

## CONTAMINATION PROBLEMS OF AMORPHOUS SILICON N-I-P SOLAR CELLS ON METAL SUBSTRATES

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### ABSTRACT

Commercial aluminium and stainless steel sheets were used as substrates for thin film silicon solar cell deposition. The influence of elemental contamination and disturbed film growth on solar cell performance and yield were studied. Diffusion during film growth was found to be more pronounced than thermally activated interdiffusion of existing films. Surface irregularities of the substrate are shown to reduce the fill factor of the solar cell. Initial efficiencies of 8.5% with single-junction amorphous silicon solar cells on both types of metal sheets were reached.

### INTRODUCTION

Amorphous silicon (a-Si:H) solar cell deposition on metal substrates has definite advantages compared to conventional p-i-n on glass technology: Cost reduction can be expected because of omitting expensive textured TCO on glass. Deposition temperatures for the *i*-layer higher than 250°C are possible (without encountering the same contamination problems), while the most critical interfaces are deposited last. *Microcrystalline* window layers are used more successfully in the n-i-p structure than in p-i-n cells, leading to higher  $V_{oc}$ -values.

The presented work is part of a project to directly integrate a-Si:H solar cells in aluminium façade elements. The main goal of this project is not the highest possible efficiency, but to reduce the cost per Watt<sub>peak</sub> of electricity by depositing very cheap solar cells on large surfaces of a low cost substrate. Another reason to choose Al as substrate material is its high ductility: efficient 'light-trapping' structures can be printed into the sheets, allowing to deposit thinner and therefore more stable a-Si:H solar cells.

Solar cell deposition on *stainless steel* substrates has been successfully accomplished and modules using stainless steel substrates are commercially available[1]. Deposition on Al sheets, meanwhile, seems to offer additional problems and no reports of solar cells on Al of reasonable quality (comparable to n-i-p cells on other substrates) are known to the authors. In a first time, many attempts in our laboratory to deposit solar cells on Al substrates failed. This failure made us focus our attention on diffusion phenomena and surface geometry as is reported in this work.

There is a certain experience about Al/Si-interfaces from two other applications: Al for interconnections on crystalline silicon wafers in microchips and Al as back contact in a-Si:H p-i-n solar cells on glass. In both cases the Al is deposited *on the silicon* substrate.

In microchip fabrication, certain high temperature process steps have to be done after depositing the Al on the Si wafer. Therefore, diffusion barrier layers are essential. Many different diffusion barrier structures have been published and research is ongoing in this field. When using thin films as barriers, not only the choice of a certain barrier *material* is important for a good protection but also its deposition method and, in general, its quality [2].

Amorphous silicon solar cells typically never exceed a temperature of 220° C during their production. Therefore the need of a barrier against diffusion between Al and Si is not obvious at first sight. Yet experience showed that *amorphous* silicon can interact with Al at temperatures as low as 170° [3] and the characteristics of a p-i-n solar cell with an Al back contact can deteriorate after an annealing step at this temperature.

In our case- deposition of a-Si:H by Very High Frequency - Glow Discharge Plasma Enhanced Chemical Vapour Deposition (VHF-GD PECVD) *on aluminium* sheets- we expect some differences w.r.t. the situations explained above. First, the diffusion takes place in a *growing* film of a-Si:H at about 220°C. Diffusion might follow here different schemes than those applying to diffusion at an interface of two existing adjacent layers (the second of which was deposited at room temperature) during an annealing step. Second, the surface of a metal sheet is never as flat

as the surface of a glass plate or that of a wafer. The barrier layer and the cell itself might have sites of reduced thickness or even pinholes. Third, a commercial metal sheet (as used in this work) always contains a certain amount of foreign elements. These foreign elements can be deliberately added metals or 'contaminants' and they often are not homogeneously dispersed in the metal but form crystals on their own or alloyed with the sheet metal. If such crystals are situated at the surface of the substrate, these areas show a different behaviour w.r.t. diffusion and growth of subsequent layers.

The phenomena that lead to the deterioration of cell performance were grouped into two classes: (i) 'isotropic' diffusion which takes place in areas, where all layers are 'ideally' grown. (ii) phenomena related to 'geometrically localised problematic spots' on the substrate or on the films. The first point was investigated by means of Secondary Ion Mass Spectroscopy (SIMS), Secondary Neutral Mass Spectroscopy (SNMS), and by measuring the collection efficiency of the solar cells; the second point by analysing statistical data about solar cell yields and by Scanning Electrons Microscope (SEM) studies.

## EXPERIMENT

In our study, n-i-p solar cells of amorphous silicon were deposited on a variety of substrates: Sheets of aluminium (some of them anodised) and stainless steel were used either without further treatment or with diffusion barriers and back contact layers based on ZnO, Si<sub>3</sub>N<sub>4</sub>, Ag, ITO. For comparison, some cells were deposited on commercial TCO on glass substrates.

Amorphous and microcrystalline silicon has been deposited by VHF-GD PECVD. Microcrystalline SiC:H was used for <p>-layers and ITO served as transparent front contact and antireflection layer. Substrate size was 4cm x 8cm and front contacts were deposited through a mask in order to get 36 small cells (of a surface of 0.2 cm<sup>2</sup> or 0.8 cm<sup>2</sup>) on each substrate for yield statistics. The solar cells were annealed at 180°C and 250°C. After each annealing step, IV-characteristics of all cells were measured, the yield was calculated and spectral response measurements of two selected, good cells of each substrate were done. For the statistics, a 'living' cell was defined as follows: ( $V_{oc} \times FF$ ) > 0.2 V [4].

SIMS or SNMS measurements were performed on some samples to get information about the 'isotropic' diffusion, because these methods average over a beam size of several mm<sup>2</sup>. This is a few orders of magnitude larger than the surface of 'problematic spots' which we expect to be some microns in diameter (according to our SEM pictures).

To investigate the second class of problems, i.e. 'problematic spots', and their influence on solar cell performance, we analysed the statistical data of small solar cells on a larger substrate as well as data from SEM pictures.

## RESULTS

### 'Plasma-induced' diffusion in a growing film

In a first series of solar cells metal / ITO was used as substrate and ITO as front contact. Back and front ITO were deposited by sputtering at room temperature. The cells were deposited at 220°C, and after the deposition they were annealed at 180°C. In this ITO / cell / ITO - sandwich structure it was found, that the diffusion of indium and tin *in the growing film* (substrate side) is much more pronounced and therefore dangerous to the cell than the diffusion of the same elements *during an annealing of existing films* (top side). We call this first effect 'plasma-induced' diffusion. The penetration depth of In in figure 1 for instance is 5 times higher from the substrate side ('plasma-induced' diffusion) than from the top side (thermally activated interdiffusion).

We assume that during the plasma deposition process many modes of transport of the contaminating atoms into the growing film take place, e.g. sputtering or etching and backdeposition from the plasma phase. Furthermore, the effective temperature at the surface of the growing film is higher than the measured substrate temperature due to the energy brought in by arriving radicals and ions.

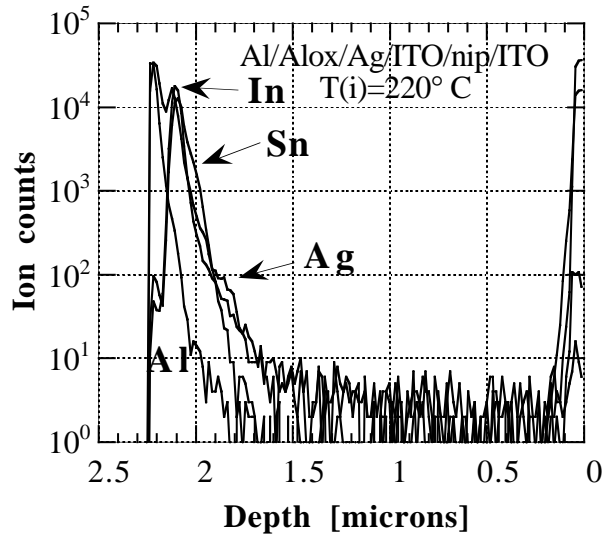


Figure 1: SIMS profiles of an n-i-p solar cell: Al/Ag/ITO/nip/ITO

To further characterise diffusion of a metal into microcrystalline and amorphous silicon during deposition by PECVD, we varied the deposition temperature of the silicon layers. We expected the penetration depth to be smaller for lower deposition temperatures according to general experience for diffusion. Surprisingly the penetration depths are much larger in the case of a low temperature silicon deposition than in the case of high temperature deposition, as table I shows. We explain this result by the fact that the silicon films are of different quality: Lowering deposition temperature leads to more voids and inner surfaces in the film [5]; these inner surfaces can be assumed to be preferred diffusion paths [6].

a-Si:H deposition temperature	Al penetration depth	Ag penetration depth
160° C	1600 nm	2350 nm
200° C	240 nm	330 nm
220° C	75 nm	175 nm

### Solar cell yield statistics

Figure 2 shows solar cell yields for selected substrates and different annealing temperatures. Depositions on metals other than Al or depositions on ZnO-protected Al sheets show high yields even after the second annealing step (250°).

The depositions on Al without protection layer(s), on the other hand, are worth a closer look (table II): In spite of the potential 'plasma-induced' diffusion of Al during deposition at 220°C and in spite of a further annealing at 180°C, we measured many working solar cells on glass / Al substrates. Just after another annealing step at 250°C, the yield of these cells was substantially reduced and the cells showed high leakage currents. These glass / Al substrates simulate an Al sheet without elemental and geometrical impurities.

Diodes deposited on actual Al *sheets* still showed high Voc-values but virtually no photocurrent and a detrimentally reduced FF.

The observed difference between an 'ideal' Al surface and a real Al sheet might be due to bad film growth on irregularities of the sheet surface or due to the lack of 'diffusion centres' on the 'ideal' surface; the latter effect raises the critical temperature for this interface.

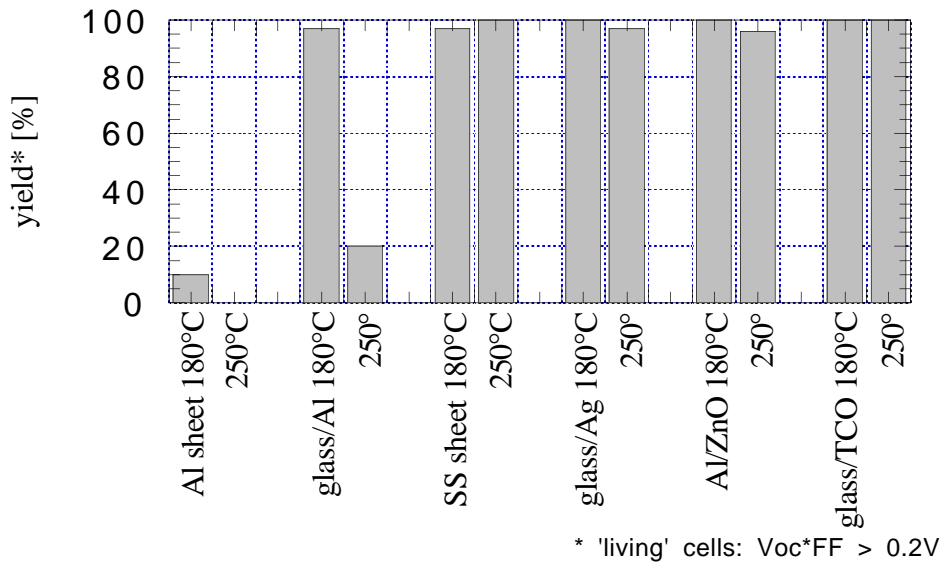


Figure 2: Solar cell yield on some selected substrates after annealing at 180°C and 250°C (Solar cell size = 0.2cm<sup>2</sup>).

substrate	annealing	typical Voc	typical FF	remarks
Al sheet	180° C	up to 840 mV	25%	almost no current under AM 1.5
glass / Al	180° C	up to 880 mV	60%	
	250°C	(800 mV)	40%	high leakage currents!

### Fill-factor reduction due to localised problems

Solar cells yield statistics show that 'problematic spots' can make a solar cell totally unfunctional. The experiment described in figure 3 shows how the same spots- but in a smaller concentration- can be responsible for just reducing the fill factor of a solar cell.

A solar cell has been deposited on an Al sheet protected by a film of ZnO of increasing thickness. The fill factors of the cells shows the following behaviour: In areas where the protective ZnO film is thinner than a critical value, the average fill factor of the solar cell is reduced!

We compared two areas on the sample: on one of them the ZnO layer has a thickness of 0.5µ, on the other it has a thickness of 1.2µ. The isotropic diffusion of Al is reduced to about the same value for both sides; even the thinner film is an effective barrier layer. A SEM study of the cell surface showed the difference between the two areas: the thicker protective film is able to cover more of the irregular spots which are present on the substrate, i.e. more than those covered by the thinner film. Therefore we conclude: The solar cell tolerates a certain number of 'problematic spots' (they might be called 'pinholes') per area; if their number is too high, the fill factor of the cell is reduced. In the worst case the fill factor is reduced to zero, the cell is not functional at all.

Solar cell:



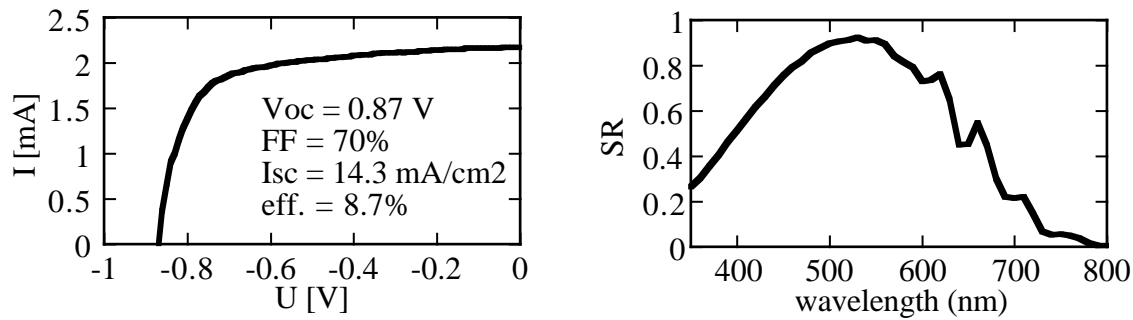


Figure 4: IV-characteristics and SR curves of the best cell on Al sheets.

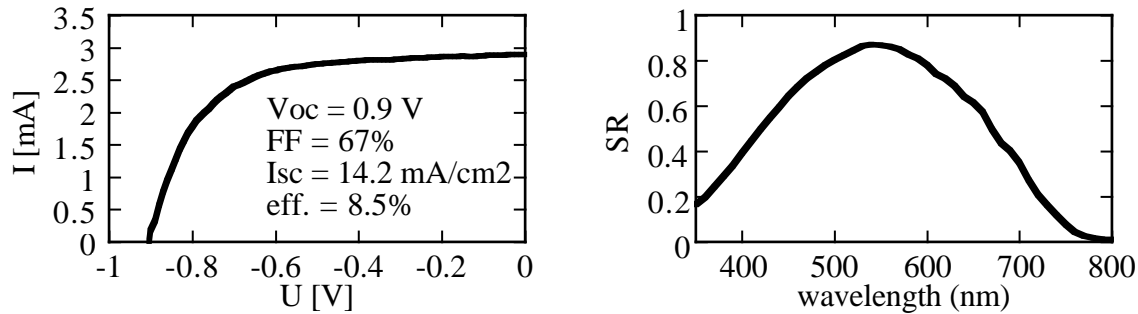


Figure 5: IV-characteristics and SR curves of the best cell on ss sheets.

## CONCLUSIONS

It was found to be easier to deposit a-Si:H solar cells on stainless steel substrates than on aluminium substrates. Without proper surface passivation, solar cells on Al sheets are unfunctional. Solar cells on glass substrates covered with pure Al thin films perform surprisingly well; one can assume that surface problems are more important than 'isotropic' Al diffusion into the silicon layers.

Yet, to obtain both good performances *and* a long lifetime (simulated by higher annealing temperatures) of the solar cells, a barrier against 'isotropic diffusion', an *i*-layer with few inner surfaces (low void density) and a passivation of 'problematic spots' on the surface of the substrate are all essential. Solar cells with sufficiently high yields, fill-factors up to 70% and initial efficiencies of 8.5% have been achieved.

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