Low-Temperature a-Si:H/GaAs Heterojunction Solar Cells

Davood Shahrjerdi, Bahman Hekmatshoar, and Devendra K. Sadana

***Abstract*—We propose a novel hydrogenated amorphous silicon (a-Si:H)/GaAs heterostructure for photovoltaic solar cells. The structure has two key advantages: 1) low-temperature processing and 2) a relatively low cost of cell fabrication compared with conventional junction structures that require epitaxial growth. We investigate the impact of different hydrogen dilution levels used during a-Si:H deposition on the electrical characteristics of heterojunction GaAs solar cells. It is interesting to note that epitaxial growth of silicon on GaAs occurred when relatively high hydrogen dilution levels were used. The prospect of silicon epitaxy in improving the cell performance is discussed.**

***Index Terms*—Heterojunction, photovoltaic solar cells.**

I. INTRODUCTION

DIRECT bandgap III–V materials are promising candidates for thin-film portable high-efficiency photovoltaic (PV) solar cell applications, due to their strong absorption properties. However, the high III-V substrate cost has always been the main impediment for their widespread use for terrestrial PV applications. Therefore, development of various layer transfer schemes to produce thin sheets of single-crystalline III–V materials to reduce substrate cost has been the active area of research [1]–[4]. Several approaches to fabricate thin-film single-crystal III–V solar cells have been published. One straightforward approach to obtain thin-film cells requires epitaxial growth of the III–V solar cell structures and its removal by a layer transfer technique [3]–[5]. The high cost of epitaxy, however, is expected to increase the final cost of the solar cell. Alternative approaches, such as the use of Schottky-type junctions [6] and zinc diffusion [1], have been proposed to eliminate the need for epitaxial formation of p/n junctions to reduce cost. In this paper, we describe an attractive approach that utilizes aSi:H/gallium arsenide (GaAs) heterojunction (HJ) solar cell for the first time. Not only does this approach use low processing temperatures ($<$200 °C) for cell fabrication, but it also offers a path for low-cost, high-efficiency PV technology when implemented in conjunction with a layer transfer technique.

HJs of a-Si:H on crystalline silicon (c-Si) was first proposed by Fuhs *et al.* [7]. This structure was later commercially developed by Sanyo (commercially known as the heterojunction with intrinsic thin layer (HIT) structure), producing high-efficiency c-Si solar cells [8]. A thin layer of a-Si:H is believed to provide exquisite surface passivation on c-Si [9]–[11]. In addition to c-Si, a-Si:H has been widely explored for passivating III–V materials. Published *C–V* and metal-oxide semiconductor field-effect transistor data from a-Si:H passivated GaAs show surface inversion indicating effective unpinning of the Fermi level at the GaAs surface [12], [13]. Effective surface passivation is equally crucial to improving the performance of PV solar cells to reduce the dark current. The reduction in surface recombination velocity (SRV) with a-Si:H is attributed to 1) the hydrogen content in the a-Si:H, contributing to passivation of surface dangling bonds; and 2) the field-effect induced passivation due to conduction and valence band offsets (ΔE_c and ΔE_v) in a-Si:H/c-Si or a-Si:H/III–V heterostructures. Proper engineering of the energy band structure of HJs is, therefore, required via a-Si:H deposition parameters. Hydrogen dilution is believed to be the key engineering parameter that allows altering energy band offsets. Theoretical studies [14] suggest that the hydrogen content strongly influences the band offset and the resulting field-effect passivation. Therefore, this paper is also aimed at systematically investigating the effect of various hydrogen dilution ratios during a-Si:H deposition on the performance of HJ a-Si:H/GaAs solar cells.

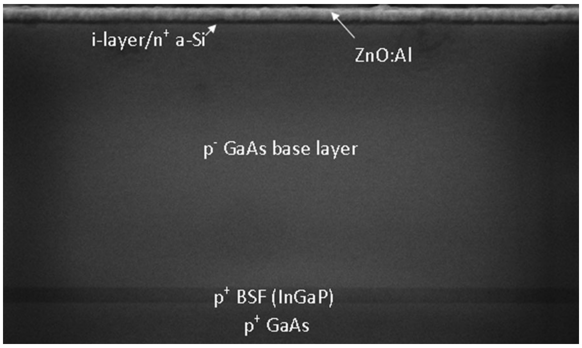

Fig. 1. Cross-sectional scanning electron microscope image of an HJ GaAs PV solar cell, illustrating the device structure.

II. EXPERIMENTS

The epitaxial solar cell structure was grown by metal–organic chemical vapor deposition (MOCVD) on (0 0 1) p-type Zn-doped GaAs substrates. Fig. 1 illustrates a cross-sectional secondary electron microscopy image of the final HJ GaAs device. The structure consists of 0.2-μm-thick lattice-matched p-type (1×10^{18} cm^{-3}) InGaP for the back-surface field, followed by a 2.5-μm-thick p-type (1×10^{17} cm^{-3}) GaAs absorbing layer.

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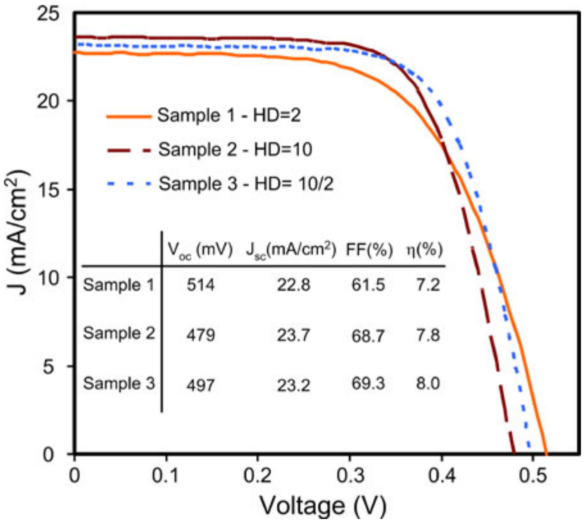
TABLE I
SUMMARY OF THE HJ GaAs DEVICE STRUCTURES STUDIED IN THIS PAPER

Layers	**Sample 1**	**Sample 2**	**Sample 3**
n^+ a-Si:H	6nm	6nm	6nm
i-layer (HD=2)	6nm	-	6nm
i-layer (HD=10)	-	8nm	8nm
GaAs absorber	2.5μm	2.5μm	2.5μm
InGaP BSF	0.2μm	0.2μm	0.2μm

The first step for solar cell fabrication included removal of the native oxide on GaAs in a dilute hydrofluoric acid (100:1) solution for 2 min. Next, samples were immediately transferred into a multichamber plasma-enhanced chemical vapor deposition (PECVD) system to deposit a stack of i/n^+ a-Si:H layers at ∼200 °C at a base pressure of $\sim 5 \times 10^{-7}$ mTorr. In order to investigate the effect of the hydrogen dilution on the performance of the HJ GaAs solar cells, three different types of i-layers were prepared with three different hydrogen dilution ratios (see Table I). The hydrogen dilution is defined as the ratio of H_2 gas flow to SiH_4 gas flow. Table I summarizes the device structures, layer thickness values, and their corresponding hydrogen dilution levels used in this study. The deposition of the a-Si:H stack was followed by ∼80-nm-thick Al-doped zinc oxide transparent conductive oxide (TCO) deposited in a dc magnetron sputtering system. Front metal contact grid was formed using a shadow mask. The shadowing loss from the metal grid was measured to be ∼8%.

III. Results and Discussion

The current density–voltage (*J*–*V*) characteristics of the cells were measured under simulated AM1.5 solar spectrum at 1 sun intensity. The illumination intensity of the solar simulator was calibrated using a reference silicon solar cell, measured by National Renewable Energy Laboratory. The 1 sun *J*–*V* characteristics from the samples with different hydrogen dilution ratios are shown in Fig. 2. It is evident from the light *J*–*V* data that sample 2 with the highest hydrogen dilution level of 10 has the highest short circuit current density J_{sc}, while sample 1 with the lowest hydrogen dilution level of 2 has the highest open circuit voltage V_{oc}). High-resolution transmission electron microscopy (HRTEM) was performed to study physical properties of the a-Si:H/GaAs interfaces. It is remarkable to note that the HRTEM micrograph (see Fig. 3) clearly shows epitaxial growth of PECVD deposited Si (with hydrogen dilution ratio of 10) on GaAs at merely 200 °C. Although epitaxial growth of PECVD a-Si:H on c-Si has been previously observed at temperatures of 150–300 °C [15], [16], it is the very first time that the epitaxial growth of Si on GaAs by PECVD is being reported at <200 °C, to best of our knowledge. The V_{oc} data indicate that the amorphous i-layer is more effective in passivating the GaAs surface than the epitaxially grown i-layer of Si (epi-Si). On the other hand, significantly improved J_{sc} is obtained due to reduced light absorption at short wavelengths in the epi-Si layer as evident from the external quantum efficiency (EQE) measurements (see Fig. 4). Since thin a-Si:H is known to effectively passivate c-Si, we prepared another sample 3, in which the i-layer was deposited as a stack of 8-nm epi-Si followed by 6 nm of a-Si:H. Comparing the light *J*–*V* data for samples 2 and 3 indicates that the improved surface passivation employing the stacked i-layer led to an increase in V_{oc} while slightly degrading J_{sc} due to increased optical losses in the stacked i-layer.



	V_{oc} (mV)	J_{sc}(mA/cm²)	FF(%)	η(%)
Sample 1	514	22.8	61.5	7.2
Sample 2	479	23.7	68.7	7.8
Sample 3	497	23.2	69.3	8.0

Fig. 2. Light *J*–*V* characteristics of the different HJ GaAs cells measured at 1 sun.

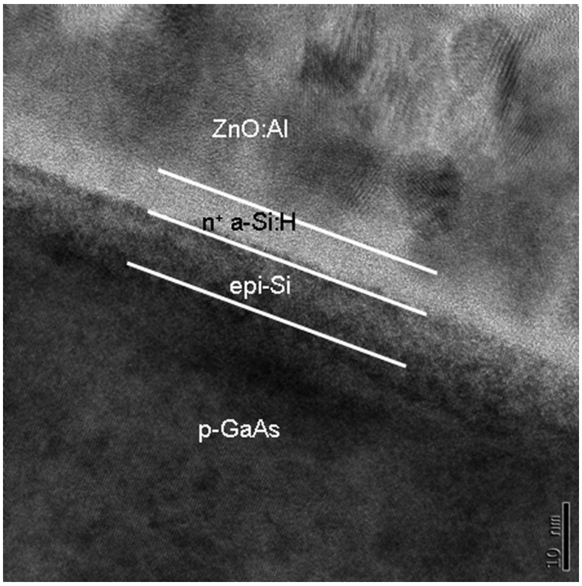


Fig. 3. High-resolution cross-sectional HRTEM image illustrating the epitaxial growth of silicon on GaAs at HD ratio of 10.

It is important to note that the performance of our HJ GaAs solar cells is primarily limited due to low V_{oc}. The total dark current density J_0 of the cells, which is shown in Fig. 5, was

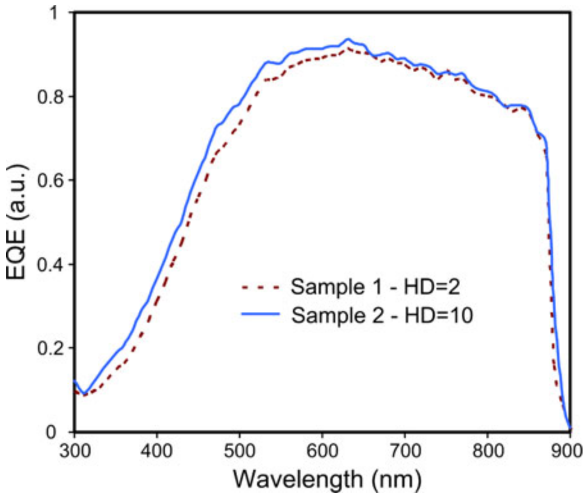


Fig. 4. EQE data for the samples 1 and 2, indicating the reduced light absorption at shorter wavelengths upon silicon epitaxy.

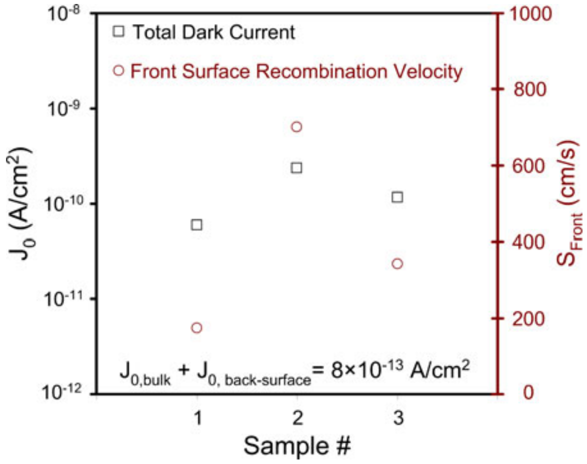


Fig. 5. Comparison of the total J_0 of the HJ GaAs cells and the corresponding SRV at the front surface, extracted from (1) and (2), respectively.

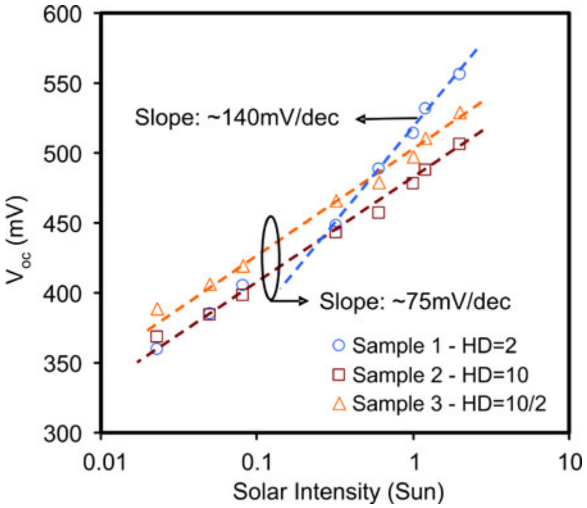


Fig. 6. Measured V_{oc} values for the different HJ GaAs cells as a function of solar intensity.

estimated from the following equation relating V_{oc}, J_{sc}, and J_0:

$$J_0 = J_{\mathrm{sc}}.\exp\left(-\frac{qV_{\mathrm{oc}}}{KT}\right). \tag{1}$$

Factors affecting the dark current density include bulk and surface recombination current densities, which depend on the minority carrier lifetime and the SRV, respectively. The total dark current density is described by the following expression:

$$J_0 = \frac{qn_iW}{\tau} + qn_i(S_{\mathrm{front}} + S_{\mathrm{back}}) \tag{2}$$

where W, n_i, τ, and S are the depletion width, intrinsic carrier concentration of GaAs, minority carrier lifetime, and SRV, respectively. Due to the high crystalline quality of the MOCVD-grown GaAs absorber and the InGaP back-surface field layer, the carrier recombination in the bulk and at the GaAs/InGaP interface is expected to be negligible. The contribution of bulk and back-surface components in total J_0 was estimated to be 8×10^{13} A/cm^2, assuming $\tau_{\mathrm{bulk}} = 25$ ns [17] and $S_{\mathrm{back}} = 2$ cm/s [18]. It is, therefore, evident that the dark current density is dominated by the front surface recombination current. Fig. 5 shows the SRV or the different samples, estimated from (2). It is notable that SRV is directly proportional to the interface state density [19]. Therefore, further reduction of trap density at the i-layer Si/GaAs interface is necessary for further improvement of the V_{oc}.

In order to further investigate surface passivation properties of GaAs for our HJ GaAs devices, V_{oc} of samples 1–3 were measured at different solar intensities (see Fig. 6), illustrating two different regimes. As can be seen from the data in Fig. 6, the stacked epi-Si/a-Si:H i-layer appears to passivate the GaAs surface more effectively than a single a-Si:H i-layer at low solar intensities, whereas at higher solar intensities the surface passivation by a-Si:H alone becomes more effective. The change in V_{oc} appears to be linear with a constant slope throughout the measured illumination range for samples 2 and 3, while two different lines can be fitted to the data for sample 1. This could be due to the illumination dependence of density and distribution of the defects in a-Si:H, influencing the surface passivation properties of GaAs by a-Si:H.

The efficiency of our HJ GaAs solar cells can be further improved by using optimum front grid contact and TCO to minimize optical losses and external series resistance, thus improving both J_{sc} and fill factor (FF). The Suns-V_{oc} measurements were also carried out on samples 1–3 to investigate the efficiency of our HJ GaAs cells in the absence of series resistance. As a result, pseudo-FFs of Samples 1–3 were measured to be 72%, 79%, and 78%, respectively. The Suns-V_{oc} data highlight the effectiveness of epi-Si in improving the FF. This combined with lower optical losses in epi-Si (than those in a-Si:H) leads to superior performance over that in conventional HJ structures with a-Si:H.

IV. CONCLUSION

In summary, we described a novel PV solar cell structure consisting of an HJ of a-Si:H on GaAs. Solar cells using this structure were successfully fabricated at <200 °C. It was shown that epitaxial Si can be grown on GaAs at <200 °C under PECVD conditions with high dilution ratio. Two structures were proposed and studied employing both epi-Si and a-Si:H on GaAs. The electrical data from HJ GaAs structures with epi-Si are shown to offer better performance to that with conventional HJ GaAs structure with a-Si:H due to reduced optical losses and parasitic series resistance in the former. It is clear from the data that further improvement in conversion efficiency requires much more effective surface passivation of the HJ interface.

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