Photovoltaic Failure Analysis: Techniques for Microelectronics and Solar

Glenn B. Alers
Department of Physics, University of California, Santa Cruz
galers@ucsc.edu
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
  - Electroluminescence imaging
  - Photoluminescence 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 photovoltaics: 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

Excessive hot carriers or leakage = Light emission

Imaging Camera (near IR-vis)

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

\[ \Delta V = I \left( \frac{\delta R}{\delta T} \right) \times \Delta T \]

AC voltage signal ~ current

Probe of local current

\[ I = \Delta V \times \text{(constant)} \]

Probe of resistance along line

OBIRCH 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

- Water bath

- Sensitive to delamination (Failed encapsulant)

- Poor contacts (solder bumps)

- ~10µm resolution

- Water bath required
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

Si chip

PCB

Soak in Dye

Si chip

PCB

Pry off top

Si chip

PCB

Stain on poor contact

PCB

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

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)
  - Photoluminescence (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

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

J. Sites et al., (www.physics.colostate.edu/groups/photovoltaic/PDFs/SitesLBIC.pdf)
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)
Different energy emission = different mechanism

- Breakdown radiation
- Band-to-band luminescence
- 300K thermal radiation
- Dislocation luminescence

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

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

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

- Photoluminescence: no bias required
  - Applicable to unpatterned cells

- Emission Intensity ~ lifetime
  - Intensity = $G \times \tau$
    (Generation rate * Carrier lifetime)
  - Fixed generation rate
    - Intensity ~ lifetime

- Quantitative lifetime
  - Not an absolute measurement
  - Calibration with known sample required
  - Transient method for calibration

- High illumination required

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)
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 \(\rightarrow\) Detect local breaks / cracks
Near IR EL: Series/shunt Resistance Mapping

Series resistance from EL

- 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

Infrared imaging of cells:
Local shunts / weak diodes

www.movitherm.com

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

\[ \text{Image} = \sum_i [B_i - D_i] \]

- Uses high speed infrared CCD cameras
- <1mK thermal resolution
- Spatial resolution =
  - Thermal Diffusion / frequency ~ 3mm

- Very quantitative (variables scale out)
- Shunt current, shunt IV
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**

![Graph of Reflectance change / temperature vs. Wavelength (nm)](image)

Silicon with 230nm oxide 800nm nitride

- **Far-IR thermal emission from glass**
- **Incident light near absorption edge**
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)

<table>
<thead>
<tr>
<th>Company Site (Alphabetical order)</th>
<th>State</th>
<th>Scanning Acoustic Imaging</th>
<th>Fluorescence Dye or Dye and Pry Emission Microscopy (EL)</th>
<th>Scanning Optical (LBIC/OBRICH)</th>
<th>Photoluminescence</th>
<th>Thermal – Infrared or Liquid Crystal</th>
<th>Thermal Reflectance</th>
<th>Voltage Contrast</th>
<th>SEM</th>
<th>X-ray imaging, 2-D and 3-D</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="http://www.alenasimaging.com">www.alenasimaging.com</a></td>
<td>MA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.apvresearch.com">www.apvresearch.com</a></td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.chiptargets.com">www.chiptargets.com</a></td>
<td>TX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.ial-fa.com">www.ial-fa.com</a></td>
<td>CO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.icchippackaging.com">www.icchippackaging.com</a></td>
<td>TX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.icfailureanalysis.com">www.icfailureanalysis.com</a></td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.martintesting.com">www.martintesting.com</a></td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.mefas.com">www.mefas.com</a></td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.movitherm.com">www.movitherm.com</a></td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.muanalysis.com">www.muanalysis.com</a></td>
<td>ON</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.ors-labs.com">www.ors-labs.com</a></td>
<td>NY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.reltron.com">www.reltron.com</a></td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.rigalab.com">www.rigalab.com</a></td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><a href="http://www.svtc.com">www.svtc.com</a></td>
<td>CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
Uniform

Sputter profile
broadened by redeposition (minor)

Sputter profile
poly-crystal material

Sputter rate varies with orientation (channeling)

VERY broad sputter profile