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Ribbon Si solar cells with efficiencies over 18% by hydrogenation of defects

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Abstract

We have fabricated 4 cm^2 solar cells on String Ribbon Si wafers and edge-defined film-fed grown (EFG) Si wafers with using a combination of laboratory and industrial processes. The highest efficiency on String Ribbon Si wafer is 17.8% with an open circuit voltage (V_{oc}) of 620 mV, a short circuit current density (J_{sc}) of 36.8 mA/cm^2 and a fill factor (FF) of 0.78. The maximum efficiency on EFG Si is 18.2% with a V_{oc} of 620 mV, a J_{sc} of 37.5 mA/cm^2 and a FF of 0.78. These are the most efficient ribbon Si devices made to date, demonstrating the high quality of the processed Si ribbon and its potential for industrial cells. Co-firing of SiN_x and Al by rapid thermal processing was used to boost the minority carrier lifetime of bulk Si from 3–5 μs to 70–100 μs. Photolithography-defined front contacts were used to achieve low shading losses and low contact resistance with a good blue response. The effects of firing temperature and time were studied to understand the trade-off between hydrogen retention and Al-doped back surface field (Al-BSF) formation. Excellent bulk defect hydrogenation and high-quality thick Al-BSF formation was achieved in a very short time (~1 s) at firing temperatures of

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740–750 °C. It was found that the bulk lifetime decreases at annealing temperatures above 750 °C or annealing time above 1 s due to dissociation of hydrogenated defects.

Keywords: Ribbon Si; String Ribbon; EFG; Hydrogenation; Silicon nitride; Solar cell

1. Introduction

String Ribbon Si wafers are grown by high-temperature strings drawn through the crucible of molten Si that is currently in multi-megawatt production at Evergreen Solar. Edge-defined film-fed grown (EFG) Si wafers are pulled directly through a graphite die via capillary action. These two vertical sheet growth techniques produce low-cost Si wafers due to the high utilization of the Si feedstock and the absence of ingot sawing and wafer etching. The high quality of the processed String Ribbon and EFG wafers has been previously demonstrated [1,2] through the measurement of high minority carrier lifetimes following cell processing. Recently record high-efficiency String Ribbon cell (17.7%) has been fabricated using thermal oxidation for front surface passivation, 60 min microwave-induced remote hydrogen plasma passivation, ZnS/MgF_2 double-layer antireflection (AR) coating and aluminum gettering for 30 min [3].

Recent research on processing String Ribbon cells has focused on industrial-type processing using screen-printing for metallization and the relatively deep junctions necessary for firing the screen-printable inks and plasma-enhanced chemical vapor deposition (PECVD) SiN_x for defect passivation. Recent cells made with screen-printing are now approaching the 16% level [4]. Therefore, we revisited laboratory cell production to demonstrate the even higher potential of this material by using industrial-type SiN_x film for AR coating and bulk and surface passivation as well as AR coating.

One of the laboratory processing schemes we have implemented is rapid thermal processing (RTP) for simultaneous Al-doped back surface field (Al-BSF) formation and passivation of bulk defects through hydrogenation from a SiN_x layer. RTP is often used for Si solar cell fabrication due to several advantages over conventional tube furnace processing, including short cell processing time, low thermal budget, high heating and cooling rates and accurate temperature control [5–7]. In this paper we pushed the RTP process toward shorter dwell times and lower temperatures than in the past to enhance the cell performance and study the effects on the resulting Al-BSF quality and defect passivation. Appropriate firing or co-firing of SiN_x and Al has been shown to be an important step for significant enhancement in bulk lifetime [8]. In this paper the process sequence has been tuned to take advantage of this effect. More specifically, the co-firing temperature and time are optimized to achieve maximum hydrogenation of defects without sacrificing Al-BSF quality. The approach is directly applicable to the industrial-type screen-printing of solar cells if the front metal contact is replaced by screen-printed contact.