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Void formation in screen-printed local aluminum contacts modeled by surface energy minimization

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ABSTRACT

We demonstrate that the presence of voids in local aluminum rear contacts of PERC solar cells reduces the Al-BSF depths when compared to filled contacts. However, since voided contacts still exhibit a shallow Al-BSF we conclude that voids form during the re-crystallization process of the Al-BSF and thus at a point in time during furnace firing, where the aluminum is liquid. We propose an analytical model for void formation which takes into account the surface energies of the silicon wafer, the liquid aluminum as well as the aluminum-oxide shells of the screen-printed aluminum layer. Using geometrical approximations the model predicts that voids occur if the contact height exceeds a certain value. Scanning electron microscope cross-section measurements demonstrate that indeed voids are observed only for contact heights larger than 21 μm. The physical reason is, that in case of large contact heights the Al melt energetically favors to wet the large surface area of the aluminum-oxide shells instead of the relatively small area of the silicon wafer surface. We find that so-called PERC+ solar cells with Al fingers as rear contacts instead of full-area Al layers exhibit significantly smaller contact heights and hence exhibit almost no voids. Additionally, PERC+ solar cells exhibit much deeper Al-BSFs compared to PERC cells over a large range of rear contact widths. Using a new analytical model for Al-BSF formation, we find that the different Al-BSF depths are described solely by the different amount of Al paste printed to the rear side of PERC and PERC+ cells. Consequently, the PERC+ cells achieve low contact recombination and high efficiencies of 21.1% for narrow contact lines around 50 μm width, whereas PERC solar cells obtain highest efficiencies of 21.2% for 80 μm wide contact lines.

1. Introduction

Passivated emitter and rear solar cells (PERC) are currently introduced into mass production [1–3] and are expected to gain around 30% market share until 2019 according to the International Technology Roadmap for Photovoltaics (ITRPV) [4]. Typical production processes for industrial PERC cells apply line-shaped laser contact openings (LCOs) that locally remove the rear passivation layer. During the firing process the aluminum in the Al paste starts to melt at temperatures around 660 °C [5]. The liquid aluminum then starts to dissolve silicon from the solid silicon surface at the LCO areas, forming trenches in the Si wafer which are filled with a liquid Al-Si melt. As the temperature further increases the ongoing dissolution of silicon increases the silicon concentration in the Al melt. Simultaneously the occurring Si concentration gradient in the Al melt causes a silicon transport away from the contact due to diffusion [6]. For a typical peak firing temperature of PERC cells of 800 °C the solubility of silicon in aluminum is around 27% [5]. This concentration, however, is in general not reached due to strong non-equilibrium conditions. During cool down the solubility of Si in aluminum decreases again until it reaches the eutectic point at 577 °C with a Si concentration of 12% [5] and the Si-Al melt solidifies. During cool down, the Al-Si melt oversaturates and a re-crystallization of silicon from the melt occurs mainly at the interface to the solid silicon. This epitaxial growth of silicon at the interface incorporates aluminum according to its solid solubility and thus forms the aluminum back surface field (Al-BSF). Since the Si concentration in the Al-Si melt cannot drop below the eutectic concentration of 12%, the trenches in the Si wafer are only partly refilled by the Al-BSF. The remaining volume of the trench can be filled with the Al-Si eutectic during solidification. However, it is often observed, that there is no eutectic in the remaining volume of the trench but instead a void has formed during the alloying process [7–9].

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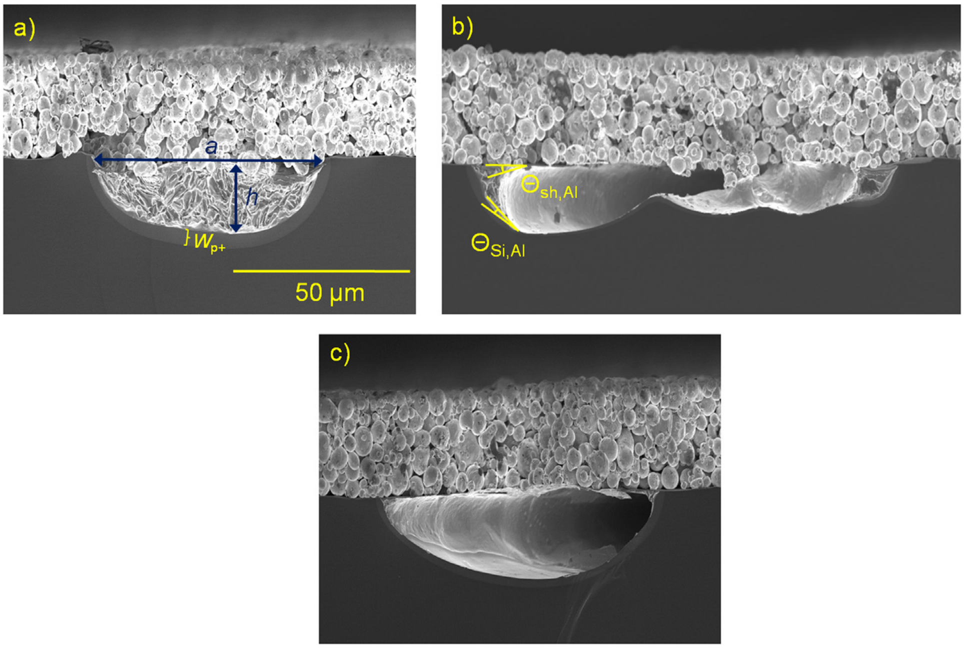

Fig. 1. Exemplary SEM cross-section images of different contact types: (a) filled contact, (b) partial void, (c) complete void. In order to account for the 45° cleavage angle relative to the contact lines the x-axis are compressed by a factor of $1/\sqrt{2}$. The specific images are taken from PERC cells with an LCO width of 46 μm (a+c) and 100 μm (b). The scale of image a) applies to all images.

Under certain conditions voids can increase the series resistance of a solar cell [10], but also very good specific contact resistances are reported for voided contacts [11]. Furthermore, there are publications that indicate a reduced BSF depth of contacts with voids compared to filled contacts [9,12,13]. However, both contact types can also exhibit comparable BSF depths [8]. It is experimentally found that increasing the Si concentration in the Al-paste suppresses void formation [6,7,9] and different approaches to achieve this have been reported. These approaches include reducing the contact line pitch [7], optimizing the firing profile [14,15], optimizing the diffusivity *D* of the Al-paste [6] and screen printing Al-fingers instead of a full-area Al layer [9,12,16]. This last approach can also be used to process novel bifacial PERC solar cells named PERC+[16]. The physical root cause of void formation has been attributed [9,17] to the Kirkendall effect [18]. Recently, however, Dressler et al. [15] investigated void rates in dependence of the applied firing temperature profile and indicated, that the Kirkendall effect does not describe the experimental data. Additionally, there are indications that void formation depends on the contact geometry [12], which is also contradicting the Kirkendall effect as the cause for void formation.

In this paper, we present an analytical model that describes void formation as an effect of minimizing the surface energy of the Al melt originating from the Al paste and provide experimental evidence for this model. We show that PERC+ cells with Al fingers exhibit a strongly reduced amount of voids compared to conventional PERC cell with full-area Al layer. Additionally, we present experimental data and an analytical model of the Al-BSF depth of PERC and PERC+ rear contacts which show that with appropriate LCO widths PERC+ cells obtain significantly deeper Al-BSFs compared to PERC cells since the Al fingers limit the Si diffusion in the aluminum leading to higher Si concentrations in the Al-Si melt during firing.

2. PERC and PERC+ solar cell process

The PERC and PERC+ solar cell process applied at ISFH are described in detail in Ref. 15. Here we just highlight the most important process steps. We use boron-doped 2 Ωcm Czochralski (Cz) grown silicon wafers. After cleaning and saw damage etch we apply a dielectric protection layer on the rear to allow for single sided alkaline texturing and $POCl_3$-diffusion. After removal of the phosphorus silicate glass (PSG) and rear protection layer we deposit an AlO_x/SiN_y passivation layer stack on the rear. For PERC we choose a SiN_y capping layer thickness of 200 nm. For PERC+ the same layer features a thickness of 80 nm to obtain improved anti-reflection properties when illuminated from the rear [16]. Then a SiN_x anti-reflection coating (ARC) is deposited on the front side for both cell types. The PERC and PERC+ solar cells then receive a line pattern of LCOs on the rear with a contact line pitch *p* for the PERC and 1.5*p* for the PERC+ solar cells [16]. For both solar cell types we apply different LCO line widths of 10, 35, 46, 100 and 150 μm while keeping the pitch constant for each solar cell type. We screen-print a full-area Al layer for the PERC cells while the PERC+ cells are printed with a 5 busbar H-pattern with Al finger opening width of 100 μm aligned to the LCOs. For both solar cell types we use the same commercially available Al paste. Subsequently both cell types receive a dual-printed 5 busbar silver front grid. We conclude the process flow by firing both solar cell types with their respective optimal set firing temperature T_{set} which is minimally lower for PERC+ compared with PERC.

3. Impact of voids on the Al-BSF depth

As shown in Fig. 1, we determine the structure of the Al-Si contacts by scanning electron microscope (SEM) cross-sections and assign the rear contacts to one of the following categories: (a) completely filled contact, (b) partial void and (c) complete void. Fig. 2 shows a schematic drawing of a rectangular contact and its geometrical quantities as used throughout this paper for comparison with Fig. 1.

In order to verify the impact of contact voids on the Al-BSF depth, we dissect many PERC solar cells fabricated at SolarWorld Innovations (SWIN) technology center [19] and measure the Al-BSF depth W_{p^+} in the middle of the contact using SEM microscopy. We