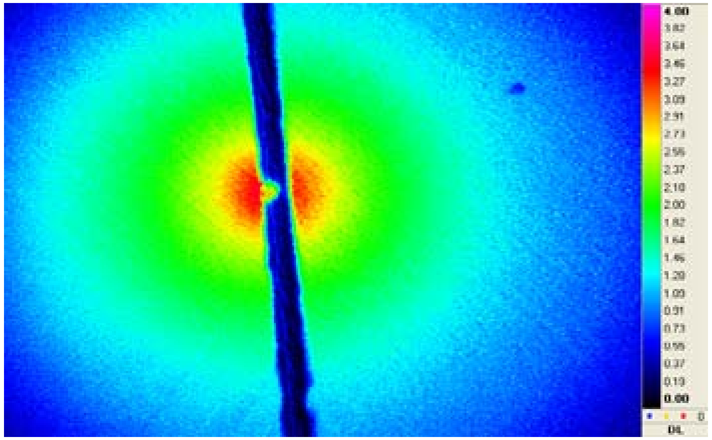
Schottky-Type Shunts

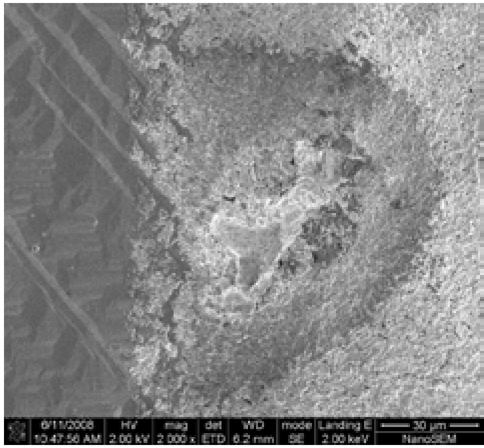






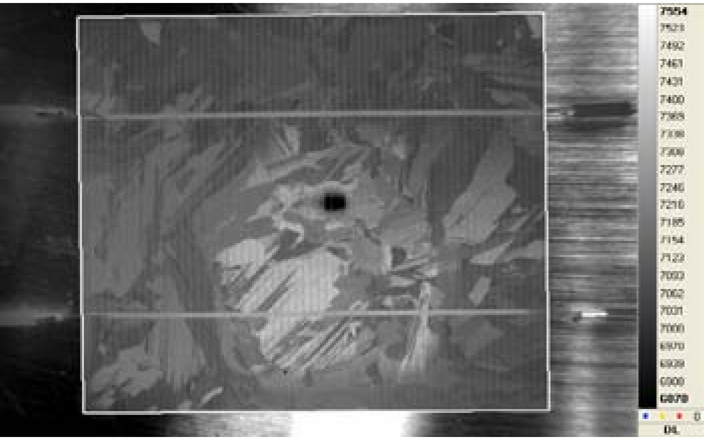


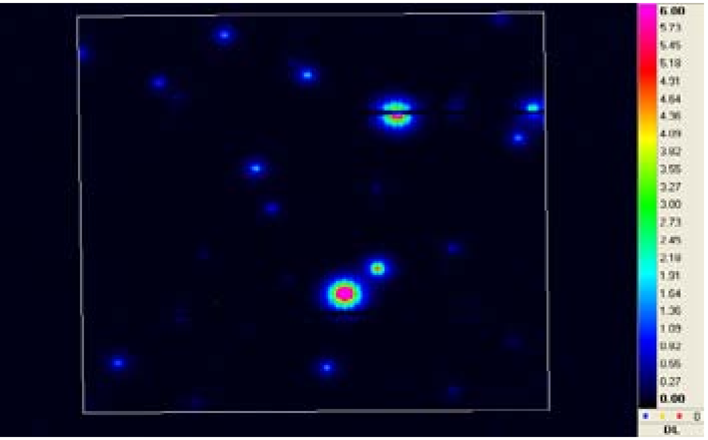


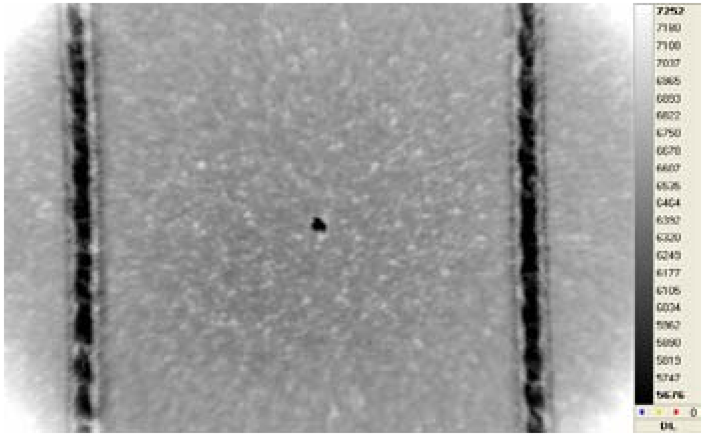


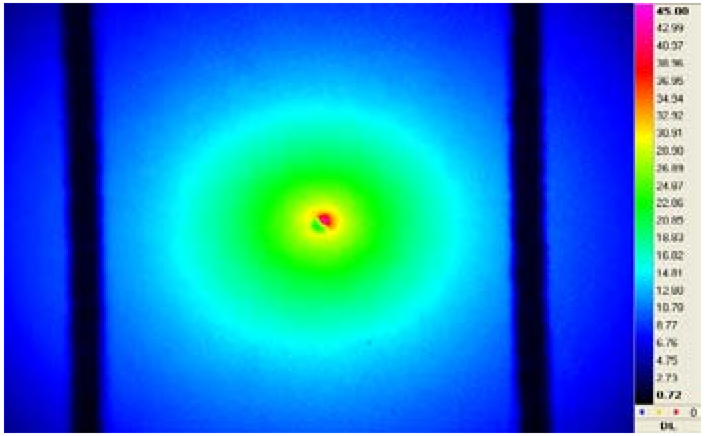
SEM images

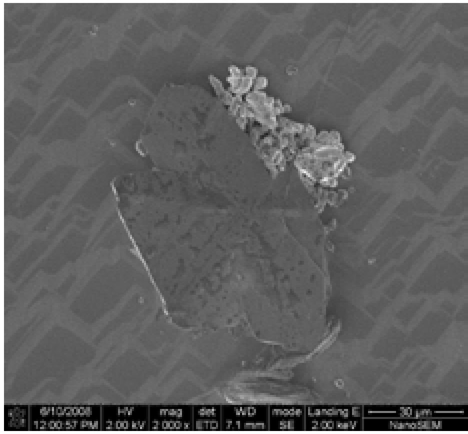
Aluminum Particles

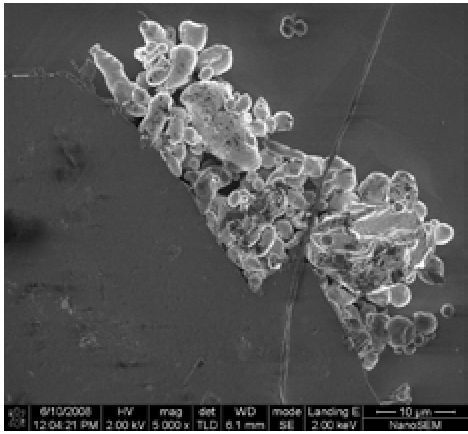












SEM images

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.