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Effects of silicate glasses in aluminum pastes on physical and electrical characteristics of screen-printed multi-crystalline silicon solar cells

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ABSTRACT

Aluminum pastes (APs) with various silicate glasses (SGs) have been synthesized to enhance physical and electrical characteristics of screen-printed multi-crystalline silicon solar cells (SPMSSCs). The improved back surface field (BSF) and decreased tortoise-shell veins were demonstrated by suitably Si–Bi–B-doped Si–Bi–Ti-based oxide SGs in APs. The promoted mechanism could be attributed to the circulating track supplied from binary SGs softened in APs during co-firing. The achievement of a conversion efficiency improvement of more than 1.34% absolute from 16.01% to 17.35% in SPMSSCs with a binary Si–Bi–Ti of 1 wt% and Si–Bi–B of 3 wt% SGs in AP was explored.

1. Introduction

Screen-printed mono- and multi-crystalline silicon solar cells have been throughout used for photovoltaic industrial solar cells [1–3]. Moreover, screen-printed (SP) technology was applied to SPMSSCs for the formation of the front and rear contacts [4]. Thus, the improvements in the interface properties of the SP metal paste/silicon base are highly desirable. Recently, the SP AP has attracted considerable attention due to the increase of the BSF in the rear side of SPMSSCs [5]. The BSF thickness is affected by the amount of the dissolved Si upon firing [6]. The microstructural properties of Al-alloyed contacts were influenced by the amount of printed paste, the alloying time, and the peak temperature [7]. Moreover, a non-uniform BSF was caused by a lack of fine Al particles in the APs [8]. An Al electrode formed from AP with Pb-free glass frits possessed a dense structure and adhered to the Si substrate very nicely [9]. Furthermore, the bowing of the cell was reduced by incorporated lead-free glass into AP [10]. Although, the effects of the firing time and peak temperature, Pb-free glass frits, as well as Al particles in APs have been addressed, the mechanisms of the binary SGs in APs are still not clear yet. Thus, the effects of various binary SGs in APs on physical and electrical characterizations of SPMSSCs were investigated.

2. Experimental

To explore the effects of various SGs in APs on photovoltaic characterizations of SPMSSCs, square samples ($156 \times 156\ mm^2$) of (100)-oriented p-type silicon wafers with 0.5–3 Ω cm and 200 ± 25 μm were prepared. The alkali texturing was performed in a solution of 5% KOH at 83 °C for 10 min. The height of the pyramid was measured to be around $3-7$ μm. The emitter was formed by phosphorus diffusion with a liquid $POCl_3$ at 880 °C. After the diffusion of phosphorus, the sheet resistance of emitter ranged from 55 to 65 Ω/sq. For passivation and anti-reflection coating, a standard SiN_x film with a thickness of 80 nm was deposited on the n^+-emitters by the decomposition of NH_3 and SiH_4 using plasma-enhanced chemical vapor deposition at a frequency of 13.56 MHz. Furthermore, an Ag grid was screen-printed on the top of the SiN_x film and dried in an infrared belt furnace at 230 °C. The active-area of the solar cell is to be around $146 \times 146\ mm^2$. For investigations on physical and electrical properties of SPMSSCs depending on the rear side metallization fraction, seven groups of APs each having different SGs were self-fabricated using a 4 wt% of SG, a 20 wt% of the resin binder and dispersing agent, as well as a 76 wt% of Al powder. The process of making AP is mixing SG powder, organic resin binder, dispersing agent, and Al powder in the agitating tank. The mixed materials were dispersed on a roll mill, yielding the AP. Various APs with 4 wt% of (a) $SiO_2/Bi_2O_3/TiO_2$ (denoted as Si–Bi–Ti), (b) $SiO_2/Bi_2O_3/ZnO$ (denoted as Si–Bi–Zn), (c) $SiO_2/Bi_2O_3/SrO$ (denoted as Si–Bi–Sr), (d) binary Si–Bi–Ti (3 wt%) and $SiO_2/Bi_2O_3/B_2O_3$ (denoted as Si–Bi–B) (1 wt%), (e) binary Si–Bi–Ti (2 wt%) and Si–Bi–B (2 wt%), (f) binary Si–Bi–Ti (1 wt%) and Si–Bi–B (3 wt%), and (g) Si–Bi–B SGs were applied to form the rear

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electrode. Then, the rear contacts were printed using various APs for BSF alloy formulation and Ag paste for the back side busbar. Finally, a 6-zone industrial infrared belt furnace was used to co-fire the Al and Ag pastes into the p-type and the n-type silicon, respectively. The peak temperature and the belt speed were set at 780 °C and 200 in./min, respectively. Sample morphologies were examined by field emission scanning electron microscopy (FESEM). The current densities–voltage curves of SPMSSCs were measured under standard test conditions (AM1.5G spectrum, 100 mW/cm^2, 25 °C).

3. Results and discussion

Fig. 1 shows the SEM cross section images of a 4 wt% of (a) Si–Bi–Ti, (b) Si–Bi–Ti, (c) Si–Bi–Zn, and (d) Si–Bi–Sr SGs in APs screen-printed on the rear surface of SPMSSCs co-fired at 780 °C. The thickness of AP screen-printed on the rear of SPMSSCs after co-firing was observed to be around 35–40 μm as shown in Fig. 1(a). The Al paste/Al–Si eutectic layer/Al–P$^+$ layer (BSF)/Si(100) stacked structure was obtained by firing the Al paste/Si(100) stacked substrate. A BSF layer can be formed by the regrown silicon due

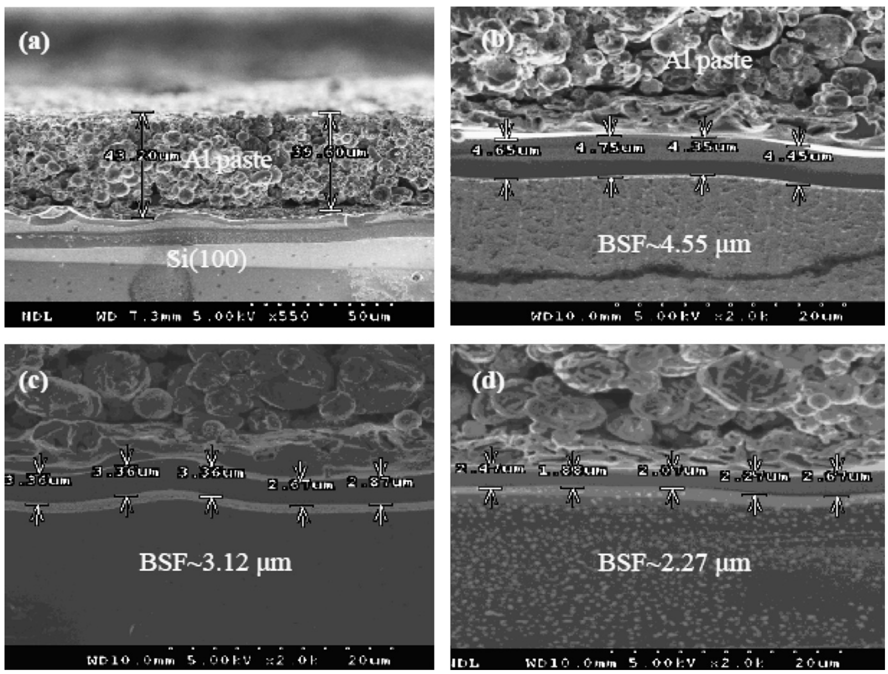

Fig. 1. SEM cross section images of a 4 wt% of (a, b) Si–Bi–Ti, (c) Si–Bi–Zn and (d) Si–Bi–Sr SGs in APs screen-printed on the rear surface of SPMSSCs co-fired at 780 °C.

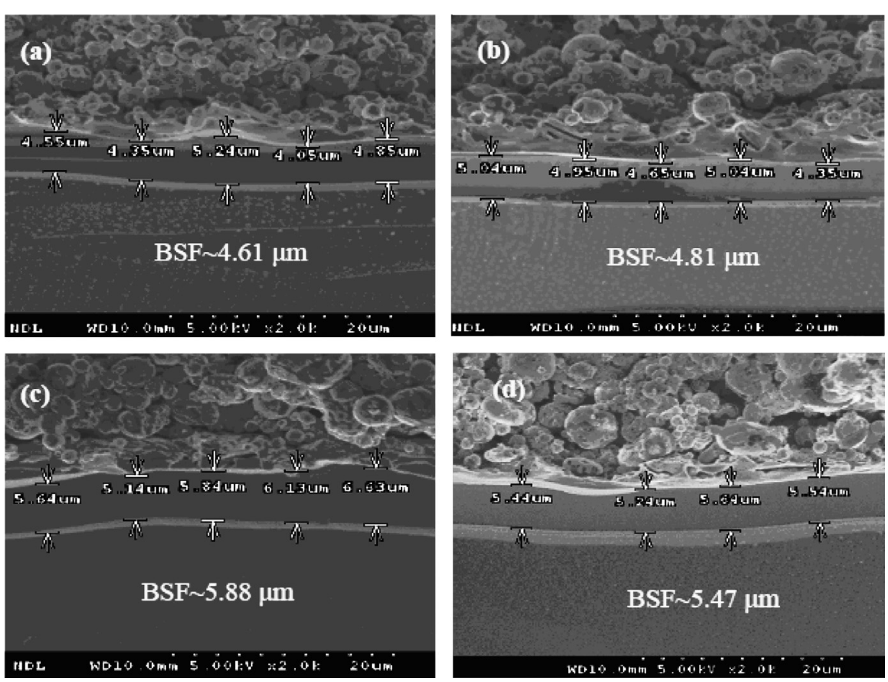

Fig. 2. SEM cross section images of (a) binary Si–Bi–Ti (3 wt%) and Si–Bi–B (1 wt%); (b) binary Si–Bi–Ti (2 wt%) and Si–Bi–B (2 wt%); (c) binary Si–Bi–Ti (1 wt%) and Si–Bi–B (3 wt%); (d) Si–Bi–B (4 wt%) SGs in APs screen-printed on the rear surface of SPMSSCs co-fired at 780 °C.