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Analysis of aluminum back surface field at different wafer specifications in crystalline silicon solar cells

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ABSTRACT

The purpose of this work is to investigate a back surface field (BSF) at a number of wafer resistivities for industrial crystalline silicon solar cells. As indicated in this manuscript, doping a crucible-grown Czochralski (Cz)-Si ingot with Ga offers a sure way of eliminating light-induced degradation (LID) because LID is composed of B and O complex. However, the low segregation coefficient of Ga in Si causes a much wider resistivity variation in the Ga-doped Cz-Si ingot. This resistivity variation in a Cz-Si wafer at different locations varies the performance, as is already known. In the light of a B-doped wafer, we made wider resistivity in Si ingot; we investigated how resistivities affect the solar cell performance as a function of BSF quality.

1. Introduction

The screen-printed aluminum back surface field (BSF) formation has been the preferred method in the photovoltaic (PV) industry for the back surface passivation of p-type Si solar cells. Theoretical calculations show that Al-BSF has the potential to provide high-quality back surface passivation [1]. When the first p-type BSF Si cell was introduced in 1972, Al doping was used to form the BSF [2]. Through research and development, the Al-BSF formation process has been simplified from Al evaporation followed by a four-hour long anneal to the screen-printing of a thick paste of Al followed by an in-line anneal in a belt furnace for a few seconds. The screen-printed Al-BSF formation is currently the most widely used technique for back surface passivation of p-type Si solar cells. Its popularity is attributed to its simplicity, low cost, and high-throughput capability. Many papers investigated the Al BSF characterizations until a recent date such as their mechanical, structural behavior and optimal processing conditions [3–9]. The formation of an Al-BSF by using a screen-printing process involves two steps: (1) full-area screen-printing of an Al paste on the back surface followed by (2) a short anneal above the Al–Si eutectic temperature (577 °C). During the 700–900 °C anneal, Si is dissolved into the Al–Si alloy melt. During the cooling down step, Si is rejected from the melt and is regrown on the surface as an Al-doped p^+ BSF layer [10,11]. Because of the nature of the process, an electrical contact is obtained on top of the BSF region without any additional steps. A critical problem with B-doped wafers is light-induced degradation (LID). Doping a crucible-grown Czochralski (Cz)-Si ingot with Ga offers a definite way of eliminating LID because LID is composed of B and O complex. However, the low segregation coefficient of Ga in Si causes a much wider resistivity variation in a Ga-doped Cz-Si ingot. In this study, the possibility of using wide variation in resistivity such as a Ga-doped wafer using B-doped p-type wafer for PV applications was examined.

2. Experimental

Cz p-type Si wafers with a diameter of 6 in, thickness of 200 μm, and the orientation ⟨100⟩ were used. After treatment by saw damage etching (SDE) using 45 wt% KOH, layers of the Si wafers damaged by sawing were removed. The Si wafers were immersed in a sulfuric and peroxide mixture (SPM) of H_2SO_4, H_2O_2, and deionized (DI) water to remove any organic contaminants. A similar hydrochloric acid and peroxide mixture (HPM) removed metal particles. After each process, wafers were washed with DI water. Both sides were textured with random pyramids in a KOH/isopropyl alcohol solution. A two-step phosphorous emitter was diffused at 850 °C, resulting in 60 Ω/square n^+ emitter. After the removal of phosphorous silica glass in buffered oxide etchant, solar cells were

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prepared with SiN_x passivated front surfaces. Al paste was screen-printed onto the entire surface, and p^+ BSF was formed. The Ag front contact was also screen-printed with Ag paste having a metallization fraction of approximately 6%. The BSF quality was controlled via the ramp-up rate in a rapid thermal process machine (RTP). RTP ramp-up was tested at 53 °C/s (high quality BSF) or 10 °C/s (low quality BSF). Cooling to 300 °C occurred over 60 s. The wafers were prepared with resistivities of 1.41, 2.66, 7.7, and 44 Ω cm.

3. Results & discussion

If it is assumed that the current transport in a solar cell is dominated by a minority carrier diffusion process, then the open-circuit voltage (V_{oc}) can be related to the short-circuit current (I_{sc}) and the diode saturation current (I_o) by the following simple expression:

$$V_{oc} = \frac{kT}{q}\ln[(I_{sc}/I_0) + 1]$$

From this equation, V_{oc} is determined by the saturation current density of the emitter, I_{oe}, and that of the base, I_{ob}. Thus, to obtain an upper limit for I_{oe}, a reasonable value of I_{ob} has to be derived. The saturation current density of the base, which also includes recombination in the bulk and at the rear side, can be obtained from the bulk lifetime and BSF saturation current, and the back surface effective recombination velocity (BSRV) at the bulk and BSF interface. The I_{ob} in the solar cell can be directly calculated in terms of I_{or} according to the equation which is measured by QSSPC:

$$I_{ob} = J_{obL}\left(\frac{I_{or} + I_{obL}\tanh\left(\frac{W_B}{L_B}\right)}{I_{obL} + I_{or}\tanh\left(\frac{W_B}{L_B}\right)}\right)$$

where I_{obL} is the ideal or wide base saturation current [12]. when the QSSPC measuring, the test structure for measuring I_{or} use a n-type wafer, instead of a BSF structure in solar cell, the front surface is passivated with SiO_2 on the wafer directly in order to achieve low front surface recombination. Al is screen printed onto another side and fired. Fig. 1 shows the numerical fitting of I_{ob} and V_{oc} according to the wafer bulk lifetime. In a solar cell, as the wafer bulk lifetime increases, V_{oc} gradually increases until it reaches a saturation value. When the lifetime exceeds 200 μs, V_{oc} does not change significantly. This numerical fitting has a wafer thickness of 300 μm, J_{sc} of 37 mA/cm^2, wafer resistivity of 1.3 Ω cm, and I_{oe} and I_{or} of 8e-14 and 3e-13, respectively. The results of the numerical fitting for the BSRV are shown in Fig. 2. The value of V_{oc} in cells having high values of V_{oc} gradually increases as the value of BSRV decreases. These fitted graphs were obtained by the practically measuring I_{0r} by using QSS-PC and then combining with the values of I_{0b} obtained by the equation mentioned above. The BSF provides a high quality passivation at the rear side of the cell, improving its collection efficiency, with the Al BSF also increasing the effective lifetime and decreasing the BSRV contrast with the metal-Si interface. To fabricate high efficiency solar cells, it is necessary to use either a Si wafer with a high lifetime, or a low-resistivity wafer, as shown in the numerically fitted graph in Fig. 3. To avoid LID, Ga-doped wafers have been chosen by many institutions. One issue of concern that has been raised with the use of Ga-doped wafers is that the low segregation coefficient of Ga in Si results in a large variation in doping concentration along the length of the ingot. This large resistivity range would produce cells with a wider distribution of V_{oc} and probably I_{sc} too. This could lead to a wider variation in module-to-module photocurrents, resulting in possible mismatch problems in array and system performance. However, if the high quality BSF increases the effective diffusion length in a solar cell, then V_{oc} is saturated at high values. To prepare high performance solar cells using wafers with wide resistivity variations within a piece of ingot, good quality passivation is needed. Thus, the control of BSF composition is more important for passivation in this case. In Fig. 3, V_{oc} of the cell built on the high quality BSF, which increased the effective diffusion length, increases as the ramp-up speed increases in RTP and then saturates when the diffusion length becomes large. In general, the recombination velocity at the rear side determines the resulting performance of the solar cell and is affected by the quality of the BSF layer. Many previous articles have reported that V_{oc} increases with the ramp-up rate, and a ramp-up rate of over 60 °C/s gives rise to a V_{oc} of 10 mV, which is higher than that obtained at under 20 °C/s. The degradation in V_{oc} with a slower ramp-up rate can be attributed to the higher degree of non-uniformity in the BSF region, which deteriorates the back passivation quality and

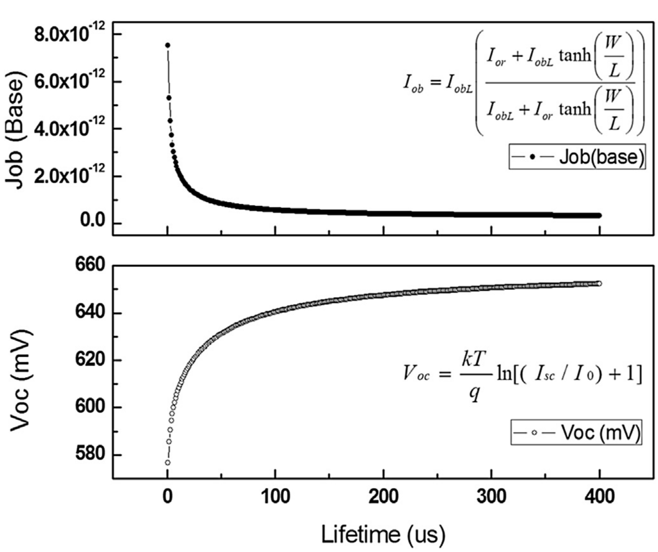

Fig. 1. Numerical fiiting with Job and Voc as a function of wafer lifetime.

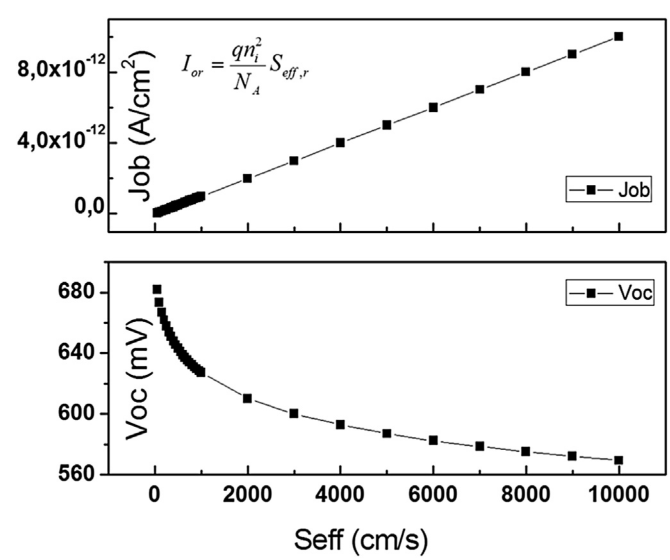

Fig. 2. Numerical fiiting with Job and Voc as a function of surface recombination velocity.