



Two-Dimensional Measurement of n+-p Asymmetrical Junctions in Multicrystalline Silicon Solar Cells Using AFM-Based Electrical Techniques with Nanometer Resolution

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TWO-DIMENSIONAL MEASUREMENT OF n^+ -p ASYMMETRICAL JUNCTIONS IN MULTICRYSTALLINE SILICON SOLAR CELLS USING AFM-BASED ELECTRICAL TECHNIQUES WITH NANOMETER RESOLUTION

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ABSTRACT

Lateral inhomogeneities of modern solar cells demand direct electrical imaging with nanometer resolution. We show that atomic force microscopy (AFM)-based electrical techniques provide unique junction characterizations, giving a two-dimensional determination of junction locations. Two AFM-based techniques, scanning capacitance microscopy/spectroscopy (SCM/SCS) and scanning Kelvin probe force microscopy (SKPFM), were significantly improved and applied to the junction characterizations of multicrystalline silicon (mc-Si) cells. The SCS spectra were taken pixel by pixel by precisely controlling the tip positions in the junction area. The spectra reveal distinctive features that depend closely on the position relative to the electrical junction, which allows us to indentify the electrical junction location. In addition, SKPFM directly probes the built-in potential over the junction area modified by the surface band bending, which allows us to deduce the metallurgical junction location by identifying a peak of the electric field. Our results demonstrate resolutions of 10-40 nm, depending on the techniques (SCS or SKPFM). These direct electrical measurements with nanometer resolution and intrinsic two-dimensional capability are well suited for investigating the junction distribution of solar cells with lateral inhomogeneities.

INTRODUCTION

Electrical properties of solar cell junctions such as the junction location and distribution, depletion width, and emitter doping profiles are critical for device performance [1-3]. Typically, the junction depth and doping profile is characterized by secondary ion mass spectrometry (SIMS) [3-5]. However, conventional SIMS is a one-dimensional technique that does not have fine enough lateral spatial resolutions. Moreover, SIMS measures the dopant element profiles, but not directly the carrier concentration, so it cannot measure a device doped by intrinsic electronic defects. Therefore, novel methods of direct electrical measurements and methods with two-dimensional (2D) fine resolutions are hiahlv desirable for the characterization of junction electrical properties.

AFM-based electrical techniques provide unique capabilities for these purposes. AFM is a structural characterization tool that measures the surface morphology or corrugation by detecting the atomic force between the probe and sample surface. AFM can also detect many types of electrical signals that can be used for electrical mapping with fine resolutions equivalent to the AFM tip sizes (a few tens of nanometers). Examples of the electrical signals are electrostatic force, capacitance, and electrical current between the tip and sample, which are used for mapping the local surface potential, carrier concentration, and conduction path in the applications of SKPFM, SCM/SCS, and conductive AFM (C-AFM), respectively [6-8]. These AFM-based electrical techniques have been significantly improved in the past decades and successfully applied to the characterization of semiconductors. In this paper, we present our significant improvements of SCM/SCS and SKPFM, and their application to determination of the junction location in mc-Si cells [9]. With the advantages of fine resolution, 2D capability, and direct electrical measurements, use of these techniques is expected to become more widespread in the photovoltaic community.

SAMPLE PREPARATIONS

Solar cell junctions were imaged by both SCM and SKPFM on cross sections of the cells. Two cleaved pieces were glued front contact to front contact into a sandwich structure using Ag epoxy. The cross section was then chemical-mechanically polished (CMP) using a set of diamond pads and finally a silica colloid. The polishing is necessary for SCM, because a high-quality oxide layer on top of the sample, which forms a metal-oxide-semiconductor (MOS) structure, is essential to the measurement [8]. It is also necessary for the SKPFM measurement, because an adequately flat surface would avoid topographic effect on the surface potential signal [9]. The sandwich structure is used to protect the vicinity of the cell front surface from damage during polishing. The polishing was carefully carried out to avoid shunting the device. For the SCM measurement, a final sample treatment was added to illuminate the sample using an ultraviolet light while annealing the sample at 300°C for 30 min, which was expected to remove the defect charges at the oxide/silicon interface and in the oxide layer [10].



Figure 1. SIMS P and B doping concentrations measured on n^+-p mc-Si cells with untextured and textured surfaces. The doping profile of the former is well defined, in contrast to the latter.

The results shown here were taken on two mc-Si cells, with and without textured surfaces. The untextured cell is a test cell for examining the validity of the AFM-based techniques by comparing them with SIMS data, because SIMS can generate a reliable doping profile of the cell. The textured cell allows demonstration of the powerful AFM-based 2D characterizations. Figure 1 shows SIMS data taken on the two cells. The dopant profile from the untextured cell shows a typical diffused junction, indicating that the metallurgical junction (MJ) is located at x_m =455±10 nm from the wafer surface. However, an artifact of surface corrugation prevented the textured cell from being well defined by SIMS.

SCANNING CAPACITANCE SPECTROSCOPY

In SCM, the conductive tip, surface oxide, and the sample form a MOS structure, and the differential capacitance, dC/dV, is mapped [8]. Quantitative delineation of carrier distribution on unipolar Si has been successful. However, carrier extraction on an asymmetrical n^+ -p or p^+ -n junction and delineation of the junction location has been challenging [10-12]. The apparent electrical junction (EJ) location as assigned nominally by a zero SCM signal, dC/dV=0, is significantly shifted by the bias voltage applied between the sample and probe (V_s) [11]. The ideal Vs, one that makes the MOS structure a flat band condition for compensating the effects of oxide and interface charges, is difficult to determine, especially for a bipolar device where the flat band V_s should be in general different for the p- and n-regions. Therefore, the apparent EJ location moves in the depletion region. An example is shown in Fig. 2, illustrating how the dC/dV profile changes width V_s.



Figure 2. SCM line profiles taken along the junction of the untextured cell, illustrating the change in the SCM dC/dV profile with V_s applied between the probe and sample.

SCS, a measurement of dC/dV as a function of V_s . provides richer characterizations than SCM. In unipolar regions, the $dC/dV-V_s$ spectra show a single peak at the flat-band voltage: positive for *p*-type material and negative for *n*-type. When the probe is positioned on the junction and its vicinity, the literature reports the spectra with a peak and a valley in opposite signs like a mixture of the two unipolar spectra, and the capacitance-voltage $(C-V_s)$ curves exhibit a U-shape [10,11,13,14]. However, the detailed spectra transition in the junction region with space intervals much shorter than the depletion width has not been discussed in the literature. Here, we present the spectra taken pixel by pixel in the junction area, and show completed spectral features and spectral transitions. More importantly, we will demonstrate the ability to determine the EJ location with a resolution of ~10 nm.

The SCM/SCS is based on Veeco's D3100 AFM and nanoscope V controller. The AC and DC voltages were applied from the sample, and the tip was virtually grounded. An RCA capacitance sensor [15] with a UHF frequency of ~1 GHz was used for detecting the small capacitance in ~10⁻¹⁸ F order. The DC voltage was $V_s = -1$ V for the SCM imaging, and the AC voltage was 1 V for both SCM and SCS measurements. Front and back contacts of the live device were connected to avoid any photovoltage generated by the AFM laser (λ =670 nm). A Pr/Ir-coated Si tip with a low spring constant of ~0.2 nN/m was used in the contact mode of AFM.

For SCS measurements, the sweeping rate of V_s was 2 Hz with 256 steps in -3 to +2 V, which is fast enough to suppress the thermal drift and slow enough to suppress the spectra hysteresis. After an SCM image was taken, the tip was moved to the designated location, a line in the



Figure 3. (a) SCM dC/dV image measured across the junction of untextured mc-Si cell. (b) Averaged dC/dV profile, calculated carrier concentrations, and built-in potential. Long vertical dashed lines indicate locations of SIMS MJ and PC1D EJ.

center of the image, and SCS were taken pixel by pixel along the line with a step of ~10 nm. For accurately determining positions where the SCS were taken, the closed-loop method of lateral scan was used, and thermal drift was suppressed by waiting for hours before the measurements. After the SCS, another follow-up SCM was taken to confirm the coincidence of the image location. For the SCS presented here, we did not observe any measureable drift of the SCM images. Taken together with the careful scanner calibration, we believe that the SCS positions are highly accurate.

Figure 3 shows an SCM image taken on the untextured cell and a dC/dV profile averaged along the vertical direction of the image. The built-in potential and carrier concentrations were simulated using PC1D software [16] and the SIMS dopant concentrations shown in Fig. 1. The EJ location, x_e =480±10 nm, was identified from the same electron and hole concentrations. Obviously, the apparent junction dC/dV=0 is not suitable for identifying the junction locations, which is ~170 nm shallower than the MJ. However, a "plateau" with a slower change is seen in the junction area, which might be due to the deep depletion [10]. The deeper end of the plateau corresponds well to the MJ. Here, we focus on the SCS around the junction area, and explore the junction identification criteria from the spectral features.

The spectra around the junction are displayed pixel by pixel. Figure 4 illustrates the spectra locations, as



Figure 4. Zoom of Fig. 3 around the junction area. Vertical solid lines indicate the locations where the spectra are shown in Fig. 5. Vertical dashed lines indicate SIMS MJ and simulated EJ locations.

indicated by the pixel numbers, and Fig. 5 shows the corresponding spectra. The spectra are shown by the $dC/dV-V_s$ and $C-V_s$ curves, with the $C-V_s$ curves obtained by numerically integrating the $dC/dV-V_s$ spectra. The spectra exhibit clear characteristics. From Pixel #45, which is ~40 nm deeper than the EJ, the dC/dV around $V_s = -3 V$ begins to change significantly and from positive to negative values. The value reaches the minimum at the EJ (#48). With the tip moving over the EJ toward the *n*-region, the dC/dV around $V_s = -3$ V changes back (#49 and #50), although the V_s range with negative dC/dV values widens rapidly. The dC/dV value around $V_s = -3$ V at the MJ (#50) is flat in a considerably large range (-3 V to ~ -1.7 V). With the tip moving further over the MJ, an additional local minimum at $V_s \sim -1.5$ V and a maximum at $V_s \sim -2.2$ V appears (#51). The local maximum on the #51 spectra rises to positive values.

These changes are presented even more clearly by the $C-V_s$ spectra. The capacitance curve begins to show a valley from the location ~40 nm deeper than the EJ (#45). The valley increases toward the EJ, and exhibits the deepest valley or the minimum valley value at the EJ (#48). As the tip moves closer to the *n*-region, the valley becomes shallow and further changes to a W-shape (#51). The W-shape is because of the positive local maximum on the $dC/dV-V_s$ spectrum. All of the changes in the spectra with the tip location happen on the negative V_s side. The spectra are unperturbed on the positive side. The U-shaped $C-V_s$ curve is essential because of charge flows from both *p*- and *n*-sides to the junction region [10-14], which results in the deepest valley at the EJ where both electrons and holes are fully compensated.



Figure 5. (a) $dC/dV-V_s$ and (b) corresponding $C-V_s$ spectra taken around the junction area, pixel by pixel. Corresponding locations are indicated in Fig. 4. (c) Zoom of Fig. 5 (b) to highlight the valley of the $C-V_s$ curves.

These spectroscopic characteristics can be used as criteria for delineating the junction. The EJ location as identified from the *C-V*_s curves is x_e =487 nm, with accuracies of sub-10 nm compared to the PC1D EJ, x_e =480 nm. The characteristic feature at the EJ is obvious, and can be clearly distinguished by the spectra from the neighboring pixels, where the step between the pixels is 12 nm. Therefore, we believe that the resolutions of the junction identification should be in 10 nm range. The tip apex radius (~30 nm) is significantly larger than the spectral resolution. This is not surprising, because the spectra are determined by the charge flow from both *n*-and *p*-sides, and the magnitudes of the flow possibly change sensitively enough around the EJ to ensure the fine spectral resolution.

As the location moves further toward the shallow *n*-region, the *dC/dV* spectra change to the typical *n*-signature with the negative valley, and the *C-Vs* spectra change from the W-shape to a monotonically decreasing curve (the spectra are not shown). These spectra are fundamentally different from those reported in the literature, where only a U-shaped *C-Vs* curve was observed in the junction area. Although the physical origins are not yet clear, it might be a result of the characteristic doping profile in our sample that is a typical solar cell n^+ -*p* junction with a ~3×10¹⁶/cm³ background doping and 455±10 nm diffused junction depth. Further quantitative modeling using the doping profile may help to understand the spectra.

SCANNING KELVIN PROBE FORCE MICROSCOPY

SKPFM probes the cantilever oscillation stimulated by an AC voltage applied between the AFM tip and sample [6,7]. The oscillation amplitude of the cantilever and the Coulomb force between the tip and sample is proportional to the contact potential difference (CPD) between them. The detected oscillation amplitude was sent to a negative feedback circuit to further apply a DC voltage to the tip, which compensates the CPD. In this case, the DC voltage

that makes the oscillation the minimum is the Kelvin probe signal, equals to the CPD between the tip and sample. Because the potential of the tip remains unmodified during scanning, the SKPFM image reflects the surface potential contrast on the sample. Detailed descriptions of the technique is given in the literature [6,7]. In our SKPFM setup, the first cantilever resonance frequency was used for the noncontact AFM imaging, and the second resonance was used in the potential measurement, which enhanced significantly the voltage sensitivity relative to the conventional SKPFM where a low frequency was used [7]. Our SKPFM is based on a Thermo Microscope CP AFM.

The SKPFM measurement directly gives the surface potential, which reflects the bulk p-n junction band bending modified by the surface band bending [9,17,18]. Figure 6(a) shows the potential profiles across the junction of the untextured cell, each of which is averaged from a SKPFM image with 64 line scans. The influence of surface band bending and surface states can be reduced by collecting SKPFM images with varying values of reverse bias (V_b) applied to the *p*-*n* junction, and subtracting the SKPFM image collected at $V_b=0$ V, as shown in Figs. 6(a) and 6(b). This is because the surface band bending does not change significantly, and both the bulk and surface potentials change similarly, with changing V_b [9,17,18]. The V_b -induced changes in the electric filed [Fig. 6(c)] were further derived by taking the first derivative of the potentials in Fig. 6(b) with respect to x, the distance below the wafer surface. A peak at x_p =490 nm is observed in the junction area.

To understand the measured potential and field profiles, the bulk potential, potential difference, and electric field in the bulk were calculated using PC1D and the SIMS doping profile (Fig. 7). Although the electric field under the various V_{bs} shows a peak at the MJ [Fig. 7(c)], the V_{b} -induced



Figure 6. (a) Electrical potential profiles taken along the junction of the untextured mc-Si cell under the various V_b s. (b) Potential difference between the V_b s and V_b =0. (c) V_b -induced changes in the electric field by taking the first derivative of the potential profiles in Fig. 6(b).

change in the electric field shows a plateau in the junction area that is caused by an additional bias voltage being uniformly applied across the junction where the carriers are deeply depleted. The V_b -induced electric field should



Figure 8. AFM and corresponding SCM images taken on a cross section of the textured mc-Si cell, showing that emitter doping is uniform and conformably follows the surface texture.

correspond to the measured field in Fig. 6(c), and the center of the plateau at x_c =495 nm is consistent with peak position x_p =490 nm. Therefore, the peak in the electric field profile as derived from the potential measurement can quantitatively identify the MJ location, with a deviation of ~40 nm from its true location. This deviation is essentially a result of the asymmetrical doping, which would mitigate with a less asymmetrical junction.

TWO-DIMENSIONAL IMAGING

One of the most important capabilities of AFM-based techniques is 2D imaging, which is well suited for characterizing the distribution of junction location and doping concentrations in inhomogeneous cells. Both SCM and SKPFM were taken on the cross section of the mc-Si cell with a textured surface. The SCM image shown here (Fig. 8) was taken on a region where the cross section cuts nearly through the peak of a pyramid on the highly textured surface. The dark, bright, and medium-bright regions indicate the *n*-doped emitter, *p*-type bulk, and Ag epoxy, respectively. The image clearly demonstrates that



Figure 7. (a) Potential profiles in the bulk; (b) potential difference between various V_b s and V_b =0; (c) electric field and V_b -induced field changes, as simulated for the untextured cell using PC1D and SIMS doping profiles.



Figure 9. (a) AFM and (b) corresponding potential images taken on a cross section of the textured mc-Si cell. (c) Image of electric field amplitude using the first 2D derivative of the potential. The stripe in (c) indicates the junction shape and location.

the doping is uniform and conformably follows the texture on the cell surface.

The SKPFM image shown in Fig. 9 was taken on a region with less surface corrugation. The potential on the emitter is significantly higher than on the bulk, and is the highest on the Ag epoxy because of the different chemistry [Fig. 9(b)]. The image of the electric field in Fig. 9(c) was obtained from the 2D derivative amplitude of the potential

$$\left|\vec{E}\right| = \left|\nabla\varphi\right| = \left|\frac{\partial\varphi}{\partial x}\vec{i} + \frac{\partial\varphi}{\partial y}\vec{j}\right|,\,$$

which shows a bright stripe at the junction. This image demonstrates again that the shape of the junction follows the cell texture, which is consistent with the SCM observation.

SUMMARY

Two AFM-based electrical methods, SCM/SCS and SKPFM, were significantly improved and used to characterize solar cell junctions. The junction location determinations were achieved by both SCS and SKPFM with resolutions of 10–40 nm, depending on the technique used and the solar cell materials and structures. These AFM-based measurements have intrinsic advantages of nanometer-scale resolution, 2D capability, and direct electrical measurements. They are expected to significantly benefit junction studies for solar cells beyond the example mc-Si cells discussed in this paper.

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