

# DEPENDENCE OF a-Si SOLAR CELL $V_{oc}$ ON DEPOSITION TEMPERATURE

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## ABSTRACT

We have investigated variations in the a-Si deposition process to achieve a high  $V_{oc}$  a-Si solar cell to be used as the top cell of a triple-junction stacked solar cell. In this investigation, a-Si n-i-p solar cells were deposited on stainless steel substrates in a multichamber RF PECVD deposition system. Different deposition conditions were explored for the intrinsic a-Si layer with the goal of obtaining high  $V_{oc}$ . After process optimization, we have achieved a  $V_{oc}$  of 1.04 V for a-Si n-i-p solar cells with the intrinsic layer deposited at 150°C at high hydrogen dilution. This  $V_{oc}$  is higher than any  $V_{oc}$  achieved for a single-junction solar cell using a-SiC as the intrinsic layer. This high  $V_{oc}$  a-Si material is a better choice for the top cell i layer of a triple-junction a-Si alloy solar cell than high bandgap a-SiC alloys.

## INTRODUCTION

Energy Conversion Devices, Inc. (ECD) has pioneered the development of high efficiency a-Si alloy solar cells and significantly advanced the development of materials, device designs, and manufacturing processes [1-5]. In ECD's photovoltaic technology, a-Si alloy solar cells are deposited on stainless steel substrate using a triple-junction device structure: SS/metal/metal-oxide back-reflector/a-SiGe bottom cell/a-Si (or a-SiGe) middle cell/a-Si top cell/TCO. Using this device structure, ECD has fabricated a small-area solar cell with 13.7% initial efficiency [3] and 4 ft<sup>2</sup> production modules with 8% stable efficiency [4]. Recently, ECD's joint venture with Canon, United Solar, has achieved a small-area solar cell with 11.2% stable efficiency [6] and a 1 ft<sup>2</sup> PV panel with 10.2% stable efficiency [7]. To further improve the solar cell efficiency, we have studied the top cell deposition process to improve its  $V_{oc}$  so that the blue portion of the solar spectrum is better utilized.

Wide bandgap alloys such as a-SiC material have been extensively studied for use as the intrinsic layer of the top cell of an a-Si alloy triple-junction solar cell in many laboratories [8]. When a-Si is alloyed with carbon, oxygen or nitrogen, its bandgap widens. However, when the bandgap is widened, the absorption of the material decreases. Thicker intrinsic layers (approximately 2000 Å, depending on the alloying ratio) are therefore needed when compared with a-Si top cell intrinsic layer, so that current matching can be maintained in a triple cell. Furthermore, as a-Si is alloyed

with carbon, the density of defect states increases rapidly. As a consequence, a-SiC top cells cannot replace a-Si top cells because the a-SiC top cells are thicker and have higher defect densities.

The bandgap of a-Si can also be widened by increasing the hydrogen content. When the a-Si deposition temperature is lower, the a-Si contains more hydrogen and its bandgap increases. However, when the deposition temperature is reduced to below 200°C, the material quality begins to deteriorate due to the increased void fraction and defect density. Strong hydrogen dilution of the gas mixture during a-Si deposition has been found to reduce the density of defect states and improve the material light stability [9,10]. When a low deposition temperature is combined with high hydrogen dilution during deposition, a-Si materials with wider bandgaps and low electronic defect densities can be achieved [11,12]. We have systematically investigated the growth of a-Si at low temperature with strong hydrogen dilution, and have incorporated this material into a n-i-p top cell to improve the solar cell open circuit voltage. In this paper, we report our studies on the improvement of high  $V_{oc}$  a-Si alloy solar cells.

## EXPERIMENTAL DETAILS

We have primarily used an a-Si n-i-p solar cell devices for the optimization of the a-Si intrinsic layer deposition. The device structure principally used for this study is SS/a-Si n<sup>+</sup>/a-Si intrinsic/ $\mu$ c-Si p<sup>+</sup>/ITO. A bare stainless steel substrate without back-reflector is primarily used in this work, since the top a-Si cell is grown on the middle cell in a triple-cell structure and does not benefit from optical enhancement from the back-reflector. a-Si n, i and p layers are deposited in the dedicated chambers of a multi-chamber load-lock deposition system. The a-Si intrinsic layers were deposited at different substrate temperatures ranging from 150 to 250°C with a wide range of hydrogen dilution, deposition pressure of 1 Torr, and a power density of 20 mW/cm<sup>2</sup>. The p layer is a heavily boron-doped microcrystalline silicon [13]. When such a  $\mu$ c-Si p<sup>+</sup> is used for the p layer, the  $V_{oc}$  of the solar cell is limited mainly by the properties of the intrinsic layer. The ITO layer was deposited using reactive evaporation of an indium-tin alloy in oxygen.

Table 1.  $V_{oc}$  and other solar cell performance data for a-Si n-i-p solar cells deposited on bare stainless steel with the intrinsic layer deposited at different temperatures

Sample No.	Dep. Temp (C)	$V_{oc}$ (V)	$J_{sc}$ (mA/cm <sup>2</sup> )	FF	Thickness of i layer (nm)
712	250	0.951	12.1	0.585	320
723	230	0.959	11.3	0.608	320
722	210	0.980	11.7	0.615	310
731	210	0.986	12.0	0.626	330
732	175	1.026	10.0	0.670	285
746	150	1.040	9.4	0.652	264

## RESULTS AND DISCUSSIONS

In Table 1, we list the solar cell performance we obtained with the intrinsic layer deposited at different temperatures, at an optimized hydrogen dilution for each deposition temperature. When the deposition occurs at low temperature and higher hydrogen dilution, the  $V_{oc}$  of a solar cell progressively increases. At 150°C, a high  $V_{oc}$  of 1.04 V is achieved for an a-Si nip solar cell. This is the highest  $V_{oc}$  reported for any single-junction a-Si solar cell. Figure 1 shows the J-V curve of a 1.04 V  $V_{oc}$  a-Si solar cell device deposited on a bare stainless steel substrate. From Table 1, we also see that the device with 1.04 V  $V_{oc}$  also has a higher FF than a device made in the same system but with an i layer deposited at 250°C.

This indicates the high quality of this a-Si material which was deposited at a low temperature using high hydrogen dilution.

We also deposited a single layer of this optimized intrinsic a-Si material on a Dow Corning 7059 glass substrate for optical measurement. Its transmission spectrum was measured using a Perkin-Elmer spectrophotometer, and from the Tauc plot,  $(\alpha h\nu)^{1/2}$  vs  $h\nu$ , we obtained a bandgap of 1.8 eV. We, therefore, conclude that the intrinsic a-Si material deposited at 150°C with high H dilution does not have a wide bandgap, as one would have expected for an amorphous material that leads to 1.04 V  $V_{oc}$ . We are unable to measure the hydrogen content of this material at this time since the film which was deposited onto a

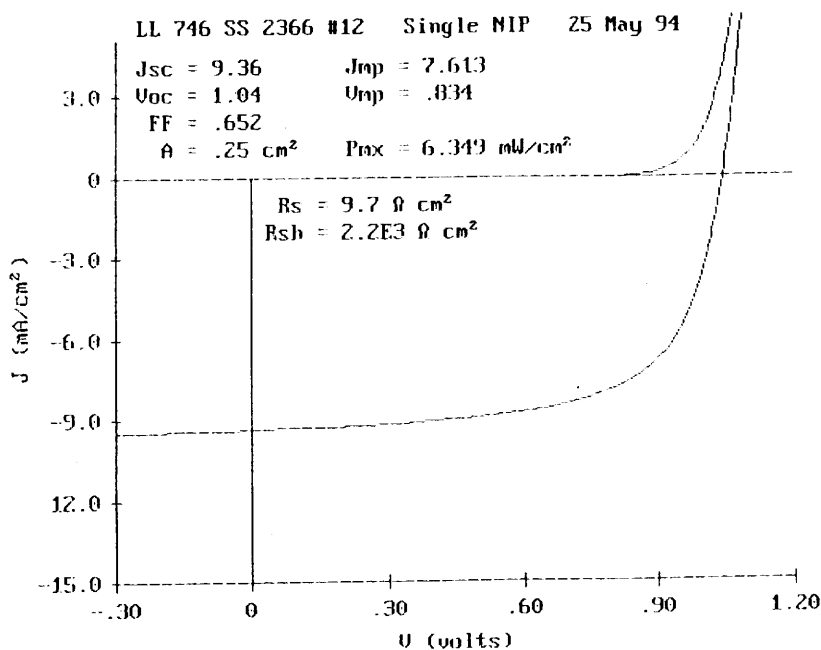


Fig. 1. J-V curve of an a-Si solar cell with the intrinsic layer deposited at 150 C with strong hydrogen dilution, showing 1.04 V open circuit voltage.

crystalline silicon substrate has a tendency to peel, probably due to high compressive stress. Fortunately, this material does not peel when it is deposited on stainless steel substrates.

When the a-Si deposition temperature is reduced, more hydrogen dilution is needed to achieve high quality material. However, when the hydrogen dilution during the a-Si layer deposition increases beyond a certain limit,  $V_{oc}$  as well as other parameters of the solar cell drastically decrease, probably due to the microcrystalline formation. Figure 2 shows the J-V curve of a device with the i layer deposited at 230°C using the high hydrogen dilution optimized for 150°C deposition. One can see that  $V_{oc}$  has dropped to 0.86 V. The FF is slightly higher than for device 723 in Table 1 because it is thinner.

We have also deposited a high  $V_{oc}$  solar cell on stainless steel coated with a textured Ag/ZnO back-reflector. To maintain high  $V_{oc}$ , the p layer was made thicker due to the texture in the under layer. A device with the same i layer as in device 746 demonstrates a  $V_{oc}$  of 0.997 V on this back-reflector. However this drop in  $V_{oc}$  is less critical since in a triple-junction device, the top cell is made on middle and bottom cells.

To demonstrate the improvement in  $V_{oc}$  in a multiple-junction device, we deposited this high  $V_{oc}$  device on a standard a-Si cell to form an a-Si/a-Si tandem device. The complete device structure is: SS/Ag/ZnO/a-Si n-i-p/high  $V_{oc}$  a-Si nip/TCO. Figure 3 is the J-V curve of such a tandem device. As a comparison, we have also deposited a tandem with both intrinsic layers deposited using regular conditions, i.e., 250°C and regular hydrogen dilutions. The J-V curve of the reference sample is shown in Figure 4. By comparing Figure 3 and 4, we find that the  $V_{oc}$  is increased from 1.768 V for the reference tandem, to 1.836 V for the tandem cell with the top cell intrinsic layer made at 150°C with high dilution. The gain in  $V_{oc}$  is around 0.07 V,

similar to the gain in  $V_{oc}$  from device 712 to 746 as shown in Table 1. The slightly lower FF in the first tandem cell is due to different mismatch.

A similar approach to achieving a high  $V_{oc}$  a-Si alloy solar cell using low temperature and high hydrogen dilution has also been used in other laboratories [11,12]. J. Yang et al. of United Solar reported the achievement of single junction solar cell with a  $V_{oc}$  of 1.023 V and a FF of 0.773 with the intrinsic a-Si layer deposited at 175°C and with high hydrogen dilution [11]. They have also found that the solar cell fabricated with this intrinsic layer is relatively more stable after prolonged light soaking.

## SUMMARY

A  $V_{oc}$  of 1.04 V has been achieved in an a-Si solar cell using an a-Si intrinsic layer deposited at relatively low temperature with high hydrogen dilution. Compared to the alternative a-SiC high bandgap intrinsic layer, this a-Si material absorbs light more efficiently and the material quality is higher. We thus conclude that the high  $V_{oc}$  a-Si material is a better choice as the top cell intrinsic layer of a triple-junction a-Si alloy solar cell than high band gap a-SiC alloys.

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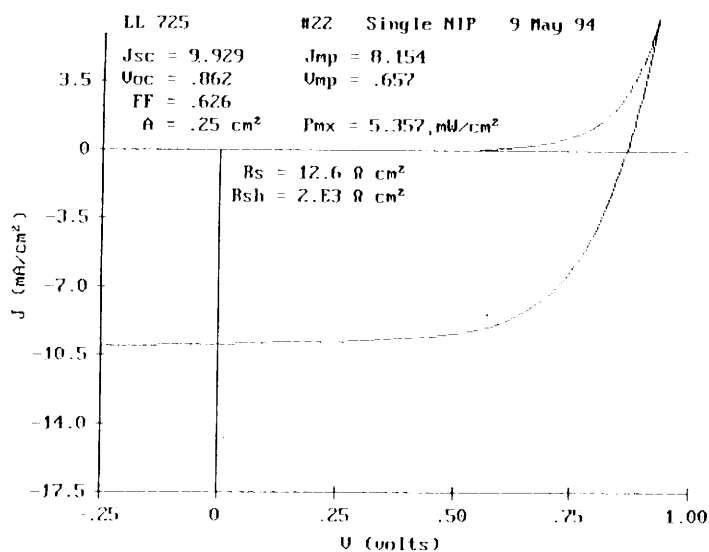


Fig. 2. J-V curve of an a-Si solar cell with the intrinsic layer deposited with the hydrogen dilution exceeding the optimum for the deposition temperature.

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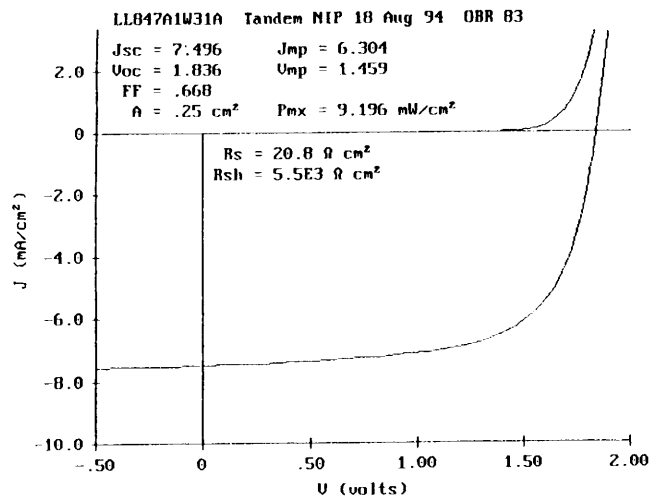


Fig. 3. J-V curve of a tandem device with the high  $V_{oc}$  a-Si top cell.

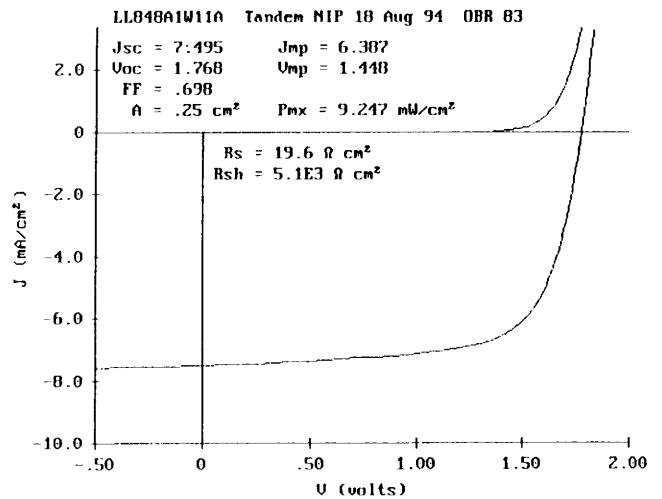


Fig. 4. J-V curve of a tandem device with regular a-Si top cell.