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Failure Analysis and Reliability Model Development for Microsystems-Enabled Photovoltaics

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***Abstract* — Microsystems-enabled photovoltaics (MEPV) has great potential to meet increasing demands for light-weight, efficient, photovoltaic solutions with high power density. This paper describes current efforts to build a reliability model for MEPVs, including the examination of failed or underperforming cells as well as the failure analysis techniques used to identify them. Early stress test results and applications of defect localization techniques, such as electroluminescence under forward and reverse bias, optical beam induced current, as well as optical beam induced resistance change, are also presented.**

***Index Terms* —photovoltaic cells, solar energy, reliability, failure analysis, thin film devices, silicon**

I. Introduction and MEPV Technology Overview

Many applications of photovoltaics, such as those for space and portable devices, have a strong need for light-weight, flexible, efficient solutions with a high specific power. Microsystems-enabled photovoltaics (MEPV) have great potential to satisfy these requirements. The MEPV approach utilizes microfabrication techniques to create arrays of thin hexagonal solar cells that are 250 µm to 1 mm in diameter and 14 µm to 20 µm in thickness [1]. These cells can be assembled onto flexible substrates and interconnected to produce arrays with high power concentration. Fig. 1 shows a bright field image of the back side of an MEPV cell using an optical microscope.

The novel fabrication and packaging techniques to create MEPV arrays result in the need for a new model to predict reliability. This paper describes the latest efforts and techniques used to create this predictive capability.

II. Failure Analysis and Reliability Techniques

The failure analysis framework consists of electrical characterization, electroluminescence (EL), optical beam induced current (OBIC), and optical beam induced resistance change (OBIRCH). EL, where the image consists of light emission collected from the device under forward bias, is used to evaluate the relative performance of each cell. In addition, EL under reverse bias is also used to localize the source of significant leakage currents.

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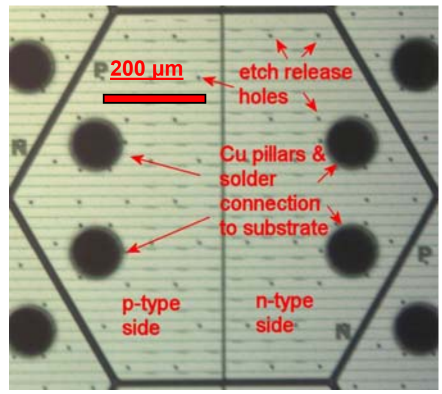

Fig. 1. Optical image of a 720 µm cell. The picture shows the metal layer that connects the p-doped (left half) and n-doped (right half) regions. The two halves take the shape of interlacing fingers that run along the center of the MEPV.

OBIC uses a raster-scanning laser stimulus with sufficient photon energy to generate electron-hole pairs that are then collected. Low-noise amplification is performed on the current signal to form an image [2]. It is used to evaluate cell performance and complements EL by providing additional information on localized efficiency thin an individual cell.

OBIRCH is similar to OBIC but uses a laser with photon energy below the band gap, resulting in localized heating. The OBIRCH image is created by measuring the currents generated by the laser-induced temperature gradients.

The MEPV cells are subjected to voltage, thermal, and light stress to explore degradation and failure mechanisms related to these factors. Results from a voltage stress study are presented in this abstract. The final paper will include results from additional studies. The findings are used to build the first reliability MEPV reliability model.

III. Results

Forward-biased EL has been established as a means to evaluate the relative performance of MEPV cells in an array before and after stress. Fig. 2 shows an example of a forward-biased EL image. The hexagonal solar cells in the image are 720 µm in diameter. Each horizontal row in the cell is connected in parallel, and the rows are connected in series. The relative brightness of each row is related to the number of functioning cells in that row. EL is able to identify nonfunctioning cells as well as partially functioning ones. Examples of both situations are represented in Fig 2.

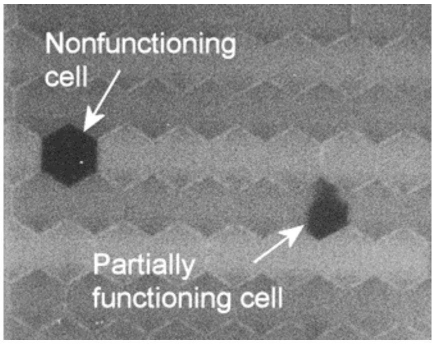

Fig. 2. Electroluminescence is used to evaluate relative efficiency of MEPV arrays. This figure shows an example of a non-functioning cell and a partially functioning one. Certain cells have area defects that limit performance.

OBIC has also been used to provide additional information on the cell functionality to complement the EL results. Fig. 3 shows an OBIC image where there is a darker region encompassing the right-half of the MEPV cell. This region covers most of the metal layer connected to the p-type silicon region and suggests poor carrier generation or collection.

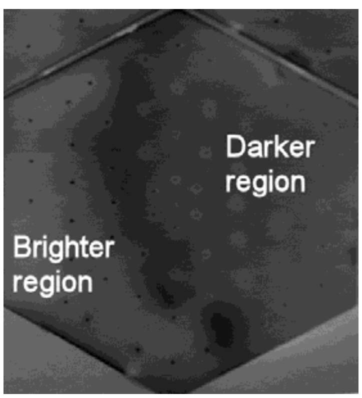

Fig. 3. OBIC image using an above-band-gap laser stimulus provides additional fidelity on the regional performance on a single MEPV cell. The darker half indicates a possible carrier generation or collection issue in the region of the right half of the metal layer.

OBIRCH allows us to evaluate the electrical connections in the MEPV cell system [2]. As shown in Fig. 4, the electrical contacts that connect the silicon to the metal layer are visible in the OBIRCH image if the cell is functioning. These contacts are not visible in the nonworking cell. The larger etch release holes, however, are still visible, suggesting that the nonfunctioning cell is still electrically connected with the array. Therefore, the failure mechanism could be related to the contacts between the silicon and metal layer. Further defect localization is necessary before subsequent destructive analysis to determine the root cause.

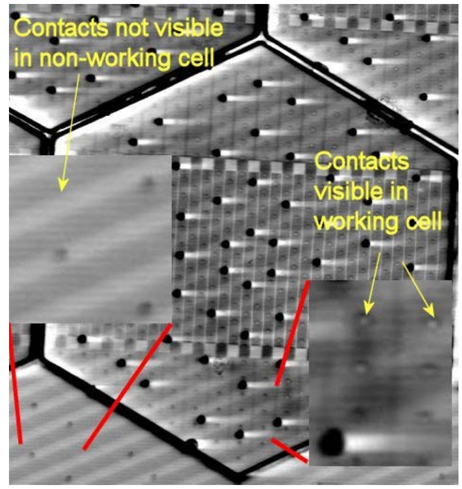

Fig. 4. OBIRCH enables the evaluation of the contacts between the silicon and metal layer. These contacts are shown as smaller dots that are not visible in the neighboring, nonfunctioning cells.

In addition to analysis through EL, OBIC and OBIRCH, mechanically polished cross sections are analyzed to determine the quality of the electrical connection between the solar cell and the metal trace lines that connect them to each other. Fig. 5 illustrates two features of interest: voids in the solder connection and absorption of the metal trace lines into the solder. The voids could lead to increased series resistance or poor connection between the solar cell and the metal trace. Further analysis with scanning electron microscopy shows that the metal trace is thinner in regions that are in contact with the solder where it is potentially consumed due to the temperature of the soldering process. Both the voids and the decreased thickness in metal traces are present in functioning cells. Additional cross sections of samples that have experienced temperature cycling will provide more insight into the long-term effects of these defects.

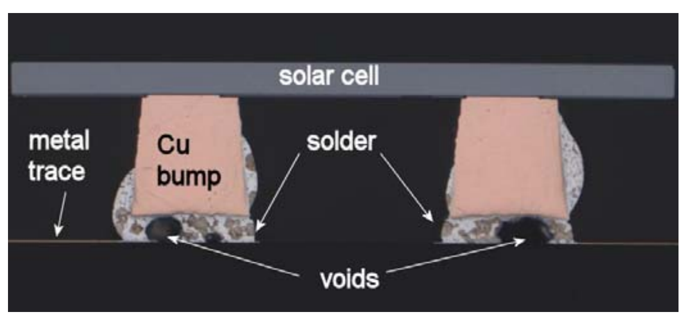

Fig. 5. Mechanical polishing and optical microscopy has been used to evaluate the quality of the solder connection between the copper legs and the gold lines. Voids such as the one shown here could be a source for increased series resistance.

The MEPV arrays have been subjected to reverse-bias voltage stress and have shown good endurance. Breakdown does not occur until 75 volts (V). Fig. 6 shows the reverse bias I-V of 28 cells in parallel and illustrates the effect of prolonged reverse-bias stress. After 11 voltage sweeps, where each sweep lasts approximately 10 seconds, the reverse-bias leakage current begins to increase dramatically, especially at the lower voltages.

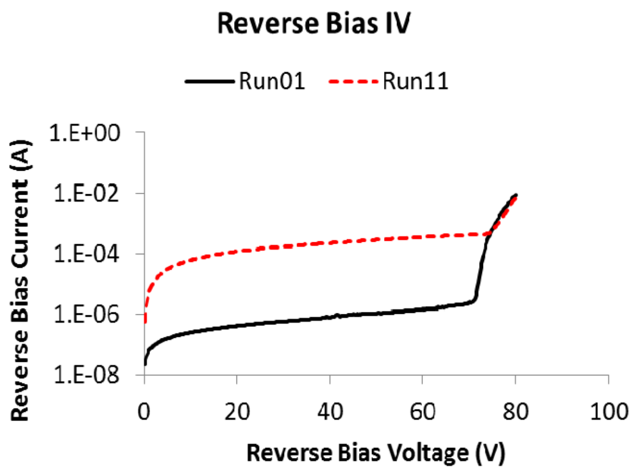

Fig. 6. Current-voltage curves before and after reverse-bias stress. Each voltage sweep takes approximately 10 seconds. Breakdown occurs at approximately 75 V. We can see that current leakage is aggravated after repeated voltage stress.

Further analysis of the sample in Fig. 6 shows that the effects of reverse-bias stress are localized. The Fig. 7 shows a portion of the forward-biased EL image of the MEPV array. The cell on the far right has a region that is not emitting light.

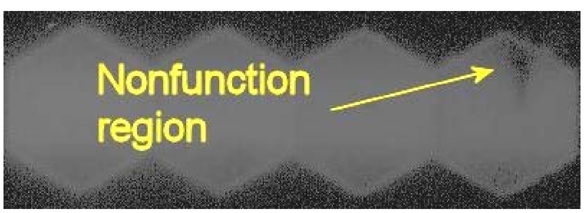

Fig. 7. Electroluminescence image of the MEPV cells measured in Fig. 6 after reverse-bias stress. The cell on the far right has a non-functioning region.

This potential-induced defect can be further localized by taking an EL image of the MEPV array under reverse (instead of forward) bias. Prior to the voltage stress, the MEPV array produced no visible light emission under reverse bias. The post-stress reverse-bias EL image of the cell of interest is shown in Fig. 8. The optical emission is shown in green and overlaid on top of a bright-field image. The EL signal suggests a current-induced dislocation path. Therefore a screening mechanism to identify MEPV cells that experience high current could lead to more resilient and reliable MEPV modules.

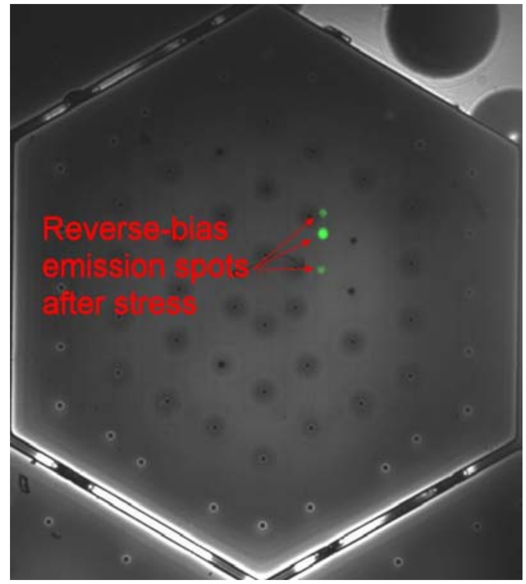

Fig. 8. Electroluminescence imaging of the MEPV cell under reverse bias shows three local defects that are the source of the leakage current.

V. Conclusions

Current research to explore the reliability of MEPV devices utilizes tools such as electrical characterization, EL, OBIC, OBIRCH and physical failure analysis to establish a failure analysis framework. These techniques are used to analyze MEPV devices before and after voltage stress to determine primary modes of failure. The final version of this paper will also include the studies of thermal and light-induced degradation and failure mechanisms. The results form the foundation of the first reliability model for this emerging technology.

References

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