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Effect of temperature on crystalline silicon solar cells processed from chemical and metallurgical route

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ABSTRACT

Effect of temperature on monocrystalline and multicrystalline silicon solar cells processed from chemical (EG-Si) and metallurgical (SoG_M-Si) routes was investigated in the range of 280–350 K. The temperature coefficients of important parameters related with the cell property were discussed. Experimental results indicate that the *T*-coefficient of conversion efficiency (η) of multicrystalline EG-Si cell processed from chemical is only 68% that of the monocrystalline EG-Si cell. Furthermore, the η of both types of SoG_M-Si cells decrease much less than that of the EG-Si cells with the increase in temperature. Additionally, the recombination fraction, the minority carrier lifetime, the carrier mobility decrease and the band-gap shrinkage were also investigated to reveal the intrinsic temperature dependence mechanism. In order to confirm the results, we used numerical simulation software AMPS-1D (analysis of microelectronic and photonic structure in one dimension program) to simulate the temperature dependence of solar cell performances. The results of numerical simulation were basically consistent with the experimental results.

1. Introduction

The report of European Photovoltaic Industry Association (EPIA) revealed that the photovoltaic grid-generating capacity of 2011 is 27.7 GW, compared with 16.6 GW in 2010, an increase of 66.86% [1]. Crystalline silicon is widely used in photovoltaic devices, making up for about 90% of the solar cell market [2]. Therefore, the research on crystalline silicon solar cells is crucially important. Silicon solar cell modules are generally exposed under the temperature ranging from 288 K to 323 K in practice, leading to enormous variations in the solar cell output [3].

In order to make full use of solar cells, analyzing the *T*-variations of solar cell performance, including the short-circuit current density (J_{sc}), the open circuit voltage (V_{oc}), the fill factor (FF) and the conversion efficiency (η) under different temperature are significantly indispensable. Previous studies have investigated the temperature dependence on silicon solar cells [4–7]. However, there are few researches on temperature dependence of EG-Si solar cells and SoG_M-Si solar cells. This article mainly focuses on the different temperature effects between multicrystalline silicon cells and monocrystalline silicon cells and the temperature dependence of EG-Si solar cells and SoG_M-Si solar cells. Although the EG-Si and SoG_M-Si solar cells have similar reductions in V_{oc} and FF with the increasing temperature, the decreases of η of EG-Si solar cells are much higher than that of the SoG_M-Si solar cells. This paper provides useful references about the advantages of SoG_M-Si solar cells.

2. Experiment and simulation

P-type EG-Si and SoG_M-Si solar cells, based on N^+–P structure have been used in this paper. The amounts of B and P were determined from glow-discharge-mass-spectroscopy (GDMS) measurements, and the resistivities were measured by using four probe method. In order to get more accurate experimental data, we have selected four different samples. The EG(A) is monocrystalline silicon cell by chemical route (Czochralski wafer, B-doped to 7.54×10^{15} cm^{-3}, ρ equals to 1.85 Ω cm). The EG(B) is multicrystalline silicon cell by chemical route (B-doped to 5.08×10^{15} cm^{-3}, ρ equals to 2.7 Ω cm). The SoG_M(A) is monocrystalline silicon cell by metallurgical route (Czochralski wafer, B-doped to 3.6×10^{17} cm^{-3} and P-doped to 3.3×10^{17} cm^{-3}, ρ equals to 1.0 Ω cm, complete degradation). The SoG_M(B) is multicrystalline silicon cell by metallurgical route (B-doped to 6.4×10^{16} cm^{-3} and P-doped to 4.1×10^{16} cm^{-3}, ρ equals to 0.6 Ω cm, complete degradation). All solar cells are diced into 6.25×3 cm^2 sizes. The N^+ emitter was fabricated by P diffusion. Both surfaces were textured by the

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Table 1
The performance parameters of solar cells at 300 K.

Sample	EG(A)	EG(B)	SoG_M(A)	SoG_M(B)
J_{sc} (mA/cm^2)	36.22	33.52	27.86	31.84
V_{oc} (mV)	623.65	613.19	594.70	613.48
η (%)	17.02	15.07	12.45	14.17

anisotropic chemical etch by the KOH solution. Then a SiN-H layer was deposited by PECVD used as antireflection coating. The Ag front and Al rear electrodes were deposited by screen printing. In addition, the performance properties of studied cells were measured under standard illumination (AM1.5; 100 W cm^{-2}) using Abet Sun 2000 Solar Simulator and Keithley 2410 source meter. From these I–V measurements, the J_{sc}, V_{oc} andη were extracted and given in Table 1.

AMPS-1D is a program developed at Pennsylvania State University [8]. It uses the first-principles continuity and Poisson's equations approach to analyze the transport behavior of optoelectronic device structures. These device structures can be compose of crystalline, polycrystalline or amorphous materials. In our simulations, the trap density of states (DOS) model and the S-R-H recombination mechanism have been taken into account. For the density of localized states in the gap of crystalline silicon, it has been assumed that there are both acceptor-like states and donor-like states modeled by exponential band tails (Urbach tails). The acceptor and donor doping concentrations (NA, ND) respectively corresponded to the doping value [B] and [P] studied through the experimental work. The initial set values of the mobility were calculated by using Klaassen model. It should be valid for compensated wafers, since it explicitly accounts for the different scattering cross sections of minority and majority dopants for both minority and majority carriers. In Table 2, we summarized the main parameters used in our simulations.

3. Results and discussion

Numerical simulation results of η, J_{sc}, FF and V_{oc} variations under the temperature ranging from 280 to 350 K were shown in Fig. 1. From Fig. 1(a and b), V_{oc} and FF decrease in line with the temperature. The decrease of V_{oc} is mainly due to the augment of saturation current density (J_o) written as follows [9]:

$$J_0 = AT^3 \exp\left(-\frac{E_g}{kT}\right) \tag{1}$$

where A is a constant and K is the Boltzmann constant. From Eq. (1), we find a higher J_o when the temperature increases.

The expression for V_{oc} is defined as follows:

$$V_{oc} = \frac{nkT}{q} \ln\left(\frac{J_{sc}}{J_o} + 1\right) \tag{2}$$

where n is the ideality factor. Obviously with a higher J_o, V_{oc} will reduce from the above equation.

The temperature dependence of V_{oc} can be modeled as [10]:

$$\frac{dV_{oc}}{dT} = -\frac{V_{g0} - V_{oc} + \gamma(kT/q)}{T} \tag{3}$$

where $V_{g0} = E_{g0}/T$ and E_{g0} is the band gap of the semiconductor at 0 K. γ includes temperature related factors determining J_o. It means that V_{oc} decreases almost linearly with increasing temperature.

The correlation between the J_{sc} and V_{oc} of p–n junction solar cell under steady state illumination can simply be described using the following single exponential model as:

$$J_{sc} = J_o\left[\exp\left(\frac{qV_{oc}}{nkT}\right) - 1\right] \tag{4}$$

The T-coefficient of J_{sc} can be deduced from Eq. (4) as:

$$\frac{dJ_{sc}}{dT} = \left[\exp\left(\frac{qV_{oc}}{nkT}\right) - 1\right] \times \frac{dJ_o}{dT} + \frac{qJ_o}{nkT}\exp\left(\frac{qV_{oc}}{nkT}\right) \times \left(\frac{dV_{oc}}{dT} - \frac{V_{oc}}{T}\right) \tag{5}$$

For monocrystalline silicon solar cells, $J_0 = 7.87 \times 10^{-11}$ mA/cm^2, $dJ/dT = 1.306 \times 10^{-11}$ mA/cm^2 k, $n = 1$, which gained from experimental measurement and theoretical calculation at 298 K [4]. Taking into consideration of related parameters, we got the theoretical calculation dJ_{sc}/dT value by Eq. (5), equals to 0.01 mA/cm^2 K.

The J_{sc} varies with temperature from 280 K to 350 K and its results obtained from the AMPS-1D numerical simulation are presented in Fig. 1(c). It is clear that the J_{sc} increases linearly with temperature. Extracting the values of J_{sc} from experimental measurements and numerical simulations, we determined the values of dJ_{sc}/dT by linear fitting. Experiment measurements were made every 5 K. The dJ_{sc}/dT values of all studied solar cells were shown in Fig. 2(a). There is a strong difference about the dJ_{sc}/dT values between EG-Si and SoG_M-Si solar cells. For the monocrystalline silicon solar cells, the experimental value of dJ_{sc}/dT is equal to 0.009 mA/cm^2 K for EG(A) solar cell, whereas the dJ_{sc}/dT is equal to 0.014 mA/cm^2 K for SoG_M(A) solar cell. In addition, it is interesting to observe that the experimental dJ_{sc}/dT values of multicrystalline EG-Si cell and multicrystalline SoG_M-Si cell are respectively

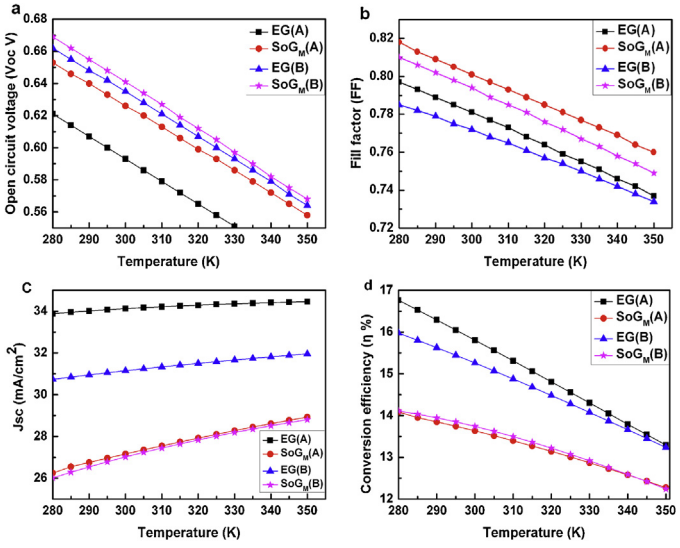

Fig. 1. AMPS-1D simulation results of V_{oc} (a), FF (b), J_{sc} (c), and η (d), as a function of temperature, with temperature in the range 280–350 K.

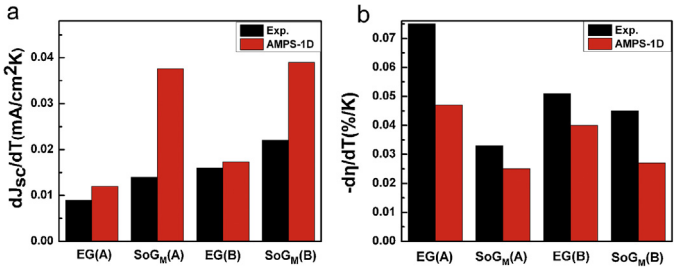

Fig. 2. T-coefficient of J_{sc} (a) and T-coefficient of η (b). Exp. is the experimental values and AMPS-1D is the simulation values.