THE EFFECT OF THE VARIATION IN RESISTIVITY AND LIFETIME ON THE SOLAR CELLS PERFORMANCE ALONG THE COMMERCIALLY GROWN GA- AND B-DOPED CZOCHRALSKI INGOTS

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ABSTRACT

A systematic study of the variation in resistivity and lifetime on cell performance, before and after light-induced degradation (LID), was performed along the B- and Ga-doped Czochralski (Cz) ingots. Screen-printed solar cells with Al-back surface field were fabricated and analyzed from different locations on the ingots. Despite the large variation in resistivity (0.57 Ω-cm to 2.5 Ω-cm) and lifetime (100-1000 μs) in the Ga-doped Cz ingot, the efficiency variation was found to be ≤ 0.5%. No LID was observed in the cells fabricated from the Ga-doped ingot. In contrast with the Ga-doped ingot, the B-doped ingot showed a very tight resistivity range (0.87 Ω-cm to 1.22 Ω-cm), resulting in very tight lifetime and efficiency distributions. However, the LID effect reduced the efficiency of these B-doped cells by about 1.1% absolute. Additionally, the use of thinner substrate and higher resistivity B-doped Cz is shown to effectively reduce the LID effect.

INTRODUCTION

It is well known that solar cells fabricated on conventional B-doped Czochralski (Cz) Si suffer from degradation caused by the illumination or injection of carriers [1,2]. It has also been established that this light-induced degradation (LID) effect results from the presence of B and O simultaneously in Si [3]. Therefore, the LID effect can be removed by eliminating either of the two components. Doping the Si ingot with Ga instead of B is a promising way to avoid the LID. However, the basic drawback of using Ga as a dopant is the low segregation coefficient of Ga in Si (κ^o=0.008). This results in a much wider variation in resistivity along the Ga-doped ingot. In addition, bulk lifetimes could also vary along the ingot because of the possible doping dependence of lifetime. The combined effect of resistivity and lifetime variation is not well understood and needs to be investigated for the performance of widely manufactured screen-printed (SP) solar cells. In this paper, B- and Ga-doped Cz ingots were grown, and the Cz Si samples from different locations along the Ga- as well as the B-doped ingots were analyzed. The two ingots were targeted to have resistivity of ~1 Ω-cm. Additionally, some thin wafers with higher resistivity B-doping (~4.3 Ω-cm) were included in the study to explore the reduction in the LID effect as proposed in the literature [4,5]. All three ingots were grown at Shell Solar Industries using the exact same growth method and equipment. The lifetime for all samples was determined by the contactless photoconductance decay (PCD) method. Manufacturable SP solar cells were fabricated and analyzed using light IV-measurement.

EXPERIMENTALS

The wafers included in this study were taken from different locations along the two Cz Si ingots: six locations from the ~1 Ω-cm B-doped ingot and nine locations from the 0.5-2.5 Ω-cm Ga-doped ingot. Additional wafers were taken from a higher resistivity B-doped ingot (~4.3 Ω-cm) and thinned down to ~230 μm from ~290 μm. Table 1 summarizes the wafers used in the study. The post-diffusion lifetime was measured on each sample by the contactless PCD method after POCl3 diffusion at ~880°C followed by etching the sample down to Si bulk. The surface was passivated by iodine/methanol solution during the PCD measurements.

Table 1. Description of Cz Si samples used in the study.

<table>
<tr><th>Ingot</th><th>Thickness</th><th></th><th colspan="9">Tail end   Seed end</th></tr>
<tr><td rowspan="2">Low-ρ B-doped</td><td rowspan="2">290μm</td><td>Location</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td colspan="4">6</td></tr>
<tr><td>ρ (Ω·cm)</td><td>0.87</td><td>0.82</td><td>0.90</td><td>0.95</td><td>1.00</td><td colspan="4">1.22</td></tr>
<tr><td rowspan="2">Ga-doped</td><td rowspan="2">290μm</td><td>Location</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td></tr>
<tr><td>ρ (Ω·cm)</td><td>0.57</td><td>0.63</td><td>0.84</td><td>0.99</td><td>1.19</td><td>1.46</td><td>1.82</td><td>2.17</td><td>2.54</td></tr>
<tr><td>Hi-ρ B-doped</td><td>230μm</td><td>ρ (Ω·cm)</td><td colspan="9">4.3</td></tr>
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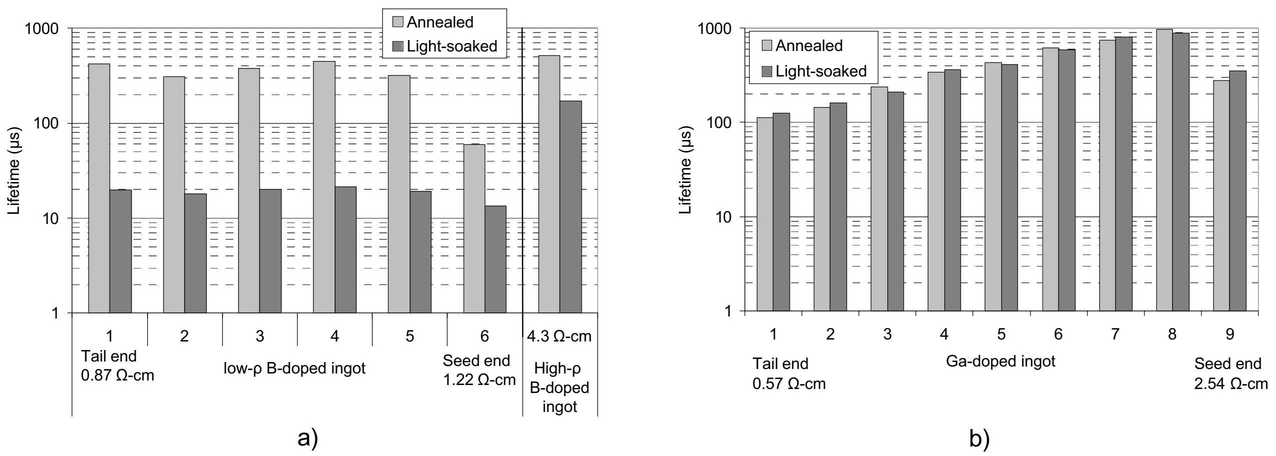

Fig 1. Post-diffusion lifetime of samples from different locations from a) low- and high-resistivity B-doped Cz ingots b) Ga-doped Cz ingot

Post-diffusion lifetime was used as a reference rather than the as-grown lifetime because 1) the high-temperature treatment was found to affect the post LID lifetime [6] and 2) impurity gettering by phosphorus could effectively improve the lifetime. As a result, the lifetime in the finished cell correlates better with the post-diffusion lifetime rather than the as-grown lifetime. The lifetime was measured after 1) 200°C anneal to remove any LID effect [1] and 2) light-soaking for >20 hrs to obtain the stabilized lifetime after LID.

SP Al-back surface field (BSF) solar cells (4 cm^2) were fabricated on all the wafers shown in Table 1. First, all the samples were textured in an alkaline etch and then $POCl_3$ diffused to obtain a ~45 Ω/sq emitter. Subsequently, SiN_x AR-coating was deposited on the front. All the samples were then subjected to full-area Al screen-printing on the backside, followed by Ag gridline printing on the front. The samples were then co-fired using rapid thermal processing. No special heat treatment was performed to minimize LID as proposed in the literature [6, 7, 8].

The I-V measurements were taken after annealing the cells at 200°C to remove any LID effect. The I-V measurements were repeated on all the cells after light soaking them for >20 hrs to obtain the stabilized cell performance after LID.

RESULTS AND DISCUSSIONS

Resistivity distribution

Table 1 shows that the low-resistivity B-doped ingot provides samples with a very tight resistivity, ranging from 0.87 Ω-cm to 1.22 Ω-cm. However, the resistivity variation is much larger (0.57-2.54 Ω·cm) in the case of the Ga-doped ingot compared to the B-doped ingot. The resistivity decreases appreciably from seed to tail end of the Ga-doped ingot because of the low segregation coefficient of Ga (κ^o=0.008) as opposed to B (κ^o=0.8) in Si.

Post-diffusion Lifetime

The post-diffusion lifetimes in annealed and light-soaked states are summarized in Figs. 1a and 1b for B- and Ga-doped ingots, respectively.

The low-resistivity boron-doped ingot showed a very tight distribution of the lifetime except at the seed end, where the lifetime was somewhat inferior. This is attributed to the swirl defects that occur in dislocation-free Si with a high density of point defects [8]. The LID effect dramatically reduced the lifetime in the low-resistivity B-doped ingot from ~300-400 μs to ~20 μs (Fig. 1a). This corresponds to a diffusion length of about 230 μm, which is less than the thickness (~290 μs) of the cell. Consequently, the bulk quality dominates the cell performance after LID rather than the recombination at the back surface or back surface recombination velocity (BSRV). The high-resistivity B-doped sample, on the other hand, exhibited a much weaker LID effect, resulting in about a factor of three degradation in lifetime from ~500 μs to ~170 μs. This stable lifetime corresponds to a diffusion length of ~740 μm, which is more than three times the sample thickness (230 μm). This ensures that the cell performance is mainly limited by the back surface recombination, rather than the bulk lifetime.

Unlike the B-doped wafers, Ga-doped wafers did not show any sign of LID. However, the lifetime varied significantly from ~100 to 900 μs from seed to tail end because of the variation in the resistivity. Both resistivity and lifetime increased gradually from tail to seed end except that lifetime showed a drop at the seed end of the ingot for the same reason as the B-doped ingot.

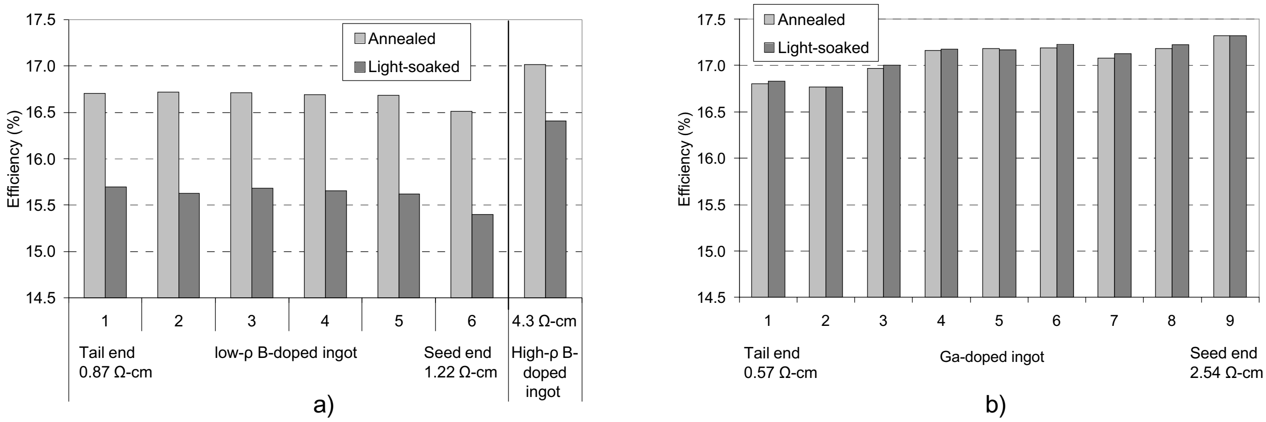

Fig 2. SP Al-BSF solar cells efficiency of samples from different locations from a) low- and high-resistivity B-doped Cz ingots b) Ga-doped Cz ingot

Performance of SP Al-BSF solar cells as a function of ingot positions

The variation in efficiency of the SP Al-BSF solar cells fabricated on wafers, taken from different ingot locations, is plotted in Figs. 2a and 2b for B- and Ga-doped ingots, respectively. Both annealed (no LID) and light-soaked (after LID) states are included in the figures.

The efficiency prior to the LID in the low-resistivity B-doped ingot was quite uniform (~16.7%), except at the seed end where the efficiency droped slightly to 16.5%. This is entirely consistent with the lifetime data in Fig. 1a, which showed fairly uniform lifetime except at the seed end. However, the efficiency of all the low-resistivity B-doped cells decreased by about 1.1% absolute after the light soaking, resulting in a final efficiency of only ~15.6%. This is in good agreement with device modeling calculations, which showed that SP cells with a simple design as ours should produce ~15.5% cells on ~20 µs lifetime material (Fig. 3).

The high-resistivity (4.3 Ω-cm) thin (230 µm) B-doped Cz cell gave an efficiency of 17%, which is somewhat better than the low-resistivity B-doped cells. The LID effect was substantially reduced with an efficiency loss of ≤0.6% absolute as opposed to 1.1% for the low-resistivity thick cells, resulting in the stabilized efficiency of 16.4%. The reduced LID effect is attributed to 1) the reduction of B concentration resulting from the higher resistivity and 2) higher diffusion length to thickness ratio resulting from thinner material. This represents another strategy for minimizing LID for B-doped Cz.

Unlike in the B-doped ingots, the efficiency spread in Ga-doped ingot prior to the LID is somewhat larger (16.8%-17.3%), with the higher resistivity seed end producing slightly higher efficiency. However, this variation in efficiency is acceptable despite the very wide variation in resistivity. Figure 4 shows that the spread in Ga-doped cell efficiency is reduced because of the increase in V_{oc} and the decrease in J_{sc} as the resistivity decreases. Moreover, there is essentially no LID observed in the Ga-doped ingot, resulting in ≥1.2% higher absolute efficiency after light soaking relative to the low-resistivity B-doped Cz ingot. This gap in stabilized efficiency was reduced to ~0.7% when higher resistivity B-doped Cz was used. These results show that the Ga-doped Cz ingot offers great potential for higher performance stabilized Cz cells. In addition, a high-quality Ga-doped ingot can be grown in the same puller used for the B-doped ingot, without any modification.

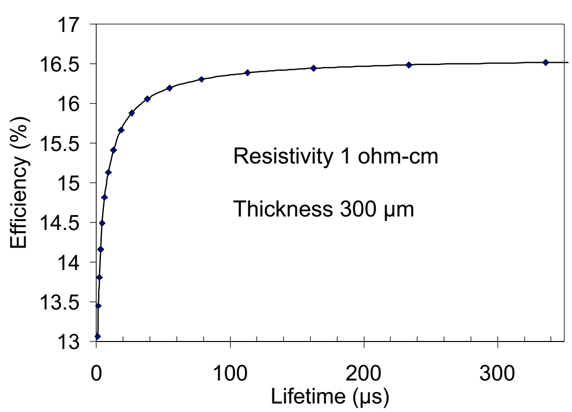

Fig 3. Simulated solar cell efficiency as a function of lifetime for 1 ohm-cm Si substrate.

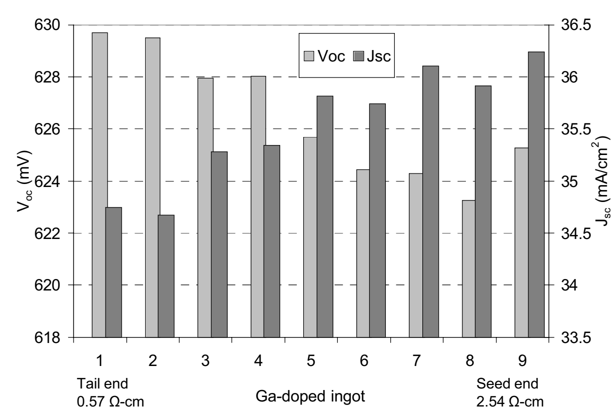

Fig 4. J_{sc} and V_{oc} as a function of ingot position in Ga-doped ingot.

Table 2. Summary of averaged efficiency from different Cz ingots.

Dopant Type	Resistivity (Ω·cm)	Efficiency (%)	
		Annealed	Stabilized
Boron	~ 1.0	16.7	15.6
	~4.3	17.0	16.4
Gallium	0.57-2.54	17.1	17.1

Table 2 summarizes the average efficiency of solar cells from the three Cz Si ingots. These data demonstrate the potential of using Ga-doped Cz instead of B-doped Cz.

CONCLUSIONS

This paper demonstrates the potential for using Ga as a dopant instead of B in p-type Cz Si to eliminate LID. Despite a large resistivity variation (0.57-2.54 Ω·cm) in the Ga-doped Cz ingot resulting from a small segregation coefficient of Ga in Si, the absolute efficiency was found to vary by <0.5%. This is the result of the competing effect of increasing V_{oc} and decreasing J_{sc} as the resistivity decreases. This results in ~1.5% higher average stabilized efficiency than the cells made on a 1 ohm-cm B-doped ingot.

The use of thinner and high-resistivity B-doped Cz lessens the detrimental effect of LID. However, the LID still remains appreciable and accounts for the efficiency reduction of ~0.6 % absolute for ~17% efficient SP cells.

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