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Determination of metal contact recombination parameters for silicon wafer solar cells by photoluminescence imaging

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Abstract

In order to reliably extract metal–silicon interface recombination parameters to aid optimization of silicon wafer solar cell designs, a test metallization pattern with regions of varying front metal contact fractions is screen printed to create special test cells, alongside solar cells with a standard H-pattern print. Both the test pattern and H-pattern cells are analyzed using intensity-dependent photoluminescence imaging (Suns-PL), and the H-pattern cells are additionally probed at each busbar to monitor their open-circuit voltage (via Suns-V_{oc} measurements). The resultant data are analyzed in two ways, the first being a simple four parameter graphical fitting to the Suns-PL plots of the regions of interest, and the second being a detailed finite element method (FEM) based simulation and numerical fitting. By accounting for the lateral balancing currents in the FEM based simulation, test patterns with imaginary isolation across the edges of the mini cells could be used, which were the easiest to fabricate. The FEM method is more rigorous and is able to replicate simultaneously the Suns-PL characteristics of both test pattern and H pattern cells, using a common set of recombination parameters.

Keywords: Metal recombination; Photoluminescence imaging; Silicon wafer solar cells; Suns-PL; Phosphorus diffused emitter

1. Introduction

Metallisation of phosphorus diffused emitters using screen printing Ag pastes is a well-established process for industrial silicon wafer solar cells (Ballif et al., 2003). Front-side Ag contact to the phosphorus diffused emitters is a key area of research, as it has a large impact on the cell efficiency and incurs significant production cost (ITRPV, 2014). Metal contacts introduce significant recombination via the high interface defect density and the emitter damage caused by the high-temperature firing step. Both this metal contact recombination, as well as the electrical resistance of the contacts, are important factors in the optimization problem of the phosphorus diffused emitter profile (Shanmugam et al., 2014). Aside from the issue of contact quality, shallow emitters are more prone to junction shunting and increased recombination losses introduced by the metallisation process than emitters with deeper junction. Hence the optimal diffused emitter for an industrial silicon wafer solar cell has a significantly heavier diffusion and lower sheet resistance than one which minimizes the emitter saturation current density (J_{0e}), although the recent vast improvements in silver paste technology are enabling a trend towards higher emitter sheet resistance (Shanmugam et al., 2014; Cooper et al., 2014).

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There are several notable studies in recent years reporting on the recombination losses associated with metallisation based on specially designed experiments (Fellmeth et al., 2011; Hoenig et al., 2011; Edler et al., 2014; Helge Hannebauer et al., 2012). Fellmeth et al. prepared samples each consisting of eight 2 cm × 2 cm solar cells of varying metal contact fractions F_M (F_M is the ratio of area of metallised regions to the total area of solar cell) on the same wafer (Fellmeth et al., 2011). By measuring the one-sun open-circuit voltage (V_{oc}) of each cell and extracting the dark saturation current density J_{01} via the one-diode model, plots of J_{01} versus F_M were constructed from which the slope from linear fits yielded the metal contact contribution $J_{0e\text{-}metal}$. Hoenig et al. printed full metal grid patterns on 156 mm × 156 mm wafers, with additional interrupted contact fingers between the fingers of the base grid (Hoenig et al., 2011). They observed a clear rise in $FF_0 - pFF$, the difference between the ideal fill factor FF_0 and the pseudo fill factor pFF (pFF is only influenced by recombination and shunting effects and it is an useful parameter to evaluate the non-series resistance related limitation of a solar cells fill factor), as the coverage of the interrupted contact fingers increased. Edler et al. studied both metal recombination at the phosphorus and boron diffused layers in bifacial solar cells (Edler et al., 2014). In this case, the difference between the finished cell V_{oc} and the implied V_{oc} determined from lifetime measurements on the samples prior to metallization was tracked as a function of the metal contact fractions on the emitter (boron) and back-surface-field (phosphorus) sides of the cell. It is interesting to note that while references Fellmeth et al. (2011) and Edler et al. (2014) observe near-unity ideality factor and good conformity to the one-diode model for their samples, with V_{oc} being the parameter that clearly changed with increasing metal contact fraction, reference Hoenig et al. (2011) focuses on $FF_0 - pFF$, which seems to imply that it is the ideality factor rather than V_{oc} that changes most obviously with metal contact fraction in their samples. It is not clear whether this difference in observation arises from the different metal test structure patterns used by the different groups, or from a difference in the metal paste tested.

In this work, we investigate the use of photoluminescence (PL) imaging on simple-to-prepare screen printed silicon cells with special test patterns, which defines different regions-of-interest on a wafer with varying metal contact fractions. Like reference Fellmeth et al. (2011), only one screen is needed to print all eight different regions of interest. The added advantage related to analysis by PL imaging is that it is a contactless technique, so that automation of the test routine can be simply accomplished without having to design a dedicated test jig with precision alignment probes. Additionally, with the help of detailed finite element method (FEM) based simulation, which accounts for lateral balancing currents along the wafer that has a non-uniform voltage distribution, we can also investigate the possibility of forgoing any efforts to isolate the regions of interest from one another, thus saving many processing steps and making the test pattern cells as easy to prepare as a standard solar cell. The simplicity of the experiment makes it conceivable to be implemented in a production environment, where a small fraction (e.g. one per 30 min, which is less than <0.1%) of the processed wafers can be diverted to an offline printer to produce the test structures, so that the metal recombination parameters can be tracked over time to aid process control and design of experiments.

2. Methodology

The PL based method described in this work, for the extraction of recombination parameters at the metal–silicon interface, requires measurements on both a finished solar cell (wafer with an H-pattern front grid) and a wafer printed with the special test pattern as shown in Fig. 1. Both patterns are printed on large-area (239 cm^2) 156 mm × 156 mm *p*-type pseudo-square Cz silicon wafers having the standard Al-BSF solar cell architecture. As shown in Fig. 1(a), the test pattern defines 8 mini cells (regions of interest) with metal fraction varying from 0% to 27%, by virtue of different nominal metal line widths ranging from 0 to 280 μm. The H-pattern in Fig. 1(b) defines a standard 3-busbar solar cell with about 7% metal contact fraction. Both the test pattern and the H pattern have the same finger pitch of 1.8 mm.

Fig. 2 shows the process flow and experimental split. Silicon wafers with 1–3 Ω cm bulk resistivity were saw damage etched and textured to generate a random-pyramid surface on both sides. Phosphorus emitter diffusion was carried out using an industrial tube diffusion furnace, which resulted in a sheet resistance of 80 Ω/sq on both wafer surfaces. Following the diffusion process, phosphorus silicate glass (PSG) removal was performed. An amorphous silicon nitride (SiN_x) antireflection coating was then deposited by plasma-enhanced chemical vapor deposition onto the front surface as an antireflection coating and passivation layer. All wafers were then metallized with full-area Al on the rear (Monocrystal, PASE 12D) and Ag paste (DuPont, PV 18) on the front for the test pattern or H pattern. Finally, all cells were fired at the optimized firing profile, and then edge isolated using a laser with nanosecond pulses.

As the mini-cells' regions of interest in the test pattern are small and not cut out of the wafer, their boundaries play a significant role in both the local open-circuit voltage V_{oc} and the ideality factor *m*. If the boundary of each region contains a physical disruption, such as an emitter laser isolation, then the boundary may introduce a large and varying edge recombination component that tends to lower the V_{oc} and raise the ideality factor of each region. On the other hand, if the boundary contains no disruption such that it is only an imaginary demarcation line, then lateral balancing current may flow in and out of each cell, which tends to raise the V_{oc} and lower the ideality factor. In either case the boundary may introduce significant bias