c-Si(n⁺)/a-Si Alloy/Pd SCHOTTKY BARRIER DEVICE FOR THE EFFECTIVE EVALUATION OF PHOTOVOLTAIC PERFORMANCE OF a-Si ALLOY MATERIALS

X. DENG, S. J. JONES, J. EVANS AND M. IZU
Energy Conversion Devices, Inc., 1675 West Maple Road, Troy, Michigan 48084

ABSTRACT

The Schottky barrier device with a metal/a-Si(n⁺)/a-Si alloy/metal structure has been widely used as an alternative evaluation tool for the photovoltaic performance of a-Si alloy material since it more reliably reflects the carrier transport in a solar cell than the conventional material characterization tool such as PDS, CPM, and SSPG, and is easier to be fabricated compared with a complete nip solar cell. However, a multiple chamber device making system is still needed to fabricate such a device since one does not want to deposit the a-Si intrinsic material to be studied together with an n⁺ layer in the same chamber. We have explored the use of a Schottky barrier device deposited on heavily doped n-type crystalline wafer substrate, c-Si(n⁺)/a-Si alloy/metal, as an evaluation tool for a-Si alloy materials. In this device, besides the evaporation of a thin semi-transparent metal layer, only the active a-Si alloy layer needs to be deposited using the plasma enhanced or other deposition techniques. We have compared the performance of such a device with that of reference n-i-p solar cells deposited at the same time and demonstrated that the FF measured under weak red light show a good correlation between these two types of devices. Therefore the c-Si(n⁺)/a-Si alloy/metal device can be used as a convenient technique to reliably evaluate the material performance in a solar cell device.

INTRODUCTION

The deposition of a-Si alloy materials including a-Si, a-SiGe, a-SiC, is often optimized using photoconductivity, photothermal deflection spectroscopy (PDS), constant photocurrent method (CPM), or steady state photocarrier grating technique (SSPG). Recent reports indicate that none of these material characterization tools can reliably predict the performance of a material in a solar cell device.[1-3] An alternate reliable and easy measurement for the photovoltaic properties of materials is therefore desirable.

The fill factor (FF) of an n-i-p (or p-i-n) solar cell device depends sensitively on the optoelectronic properties of the semiconductor materials, in particular the minority carrier diffusion length.[4] It is widely accepted that the FF can be used as one of the most reliable measurements for the quality of intrinsic materials as long as these devices can be fabricated reproducibly and consistently. However, a complete solar cell device must include: an n layer, a p layer, and a TCO layer, as well as the intrinsic layer itself. Therefore, the FF and other device performance parameters depend not only on the i-layer quality but also on the consistency and reproducibility of all the other layers. In addition, many laboratories focusing on materials research do not have device making and characterization facilities.

The metal/a-Si(n⁺)/a-Si alloy/metal Schottky barrier device has been widely used as an alternative evaluation tool for the photovoltaic performance of a-Si alloy material,[5-11] since it

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1) more reliably reflects the carrier transport in a solar cell than the conventional material characterization tool such as PDS, CPM, and SSPG, and 2) is easier to be fabricated compared with a complete solar cell. However, such a device still needs the deposition of an n$^+$ a-Si layer and thus a multiple chamber device making system since one does not want to deposit the a-Si intrinsic material to be studied together with an n$^+$ layer in the same chamber.

In this work, we have studied a new Schottky barrier device with heavily doped n-type c-Si for the back ohmic contact. Such a new test structure greatly improved the convenience for the fabrication, and therefore can be widely used as an evaluation tool for measuring a-Si alloy transport properties.

DEVICE STRUCTURE, FABRICATION AND MEASUREMENT

The structure of the device investigated in this work is: c-Si(n')/a-Si alloy/metal. In this device, a Schottky barrier is formed at the a-Si/metal contact and an ohmic contact was formed at the c-Si(n$^+$)/a-Si contact. The c-Si is heavily phosphorus doped crystalline wafer substrate with resistivity lower than 0.02 Ohmcm. Amorphous Si alloy is the material to be evaluated and the metal layer is a thin palladium layer.

In this device, n$^+$ c-Si rather than n$^+$ a-Si is used as the substrate to eliminate the deposition of n' a-Si. In many laboratories which do not have multichamber PECVD deposition systems, an n' a-Si layer has to be deposited in the same chamber as the a-Si alloy material. Therefore, cross contamination may occur during the deposition of the a-Si alloy intrinsic material. In addition, the performance of a-Si(n')/a-Si(i)/metal also depends on the thickness and doping of the n layer, and may not be easily reproducible between laboratories. After long exposure to air, reconditioning of the n' a-Si surface using chemical or plasma etch may not yield reproducible results. On the other hand, c-Si is a relatively low cost, reproducible, and easily obtainable substrate. Therefore, we selected n' c-Si as the substrate in this study.

We selected a thin palladium metal layer for the semi-transparent Schottky contact as was done in other laboratories. Pd is among the metals that have a high work function. It was reported that the barrier height for a-Si/Pd Schottky contact is 0.9-1.0 Volt.[7] The thickness was controlled such that the thickness monitor in the metal evaporator reads 75-100 A. The thin Pd layer is semi-transparent and light can shine through the Schottky contact for the I-V and spectral response measurements.

In the process of c-Si/a-Si/Pd device fabrication, a 15 mil thick c-Si wafer with resistivity of 0.012-0.02 Ohmcm was used as the substrate. The wafer was polished on one side and the polished side was used for the a-Si alloy layer growth. Before the c-Si substrate is loaded into the chamber for the deposition of the a-Si alloy layer, the c-Si was etched in a buffered HF solution for a few min to remove the surface oxide layer. This was followed by a deionized water rinse and blow dry. After loading, the substrates were baked at 250 C for 30 min and then etched with hydrogen plasma for 2 min.

Together with these c-Si substrates, a set of stainless steel substrates pre-coated with an a-Si n$^+$ layer were also loaded into the system for the deposition of reference nip solar cells. Amorphous Si alloy materials (a-Si and a-SiGe) with different thicknesses were deposited on these substrates at 250 C using PECVD with a gas mixture of H_2, SiH_4, Si_2H_6, and/or GeH_4.

After the glow discharge deposition of the a-Si alloy layer, samples were transferred to a vacuum evaporator for the Pd deposition. An effort was made to minimize exposure of the sample to air to less 10 min. A glass substrate was also loaded into the evaporation system for monitoring the thickness and the optical transmission of the Pd layer. Approximately 50-200 A of Pd was evaporated at 0.2 A/sec at 25 C through a mask to complete the c-Si/a-Si/Pd Schottky barrier device.

While the c-Si/a-Si alloy samples were loaded into the evaporator, the SS/a-Si(n$^+$)/a-Si samples were reloaded back into the p chamber of the multichamber deposition system for the deposition of the µc-Si p$^+$ layer. These nip devices will be used as reference samples for comparison of device performance.

In measuring the I-V characteristics of these devices, we applied a drop of Ag paste at a corner of the Pd film to assure good contact between the probe and the metal film. Another thin Ag paste layer was applied, or Ag metal layer was evaporated on to the other side of the c-Si substrate to improve the probe contact. We then measured I-V curves under various lights to obtain the device FF. As we will show, the FF of Schottky barrier device sensitively reflects the transport quality of the intrinsic layer as in an n-i-p solar cell. Short circuit current can also be obtained after correction with the optical transmission of the Pd layer on glass.

We also measured the I-V curve with 628 nm HeNe laser light since red light is more uniformly absorbed by the a-Si layer and the FF better reflects the bulk transport properties. A lens was placed in front of the HeNe laser tube to broaden the laser light spot. The measurement with HeNe light has several advantages: it is more uniformly absorbed by the material; and the photon flux can be easily calibrated so that the short circuit current and the quantum efficiency can be calculated. In addition, HeNe laser light is usually available in most laboratories.

RESULTS AND DISCUSSION

Figure 1 illustrates the J-V curves of a c-Si(n')/a-Si/Pd with a 2000 A thick i layer measured under a solar simulator (curve 1a), simulator light after red cut-on filter (curve 1b) and a HeNe laser light with a flux of 10^{16} photons/cm^{2}sec (curve 1c). Curves b and c were enlarged by a factor of 10 to fit all three curves in one graph. From curve 1a, the FF is around 0.59. As we will show, the value of this FF depends sensitively on the quality and the of the intrinsic layer. From this curve, one finds that the V_{oc} is 0.47 V, which is typical for a Schottky barrier device with barrier height of 0.9-1.0 V and measured at room temperature. The J_{sc} under simulator light is around 3.5 mA/cm^2., which is lower than that of an nip device with similar intrinsic layer thickness due to the absorption of Pd film and Pd$_2$Si formed at the a-Si/Pd interface.

In order to demonstrate the response of the Schottky barrier device FF to the deposition conditions of the intrinsic a-Si alloy material, we have fabricated c-Si(n$^+$)/a-Si/Pd Schottky barrier devices with different a-Si and a-SiGe intrinsic layers to show the dependence on the intrinsic layer quality and thickness. Along with the fabrication of these devices, a set of reference n-i-p solar cells were fabricated at the same time with the i layer deposition. In Table I, we list the device performance data for all of the Schottky barrier devices and the reference n-i-p solar cells. The first set of data in the top of Table I is for Schottky devices with a-Si

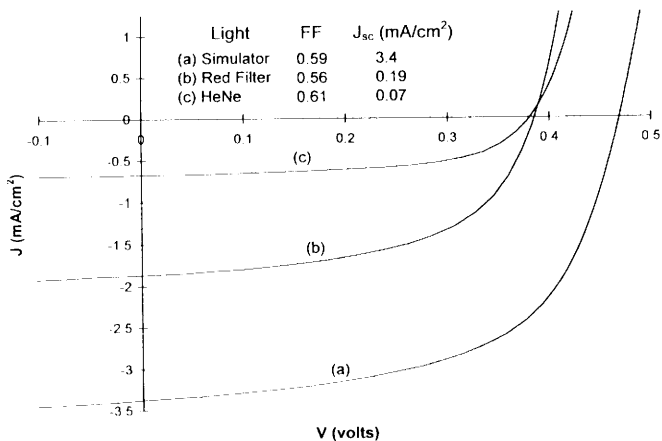| Light	FF	J_{sc} (mA/cm^2)
(a) Simulator	0.59	3.4
(b) Red Filter	0.56	0.19
(c) HeNe	0.61	0.07

Figure 1 J-V curve of a c-Si(n+)/a-Si/Pd Schottky barrier device measured under (a) solar simulator; (b) simulator with red filter; and (c) HeNe laser light. The vertical scale for curve (b) and (c) were enlarged by a factor of 10.

intrinsic layers of different thicknesses and a-SiGe intrinsic layer which is 2000 A thick. The second set of data is for n-i-p devices (n//i//p) which were made with a vacuum break between the layers so that the Schottky barrier devices can be made at the same time. The third set of data is for n-i-p devices made without vacuum break between the deposition of different layers. From Table I, we observe that the FF for all of these devices decreases with increased Ge content in the a-SiGe alloy and with increased thickness of the a-Si layer. The correlation in FF between the Schottky barrier devices and the reference nip devices is consistent.

Compared with the FF measured under the simulator light, the FF measured under a weak red light, such as the HeNe laser light, better reflects the intrinsic layer quality since red light is more uniformly absorbed by the bulk of the intrinsic layer and thus depends less on any possible variations at the interfaces. To better show the correlation, we plot in Figure 2 the FF for the Schottky barrier devices as a function of those for n-i-p devices with the same i layer. For FF measured with both the HeNe light and the simulator light after a red filter, we observe a good correlation. Withthe measured FF for a Schottky barrier device made with a new a-Si alloy material, from Figure 2 one would find out the expected FF of an n-i-p device made with this material. Of course, since the FF for an nip solar cell device depends also on other device layers, such as the p, n, and ITO layers, the relation in Figure 2 should not be extrapolated for devices made at different laboratories. However, the relative change in the FF of Schottky barrier device for materials made with different deposition conditions can be used as a yard stick for the optimization of the intrinsic layer deposition.

The c-Si(n$^+$)/a-Si alloy/Pd Schottky barrier device has several advantages over nip solar cell as an a-Si alloy evaluation tool. It can be easily fabricated. Its FF under weak HeNe light depends less sensitively on the p-i interface, due to the easy formation and good reproducibility of the Pd$_2$Si interface. The use of c-Si(n$^+$) as the substrate minimizes the deposition of other solar cell layers such as p, n and ITO layers, so that a multichamber device

Table I J-V performance of c-Si(n$^+$)/a-Si alloy/Pd Schottky barrier devices and a-Si alloy n-i-p solar cells under the illumination with different lights.

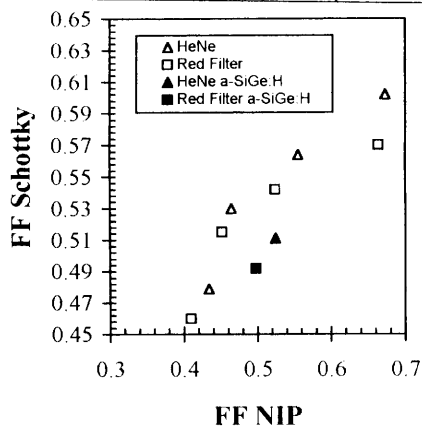| Devices	i-layer thick -ness (Å)	Simulator (100mW /cm2)						HeNe Laser (10^{16} photons /cm2s)		
		FF	Jsc (mA /cm^2)	V$_{oc}$ (V)	R$_s$ (ohms /cm^2)	FF-red (red filter)	FF-blue (blue filter)	FF	Jsc (mA /cm^2)	V$_{oc}$ (V)
c-Si/ a-Si:H/ Pd	2000	0.577	3.5	0.47	20	0.570	0.610	0.602	0.07	0.38
c-Si/ a-Si:H/ Pd	3000	0.536	3.9	0.48	25	0.542	0.580	0.564	0.12	0.39
c-Si/ a-Si:H/ Pd	4000	0.552	4.6	0.49	19	0.515	0.605	0.530	0.15	0.40
c-Si/ a-Si:H/ Pd	5000	0.474	4.5	0.48	37	0.460	0.507	0.479	0.20	0.41
c-Si/ a-SiGe:H/ Pd	2000	0.31	5.1	0.487	16	0.492	0.513	0.511	0.31	0.24
N//I//P a-Si:H	2000	0.594	9.8	0.95	24	0.664	0.720	0.673	0.33	0.82
N//I//P a-Si:H	3000	0.530	10.8	0.95	24	0.524	0.691	0.555	0.52	0.83
N//I//P a-Si:H	4000	0.516	11.2	0.95	16	0.452	0.684	0.464	0.71	0.83
N//I//P a-Si:H	5000	0.493	12.0	0.95	18	0.410	0.669	0.434	0.73	0.82
N//I//P a-SiGe:H	2000	0.484	12.8	0.65	16	0.498	0.630	0.524	1.0	0.54
nip a-Si:H	2000	0.657	11.2	0.95	11	0.655	0.749	-	-	-
nip a-Si:H	3000	0.601	12.1	0.94	8.9	0.570	0.735	-	-	-
nip a-Si:H	4000	0.560	13.0	0.94	9.1	0.503	0.728	-	-	-
nip a-Si:H	5000	0.534	13.3	0.94	9.2	0.415	0.720	-	-	-

Figure 2 Corrrelation between the FF for Schottky barrier devices and those for n-i-p devices with the same intrinsic layer.

making deposition system is not needed for the intrinsic material characterization. The good correlation shown in Figure 2 demonstrates the effectiveness of this new evaluation technique.

SUMMARY

c-Si(n')/a-Si alloy/Pd Schottky barrier device studied here can be used as an evaluation tool for the photovoltaic properties of solar cell materials. Such a device is demonstrated to provide reliable and direct information on the photovoltaic properties. In addition, due to the simplicity of the device structure, it can be fabricated without multichamber solar cell deposition facilities. Such a new device structure can be used for effective optimization of deposition conditions of amorphous silicon alloy materials.

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