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Performance improvement of p-type silicon solar cells with thin silicon films deposited by low pressure chemical vapor deposition method

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Abstract

It is known that surface passivation plays a significant role in upgrading solar cell performance. In this study, silicon thin films deposited by LPCVD (low pressure chemical vapor deposition) are used to passivate the surface of solar-grade p-type crystalline silicon solar cells for the first time. Intrinsic amorphous silicon films and poly-silicon films were obtained on the front and rear surfaces of solar wafers at the deposition temperatures of 560 °C and 620 °C, respectively. Both kinds of silicon films proved to be effective in improving the open-circuit voltage owing to surface passivation for crystalline silicon solar cells. Optical spectral responses in the short and long wavelength ranges (e.g. the range 300–600 nm and the range 850–1100 nm, respectively) also showed an improvement in photogenerated current resulting from reduced surface recombination rates on the front and back surface.

Keywords: Surface passivation; Amorphous silicon; Poly-silicon; Low pressure chemical vapor deposition; Effective lifetime

1. Introduction

Single crystalline silicon (c-Si) wafer-based solar cells provide high module efficiencies and long-term stability in performance. In recent years, many industries have put lots of efforts in investigating different techniques for producing high efficiency c-Si wafer-based solar cells while trying to lower down fabrication cost per peak power. Surface passivation is one of key requirements in optimizing the performance of c-Si wafer-based solar cells. Many research works have investigated the technological and physical features of passivation layers based on thermally grown silicon dioxide (SiO_2) (Chen et al., 1993; Hoex et al., 2006a), aluminum oxide (Al_2O_3) (Hoex et al., 2006b), silicon nitride (SiN_x) (De Wolf et al., 2005; Schmidt and Aberle, 1999; Bousbih et al., 2012), amorphous silicon oxides (a-SiO_x) (Fujiwara et al., 2007; Mueller et al., 2007), amorphous silicon carbide (a-SiC_x) (Martin et al., 2001; Schmidt et al., 2001) as well as hydrogenated amorphous silicon (a-Si:H) (Olibet et al., 2007; De Wolf et al., 2008; Schulze et al., 2010; Damon-Lacoste et al., 2009).

The surface of silicon wafer has many dangling bonds and other defects, which act as recombination centers (Buonassisi et al., 2005). Reducing the surface recombination of solar cells is known to increase the open-circuit voltage and the fill-factor (FF) (Green et al., 1995; Kerr and Cuevas, 2002). Surface passivation can be achieved by two different passivation mechanisms. The first mechanism is based on the reduction in the density of defect states at the surface. The surface defect density can be reduced significantly by the passivation of unsaturated Si bonds. The

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second mechanism to reach surface passivation is based on a reduction of the electron and hole recombination at the semiconductor surface by field-effect passivation. As recombination processes require both electrons and holes, a lower recombination rate is obtained when the electron and hole concentration at the interface are more different in magnitude. The electron or hole concentration can be altered by electrostatic shielding of the charge carriers through an internal electric field present at the interface. This internal electric field can be obtained by the presence of fixed electrical charges at the semiconductor interface. Surface passivation is an effective method for an increase in solar cells efficiency.

In photovoltaic (PV) industry, SiN_x:H and SiO_2 are the two most common passivation materials, and have been applied to the silicon solar cells for a long time. Hydrogens that are contained in SiN_x:H films can diffuse into silicon and thus passivate the defects in subsequent thermal processing (Dekkers et al., 2006).This effect is constrained by the limited volume of the SiN_x:H film. On the other hand, the solar cell efficiency would decrease when SiN_x:H is deposited on the back side of a p-type silicon substrate because positive built-in electric charges can induce a parasitic shunting (Dauwe et al., 2002). Thermally grown oxide is also an effective surface passivation material for n- and p-type c-Si and has been used in the record-high-efficiency passivated emitter and rear locally-diffused (PERL) c-Si solar cell (Zhao et al., 1999; Razykov et al., 2011). Thermal SiO_2 has proved to be able to reduce density of interface states. High growth temperature of SiO_2 typically lead to a significant degradation of the bulk lifetime (Lee, 2003).

To passivate the surface defects of a silicon wafer, either a-Si:H or SiN_x is usually deposited on the surfaces of solar wafers by a plasma enhanced chemical vapor deposition (PECVD) method in industry. However, if the surface passivation is done on both sides (i.e., the front and back surfaces), the process needs to be done with one surface being deposited first and then another. And this might cause a cost issue or a throughput problem. Low pressure chemical vapor deposition (LPCVD) methods have been intensively used in fabricating MOSFET gate electrodes as well as load resistors in IC circuits (Lai et al., 2006). Also, LPCVD-grown poly-silicon has been suggested to be a material for EEPROM memories and thin-film transistors (Hatalis and Greve, 1987). In this study, we investigate the performance of a solar-grade p-type c-Si solar cell by examining its effective carrier lifetime after deposited with silicon thin films by LPCVD.

2. Experimental methods

We used a commercial manufacturing process to fabricate our samples. External quantum efficiency (EQE) and energy conversion efficiency were measured. It is noticeable that deposition of silicon thin films can be done on both sides of a wafer simultaneously by using LPCVD. Therefore, for two-side deposition of silicon thin films, LPCVD is suggested to be a good choice.

In this study, we utilized solar-grade (1 0 0)-oriented c-Si p-type Czochralski (Cz) wafers with a thickness of ~190 μm, a pseudo-square area of 12.5 cm × 12.5 cm, and a resistivity of 1–3 Ω cm. Fig. 1 shows the process for solar cells fabricated. These wafers were first cleaned and then dipped in an alkaline solution to form a pyramid-like surface on both sides. After cleaned and dried, the wafers were placed back to back in pair on a quartz boat and loaded into a high-temperature diffusion furnace with $POCl_3$ as a dopant source. These wafers were diffused on only one surface of their own, resulting in an n-type emitter with a sheet resistance of ~55 Ω/square. The phosphorous glass (PSG) was afterwards removed by a dilute HF solution.

The wafers were then divided into three groups. Group A followed steps of a standard process, i.e., edge isolation, deposition of anti-reflection coating (ARC), metallization on both sides and then co-firing. The edge isolation was achieved by plasma etching to remove the phosphorus dopant around the edge of the wafer so that the front emitter was electrically isolated from the back surface. Deposition of ARC was carried out to form a SiN_x film of ~82 nm thickness by a PECVD (plasma enhanced chemical vapor deposition) system, followed by screen-printing silver paste to form a metal contact on the front surface in an H-shaped grid pattern, while the back contact was screen printed all over the back surface using aluminum paste. The two-side contacts were then co-fired in a belt furnace.

Wafers in groups B and C followed the same process as that for group A except that a 15-nm thick silicon film was deposited on both sides of these wafers after PSG removal. Deposition of amorphous-silicon (a-Si) films was done by LPCVD at 560 °C for group B and deposition of poly-silicon films was done by LPCVD at 620 °C for group C. Because of different deposition temperatures, groups B

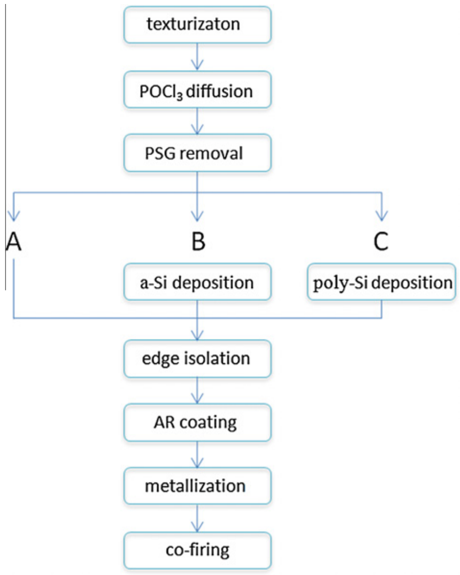

Fig. 1. Process flow diagram for solar cells fabricated in this study.