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Effects of oxygen related thermal donors on the performance of silicon heterojunction solar cells

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ABSRACT

The influence of oxygen-related thermal donors (TDs) on the performance of silicon heterojunction (SHJ) solar cells was explored experimentally in this paper. It is found that a certain number of thermal donors could do much harm to the performance of SHJ solar cells. The efficiency of SHJ solar cells is usually reduced by a value of ~ 1% absolute in the case of thermal donors with a concentration of nearly 10^{15} cm^{-3}. The microwave photoconductance decay and Hall Effect studies have proved that the TDs can significantly reduce the carrier lifetime of n-type silicon substrate, but have no influence on the carrier mobility. Deep level transient spectroscopy (DLTS) measurements have further demonstrated that the TDs cause an energy level at Ec-0.13 eV with carrier capture cross-section of 10^{-15} cm^2, which is responsible for the reduction of carrier lifetime and solar cell efficiency.

1. Introduction

The first diffused p-n junction silicon solar cell was developed in the early 1950s with a conversion efficiency of around 4.5%. From then on, the efficiency of silicon solar cells has significantly improved [1]. So far, one of the highest efficiencies was at around 25.6%, achieved on the n-type silicon heterojunction with an intrinsic thin-layer interdigitated back contact (SHJ-IBC) structure [2]. Therefore, the heterojunction with intrinsic thin-layer has become one of the most promising solar cell structures, due to its high efficiency and potential low cost. The main features of SHJ solar cells are low temperature processes and little light-induced degradation [3–5].

Silicon materials made for SHJ solar cells are usually n-type single-crystalline Czochralski (CZ) silicon. It is well known that oxygen is one of the most important impurities in CZ silicon, with the concentration of about 10^{18} cm^{-3}. The effects of oxygen and related defects in CZ silicon on the performance of solar cells have been studied intensively [6,7]. During the cooling process of CZ silicon ingots or the annealing in the temperature range of 350–500 °C, oxygen impurities inevitably accumulate to form thermal donors (TDs) [8–10]. It has been known that the TDs are doubly ionized at room temperature in standard resistivity Si, which means that one TD can provide two free electrons. The double-donor character of TDs will cause a downward shift of resistivity in n-type phosphorus (P)-doped silicon. Especially, for the sample with high concentration of oxygen impurities or subjected to a long-time heat treatment in the temperature range of 350 – 500 °C, the TD concentration could be high enough to cause the obvious doping effect. Based on the measurements of Hall effect, Fourier transform infrared spectrometry (FTIR) and deep level transient spectroscopy (DLTS), 16 families of TDs have been resolved [11–13], which usually introduce two donor levels, i.e., $E_1 = Ec - 0.05$ eV and $E_2 = Ec - 0.15$ eV [14,15].

The TDs can be generally eliminated in the high temperature courses of homo-junction cell processes, so their influence on the performance of wafers and solar cells does not get enough attention. With the developments of high efficiency and low temperature SHJ solar cell process, this issue starts to become more and more important [16–18]. Since the maximum temperature of SHJ processes remains below 300 °C, as mentioned above, the as-grown TDs are still retained in the bulk of silicon wafers. Recently, theoretical simulation results have pointed out that the TDs can significantly deteriorate the performance of SHJ cells [19]. However, few experimental data have ever been reported as of today [20].

In this paper, we have experimentally investigated the influence of oxygen-related TDs on the performance of SHJ solar cells. The evolution of SHJ solar cell performances with the TDs is explored. Meanwhile, DLTS measurements have been performed to reveal the energy levels associated with the recombination activity of TDs. The results are quite of significance for understanding the mechanism of the

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TDs influencing on the performances of SHJ solar cells.

2. Experimental details

One n-type phosphorus-doped CZ silicon crystal ingot with a diameter of 6-in. is grown by the magnetic field application and thermal field modification. Two kinds of wafers with a thickness of 190-µm cutting from different parts of the ingot were used in our experiments, which were labeled as A and B here. The interstitial oxygen concentrations in the wafer A and B were 2.5×10^{17} and 5.5×10^{17} cm^{-3}, respectively, determined by means of FTIR after polishing at room temperature with a calibration factor of 3.14×10^{17} cm^{-2}, with an error less than 10% through repeated experiments. After etching in an alkaline KOH solution to remove the sawing damaged layer, some wafers were subjected to 450 °C heat treatments [21] in a clean furnace for 0–50 h with argon protection to intentionally generate TDs. The resistivities of the wafers were measured by a four point-probe measurement at room temperature before and after different thermal treatments. The initial TD concentration can be derived from the resistivity variation of the samples ($n_0 =$ [P] + 2[TD]) before and after a 650 °C thermal treatment in a clean furnace with argon protection for 30 min. Here n_0 is the majority carrier concentration calculated from the value of resistivity, [P] is the doping concentration of phosphorus, and [TD] is the concentration of TDs. As the influence of TDs on the majority carrier mobility is negligible, standard mobility models have been used for the conversion from resistivity into [TD] data. For further measurements, some silicon wafers were cut into several 1 cm × 1 cm sized samples prepared from the wafer center. The carrier mobility in the samples were measured by a Hall effect system (Lakeshore 7700 A) after four Ohmic contacts by employing Al electrodes with a diameter of 1-mm and thickness of 200-nm were fabricated on top of the samples. Detailed parameters and measurement data of the wafers are shown in Table 1.

Meanwhile, the far-infrared absorption bands related to the TDs were inspected by FTIR (Bruker Vertex 70 v) at 10 K at a resolution of 1.0 cm^{-1}. The IR-spectra were accumulated 200 times. In order to further reveal the parameters of the TD-induced energy levels, the DLTS (Phys Tech FT1030, 1 MHz) measurements were performed. Schottky diodes by employing Au electrodes with a diameter of 1-mm and thickness of 80-nm were fabricated on top of the samples, an In/Ga layer was pasted on the backside surface to form Ohmic contact. The reverse voltage (U_R) of − 2 V was kept and the filling-pulse voltage (U_p) of 0 V was applied with the period (T_P) of 100 ms and duration (T_W) of 50 ms.

The SHJ solar cells were fabricated using a standard process, i.e., an intrinsic *a*-Si:H layer followed by a p-type *a*-Si:H layer was deposited on the 15.6 cm × 15.6 cm textured n-type CZ Si wafer to form a p-n heterojunction. Subsequently, the intrinsic and n-type *a*-Si:H layers were deposited to obtain a back surface field (BSF) structure. In the meantime, the effective lifetime (τ_{eff}) was inspected by the Sinton lifetime tester (WCT-120) with an excess carrier density of 1×10^{15} cm^{-3}. Next, the transparent conducting oxide (TCO) layers were deposited on the top of the doped *a*-Si:H layers. Finally, metal grid electrodes of 4 busbars were formed using a screen-printing method. The solar cell performances were measured under the standard conditions (one sun, AM 1.5 Global spectrum, 25 ± 1 °C), using a Berger Flasher PSS 10 solar simulator. The illumination intensity was calibrated using a reference cell obtained from FISE (Fraunhofer Institute for Solar Energy Systems), Germany. The leakage current (J_0) values of solar cell are extracted through plotting the inverse τ_{eff} reduced by the inverse intrinsic lifetime (τ_{intr}) versus the excess carrier density (Δn), based on the following formulas:

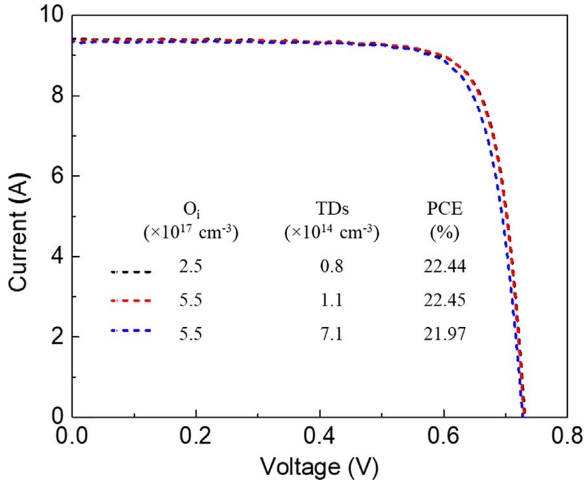

Fig. 1. Experimental I-V curves of SHJ solar cells with different TD and oxygen concentrations.

$$\frac{1}{\tau_{eff}} - \frac{1}{\tau_{intr}} = \frac{1}{\tau_{SRH}} + \frac{J_0(N_d + \Delta n)}{q n_i^2 W} \tag{1}$$

where τ_{intr} is resulting from Auger and radiative recombination, τ_{SRH} is the lifetime determined by SRH defect recombination, W is the substrate thickness, q is the elementary charge, N_d is the base doping density, and n_i is the intrinsic carrier density.

3. Results and disscusions

We first investigated the influence of interstitial oxygen concentration on the performance of solar cells. The I-V curves of SHJ solar cells based on two kinds of wafers with different oxygen concentration are shown by the black and red lines in Fig. 1. Note that the concentration of TDs for both kinds of samples are almost the same, about 1×10^{14} cm^{-3}, but the oxygen concentrations are 2.5×10^{17} and 5.5×10^{17} cm^{-3}, respectively. It can be seen that the I-V characteristics are coincident with each other. This suggests that the interstitial oxygen impurities themselves are not harmful for the solar cell performances when the oxygen concentration is not very high. However, for the samples with different TD concentration, the I-V curves of solar cells are obviously different even though the oxygen concentrations are the same, as revealed by the red and blue lines in Fig. 1. The TDs with a higher concentration of 7.1×10^{14} cm^{-3} give an obviously harmful influence on the performance of solar cells. Based on this result, we can conclude that the TDs instead of interstitial oxygen should be responsible for the deterioration of the SHJ solar cell performances. However, it should be mentioned here that the formation of TDs is strongly dependent on both the initial oxygen concentrations and the thermal history of sample. For the conventional production of CZ

Table 1
Description of silicon wafers.

Sample	A_1	A_2	B_1	B_2	B_3	B_4
Heat treatment	As-grown	450 °C/50 h	As-grown	450 °C/15 h	450 °C/35 h	450 °C/50 h
ρ (Ω·cm)	4.50	4.31	4.10	3.19	2.02	1.98
TDs (×10^{14} cm^{-3})	0.1	0.8	1.1	2.7	7.1	7.5
Hall mobility (cm^2/Vs)	1450	1440	1435	1415	1385	1370