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Local Resistance Measurement for Degradation of c-Si Heterojunction with Intrinsic Thin Layer (HIT) Solar Modules

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Abstract— **Silicon heterojunction with intrinsic thin layer (or HIT) modules typically degrade at a rate of less than 1% annually in solar fields with dominant degradation in open-circuit voltage and some degradation in series resistance. However, detailed mechanisms can differ from module to module. Here, we study increases in local series resistance that occur over long-term field deployment, indicated by cell areas where the photoluminescence intensity does not degrade but the electroluminescence degrades significantly. To directly measure the local series resistance, we have cored out the local electroluminescence-degraded area, and we measured the sheet resistance by 4-point-probe and local nm-scale resistance using scanning spreading resistance microscopy (SSRM). The results by 4-point-probe show scattered sheet resistance that can be caused, for example, by nonuniform current paths through the transparent conductive oxide layer, the a-Si:H emitter, or the near-junction c-Si inversion layer. In contrast, the SSRM results indicate a relatively uniform and non-degraded resistivity on smaller nanometer spatial scales. SSRM is an atomic force microscopy-based two-terminal resistance mapping technique that measures the local resistance in nm-volume beneath the probe. The consistent resistances measured on the control and degraded samples can exclude the degradation of transparent conductive oxide resistance.**

Keywords—Heterojunction with intrinsic thin layers (HIT) solar cells, solar module degradation, series resistance, scanning spreading resistance microscopy (SSRM), atomic force microscopy (AFM).

I. INTRODUCTION

The reliability and degradation rates in field-deployed modules become increasingly important with the massive deployment of solar modules. Silicon heterojunction with intrinsic thin layer (HIT) technology is one of the highest-efficiency c-Si-based solar cells and has been deployed in solar farms in large scales for over 10 years. Like other photovoltaic technologies, HIT modules typically degrade at a rate of less than 1% annually in solar farms [1][2]. The degradation is mainly in open-circuit voltage (V_{OC}), with some increase in series resistance (Rs), which can be different from other technologies [3]. However, detailed mechanisms can differ from module to module. In some cells, although the photoluminescence (PL) intensity remains uniform, the electroluminescence (EL) at high current densities shows significant nonuniformity (Fig. 1). This difference between the PL and EL patterns points to a local Rs increase with long-term field deployment [4]. The lower EL intensity is caused by drops in local current density due to higher Rs, whereas the open-circuit PL is dominated by semiconductor quality and local defect configuration, which should not be affected by contact effects that cause Rs. Figure 1c shows the corresponding cell image collected by dark lock-in thermography, where the degraded area of the cell appears less hot because of the lower current density.

To directly measure the local Rs, we have cored out EL-degraded areas as indicated by the circle in Fig. 1 and measured the local Rs. We have measured the sheet resistance by 4-point-probe and local nm-scale resistance using scanning spreading resistance microscopy (SSRM). The results by 4-point-probe show scattered sheet resistance that can be caused by effects such as nonuniform current paths through the transparent conductive oxide (TCO) layer, a-Si:H emitter, or near-junction c-Si inversion layer. In contrast, the SSRM results indicate a relatively uniform and non-degraded local resistivity of the TCO, which can exclude the degradation of TCO as the primary cause of Rs increase in the weathered module.

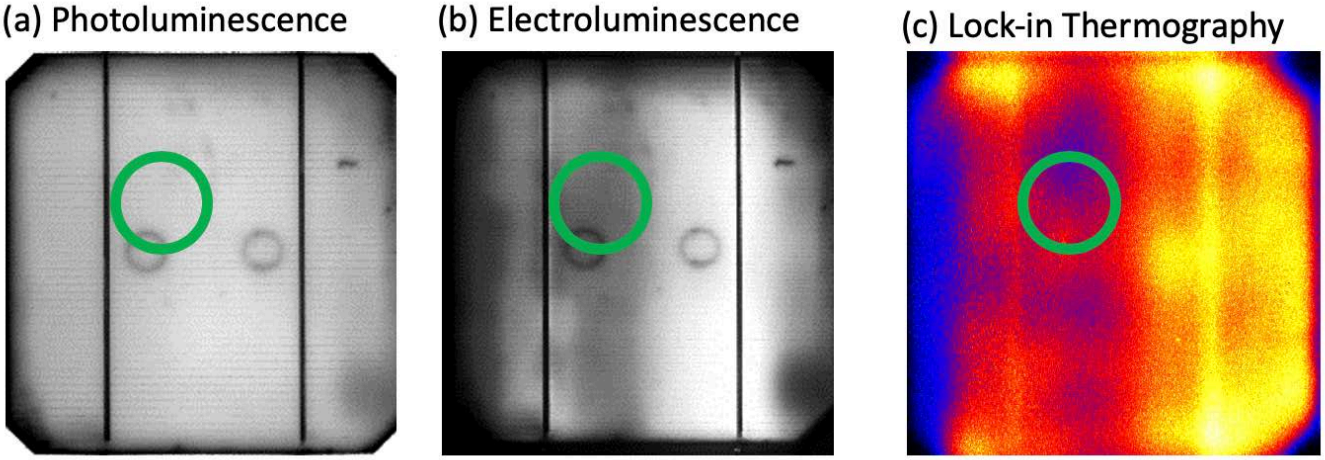

Fig. 1 (a) Photoluminescence, (b) electroluminescence, and (c) dark lock-in thermography highlighting a cell within a HIT module that had series resistance issues. The circled region is an example of an area that was cored to study the series resistance degradation.

II. EXPERIMENTAL

We cored out the EL-degraded areas in field-degraded modules by cutting through the backsheet, HIT cell, and front EVA. The cell was detached from the front-side EVA/TCO interface by removing the backsheet, attaching a metal stub to the back-side EVA, and applying a turning force [5].

The macroscopic sheet resistance was measued by four probes linearly aligned ~1 mm apart from each other. The probes were contacted with the TCO surface in a constant contact force controlled by springs. A constant electrical current was flowed through the outer two of the probes, and voltage drop was measured between the inner two probes to exclude the effect of contact resistance.

SSRM is an atomic force microscopy (AFM)-based, two-terminal resistance-mapping technique (Fig. 2) [6][7][8][9]. A logarithmic-scale amplifier was employed to increase the current sensitivity in a wide range of 10^{-3}~10^{-15}A (mA~fA), and it can measure the resistance in the range of 10^{3}–10^{15} Ω. Because the probe-sample contact area is small—on the nm-scale, which is much smaller than the ~100-nm probe size—it can measure the resistivity in the 10^{-3}~10^{9} Ωcm range. The AFM (Veeoco D5000 and Nanoscope V) is set in an Ar glove box and uses diamond-coated Si probes (BrukerNano, DDESP) to enhance the durability of the probes.

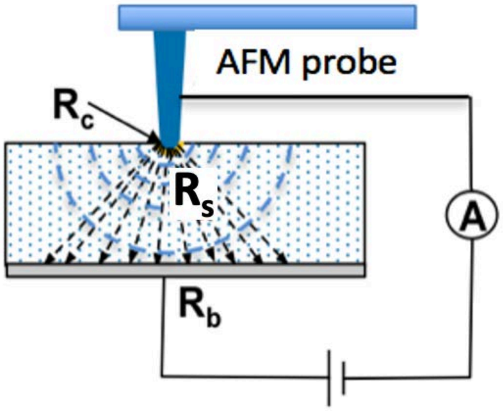

Fig. 2 A schematic showing the SSRM measurement setup and equivalent circuit.

III. RESULTS AND DISCUSSIONS

We first show preliminary macroscopic sheet resistance measurements, then discuss the SSRM local resistance measurements on TCO.

The left side of Fig. 3 shows the sheet resistance measured on three samples cored from a control HIT module that was kept in the dark, and the right side shows the measurements on five

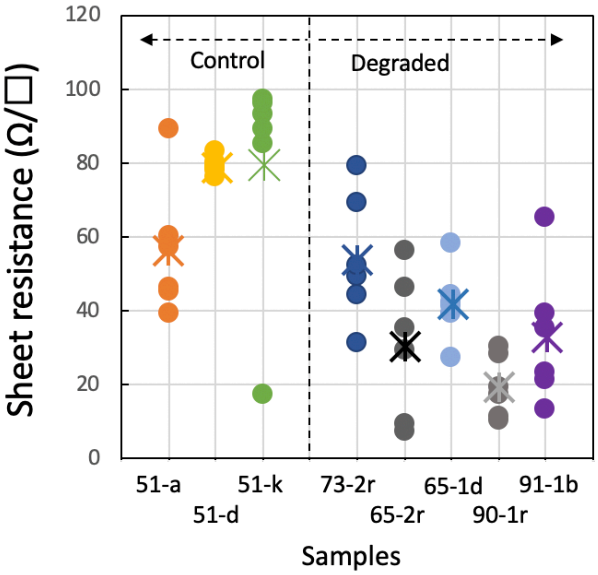

Fig. 3 Sheet resistance measured on three control samples (left side) and five degraded samples (right side) by the 4-point probe method. Each sample was measured five times, and the average values are indicated by the cross symbols.

pieces from the dark EL areas of a field-degraded module. The measurement locations were randomly chosen in these cored samples. Both control and degraded modules were from the same commercial productions of HIT modules. The resistance data are significantly scattered in all the samples, varying from 10 to 100 Ω/□ with an average value of 49 Ω/□. Currently, the reasons are unclear for data scattering and whether or not it reflects the true sheet resistances of TCO. The current path could flow through the underlaying c-Si devices in differing degrees [10]. The coring process could induce defects, and the measurement current could flow across the defects. Further, the TCO thickness might be nonuniform across the samples because of the coring process.

To measure the resistivity of TCO locally to avoid uncertainties from defects or TCO thickness variations, we employed SSRM, which measures the resistance dominated only by the local nm-volume beneath the probe [6][7][8][9]. SSRM is a two-terminal resistance measurement with the probe and the widely electrically connected cell back contact. Because of the probe/sample nm-scale contact area, the current spreads quickly with distance away from the probe, and the voltage applied between the probe and back contact drops mainly near the probe. Therefore, the measured resistance $R=V/I$ is dominated by the local resistance of sample, no matter how the current route flows through the underlying c-Si device, through the TCO sheet transport, or across a defect area or not.

The TCO thickness (50–100 nm) should be much larger than the depth of the local nm-scale volume that dominates the resistance measured by SSRM, so the measured resistance is solely determined by the local TCO resistivity. The SSRM measurement requires a small local scanning area and a slow scan rate to keep well-controlled probe/sample contact; otherwise, the resistance mapping would be dominated by small uncertainties in the probe/sample contact. An example of such artifacts is shown in Fig. 4 in a large scan size of 20 μm. The mapped resistance (Fig. 4a) in this case is dominated by the unstable probe/sample contact, although such scan sizes in rough samples with surface texture give good AFM images of the surface morphology (Fig. 4b). Therefore, we focus on small scan areas of <1 μm with a slow scan rate of 0.1 Hz, which gives reliable resistance mapping (Fig. 5). The resistance is relatively uniform across the scanned areas (Fig. 5a), and the surface morphology is flat in the 10-nm range (Fig. 5b). The resistance is in the kΩ range because of the nm-sized probe/sample contact area. To keep the probe firmly on the sample surface, the probe needs to be pressed with ~μN force on the sample surface, which results in the probe pressed ~5 nm deep into the TCO. Figure 5(c) shows an AFM image of a larger scanned area than the SSRM measurement, and Fig. 5(d) shows a line profile across the dashed line in Fig. 5(c). The image and line profile indicate a scratched area of ~5-nm depth by the hard probe/sample contact force. The diamond-coated Si probe is relatively strong to wear out, usually can sustain more than 50 reliable imaging before it wears out.

We measured multiple areas on each of the samples. Figure 6 shows the results on three control samples and four degraded samples. Each point in Fig. 6 is an average value from a resistance image such as Fig. 5(a). The measured resistances are relatively uniform around 1 kΩ, with some degree of data scattering that can be induced by the minor uncertainties of local probe/sample contacts. Care was taken to reduce measurement uncertainty, such as the slow scan rate, small scan area, and measurement order of A, B, C…. C, B, A, then A, B, C… as well as alternatively one control sample then one degraded sample. All the measurements used the same probe to reduce the uncertainty induced by probes. Quantitatively, the absolute resistance value can be affected by individual probes because of the probe size and shape scatters. However, the qualitative comparisons are reliable between the samples, i.e., the trend in which sample the resistance is larger or smaller. Therefore, we can exclude the speculation that the Rs degradation in the dark EL area is due to TCO degradation.

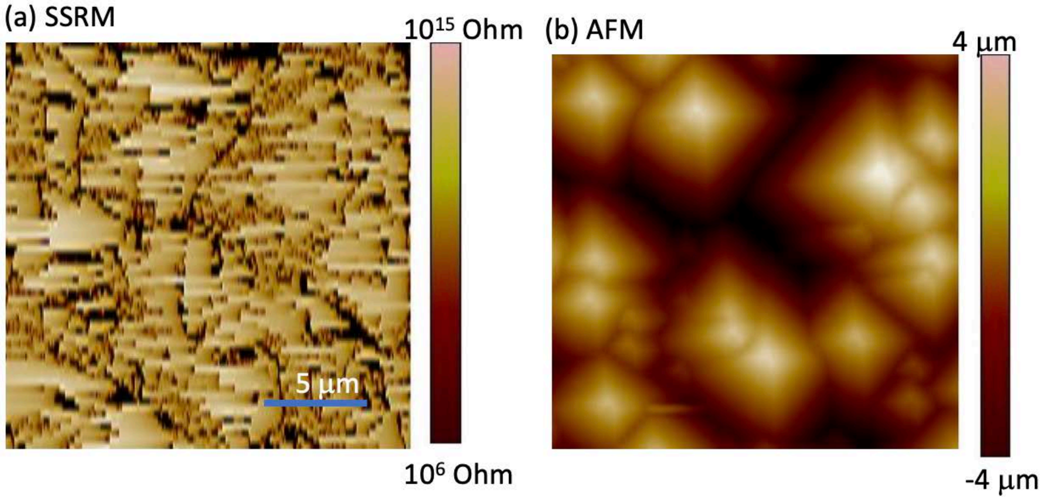

Fig. 4 (a) A SSRM resistance image taken on a large area (20 μm) of a control sample; (b) the corresponding AFM image.

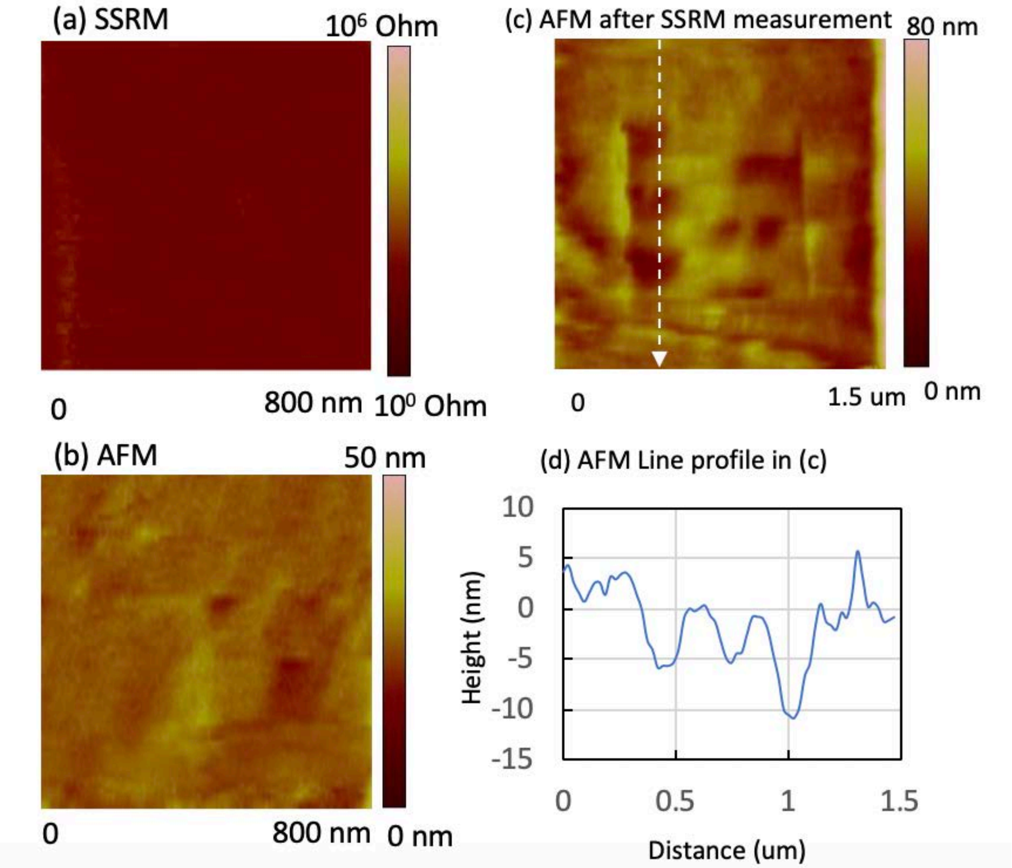

Fig. 5 (a) A SSRM resistance image and (b) the corresponding AFM image taken on a control sample showing an example of the resistance measurement on a local small area (800 nm). (c) Shows an AFM image taken on a larger area of 1.5 µm after the SSRM measurement, and (d) shows a line profile along the line in (c).

So far, we could not identify the mechanism for Rs degradation by the 4-point-probe measurement and SSRM measurement on the TCO. Follow-up experiments are underway to perform resistance mapping on HIT cell cross-sections, which we have previously used to map resistance of CdTe solar cells [11]. Preliminary results show resistance contrasts between ITO, c-Si depletion region, and bulk Si; but they did not clearly show large difference between the degraded and control samples. Improved measurement parameter settings and cross-section sample preparation, as well as carrier delineation and junction characterization using other nanoelectrical probes of scanning capacitance microscopy (SCM) [12][13], are underway to reveal the mechanism of this Rs degradation.

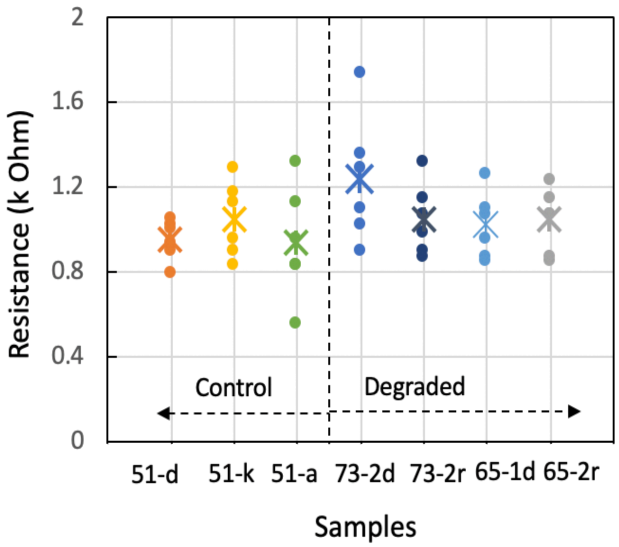

Fig. 6 SSRM local resistance measurements on three control samples (left side) and four degraded samples (right side). Each sample was measured six times, and the average values are indicated by the cross symbols.

IV. SUMMARY

We have measured the local sheet resistance by 4-point-probe and local TCO resistance by SSRM for identifying the series resistance degradation mechanisms of field-deployed HIT modules. The sheet resistance shows scattered data, and SSRM local resistance measurement shows relatively uniform local nm-volume resistance of TCO. By qualitatively comparing the SSRM resistance on control and degraded samples, we can exclude speculations of TCO resistance degradation. Follow-up experiments by two different measurement approaches are underway to identify the resistance degradation.

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