Lifetime Enhancement and Low-Cost Technology Development for High-Efficiency Manufacturable Silicon Solar Cells

A. Rohatgi, V. Yelundur, J. Jeong

University Center of Excellence for Photovoltaics Research and Education, School of
Electrical and Computer Engineering, Georgia Institute of Technology,
Atlanta, GA 30332-0250

Abstract

A low-cost, manufacturable defect gettering and passivation treatment, involving simultaneous anneal of a PECVD SiN_x film and a screen-printed Al layer, is found to improve the lifetime in Si ribbon materials from 1-10 μs to over 20 μs. Our results indicate that the optimum anneal temperature for SiN_x-induced hydrogenation is 700°C for EFG and increases to 825°C when Al is present on the back of the sample. This not only improves the degree of hydrogenation, but also forms an effective back surface field. Controlled rapid cooling was implemented after the hydrogenation anneal and contact firing to improve the retention of hydrogen at defect sites using RTP. RTP contact firing improved the performance of ribbon solar cells by 1.3-1.5% absolute when compared to slow, belt furnace contact firing. Enhanced hydrogenation and rapid heating and cooling resulted in screen-printed Si ribbon cell efficiencies approaching 15%. A combination of screen-printed Al and a two minute RTP anneal in an oxygen ambient produced simultaneously a high quality rapid thermal oxide (RTO) and an aluminum back surface field (Al-BSF) with a back surface recombination (BSRV) of 200 cm/s 2-3 Ohm-cm single and multicrystalline silicon solar cells. In addition, RTO/SiN_x stack passivation was found to be superior to SiN_x surface passivation. RTO/SiN_x passivation reduces the BSRV to ~10 cm/s on 1-2 Ohm-cm p-type single crystal Si and also lowers the J_{oe} of 40 and 90 Ohm/sq emitters by a factor of three and ten, respectively. Integration of RTP emitters, screen-printed RTP Al-BSF and RTO produced 19% and 17% efficient monocrystalline cells with photolithography and screen-printed contacts, respectively.

1. Introduction

The U.S. PV Industry Roadmap has identified the development of 18% efficient thin Si solar cells as a top R&D goal to be achieved in the next 3-10 years [1]. Si ribbon materials such as Edge-defined Film-fed Grown (EFG), dendritic web, and String Ribbon Si may offer the substrates of choice to meet this goal because thin (~100 μm) ribbon samples can be grown directly from the melt, eliminating losses associated with wafer slicing and etching. Although the low-cost growth of Si ribbon samples makes them attractive photovoltaic substrates, the as-grown minority carrier lifetime is typically in the range of 1-10 μs, which is not suitable for high-efficiency cells (~18%). In this study, several manufacturable gettering and passivation techniques, including P and Al gettering and hydrogen passivation via post-deposition anneal of PECVD SiN_x films, are examined for the improvement in the lifetime of ribbon Si materials. In addition to lifetime improvement, rapid and low-cost technologies are developed to improve front and back surface passivation for achieving high efficiency thin cells. Finally, high efficiency mc-Si and single crystal cells are fabricated and analyzed to demonstrate and quantify the positive impact of gettering, hydrogenation, and technology advancement on Si cell efficiencies. Sections 2 and 3 of this paper show the development of low-cost rapid technologies to improve front and back surface recombination velocity, while section 4 deals with bulk lifetime enhancement and contact firing schemes.

2. Development of Rapid and Improved Al-Back Surface Field (Al-BSF) for Si Solar Cells

Figure 1 shows that RTP alloying of the screen-printed Al, with a ramp-up rate of ≥1200°C/min, reduces the BSRV to approximately 200 cm/s for single crystal solar cells formed on 2.3 Ω-cm, p-type Si. This represents an improvement of about a factor of 10 to 1000 compared to devices with poor or no BSF. It was found that an Al-BSF formed in a belt furnace with a somewhat slower ramp-up rate, produced a non-uniform BSF with a surface recombination velocity of 1000 cm/s. The Al-BSF formed by screen-printing and rapid alloying has been integrated into an industrial-type fabrication sequences to achieve solar cell efficiencies in excess of 17.0% on planar 2.3 Ω-cm float zone Si, a 1-2% (absolute) improvement over analogous cells made with un-optimized Al-BSF's or highly recombinative rear surfaces [2].

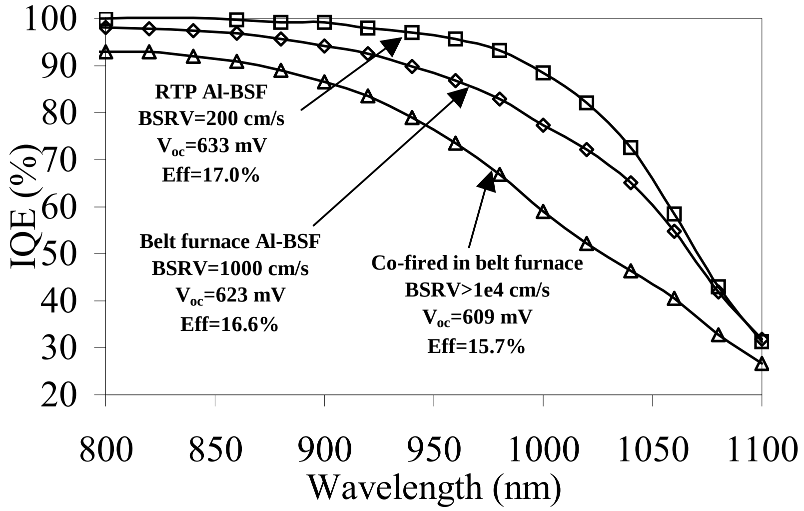

Figure 1: Impact of reduced S_b due to RTP Al-BSF alloying on the long wavelength Interval Quantum Efficiency (IQE) of screen-printed solar cells.

3. Development of a Novel RTO/SiN Stack for Effective Front and Back Surface Passivation for Silicon Solar Cells

In an effort to develop a low-cost, rapid, and effective surface passivation scheme, which can also withstand screen-printed metal firing, we conducted a comprehensive study using several promising dielectric films. The results in Figure 2 show that the passivation quality of all the single layer films, including TiO_2, SiN and a rapid thermal oxide (RTO), degrades severely after the firing of screen-printed contacts. In contrast, a rapid and novel surface-passivating scheme, composed of a thin (100 Å) rapid thermal oxide (RTO) capped with ~750 Å direct PECVD SiN, not only provides excellent front and back surface passivation and antireflection coating, but can also withstand 700-800°C screen-printed contact firing. Compatibility with this post-deposition anneal makes the RTO/SiN stack passivation scheme very attractive for next generation cost-effective, thin, bifacial solar cells where a similar anneal will be required to form front and back screen-printed contacts.

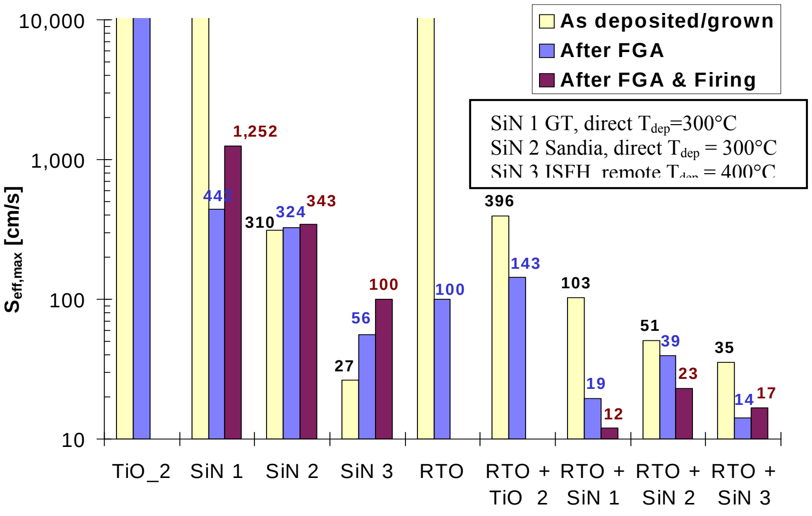

Figure 2: Impact of forming gas anneal (FGA) and a screen-printed metal firing anneal on S_{eff}.

To examine the potential of this novel surface passivation scheme, bifacial, screen-printed cells were fabricated on 0.65 ohm-cm float-zone silicon with front and back RTO/SiN stack passivation, and co-firing of the front and back Ag grid through the stack. This resulted in front illuminated efficiency of 17% and a rear illuminated efficiency of 11.6%. IQE analysis gave an effective BSRV of 340 cm/s, which was largely due to screen-printed metal of the back. In addition, direct J_{oe} measurements showed that stack passivation also reduces the J_{oe} of 40 and 90 Ohm/sq emitters by a factor of three and ten, respectively [3].

4. Understanding and Implementation of Manufacturable Defect Gettering and Passivation Technologies in Low-Cost Silicon Ribbons

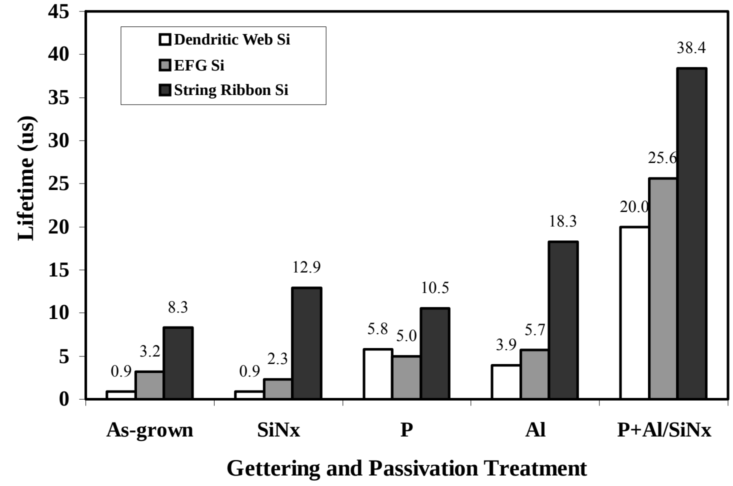

Figure 4: Al-enhanced SiN_x-induced defect passivation in Si ribbon materials.

To take full advantage of the reduced BSRV in the above sections, bulk lifetime for 100 µm thick material should be ≥20 µs, resulting in a diffusion length 2-3 times the cell thickness. Unfortunately, most mc-Si ribbon materials, which can be grown thin, show as-grown bulk lifetimes of only 1-6 µs. To raise the bulk lifetime in low-cost materials, such as dendritic web, EFG, and String Ribbon Si, to over 20 µs, we have investigated low-cost, manufacturable defect gettering and passivation treatments, including phosphorus and aluminum gettering and the post-deposition anneal of a PECVD SiN_x film for defect hydrogenation. Figure 4 shows that the lifetime of EFG and dendritic web Si did not increase after PECVD SiN_x film deposition and anneal at 850°C in a belt furnace, while the lifetime of String Ribbon showed a moderate increase from 8.3 µs to 12.9 µs. The ~930°C P and 850°C Al gettering treatments improved the lifetime in all three ribbon materials but were unable to raise the lifetimes over 20 μs. To identify any interaction between the Al gettering and hydrogen passivation processes, the SiN_x-induced hydrogenation and Al gettering treatments were performed simultaneously at 850°C after the P gettering. The simultaneous anneal of SiN_x and Al increased the lifetime in EFG, dendritic web, and String Ribbon Si to 25.6 μs, 20.0 μs, and 38.4 μs, respectively. The significant enhancement in lifetime achieved after the simultaneous anneal of SiN_x and Al indicates that there is a positive synergistic interaction between the SiN_x-induced hydrogenation on the front and Al-Si alloying at the back of the sample which enhances the lifetime to over 20 μs in all three materials. Our FTIR analysis of annealed SiN films has shown that the release of hydrogen from the film increases as the anneal temperature increases [4]. We have found that the optimum anneal temperature for the Al-enhanced SiN_x-induced hydrogenation is 825°C [5], making the defect passivation treatment compatible with the formation of an effective Al-BSF. We have also found that rapid cooling after the simultaneous SiN/Al anneal improves defect passivation by improving the retention of hydrogen at the defects [5]. Based on these results and recent theoretical calculations [6,7], we have proposed a three-step physical model in which defect passivation is governed by the release of hydrogen from the SiN_x film due to annealing, the generation of vacancies during Al-Si alloying, and the retention of hydrogen at defect sites due to rapid cooling [4].

While the 850°C/ 2 min. anneal is beneficial for bulk passivation, it is not suitable for front contact firing. Therefore we have developed an RTP contact firing scheme with rapid heating, to improve the Al-BSF, and rapid cooling to improve the retention of hydrogen at the defects. Table 1 shows that RTP contact firing, with very fast heating and cooling rates, improves the performance of ribbon solar cells by 1.3-1.5% absolute when compared to slow, belt furnace contact firing, where cooling rates were <10°C/s. The efficiency enhancement from RTP contact firing of ribbon cells is reflected in improved bulk and surface passivation (J_{sc} and V_{oc}) and contact quality (FF).

Contact Firing			V_{oc} (mV)	J_{sc} (mA/cm^2)	FF	Eff (%)
RTP	Float Zone	Average	621	34.2	0.777	16.5
		High	622	34.3	0.779	16.6
	EFG	Average	573	32.1	0.749	13.8
		High	585	32.8	0.757	14.6
	String Ribbon	Average	574	31.6	0.762	13.8
		High *	600	31.6	0.778	14.7
Belt Furnace	Float Zone	Average	614	33.7	0.770	15.9
		High	615	33.9	0.771	16.1
	EFG	Average	554	30.1	0.743	12.4
		High	566	30.9	0.751	13.1
	String Ribbon	Average	553	29.7	0.738	12.1
		High	575	31.1	0.747	13.4

* - confirmed by Sandia National Labs.

Table 1: Impact of RTP front contact firing on float zone, EFG, and String Ribbon Si solar cells.

Figure 4 shows LBIC scans, made with the *PVSCAN 5000* system using a 905 nm laser, of String Ribbon cells taken from consecutive sections of the ribbon to identify defects and their activity. Note that these samples have similar crystallographic defect structures. The LBIC response in intragrain regions improved from 0.58 A/W to 0.64 A/W with RTP contact firing as opposed to slow belt firing. Fig. 4 reveals a defect whose activity decreases as the defect extends from Cell 1-3 into Cell 16-1. The cell efficiency data in Table 1 and LBIC analysis in Figure 4 indicate that RTP firing of screen-printed contacts is more effective in retaining the hydrogen at defects that was introduced during the 850°C Al/SiN_x anneal. Conversely, the slow ramp rates during belt furnace contact firing result in increased dehydrogenation of defects, increasing their electrical activity. We have also shown that RTP contact firing improves the quality of the Al-BSF formed in the belt furnace [8], which may also contribute to the enhancement in cell performance seen in Table 1.

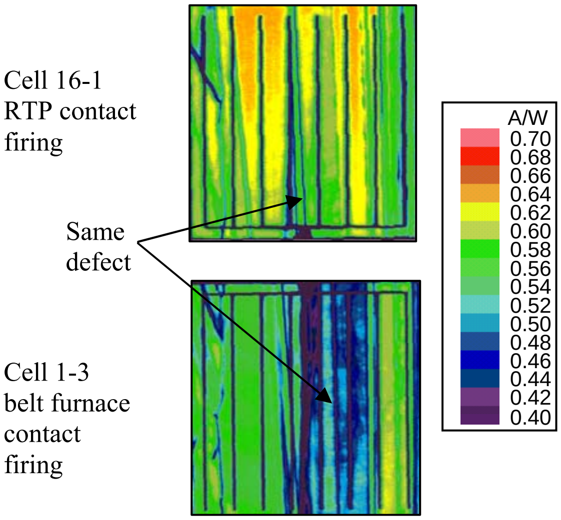

Figure 4: Improved passivation of intergrain and intragrain defects with RTP contact firing.

5. Conclusions

Several low-cost rapid technologies have been developed to enhance the bulk defect and surface passivation of Si solar cells. Formation of screen-printed Al-BSF and RTO/SiN_x stack passivation by RTP/PECVD resulted in substantial reduction in cell processing time and front and back surface recombination velocities. Cell efficiencies of 19.3% and 17% were achieved on float zone Si using photolithography and screen-printed contacts, respectively. Screen-printed bifacial float zone Si cells with RTO/SiN_x surface passivation also resulted in an efficiency of 17%. SiN_x-induced hydrogen passivation of Si ribbons has been found to be most effective when the SiN_x post-deposition anneal includes controlled rapid cooling and backside Al alloying. Vacancies generated during Al alloying enhance the dissociation of hydrogen molecules and the flux of atomic hydrogen deep into the bulk Si to improve bulk passivation. RTP contact firing was found to be more effective in preserving the hydrogen defect passivation achieved during the initial hydrogenation step and has resulted in 4-cm^2 screen-printed cell efficiencies as high as 14.7% on 300 μm thick String Ribbon Si and 14.6% on 300 μm EFG Si.

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