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Impact of solar irradiance intensity and temperature on the performance of compensated crystalline silicon solar cells

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ABSTRACT

Low-cost upgraded metallurgical grade silicon (UMG-Si) with inherent boron (B) and phosphorus (P) compensation is a novel material for photovoltaic application. This paper presents the impact of solar irradiance intensity and temperature on the performance of compensated crystalline silicon solar cells. For the same rated output power, compensated crystalline silicon solar cells generate less electricity than the reference silicon solar cells at low irradiance intensity, owing to the strong injection dependence of the carrier lifetime due to high concentration of B–O complexes in compensated silicon. However, at high temperature, compensated crystalline silicon solar cells generate more electricity than the reference silicon solar cells, which mainly originates from the lower temperature-variation of the minority electron mobility in compensated silicon. It suggests that compensated silicon solar cells will be more appropriate for high irradiation application, which often contains high irradiance intensity and high temperature. These results are of great significance for understanding the actual outdoor performance of the solar cells based on the UMG-Si and their application in the photovoltaic (PV) industry.

1. Introduction

Upgraded metallurgical grade silicon (UMG-Si) directly purified by the metallurgical routes has attracted more and more attention in recent years due to the requirement of low cost and therefore has been used to fabricate solar cell in photovoltaic (PV) industry [1,2]. However, the typical characteristic of UMG-Si is the dopant compensation since electrical dopants, such as boron (B) and phosphorus (P), cannot be easily removed via the metallurgical routes [3–6]. Owing to the increased ionized impurity scattering, the dopant compensation might lead to the reduction in both majority and minority carrier mobilities [7,8], but the minority carrier lifetime could get improved benefitting from dopant compensation [9,10]. This counterbalance could result in some improvement in the minority carrier diffusion length [9,10]. Kraiem et al. reported industrial multicrytalline (mc) silicon solar cells with an efficiency of 16.2% and Czochralski (CZ) silicon solar cells with an efficiency of 17.6% using 100% UMG-Si [11]. By adopting a low-temperature dielectric surface passivation on front and rear, Engelhart et al. presented mc UMG-Si solar cells with an efficiency of 18.4% [12]. Recently, Einhaus et al. showed n-type UMG-Si heterojunction (HJ) solar cells with an efficiency of 19.0% [13]. Our previous study shows that compensated silicon solar cells could have a higher open-circuit voltage (V_{oc}), due to a larger net doping concentration (p_0) in the base region, therefore having a comparable efficiency with the conventional ones [8].

It is worth noting that the measurement of the solar cell efficiency (η) is generally performed under the standard test conditions (STC), e.g., an irradiance intensity of 1000 W/m^2 with a spectral distribution conforming to the air mass (AM) 1.5 G spectrum, and a PV device temperature of 25 °C. However, the STC cannot represent the actual outdoor conditions in most regions of the world. The instantaneous power output of a PV module mainly depends on the solar irradiance intensity and operating temperature which significantly vary with the geographical location, climatic conditions, time of day and season [14–17]. Thus, it is necessary to study the performance of solar cells under variable solar irradiance intensities and temperatures in order to be able to provide the accurate prediction of the energy production of PV systems.

In this paper, we have investigated the impact of solar irradiance intensity and temperature on the performance of

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compensated crystalline silicon solar cells. For the reference, the conventional crystalline silicon solar cells are also analyzed in the same measurements. It is found that at low irradiance intensity the performance of compensated crystalline silicon solar cells is relatively worse than that of the reference silicon solar cells, while at high temperature it is relatively better than that of the reference silicon solar cells. These results are of significance for understanding the actual outdoor performance of the solar cells based on the UMG-Si and their application in the PV industry.

2. Experimental procedure

Three 6 in. CZ silicon crystals were grown under the same conditions. One is a conventional B-doped silicon crystal for reference. The other two are compensated silicon crystals grown with electronic grade silicon (EG-Si) voluntarily doped with B and P, labeled as C1 and C2, respectively. All the wafers were sampled from the head part of these crystals. The resistivity ρ of wafers was measured using the four-point-probe (FPP) technique after 650 °C annealing for 30 min in Ar ambient to eliminate the grown-in thermal donors (TDs). The concentrations of B and P in compensated wafers were determined by secondary ion mass spectrometer (SIMS), while the B concentration in the reference wafers was derived from the measured resistivity [18]. The interstitial oxygen concentrations in these wafers were determined by a Fourier transform infrared spectroscope (FTIR, Bruker, IFS 66V/S) with a calibration coefficient of 3.14×10^{17} cm^{-2}. The detailed parameters of these wafers are shown in Table 1. All these wafers were fabricated into solar cells on the same production line at the Trina Solar Company by a standard process, including acid etching, P diffusion, anti-reflection coating deposition, screen-printing and contact firing. Then, these solar cells were cut into small solar cells (840 mm^2 active area) using a high repetition rate Nd:YVO_4 pulsed laser operating at 355 nm. These small solar cells were used for assessing the effect of irradiance intensity and temperature. To stabilize the effect of the metastable B–O complexes under illumination [19–21], all the studied solar cells were first placed under illumination at 323 K for 24 h to ensure that all the B–O complexes were activated and the measured efficiencies of these solar cells were stable. We experimentally checked that there were no more changes in the V_{oc} with additional illumination. So, all these solar cells should achieve complete stabilization. This is also of practical interest since the aim of our study is indeed to compare the performance of the reference and compensated silicon solar cells under real working conditions, which includes full B–O complexes activation.

To investigate the impact of irradiance intensity, current–voltage (*I–V*) characteristics of the solar cells were measured in the irradiance intensity range of 100–1000 W/m^2, using different neutral filters in the light path of the solar simulator. During the measurement process, the temperature was kept as defined in STC (25 °C). Due to the use of filters, some additional inhomogeneity and a change in spectral composition of irradiance may be induced. Wavelength-dependent absorption graphs of these filters showed the relative deviation of less than 1.5% in wavelength-resolved absorption. This deviation was negligible since it was far below the spectral mismatch of the used light source compared to AM1.5G spectrum. Irradiance intensity was calculated from the ratio of the short-circuit current density J_{sc} of the reference silicon solar cell in the case of applying the filters to the J_{sc} measured at STC, assuming that the J_{sc} was directly proportional to irradiance intensity. It should be mentioned that a possible non-linearity of the J_{sc} with irradiance for compensated silicon solar cells might occur and could be not detected in our study. The values of the series and shunt resistances R_s and R_{sh} were determined by fitting the measured *I–V* curves using the software tool IVFit [22]. The R_s and R_{sh} were denoted as "apparent" resistances, as a fitting route which calculates from the differential resistance at the V_{oc} and J_{sc} was used. To determine the impact of temperature, the solar cells were placed on a heating chunk under standard illumination condition (AM1.5G; 1000 W/m^2). The temperature was varied from 300 K to 330 K, and the *I–V* characteristics of the solar cells were measured after the temperature was stabilized.

Table 1
Detailed parameters of the reference and compensated silicon wafers.

Sample	Resistivity (Ω cm)	B concentration (cm^{-3})	P concentration (cm^{-3})	O concentration (cm^{-3})
Reference	2.20	6.3×10^{15}	NA	1.0×10^{18}
C1	0.64	4.1×10^{16}	1.2×10^{16}	1.0×10^{18}
C2	2.84	1.1×10^{17}	9.1×10^{16}	1.0×10^{18}

3. Results and discussion

3.1. Impact of irradiance intensity

Fig. 1 shows the typical *I–V* and power–voltage (*P–V*) characteristics of the reference silicon solar cells investigated in this study at 25 °C subjected to different irradiance intensities. It can be seen that with the irradiance intensity decreasing, the V_{oc} decreases slightly while the J_{sc} decreases very sharply. Therefore, the maximum output power decreases with the irradiance intensity decreasing as expected.

Fig. 2 shows the electrical parameters of the reference and compensated silicon solar cells at various irradiance intensities. One can see that the J_{sc} for all these solar cells is generally linear with the irradiance intensity. Therefore, the impact of nonlinearity of the J_{sc} with irradiance in our study is very small for compensated silicon solar cells, as can be seen from Fig. 2a. The V_{oc} is logarithmically dependent on the irradiance intensity. Due to the logarithmic irradiance scale, the apparent linear relationship between the V_{oc} and irradiance intensity can be seen for all the solar cells (Fig. 2b). The fill factor *FF* presents an initial increase and subsequent decrease with the irradiance intensity decreasing (Fig. 2c). The increase in *FF* upon lowering the irradiance intensity could be explained by the series resistance effects, as a lower current leads to quadratically lower Joule losses. It should be mentioned that the Joule losses are linearly dependent on the series resistance, but they are quadratically dependent on the current. So, the current has a bigger impact on the Joule losses than the series resistance. Upon lowering the intensity, the current decreases very sharply, which could counterbalance the effect of

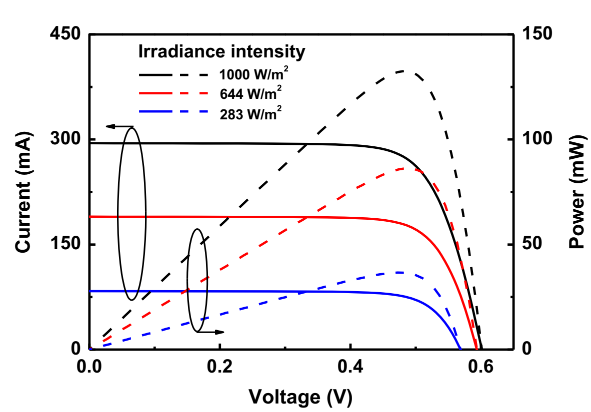

Fig. 1. Current–voltage (*I–V*) and power–voltage (*P–V*) characteristics of solar cells at 25 °C under various irradiance intensities.