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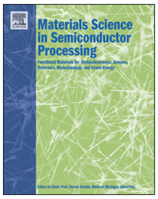

Rear-surface line-contact optimization using screen-print techniques on crystalline solar cells for industrial applications

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ABSTRACT

This paper explores the utility of single-crystalline silicon solar cells that are treated with the screen-print technique to implement line contacts at the cells' rear surfaces. We designed rear-surface line-contact (RSLC) solar cells using screen-print methods on *n*-type wafers ($125 \times 125\ \text{mm}^2$) in order to produce rear surface passivation layers. The performances of these cells were then evaluated and compared to laser fired contact solar cells. We examined the rear surface passivation quality of a stack consisting of an aluminum oxide (Al_2O_3) passivation layer deposited by atomic layer deposition, overlaid with a silicon nitride (Si_3N_4) layer deposited by plasma-enhanced chemical vapor deposition. The initial outstanding surface passivation quality provided by the Al_2O_3/Si_3N_4 stacks remained high after annealing, as indicated by the average light-beam-induced-current value ($85.1\ \text{mA/cm}^2$) for the developed RSLC cells. RSLC cells exhibited conversion efficiencies of up to the optimal 18.48%, demonstrating that line-contacting processes were consistent with print screen and that the simplification of electrode process may be realized for industrial applications.

1. Introduction

Over the last several decades, the depletion of fossil fuels and the concern over environmental impact of non-renewable sources have inspired initiatives to develop environmentally friendly energy technologies across the globe. Compared to conventional energy sources, photovoltaic (PV) solar cells have significantly less environmental impact by avoiding the emission of greenhouse gases. The primary focus of the PV industry as of now is to lower the manufacturing cost of solar cell modules. Both single- and poly-crystalline silicon (s-/pc-Si) solar cells are economical, reliable, commercially available, and commonly used in a variety of PV systems [1-3]. The confinement of light within a solar cell is one of the most important factors affecting the conversion efficiency (η) of crystalline silicon (c-Si) solar cells as higher light confinement equates to higher conversion efficiency. In particular, the front and rear surfaces of the solar cells require surface preparations for optimal light trapping. To achieve this result, we can add pyramidal texturing of the front surface and polishing of the rear surface. This is done by texturing and covering the front surface of the solar cell with an antireflective coating [4]. An efficient AR layer not only reduces optical reflection from the front surface but also simultaneously passivates both the surface and bulk of the cell [5,6].

The efficiency of c-Si solar cells is limited primarily by minority carrier recombination. To overcome this limitation, solar cells must be imbued with a high level of surface passivation. The passivation of the dielectric layer at the rear surface also improves the internal reflectivity, which reduces absorption losses caused by the rear aluminum (Al) electrodes. Since recombination loss is proportional to the density of defects at the Al-Si interface, passivation further enhances cell efficiency by reducing the number of interfacial defects. Several approaches for solar cells with a local back surface field (LBSF) that could potentially improve solar cell performance are currently under evaluation [7,8]. Typically applied to industrial c-Si solar cells, a LBSF with Al distributed across the entire rear electrode area behaves like a p-n junction, and an electric field is formed at the interface. This Al-LBSF provides an Ohmic contact and moderates rear passivation, thus reducing the recombination velocity at the rear electrodes and improving the probability of minority carrier collection.

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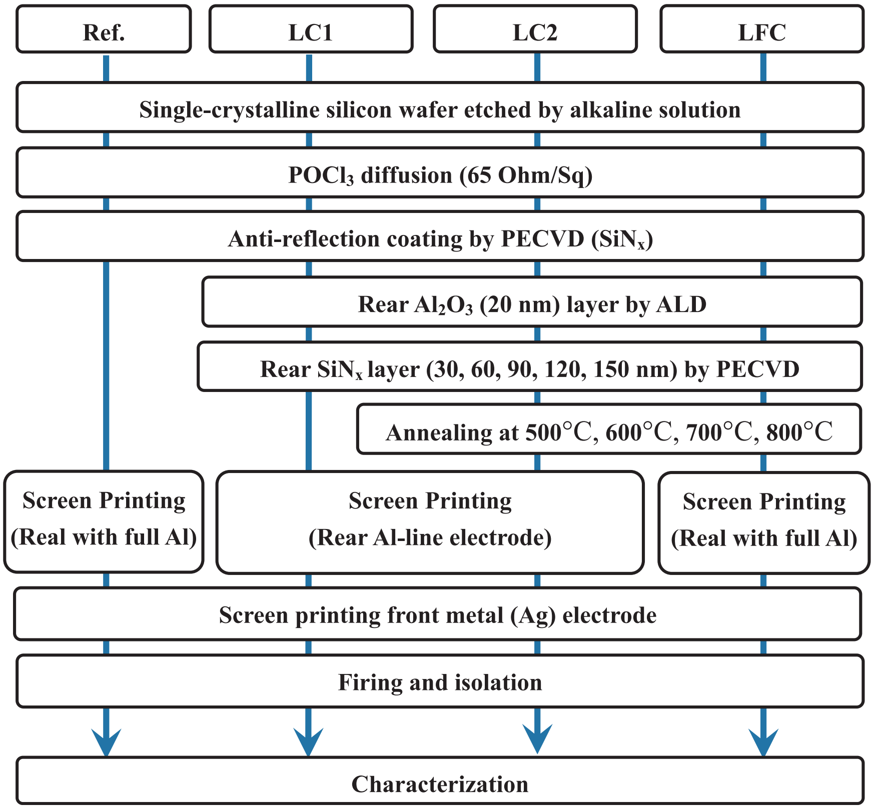

Fig. 1. Process flow diagram for the processing of rear surface line contact (RSLC) solar cells with samples LFC, LC 1, LC 2, and Ref. (the reference cell).

The next generation of high efficiency cell designs adds passivation layers by thermally oxidizing the silicon surfaces. Al_2O_3 with a large negative fixed charge at the interface is a promising candidate as a c-Si surface passivation material [9–11]. A common approach to improving the thermal stability of a given passivation technique is the addition of a capping layer [12,13]. Recent publications have indicated that contact formation in LBSF cells is considerably affected by process conditions [14,15]. One approach to reducing these effects is the application of a passivating dielectric layer across the full extent of the rear surface area. An Al_2O_3 layer deposited on the rear surface makes local contact with the c-Si at small point apertures in the dielectric. These apertures can be formed by laser fired contact (LFC) [16–18], laser ablation [19–22], and line contact produced with a screen printed technique [23,24]. In the LFC process, fired contact formation in the p^+ region creates a LBSF, which decreases carrier recombination at the contacted surfaces. The capability of this laser processing for introducing molten material into c-Si wafers is well known, as are the advantages offered by laser processing to extend cell lifetime (τ_p) by limiting defects and internal stress [25]. However, laser processing also leads to a reduction in the open circuit voltage (V_{oc}) and fill factor (***FF***) due to potential laser-induced damage [25]. Alternatively, screen-print technique can be a great substitute to laser processing as it is swift, simple, reliable, and relatively inexpensive. Unlike laser processing, the screen-print technique does not suffer from the effects of molten states or laser-induced damage, significantly reducing the complexity and increases the speed of the process.

This paper proposes the application of screen printed technique to produce rear-surface line-contact (RSLC) solar cells for achieving higher conversion and quantum efficiencies, longer minority carrier lifetimes, and improved light-beam- induced-current (LBIC) values. A screen printed method was used to produce Al lines in rear surface layers, and the resulting samples were compared with those treated with the LFC process. We evaluated the suitability of screen print metallization, specially designed for LBSF solar cells contacted with the screen-print technique.

2. Experimental procedure

Experiments used p-type (boron-doped) sc-Si wafers obtained from the ingot by wire sawing thicknesses of 200 μm, each with an area of $125 \times 125\ \mathrm{mm}^2$ and line resistances in the range of 0.5–3 Ω-cm (Sino-American Products, Inc.). First, the wafers were cleaned using the RCA cleaning technique [26], which removed preexisting oxides present in naturally occurring contaminations. Afterwards, the wafers were textured on both sides in an alkaline (KOH/IPA-based) chemical tank, resulting in randomly distributed pyramids. The n^+ emitter was formed on wafer surfaces by a $POCl_3$ diffusion performed in a high temperature diffusion furnace, resulting in a sheet resistance of 65 Ω/sq. After the $POCl_3$ diffusion, the phosphorus silicate glass (PSG) and most residues were removed by etching in a dilute HF solution. Centrotherm PV AG, of Germany, coated the front surface with a silicon nitride (Si_3N_4) antireflective layer with a thickness of approximately 90 nm, using plasma-enhanced chemical vapor deposition (PECVD) at 450 °C for 30 min. In order to make the electrode contacting directly with the Si substrate and avoiding any damage on the passivation layer, a screen printed metallization was used at rear and front. The rear surface was polished with a sodium hydroxide solution. A rear surface passivation layer of Al_2O_3 was deposited by thermal atomic layer deposition (ALD) and overlaid with a protective layer of Si_3N_4. Finally, conjoined solar cells were annealed together in an infrared furnace (TPS-MD200), and were then severed from one another with a dicing saw.

To simplify characterization of terrestrial solar cells, a Keithley 4200 instrument measured the induced current density–voltage (***J-V***) curves of the cell prototypes using a Wacom solar simulator (Model: WXS-220S-L2), with an air mass (AM) coefficient of AM1.5 G and illumination of $1000\ \mathrm{W/m^2}$. The effective lifetime of the minority carriers (τ_{eff}) was determined using a HITACHI U-3010 lifetime tester and was corroborated by measurements of microwave-detected