GaInP/GaAs DUAL JUNCTION SOLAR CELLS ON Ge/Si EPITAXIAL TEMPLATES

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ABSTRACT

In this study, we report synthesis of large area (> 2 cm^2) crack-free GaInP/GaAs double junction solar cells on 50 mm diameter Ge/Si templates fabricated using wafer bonding and ion implantation induced layer transfer techniques. Defect removal from the template film and film surface prior to epitaxial growth was found to be critical to achievement of high open circuit voltage and efficiency. Cells grown on templates prepared with chemical mechanical polishing in addition a wet chemical etch show comparable performance to control devices grown on bulk Ge substrates. Current-voltage (I-V) data under AM 1.5 illumination indicate that the short circuit current is comparable in templated and control cells, but the open circuit voltage is slightly lower (2.08V vs. 2.16V). Spectral response measurements indicate a drop in open circuit voltage due to a slight lowering of the top GaInP cell band gap. . The drop in band gap is due to a difference in the indium composition in the two samples caused by the different miscut (9° vs. 6°) of the two kinds of substrates.

INTRODUCTION

To achieve an optimal bandgap sequence for conversion of the solar spectrum in four or more junction solar cells, lattice-mismatched structures will be required. While current metamorphic growth techniques are proving useful in three junction cell applications[1-4], they are limited in the degree of mismatch that they can accommodate. Wafer bonding, on the other hand, can accommodate any degree of lattice mismatch and isolate the defects at the bonded interface between mismatched layers. In this way, materials with a wide variety of lattice parameters can be integrated into a single device.

In our approach to development of a near optimal four-junction solar cell, we use templates for subcell growth employing two lattice parameters, and two bonded interfaces. The first brings together our active material systems, which are based on the GaAs and InP lattice constants. The second allows us to utilize a Si substrate as the overall cell substrate rather an expensive InP substrate. . The final structure will consist of a GaInP/GaAs/GaInAsP/GaInAs four junction solar cell on a Si substrate. Toward this end, we have developed a process for fabrication and characterization of GaInP/GaAs dual junction solar cells on Ge/Si epitaxial templates. In other work, we have demonstrated other key components of multijunction cell development, including high quality InGaAs solar cells on InP/Si templates[5] as well as low-resistance bonded interfaces between GaAs and InP wafers[6].

Wafer bonding and layer transfer allow high-quality single crystal films of one material to be directly bonded to another material. In this process, He^{2+} and/or H^+ are implanted into the device material of choice, for example Ge in this work. Then, the surfaces of the device material and the handle substrate are cleaned and plasma activated. The two materials are then bonded together and with pressure and heat, the implanted ions coalesce and form a crack at the peak implant depth. After the process is complete, a thin film, whose thickness corresponds to the peak implant depth, is bonded to the handle substrate. We have demonstrated up to 50mm wafer layer transfer as shown in Figure 2.

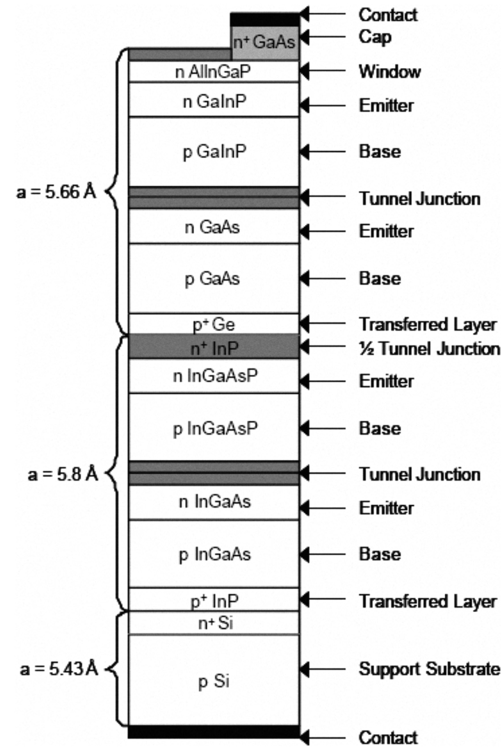

Fig. 1. Schematic of the proposed wafer bonded four-junction solar cell, where **a** denotes the lattice constant of the materials.

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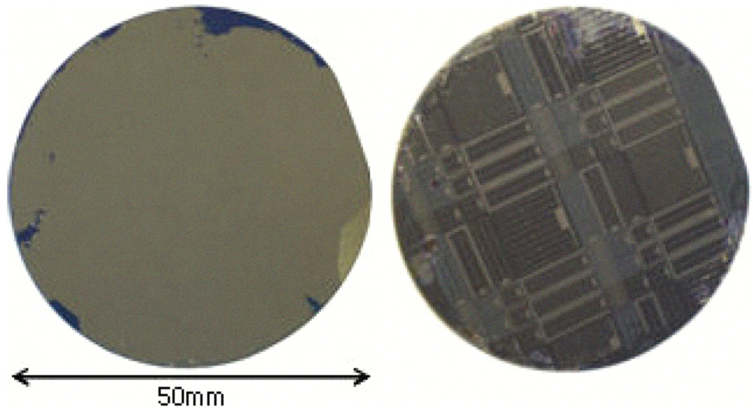

Fig. 2. Optical micrographs of a full 50mm Ge/Si template made with layer transfer and wafer bonding (left), and GaInP/GaAs solar cells grown on a Ge/Si template (right).

EXPERIMENTAL PROCEDURES

Ge/Si templates were fabricated using implantation of H^+ into Ge substrates. These implanted substrates were then hydrophobically bonded to Si substrates. At elevated temperature and pressure, the implanted Ge wafers split along the peak implantation position.

With Ge on Si epitaxial templates, the as-transferred film has an RMS roughness of ~20nm and has a near surface region with a high concentration of residual crystal defects from the ion implantation process. If they are not removed, these defects lead to threading dislocations that propagate from the template into the epitaxial films, as shown in Fig. 3(a). To prepare these templates for epitaxial growth, we must remove the damage layer and minimize the surface roughness. The damaged layer is removed with a simple wet etch, dilute CP-4, and the surface roughness is abated with a touch polish on a Logitech PM5 polisher. After this processing, the template has an RMS roughness of <1nm and the near surface damaged region is gone, as shown in Figure 3. Once the epitaxial template is prepared, we process dual junction GaInP/GaAs solar cells on Ge/Si templates as well as control bulk epi-ready Ge wafers. The resulting cell structure is shown schematically in Figure 4 and experimentally at right in Fig. 2.

RESULTS

After cell processing, we characterize cells via spectral response and light I-V measurements. The data are shown in Figure 5. The spectral response measurements, indicate comparable performance in cells grown on Ge/Si templates as in cells grown on bulk Ge before the AR coating is applied. After the application of the AR coating, the GaAs cell shows a significant drop in performance relative to the control cell. In addition, there is a shift of approximately 60meV in the band gap of the GaInP cell on the Ge/Si template. This can be explained by the different miscut of Ge wafers used in making the template as in the bulk control wafer. The bulk Ge wafer had a miscut of 6°, whereas the Ge wafer used in making the Ge/Si template was 9°. The miscut of the Ge growth surface changes the adsorption of indium; higher miscut typically lowers the incorporated indium composition under the same growth conditions[7]. To probe this more carefully, high-resolution X-ray diffraction rocking curves were performed about the central Ge (001) peak. These measurements show that

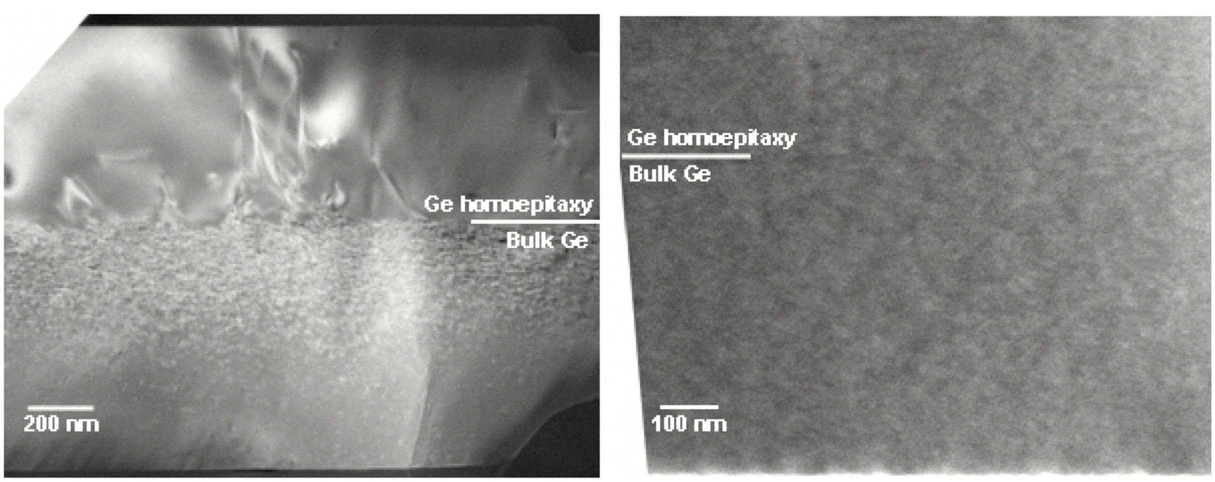

Fig. 3. Cross-sectional transmission electron microscopy images of Ge homoepitaxy on a Ge/Si template without damage removal (left) and with damage removal (right). The white line is at the interface of the substrate and the homoepitaxy.

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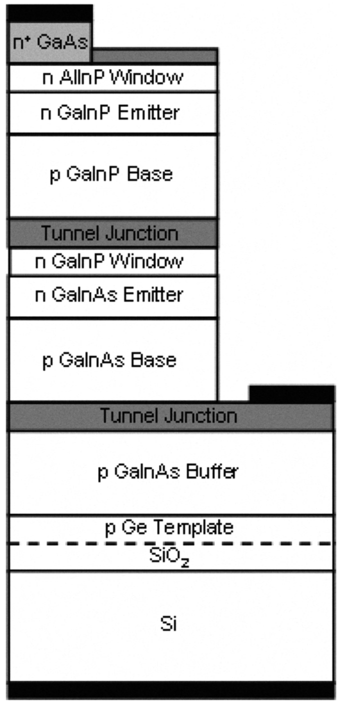

Figure 4. Schematic cross-section of the dual junction solar cell grown and processed by Spectrolab. The bonded interface is shown by a dashed line.

the top cell on the epi-ready Ge wafer is 691 arc seconds compressively strained, which corresponds to an indium composition of 53%. The GaInP cell on the Ge/Si template, however, is lattice matched, corresponding to an indium composition of 49.5%. Increasing the indium composition by 3.5% corresponds to a decrease of 64 meV in the band gap[8], which correlates well with our spectral response measurements.

In the light I-V data, the short circuit current is comparable between some control cells and the template sample. In addition, the fill factors are the same between the control and template grown cells. However, the open circuit voltage is lower in the cells grown on Ge/Si, which is primarily due to the lower band gap of the top cell. Overall, after AR coating, the control cell showed an efficiency of 17.2-19.9%, whereas the Ge/Si templates had an efficiency of 15.5-15.7%.

CONCLUSIONS

We have demonstrated high efficiency GaInP/GaAs dual junction solar cells on Ge/Si templates. In combination with the results from bottom cells grown on InP/Si templates and the low-resistance bonded interfaces, these results enable the fabrication of the full four junction bonded GaInP/GaAs/InGaAsP/InP on Si solar cell.

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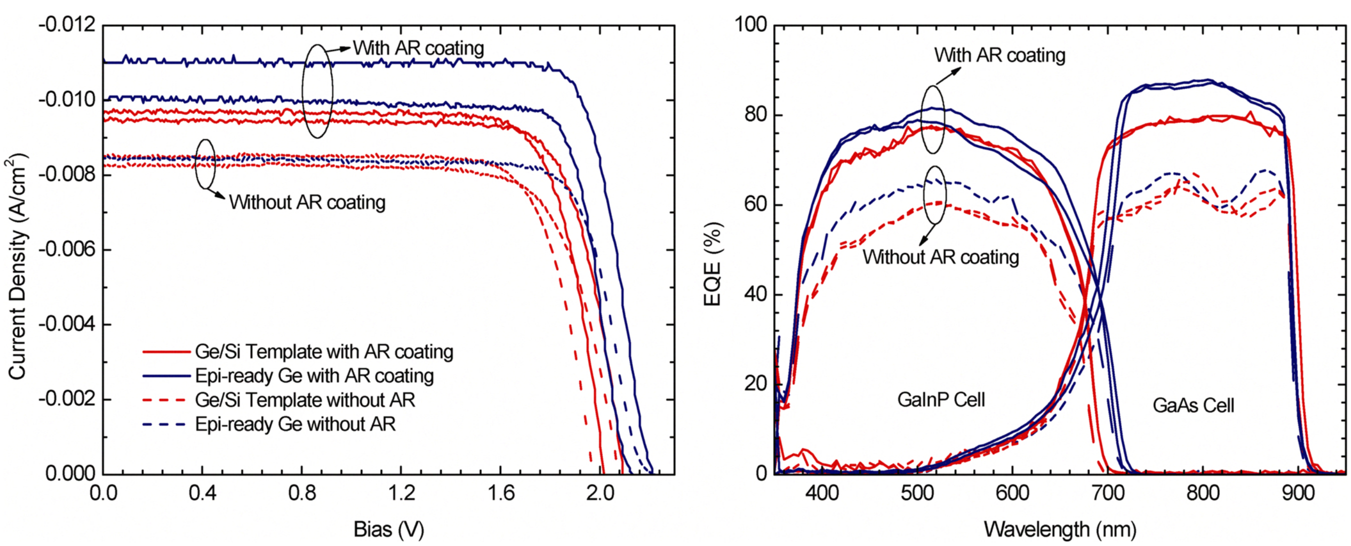

Figure 5. Photovoltaic I-V curves (left) and spectral response (right) for the GaInP/GaAs solar cells grown on Ge/Si epitaxial templates and on a bulk epi-ready Ge substrate.

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