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Reliability Model Development for Microsystems-Enabled Photovoltaics

Benjamin B. Yang, Jose L. Cruz-Campa, Gaddi S. Haase, Paiboon Tangyunyong, Murat Okandan, Gregory N. Nielson

Sandia National Laboratories, Albuquerque, NM, 87185, USA

Abstract — **Microsystems-enabled photovoltaics (MEPV) utilizes microfabrication techniques to achieve various scaling advantages and attain high power density and efficiency. This paper describes accelerated test results for silicon MEPV that were used for development of a reliability model. MEPV has previously demonstrated good resilience to high reverse bias voltages. We further study this performance parameter by examining the degradation effects of prolonged reverse bias stress at voltage levels below breakdown. Light-induced degradation is examined through extended exposure to the output of a 405 nm laser diode. Samples are also subjected to moderate temperature cycling. The post-stress samples are evaluated through electrical tests and defect localization techniques. The results can be used to generate lifetime predictions and provide insights into design improvements for more reliable MEPV.**

Index Terms **—microsystems enabled photovoltaics, reliability, reverse bias, thin film, silicon**

I. Introduction

Photovoltaics (PV) is an attractive energy source for many reasons. These advantages include ready availability at almost any location and great potential as a source of portable power for remote applications where alternatives may be difficult or expensive to implement. The demand to bring these advantages into fruition is driving a push towards PV solutions with good efficiency, flexible configurations, and high power density.

Microsystems-enabled photovoltaics (MEPV) is a technology that shows promise in meeting these requirements. It uses microfabrication techniques to create miniature solar cells with diameters ranging from 250 micrometers (μm) to 1 millimeter (mm) in diameter and approximately 20 μm in thickness [1]. This approach allows the designer to benefit from various scaling advantages [2] and achieve very high power densities as a result—as much as 450 Watts/kilogram (W/kg) has been demonstrated [3]. As such, miniature microfabricated PV is receiving growing attention and development as an ultra-portable alternative energy source [4].

Equally important, especially for remote power applications where system repair could be difficult, is the PV system reliability. Currently, much research has focused on technology demonstration and development as many challenges remain to be solved. There has been some work examining the potential reliability of the microsystems approach to PV [5] as well as developing failure analysis and defect localization techniques [6]. In this paper, we perform accelerated stress tests to experimentally explore the reliability of silicon MEPV. The results supplement the development of microsystems-based PV technology by laying the groundwork for lifetime prediction capabilities and identifying areas of improvement in existing designs.

II. MEPV Overview

Fig. 1 provides an image of the backside of an MEPV cell on a silicon wafer prior to release and final assembly. The metal layer comes in two halves that form an interdigitated back contact. One half connects to p-doped regions of silicon and the other half connects to n-doped regions. Electrical contact with the substrate interconnects is made through four pillars of electroplated copper. Once the fabrication steps are complete on the wafer, etch release holes are used to release the MEPV and attach it to the final substrate. Further details on MEPV design and fabrication can be found in [1].

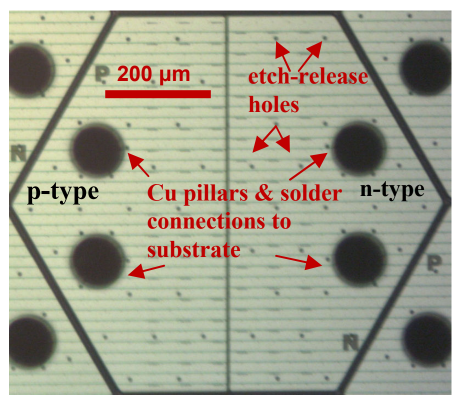

Fig. 1. Bright field image of a 720 μm diameter MEPV cell. The metal layer, shown in white, is separated into two electrically isolated regions that are connected to p-doped and n-doped regions of silicon. The etch release holes used to release the MEPV from the initial silicon wafer are visible, as are the electroplated copper pillars with solder that connect the device to the final substrate.

The MEPV is interconnected on the final substrate to form hexagonal arrays. The reduced feature dimensions and increased concentration of PV cells, interconnects, and contacts creates new opportunities as well as challenges for reliability and failure analysis.

III. Accelerated Test Approach

Three types of stresses are experimentally examined in the current version of this paper: reverse bias stress, light-induced degradation (LID), and temperature cycling. The test bench for reverse bias stress and light-induced degradation consists of analytical probes that connect the MEPV array to a parametric analyzer as shown in Fig. 2.

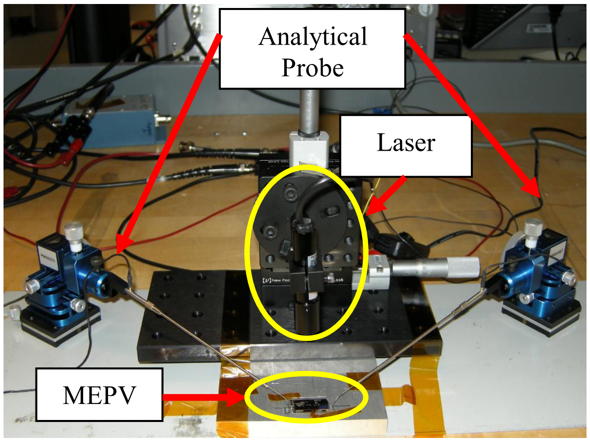

Fig. 2. Photograph of the test setup for reverse-bias stress and light stress. The reverse-bias stress and subsequent leakage current evaluation is performed using a parametric analyzer. A 4.5 mW, 405 nm focusable laser diode is used to provide light exposure. A projection head was used to reshape the laser beam and limit exposure to an individual row of MEPV cells.

PV cells undergoing partial shading experience significant reverse bias stress. The effect of long-term exposure to this stress factor to reverse bias leakage current is explored in this paper.

LID has been observed to lower long-term cell efficiency for boron-doped p-type silicon PV, which is applicable to MEPV [7]. Its exact effects, however, have not been observed and quantified for this technology. The accelerated stress of higher energy photons was implemented by exposing a row of MEPV cells connected in parallel to a laser diode with an operating power of 4.5 mW at a wavelength of 405 nm. A projection head was attached to the laser to shape and focus the beam such that exposure can be reduced to a single row of MEPV cells. The setup is placed in a dark enclosure during the experiment to ensure that the laser is the primary source of light on the sample. The laser spot size covers an area of 2 mm by 3 mm, resulting in a power density of 750 W/mm^2. For comparison purposes, the one-sun AM1.5 spectrum has approximately 0.88 W/mm^2 assuming a 1 nm bandwidth. As such, this configuration should contain significant acceleration when compared to what is expected from terrestrial field use.

Temperature cycling can cause damage to the packaging of the MEPV module due to mismatches in the coefficient of thermal expansion of various materials. Of particular concern are the solder joints that interconnect the MEPV cells in a module. An initial exploration of temperature cycling effects was performed by exposing an MEPV module with 422 working cells to 250 temperature cycles of -20^{o}C to 50^{o}C. Light-induced voltage alteration (LIVA), a technique similar to optical beam induced current, was used to verify the functionality of each individual cell before and after testing. The dark IV was also measured before and after the stress test.

IV. Results of Reverse Bias

Previous work has shown silicon MEPV to be robust to reverse bias stress with a high breakdown voltage of -75V. Fig 3 shows measured leakage current for MEPV cells exposed to a sub-breakdown voltage of 60 V reverse bias over the course of 300 hours. The current-voltage (IV) curves were taken in 2-hour intervals throughout the process where the current is averaged over all working cells that were connected in parallel. The blue curve represents the first measurement and the red curve represents the final IV sweep. A minor increase in reverse bias leakage current was observed, where the leakage current at -40 V increased by 11%.

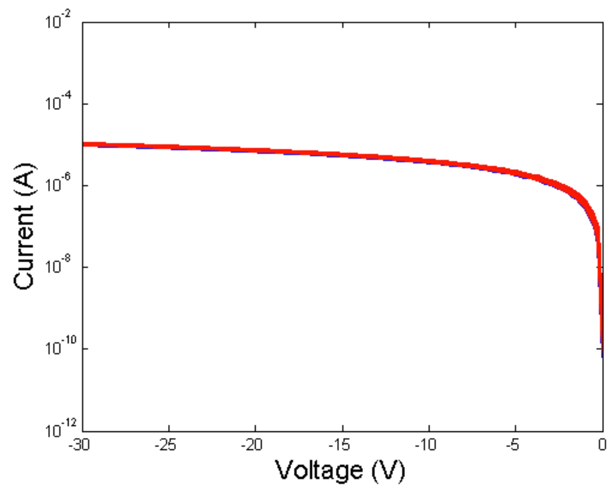

Fig. 3. Reverse bias IV measurements of MEPV cells undergoing 60 V reverse bias stress after 450 hours. The curves are taken at 2-hour intervals and the color transition from blue to red indicates the relative order of IV sweeps, with the red curve being the most recent. The reverse bias increased by 11% at -40 V. The blue lines are not visible indicating minimum change.

A similar experiment for MEPV cells exposed to 55 V of reverse bias stress is shown in Fig. 4 with the same color scheme as Fig. 3. An initial increase in reverse bias leakage was observed within the first 50 hours of testing. During the subsequent 400 hours, however, the rate of reverse bias leakage increase slowed, resulting in an additional 11% increase at -40 V after 450 hours of testing. It is unclear why this initial increase was not observed in the previous 60 V reverse bias test, which remains a topic of future study.

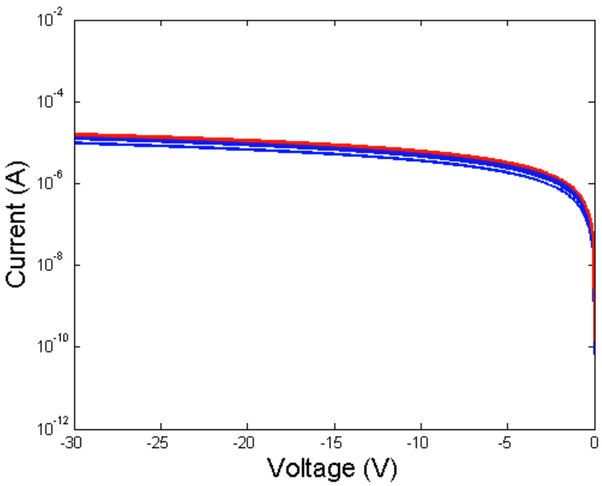

Fig. 4. Reverse bias IV measurements of MEPV cells undergoing 55 V reverse bias stress after 450 hours. The curves are taken at 2-hour intervals and the color transition from blue to red indicates the relative order of IV sweeps, with the red curve being the most recent. There was an initial steep increase in reverse bias leakage that took place in the first 50 hours. The leakage current subsequently increased by 11%, which is similar to the measurement from the 60V reverse bias stress measurement.

The forward dark IV measurements corresponding to the reverse bias traces of Fig. 4 are shown in a linear scale in Fig. 5. A noticeable decrease in forward bias current was observed, despite minor changes in the reverse bias current. This drop could result in a decreased fill factor. This finding suggests that monitoring reverse bias leakage alone is insufficient. Continued monitoring of cell efficiency during reverse bias stress tests will provide a more complete picture on its effects on module performance.

V. Results of Light-Induced Stress

The effects of LID were measured by monitoring the dark IV characteristics of the MEPV cells at 2-hour intervals during exposure to the 405 nm laser light. The results of the reverse bias dark IV curves are shown in Fig. 6. The color scheme is similar to the plots in Section IV, where the blue curve represents the first measurement, and the red curve represents the final IV sweep. The current is averaged across all working cells connected in parallel.

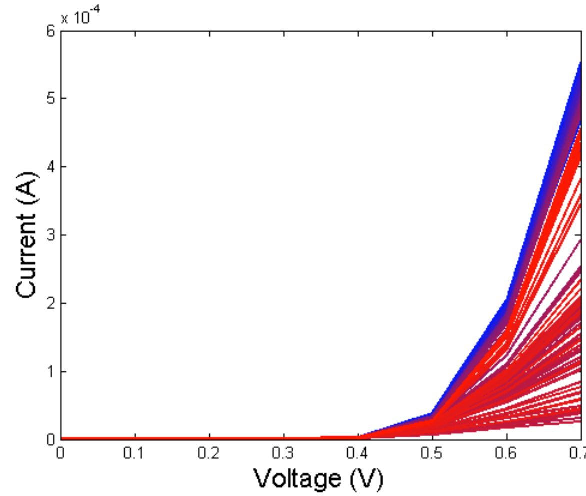

Fig. 5. Forward bias IV measurements of MEPV cells undergoing 55 V reverse bias stress after 450 hours. The curves are taken at 2-hour intervals and the color transition from blue to red indicates the relative order of IV sweeps, with the red curve being the most recent. A noticeable change in forward bias IV characteristics was observed during reverse bias stress that could result in loss of fill factor.

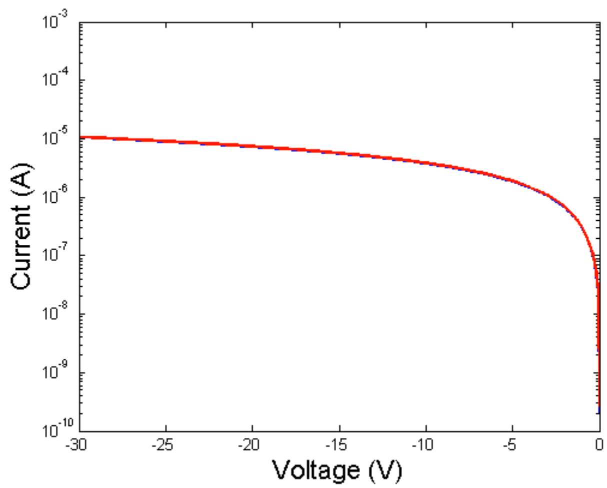

Fig. 6. Reverse bias IV curves of MEPV cells undergoing exposure to 405 nm laser light over the course of 500 hours. The curves are taken at 2-hour intervals and the color transition from blue to red indicates the relative order of IV sweeps with the red curve being the most recent. There is a negligible effect on reverse bias leakage. The variation visible within the figure falls within measurement error of the parametric analyzer.

Exposure of the laser light produced no measureable change in the reverse bias IV characteristics. The variation that is visible within Fig. 6 were found to be within the error range for the parametric analyzer. Fig. 7 plots the corresponding forward bias dark IV curves.

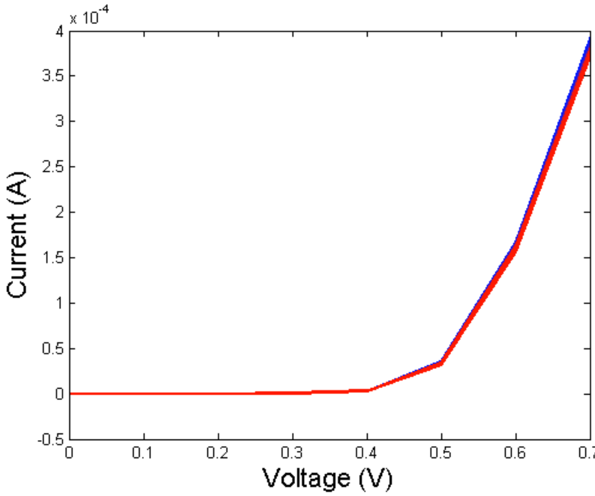

Fig. 7. Forward bias IV curves of MEPV cells undergoing exposure to 405 nm laser light over the course of 500 hours. The curves are taken at 4-hour intervals and the color transition from blue to red indicates the relative order of IV sweeps, with the red curve being the most recent. Changes in the IV characteristics are measureable but slight, with the output current decreasing by approximately 5% at 0.7 V.

Unlike the reverse bias plot, exposure to the laser decreased the forward bias output current of the MEPV cells. The change was approximately 5% at 0.7 V compared to pre-exposure values. This drop indicates a decrease in fill factor and cell efficiency. The effects, however, are minor compared to the reverse bias stress results.

Given the significant acceleration factor generated by the coherent light source of the laser and the minor amount of change observed in the IV characteristics, we arrive at the preliminary conclusion that LID is not a significant source of degradation in MEPV.

VI. Temperature Cycling Results

An MEPV module with less than 100% yield was used to evaluate the effects of temperature cycling on MEPV. As a starting point, the temperature cycle was set at -20°C to 50°C. These temperatures were chosen to represent the extremes of an outdoor environment with minimal acceleration other than the number of cycles.

LIVA was used to evaluate the functionality of each individual cell before and after temperature cycling. The LIVA technique is analogous to optical beam induced current and is described in greater detail in [8]. A total of 422 cells were determined to be working prior to temperature cycling. After temperature cycling, all cells remained functioning. The LIVA image after temperature cycling is shown in Fig. 8 and matches that of pre-cycling measurements.

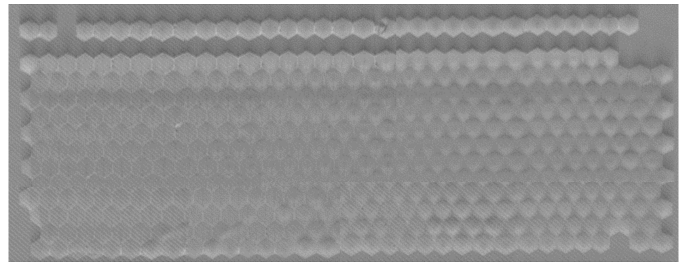

Fig. 8. Light-induced voltage alteration, a technique similar to optical beam induced current, measurements of an MEPV module after more than 250 cycles of temperature cycling from -20°C to 50°C. All 422 cells that were found functional prior to the temperature cycling were still working.

Fig. 9 compares the dark IV curve of the module before and after temperature cycling. Instead of degradation, the performance of the module improved modestly in the form of an increase in fill factor. It is possible that the high-temperature portion of the cycle annealed the device, thus improving its functionality.

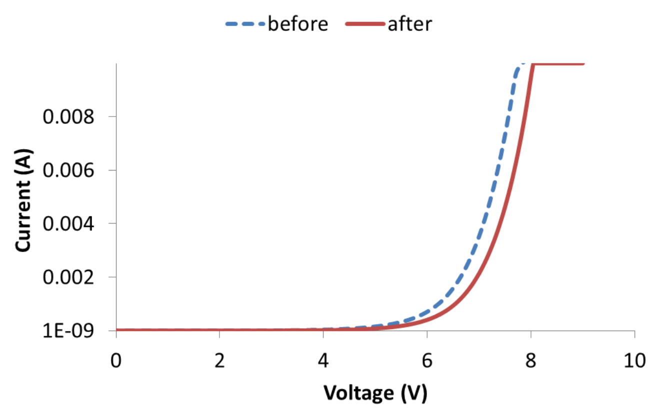

Fig. 9. Dark IV curves of the module in Fig. 8 before and after temperature cycling. The fill factor actually improved after the test, potentially due to an annealing effect from the high temperature exposure.

Additional testing at more extreme temperatures is needed to fully characterize its robustness. The current results establish the ability of the MEPV modules studied to withstand outdoor temperature swings for short durations or longer.

VII. Conclusions

While much emphasis is placed on the development and feasibility of miniature solar cells, exploration of reliability and failure analysis techniques are equally important for remote power applications. This paper explores the robustness of MEPV modules to three stress factors: reverse bias, light-induced-degradation, and temperature cycling.

MEPV was found to have good robustness to reverse bias stress, with only minor increases in reverse bias leakage detected after 450 hours of testing. Additional testing is needed in order to generate sufficient data for a degradation model. Furthermore, in-situ evaluation of cell efficiency will provide additional information on the effects of reverse bias on performance. Through additional testing, LID was found to have a minor effect on cell performance. Moderate temperature cycling caused no failures in the MEPV cells examined in this study.

Further testing in the form of additional reverse bias stress levels and more aggressive temperature cycling is needed to better understand the reliability of MEPV under field use. The data gathered through such experiments can be used to develop a reliability model for lifetime prediction, as well as identify areas of improvement for more robust MEPV.

VIII. Acknowledgements

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