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Full paper

Insight into interfaces and junction of polycrystalline silicon solar cells by kelvin probe force microscopy

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ABSTRACT

Kelvin probe force microscopy (KPFM) is a powerful tool to measure surface potential with resolutions in the order of atomic/nanometer scales, and could also provide direct measurements of the surface potential on interfaces and junctions of solar cell devices. In this paper, the whole surface potential distribution along the cross-section of the polycrystalline silicon solar cell was illustrated by KPFM for the first time. Interestingly, the surface potential presents a two-stepwise downward profile from Al electrode to Ag electrode, and surface potential skip-steps occur at Al/p-Si interface and p-n junction, respectively. Notably, the p^+ layer due to the Al doping was firstly identified by KPFM. Devices of three different efficiencies are tested and showed that the skip-step value at Ag/Si interface is linearly correlated with the device efficiency. So the surface potential skip-step value at Ag/Si interface is proposed to be an important parameter to evaluate the quality of Ag/Si interface. By combination of SEM, TEM and KPFM characterizations with performance measurement of the solar cells, we get deep insight relationships of compositions and morphologies around metal/semiconductor interfaces and junction in the atomic and nanometer scales, and find correlations between these structures and electrical/photoelectrical properties of devices. These studies are helpful to understand the device physical properties and provide potential routes to improve device efficiency.

1. Introduction

Polycrystalline silicon solar cells take a great market share due to its high efficiency, long-term stability and low cost. Although the power conversion efficiency of polycrystalline silicon solar cell has exceed to 18%, there are few directly tools to research the interfaces and the operating principle of solar cell. It is well known that the quality and properties of the interfaces between different layers is the key part to determine the device performance in all heterojunction-based devices [1–3]. There exist three interfaces or junction of Ag-/n-Si, n-Si/p-Si and p-Si/Al in a classical device structure (Ag/n-Si/p-Si/Al) of polycrystalline silicon solar cell, which are the core structures to determine the device efficiency. So it is very important to get insight into relationship between these interfaces and junction and performance of polycrystalline silicon solar-cells by creating novel measurement methods with resolutions in the order of atomic and nano-scales versus electrical or photo-electrical properties, which will be helpful to control the quality of these interfaces for obtaining high-efficiency devices. Many efforts have been devoted to observe the morphology of these interfaces by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). In comparison, there still lack appropriate tools to measure the electrical properties of these interfaces, including junction location, depth, and electrical potential distribution in the whole devices.

One kind of functions in atomic force microscopy (AFM) is Kelvin probe force microscopy (KPFM), which is also known as surface potential microscopy. Since its first introduction by Nonnenmacher et al. in 1991 [4], KPFM has been used extensively as a unique method to characterize the atomic and nano-scale electronic or electrical properties of metal/semiconductor surfaces and semiconductor devices. Recently, KPFM has been demonstrated as a powerful tool for surface potential measurements, due to of its atomic-level spatial resolution [5–10].

The surface potential relates to many surface phenomena, including catalytic activity, reconstruction of surfaces, doping and band-bending of semiconductors, charge trapping in dielectrics and corrosion [11–14]. Combining TEM, SEM and KPFM characterizations, we can get the mapping of composition and surface potential to give information

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about the distribution of electron of the local structures on the surface of polycrystalline silicon solar cells [15–20]. It will be very helpful to observe the surface potential distribution at atomic or nano scales for the device evaluation and design.

In this paper, the whole surface potential distribution along the cross-sections of the polycrystalline silicon solar cell was illustrated by KPFM for the first time. Moreover, by combination of TEM, SEM and KPFM characterization with performance measurement of polycrystalline silicon solar cells, three devices with different efficiencies were tested and showed that there existed a linear correlation between the surface potential distribution and the device efficiency. These studies are helpful to understand the device physical properties and provide potential routes to improve solar cell efficiency [21–23].

2. Experimental section

2.1. Device fabrication

Polycrystalline silicon solar cell devices used in this research are prepared by screen-printing DuPont PV18H silver paste on the commercial semi-finished devices with a SiN_x/n-Si/p-Si/Al configuration and subsequently performing calcination in a seven-section meshbelt furnace. The semi-finished devices were bought from Tian-Si New Energy Company. The seven-section meshbelt furnace was designed by ourselves and assembled by Hefei Ke-Jing Materials Technology Company.

2.2. Device characterization

The current density versus voltage (J–V) characteristic curves of the devices are recorded using a Keithley 2602A sourcemeter (Keithley Instruments Inc., Cleveland, OH, USA) under one sun, AM 1.5G irradiation (100 mW/cm^2) from a solar simulator (Abet Technologies Model 11000A Sun 3000 Solar Simulator). The illumination intensity is calibrated using a standard single crystal silicon solar cell. All of the measurements are performed under ambient atmosphere at room temperature (25 °C).

2.3. Device cross-section preparation

The cross-section samples of polycrystalline silicon solar cell are processed by an Ar^+ Ion Beam Milling System (Leica EM TIC 3X, Leica Inc). First, a cleaved polycrystalline silicon solar cell (12 mm×3 mm, cut by laser cutting machine) is loaded into the high vacuum chamber. Then it is milled by three Ar^+ ion beams using beam voltage of 7.5 kV and beam current of 2.8 mA for 3.5 h and then polishing with voltage of 4.5 kV and beam current of 1.6 mA for 1.5 h. (Fig. 1a). A fresh and smooth cross-section of polycrystalline silicon solar cell can be achieved. And the surface potential along the cross-section was directly measured by KPFM (Fig. 1b).

2.4. Device cross-section characterization

The morphology of the cross-sections for polycrystalline silicon solar devices are characterized using SEM (SEM, ZEISS Supra 55-VP). The interface of Ag/glass/Si of the samples were analyzed by transmission electron microscope (TEM, FEI Tecnai G2 F30). And energy dispersive X-ray spectroscopy (EDX) was employed to analyze the surface element distribution and composition of samples. The sample of the interface of Ag/glass/Si for TEM was prepared by Focused Ion Beam (FIB, FEI, Scios) followed by Ion Beam Modulating (Fig. S3). Firstly, a relatively flat region was selected, then Pt was deposited on the surface of selected section for protecting the interface with a thickness of Pt deposited up to 1 μm. A Ga ion beam (30 kV, 1 nA) was employed to cut all selected areas. Then the cut cross-sectional sample was transferred to a special Company "U" style copper network for further ion milling. A final sample suitable for TEM with a thickness of ~20 nm or so was obtained by ion milling repeated with different Ga ion beam followed by (30 kV, 50 pA), (20 kV, 50 pA), (10 kV, 30 pA), (5 kV, 16 pA) and (2 kV, 8 pA). The KPFM surface potential measurements of device cross-sections are carried out by a MultiMode 8-HR AFM (Bruker Corporation, Germany) using Pt/Ir-coated conducting tips (SCM-PIT) with a resonance frequency of 75 kHz and a spring constant of 2.8 N/m. A two-pass scan amplitude modulated KPFM (AM-KPFM) is used to measure the surface potential in a glove box (H_2O < 1 ppm, O_2 < 1 ppm). During the first pass, standard alternating current (AC) mode imaging (typical tip oscillation amplitude 20 nm) is performed to acquire the topography and phase signal of the sample; in the second pass, the tip is lifted up by a certain height (typically 80 nm) and scanned on the basis of the topography line obtained from the first pass. An AC voltage is applied to actuate the cantilever, and the direct current (DC) voltage applied to the tip that nullifies the tip–sample interaction is collected as the SP signal. The device-wiring configuration during cross-section characterization is shown in Fig. 1b. Ag electrode is grounded when scanning Part I (Ag/n-Si/p-Si), and Al electrode is grounded when scanning Part II (Al/p-Si).

3. Results and discussions

We have prepared three polycrystalline silicon solar cell devices with different power conversion efficiencies (PCE=8.81%, 13.25% and 15.27%) by adopting different calcination conditions. Three kinds of calcination conditions are presented in Fig. S1. It is easy to find that the main difference between these three conditions is the annealing time at the highest temperature. The longest annealing time led to a lowest efficiency (8.81%), and the highest efficiency (15.27%) was originated from the moderate annealing time. J–V curves are presented in Fig. 1c, and the corresponding photovoltaic parameters are listed in Table S1. As shown in Fig. S2, the efficiency was positively correlated with short-circuit current density (J_{sc}) and fill factor (FF), which are significantly

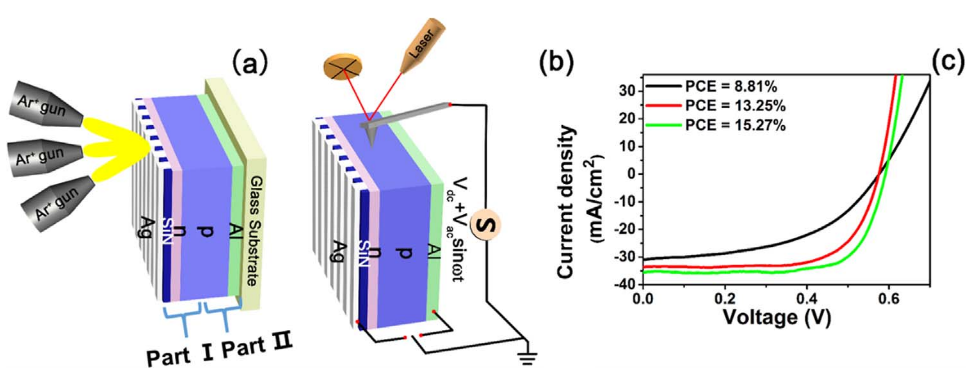

Fig. 1. (a) Schematic illustration of Ar^+-beam milling configuration to expose a smooth cross-section of polycrystalline silicon solar cell device; (b) Schematic illustration of the surface potential measurement by KPFM along the cross-section; (c) J–V curves of polycrystalline silicon solar cell devices under standard test condition (AM 1.5G illumination, 100 mW/cm^2, 25 °C).