AN EXPERIMENTAL STUDY OF AL-ALLOYED pp^+ JUNCTIONS FOR BSF SOLAR CELLS

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SUMMARY.

n^+pp^+ bifacial BSF solar cells are used to experimentally analyse the behaviour of Al-alloyed high-low junctions, formation mechanisms of the high-low junction are explained, and used to calculate its effective surface recombination velocity. It is concluded that thick Al layers and high alloying temperatures (over 800°C) are necessary to obtain low values of Seff. These conclusions are checked with experimental results of other workers. Recommendations for BSF solar cell processing are given.

1. INTRODUCTION.

Al-alloying diffusion has been considered for long an appropriate way for automated processing of low cost silicon solar cells. Nowadays this technology has stirred new interest in producing high efficiency MIS-BSF solar cells taking advantage of the low annealing temperature of Al, which prevents degradation of the base lifetime (1, 2).

The objective of this work is to determine the capability of Al-alloyed technology to form high quality high-low junctions both for conventional and bifacial BSF cells.

For that, we have used the Double Sided Surface Field (DSSF) cell. This cell has a BSF-like structure (n^+pp^+) capable of being illuminated on both sides (3), Fig. 1. When front illuminated, the behaviour of the DSSF cell is similar to that of a BSF cell. The importance of the ratio between the minority carrier diffusion length in the base (L) and the base thickness (w) and the decisive influence of the effective surface recombination velocity of the high-low junction (Seff)(3) have been shown already. For back illumination the effect of these three parameters L, w and Seff in the short-circuit current rises dramatically since most of the carriers have to be effectively reflected by the high-low junction and travel across the whole bulk of the cell.

As a consequence the DSSF structure has higher sensitivity than conventional BSF cells for studying the high-low junction. Histograms of L vs. the Al-quality and of Seff vs. the alloying temperature are presented and discussed.

Our results are compared with experimental results reported by other workers and a discussion of the potential of the Al technology to produce effective high-low junctions is included.

2. HIGH-LOW JUNCTION FORMATION

As temperature rises during the alloying thermal cycle above the aluminum-silicon eutectic melting point of 577°C an Al-Si liquid-phase is formed. The deposited Al dissolves Si from the wafer to reach a liquid-phase composition given by the phase-diagram at the alloying temperature. In the binary-system diagram of Fig. 2, F is the Si weight percentage of the liquid-phase at the alloying temperature. The total weight of dissolved Si is then: p_{Al} (F/(100-F)) where p_{Al} is the weight of deposited Al.

As the sample is cooled down from the alloying temperature the concentration of Si in the liquid-phase decreases following the liquidus curve of the phase-diagram. The excess Si segregates at the Si-liquid interphase in a similar way as in a liquid-phase epitaxy. A recrystallized Si layer, doped at the limit solubility of Al into Si at the particular temperature, grows on top of the substrate. When the liquid phase reaches the eutectic composition (E) no more Si segregates and the remaining liquid solidifies.

The net weight of the recrystallized Si is

$$p_{Si} = p_{Al} \left(\frac{F}{100-F} - \frac{E}{100-E} \right) \qquad (1)$$

The thickness of the p^+-layer, W_{p+}, is then

$$W_{p+} = \frac{p_{Al}}{A \cdot \rho_{Si}} \left(\frac{F}{100-F} - \frac{E}{100-E} \right) \qquad (2)$$

Where A is the sample area; and ρ_{Si} is the Si specific weight.

Formula (2) has been experimentally confirmed by measuring the weight of deposited Al and the weight of the remaining eutectic alloy after the thermal step.

3. EXPERIMENTAL

DSSF Solar cells were fabricated on <100>, 5-8 Ω.cm, p-type Si wafers. They were thinned to 100 µm by means of an alcaline etchant. A Phosphorous predeposition was carried out at 875°C during 30 min. from a liquid source. Aluminum was evaporated or sputtered on one face once the n^+-layer was removed from it. The sample was annealed in forming gas atmosphere at various temperatures ranging from 650° to 825°C during 30 min. The amount of deposited Al was kept constant at 0.3 mgr/cm^2.

Two qualities of evaporated Al were used: 99% and 99.999%. Also Al and Al-Si eutectic alloy, both 99.995% pure, were sputtered from Materials Research Corp. targets. The remaining Al-Si eutectic alloy formed during the annealing step was eliminated by ultrasonic vibration in a 5% HF solution. Sheet resistances of the p^+-layer between 100 and 500 Ω/□ were measured.

Measurements of the photogenerated current (AM1) and open-circuit voltage were made at 25°C at this stage of the process on 1 cm^2 scribed samples.

The results of these measurements and a carefull interpretation of them have been described elsewhere (4). Every sample was characterized by values of L (minority carrier diffusion length in the base) and Seff (effective surface recombination velocity of the high-low junction, comprised in certain intervals. This statistical procedure was selected due to the lack of reproductibility of the Al-alloyed technique. The results of this estimation are presented in form of histograms (Fig. 3).

Histograms of Seff as a function of the annealing temperature are shown on the right hand side of Fig. 3. A decrease of Seff as the alloying temperature increases is noticeable. The smaller Seff is 300 cm/sec. Typical values are between 1000 and 3000 cm/sec.

The left side of Fig. 3 displays histograms of the number of samples which correspond to a certain L interval depending on the type of Al. The 99.999% Al statistically shows a better diffusion length than the 99% Al. About the sputtered material, the Al-Si, eutectic alloy seems to be superior than single Al. The comparison between the 99.999% evaporated Al and the sputtered Al indicates undoubtly the higher performance of the first. The highest observed diffusion length is 180 μm. Typical values are between 80 and 120 μm.

4. DISCUSSION

There are two reasons that explain the behaviour of Seff with the annealing temperature. First, the limit solubility of Al into Si increases as the annealing temperature increases. And second, for a given weight of deposited Al a tnicker p^+-layer results at higher temperatures (see eq. 3). These two effects collaborate to reduce the Seff of the high-low junction. We have modeled this structure through the high-low junction model (5). A diffusion length of 10 μm is assumed from reference (6).

Heavy doping effects are included from the experimental work of Slotboom and de Graaff (7). Reasonable agreement with the experiments was obtained when the recombination velocity of the exterior surface is between 10^5 to ∞ cm/sec. This is shown by the two lines superimposed at the histograms.

In general the model correctly predicts the lower limit of Seff. However there is a number of samples which show higher Seff than the theoretical expectations. This can be interpreted by considering that the preferential dissolution of Si along particular crystallographic directions produces a greater effective high-low junction area than the cell area. Also a diffusion length of 10 μm in the p^+-layer could be perhaps an optimistic estimation.

In the case of BSF solar cells there is an infinitely recombining contact at the outer surface. To be an effective high-low junction the p^+-layer should be at least thicker than the minority carrier diffusion length. According to eq. 3 deposited Al layers should be 5 to 20 times thicker than the p^+-layer. This fact explains the well known conclusion that screen printing deposition methods are better than evaporation (8).

Selected experimental results reported in the literature are displayed on Table I. Thin evaporated Al layers lead to ineffective high-low junctions in comparison with thick film depositions. The best results of Frisson et al. (9) have been obtained by firing a 25 μm thick layer of an Al paste deposited by screen printing (10).

The short diffusion lengths reported in this work are probably due to heavy impurities like Fe, Cu or Zn which are present in important amounts in the evaporated or sputtered Al material. These are very fast diffusing impurities and in 30 minutes establish a nearly constant impurity concentration all along the bulk of the semiconductor, almost independently of the annealing temperature. This statement has been confirmed by reducing the annealing time down to 40 seconds with slow (5 min) pull, in and out, from the furnace. Since the recrystallization of the Si takes place during the cooling of the sample, this technique only affects the rapid diffusion of metallic impurities. Results on a 1 cm^2 250 μm thick sample alloyed at

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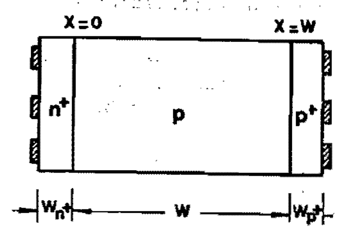

Fig. 1. Bifacial BSF Cell (D

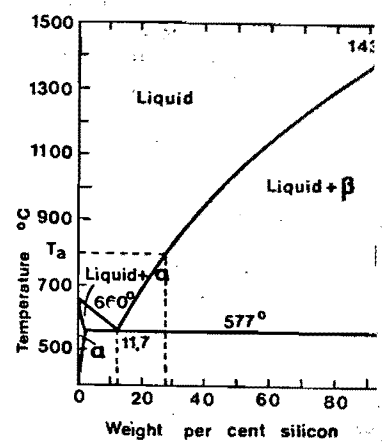

Fig. 2. Al-Si Phase diagram.

Reference	Struc
Mandelkorn et al. (13)	BSF
Tarr et al. (2)	MIS-B
Frisson et al. (9)	BSF
Gay (8)	BSF
This work	DSSF

Table I: Experimental reported

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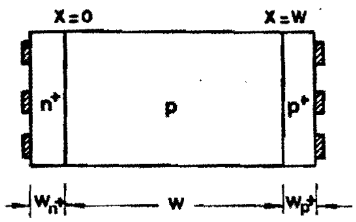
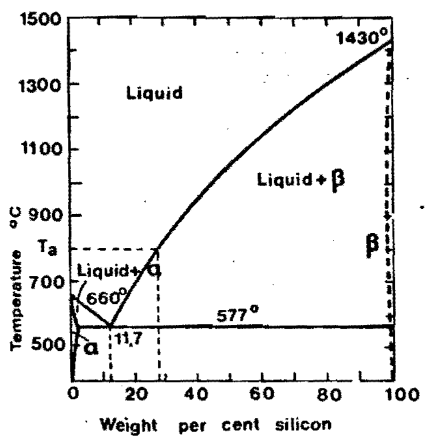


Fig. 1. Bifacial BSF Cell (DSSF).



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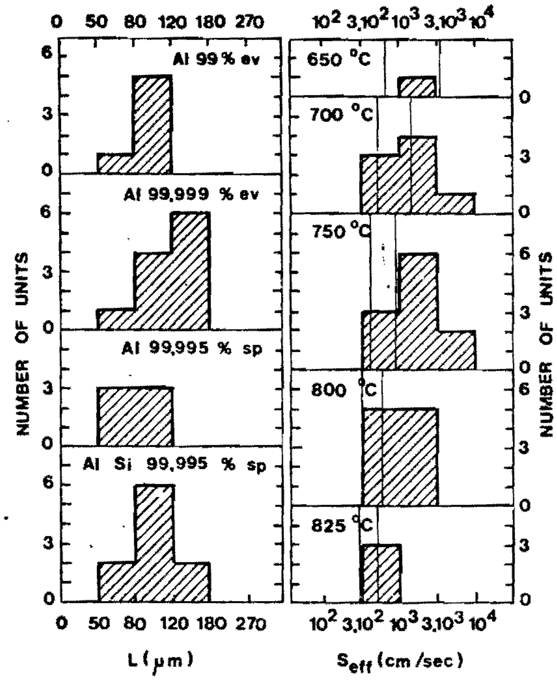

Fig. 3. Histograms representing the number of samples experimentally assigned to every L and Seff interval vs. the Al quality and the annealing T respectively. On the Seff histograms the vertical lines are theoretical results.

Reference	Structure	Al dep. method	Ta (°C)	V_{oc} (mV)
Mandelkorn et al. (13)	BSF	evaporation	850	580
Tarr et al. (2)	MIS-BSF	paste	850	576
Frisson et al. (9)	BSF	powder	780	611
Gay (8)	BSF	paste	75-875	599
This work	DSSF	evaporation	825	578

Table I: Experimental reported results on Al-alloyed BSF solar cells. V_{oc} data are normalized at I_{sc} = 30 mA and T = 25°C.

825°C (99.999% Al) are I_{scf} = 26.8 mA, I_{s}[illegible] = 7.6 mA (no AR coating); V_{ofc} = 575 mV and V_{ocb} = 543 mV, measured at AM1 and 25°C. The estimated value of Seff is 300 cm/sec and L is 300 μm, considerably longer than in the 30 min. annealing experiment.

We explain in this way the behaviour of V_{oc} and I_{sc} reported by Gay with increasing annealing time (8). He noticed as well a degradation on the performance of the solar cell when the annealing time was too short (8, 11). We explain this observation indicating that the thermal inertia of holder and samples provokes the real annealing temperature to be lower than expected. As previously discussed, this fact could produce a higher Seff.

There is an important reason to expect better diffusion lengths in the base of the cell when an Al-Si alloy is used rather than pure Al. The preferential dissolution of Si along particular crystallographic directions in the lattice produces deep spikes into the base. Roberts and Wilkinson (12) found that the mean depth of these spikes can be reduced to one half by using Al-Si eutectic alloy instead of single Al. Although our experiments could be affected by the real purity of the targets it is reasonable to affirm that an Al-Si alloy with a composition given by the liquidus curve of the binary system at the annealing temperature (F) would drastically reduce the number and depth of these spikes. This would enhance the minority carrier diffusion length in the base.

5. CONCLUSIONS.

The conclusions of this work are five recommendations for BSF solar cell processing: a) deposit a heavy layer of Al, b) alloy at a temperature higher but close to 800°C, c) alloy during 1 minute, d) use pure pastes and e) Al-Si pastes with the composition of the liquid phase at the alloying temperature.

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THE INFLUENCE OF SURFACE

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J.NIJS, F. D'HOORE, R.M

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Summary

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1. INTRODUCTION

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