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Thin-Film Module Reverse-Bias Breakdown Sites Identified by Thermal Imaging

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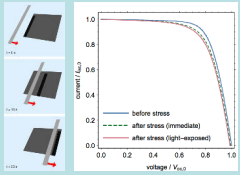
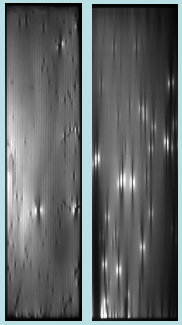
- **Partial shading stresses cells when current matching forces shadowed cells into reverse bias.**
- **If reverse breakdown is uniform, current and heat are spread uniformly.**
- **But, if breakdown is localized, high current density generates substantial heat within the cells and can create permanent damage and degradation.**

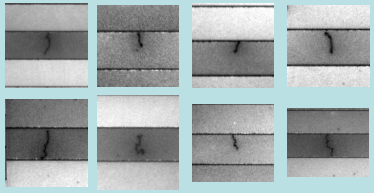


Experiment showed 5% immediate power loss from partial shading.

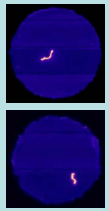
Damage in Monolithic Thin-Film Photovoltaic Modules Due to Partial Shade
Timothy J. Silverman, Lorelle Mansfield, Ingrid Repins, and Sarah Kurtz,
IEEE J. of Photovoltaics 6, (5) pp. 1333-1338, 2016.



- EL images of modules that have aged and degraded for years in the field.
- Dark areas show shunt-like defects that result in voltage drops and extension of low EL intensity along the cell near the shunt.
- Bright areas result from higher current density as carriers crowd toward the shunt defects.



PL images of shunt defects in the modules show "wormlike" defect features where material has become damaged and is leading to higher carrier recombination. The drop in voltage due to the shunts also causes the cell area near the defect to emit a lower PL intensity.



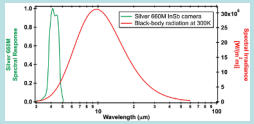
ILIT imaging shows that carrier recombination through the shunts results in increased heating.

Thermal Imaging with InSb Camera

Cedip Silver 660M FLIR SC5600-M

Lock-In Thermography

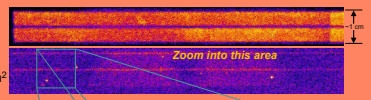
- Dark (DLIT): forward or reverse bias.
- Illuminated (ILIT): light-induced forward bias.



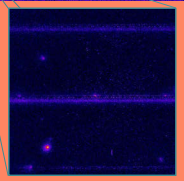
- InSb infrared camera cooled to ~76 K,
- 640 x 512 array of 14-bit, 15 μm square pixels,
- 100 Hz frame rate,
- Lock-in detection, similar to averaged subtractions of dark, no-bias background image from biased image,
- Use ~1 to 30 Hz for bias pulses,
- Total acquisition time of seconds to minutes,
- Varying bias for defect characterization,
  - Ohmic-type, Schottky-type, pre-breakdown, and recombination-induced.

CIGS – early-breakdown detection

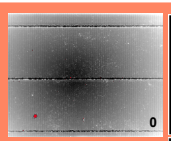
- Limit current flow during reverse bias to locate defect sites without causing permanent damage.



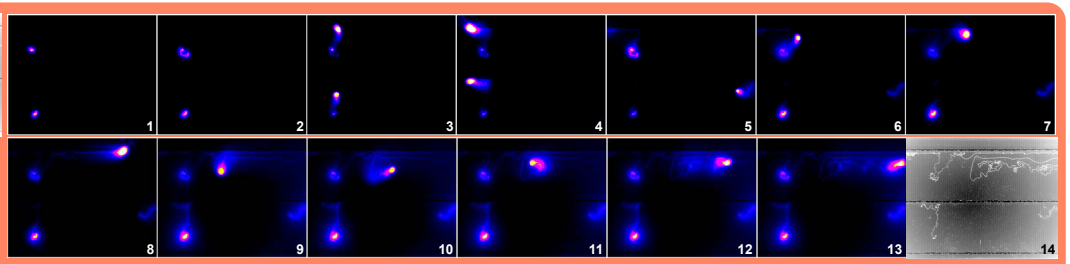
DLIT imaging shows fairly uniform heating of two series-connected CIGS cells in forward bias (top). With limited current, the reverse-bias DLIT image identifies possible breakdown sites (bottom).



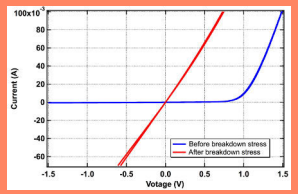
Zooming in for higher spatial resolution shows the location of defects in their pre-breakdown state.



Thermal image with $DLIT_{rev}$ overlay (red) showing suspected early-breakdown defect sites (frame 0).

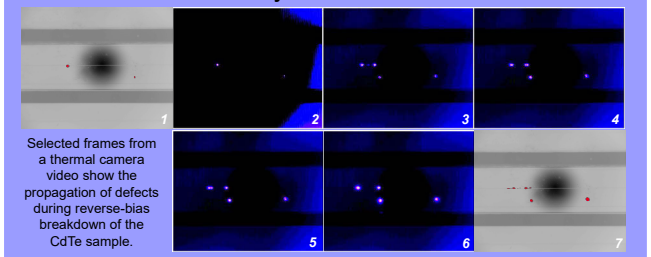


Selected frames from a thermal camera video show the propagation of wormlike defects during reverse-bias breakdown of the CIGS sample. Frame 1 shows heating at the defects when current density is limited to a low value (<30 mA/cm² total area). Frames 2 and 3 show how the defects begin to propagate when current density is increased to ~60 mA/cm². Frames 4 through 13 show how breakdown sustainably travels for roughly a minute within the cells and along scribe lines at a high current density of ~150 mA/cm². After stressing, the thermal camera captures the accumulated damage due to breakdown defect propagation as shown in frame 14.



I-V curves collected before and after reverse-bias stressing are shown for the two series-connected CIGS cells. Reverse-bias breakdown has created permanent shunting within the device.

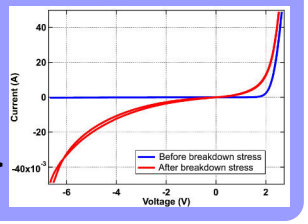
CdTe – early-breakdown detection



Selected frames from a thermal camera video show the propagation of defects during reverse-bias breakdown of the CdTe sample.

Frame 1 shows the starting current-limited DLIT image in red overlaid on the gray-scale thermal image. The dark spot is due to reflection of the cold camera sensor. Frame 2 shows heating at the defects when current density is limited to a low value (40 mA/cm²). Frame 3 shows how breakdown travels quickly along the scribe lines, and an additional defect becomes apparent when the current density is increased to ~100 mA/cm².

Then, frames 4 through 6 show how the defect heating changes rather slowly for roughly a minute. After stressing, the thermal camera captures the accumulated damage due to breakdown defect propagation as shown in frame 7, where the DLIT image in red is overlaid on the gray-scale thermal image.

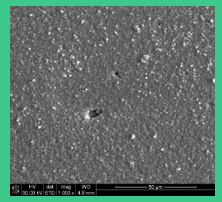


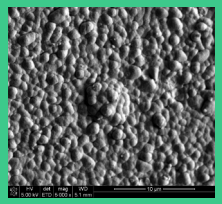
I-V curves collected before and after reverse-bias stressing are shown for the two series-connected CdTe cells. Reverse-bias breakdown has created permanent shunting within the device.

Microscopic views of early-breakdown defect before propagation and wormlike defect formation

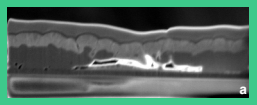
CIGS pinhole/crater type defect | **CIGS nodule/bump type defect**

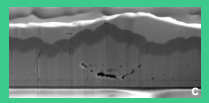
Overhead scanning electron microscope (SEM) views





Focused ion beam cross-sectional SEM views





CdTe void type defect

SEM cross-sectional views show ~10 μm size features associated with the initiation of early reverse-bias breakdown. The hole/void type of defects are within the absorber layer of CIGS (a) and CdTe (b). A smaller void-type defect of ~5 μm size shows a curved feature in CIGS (c).

Summary

- Partial shading on thin-film modules can lead to degradation when early-breakdown defects cause localized heating and permanent damage.
- Reverse bias was applied while limiting the current to prevent thermal runaway.
- DLIT imaging was used to locate sites where heating shows that early breakdown will likely occur.
- Thermal imaging revealed that the identified defects were the initiating sites for early breakdown, and thermal video recorded the defect propagation.
- Defects such as film pinholes or voids appear to be weaknesses for reverse bias and may be origins for the formation of wormlike defects under conditions of partial shading.
- Since defects appear to be related to deposition and processing conditions, possible mitigation strategies might include the following:
  - Improve processing to minimize small structural defects and maximize uniformity,
  - Monitor for defects during manufacturing,
  - Develop preventive maintenance procedures and equipment cleaning routines to maintain high-quality film uniformity and prevent processing-related defects,
  - Implement more advanced processing methods or cell architectures to minimize the formation and impact of grown-in structural defects.

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