

Distribution of Local Open-Circuit Voltage on Amorphous and Nanocrystalline Mixed-Phase Si:H and SiGe:H Solar Cells

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DISTRIBUTION OF LOCAL OPEN-CIRCUIT VOLTAGE ON AMORPHOUS AND NANOCRYSTALLINE MIXED-PHASE Si:H AND SiGe:H SOLAR CELLS*

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ABSTRACT

Local open-circuit voltage (V_{oc}) distributions on amorphous and nanocrystalline mixed-phase silicon solar cells were measured using a scanning Kelvin probe microscope (SKPM) on the p layer of an $n-i-p$ structure without the top ITO contact. During the measurement, the sample was illuminated with a laser beam that was used for the atomic force microscopy (AFM). Therefore, the surface potential measured by SKPM is the sum of the local V_{oc} and the difference in workfunction between the p layer and the AFM tip. Comparing the SKPM and AFM images, we find that nanocrystallites aggregate in the amorphous matrix with an aggregation size of $\sim 0.5 \mu\text{m}$ in diameter, where many nanometer-size grains are clustered. The V_{oc} distribution shows valleys in the nanocrystalline aggregation area. The transition from low to high V_{oc} regions is a gradual change within a distance of about $1 \mu\text{m}$. The minimum V_{oc} value in the nanocrystalline clusters in the mixed-phase region is larger than the V_{oc} of a nc-Si:H single-phase solar cell. These results could be due to lateral photo-charge redistribution between the two phases. We have also carried out local V_{oc} measurements on mixed-phase SiGe:H alloy solar cells. The magnitudes of V_{oc} in the amorphous and nanocrystalline regions are consistent with the J-V measurements.

INTRODUCTION

It has been shown that the best hydrogenated amorphous silicon (a-Si:H) solar cells are deposited under the condition close to the amorphous/nanocrystalline transition, but still in the amorphous regime [1], whereas the best hydrogenated nanocrystalline silicon (nc-Si:H) solar cells are deposited under the condition close to the transition, but in the nanocrystalline regime [2]. Solar cells made under the transition condition are called mixed-phase solar cells and show a distribution of open-circuit voltage (V_{oc}) ranging from 0.5 to 1.0 V [3,4]. One interesting phenomenon in the mixed-phase solar cells is the light-soaking-induced V_{oc} increase [3,4], which is opposite to the light-soaking-induced V_{oc} decrease in conventional a-Si:H cells caused by the Staebler-Wronski effect [5]. Our original explanation for the light-induced V_{oc} increase was light-induced structural changes from the crystalline to amorphous phase [3,4]. Subsequently, we proposed a complementary model with two parallel-

connected diodes (two-diode) for explaining the V_{oc} changes with crystalline volume fraction and light-induced V_{oc} increase in the mixed-phase solar cells [6]. The key element in the two-diode model is that the amorphous phase and crystalline phase can be considered as two separate diodes with significantly different characteristics of a-Si:H and nc-Si:H solar cells. However, the challenge is that the nanocrystallites observed by X-ray diffraction and Raman are very small with a size of a few nm to 30 nm. It is difficult to believe that such small grains can form complete diodes through the intrinsic layer. Recently, we used a conductive atomic force microscope (c-AFM) to measure the local current flow and found that the nanocrystallites aggregated and the nanocrystalline aggregation area showed a significantly higher forward current than the amorphous area [7].

In this paper, we report our new results of local V_{oc} distribution in the mixed-phase solar cells measured using a scanning Kelvin probe microscope (SKPM). We have established this nanometer-scale measurement technique [9,10] and applied this method for mapping the two-dimensional electrical potential distributions in III-V, Cu(In,Ga)Se₂, and a-Si:H solar cells [10-12]. The measurement results have improved our understanding of device physics in the solar cells and provided us a direct method to assess the quality of the p-n junctions.

EXPERIMENTAL

Mixed-phase Si:H and SiGe:H $n-i-p$ structures were deposited onto a $4 \times 4 \text{ cm}^2$ stainless-steel substrate. The n layer is an a-Si:H layer doped with phosphorus and the p is a nc-Si:H layer doped with boron. The i layer was deposited under the condition of the amorphous/nanocrystalline transition regime. Due to the high sensitivity of the transition to the plasma properties, the mixed-phase solar cell shows different characteristics at different locations even on the same substrate. Figure 1 (a) shows the solar cell distribution on the $4 \times 4 \text{ cm}^2$ stainless-steel substrate, where the large circles are indium tin oxide (ITO) dots with a area of 0.25 cm^2 and the small ones of 0.05 cm^2 . Figure 1 (b) plots the V_{oc} of the 16 large solar cells. One can see that the center area shows an amorphous signature, the outer region a mixed-phase, and the corners substantially nanocrystalline characteristics.

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The SKPM measurements were made at the three areas labeled with A, B, and C, as shown in Fig. 1(a), where no ITO was deposited. The SKPM technique is based on the non-contact mode of AFM [8-10]. Similar to the classical Kelvin probe, SKPM measures the contact potential difference (CPD) between the sample surface and the probe. However, unlike the classical Kelvin probe using a small ac current signal, SKPM measures the Coulomb force between the sample and the AFM tip. The extremely small distance between the tip and sample surface (\sim nm) and the extremely force-sensitive cantilever (\sim nN/m) ensure high resolutions in both spatial (\sim 30 nm) and energy (\sim 10 mV). Details of the technique are described elsewhere [9,10].

RESULTS AND DISCUSSIONS

During the SKPM measurements, a built-in laser (used for the AFM operation) with 1.85-eV photon energy is used to illuminate the sample. In the thermal equilibrium state in the dark, the CPD measured by SKPM is the workfunction difference (WD) between the sample and the tip, as illustrated by Fig. 2(a). However, when the solar cell sample is illuminated, the CPD is the sum of WD and the local V_{oc} , as shown in Fig. 2(b). To obtain the V_{oc} distribution, the WD of the p layer must be measured and subtracted from the measured CPD of the $n-i-p$ structure. We deposited a p -type nc-Si:H layer directly on stainless-steel substrates and measured the CPD. Because the p layer is heavily doped and there is no $p-n$ junction in the sample, the measured CPD should be close to the WD, even though the sample is illuminated by the laser light during the measurement.

Figure 3 shows the SKPM CPD and the corresponding AFM topographic images taken on the amorphous, substantially nanocrystalline, and mixed-phase regions, as well as on the p -type nc-Si:H single layer. The potential distributions are relatively uniform on the amorphous and nanocrystalline single-phase regions, as shown in Fig. 3 (a) and (c), as well as on the p layer in Fig. 3 (g). The microstructures on the morphology of the amorphous region [Fig. 3 (b)] show a small surface roughness in this region, while the cauliflower-like structures in the nanocrystalline region [Fig. 3 (d)] are

aggregates of nanometer-size grains, which results in a large surface roughness. On the mixed-phase region, a few large cauliflower-like structures appear on the

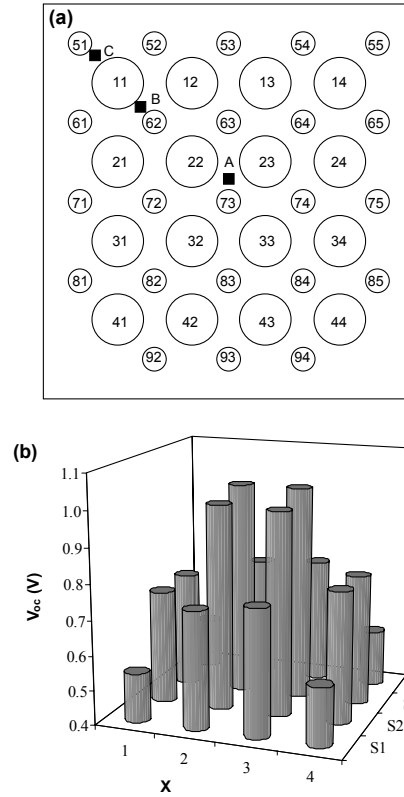


FIG. 1. (a) Solar cell distribution on a 4 cm \times 4 cm substrate. The squares labeled A, B, and C are the three areas where SKPM electrical potential and AFM morphology images are taken. (b) V_{oc} distribution of the sixteen 0.25-cm² cells on the same substrate.

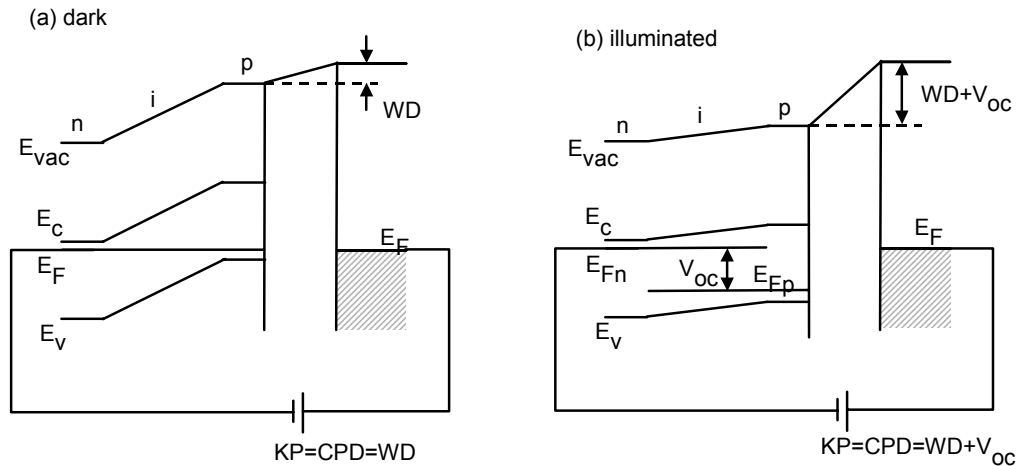


Fig. 2. Schematic band diagrams in the SKPM measurements. In (a), the SKPM measures the WD between the tip and the sample surface in the thermal equilibrium state; and in (b), it measures the sum of WD and V_{oc} when the sample is illuminated.

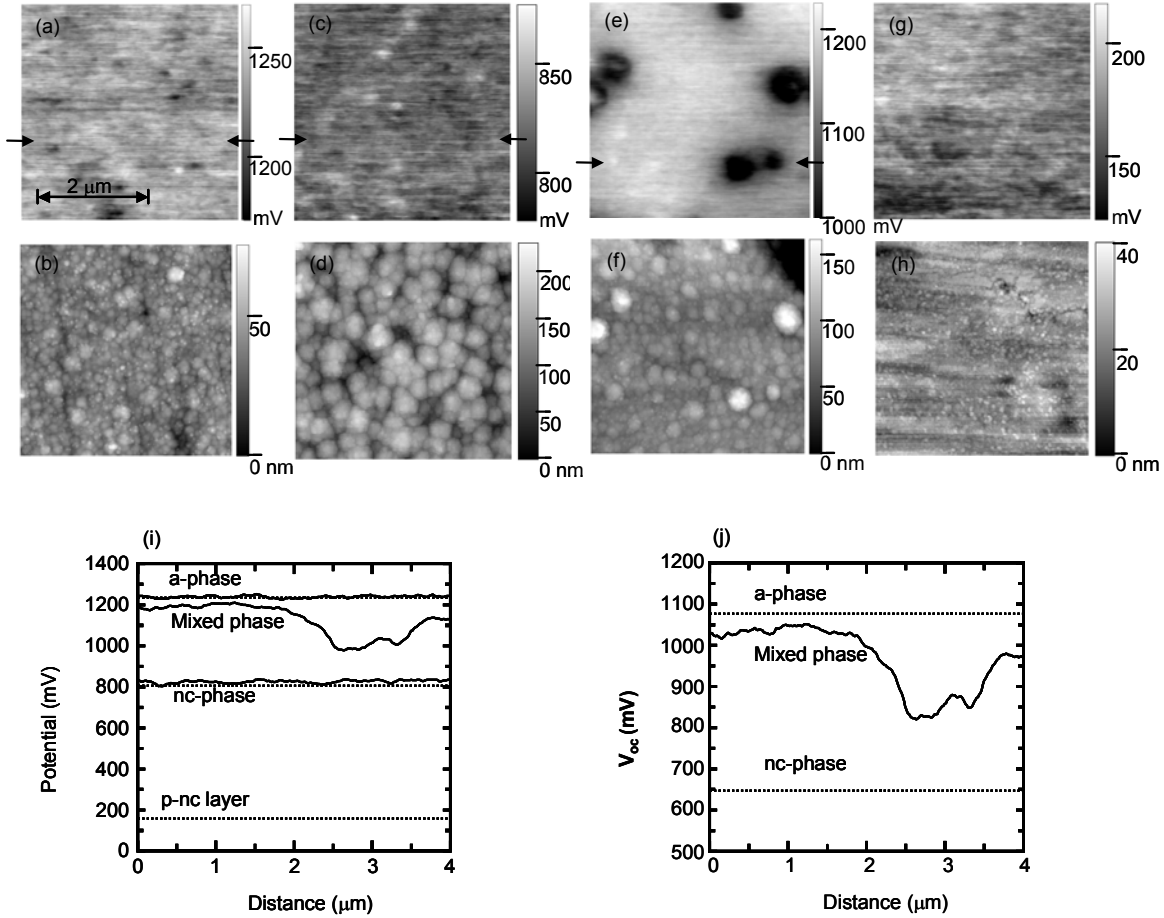


Fig. 3. SKPM potential and the corresponding AFM topographic images taken on (a) and (b) the amorphous phase, (c) and (d) the nanocrystalline phase, (e) and (f) the mixed-phase regions of an *n-i-p* solar cell. (g) and (h) were taken on a *p*-type nc-Si:H layer directly deposited on the stainless-steel substrate. Solid-line profiles in (i) show the potentials along arrows in (a), (c), and (e). Dotted straight lines in (i) show averaged potential values over several SKPM images. (j) shows the V_{oc} line profile in the mixed-phase deduced from the potentials in (i).

topographic image [Fig. 3 (f)], which correspond to the valleys in the V_{oc} distribution image [Fig. 3 (e)]. Note that the sizes of the V_{oc} valleys are larger than the corresponding nanocrystalline aggregates that appeared in the AFM image.

Figure 3 (i) shows line profiles of the SKPM images of the amorphous, nanocrystalline, and mixed-phase regions along the lines indicated by the arrows in Fig. 3 (a), (c), and (e), respectively. The three dotted straight lines are the averaged values through several SKPM images of the amorphous and nanocrystalline regions, and the *p* layer. The difference between the amorphous and nanocrystalline regions is 0.45 V, which is consistent with the V_{oc} difference between a-Si:H and nc-Si:H solar cells measured by J-V characteristics. Figure 3 (j) shows the V_{oc} line profile of the mixed-phase region obtained by subtracting the *p*-layer potential from the potential profile in Fig. 3 (i). Two important features are observed from this plot. First, the minimum V_{oc} value in the nanocrystalline valleys is much larger than the average value in the fully nanocrystalline region, as indicated by the bottom straight line. Second, the transition from the low to high V_{oc} regions is a gradual change within a

distance of about 1 μm. We think these two phenomena are related and caused by the lateral charge redistribution. The electrical interaction between the two phases by the relatively conductive *p* layer and the charge redistribution near the amorphous/nanocrystalline boundary in the bulk of the *i* layer could be a mechanism.

Although there is a lateral interaction between the amorphous phase and nanocrystalline aggregation areas, the V_{oc} characteristic shows a clear distinction between the two phases. This is consistent with our recent C-AFM measurement on the mixed-phase cells [7]. The two-dimensional electrical current images show much larger local current flow through the nanocrystalline aggregates than through the surrounding a-Si:H matrix. However, unlike the gradual potential transition that is related to the charge redistribution around the amorphous/nanocrystalline boundary, the transition of local current flow between the two phases is sharp at the boundary, because of the much smaller bandgap and higher conductivity in the nanocrystalline aggregates than in the surrounding amorphous regions.

We also measured the local V_{oc} distributions in mixed-phase SiGe:H alloy solar cells (Fig. 4). In general, the

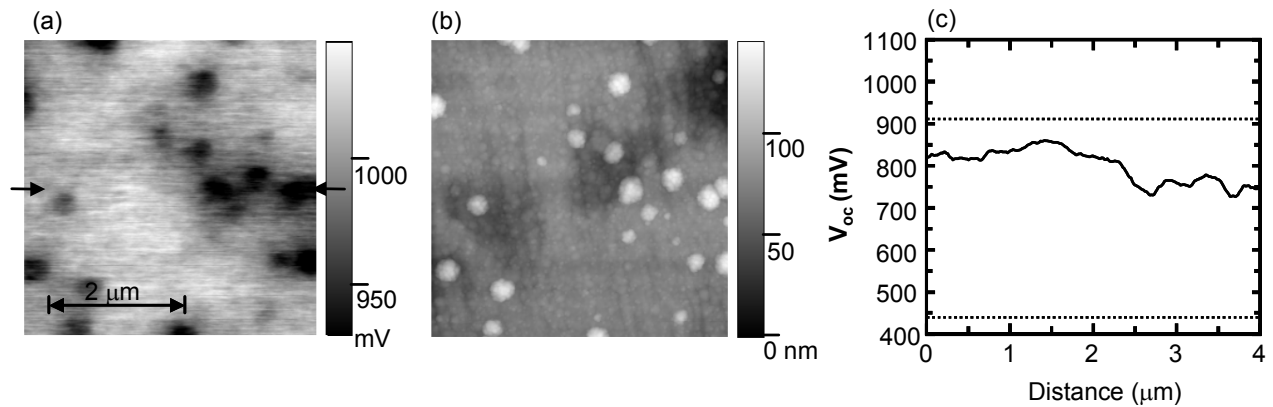


Fig. 4. (a) A SKPM electrical potential and (b) the corresponding topographic images taken on a mixed-phase a-SiGe:H solar cell. The solid curve in (c) shows a potential line profile along the arrows in (a), and the two dotted straight lines show averaged potential values take on the amorphous and nanocrystalline regions.

results are similar to the mixed-phase Si:H cells. However, some differences are noticed. First, the V_{oc} values are lower than the corresponding values in the mixed-phase Si:H cells. Second, the size of the nanocrystalline aggregates is also smaller than that in the mixed-phase Si:H cells. Third, the V_{oc} of the nanocrystalline aggregate is more heavily influenced by the surrounding amorphous matrix, showing smaller depth in the valley than the mixed-phase Si:H cells. Fourth, the transition from the low to high V_{oc} regions becomes even broader.

The phenomena above may result from the small size of nanocrystalline aggregates and/or heavy electrical interaction between the amorphous phase and nanocrystalline aggregates. The electrical interaction may relate to the electronic structure in the i layer, such as band alignment at the amorphous/nanocrystalline boundary. In addition, the conductivity of the SiGe:H alloy materials is higher than that of the Si:H materials. The heavier V_{oc} smooth-out in the mixed-phase SiGe:H cell could be partially caused by the high conductivity in the SiGe:H materials.

SUMMARY

By combining SKPM and AFM, we have developed a method to measure the local V_{oc} distribution in mixed-phase solar cells. The results clearly show the nanocrystalline aggregation. The V_{oc} is smaller in the nanocrystalline aggregates than in the surrounding amorphous matrix, and the transition from the low to high V_{oc} is a gradual change. Although there are some lateral charge redistributions, a clear distinction between the amorphous and nanocrystalline regions has been observed. The current SKPM results and previous C-AFM results provide extra support for the two-diode model for explaining the carrier transport in mixed-phase solar cells.

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