Development of High Stable- Efficiency, Triple-Junction a-Si Alloy Solar Cells

**Annual Subcontract Report
July 18, 1994 – July 17, 1995**

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Troy, Michigan

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A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC36-83CH10093

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NREL technical monitor: W. Luft

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Preface

This Annual Technical Progress Report covers the work performed by Energy Conversion Devices, Inc. (ECD) for the period of July 18, 1994, to July 17, 1995, under NREL Subcontract ZAN-4-13318-11 entitled "Development of High, Stable-Efficiency Triple-Junction a-Si Alloy Solar Cells". This research was carried out under the general directions of Mr. S. R. Ovshinsky and Dr. Masat Izu.

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Executive Summary

Objectives

The overall objective of this three-year, cost-shared, amorphous silicon research program is to develop advanced technologies and to demonstrate stable 14% efficient triple-junction a-Si alloy solar cells. The technologies developed in this program will then be incorporated into ECD's continuous roll-to-roll deposition process to further enhance ECD's photovoltaic manufacturing technology.

Technology

In ECD's solar cell design, triple-junction a-Si alloy solar cells are deposited onto stainless steel (SS) substrates coated with Ag/ZnO back-reflector layers. This type of cell design enables us to use a continuous roll-to-roll deposition process to manufacture a-Si PV materials in high volume at low cost. Using this cell design, ECD has previously achieved 13.7% initial solar cell efficiency using the following features: 1) a triple-junction two-bandgap, spectrum-splitting solar cell design; 2) a microcrystalline silicon p-layer; 3) a bandgap profiled a-SiGe alloy as the bottom cell i-layer; 4) a high performance Ag/ZnO back-reflector; and 5) a high performance tunnel junction between component cells. We have also applied the technology into ECD's 2 MW/yr a-Si production line and achieved the manufacturing of 4 ft² PV modules with 8% stable efficiency.

Approaches

In this program, we are further advancing ECD's existing PV technology toward the goal of 14% stable solar cells by performing the following four tasks:

1. Improving the Stability of the Intrinsic a-Si Alloy Materials

Incorporating fluorine into a-Si material improves its stability. It is believed that a small amount of fluorine in a-Si alloy material can be beneficial in terms of passivating dangling or weak bonds. In particular, we have previously demonstrated that the a-Si:H:F material exhibits low defect density after prolonged light soaking compared with unfluorinated a-Si:H made in the same system. Under this task, we are optimizing the deposition process of a-Si:H:F material and demonstrating the improved stability in solar cell devices.

2. Improving the Quality of Low Bandgap a-SiGe Alloy

Under this task, we are optimizing the deposition of a-SiGe alloy to further improve the material quality, especially for low bandgap a-SiGe alloys. The new deposition processes we are investigating includes a-SiGe deposition using a cathode plate with a controlled bias and ion bombardment in an RF PECVD system. The improved narrow bandgap material will be demonstrated in devices.

3. Improving p^+ Window Layers

ECD has previously developed a proprietary $\mu\text{-Si } p^+$ material for the p-layer of a-Si solar cells. Compared to its amorphous counterpart, this $\mu\text{-Si } p^+$ offers high built-in potential due to its small activation energy; low optical loss (due to its wide bandgap) and low electrical loss (due to its low resistivity). In this program, we will attempt to further improve the p^+ layer by appropriately alloying the a-Si p^+ material with oxygen or carbon to widen the bandgap. The optimized $\mu\text{-SiO}$ and $\mu\text{-SiC } p^+$ materials are expected to further improve the transmission of the p-layer and V_{oc} of devices.

4. Development of High Stable Efficiency Triple-Junction a-Si Alloy Solar Cells

Under this task, we will incorporate the developments of Tasks 1 through 3 into triple-junction solar cells to achieve a high stabilized efficiency. We will further optimize other device-related aspects including the tunnel junction, back-reflector, top conductor, interface layer and component cell matching.

Major Accomplishments in Phase I

1. We have demonstrated, in n-i-p solar cells, the improved stability of a-Si:H:F materials when deposited using a new fluorine precursor. Single-junction n-i-p solar cells with 300 nm to 350 nm a-Si:H:F intrinsic layers were deposited onto Ag/ZnO back-reflectors in one of our multichamber deposition systems (LL1). The initial efficiency of the a-Si:H:F devices are around 9%, which is the same as the baseline unfluorinated a-Si:H n-i-p solar cells deposited in this machine. After 1680 hours of one sun light soaking at 50 °C, the a-Si:H:F devices showed a degraded efficiency of around 8%. The degradation in efficiency with light soaking is around 13%, which is lower than the 17% drop for the baseline a-Si:H n-i-p device with a 300 nm thick i-layer after the same amount of light soaking. The improved stability of a-Si:H:F devices meets the Phase I milestone under Task 1.

2. We have investigated a c-Si(n^+)/a-Si alloy/Pd Schottky barrier device for the effective evaluation of photovoltaic performance of a-Si alloy materials. In this device, the intrinsic a-Si alloy materials to be studied are deposited onto a heavily doped n^+ crystalline silicon wafer and a thin layer of palladium (Pd) is subsequently evaporated on top to complete the device structure. The fill factor of such a device under weak red-light reflects the minority carrier transport properties, just as in a real solar cell. We compared the J-V characteristics of these Schottky barrier devices with standard a-Si and a-SiGe n-i-p solar cells having the same intrinsic layer, and established a good correlation between the fill factors of these two type of devices. The c-Si(n^+)/a-Si alloy/Pd device offers a convenient technique to reliably evaluate the material performance in a solar cell device.

3. We have optimized the deposition of the intrinsic a-Si layer and the boron doped $\mu\text{-Si } p^+$ layer to improve the V_{oc} . As a result, a V_{oc} of 1.053 V was achieved for a single-junction a-Si n-i-p solar cell. After 2500 hours of light soaking, the stable V_{oc} of these devices is 1.014 V. This

high V_{oc} is achieved by depositing the intrinsic a-Si layer with high hydrogen dilution at relatively low temperature. The high stable V_{oc} of these devices meets the phase I milestone under Task 3.

4. We designed a novel structure for the p-n tunnel junction (recombination layer) in a multiple-junction solar cell. In this structure, the doping level of the p-layer is graded so that the sublayer near the p-n tunnel junction has heavier doping to reduce the series resistance and the sublayer near the p-i interface has less doping to maintain high V_{oc} . We have demonstrated the improved tunnel junction in the solar cell V_{oc} and FF using an n-i-p-n device structure, which is a standard single-junction n-i-p device with a tunnel junction stacked on top.

5. We have installed, at ECD's expense, a new solar cell deposition system (LL2). After initial optimization, we have achieved a baseline for single-junction a-Si n-i-p devices with 10.6% initial efficiency and baseline for triple-junction a-Si devices with 11.2% initial efficiency.

6. We have collaborated with Harvard University to evaluate the Harvard's cathodically deposited a-SiGe material in n-i-p solar cell devices. These devices were then compared with devices having intrinsic layers deposited using a conventional deposition technique. We did not find any improvement from this cathodically deposited a-SiGe over a-SiGe narrow bandgap material deposited on anode at ECD.

7. We have optimized the deposition parameters of a-SiGe with high Ge content. A bandgap profiled a-SiGe alloy solar cell demonstrates a maximum power output (P_{max}) of 3.6 mW/cm^2 measured under a Xenon solar simulator with a 610 nm cut-on optical filter. After 300 hours of one-sun light soaking, the P_{max} measured with 610 nm filter for this device is stabilized at 2.94 mW/cm^2 , which is higher than the 2.5 mW/cm^2 Phase I milestone under Task 2.

Major Milestones of Tasks Under Phase I

	Task goal	Results	Goal achieved?
Task 1	8% stabilized efficiency for midgap single cell	8% stabilized efficiency for midgap single cell	Yes
Task 2	2.5 mW/cm^2 stabilized P_{max} (610nm) for a-SiGe cell	2.8 mW/cm^2 stabilized P_{max} (610nm) for a-SiGe cell	Yes
Task 3	1.00 V stabilized V_{oc} for wide bandgap cell	1.014 V stabilized V_{oc} for wide bandgap cell	Yes
Task 4	11% stabilized triple-cell	11.2% initial triple-cell Expected to stabilize at 9.5-10% efficiency	No yet achieved

Section 1

Introduction

During the past fifteen years, ECD has pioneered and developed a unique, proprietary a-Si based PV technology embodying several important innovations.¹⁻¹⁵ These include: 1) a record-setting, high efficiency, triple-junction spectrum-splitting thin-film a-Si alloy device structure; and 2) a fully automated roll-to-roll continuous substrate thin-film solar cell manufacturing process.

ECD has achieved in the past 13.7% initial active-area solar cell efficiency⁵ using the following features: 1) a triple-junction solar cell design; 2) a microcrystalline silicon p-layer; 3) a bandgap profiled a-SiGe alloy as the bottom cell intrinsic layer; 4) a high performance Ag/ZnO back-reflector; and 5) a high performance tunnel junction between the component cells. ECD's US PV joint venture, United Solar Systems Corp., recently achieved a 10.2% stable triple-junction a-Si alloy solar panel with over 1 ft² area.¹¹ ECD has achieved 4 ft² production modules with 9.5% initial and 8% stable module efficiencies using a 2 MW continuous roll-to-roll manufacturing line.⁹ All of these have established world records. Under this Amorphous Silicon Research program, we are further advancing this technology to meet long-term efficiency and cost goals set by the Department of Energy.

The overall objective of this three-year, cost-shared, amorphous silicon research program is to develop advanced technologies and to demonstrate stable, 14% efficient, triple-junction a-Si alloy solar cells. The technologies developed in this program will then be incorporated into ECD's continuous roll-to-roll deposition process to further enhance ECD's photovoltaic manufacturing technology.

Specifically, the overall research is divided into four task areas:

- Task 1: Improving the stability of the intrinsic a-Si alloy materials;
- Task 2: Improving the quality of the low bandgap a-SiGe alloy;
- Task 3: Improving the quality of the p⁺ window layer for wide bandgap a-Si alloy solar cells; and
- Task 4: Developing high stable-efficiency, triple-junction, a-Si alloy solar cells.

In ECD's solar cell design, triple-junction a-Si alloy solar cells are deposited onto a SS substrate coated with Ag/ZnO back-reflector layers (see Figure 1-1). This type of cell design enables us to use a continuous roll-to-roll deposition process to manufacture a-Si PV materials in high volume at low cost.

We are primarily utilizing three PECVD systems designated as Load Lock 1 (LL1), Load Lock 2 (LL2), and the Box system to perform deposition of materials and devices. The first two systems are multi-chambered, load-locked systems and the Box system is a single chamber deposition system.

The LL1 deposition system has been primarily used for the study of new materials and device designs (Task 1 and 2). The LL2 system has been primarily use to demonstrate high efficiency

		Grid
ITO		
p3	uc-Si	p
i3	a-Si	intrinsic
n3	a-Si	n
p2	uc-Si	p
i2	a-SiGe	intrinsic
n2	a-Si	n
p1	uc-Si	p
i1	a-SiGe	intrinsic
n1	a-Si	n
ZnO		
Ag		
Stainless Steel		

Figure 1-1 Structure of ECD's triple-junction a-Si alloy solar cell.

solar cells (Task 4). The Box system has been used to study single a-SiGe and p^+ window layers (Task 2 and 3). The development made in the Box system will be incorporated in the Load Lock systems to improve triple-junction cell efficiency.

This report summarizes the main results of the research effort under the phase I of this subcontract. In Section 2, we describe our experimental results that demonstrate improved stability for a-Si:H:F materials. In Section 3, we summarize our collaboration study with Harvard on a-SiGe solar cell using cathodically deposited a-SiGe, and the optimization of a-SiGe deposition using hydrogen dilution. In Section 4 we discuss our research on improving the V_{oc} of wide bandgap solar cells and the achievement of 1.053 V initial and 1.014 V stable open circuit voltage. In Section 5, we describe our efforts to develop μ c-Si alloy materials for use as the solar cell p-layers. In Section 6, we report on our development of a Schottky barrier device for use as a materials evaluation tool for a-Si alloy materials. In Section 7, we describe our research efforts to improve the performance of single-junction solar cells. In Section 8, We describe our optimization study for tunnel-junction deposition. In Section 9, we summarize our work on the development of high stable efficiency triple-junction solar cells.

Section 2

Improving the Stability of the Intrinsic a-Si Alloy Materials

2.1 Introduction

Early research at ECD revealed an improved quality of hydrogenated amorphous silicon (a-Si, also denoted as a-Si:H) by appropriately incorporating fluorine into the material.¹ The beneficial effect is believed to be due to the stronger Si-F bonding which reduces the light-induced degradation, and passivates the weak and dangling bonds.

2.2 a-Si:H:F Materials

To study the effect of fluorine incorporation on the stability of a-Si material, we have recently extended the research and investigated the deposition of fluorinated amorphous silicon (a-Si:H:F) materials using fluorine (F₂) diluted in helium as the source gas.⁸ It was found that this a-Si:H:F material showed a lower stable density of defect states after light soaking when compared with samples deposited in the same reactor without fluorine.

In this study, fluorinated a-Si was prepared with a gas mixture of SiH₄ or Si₂H₆ and F₂ diluted in He at deposition temperatures up to 430 °C. Table 2-1 lists the deposition conditions for a typical a-Si:H:F film (F1) together with two a-Si:H films (H2 and H3) used for reference. Sample H2 was made at the same temperature and with the same gas mixture as sample F1 except without F₂. The high temperature (430 °C) and high negative bias (-150 V) on the substrate are likely to promote F mobility on the growth surface, which consequently leads to high quality material.

Table 2-1. Deposition conditions of a-Si:H:F material using F₂/He and reference a-Si:H material

Sample	Type	Gas Mixture	Pressure (mTorr)	T _s (C)	Power (W)	Bias (V)	Time (min)	Thickness (μm)
F1	a-Si:H:F	Si ₂ H ₆ :F ₂ :He=1:1.7:40	250	430	10	145	300	2.1
H2	a-Si:H	Si ₂ H ₆ :He=2.7	250	430	4	69	40	1.8
H3	a-Si:H	SiH ₄	250	250	2	16	150	2

We light soaked samples F1, H2 and H3 under 800 mW/cm² of white light for 72 hours. The Photothermal Deflection Spectroscopy (PDS) spectra of these three samples before (F1a, H2a, H3a) and after (F1b, H2b, H3b) light soaking are shown in Figure 2-1. The density of defect

states (N_s), calculated from PDS absorption spectra are also given in Figure 2-1. Although the density of defect states of sample F1 is higher than sample H3 in the initial state, the defect density of sample F1 is the lowest among the three samples in the final state. The low stable defect density in a-Si:H:F is possibly due to the strong passivation of dangling bonds and weak bonds by fluorine. Since F is the most electronegative of the elements, it bonds to Si almost twice as strongly as H. When properly incorporated, F can replace weakly bonded H and passivate dangling and weak bonds more efficiently. Structural changes due to the enhanced film surface etching with F during deposition might also be the cause for improved material stability.

2.3 a-Si:H:F Solar Cell Device Deposited Using F_2/Ne as a Source Gas

We have studied the deposition of a-Si:H:F material using F_2 diluted in inert gases such as argon, neon, and helium. However, when F_2 diluted Ar (F_2/Ar) is used, the growth surface suffers a heavy bombardment from the Ar ions during deposition. On the other hand, the use of He as a source gas make the leak detection of the vacuum system more difficult. Therefore, neon is used as a fluorine diluent for the deposition of a-Si:H:F material.

A series of single-junction a-Si:H:F n-i-p devices were deposited in the LL1 system using F_2/Ne as the fluorine source gas. This deposition system consists of six chambers: a load chamber, an n chamber, a p chamber, an i chamber for the standard intrinsic layer deposition, a semi-i chamber for miscellaneous research studies including the a-Si:H:F study, and a transfer jar at the center for substrate-holder transportation. In this system, all of the chambers are isolated by gate valves to minimize cross contamination. The n-i-p structures are deposited onto bare SS or SS/Ag/ZnO substrates. The Ag/ZnO back reflector layers were deposited previously in ECD's continuous roll-to-roll back-reflector sputtering machine.

As in standard cell fabrication, ITO top contacts are reactively evaporated onto the existing SS/n-i-p structures. Ag grids are then evaporated onto the ITO using a separate evaporator to complete the device.

We have deposited a-Si:H:F devices with 300 nm thick intrinsic layers. These devices were deposited using a variety of conditions including different F_2/Ne flow rates, different deposition temperatures for the i-layer, and with and without the a-Si buffer layers on both sides of the a-Si:H:F i-layer. As a result, we found that all of the fluorinated devices in this group showed lower conversion efficiency compared with the unfluorinated standard a-Si:H n-i-p devices. The light soaking degradation of these a-Si:H:F devices does not exhibit an improvement from that of a-Si:H devices either. Therefore, adding F_2/Ne into the gas mixture does not seem to produce material with improved stability compared with standard glow discharge deposited a-Si:H.

We have analyzed the intrinsic material deposited using F_2 as the source gas. There is about 0.5 to 1% oxygen in these a-Si:H:F materials as measured by Auger and Wavelength Dispersive Spectroscopy. This unwanted oxygen may be incorporated into the material from the F_2 gas source. According to the gas analysis report, the purity of F_2 was 97.5% before it was mixed with Ne. In the 2.5% contamination of F_2 gas, there is a significant amount of oxygen, which may be responsible for the oxygen contamination in the a-Si:H:F films deposited using F_2/Ne .

Figure 2-1 PDS spectrum of a-Si:H:F and a-Si:H thin films before and after light soaking

Unfortunately, F_2 with 97.5-98% purity is the purist F_2 gas available on the market. It is also known from the study of Knight et al.¹⁶ that the addition of Ne to the gas plasma can lead to the formation of columnar film microstructure and the possibility of oxygen being incorporated upon exposure to air. This may also be why the films made with F_2/He seems to be better than those made with F_2/Ne .

2.4 a-Si:H:F Devices with Improved Stability Using New Fluorine Precursor

In order to reduce the contamination induced from the source gas, we identified a new fluorine precursor with 99.99% purity. This new precursor can be mixed with hydrogen for dilution, and it produces only atomic fluorine in plasma rather than silicon fluoride radicals. Therefore, fluorine would preferably bond to silicon in monofluoride form.

n-i-p solar cells, with this a-Si:H:F intrinsic layer, were deposited on SS/Ag/ZnO back-reflectors in the LL1 deposition system. The n- and p-layers were standard doped layers for single-junction devices. The a-Si:H:F intrinsic layers were deposited under the following conditions:

Gas mixture:	52 sccm H_2 , 1.5 sccm of Si_2H_6 , and 0.1 sccm of fluorine precursor
Temperature:	300°C
Power:	5 Watt
Pressure:	600 mTorr
Time:	22 min. at a deposition rate of 0.23 nm/sec.

The a-Si:H:F layer thickness is around 300 nm. Figure 2-2(a) is the J-V curve of such an a-Si:H:F single-junction solar cell before light soaking. Figure 2-2(b) is the same device measured under weak blue and red light. The initial solar cell efficiency is 9.0%, which is approximately the same as the efficiency for the baseline a-Si:H device deposited in this deposition system.

We have light-soaked this a-Si:H:F single-junction solar cell device under one sun light at 50 °C. After 1680 hours of light soaking, the solar cell showed a degraded efficiency of 8.0%, representing a 12 % drop in efficiency with light soaking. Figure 2-3a is the J-V curve for this device under AM1.5 light after 1680 hours of light soaking. Figure 2-3b is the J-V curve under weak blue and red light after 1680 hours of light soaking. Table 2-2 lists the J-V data after each light soaking step for this a-Si:H:F device. From the table, we find that the degradation has already come to a saturation point after 97 hours of light soaking.

In comparison, unfluorinated a-Si:H n-i-p solar cells, deposited in the same reactor with similar deposition conditions, show relatively higher degradation after similar light soaking. For example, the baseline a-Si:H single-junction solar cells without fluorine also have initial efficiency of 9% for this deposition system. The light soaking degradation after 1000 hours is typically 16-20% for devices with 300 nm thick intrinsic a-Si:H layers. Table 2-3 lists the light soaking data of the a-Si:H:F device and the a-Si:H reference device. From these data, we conclude that the fluorine incorporation into these a-Si:H:F films has led to improved stability.

LL945A1W32A Single NIP 5 Jan 95 F2,0BR83

Figure 2-2a J-V curve of a-Si:H:F device before light soaking measured under AM1.5

Figure 2-2b J-V curve of a-Si:H:F device measured under weak blue and red light.

Figure 2-3a J-V curve of a-Si:H:F device after 1680 hours of one sun light soaking at 50 °C.

Figure 2-3b J-V curve of a-Si:H:F device after 1680 hours of light soaking measured under weak blue and red light.

Table 2-2 Solar cell data of an a-Si:H:F devie (LL945) after different light soaking steps under one sun at 50°C

Light Soaking	Substrate	Dot	V _{oc} (v)	J _{sc} (mA/cm ²)	FF	Eff	FF _b	FF _r
0 hrs.	SS	32	0.937	10.23	0.625	5.99	0.738	0.625
0 hrs.	BR	22	0.932	15.37	0.638	9.14	0.744	0.661
0 hrs.	BR	24	0.934	14.49	0.642	8.69		
0 hrs.	BR	32	0.931	15.16	0.636	8.89	0.741	0.663
0 hrs.	BR	33	0.931	15.05	0.637	8.93	0.738	0.664
97 hrs.	BR	32	0.897	14.89	0.596	7.96	0.679	0.595
384 hrs.	BR	11	0.896	15.12	0.589	7.97	0.676	0.589
384 hrs.	BR	12	0.896	14.91	0.589	7.87	0.673	0.585
384 hrs.	BR	13	0.897	14.33	0.59	7.58	0.678	0.589
384 hrs.	BR	22	0.896	15.1	0.592	8.01	0.671	0.589
384 hrs.	BR	23	0.897	14.72	0.591	7.8	0.677	0.591
384 hrs.	BR	31	0.897	15.54	0.596	8.3		
384 hrs.	BR	41	0.897	15.15	0.597	8.12	0.68	0.595
384 hrs.	BR	43	0.897	14.42	0.592	7.66	0.671	0.591
1056 hr	BR	11	0.885	15.13	0.592	7.92	0.672	0.59
1056 hr	BR	12	0.885	14.91	0.589	7.77	0.674	0.587
1056 hr	BR	22	0.883	15.05	0.589	7.82	0.672	0.591
1056 hr	BR	31	0.883	15.45	0.594	8.1	0.666	0.583
1056 hr	BR	43	0.888	14.43	0.592	7.59	0.676	0.59
1680 hr	BR	11	0.888	15.03	0.588	7.85	0.672	0.584
1680 hr	BR	12	0.886	14.9	0.59	7.78	0.667	0.584
1680 hr	BR	22	0.887	15.15	0.589	7.92	0.671	0.587

Table 2-3 Comparison of the light soaking degradation of an a-Si:H:F single-junction solar cell and an a-Si:H reference single-junction solar cell

Solar cell i-layer	Light soaking	V_{oc} (V)	J_{sc} (mA/cm ²)	FF	Eff (%)	Drop in Efficiency
a-Si:H:F on Ag/ZnO	0 hrs	0.932	15.37	0.638	9.14	-----
	380 hrs	0.896	15.10	0.592	8.01	12.3%
	1680 hrs	0.887	15.15	0.589	7.92	13.3%
a-Si:H on SS	0 hrs	0.951	10.86	0.601	6.21	-----
	380 hrs	0.916	10.29	0.554	5.22	15.9%
	620 hrs	0.910	10.38	0.550	5.20	16.3%

2.5 Discussion

Having demonstrated the improved stability of a-Si:H:F devices, an important question that needs to be answered is: what is the function of fluorine and how much fluorine is actually in these films? To answer these questions, SIMS measurements were used to identify the amount of fluorine in these samples. Figure 2-4 is the SIMS analysis depth profile measured at Evans East, Inc. for the a-Si:H:F device which showed an 8% stable efficiency. To our surprise, the amount of fluorine in this film is only on the order of $1.0 \times 10^{18}/\text{cm}^3$. A sample made without fluorine precursor in the gas mixture shows a small fluorine concentration of about $5 \times 10^{17}/\text{cm}^3$, which may have been incorporated from the walls of the deposition chamber that was also used to deposit the a-Si:H:F materials.

There could be three mechanisms in which fluorine in the gas plasma improves material stability: 1) fluorine incorporation reduces the amount of weak bonds; 2) fluorine incorporation reduces dangling bonds; and 3) etching from fluorine plasma helps to produce a denser amorphous material which is more stable.

Since we have seen a concentration of only $1.0 \times 10^{18}/\text{cm}^3$ fluorine in the device demonstrating this improved stability, the majority of weak bonds would not have a fluorine nearest neighbor. If the weak bond reduction case holds true, it would have to be an indirect result of the conditions surrounding material growth rather than the chemical composition of the material. Therefore, it is more likely that the improved stability in the a-Si:H:F is from a reduction in dangling bonds and/or production of a denser material from etching of fluorine plasma.

2.6 Summary

Appropriate incorporation of fluorine into the a-Si:H material has improved its stability. This improvement is demonstrated in solar cell devices. The amount of fluorine found in the more stable material is on the order of $1.0 \times 10^{18}/\text{cm}^3$. It is likely that the use of fluorine improves the materials stability through 1) dangling bond reduction, and/or 2) fluorine plasma etching which produces a denser material with higher stability.

29 Jun 95

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Figure 3

Figure 2-4 SIMS analysis depth profile of an a-Si:H:F device.

Section 3

Amorphous SiGe Narrow Bandgap Materials and Devices

3.1 Introduction

ECD has pioneered the development of high quality low bandgap a-SiGe and developed proprietary deposition conditions to produce high quality a-SiGe with a 1.4 eV to 1.5 eV bandgap. This material was used to achieve 13.7% initial efficiency for triple-junction a-Si alloy solar cells.

To better utilize the long wavelength part of the solar spectrum and achieve a higher efficiency multiple-junction a-Si alloy solar cell, we need to develop a higher quality material with still lower bandgap for the bottom cell intrinsic layer. In particular, a 1.3 eV bandgap alloy with properties that are at least comparable with those for the current 1.5 eV alloy is desired.

The deterioration in the material and cell properties with increased Ge content beyond 20 at. % is well documented. However, improvements in the properties of a-Ge and Ge-rich a-SiGe alloys with increased ion bombardment of the growing surface have been suggested. In particular, Aoki et al.¹⁷ using an ECR microwave plasma process found that the optoelectronic properties of a-Ge are improved when a negative bias of around 150 V is applied to the substrate. Also, Paul et al.¹⁸ of Harvard University and Karg et al.¹⁹ from Siemens have found that a-Ge and Ge-rich a-SiGe alloys deposited on the cathode has much better optoelectronic and structural properties. In the case of a-Ge, the photoconductivity of this material deposited on the cathode is two orders of magnitude better ($\eta\mu\tau = 3 \times 10^{-7} \text{ cm}^2/\text{V}$) and the density of defect states is one magnitude lower ($N_s = 5 \times 10^{16} / \text{cm}^3$ and at 0.7 eV $\alpha = 8.3 \text{ cm}^{-1}$) than the best a-Ge deposited on the anode, the electrode which is typically used for device quality a-Si. While not proven, it has been speculated that the improved properties are a result of the relatively high amount of ion bombardment of the cathode surface.

While it does seem that the material properties for Ge-rich a-SiGe alloys are improved with some amount of ion bombardment, these types of alloys have yet to be incorporated into a device. Thus in terms of solar cell use, they have not been truly tested. As part of our work, we have begun a collaborative effort with the Harvard group to incorporate their a-SiGe into n-i-p devices. Several devices have been made and the results are discussed below.

3.2. Collaboration with Harvard to Demonstrate the Cathode Deposited a-SiGe in Solar Cells

Using n- and p-layers produced at ECD using the LL1 system, several devices have been made using Harvard's alloy as the i-layer. The exact procedure followed in making these devices is listed below:

- 1) n-layers were deposited on SS substrates at ECD using LL1;

- 2) the day after n-layer deposition, a-SiGe i-layers were grown at Harvard. (In some cases, a thin a-Si buffer layer was then deposited without breaking vacuum);
- 3) on the third day, the i-layer/buffer layer surface was “cleaned” using a short hydrogen plasma etch and a p-layer was then deposited, again using LL1 at ECD; and finally
- 4) ITO/Ag contacts were deposited and the cells were measured at ECD.

We found that it was not necessary to etch the n-layer surface prior to depositing the i-layers. To test the effects of exposing each layer to air prior to the next deposition, we made two a-SiGe devices under nominally the same conditions except in one case each layer was exposed to air prior to the next deposition, while for the other device the n-i-p section was made without breaking vacuum. The cell performances for both of these devices are shown in table 3-1. These devices were made without a full scan of deposition parameter space to find the optimum conditions for a $V_{oc} = 0.45$ V device prepared in this particular system. With the air exposure, slightly lower J_{sc} , V_{oc} and FF are obtained. However, the FF measured using weak red light (FF_r), a parameter typically used to judge bottom cell i-layer quality, is similar for both of the devices. Thus, we chose to use FF_r as a measure of the quality of the Harvard material.

Table 3-1a-SiGe devices made with and without air exposure after each layer deposition

Run Number	Air Exposure ?	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	FF_r	Pmax (mW/cm ²)
LL986	No	14.3	0.46	0.39	0.45	2.5
LL996	Yes	13.3	0.43	0.37	0.45	2.0

The properties for the cells made with the Harvard a-SiGe material are listed in Table 3-2. For comparison, data for a device (LL 996) made in LL1 with a $V_{oc} = 0.45$ V are also included in the table. During the preparation of this device, it was exposed to air overnight after both the n and i-layer depositions to mimic the conditions the Harvard samples were prepared under. For all of the devices listed in the table, the i-layer thicknesses were measured and found to be between 150 and 200 nm. As can be seen from the table, devices with two different bandgaps were made, with and without buffer layers. While these parameters were varied, no discernibly large differences in FF_r can be seen between the data for the Harvard and ECD prepared devices. Since the conditions used for making the ECD device may not have been optimum, larger FF_r may be obtainable for Ge-rich devices made on the anode.

Table 3-2 J-V Properties for n-i-p solar cells made with Harvard a-SiGe material

Devices	E_g (eV)	Buffer Layer?	V_{oc} (V)	FF_r
Harvard 483A	1.4	No	0.42	0.39
Harvard 483D	1.4	No	0.44	0.39
Harvard 485A	1.4	No	0.42	0.38
Harvard 485D	1.4	No	0.45	0.41
Harvard 498	1.4	No	0.44	0.43
Harvard 502	1.4	Yes	0.50	0.41
Harvard 501	1.5	No	0.53	0.45
Harvard 500	1.5	Yes	0.55	0.44
ECD LL996	-	No	0.43	0.45

The fact that the devices prepared on the cathode do not have significantly larger FF_r than those for anode deposited cells is consistent with the rather average hole transport properties for the Harvard material. Ambipolar diffusion lengths of 60-70 nm were obtained at Harvard for the cathode deposited material, assuming a surface recombination velocity of zero. If a surface recombination velocity of infinity is assumed, one obtains diffusion lengths from 130 to 170 nm. Since the cell performance for a-Si devices are limited by the hole transport, we have little hope of preparing superior devices by straight incorporation the Harvard material into a cell structure.

However, by slightly doping the i-layer material to improve the hole transport, the electron transport may still be adequate enough, considering that it is so good in the intrinsic material, to prepare superior devices. The Siemens group has reported improvements in their devices made with cathode deposited a-Ge when they slightly dope the i-layers with boron.²⁰ Besides collaboratively studying the effects of doping over the next year, we may also try to incorporate Ge grading schemes to the i-layers to further enhance hole transport.

3.3 Optimization of a-SiGe Bottom Cell

After we installed the new LL2 deposition machine, we optimized the deposition of narrow bandgap a-SiGe solar cells using techniques previously developed at ECD.⁷ Three bandgap profile schemes: 1) a flat bandgap, 2) a graded bandgap with an a-Si buffer layer, and 3) a double graded

bandgap with a-Si buffer layers, as shown in Figure 3-1, were used to optimize the a-SiGe deposition conditions.

For the flat bandgap a-SiGe solar cells, three devices with different Ge concentrations in the i-layer were fabricated on both bare SS and SS/Ag/ZnO substrates. Table 3-3 shows the i-layer deposition conditions and solar cell performance. As expected, when the Ge concentration increases, the solar cell J_{sc} increases, while V_{oc} and FF decrease at the same time. When the GeH_4 to Si_2H_6 ratio is about 50:50 (sample L2101), the FF drops down to around 0.55. However, without enough Ge in the i-layer, the J_{sc} is only around 17 mA/cm² (see sample L2103). Therefore, none of the three devices would be a good candidate as the bottom cell of a triple-junction solar cell.

Table 3-3 Device performances of three a-SiGe solar cells with different Ge contents in the i-layer deposited on SS and BR substrates

Run #	i-layer gas $GeH_4/Si_2H_6/H_2$	Substrate	V_{oc} (V)	J_{sc} (mA/cm ²)	FF	R_s (Ω -cm ²)	Eff (%)
L2101	1.5/1.5/54.0 (50:50)	SS	0.574	14.48	0.547	9.4	4.55
		BR	0.552	19.13	0.553	5.5	5.83
L2103	0.82/1.0/33.1 (45:55)	SS	0.674	13.68	0.597	7.3	5.51
		BR	0.667	17.11	0.574	5.9	6.55
L2106	0.68/1.0/30.6 (40:60)	SS	0.708	12.16	0.640	6.1	5.51
		BR	0.689	15.84	0.606	5.5	6.62

We then fabricated three single-junction a-SiGe devices with different degrees of bandgap grading (see Figure 3-1b). During the a-SiGe i-layer deposition, the Si_2H_6 flow was fixed, while the GeH_4 flow was increased linearly. The highest Ge content, hence the smallest bandgap, is near the p-i interface. The graded bandgap results in a majority of the carriers being generated near the p-layer so that the average distance that holes travel before collection is less. In addition, it generates an internal field which helps holes to drift towards the p-layer. Approximately 20 nm thick a-Si buffer layers were deposited on both sides of this a-SiGe layer to ensure good interfaces. Table 3-4 shows the device performance of these a-SiGe solar cells measured under AM1.5 light and Table 3-5 shows the device performance of these a-SiGe solar cells measured under AM1.5 light with a 610 nm cut-on filter, i.e., a red filter to simulate the absorption of the top and middle component

(a)

(b)

(c)

Figure 3-1 Bandgap grading profiles investigated during Phase I for a-SiGe narrow bandgap solar cells.

cells in a triple-junction solar cell. Among the three devices, sample L2230 shows the highest $P_{\max}$. The one sun $P_{\max}$ is 8.2 mW/cm^2 and the $P_{\max}$ after 610 nm red filter is 3.66 mW/cm^2 . Figure 3-2 shows the J-V curve of this single-junction a-SiGe solar cell measured under the xenon solar simulator with a 610 nm red filter.

Table 3-4 Device performance of a-SiGe solar cells with different bandgap grading in the a-SiGe i-layer, measured under AM 1.5 light

Run #	$\text{Si}_2\text{H}_6/\text{GeH}_4$ (5 sccm)	i-layer thickness (nm)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	R_s (Ωcm^2)	$P_{\max}$ (mW/cm^2)
L2230	1.0/0.68-1.00	185	0.699	20.40	0.599	5.7	8.17
L2156	1.0/0.54-1.22	196	0.612	19.01	0.531	9.4	6.18
L2187	1.5/1.20-2.00	169	0.620	19.86	0.525	8.5	6.47

Table 3-5 Device performance of a-SiGe solar cells with different bandgap grading in the a-SiGe i-layer, measured under AM 1.5 light with a 610 nm cut-on filter

Run #	$\text{Si}_2\text{H}_6/\text{GeH}_4$ (sccm)	i-layer thickness (nm)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	R_s (Ωcm^2)	$P_{\max}$ (mW/cm^2)
L2230	1.0/0.68-1.00	185	0.639	9.14	0.627	9.6	3.66
L2156	1.0/0.54-1.22	196	0.569	8.18	0.548	16.4	2.55
L2187	1.5/1.20-2.00	169	0.594	8.55	0.560	14.9	2.84

L223044U11D Single NIP 28 Nov 95 L-SOHS 610NM

Jsc = 9.142 Jmp = 7.451

Voc = .639 Vmp = .491

FF = .627

A = .25 cm² Pmax = 3.661 mW/cm²

Rs = 9.6 Ω cm²

Rsh = 1.2E3 Ω cm²

J (mA/cm²)

U (volts)

Figure 3-2 J-V curve of a single-junction a-SiGe narrow bandgap solar cell measured under AM1.5 light with a 610 nm red filter.

We have also fabricated a-SiGe devices with i-layers deposited at different substrate temperatures. Table 3-6 shows two devices having a-SiGe i-layers deposited at 250 and 300 °C. The device deposited at higher temperature has a higher fill factor indicating a superior quality a-SiGe material as has been suggested previously.²¹ This higher substrate temperature enhances the surface mobility of Ge atoms during growth, and consequently improves the material's quality.

Table 3-6 Device performance of a-SiGe solar cells with i-layer deposited at different temperatures

Run #	T _s (°C)	i-layer thickness (nm)	V _{oc} (V)	J _{sc} (mA/cm ²)	FF	R _s (Ωcm ²)	P _{max} (mW/cm ²)
L2257	250	210	0.688	20.39	0.554	8.7	7.78
L2230	300	185	0.669	20.40	0.599	5.7	8.17

To further improve the a-SiGe bottom cell, we deposited a-SiGe cells with a double graded profile as shown in Figure 3-1(c). Figure 3-3 shows the J-V curve for such a device (L2241) measured under the simulator with a 610 nm filter. The results are similar to those for L2230. Therefore, both profiles (b) and (c) in Figure 3-1 can be used to fabricate narrow bandgap a-SiGe bottom cells.

We have light soaked a representative device from each of the three group of samples having different bandgap profiles. Table 3-7 lists the light soaking performance measured with a 610 nm filter after each light soaking step. After 300 hours of one-sun light soaking, the a-SiGe devices with optimized bandgap profiles and deposition conditions have a degraded P_{max} of around 2.94 mW/cm², as is shown in Figure 3-4.

3.4 Optimization of a-SiGe Middle Cell

When a-Si is used as the middle cell i-layer of a triple-junction solar cell, the i-layer needs to be at least 450 nm thick to achieve component cell current matching. Such a cell shows large light soaking degradation. In order to improve triple-junction solar cell light stability, a middle cell with relatively thinner a-SiGe was optimized in the LL2 deposition system.

Table 3-8 shows the deposition temperature and GeH₄ and Si₂H₆ gas flows for three a-SiGe middle component cells deposited on SS. A J_{sc} of 14 mA/cm² is needed for such a device on SS substrate to achieve current matching. Among this group of samples, L2184 shows the highest

Figure 3-3 J-V curve of an a-SiGe solar cell with double graded bandgap profile, measured under AM1.5 light with a 610 nm red filter.

L2241A4W13E Single NIP 13 Dec 95 L-S 308 HRS 610NM

$J_{SC} = 9.488$ $J_{mp} = 7.499$
 $V_{OC} = .588$ $V_{mp} = .392$
 $FF = .527$
 $A = .25 \text{ cm}^2$ $P_{max} = 2.936 \text{ mW/cm}^2$

$R_s = 17.5 \Omega \text{ cm}^2$
 $R_{sh} = 7.2E2 \Omega \text{ cm}^2$

Figure 3-4 J-V curve of an a-SiGe solar cell after 300 hours of one sun light soaking at 50 °C, measured under AM1.5 light with a 610 nm red filter.

$P_{\max}$ and is therefore used as the standard middle cell i-layer. Figure 3-5 is an initial J-V curve of an a-SiGe middle component cell.

Table 3-7 $P_{\max}$ measured under AM1.5 light with 610 nm filter for a-SiGe solar cells with different bandgap grading profiles, after different light soaking times

Light Soaking Time (hr)	$P_{\max}$ (mW/cm ²)		
	L2106 (a)	L2230 (b)	L2241 (c)
0	2.56	3.66	3.63
300	2.13	2.89	2.94
1000	2.01	(*)	(*)

(*) Not available yet.

Table 3-8 Deposition conditions and device performance of a-SiGe middle component cells deposited on SS

Run #	T_s (°C)	$\text{Si}_2\text{H}_6/\text{GeH}_4$	i-layer thickness (nm)	V_{oc} (V)	J_{sc} (mW/cm ²)	FF	R_s (Ωcm^2)	$P_{\max}$ (mW/cm ²)
L2163	250	1.5/0.270	300	0.889	13.58	0.596	12.3	7.20
L2165	250	1.5/0.375	270	0.827	13.63	0.619	9.0	6.98
L2184	300	1.5/0.375	300	0.849	14.82	0.581	9.4	7.31

3.5 Summary

We have studied and evaluated the a-SiGe material deposited at Harvard on the cathode plate using n-i-p solar cells. These solar cells did not show better performance than cells with a-SiGe i-layers having similar bandgap deposited at ECD on anode.

L2184A1W41A Single NIP 30 Aug 95 S.SSI/GE IT03271

Figure 3-5 J-V curve of an a-SiGe cell being used as the middle component cell of a triple-

We have optimized the deposition of a-SiGe solar cells with different bandgap grading profiles and with different deposition conditions. Both narrow and middle bandgap a-SiGe cells have been improved in the LL2 system. The optimized a-SiGe narrow bandgap solar cells show a stabilized $P_{\max}$ of 2.94 mW/cm^2 , measured after a 610 nm red filter, after 300 hours of one-sun light soaking at 50°C . These devices are expected to have stabilized $P_{\max}$ higher than 2.5 mW/cm^2 , which is the Phase I goal under Task 2.

Section 4

Wide Bandgap Solar Cells

4.1 Introduction

The open circuit voltage (V_{oc}) of a-Si single-junction solar cell with $\mu\text{c-Si}$ p-layer⁶ deposited in our laboratory is normally in the range of 0.93-0.96 V. In an effort to optimize the top component cell for a triple-junction solar cell, we realized that the major limitation to the V_{oc} is not the p-layer but the intrinsic a-Si layer. We have therefore launched a study to improve the V_{oc} of the single-junction a-Si top cell by improving the a-Si intrinsic layer deposition conditions.

Wide bandgap alloys such as a-SiC 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.²² 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 200 nm, 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-junction 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 i-layers need to be thicker and have higher defect densities.

Thus, it may be more beneficial to widen the bandgap by increasing the hydrogen content in the a-Si cells.^{23,24} It has been shown that this can be done by lowering the substrate temperature. In addition, to maintain a reasonable film quality, the amount of hydrogen dilution usually has to be raised as the temperature is lowered. Other laboratories have used these conditions to prepare high V_{oc} a-Si solar cells.^{25,26} It has also been found that the solar cells fabricated with this intrinsic layer are relatively more stable after prolonged light soaking. We have systematically investigated the growth of a-Si at low temperature with strong hydrogen dilution, and have incorporated this material into an n-i-p top cell to improve the solar cell open circuit voltage.

4.2 Experimental Details

We have primarily used an a-Si n-i-p solar cell device for the optimization of the a-Si intrinsic layer deposition. The device structure principally used for this study is SS/a-Si n^+ /a-Si intrinsic/ $\mu\text{c-Si}$ p^+ /ITO. A bare SS substrate without back-reflector is principally 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, a deposition pressure of 1 Torr, and a power density of 20 mW/cm². The p-layer is heavily boron-doped microcrystalline silicon.⁶ When such a $\mu\text{c-Si}$ p^+ is used for the p-layer, the V_{oc} of the solar cell is limited mainly by the properties of the intrinsic layer. As is usually done, the ITO layer was deposited using reactive evaporation of an indium-tin alloy in oxygen.

4.3 Results and Discussions

In table 4-1, we list the solar cell performance for single-junction a-Si devices made with heavily H₂ diluted plasmas at different substrate temperatures. All of these devices were deposited on bare SS with no back reflector. The progressive increase in V_{oc} with the decreasing substrate temperature is apparent. At 150 °C, a high V_{oc} of 1.04 V is achieved. After further improving the deposition process, we have achieved cells with initial V_{oc} of 1.053 V. The J-V curve for such a device is shown in Figure 4-1. This 1.053 V value is the highest V_{oc} reported for any single-junction a-Si solar cell. The FF for the 1.05 V device is high, indicative of a high quality a-Si i-layer material. As the substrate temperature is lowered beyond 150 °C, the cell properties dramatically deteriorate, possibly due to polysilicon chain or microcrystalline formation. We should note that in terms of FF the material deposited at the higher substrate temperatures were not made under optimum conditions. Less hydrogen dilution and different RF powers are typically used when $T_s \sim 230$ -250 °C. Also to obtain the high V_{oc} cells with the optimum cell properties, the p-layer preparation conditions were correspondingly adjusted.

Table 4-1 Cell performance for devices made at different substrate temperatures with high hydrogen dilution

Cell Number	Substrate Temperature (°C)	V_{oc} (V)	J_{sc} (mA/cm ²)	FF	i-layer thickness (nm)
LL712	250	0.951	12.1	0.585	320
LL723	230	0.959	11.3	0.608	320
LL722	210	0.980	11.7	0.615	310
LL731	210	0.986	12.0	0.626	330
LL732	175	1.026	10.0	0.670	285
LL746	150	1.040	9.4	0.652	264
LL853	125	0.398	6.7	0.619	-

To study the properties of this new i-layer material, single layer films were deposited for materials characterization. However in most cases, the films peeled off the substrates even for the thinnest films, suggesting high compressive stress in these films.^{27,28} We were able to get some films to stick to 7059 glass for optical absorption measurements. From a Tauc plot, we obtained a bandgap of 1.80 eV, a typical value for a-Si. Although the extrapolation in the Tauc plot gives 1.80 V, the absorption coefficient of this high V_{oc} material is indeed lower than that of conventional a-Si. Therefore, this material has typical Tauc gap, but a rather high E_{04} value for "device quality" a-Si. Various approaches to keep the highly stressed films on glass substrates are being investigated. Extensive study of material properties for this high V_{oc} a-Si material will be performed after we succeed in adhering the films to the substrates.

L1031A4W14A Single NIP 23 Mar 95 WBI SS 2000P 0HR

Jsc = 7.287 Jmp = 6.329

Voc = 1.053 Vmp = .887

FF = .732

A = .25 cm² Pmx = 5.612 mW/cm²

Rs = 10.9 Ω cm²

Rsh = 3.1E3 Ω cm²

Figure 4-1 J-V curve of wide bandgap a-Si single cell showing 1.053 V initial V_{oc}.

When the a-Si deposition temperature is reduced, more hydrogen dilution is needed to achieve high quality material. However, when the hydrogen dilution increases beyond a certain limit, V_{oc} as well as other parameters of the solar cell drastically decrease, probably due to microcrystalline formation. Figure 4-2 shows the J-V curve of a device with the i-layer deposited at 230 °C using the high hydrogen dilution level which is optimized for 150°C wide bandgap a-Si deposition. One can see that V_{oc} has dropped to 0.86 V. The FF is slightly higher than for device LL723 in Table 4-1 because it is thinner.

Table 4-2 summarizes the cell performance for these high V_{oc} devices as a function of i-layer thickness. We remind the reader that these cells were prepared without back-reflectors. The expected trends of increasing J_{sc} as well as the decrease in FF with increasing i-layer thickness are obvious. We found that beyond an i-layer thickness of 200 nm, the V_{oc} decreases slightly to a value of 1.02 V at a thickness of 400 nm.

Also included in the table is the trend in the properties for the devices with increased light soaking. After 2500 hrs of light soaking, these cells degrade by 13-20% with the thinner samples degrading less as expected. Figure 4-3 shows the J-V curve of a wide bandgap a-Si single cell demonstrating 1.014 V stable V_{oc} after 2500 hours of one sun light soaking at 50 °C. This is the highest stable V_{oc} reported for single-junction a-Si solar cells. As we see from the table, after this amount of light soaking, all of the cells with i-layer thicknesses less than 300 nm have stable V_{oc} greater than or equal to 1.00V after 2500 hours of light soaking.

Table 4-2 Properties for high V_{oc} cells made with different i-layer thicknesses during the initial state and after light soaking for different times

Sample	i-layer thickness (nm)	Light soaking Time (hrs)	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	P_{max} (mW/cm ²)
L1036	150	0	6.88	1.04	0.742	5.26
		72	6.76	1.01	0.696	4.74
		2500	6.47	1.01	0.696	4.57
L1031	200	0	7.29	1.05	0.732	5.60
		72	7.13	1.01	0.686	4.96
		2500	6.95	1.01	0.646	4.53
L1041	240	0	8.17	1.03	0.707	5.96
		72	7.68	0.998	0.634	4.86
L1014	280	0	8.15	1.03	0.691	5.78
		72	8.17	1.01	0.645	5.27
L1032	400	0	11.59	1.02	0.592	6.96
		72	10.88	0.997	0.551	5.86
		2500	10.76	0.977	0.556	5.84

Figure 4-2 J-V curve of a-Si device with i-layer deposited at relatively high temperature (230 °C) with too strong a dilution.

Figure 4-3(a) J-V curve of a wide bandgap a-Si single cell after 2500 hours of one sun 50 °C light soaking, showing 1.014 V stabilized V_{∞} .

Figure 4-3(b) J-V curve of a wide bandgap a-Si single cell after 2500 hours of one sun 50 °C light soaking, measured under weak blue and red lights.

When these high V_{oc} devices are grown on Ag/ZnO back reflectors, the V_{oc} are lower. Table 4-3 displays initial cell data for devices prepared on bare SS and SS/Ag/ZnO substrates in the same n-i-p deposition. For the cells with i-layer thicknesses below 300 nm, V_{oc} is generally 30 mV smaller for the devices with back reflector. The thicker devices display smaller differences. These differences have been minimized by increasing the p-layer thicknesses. However since these high V_{oc} n-i-p devices will be used as the top cell of a triple, they will be deposited on top of the middle and bottom cells so this drop in V_{oc} will be less critical in the multijunction devices.

Table 4-3 Data for high V_{oc} devices prepared on bare SS and SS/Ag/ZnO substrates in the same n-i-p deposition

Sample	i-layer thickness (nm)	Substrate	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	P_{max} (mW/cm ²)
L1036	150	Bare SS	6.88	1.04	0.742	5.26
		Ag/ZnO	9.90	1.01	0.715	7.17
L1031	200	Bare SS	7.29	1.05	0.732	5.60
		Ag/ZnO	10.41	1.01	0.705	7.40
L1032	400	Bare SS	11.59	1.02	0.592	6.96
		Ag/ZnO	14.78	1.01	0.610	9.14

To demonstrate the improvement in V_{oc} in a multijunction device, we deposited the best high V_{oc} n-i-p device on a standard a-Si cell to form an a-Si/a-Si tandem structure. The complete device structure is: SS/Ag/ZnO/standard a-Si n-i-p/high V_{oc} a-Si n-i-p/TCO/Ag grid. Figure 4-4 displays the J-V curve of such a tandem device. As a comparison, we have also fabricated a tandem device with both intrinsic layers deposited using the standard conditions, i.e. 250 °C and regular hydrogen dilutions. The reference J-V curve for such a reference device is shown in figure 4-5. In the tandem device, the V_{oc} has increased from 1.77 V to 1.84 V with the use of the high V_{oc} top cell. The 68 mV gain is approximately the same as the gain noted in the single devices (from 0.96 to 1.04-1.05 V). The slightly lower FF in the first tandem-junction cell is due to a different mismatch in currents. We have incorporated the high V_{oc} cells into the triple-junction design and report the results in a later section of this report.

4.4 Summary

An initial V_{oc} of 1.053 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. After 2500 hours of light soaking under one sun at 50 °C, the V_{oc} has stabilized at 1.014 V. 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 bandgap a-SiC alloys.

LL847A1W31A Tandem NIP 18 Aug 94 OBR 83

Jsc = 7.496 Jmp = 6.304

Voc = 1.836 Vmp = 1.459

FF = .668

A = .25 cm² Pmx = 9.196 mW/cm²

Rs = 20.8 Ω cm²

Rsh = 5.5E3 Ω cm²

Figure 4-4 J-V curve of a tandem-junction solar cell with wide bandgap a-Si as the top cell intrinsic layer.

LL0401W11A Tandem HP 10 Aug 94 OBR 03

$J_{SC} = 7.495$ $J_{mp} = 6.307$
 $V_{OC} = 1.768$ $V_{mp} = 1.448$
 $FF = .698$
 $A = .25 \text{ cm}^2$ $P_{mx} = 9.247 \text{ mW/cm}^2$

$R_s = 19.6 \Omega \text{ cm}^2$
 $R_{sh} = 5.1E3 \Omega \text{ cm}^2$

Figure 4-5 J-V curve of a tandem solar cell with a regular top i-layer for reference.

Section 5

Microcrystalline Silicon Alloy As Novel p Materials

5.1 Introduction

With the boron doped microcrystalline Si as the p-layers, we routinely obtain V_{oc} of 0.95-0.96 V for single-junctions a-Si devices made using our solar cell deposition systems. The microcrystalline layer, with its wider bandgap, also leads to higher currents as compared with devices with amorphous p-layers.

The μ c-Si p-layer still has some volume fraction of amorphous phase, which has smaller bandgap and hence less transmission than the microcrystalline phase. In order to achieve higher current and higher V_{oc} for a-Si devices, we are exploring microcrystalline silicon oxide (μ c-SiO) and microcrystalline silicon carbide (μ c-SiC) p-layers by alloying the amorphous silicon phase of the p-layer with oxygen or carbon to widen its effective bandgap.

A similar approach of widening the bandgap and improving the current by alloying Si with O has been studied by researchers at Fuji Electric for their amorphous p-layers.^{29,30} With the a-SiO_x p-layer, they have obtained 18.8 mA/cm² short circuit current densities in a single-junction a-Si p-i-n solar cell with 400 nm thick a-Si i-layers. Although Fuji's a-SiO_x layer has a 2.15 eV bandgap, the V_{oc} for their p-i-n devices is only 900 mV. This is because the amorphous oxidized material has a broader valence band tail and a fermi level which is farther from the bandedge than that for μ c-Si. Devices made with our μ c-SiO and μ c-SiC p⁺ layers are expected to have significantly higher V_{oc} and higher J_{sc} than those with a-SiO_x p⁺ layers.

Along the same lines, Ma et al.³¹ have produced microcrystalline SiC p-layers using ECR microwave plasmas. With this larger bandgap material, they also obtained higher short circuit currents (19.6 mA/cm²) as compared with cells made with the conventional boron-doped a-Si p-layers. The V_{oc} values for cells with this new p-layer were around 0.94 V, a value we routinely match or exceed with our μ c-Si p-layer. Thus if we alloy our p-layer with O or C while maintaining its microcrystalline state, we should at least see an improvement in J_{sc} while maintaining or improving the V_{oc} . In addition, unlike ECR microwave deposition, the growth technique we are exploring is easily scaleable to large area PV manufacturing processes.

5.2 Experimental

Both types of alloys were prepared using ECD's Box deposition system. We used SS/n/i produced in ECD's roll-to-roll machine as the substrate for this study. The i-layer was nominally 300 nm thick. These n-i layers lead to 6.2-6.7% devices when standard LL1 p-layers were deposited on them.

CO₂ and CH₄ were used as source gases for μ c-SiO and μ c-SiC deposition and their flows were systematically varied. SiH₄, BF₃ and H₂ were the other gases used. Total gas flow, chamber pressure, substrate temperature, applied power and substrate bias were also systematically varied.

After p-layer deposition, our standard ITO and Ag grids were deposited onto the p-layers to complete the devices.

5.3 Microcrystalline SiO

Table 5-1 displays the properties for cells made with varying CO₂ flow while all other parameters were nominally fixed. The unoxidized $\mu\text{c-Si}$ p-layers were prepared under similar conditions to those used for the LL1 p-layer except that relatively thicker p-layers were used so that any possible small change in p-layer thickness with varying CO₂ flow would not alter V_{oc} drastically.

Table 5-1 Properties for cells made with varying amounts of CO₂ flow while all other parameters were nominally fixed

Sample	Relative CO ₂ flow (sccm)	J _{sc} (mA/cm ²)	V _{oc} (V)	FF	P _{max} (mW/cm ²)	R _s (Ωcm^2)
563	0	9.6	0.95	0.66	6.0	10
520	0	9.4	0.95	0.68	6.0	8
538	1.0	9.9	0.96	0.63	6.0	13
547	1.0	9.4	0.95	0.64	5.8	12
540	2.0	10.2	0.96	0.56	5.4	37
544	2.0	9.6	0.95	0.52	4.7	52
541	5.0	No measurable J-V curves				

As can be seen from the data, the V_{oc} stays constant and the J_{sc} is improved slightly as the CO₂ flow is increased. However, the series resistance increases and the FF decreases at the same time. We believe the deterioration in the cell properties is related to an observed formation of powder in the chamber when CO₂ was incorporated into the gas mixture. By increasing the substrate temperature by 40 °C from 140 to 180 °C, we were able to almost entirely eliminate the powder formation. And, as can be seen from the data listed in Table 5-2, the FF and R_s values for cells prepared at this higher temperature (180 °C) are comparable to those for the cells with unoxidized p-layers made at the lower temperature (samples 520 and 563 in Table 5-1). However, the cost of using the higher temperature was a drop in V_{oc} . We are still trying to improve the V_{oc} for deposition at higher temperature and to reduce powder formation for deposition at lower temperature through alteration of other deposition conditions such as hydrogen dilution and chamber geometry.

5.4 Microcrystalline SiC

In the deposition of $\mu\text{c-SiC}$, we used a gas mixture of SiH₄, H₂, BF₃ and CH₄ and started with the deposition conditions which produce a high quality $\mu\text{c-Si}$ p-layer. Table 5-3 displays cell data for devices with p-layers made with varied methane flow at 140 °C and 180 °C. As we see from the table, devices with $\mu\text{c-SiC}$ p-layers show slightly higher J_{sc} as compared with $\mu\text{c-Si}$ p-layers

deposited at 180 °C. However, $\mu\text{c-Si}$ p-layer deposited at 140 °C results in the same J_{sc} as that of $\mu\text{c-SiC}$. We have also investigated deposition of $\mu\text{c-SiC}$ p-layer at 140 °C and found that the lower temperature results in a device with a higher R_s and a lower FF. This is likely due to the powder formation in the deposition chamber when we deposit $\mu\text{c-SiC}$ at lower temperatures.

Table 5-2 Properties for cells made at different p-layer substrate temperatures while all other parameters were nominally fixed

Sample	Substrate Temp. (°C)	Relative CO ₂ flow (sccm)	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	P_{max} (mW/cm ²)	R_s (Ωcm^2)
544	140	2.0	9.6	0.95	0.52	4.7	52
550	180	2.0	9.3	0.91	0.67	5.7	9
554	180	2.0	9.1	0.89	0.67	5.3	9

Table 5-3 Properties for cells made with varying amounts of CH₄ flow while all other parameters were nominally fixed

Sample	Subst. Temp. (°C)	Relative CH ₄ flow (sccm)	J_{sc} (mA/cm ²)	V_{oc} (V)	FF	P_{max} (mW/cm ²)	R_s (Ωcm^2)
684	140	0	11.1	0.93	0.66	6.8	8.6
685	140	0	11.1	0.92	0.68	6.9	7.3
686	180	0	10.8	0.93	0.69	6.9	8.5
687	180	0	10.7	0.91	0.66	6.4	7.3
690	180	1.0	11.6	0.94	0.64	7.0	8.6
691	180	1.0	12.0	0.91	0.65	7.1	7.6
692	180	2.0	11.5	0.93	0.64	6.9	8.5
693	180	2.0	11.8	0.92	0.65	7.0	8.0

While $\mu\text{c-SiC}$ p-layers deposited at 180 °C show performance similar to that of the $\mu\text{c-Si}$ p-layer, it degrades with air exposure. Table 5-4 shows performance of devices with $\mu\text{c-SiC}$ p-layer and $\mu\text{c-Si}$ p-layer before and after weeks of air exposures. Performance of devices with $\mu\text{c-Si}$ p-layers is unchanged while those with $\mu\text{c-SiC}$ p-layers degraded significantly. From Auger measurement, we found a significant amount of oxygen in the unstable $\mu\text{c-SiC}$ p-layers. We suspect that the changes with air exposure are related to the formation of columnar microstructure.

We have also studied the deposition of $\mu\text{c-Si}$ and $\mu\text{c-SiC}$ with relatively less hydrogen dilution compared with devices shown in Table 5-4. Table 5-5 shows the performance of devices with both $\mu\text{c-SiC}$ and $\mu\text{c-Si}$ p-layers. The J_{sc} of the $\mu\text{c-Si}$ device has decreased. However, the J_{sc} and other solar cell performance characteristics of the $\mu\text{c-SiC}$ device remain the same. Therefore,

before any extended air exposure, the solar cell performance of devices with $\mu\text{c-SiC}$ p-layer is superior to that of $\mu\text{c-Si}$ p-layers deposited at this same dilution level. We are still in the process of gaining further understanding of the growth of $\mu\text{c-SiC}$ material deposited at different temperatures and with different hydrogen dilutions, and the mechanism that caused the degradation due to the extended air exposure.

Table 5-4 Properties for cells with $\mu\text{c-Si}$ and $\mu\text{c-SiC}$ p-layers, before and after the devices are exposed to air for an extended period of time

Sample	Relative CH_4 flow (sccm)	When J-V curve taken	J_{sc} (mA/cm^2)	V_{oc} (V)	FF	P_{max} (mW/cm^2)	R_s (Ωcm^2)
615 $\mu\text{c-Si p}^+$	0	< 24 hrs after deposition	10.4	0.957	0.647	6.43	8.5
		2 months after deposition	10.4	0.949	0.644	6.39	8.7
713 $\mu\text{c-Si p}^+$	0	< 24 hrs after deposition	11.7	0.942	0.638	7.00	8.7
		3 weeks after deposition	11.7	0.939	0.639	7.04	8.5
705 $\mu\text{c-SiC p}^+$	1.5	< 24 hrs after deposition	12.0	0.952	0.661	7.58	6.9
		2 days after deposition	11.8	0.910	0.615	6.59	9.7
719 $\mu\text{c-SiC p}^+$	1.5	< 24 hrs after deposition	11.9	0.932	0.665	7.35	7.9
		2 days after deposition	11.9	0.904	0.607	6.53	9.1

Table 5-5 Properties for cells made with relatively less hydrogen dilution compared with samples shown in Table 5-4 and varying amounts of CH₄ flow while all other parameters were nominally fixed

Sample	Relative CH ₄ flow (sccm)	J _{sc} (mA/cm ²)	V _{oc} (V)	FF	P _{max} (mW/cm ²)	R _s (Ωcm ²)
579	0	9.6	0.92	0.67	5.9	7.8
617	0	9.7	0.94	0.66	6.0	8.6
580	0.05	9.9	0.93	0.67	6.2	7.9
574	0.13	9.8	0.92	0.67	6.0	7.5
599	0.30	10.1	0.89	0.66	6.0	7.5
600	0.50	10.5	0.90	0.67	6.3	6.9
617	0.50	11.3	0.90	0.65	6.6	7.7
620	0.80	10.9	0.95	0.66	6.8	7.9
619	1.2	11.3	0.92	0.65	6.7	8.2
626	1.2	10.8	0.90	0.68	6.6	6.8
624	2.4	11.3	0.91	0.65	6.6	8.2
625	3.2	11.2	0.90	0.67	6.7	7.5

5.5 Summary

We have begun initial studies of boron doped microcrystalline SiO and SiC alloy systems as wide bandgap p-layers. In both cases, because of powder formation, substrate temperatures higher than those typically used to deposit our μc-Si p-layers were required to make the best material with reasonable FF. However, use of these higher temperatures caused lower V_{oc} values to be obtained. For the SiC alloys, higher short circuit currents and better efficiencies were found in the initial state for p-layers prepared with CH₄ under moderate hydrogen dilution conditions, and no benefit was found when higher dilution conditions were used.

Section 6

Schottky Barrier Devices as a-Si Alloy Materials Evaluation Tool

6.1 Introduction

The deposition of a-Si alloy materials including a-Si, a-SiGe and a-SiC is often optimized using single layer measurements such as photoconductivity, Photothermal Deflection Spectroscopy (PDS), Constant Photocurrent Method (CPM) or Steady State Photocurrent 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.²⁵ An alternative, reliable and easy measurement for the photovoltaic properties of materials is therefore desirable.

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, since it, 1) more reliably reflects the carrier transport in a solar cell than the conventional material characterization tools previously mentioned, and 2) is easier to fabricate than a complete solar cell. However, such a device still requires the deposition of an n^+ a-Si layer and thus a multiple chamber device producing 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 a heavily doped n-type c-Si substrate for the back ohmic contact. Such a new test structure is easily fabricated and therefore can be widely used as an evaluation tool for measuring a-Si alloy transport properties. With n^+ c-Si rather than n^+ a-Si, laboratories which only have single chamber systems can conveniently produce these devices without having to prepare doped layers.

6.2 Device Structure, Fabrication and Measurement

The specific structure of the device we used is: c-Si(n^+)/a-Si alloy/Pd. In this device, a Schottky barrier is formed at the a-Si/metal contact and an ohmic contact is formed at the c-Si(n^+)/a-Si interface. The c-Si is a heavily phosphorus doped crystalline wafer substrate with resistivity lower than 0.02 Ωcm . We selected a thin Palladium metal layer for the semitransparent Schottky contact, as was done in other laboratories, because of its high work function.³²

For the production of the devices, the c-Si wafer was etched in a buffered HF solution for a few min prior to loading into the chamber for the a-Si alloy growth 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 $^{\circ}\text{C}$ for 30 min and then etched with a hydrogen plasma for 2 min.

Together with the c-Si substrates, a set of SS substrates, precoated with an a-Si n^+ layer, were also loaded into the system for the deposition of reference n-i-p solar cells. After a-Si alloy i-layer deposition and the removal of the c-Si/a-Si alloy samples from the multiple chamber deposition system, these SS/a-Si(n^+)/a-Si alloy samples were loaded back into the p chamber for deposition of the $\mu\text{c-Si}$ p-layer, while the c-Si(n^+)/a-Si alloy samples were immediately transferred to a

vacuum evaporator for the Pd deposition. An effort was made to minimize exposure of the sample to air to less than 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 5-20 nm of Pd was evaporated at 0.02 nm/sec at 25 °C through a mask to complete the c-Si/a-Si/Pd Schottky barrier device.

In measuring the J-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. Ag was also applied as a paste or an evaporated layer to the other side of the c-Si substrate to improve the probe contact.

6.3 Results

Figure 6-1 illustrates the J-V curves of a c-Si(n⁺)/a-Si/Pd device with a 20 nm thick i-layer measured under our typical AM1.5 white light (curve a), the same simulator light after a red cut-on filter (curve b) and a broadened 628 nm HeNe laser light with a flux of 10¹⁶ photons/cm²sec (curve c). The curve in (b) and (c) were enlarged by a factor of 10 in Figure 6-1. Measurement with the HeNe light has several advantages: the light is more uniformly absorbed by the material, the photon flux can be easily calibrated so that the short circuit current and the quantum efficiency can be calculated and the laser itself is usually available in most laboratories. From curve a, the FF is around 0.59. The V_{oc} is 0.47 V, which is typical for a Schottky barrier device with a barrier height of 0.9-1.0 V at room temperature. The J_{sc} of 3.5 mA/cm² is lower than that for a standard n-i-p device with similar intrinsic layer thickness due to the absorption of Pd film and Pd₂Si formed at the a-Si/Pd interface.³³

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 devices with different a-Si and a-SiGe intrinsic layers to show the dependence on the intrinsic layer quality and thickness. Table 6-1 lists the device performance data for all of the Schottky barrier devices and the reference n-i-p solar cells, fabricated at the same time with the i-layer deposition. The first set of data in the top of the table is for the a-Si Schottky devices with different intrinsic layer thicknesses and an a-SiGe Schottky device with a 200 nm thick i-layer. The second set of data is for n-i-p devices 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 breaks between the different layer depositions. 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, as should be expected. The correlation in FF between the Schottky barrier devices and the reference n-i-p devices is consistent.

Compared with the FF measured under the simulator light, the FF_r 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 intrinsic material and thus depends less on any possible variations at the interfaces. To better show the correlation, Figure 6-2 plots the FF for 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. With the measured FF for a Schottky barrier device made with a new material, one could use the trend seen

Figure 6-1 J-V curves of a c-Si(n+)/a-Si/Pd Schottky barrier device measured under (a) solar simulator; (b) weak red light; and (c) HeNe laser light.

Table 6-1 J-V performance of c-Si (n^+) / a-Si alloy/Pd Schottry barrier devices and a-Si alloy n-i-p solar cells under the illumination of different lights.

Devices	i-layer thickness (nm)	Simu- lator (100 W/cm ²)						(10 ¹⁶ HeNe photons /cm ² s) Laser		
		FF	J _{sc} (mA/cm ²)	V _{oc} (V)	R _s (Ω /cm)	FF _r	FF _b	FF	J _{sc} (mA/cm ²)	V _{oc} (V)
c-Si/a-Si:H/Pd	200	0.577	3.5	0.47	20	0.570	0.610	0.602	0.07	0.38
c-Si/a-Si:H/Pd	300	0.536	3.9	0.48	25	0.542	0.580	0.564	0.12	0.39
c-Si/a-si:H/Pd	400	0.552	4.6	0.49	19	0.515	0.605	0.530	0.15	0.40
c-Si/a-Si:H/Pd	500	0.474	4.5	0.48	37	0.460	0.507	0.479	0.20	0.41
c-Si/a-SiGe:H/Pd	200	0.31	5.1	0.48	16	0.492	0.513	0.511	0.31	0.24
N / I / P a-Si:H	200	0.594	9.8	0.95	24	0.664	0.720	0.673	0.33	0.82
N / I / P a-Si:H	300	0.530	10.8	0.95	24	0.524	0.691	0.555	0.52	0.83
N / I / P a-Si:H	400	0.516	11.2	0.95	16	0.452	0.684	0.464	0.71	0.83
N / I / P a-Si:H	500	0.493	12.0	0.95	18	0.410	0.669	0.434	0.73	0.82
N / I / P a-SiGe:H	200	0.484	12.8	0.65	16	0.498	0.630	0.524	1.0	0.54
nip a-Si:H	200	0.657	11.2	0.95	11	0.655	0.749	-	-	-
nip a-Si:H	300	0.601	12.1	0.94	8.9	0.570	0.735	-	-	-
nip a-Si:H	400	0.560	13.0	0.94	9.1	0.503	0.728	-	-	-
nip a-Si:H	500	0.534	13.3	0.94	9.2	0.415	0.720	-	-	-

Figure 6-2 Correlation of FF between Schottky barrier device and regular a-Si n-i-p solar cell device having the same i-layer.

in Figure 6-2 to find the expected FF of an n-i-p device made with this material. Of course, since the FF for an n-i-p solar cell depends also on other device layers, such as the p, n and ITO layers, the relation in Figure 6-2 should not be extrapolated for devices made at different laboratories. However, the relative change in the FF of the 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.

Finally, the c-Si(n^+)/a-Si alloy/Pd Schottky barrier device has several advantages over the n-i-p 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 Pd₂Si interface), and the use of the c-Si(n^+) as the substrate minimizes the deposition of other solar cell layers such as p, n and ITO layers. We believe that this is an excellent tool for laboratories with single chamber systems to use.

6.4 Summary

The 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.

Section 7

Optimization of Single-junction a-Si Solar Cell

7.1 Introduction

The optimization of single-junction a-Si n-i-p solar cell fabrication is performed in two solar cell deposition systems: LL1 and LL2. Both are multi-chamber systems that deposit doped and undoped layers in separate chambers. The main purpose of this optimization is to establish a good base line solar cell deposition.

7.2 Light Soaking of Single Cells with Different Thicknesses

We have produced, in the LL1 deposition system, a set of a-Si n-i-p solar cells with different i-layer thicknesses on bare SS substrate. Table 7-1 list the J-V performance of this set of devices. After the initial measurement, this set of devices was soaked under one sun light for degradation. The temperature of these devices was measured at around 58 °C during light soaking. In Table 7-1, we also list the J-V data for all the devices after different light soaking steps. The degradation losses after 620 hours of light soaking are around 10%, 17% and 20% for devices with i-layer thicknesses of 100 nm, 300 nm, and 500 nm, respectively. The degradation occurred primarily during the first 100 hours of light soaking.

7.3 Optimizing Single Cell Efficiency and Baseline Performance

After the installation of the our LL2 deposition system, we have systematically optimized the deposition conditions for single-junction n-i-p solar cells. The initial optimization included:

1. varying the gas mixture, hydrogen dilution, doping level, temperature, thickness, RF power for the deposition of boron doped μ c-Si as the p^+ layer;
2. varying the hydrogen dilution, temperature, RF power and thickness for the deposition of the intrinsic layer;
3. varying the doping and thickness for the deposition of the n-layer;
4. adjusting the deposition pressure to improve the uniformity and ensuring tight process control to improve reproducibility;
5. varying machine cleaning, purging, and baking procedures to ensure the deposition of highest quality material on a routine basis; and
6. varying the parameters used for the deposition of indium-tin-oxide top contact.

After optimization of all of the above parameters, we have achieved the deposition of single-junction solar cells with 10.6% initial active area efficiency. The J-V characteristics include a V_{oc} of 0.944 V, J_{sc} of 16.4 mA/cm² and FF of 0.687, as shown in Figure 7-1. Figure 7-2 shows the J-V curves measured under weak blue and red light.

To ensure a consistent base line for the properties for the standard a-Si solar cell with nominally 300 nm thick i-layer, we produced seven a-Si single-junction solar cells in series. The first five

Table 7-1. Device performance of single-junction a-Si n-i-p solar cells deposited on bare SS with different I-layer thicknesses, after different light soaking times

Sample No.	i-layer thickness	light-soaking hours	Cell #	V _{oc}	J _{sc}	FF	Efficiency	Drop in Efficiency
	(nm)	(h)		(V)	(mA/cm ²)		(%)	(%)
1	500	0	33	959	12.19	.524	6.13	----
		120	33	921	10.37	.527	5.04	18.0
		380	33	914	10.30	.523	4.92	20.0
		620	22	914	9.80	.520	4.68	20.0*
2	400	0	23	939	10.70	.510	5.12	----
		120	23	919	9.40	.511	4.41	14.0
		380	23	913	9.22	.509	4.28	16.5
		620	23	.912	9.24	.506	4.27	16.6
3	300	0	32	.951	10.86	.601	6.21	----
		120	32	.917	10.20	.553	5.17	16.8
		380	32	.916	10.29	.554	5.22	16.8
		620	31	910	10.38	.550	5.20	16.6*
4	100	0	23		7.58	.716	5.24	----
		120	23		7.49	.685	4.74	9.5
		380	ALL	SHUNTED				

* Different cells of the same sample

Jsc = 16.392 Jmp = 13.874

Voc = .944 Vmp = .767

FF = .687

A = .25 cm² Pmax = 10.638 mW/cm²Rs = 5.3 $\Omega \cdot \text{cm}^2$ Rsh = 8.3E2 $\Omega \cdot \text{cm}^2$

Figure 7-1 J-V curve of an optimized single-junction a-Si solar cell, showing 10.6% initial efficiency.

L21864C33B Single HP 13 Oct 95 R2157 IT03290

	BLUE	RED
Jsc =	1.019	.815
Voc =	.842	.829
FF =	.704	.716

A = .05 cm²

Figure 7-2 J-V curve of an optimized single-junction a-Si solar cell measured under weak blue and red lights.

were deposited under identical condition as device L2186 (shown in Figure 7-1), and the last two devices have 10% thinner and 10% thicker i-layers, respectively. The J-V performance of these seven devices deposited on both bare SS and Ag/ZnO back-reflector are summarized in Table 7-2. From the table, we find that the device performance is very consistent. The FF is around 0.68 and the red fill factor is around 0.71. The samples with thinner and thicker i-layers show approximately the same FF. The weak dependence of the FF on i-layer thickness at around 300 nm is further evidence of the high quality of a-Si materials deposited in this deposition system.

7.4 Summary

The deposition of single-junction a-Si solar cells have been optimized in both small area solar cell deposition systems at ECD. Solar cells with different i-layer thicknesses were studied and their light soaking degradation have been tested. We have improved the deposition of a-Si n-i-p solar cells and achieved single-junction a-Si solar cell with 10.6% initial efficiency. The deposition of high performance single cells in this system has been demonstrated to be reproducible and consistent after process optimization.

Table 7-2 Device performance of consecutively deposited single-junction a-Si n-i-p solar cells, demonstrating improved baseline solar cell fabrication

Run #	Substrate	i-layer thickness (nm)	V _{oc} (V)	J _{sc} (mA/cm ²)	FF	P _{max} (mW/cm ²)	FF _b	FF _r
L2186-1	SS	327	0.945	11.39	0.675	7.27	0.747	0.706
L2186-4	BR	327	0.947	16.04	0.697	10.59	0.704	0.716
L2217-1	SS	320	0.939	11.70	0.670	7.36	0.734	0.711
L2217-4	BR	320	0.929	15.77	0.667	9.63	0.688	0.713
L2218-1	SS	330	0.935	11.30	0.670	7.08	0.744	0.714
L2218-4	BR	330	0.924	16.46	0.672	10.22	0.661	0.704
L2219-1	SS	320	0.944	12.00	0.682	7.72	0.727	0.723
L2219-4	BR	320	0.923	15.98	0.681	10.05	0.657	0.704
L2220-1	SS	320	0.933	11.84	0.670	7.40	0.737	0.720
L2220-4	BR	320	0.927	16.09	0.680	10.14	0.682	0.715
L2221-1	SS	310	0.928	11.37	0.696	7.34	0.738	0.712
L2221-3	BR	310	0.942	15.96	0.674	10.13	0.659	0.703
L2222-1	SS	280	0.930	11.59	0.705	7.60	0.732	0.734
L2222-4	BR	280	0.949	15.06	0.675	9.65	0.667	0.710
L2223-1	SS	360	0.940	11.70	0.663	7.30	0.733	0.721
L2223-4	BR	360	0.929	15.19	0.669	9.45	0.690	0.711

Section 8

Optimization of Tunnel Junction

8.1 Introduction

In a triple-junction a-Si alloy solar cell, there are two tunnel junctions: one between the p-layer of the bottom cell and the n-layer of the middle cell, and the other between the p-layer of the middle cell and the n-layer of the top cell. The high density of defect states induced from heavy doping in the tunnel-junction doped layers results in heavy recombination of the collected carriers from both nearby component cells. In this way, no reverse voltage will be formed and the resistance from the tunnel junction can be minimized.

ECD uses a proprietary microcrystalline p-layer in the a-Si n-i-p solar cell device. This p-layer provides high V_{oc} due to the wider bandgap, provides low activation energy, high transmission due to the wider bandgap, and provides better fill factor due to the low resistivity and high built-in field.

In ECD's solar cell design, the tunnel junction is formed between $\mu\text{c-Si } p^+$ layer and the a-Si n^+ layer. The $\mu\text{c-Si } p^+$ layer offers advantages over its amorphous counterpart as the tunnel-junction p-layer due to its higher density of recombination states near the grain boundary. We have performed a study to optimize and improve the tunnel-junction performance.

8.2 Optimization of Tunnel Junctions

The series resistances of the triple-junction cells deposited in the newly installed LL2 system were initially high, which was mainly due to the poor tunnel junctions between component cells. Significant effort was devoted to improving the tunnel junctions. In this section, we describe the optimization of tunnel-junction deposition in the LL2 system.

The p-layer deposition condition plays a crucial role in determining the tunnel-junction performance. Figure 8-1a through 8-1d show the J-V curves for four n-i-p-n solar cells (L2157 through L2160) with the p-layer deposited at different temperatures. From this group of samples, we find that the p-layer deposited at 120 °C is most suitable for the tunnel-junction p-layer since it provides the lowest R_s and highest V_{oc} . We then studied the dependence of tunnel-junction performance on the p-layer thickness. Figure 8-2 is the J-V curve for an n-i-p-n device with a p-layer deposited for 4 min, which is half of the time for the other four samples. The V_{oc} was improved to 0.88 V and the R_s was reduced to 15 Ωcm^2 . By reducing the n-layer thickness to half, we have further reduced R_s down to 10 Ωcm^2 and improved the V_{oc} up to 0.89 V, as shown in Figure 8-3. Table 8-1 summarizes the deposition conditions and V_{oc} and R_s for these six n-i-p-n samples.

Figure 8-1 J-V curve of a-Si n-i-p-n tunnel-junction test device with p-layer deposited at different temperatures: (a) 50 °C; (b) 80 °C; (c) 120 °C; and (d) 150 °C.

Jsc = 9.879 Jmp = 8.006

Voc = .881 Vmp = .681

FF = .627

A = .25 cm² Pmx = 5.454 mA/cm²

Rs = 15. Ω cm²

Rsh = 1.6E3 Ω cm²

J (mA/cm²)

67

U (volts)

Figure 8-2 J-V curve of a-Si n-i-p-n device with thinner p-layer compared to that shown in figure 8-1.

L2164A3M43A Single MP 7 Jul 95 00140 P-M IT03193

$J_{sc} = 9.767$ $J_{mp} = 0.208$
 $V_{oc} = .888$ $V_{mp} = .689$
 $FF = .652$
 $A = .25 \text{ cm}^2$ $P_{mx} = 5.652 \text{ mW/cm}^2$

$R_s = 10.3 \Omega \text{ cm}^2$
 $R_{sh} = 1.4E3 \Omega \text{ cm}^2$

Figure 8-3 J-V curve of a-Si n-i-p-n device with thinner n-layer compared to that shown in Figure 8-2

Table 8-1 Performance of n-i-p-n devices with different p- and n-layer deposition temperatures and thicknesses

Device No.	temp (p) (°C)	time (p) (min)	temp (n) (°C)	time (n) (min)	V _{oc} (V)	R _s (Ωcm ²)
L2157	50	8	250	2	0.59	160
L2158	80	8	250	2	0.81	88
L2159	120	8	250	2	0.86	23
L2160	150	8	250	2	0.84	34
L2162	120	4	250	2	0.88	15
L2164	120	4	250	1	0.89	10

We then incorporated the improved tunnel junction into the triple-junction solar cell. Four triple-junction cells were deposited under identical conditions except for the n-layer thickness. Table 8-2 summarizes the n-layer deposition times and the triple-junction device performance. The 1 min n-layer deposition did result in lower R_s as in L2164. However, the V_{oc} dropped from 2.20 V to 1.96 V when the n-layer deposition time was reduced from 2.0 min to 1.0 min. The thin n-layer deposited in 1 min is not sufficient to provide a high V_{oc} for the n-i-p junction. The test device n-i-p-n is not effective to reveal this shortcoming. From Table 8-2, we find that a 1.5 min deposition time for the tunnel-junction n-layers (n2 and n3) provides both a reasonably high V_{oc} (2.20 V) and a low R_s (49 Ωcm²).

Table 8-2 Device performance of triple-junction a-Si/a-SiGe/a-SiGe solar cells with different tunnel-junction n-layer thicknesses

Run#	n ₁ -layer dep. time (min)	n ₂ -layer dep. time (min)	n ₃ -layer dep. time (min)	V _{oc} (V)	J _{sc} (mA/cm ²)	FF	R _s (Ωcm ²)	Eff
L2166	2.0	1.5	1.5	2.203	6.55	0.623	49.4	9.00
L2167	1.0	1.0	1.0	1.959	6.35	0.641	44.1	7.97
L2168	2.0	1.5	2.0	2.172	6.59	0.637	52.8	9.12
L2169	2.0	2.0	2.0	2.174	6.17	0.682	95.4	9.14

To check the performance of the tunnel junction with a 1.5-min thick n-layer, we have deposited an a-Si/a-Si tandem device using the optimized tunnel-junction deposition condition, as shown in Figure 8-4. This tandem-junction cell (L2200) shows high V_{oc} , low R_s and high FF.

8.3 Improved Tunnel Junction Using Doping Graded p-layer

When multiple n-i-p solar cells are stacked on top of each other to form a multiple-junction solar cell, a tunnel junction is formed between the p-layer of the first n-i-p and the n-layer of the second n-i-p. In order to promote strong recombination at the tunnel junction, a relatively more heavily doped p-layer is used to form a good tunnel junction. The more heavily doped p-layer gives more electronic defects for the enhanced recombination, and lower resistivity for the better tunnel junction.

However, when the more heavily doped p-layer is used at the tunnel junction to achieve lower series resistance (better fill factor), the V_{oc} of the n-i-p cell is slightly reduced. This is due to the reduced bandgap when the p-layer is more heavily doped. In order to obtain a low series resistance tunnel junction without the V_{oc} loss, we utilized a new p-layer in which the doping concentration in the p-layer is graded. We believe that the V_{oc} is mostly governed by the boron doping concentration near the p-i interface, while the tunnel-junction performance is mostly governed by the boron doping concentration near the p-n interface. By using relatively more doping near the p-n tunnel junction and relatively less doping near the p-i interface, we can achieve a high V_{oc} and low series resistance tunnel junction.

The first approach towards the dopant graded p-layer was to use two boron doped sublayers with different doping levels as the p-layer. We use an n-i-p-n structure to evaluate the performance of the p-n tunnel junction in terms of V_{oc} loss, junction series resistance and J-V cross-over. In Table 8-3, we list several representative samples with n-i-p and n-i-p-n structures and with different p layers, deposited on bare SS substrates.

The data for a standard n-i-p sample (LL866) is displayed in Table 8-3 and shows a V_{oc} of 0.961 V and an R_s of $10.9 \Omega\text{cm}^2$. When an n-layer is deposited over the p-layer, the R_s increases and the J-V curve shows a cross-over. A heavier boron doping in the p-layer is therefore used to reduce R_s . Sample LL809 is a typical n-i-p-n cell in which a p-layer has been deposited with heavier doping, which is optimized for the p-layer at the tunnel junction of multiple-junction solar cell. Due to the use of more doping (7 sccm BF_3 during deposition), the R_s is kept low. However, the V_{oc} has dropped sizably, from 0.961 V to 0.906 V.

Sample LL860 was deposited with a p-layer consisting of two sublayers with different doping, each with approximately half of the thickness of the original p-layer. The R_s is still low, at $13.8 \Omega\text{cm}^2$, and V_{oc} has increased from 0.906 (for LL809) to 0.920 V. Figure 8-5 shows the J-V curves for this device under AM1.5 light. In order to further increase the V_{oc} of the n-i-p-n structure, we increased the thickness of the less doped sublayer, as shown in the table for sample LL871 and in Figure 8-6. The R_s is not increased, however, the V_{oc} was increased from 0.92 V to 0.938 V compared to LL860. The high V_{oc} is due to the p-sublayer with relatively lighter

Jsc = 5.156 Jmp = 4.335

Voc = 1.804 Vmp = 1.48

FF = .69

A = .25 cm² Pmax = 6.415 mW/cm²Rs = 18.5 $\Omega \cdot \text{cm}^2$ Rsh = 3.9E3 $\Omega \cdot \text{cm}^2$

Figure 8-4 J-V curve of an a-Si/a-Si tandem-junction solar cell having optimized tunnel junction.

LL860A1W22A Single NIP 14 Sep 94 NIPN

Figure 8.5 I-V curve of an n-i-n device with tunnel junction n-layer having graded doping

$J_{SC} = 9.364$ $J_{MP} = 7.047$
 $V_{OC} = .938$ $V_{MP} = .712$
 $FF = .571$
 $A = .25 \text{ cm}^2$ $P_{MX} = 5.016 \text{ mW/cm}^2$

$R_s = 13. \Omega \text{ cm}^2$
 $R_{sh} = 1.6E3 \Omega \text{ cm}^2$

Figure 8-6 J-V curve of an n-i-p-n device with tunnel-junction p-layer having relatively thicker sublayer with less doping.

doping near the p-i interface, and the low R_s is due to the p-sublayer with relatively heavier doping near the p-n interface.

One may notice also that the J_{sc} has also decreased for LL871 due to the thicker p-layer. In a real tandem or triple-junction device, the light from the sun will have to travel through the top n-i-p layers before it reaches this tunnel-junction p-layer. The effect on the J_{sc} will be negligible unlike in the n-i-p-n test device. Therefore, when LL871 is used in a multiple-junction device, a 32 mV gain in V_{oc} will be achieved without any loss in FF or J_{sc} . When the doping profile in the tunnel-junction p-layer is further optimized, more improvement in multiple-junction device is expected. In addition, a graded phosphorus doping in the tunnel-junction n-layer may also lead to improved performance of the tunnel-junction due to the same reason.

8.4 Summary

The tunnel-junction deposition in the newly installed LL2 system has been systematically investigated and optimized. The optimized tunnel junction results in much reduced R_s in the triple-junction solar cells.

We investigated a new tunnel-junction design, in which a doping graded p-layer is used. We have demonstrated that a p-layer having higher boron doping near the p-n interface and lower doping near p-i interface results in higher V_{oc} and lower R_s for the solar cell compared with ungraded tunnel-junction p-layer.

Table 8-3. The solar cell V_{oc} , FF_r and R_s for n-i-p and n-i-p-n devices with different p layers

Sample	Structure	Treatment	V_{oc} V	FF	FF _r	R_s Ω/cm ²	J_{sc} mA/cm ²	P_{max} mW/cm ²
LL866	n-i-p	Single 55 sec, 3 sccm BF ₃	0.961	0.589		10.9	11.8	6.65
LL809	n-i-p-n	Single 55 sec, 7 sccm BF ₃	0.906	0.560		12.1	10.8	5.48
LL860	n-i-p-n	Double 30 sec, 3 sccm BF ₃ near p-i 30 sec, 7 sccm BF ₃ near p-n	0.920	0.559	0.507	13.8	9.77	5.03
LL871	n-i-p-n	Double 55 sec, 3 sccm BF ₃ near p-i 30 sec, 7 sccm BF ₃ near p-n	0.938	0.571	0.503	13.0	9.36	5.02

Section 9

Optimization of Triple-junction a-Si Alloy Solar Cell

9.1 Introduction

A significant portion of the research effort in the development of high stable efficiency triple-junction solar cells is in the optimization of component cells and the tunnel junction, as we described in previous sections. In this section, we describe solely the research effort on the deposition of triple-junction solar cells. The triple-junction devices are deposited in both the LL1 and the LL2 device deposition systems in our laboratory. They were deposited on SS substrates coated with textured Ag/ZnO back-reflector. After the deposition of n-i-p-n-i-p-n-i-p layers using PECVD, ITO is deposited as the top electrode and an anti-reflection coating, using reactive evaporation in oxygen.

9.2 Triple-Junction Solar Cell Deposition in LL1 Deposition System

Since we have not established an a-SiGe middle cell i-layer deposition in the LL1 system, a-Si/a-Si/a-SiGe triple-junction devices with a-Si middle cell were deposited. The top cell intrinsic layer was made with the wide bandgap a-Si material deposited at low temperature and high hydrogen dilution, as described earlier in Section 4. Figure 9-1 is the J-V curve of the a triple-junction solar cell produced in the LL1 system. The initial efficiency is 9.6%. The V_{oc} of this triple device is 2.56 V, a high value which reflects the use of a high V_{oc} top cell and a-Si as the middle cell. The FF of the triple-junction cell is also high. The limitation in efficiency is in the short circuit current. From the QE curve of this triple-junction cell, we measured 6.15, 5.03 and 6.24 mA/cm² short circuit current for the top, middle and bottom component cells respectively. Obviously the current is limited by the middle cell. Also, the total current is low, around 17.4 mA/cm², and the blue response at 400 nm is low, with QE=0.5 at 400 nm. The solar cell efficiency is expected to be improved after we improve the J_{sc} through implementing the following adjustments: 1) the middle cell to be made thicker, or made with an a-SiGe middle cell i-layer; 2) the bottom cell to have more Ge to increase the red response; and 3) the top p-layer (p3) to be made thinner to enhance the blue response.

9.3 Triple-Junction Cell Optimization in LL2 Deposition System

The LL2 deposition system is operated in parallel to produce triple-junction solar cells. Figure 9-2 is the J-V curve of one of the first triple-junction cells made in the LL2 deposition system. Figure 9-3 is the QE curve for this triple-junction cell. Compared with the properties for the cell made in LL1, the short circuit current is higher; however, the FF is low, due to a poor tunnel-junction between the component cells. The series resistance was around 150 Ω cm².

In order to improve triple-junction cell efficiency, we have optimized the deposition of the triple-junction cell in the following areas: 1) tunnel junction, as described in Section 8-2; 2) a-SiGe bottom cell, as described in Section 3-3; 3) a-SiGe middle cell, as described in Section 3-4; 4) quality of intrinsic a-Si layer for the top cell i-layer; and 5) component cell current matching.

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Jsc = 5.358 Jmp = 4.625

Voc = 2.558 Vmp = 2.07

FF = .699

A = .25 cm² Pmx = 9.575 mW/cm²

Rs = 52.1 Ω cm²

Rsh = 2.3E5 Ω cm²

Figure 9-1 J-V curve of the a triple-junction cell produced in the LL1 system with wide

$J_{sc} = 6.485$ $J_{mp} = 5.401$
 $V_{oc} = 2.286$ $V_{mp} = 1.65$
 $FF = .601$
 $\eta = .25 \text{ cm}^2$ $P_{max} = 8.911 \text{ mW/cm}^2$

$R_s = 154.2 \text{ } \Omega \text{ cm}^2$
 $R_{sh} = 5.2E3 \text{ } \Omega \text{ cm}^2$

Figure 9-2 J-V curve of one of the first triple-junction cell deposited in LL2 system before optimization.

Figure 9-3 QE curve of the triple shown in figure 9-2.

After these improvements, we have deposited triple-junction a-Si solar cells with 11.2% initial efficiencies ($J_{sc}=7.16 \text{ mA/cm}^2$, $V_{oc}=2.321 \text{ V}$ and $FF=0.672$). Figure 9-4 is the J-V curve for one of these 11.2% triple-junction cells. The 11.2% triple-junction devices are expected to have around 9.5-10% stabilized efficiency. Figure 9-5 is the QE curve of this improved triple-junction cell device, showing high spectral response in all regions and a desirable current matching among the component cells.

9.4 Summary

Triple-junction a-Si alloy solar cells were deposited and optimized in parallel in both the LL1 and LL2 deposition systems. After incorporating the optimization in the component cells and the tunnel junction as we described in the previous sections as well as the improvement in triple-junction device deposition, we have achieved, using the newly installed LL2 deposition system, triple-junction solar cells with 11.2% initial efficiencies.

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$J_{sc} = 7.155$ $J_{mp} = 6.418$

$V_{oc} = 2.321$ $V_{mp} = 1.739$

$FF = .672$

$A = .25 \text{ cm}^2$ $P_{max} = 11.158 \text{ mW/cm}^2$

$R_s = 56.4 \ \Omega \cdot \text{cm}^2$

$R_{sh} = 2.4E4 \ \Omega \cdot \text{cm}^2$

Figure 9-4 J-V curve of a triple-junction cell after preliminary optimization, showing 11.2% initial efficiency.

Figure 9-5 QE curve of the triple-junction cell showing 11.2% initial efficiency.

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13. ABSTRACT (Maximum 200 words) This report describes work performed by Energy Conversion Devices, Inc. (ECD) under a 3-year, cost-shared amorphous silicon (a-Si) research program to develop advanced technologies and to demonstrate stable 14%-efficient, triple-junction a-Si alloy solar cells. The technologies developed under the program will then be incorporated into ECD's continuous roll-to-roll deposition process to further enhance ECD's photovoltaic manufacturing technology. In ECD's solar cell design, triple-junction a-Si alloy solar cells are deposited onto stainless-steel substrates coated with Ag/ZnO back-reflector layers. This type of cell design enabled ECD to use a continuous roll-to-roll deposition process to manufacture a-Si PV materials in high volume at low cost. Using this cell design, ECD previously achieved 13.7% initial solar cell efficiency using the following features: (1) a triple-junction, two-band-gap, spectrum-splitting solar cell design; (2) a microcrystalline silicon p-layer; (3) a band-gap-profiled a-SiGe alloy as the bottom cell i-layer; (4) a high-performance Ag/ZnO back-reflector; and (5) a high-performance tunnel junction between component cells. ECD also applied the technology into its 2-MW/yr a-Si production line and achieved the manufacturing of 4-ft ² PV modules with 8% stable efficiency. During this program, ECD is also further advancing its existing PV technology toward the goal of 14% stable solar cells by performing the following four tasks: (1) improving the stability of the intrinsic a-Si alloy materials; (2) improving the quality of low-band-gap a-SiGe alloy; (3) improving p ⁺ window layers; and (4) developing high stable-efficiency triple-junction a-Si alloy solar cells.			
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