Photovoltaic Failure Analysis: Techniques for Microelectronics and Solar

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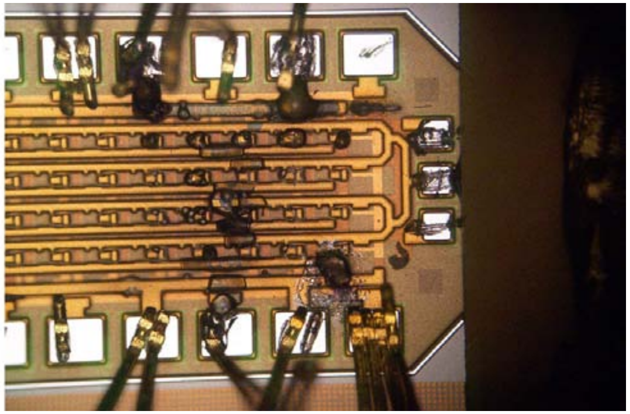
Review of Failure Analysis Techniques

- **Review failure analysis techniques from microelectronics**
  - **Non-destructive probes for:**
    - Electrical defects (EMMI, voltage contrast)
    - Physical defects (x-ray, acoustic, adhesion)
  - **Most FA tools built for 200mm wafers**

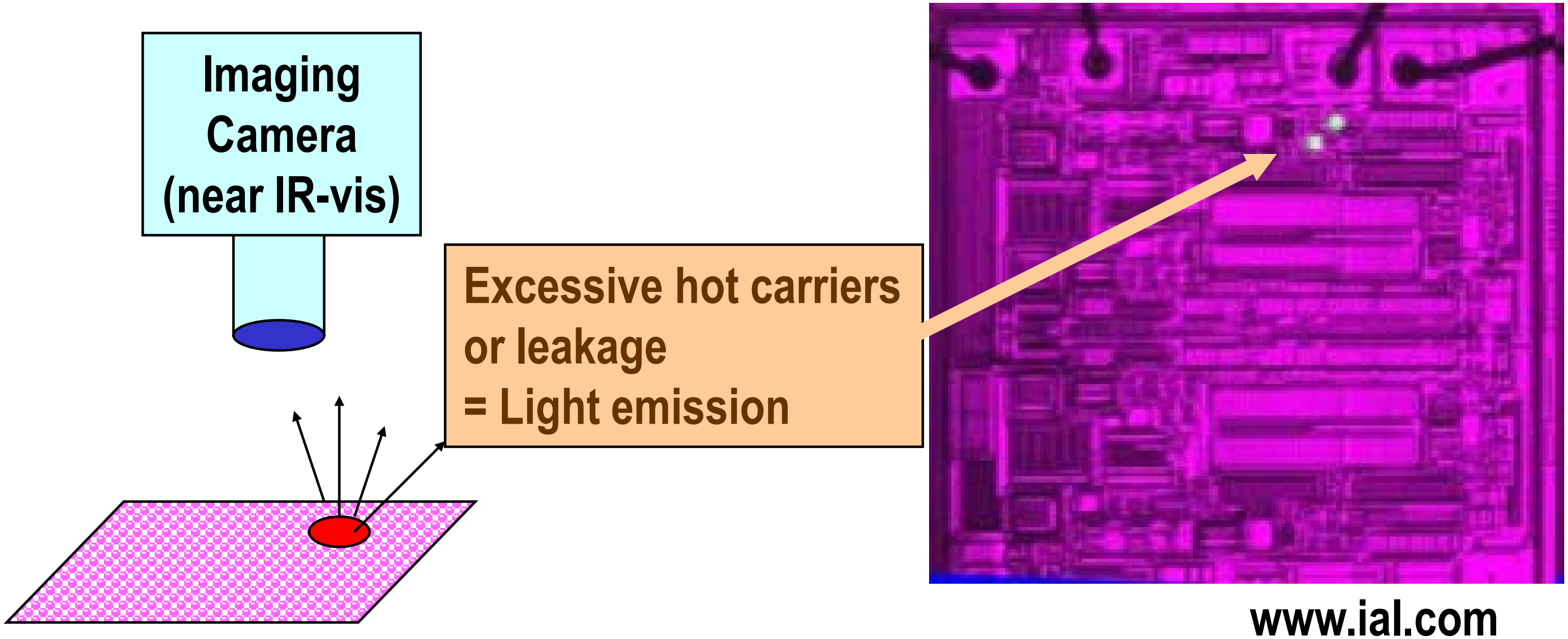


- **Comparison to common techniques for PV industry**
  - **Light beam induced current**
  - **Electroluminesence imaging**
  - **Photoluminesence imaging**
  - **Thermal imaging**
- **Review of companies that provide FA services**

Techniques are the same: Only the acronyms have changed
Focus for electronics is resolution

Electrical Defect Inspection: Light Emission

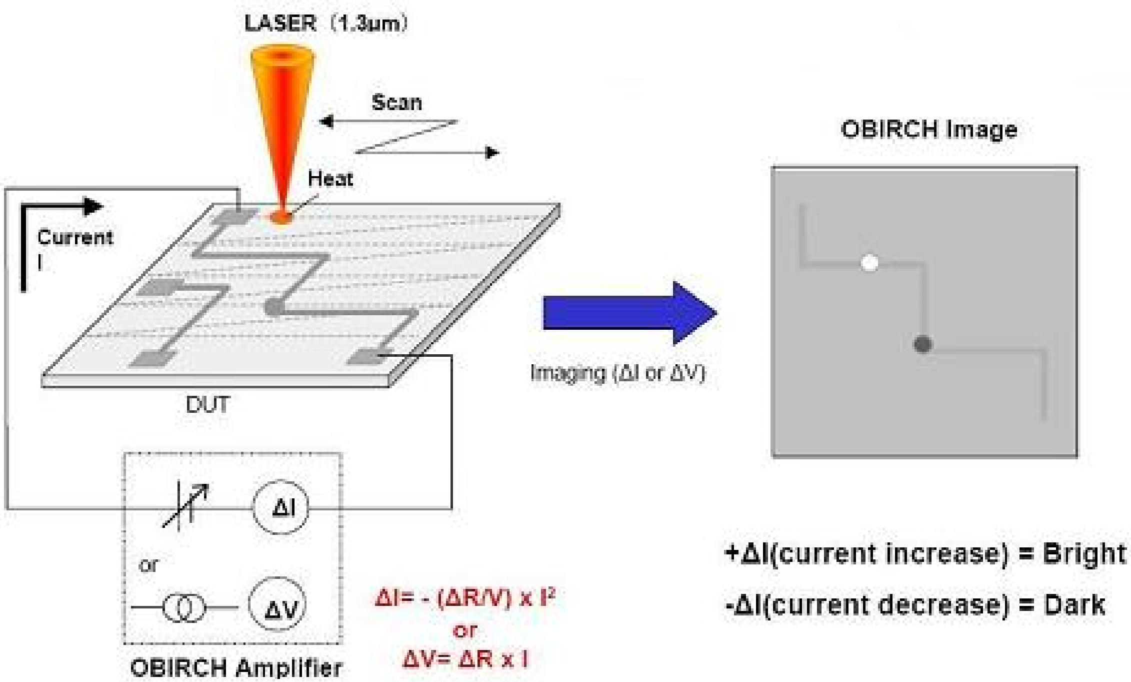
- **Light emission imaging**
  - PEM (photoelectron microscopy)
  - EMMI (emission microscopy)
  - LEM (Light emission microscopy)
  - For photovooltaics: EL/PL imaging
- **Hot carrier generation or leakage**
  - CMOS: low static power consumption
  - Electrons injected above conduction band
  - Broad light emission
  - Imaged during different vectors / operation



www.ial.com

Scanning Optical Probes

- OBIRCH (Optical Beam Induced Resistance Change)
  - Scan line with pulsed laser beam = local heating
  - Voltage (resistance) change from local heating ~ current in line



Probe beam = local heating
$\Delta V = I\,(\delta R/\delta T) * \Delta T$

AC voltage signal ~ current

Probe of local current
$I = \Delta V * (\text{constant})$

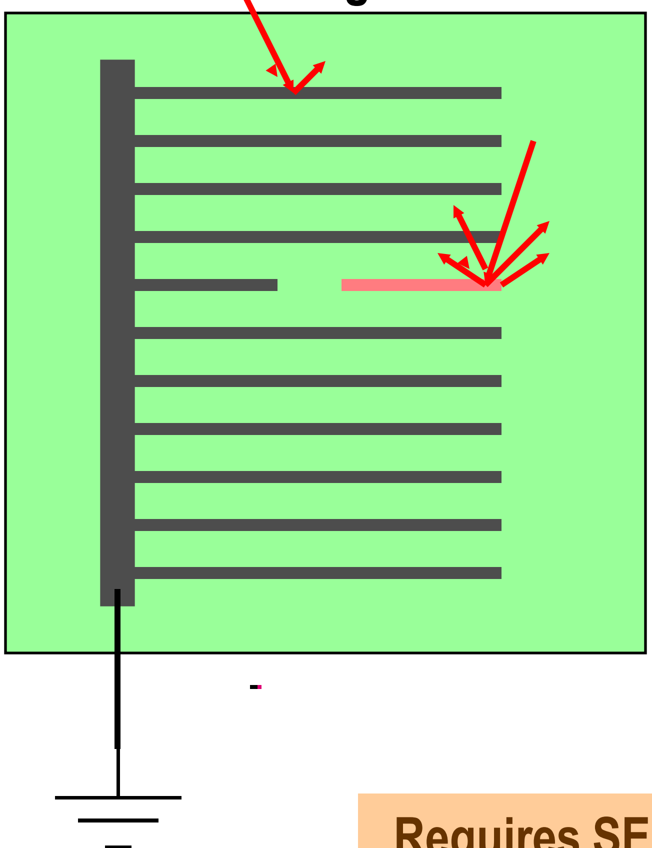
Probe of resistance along line

OBRICH gives local quantitative probe of current in interconnect
Analogous to LBIC for photovoltaics

Scanning e-beam: Voltage Contrast Images

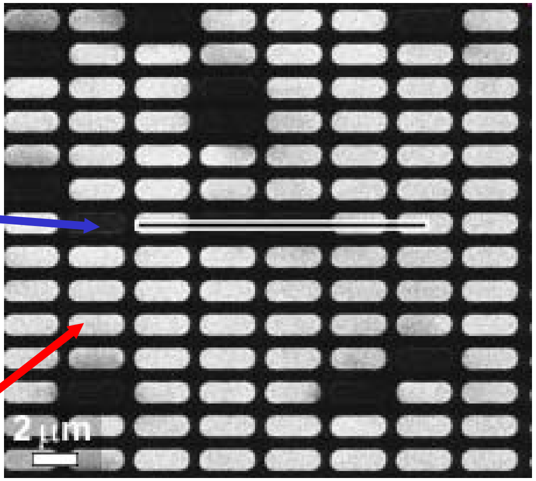
- Voltage contrast microscopy (SEM)

Electron Beam
>> ground = few secondary e-



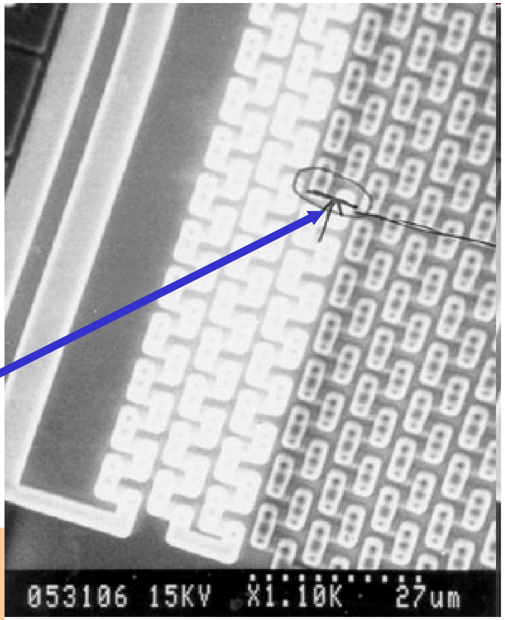
Good bits (dark)

Bad bits (bright)



Line with poor ground Connection:
Charge buildup
Bright in SEM

Break in line

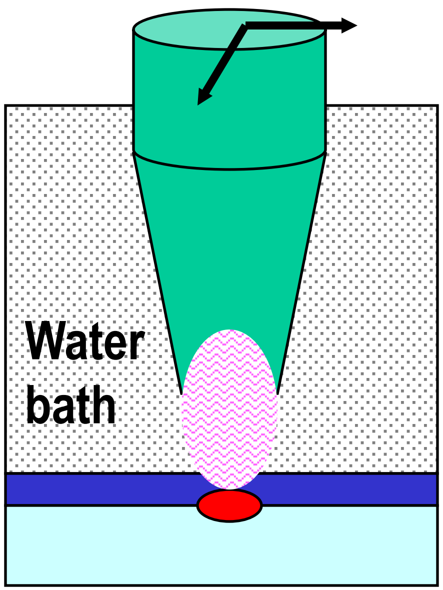


Requires SEM (up to 300mm samples)
Very fast with high or low magnification

Physical Defects: Acoustic Microscopy

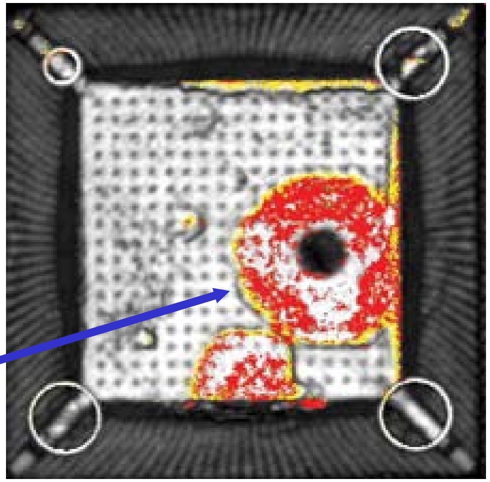
- **SAM = Scanning Acoustic Microscopy**

Ultrasonic Transducer

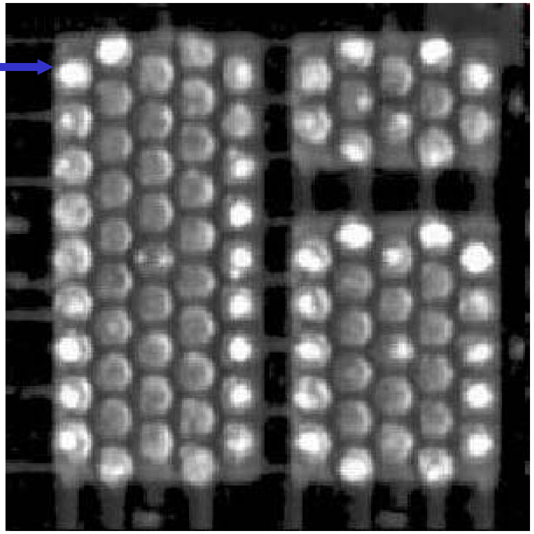


~10μm resolution
Water bath required

Sensitive to delamination
(Failed encapsulant)

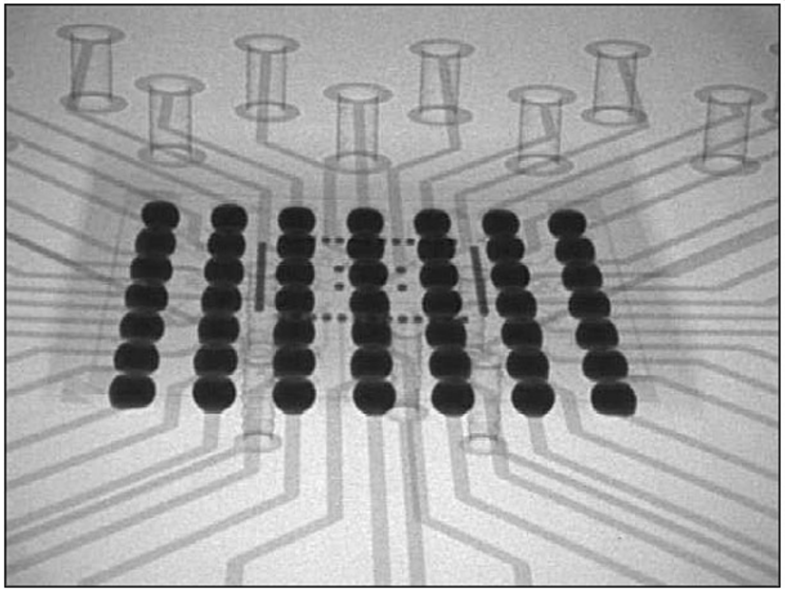


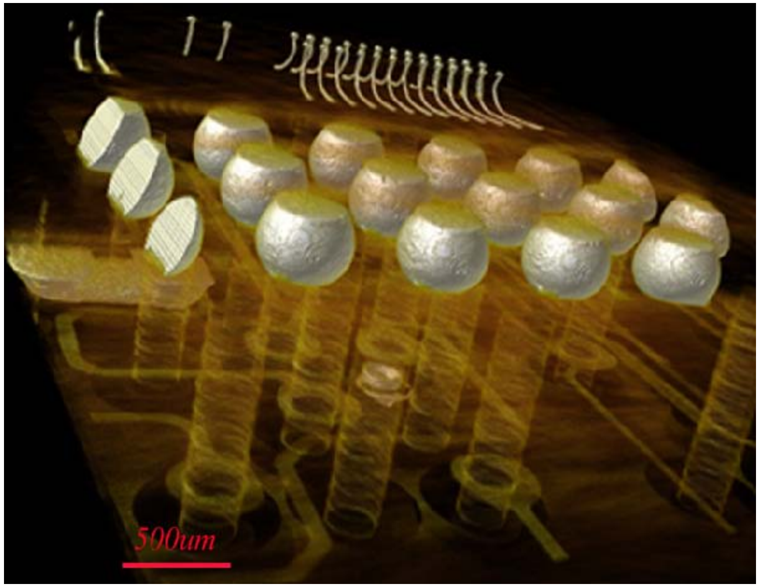
Poor contacts
(solder bumps)



Physical Defects: X-ray tomography

- **X-ray tomography**
  - 2-dimensional and 3-dimensional imaging
  - Best for embedded metals in dielectric
  - Composition information also available
  - Sample sizes up to 200mm

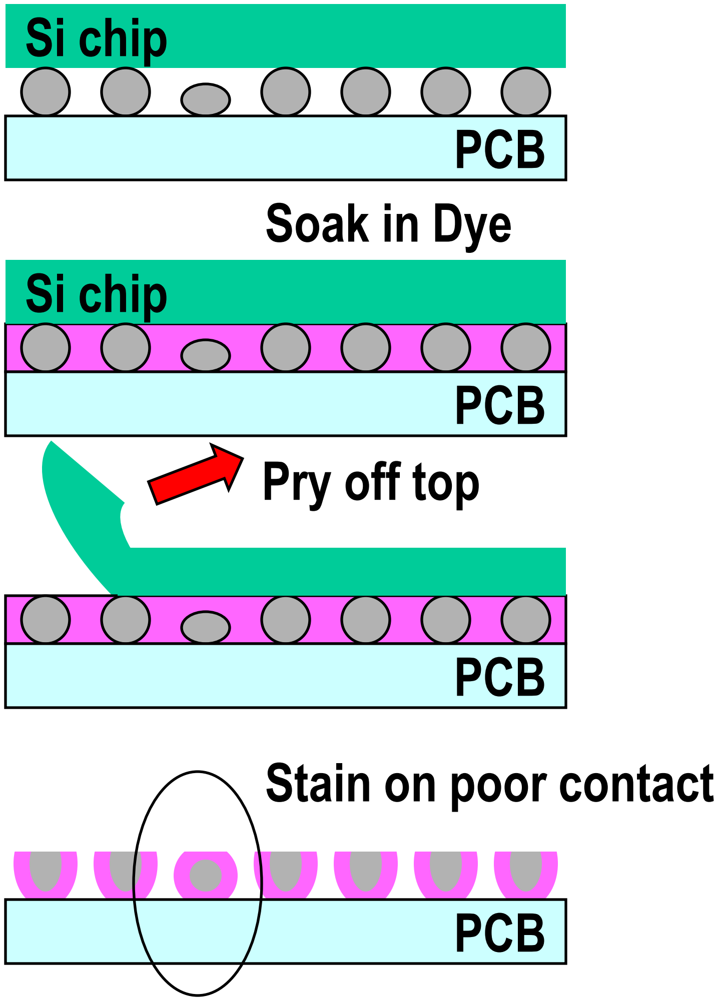


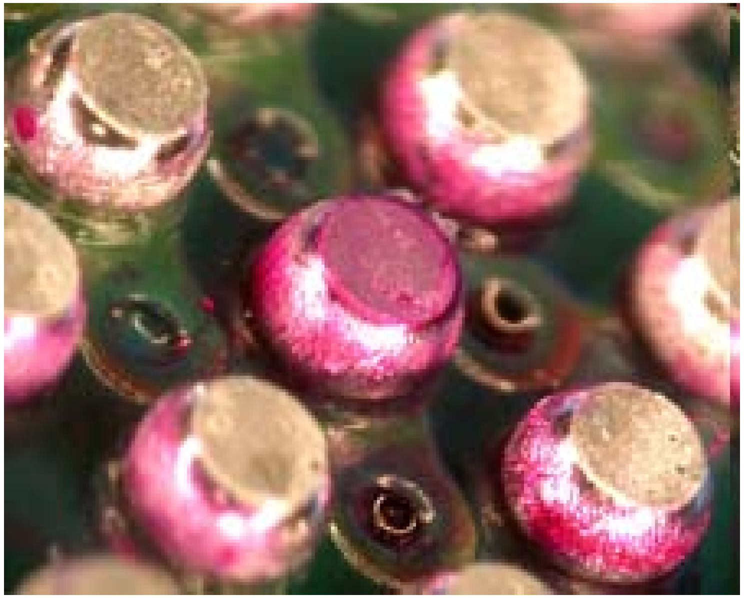


Time intensive, not sensitive to contact resistance / microcracks

Physical Defects: Dye and Pry

- Destructive Test for cracks and poor contacts
  - Applied after thermal cycling or HTOB test

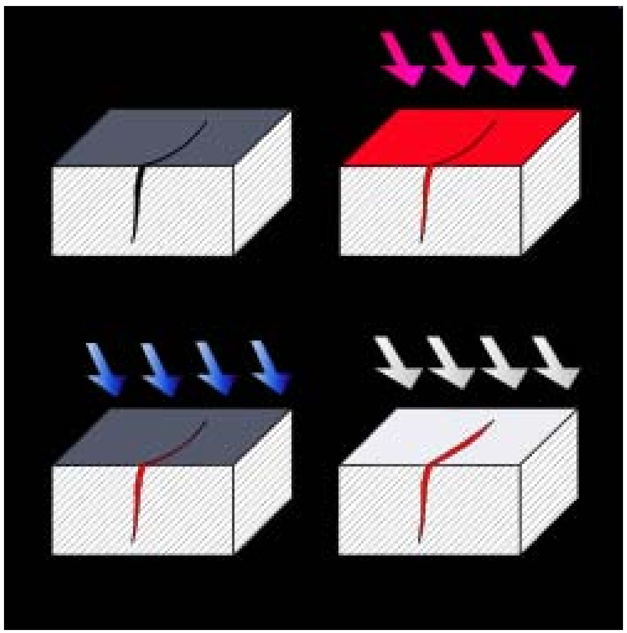


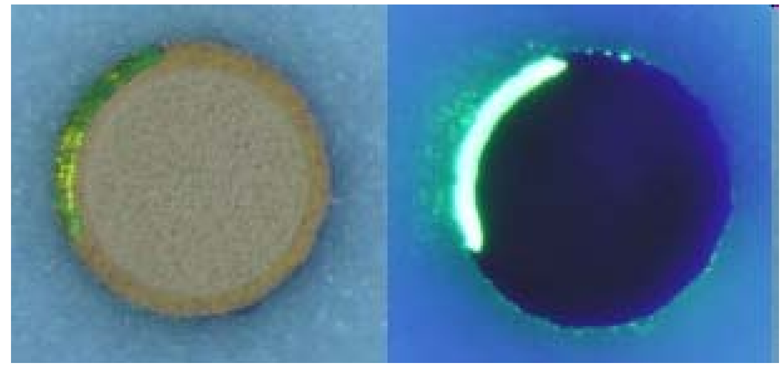


Destructive test
Sensitive to partial failures

Florescence Dye Staining

- Florescence Dye Imaging
  - Paint part with florescent dye
  - Remove dye (apply developer)
  - Image with UV





Example: metal feedthrough in glass

Commonly applied to mechanical parts / boilers / etc..
Applicable to field testing

Electrical defects: Thermal Imaging

- Thermal hot spots in chips: Electronics focus on **RESOLUTION**

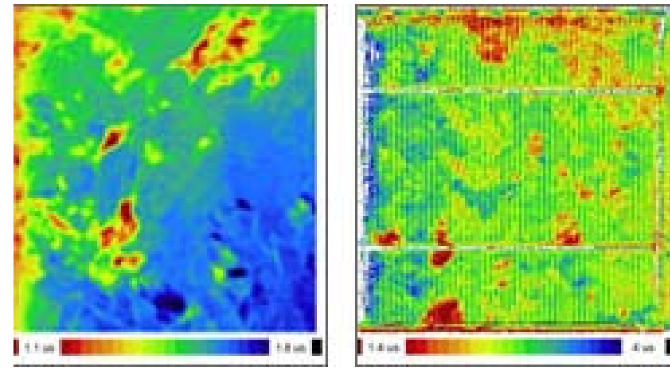
Table 1 Summary of popular high-resolution thermal measurement techniques in micrometer-nanometer range

Method	Principle	Resolution: Spatial (μm)	Resolution: Temperature (K)	Resolution: Response time (s)	Imaging?
Microthermocouple	Seebeck effect	50	0.01	5 m	No
Infrared thermography	Planck blackbody emission	3–10	0.02 (if blackbody) -1 K	10 μm (single point) -0.5 m (image)	Yes
Liquid crystal thermography	Crystal phase transitions (change color)	2–5	0.5 (near phase transition)	3 m	Yes
Thermoreflectance	Temperature dependence of reflection	0.3–0.5	0.01	0.006–0.1 μm	Yes
Scanning thermal microscopy (SThM)	Atomic force microscope with thermocouple or Pt thermistor tip	0.05 (surface morphology)	0.1	10–100 μm	Scan
Fluorescence thermography	Temperature dependence of quantum efficiency	0.3	0.01	200 μm	Scan
Optical interferometry	Thermal expansion, Michelson type	0.5	0.0001 (1 fm)	0.006–0.1 μm	Scan
Micro-Raman	Shift in Raman frequency or ratio of Stokes/anti-Stokes amplitudes	0.5	1	1 μm	Scan
Near field probe (NSOM)	Use near field to improve optical resolution	0.05	0.1–1 (S/N dependent)	0.1–10 μm	Scan
Built-in temperature sensors	Fabricate a thermal sensor integrated into the device	100s	0.0002–0.01	1 μm	No

Thermal imaging well developed for photovoltaics

Common Photovoltaic Failure Analysis

- **Current induced probes**
  - **LBIC / EBIC / XBIC (light / electron / x-ray beam induced current)**
  - **Spatial mapping of quantum efficiency**
  - **Local mapping of carrier lifetime**
  - **Shunt / series resistance mapping**



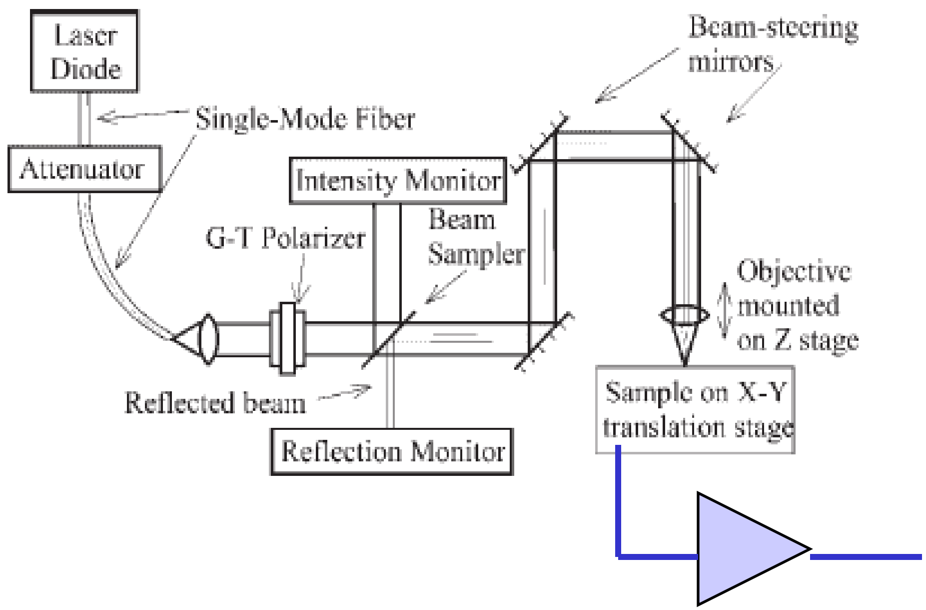
- **Emission Spectroscopy**
  - **Information depends on emission energy**
    - Elecroluminescence (visible – near infrared)
    - Photoluminesence (near infrared)
    - Thermal imaging (far infrared)
  - **Local mapping of current density**
  - **Local mapping of carrier lifetime**
  - **Shunt / series resistance mapping**

Laser Beam Induced Current (LBIC)

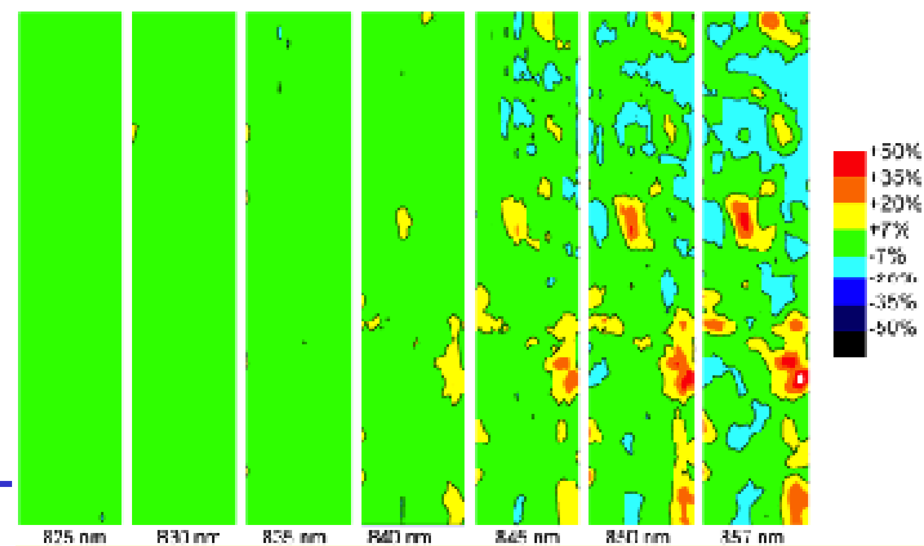
OBRICH for microelectronics

- **Spatial resolution of current across solar cell**
  - **Maps quantum efficiency and carrier diffusion length across solar cell**
  - **Most sensitive near band edge -- choose wavelength carefully (unlike OBRICH)**

Scanning local illumination of solar cell



Current output across solar cell



Commercial tools available (Semilabs)
Services available (analogous to OBRICH)

J. Sites et al., (www.physics.colostate.edu/groups/photovoltaic/PDFs/SitesLBIC.pdf)

Electron Beam Induced Current

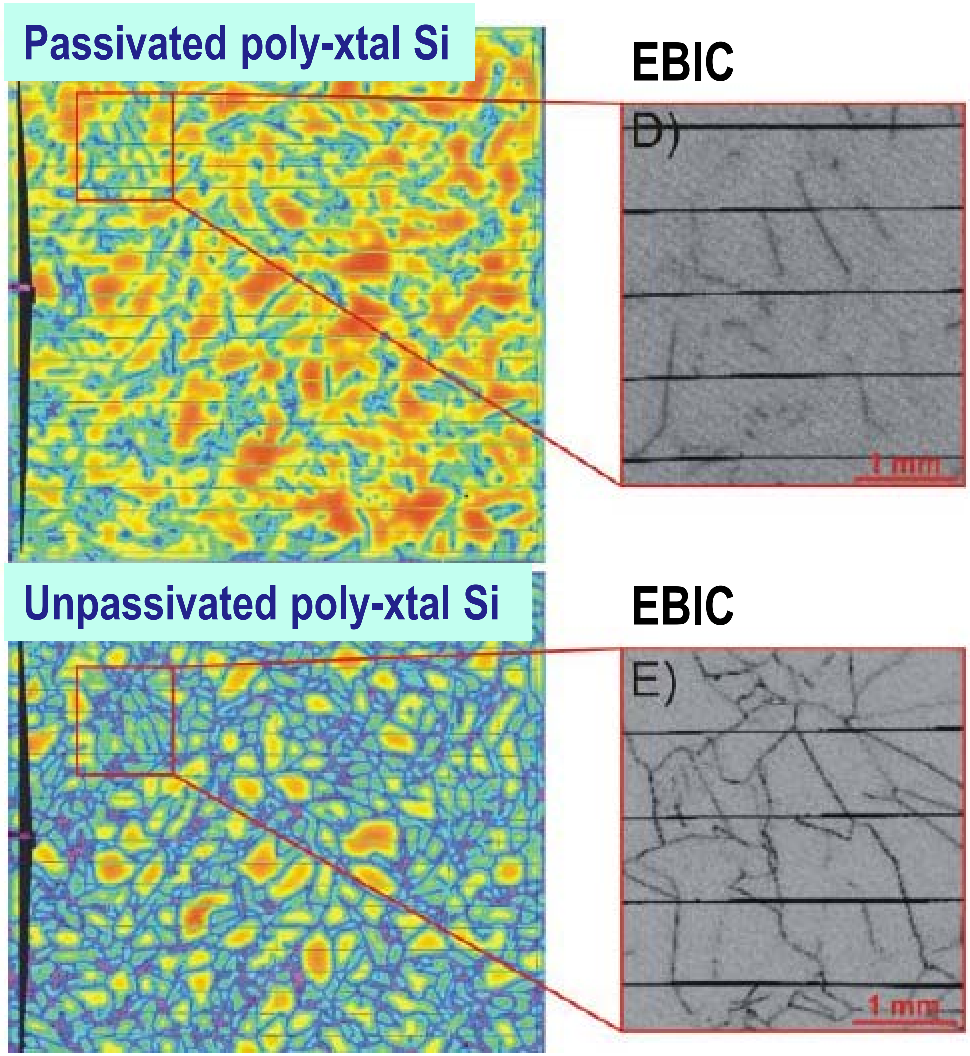
Performed in SEM

- Spatial resolution of LBIC limited by spot size and carrier diffusion

Internal quantum Efficiency maps

Greater carrier lifetime = greater efficiency

Positive impact of passivation



Inject electrons directly into Si (>10keV)

Shorter lifetime = dark at grain boundaries

Higher resolution (<10nm spot size)

- **Grain boundaries**
- **Dislocations**

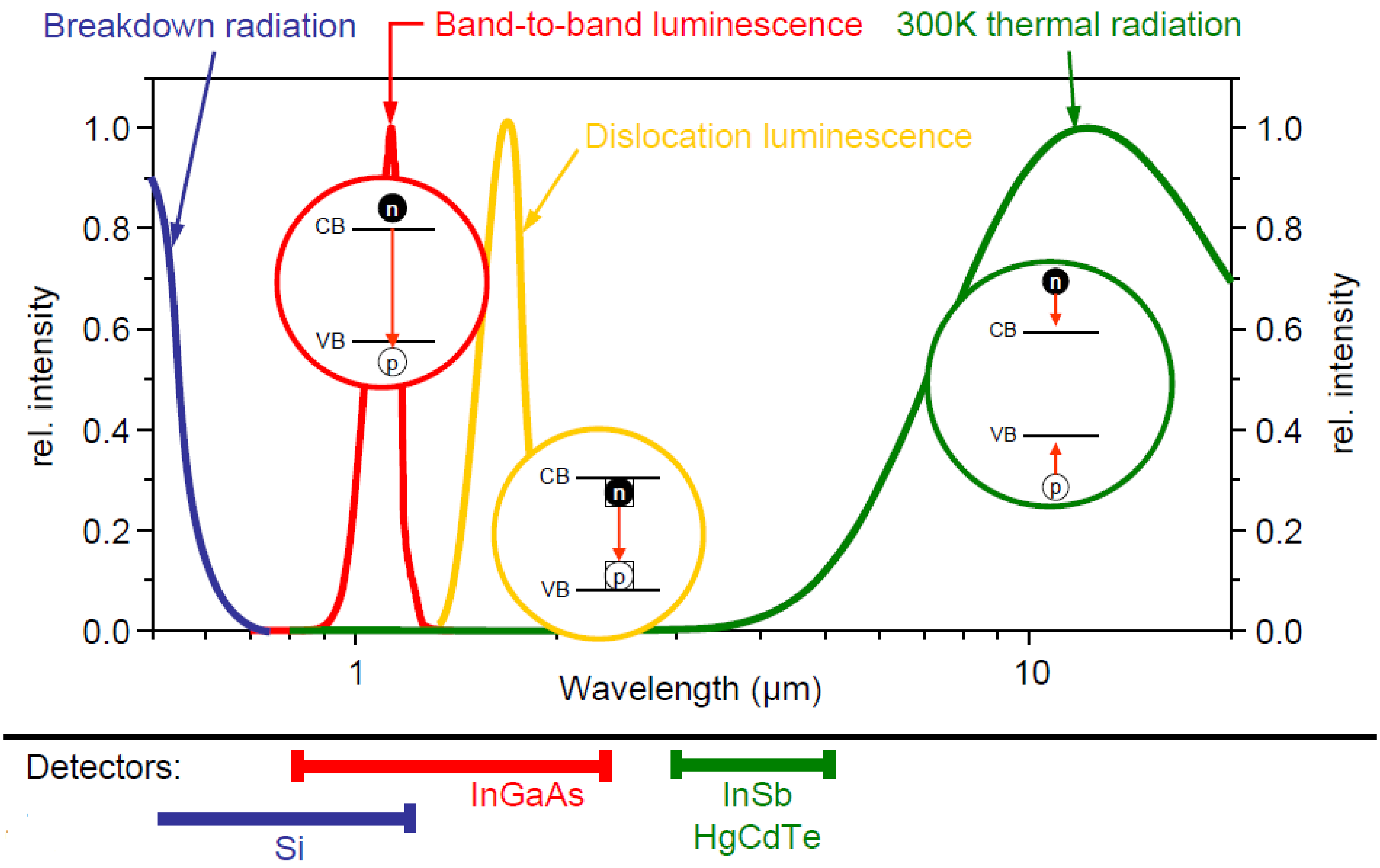
Low temperatures required for best resolution

A. Zuschlag et al., EU PV Energy Conf. (2008)

Optical Emission from Si (EL and PL)

For microelectronics (EMMI, PEM, etc.)

- **Different energy emission = different mechanism**



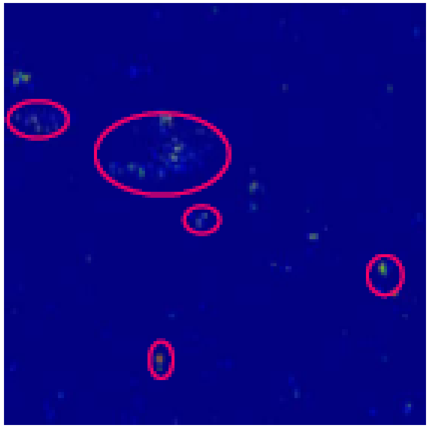
M. Kasemann et al., EU PV Sol. Energy Conf. (2008)

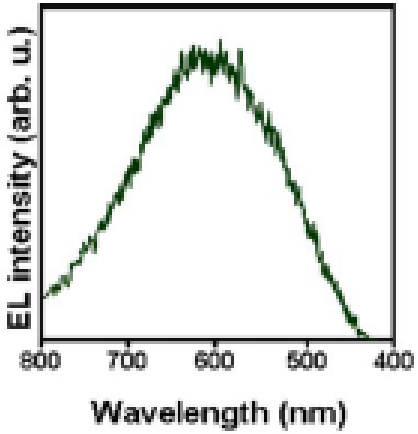
Visible Electroluminescence: Pre-breakdown

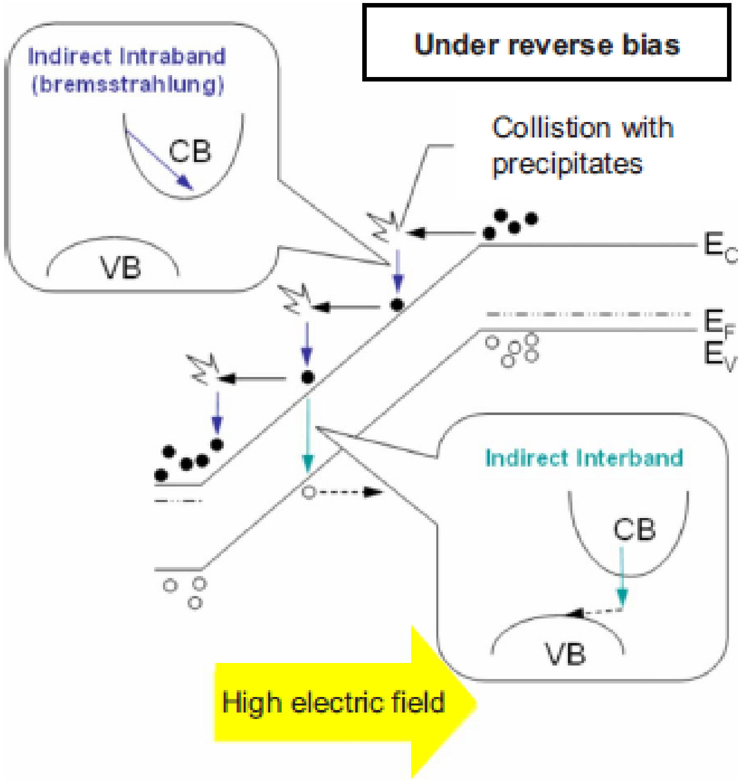
Hot carriers for electronics

Visible Emission Under Reverse Bias:

- localized EL spots visible (5-10V)
- Spectrum in visible







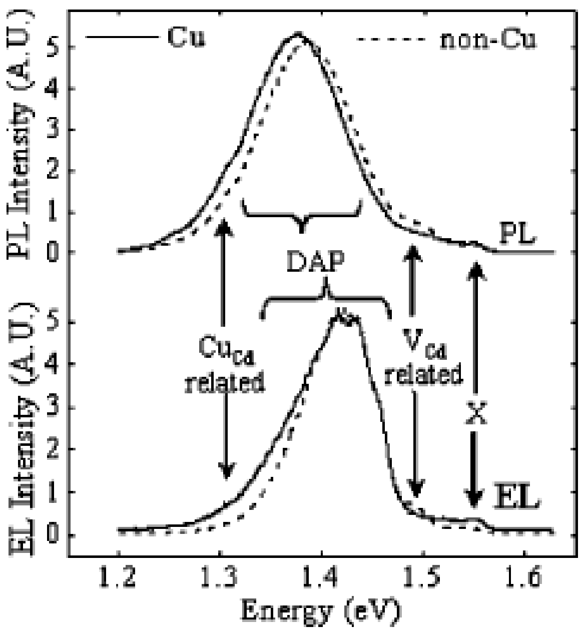
Energenic electrons with large reverse bias:

- "Avalanche" breakdown or "Zener" breakdown = broadband emission
- Correlation to metallic impurities
- Correlated to local heating

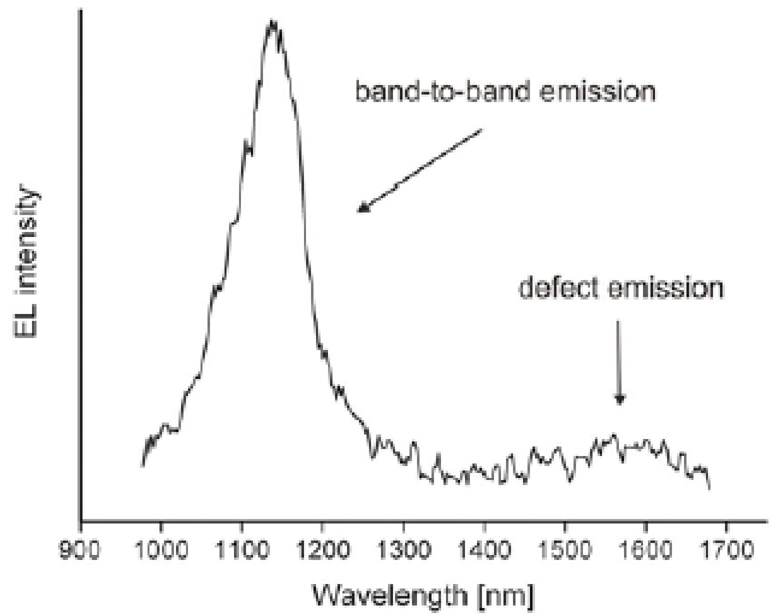
Kitiyanan et al, J. Appl. Phys 106, 043717 (2009)

Near-IR : Band-Band Emission

- **Strongest EL and PL emission from band-band**
  - **CdTe = direct bandgap(strong), Si = indirect (weak)**
- **Weaker emission from impurity states (band-tail)**



EL and PL emission from Cu-CdTe
DAP = Donar acceptor pair
Feldman et al, Appl. Phys. Lett. 85, 1530 (2004)



PL emission from poly Si
Band to band and defect (band edge)
Dreckschmidt et al, EU PV energy Conf (2007)

Carrier Lifetime mapping with Photoluminescence

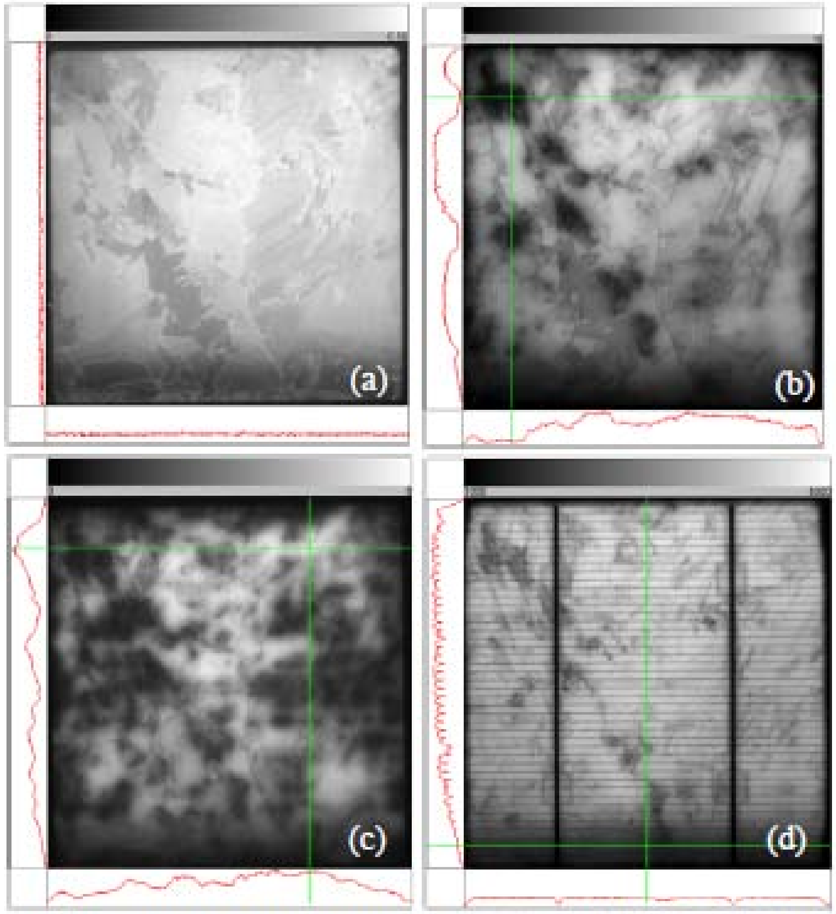


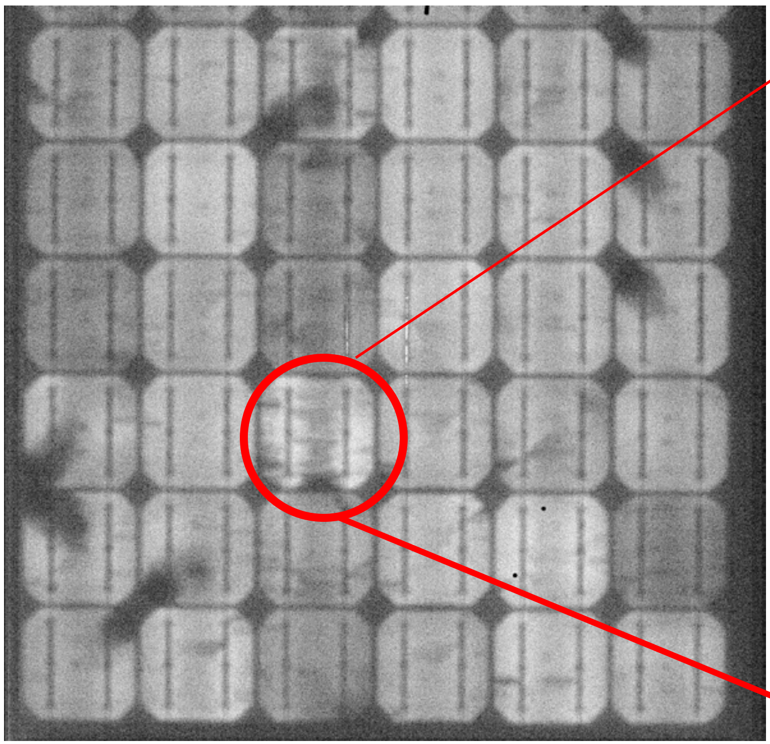
Figure 3: *Effective Minority carrier lifetime in µs from PL images measured on 5-inch mc-Si sister wafers after (a) surface damage etch, (b) emitter diffusion, (c) SiN deposition (not fired), (d) fully processed cell [color scale in counts per pixel and second for (d)].*

Trupke et al., PVSC (2008)

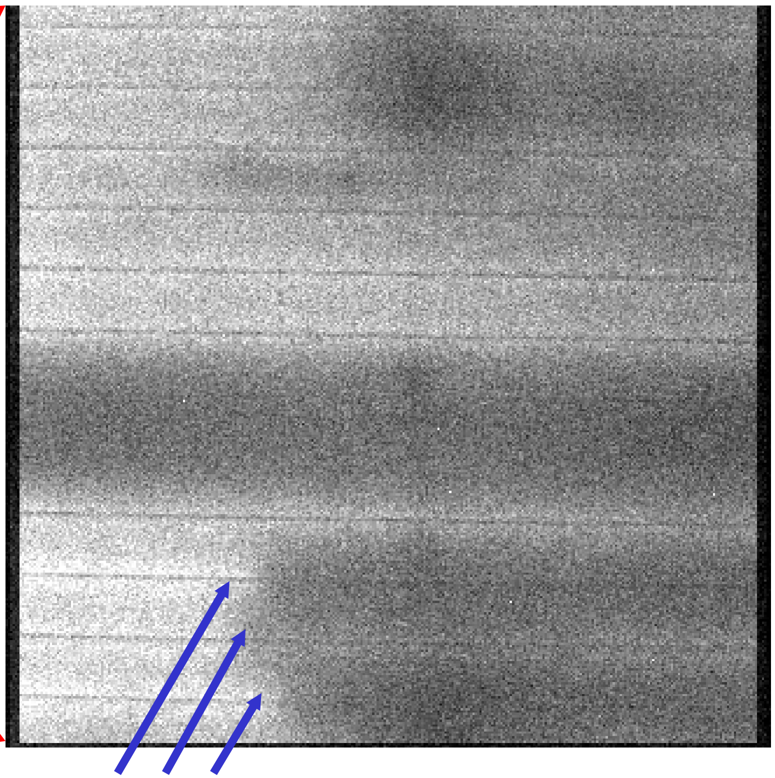
- **Photoluminescence: no bias required**
  - **Applicable to unpatterned cells**
- **Emission Intensity ~ lifetime**
  - **Intensity = G * τ**
    (Generation rate * Carrier lifetime)
  - **Fixed generation rate**
    - Intensity ~ lifetime
- **Quantitative lifetime**
  - **Not an absolute measurement**
  - **Calibration with know sample required**
  - **Transient method for calibration**
- **High illumination required**

Mapping Module Current with EL

- EL emission proportional to local current
  - Forward bias, image in NIR



Non-uniform EL emission of cell

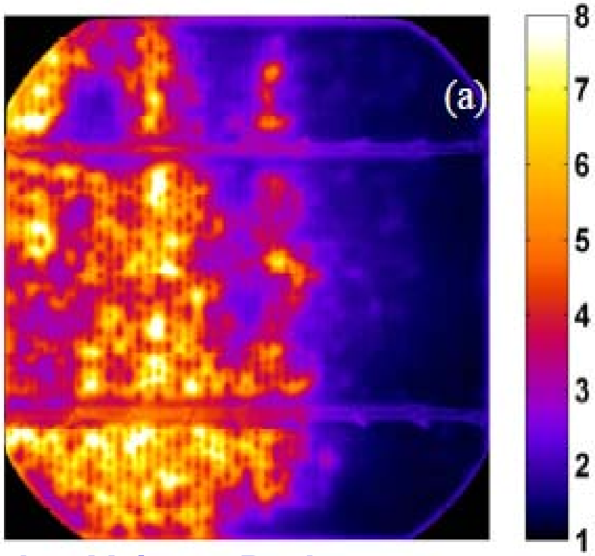


Broken contact lines on cell

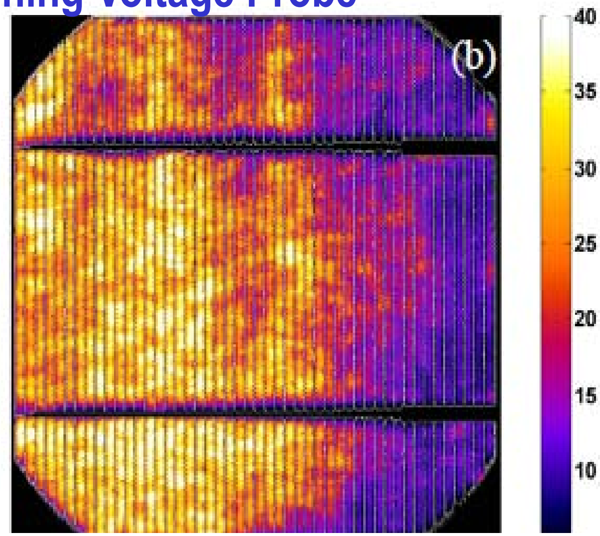
Electroluminescence intensity ~ current → Detect local breaks / cracks

Near IR EL: Series/shunt Resistance Mapping

Series resistance from EL



Scanning Voltage Probe



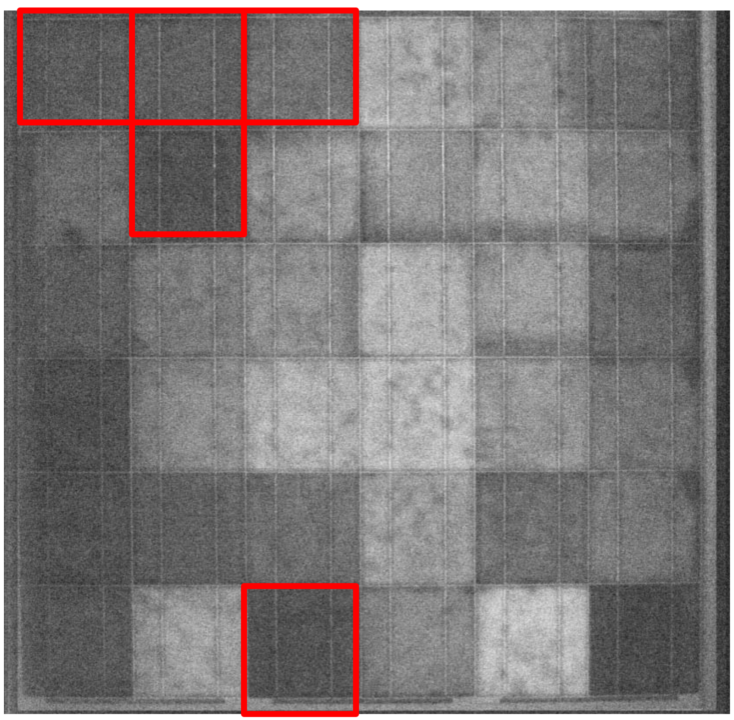
- **EL sensitive to local current and voltage**
  - Carrier diffusion length extraction
  - Diffusion depends on potential
- **Quantitative series and shunt resistance**
  - Difficult to determine why region is dark
  - Possible to extract voltage
  - Non-linear IV dependence → modeling
- **Qualitative: Bias dependence**
  - Current has turn-on voltage
  - Region always dark = High series R
  - Region dark at low current = Low shunt R

Trupke et al., Appl. Phys. Lett 90, 093506 (2007)

Electroluminescence Applied to Modules

- EL emission has turn on voltage near Voc
  - Shunted cells = lower Voltage at given current relative to good cells
  - Cell-cell contrast will depend on bias current

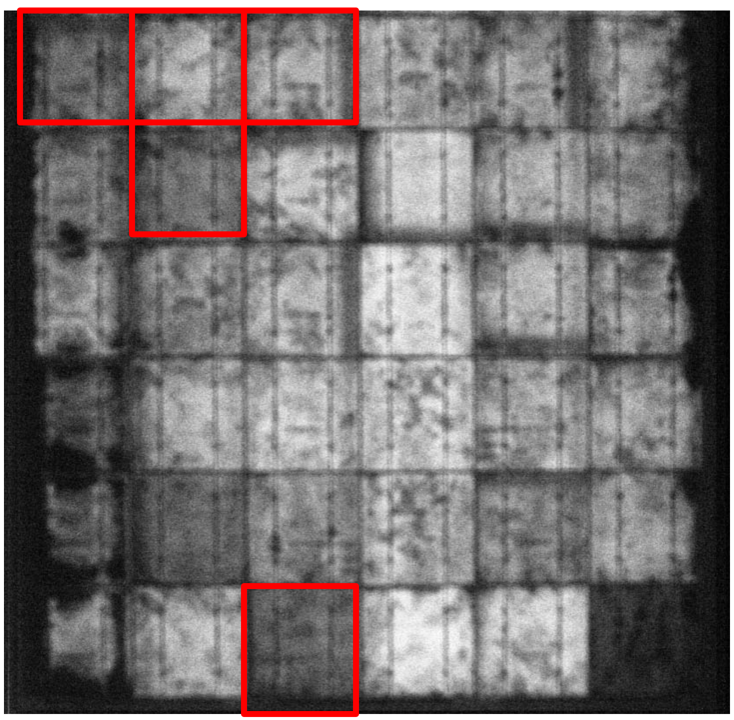
0.75 A / 35V Bias



Bad cells at low bias

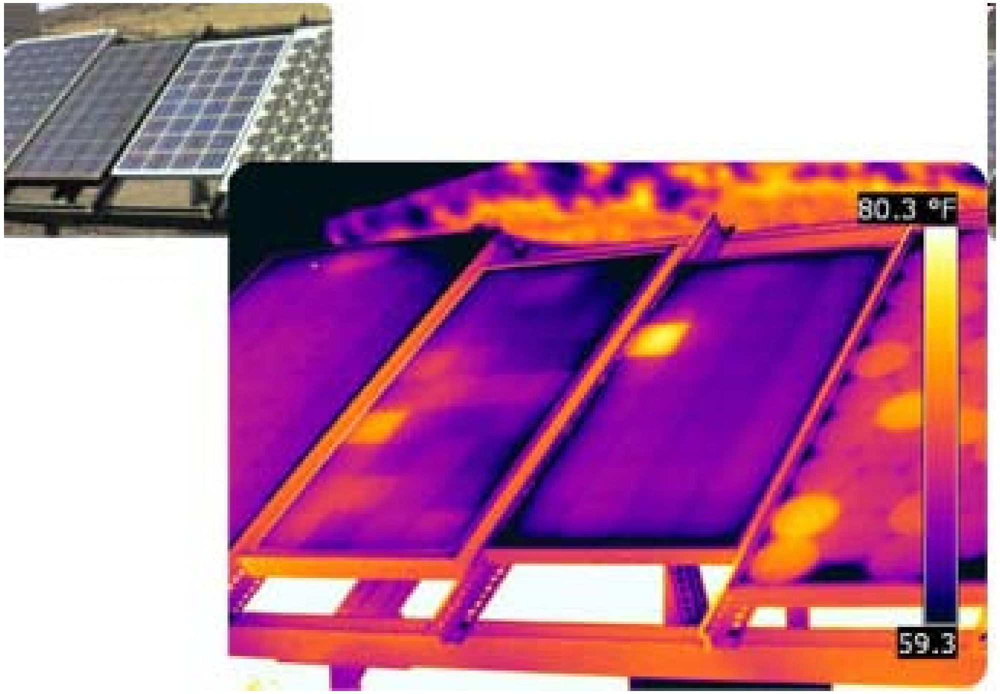
Cells “OK” at high bias

3 A / 45V Bias



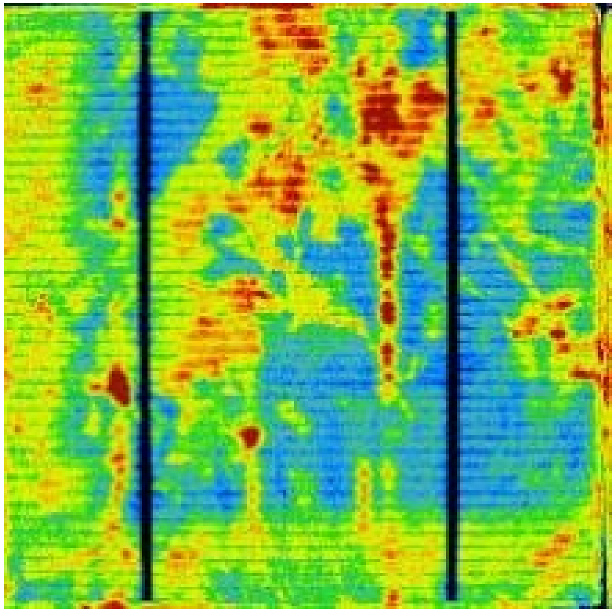
Far-IR: Thermal Emission Imaging

Infrared imaging of modules:
Shunted cells



www.movitherm.com

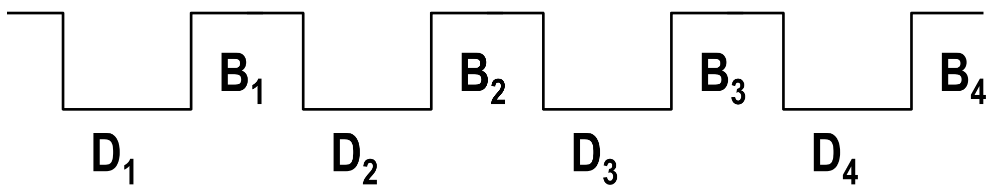
Infrared imaging of cells:
Local shunts / weak diodes



Infrared Imaging: industry standard for PV analysis

Lock-in Thermography

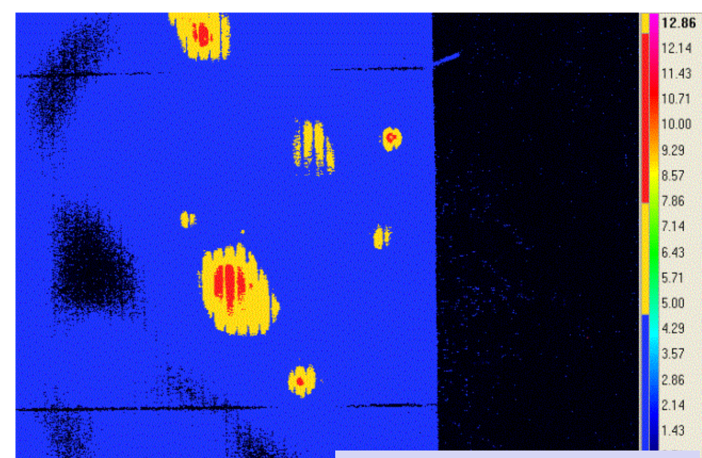
- **Static IR images: Thermal Spreading**
  - Temperature wants to be uniform = low resolution
- **Lock-in thermography: pulses**



Series of Dark images (D)
Series of Bright images (B)
Image = Σ_i [Bi – Di]

  - Uses high speed infrared CCD cameras
  - <1mK thermal resolution
  - Spatial resolution =
    - Thermal Diffusion / frequency ~ 3mm
- **Very quantitative (variables scale out)**
  - Shunt current, shunt IV

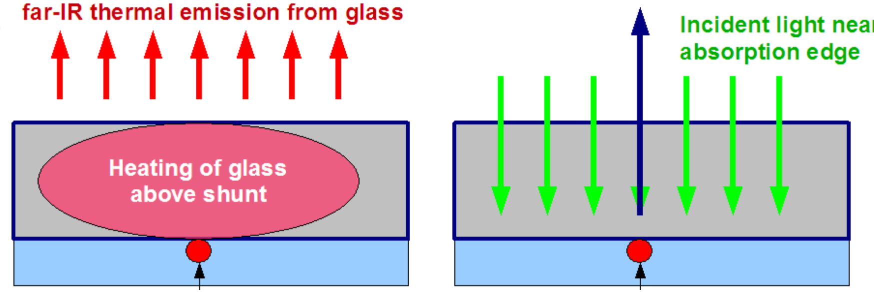
$$I_{\text{shunt}} = \frac{I_{\text{cell}}\left(\overline{T^{-90°}_{\text{shunt}}} - \overline{T^{-90°}_{\text{hom}}}\right)}{\overline{T^{-90°}_{\text{cell}}}} \frac{A_{\text{shunt}}}{A_{\text{cell}}}$$



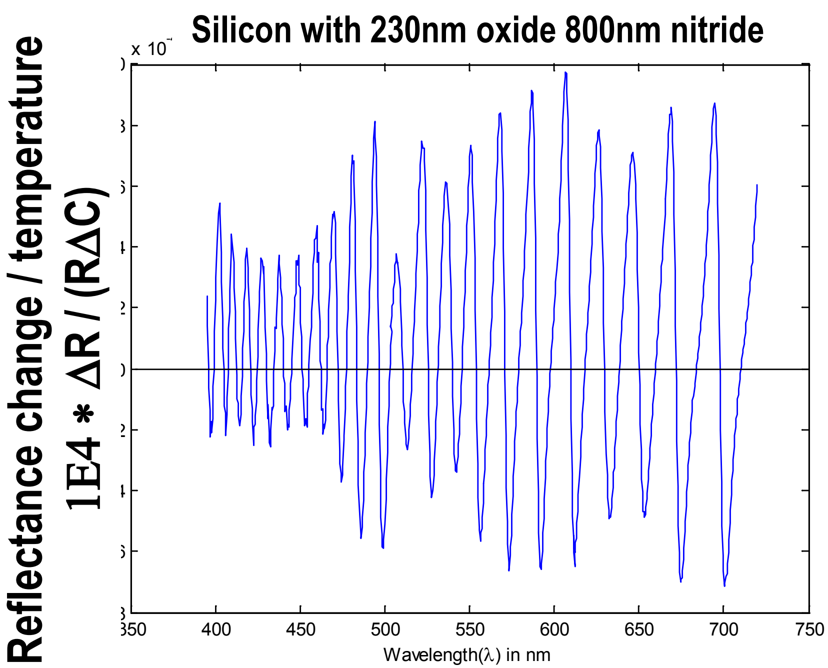
Shunt Current (NREL)

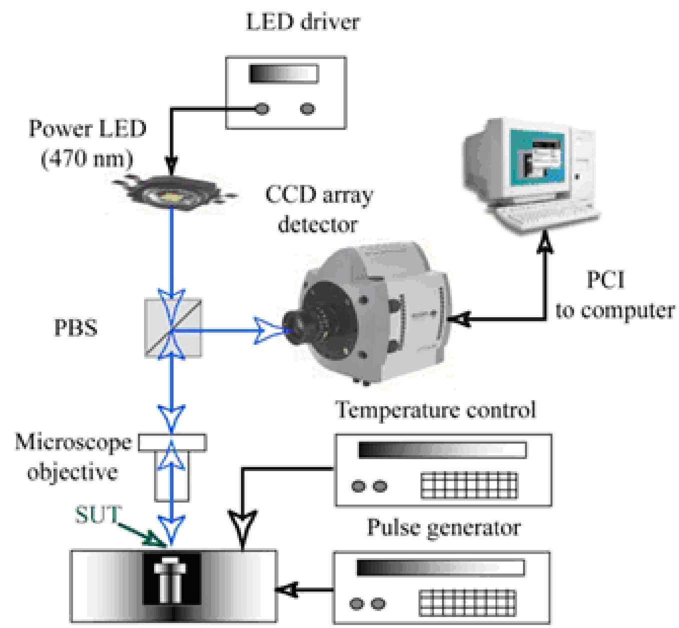
Infrared Limitations

- Most PV glass is not transparent in IR
  - Imaging glass, not defects
  - Limits resolution to thickness of glass
- Imaging is in infrared = lost physics



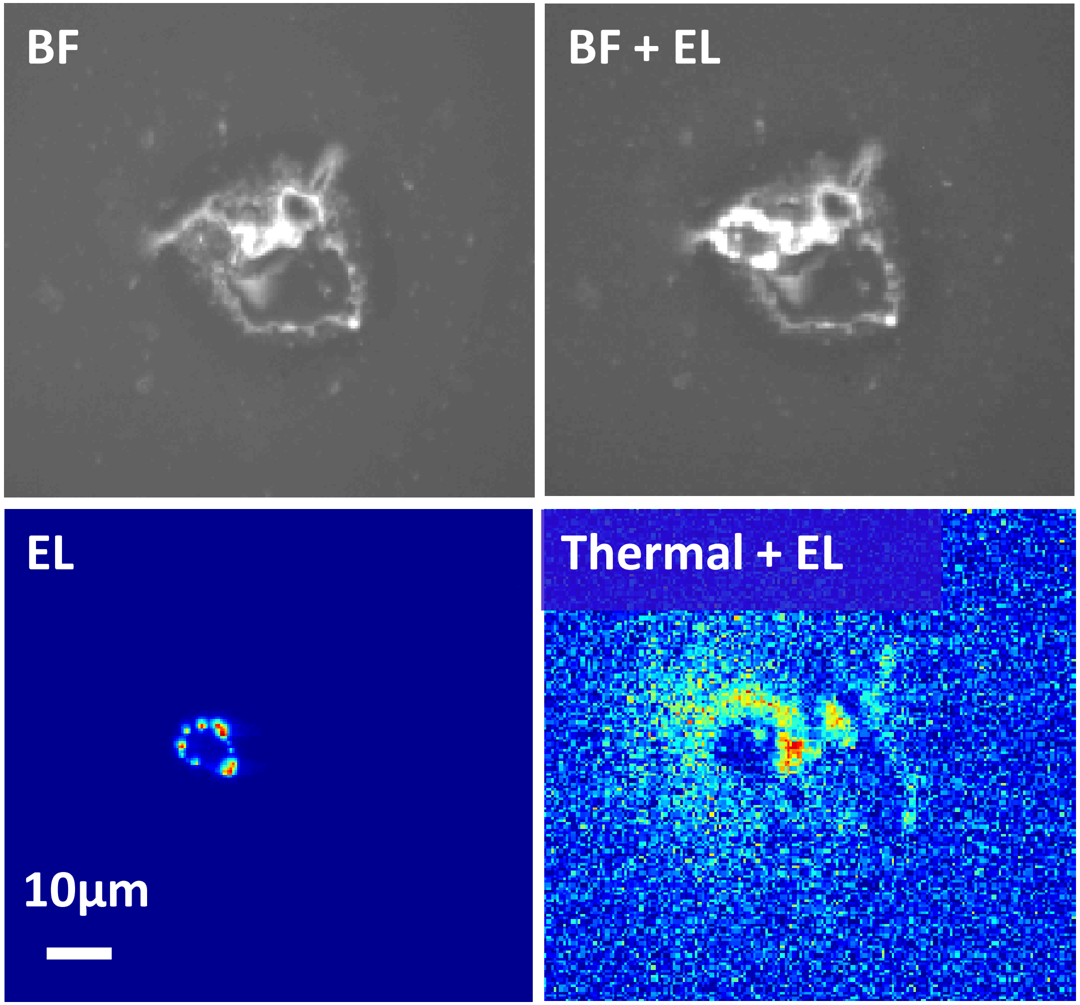
Thermalreflectance imaging in visible





Thermalreflectance imaging (see poster)

- Thermal imaging in visible
  - Glass is transparent
  - Combined images
    - brightfield
    - electroluminescence
    - thermal
  - Silicon camera
    - high pixel count
    - inexpensive



- Example for poly-Si
- Available as tool or service

PARTIAL list of Failure Analysis Service Companies

- **NOT an endorsement by UCSC or NREL**
  - North American companies that service electronics and photonics
  - Incomplete list (I am sorry for those that I left off)

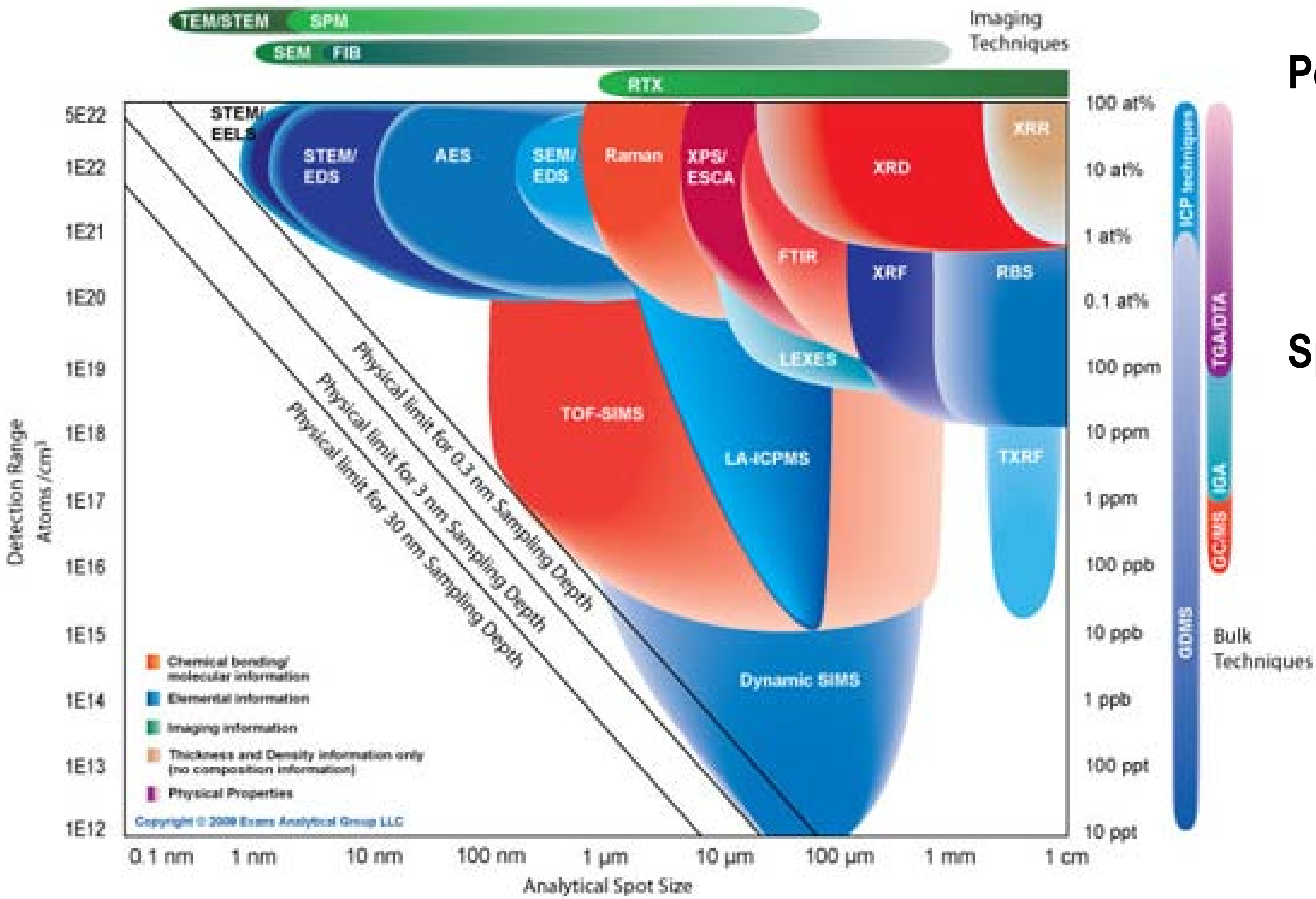
Company Site (Alphabetical order)	State	Scanning Acoustic Imageing	Florescence Dye or Dye and Pry	Emission Microscopy (EL)	Scanning Optical (LBIC/OBRICH)	Photoluminescence	Thermal – Infrared or Liquid Crystal	Thermal – Thermalreflectance	Voltage Contrast SEM	X-ray imaging, 2-D and 3-D
www.alenasimaging.com	MA							■		
www.apvresearch.com	CA			■		■		■		
www.chiptargets.com	TX	■	■	■			■			
www.ial-fa.com	CO	■		■					■	■
www.icchippackaging.com	TX	■	■							■
www.icfailureanalysis.com	CA	■		■	■					■
www.martintesting.com	CA	■					■			■
www.mefas.com	CA	■		■			■		■	■
www.movitherm.com	CA						■			
www.muanalysis.com	ON			■	■	■	■			
www.ors-labs.com	NY	■					■			■
www.reltron.com	CA			■			■			
www.rigalab.com	CA		■		■				■	■
www.svtc.com	CA								■	

Microelectronics and PV failure Analysis

- **Most microelectronics techniques applicable to PV industry**
  - Only acronym is different
- **Different requirements for each industry**
  - Focus for microelectronics is resolution
  - Focus of photovoltaics is throughput and wide area
- **Future: two industries will converge**
  - Transition to thin film technology from crystalline Si
  - Focus on yield improvement
  - Focus on reliability improvement

Physical Microanalysis

- Wide range of surface / composition analysis



Penetrating probes
- XRF/XRD/XRR
- RBS
- FTIR

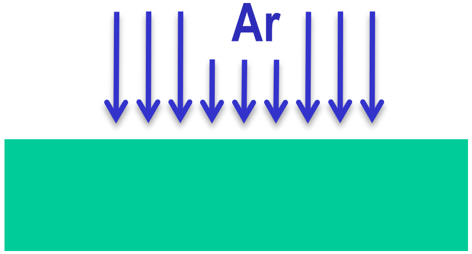
Sputtered / surface
- SIMS
- AES
- SEM/EDS

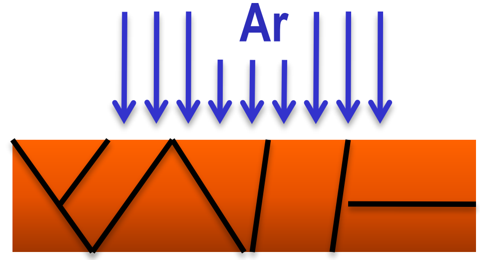
From EAG Inc. (www.cea.com)

Warning with sputtered microanalysis probes

Sputtering profile for single vs. poly crystalline samples

Sputter profile single crystal material





Sputter profile poly-crystal material

Sputter profile Uniform

Sputter rate varies with orientation (channeling)

Sputter profile broadened by redeposition (minor)

VERY broad sputter profile