KELVIN PROBE FORCE MICROSCOPY STUDY OF ELECTRIC FIELD HOMOGENEITY IN EPITAXIAL SILICON SOLAR CELLS CROSS-SECTION

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Using Kelvin probe force microscopy, cross-section measurements along the PIN junction of an epitaxial silicon solar cell were performed under operating conditions (illumination, voltage bias). Surface potential profiles show coherent behaviors with theoretical expectations when the device is under increasing illumination intensity, increasing voltage bias, or under illumination at different wavelengths. Using measurements under voltage bias, we propose a methodology to investigate the electric field homogeneity along the PIN junction. It is shown that the electric field is not homogeneous for the cell measured and it is suggested that this might be due either to preparation steps or to inhomogeneous defective layer along the PIN junction.

Keywords: Kelvin Probe Force Microscopy, Heterojunction, Epitaxial Silicon, Silicon Solar Cell, Electric Field

1 INTRODUCTION

In order to make photovoltaics more competitive in the energy landscape, one of the most promising ways is to reduce the wafer thicknesses while keeping the efficiency and the reliability of the solar cell high enough. According to the 2015 ITPV roadmap \cite{1}, the incremental path would reduce the average wafer thicknesses from 160µm in 2015 to 100µm in 2025. However, new technologies of silicon solar cells, such as epitaxial silicon heterojunctions (eSi), offer disruptive paths to achieve wafers one order of magnitude thinner while keeping efficiencies competitive. For example, Solexel reached 21.2% efficiency epitaxial silicon solar cells using 35µm wafers \cite{2}. In our laboratory, we developed an expertise on epitaxial ultra-thin silicon solar cells grown by low temperature (<200°C) plasma enhanced chemical vapor deposition (PECVD) enabling to cut down thermal budgets \cite{3-5}. One of the challenges of performing deposition at low temperatures is that epitaxial layers can more easily incorporate impurities coming from the deposition chamber and hence the expected eSi intrinsic layers, are often unintentionally doped \cite{6}. This phenomenon directly affects the local electrical properties, in particular the electric field, which has no reason to be homogeneous along the PIN junction and may rather collapse at the junction.

To investigate the electrical properties at the nanoscale, AFM electrical extensions have proved to be powerful tools. Recently, these techniques have raised the interest of the photovoltaic community because their nanoscale resolution enables cross-section analysis and contrary to optical and electron microscopy, they enable analysis under low injection regimes. Therefore, they are unique tools to investigate solar cell devices under operating conditions at the nanoscale. In particular, Kelvin Probe Force Microscopy (KPFM) is becoming popular for investigating solar cell cross-sections under illumination \cite{7} and voltage bias \cite{8}.

In this study, we first investigate the effect of various wavelengths of illumination and voltage bias on KPFM measurement on the cross-section of PECVD few micrometers thick epitaxial silicon solar cells. Then, we explain our method to extract the electric field from KPFM measurements. We show that the electric field varies along the PIN junction. This suggests that the incorporation of undesired impurity elements during the epitaxial growth process can lead to electrical inhomogeneity in the solar cell device.

2 MATERIALS AND METHODS

2.1 Kelvin Probe Force Microscopy

Kelvin Probe Force Microscopy technique enables surface potential measurements. This potential corresponds to the difference between the tip work function and the sample surface work function, below the tip. Since the tip work function remains constant during the scans, the measured surface potential changes are directly linked to changes of the surface work function.

We performed single pass KPFM measurements in amplitude modulation (AM) mode. We used silicon probes coated with Pt/Ir and a force constant of 2.7N/m. on Agilent 5500 AFM microscope. We worked in controlled nitrogen atmosphere to avoid tip induced oxidation.

2.2 Studied Epitaxial Silicon Solar Cell

To fabricate the epitaxial silicon solar cell, we deposited intrinsic epitaxial silicon with a thickness of 3 µm on a heavily boron-doped (100) oriented 525µm thick Si wafer with a resistivity of 0.002-0.005Ω·cm. The deposition was done in an RF-PECVD reactor from the dissociation of 6% silane in a hydrogen gas mixture (SiH\textsubscript{4}/(SiH\textsubscript{4}+H\textsubscript{2})=0.06) with an RF power density of 50mW.cm\textsuperscript{-2} and under a pressure of 2Torr, resulting in a deposition rate of 0.15nm.s\textsuperscript{-1}. Then, 15nm of n− hydrogenated amorphous silicon (a-Si:H) layer is deposited on the eSi layer at the constant temperature of 175°C. Finally, the area of the cell (2x2cm\textsuperscript{2}) was determined by sputtering ITO through a shadow mask and evaporating an aluminum grid above.
2.3 Cross-section preparation

Once the solar cell was fabricated, we prepared the cross-section for measurements. First, the cell was cleaved in the zone of interest. Then, we performed mechanical polishing using six grinding disks with decreasing diamond grain size. Since, KPFM is sensitive to topographical artefacts, a polishing step is necessary to prevent a topographical imprint in the surface potential image [9]. The ITO, a-Si:H layers and a part of the epitaxial layer may be removed from the cross-section because of rounding effects due to polishing.

2.4 Measurements under illumination and voltage bias

To analyze the effect of operating conditions (illumination and voltage bias) on the surface potential and related field distribution, we positioned the epitaxial silicon solar cell on a cross-section holder which integrates an optical fiber and electrical contacts for the solar cell (Fig.1). We used fiber coupled LED light sources with varying intensities to study the effect of the injection level. Three wavelengths were used: λ=455nm (blue), λ=530nm (green), λ=625nm (red).

Figure 1: Schematic of the epitaxial silicon solar cell placed on the cross-section holder. The PIN solar cells consists of a P++ c-Si wafer, a non-intentionally doped I-epi-Si absorber and an n++ a-Si:H layer, capped with a transparent ITO and Ag contacts.

3 RESULTS AND DISCUSSION

3.1 Influence of wavelength illumination

Under illumination, the surface potential distribution across the PIN junction has following expected form:

- The surface potential in the p++ wafer remains constant because it is grounded and highly doped.
- In the n++ a-Si:H layer under the illumination, the surface potential is the difference between the vacuum level and the quasi Fermi level of electrons which are majority carriers in this layer. Since the vacuum level remains constant with and without light, the surface potential evolves as the opposite of the quasi Fermi of electrons. Under illumination, the quasi Fermi of electrons in the n++ a-Si:H layer split from the quasi-Fermi level in the p++ c-Si wafer by the $V_{oc}$ value. Thus, the surface potential in the n++ a-Si:H layer is supposed to decrease by a value close to the $V_{oc}$ with increasing illumination.

- The surface potential in the epitaxial layer is expected to evolve progressively from 0V close to the wafer to the $V_{oc}$ value close to the n++ a-Si:H layer.

Figure 2 shows the surface potential distribution superimposed on 3D topographical images. Each 3D image was taken under an illumination intensity corresponding to a voltage measured directly on the AFM stage equal to $V_{oc}$. It can be seen that with increasing $V_{oc}$ with increasing illumination, the surface potential in the epitaxial layer decreases whereas the surface potential on the wafer remains almost constant.

![Figure 2: Surface potential color coded (right bar) on the 3D topographical images (scan area : 1.5x5µm) under increasing illumination intensities (corresponding to increasing Voc, left values)](image)

Figure 3 shows surface potential profiles across the PIN junction in the dark and under the illumination with three different wavelengths inducing an open circuit voltage of 400mV. We found there is no impact of wavelength on the band structure. In the dark, the open circuit voltage is different from 0V because of the AFM laser that spills over the cantilever inducing a parasitic photovoltage. This laser induced photovoltage is very dependent on the orientation of the cross-section holder on the AFM stage. That is why it reaches 140mV in Fig. 3 and only 2mV in Fig. 2. The photovoltage measured by KPFM close to the edge is the difference between the surface potential value with the light off (-0.45V) and with the light on (-0.63V), giving value of 0.18V. This value is lower than the photovoltage measured by the voltmeter which is equal to 0.26V (the $V_{oc}$ with the light on is 0.4V and the $V_{oc}$ with the light off is 0.14V). The difference between photovoltages can be explained by surface states on the sample cross-section that reduces the surface potential variations.
3.2 Influence of voltage bias

As for measurements under the illumination, it is expected that the surface potential of the highly doped crystalline silicon wafer remains constant and with an increasing voltage bias, the quasi-Fermi level of electrons increases above that of holes by the value of the applied voltage bias. Therefore, the surface potential in the n⁺ a-Si:H layer is expected to decrease by this value when increasing voltage bias.

Figure 4 shows surface potential profiles under different voltage biases. The measurements show that the tendency with increasing voltage bias is the same as the one explained above. The decrease of the surface potential on the wafer for positive surface potential values can be explained by a series resistance in the wafer. On the edge of the cross-section, the steps between surface potentials are constant as the applied voltage bias is changed also by a constant setp. This implies a linear relationship.

3.3 Electric field analysis

Since the electrical field is the first derivative of the surface potential, we can perform electric field analysis along the PIN junction. Jiang et al. have used this technique to locate pn junction in multi-crystalline silicon solar cells [8]. For epitaxial silicon solar cells, this is important in order to study impact of the unintentional doping of the epi PECVD c-Si layer on electric field distribution.

To obtain the electric field distribution, we process surface potential data recorded at two different voltage biases to minimize topographical artefacts: First, the profiles at +0.5V and -0.5V are subtracted. We choose two extreme voltage biases in order to increase signal/noise ratio. Then, the raw (subtracted) data are smoothed by a linear interpolation to remove thermal noise with minimum effect on the profile. Finally we draw the profile of the electric field by taking the first derivative of the smoothed surface potential profile.

Figure 5 shows the electric field obtained using this method in three different zones along the PIN junction. It can be seen that for three different profiles the electric field peak is centred at the interface between the c-Si wafer and the epitaxial layer. Besides it does not extend deeply inside the epitaxial layer which provides a strong indication that the epitaxial film is probably lightly n-doped. Moreover, the shape of the profiles is different. In scan area 1 and 3, the peak is asymmetric and broad whereas in scan area 2, the peak is more symmetric, higher and narrower. These measurements suggest that either the preparation polishing step has altered the electric field inside the epi-Si or that an inhomogeneous defective layer along the junction is created during the first steps of the growth of epitaxial silicon.

Figure 5: Electric Field obtained by our method on three different areas along the PIN junction of the solar cell.

4 CONCLUSION

In this work, we have shown that KPFM enables the study of solar cell devices cross-section under operating conditions. We have reported the effect of the illumination and applied bias on surface potential profiles. Our measurements are coherent with theoretical expectations and enable a consistent analysis. Finally we present an approach to evaluate the electric field along the PIN junction with nanoscale resolution. We show that the electric field is not homogeneous and we suggest that the inhomogeneity might be either due to the preparation process that includes mechanical polishing or to inhomogeneous defective layer at the interface between the epi-Si layer and the c-Si wafer.
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6 REFERENCES


