DESIGN APPROACHES AND MATERIALS PROCESSES FOR ULTRAHIGH EFFICIENCY LATTICE MISMATCHED MULTI-JUNCTION SOLAR CELLS

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ABSTRACT

In this study, we report synthesis of large area (>2cm^2), crack-free GaAs and GaInP double heterostructures grown in a multi-junction solar cell-like structure by MOCVD. Initial solar cell data are also reported for GaInP top cells. These samples were grown on Ge/Si templates fabricated using wafer bonding and ion implantation induced layer transfer techniques. The double heterostructures exhibit radiative emission with uniform intensity and wavelength in regions not containing interfacial bubble defects. The minority carrier lifetime of ~1ns was estimated from photoluminescence decay measurements in both double heterostructures.

We also report on the structural characteristics of heterostructures, determined via atomic force microscopy and transmission electron microscopy, and correlate these characteristics to the spatial variation of the minority carrier lifetime.

INTRODUCTION

High efficiency triple junction solar cells have recently been produced with efficiencies exceeding 39% [1]. To achieve the highest efficiencies, the band gaps of the materials used in multi-junction solar cells must be optimized to efficiently absorb as much of the solar flux as possible. This is complicated by the additional requirement in monolithic devices that all the materials be lattice-matched. Future ultra-high efficiency multi-junction solar cells will utilize lattice-mismatched structures to achieve an optimal bandgap sequence for solar energy conversion. While lattice-mismatched multi-junction cells have been fabricated recently using metamorphic growth approaches [2], use of direct wafer bonding techniques to enable lattice mismatch accommodation at the subcell interfaces facilitates considerably more design freedom and inherently higher quality, defect-free, active regions. Our work has focused on a four-junction InGaP/GaAs/GaInAsP/InGaAs cell featuring two optimized, internally lattice-matched two-junction subcells (see Fig.1). The top two junction cell is grown on a template lattice-matched to GaAs, whereas the bottom two junction cell is grown on a template lattice-matched to InP. Subcells are integrated via a direct bond interconnect between the GaAs and GaInAsP.

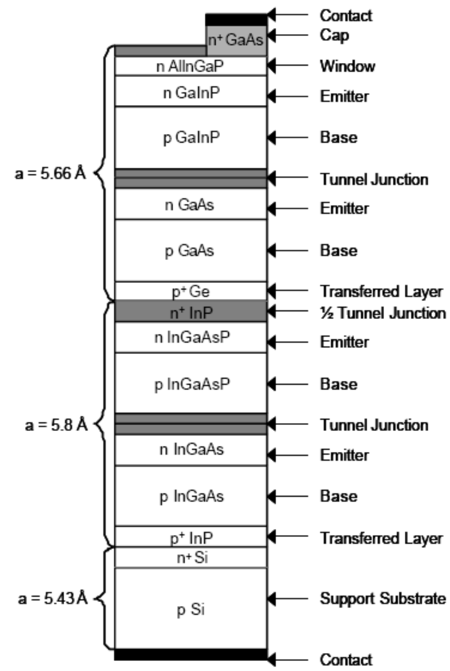

Fig. 1. Schematic of the proposed wafer bonded four-junction solar cell, where **a** denotes the lattice constant of the materials.

For this structure to be viable, we require ohmic contacts at the bonded interfaces (series resistance can degrade the efficiency of concentrator solar cells) and good quality epitaxial growth on bonded templates. The bonded templates are created by layer transfer and wafer bonding utilizing co-implantation of H^+ and He^{2+} for the layer splitting process. In this manner, we can carefully control the thickness of our transferred film. As-transferred, these films are rough (RMS>10nm) and they have a ~200nm thick damaged layer that must be removed to enable further epitaxial growth. Damage can be removed and the roughness can be abated for both the Ge/Si and the InP/Si transferred films using a simple wet etch (see Fig. 2). In addition, the morphology of the surface roughness could affect the quality of the epitaxial films grown on the template, so we also explored the effects of Ge homoepitaxy on our transferred layers.

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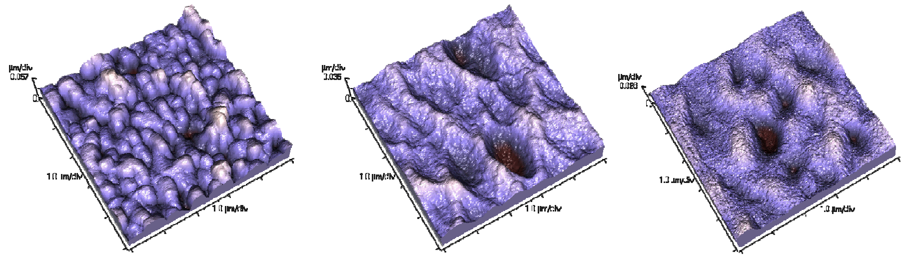

Fig. 2. 5μm x 5μm AFM scans of Ge/Si template as-transferred (RMS = 20nm), after wet-etch (RMS = 9nm), after wet-etch + 200nm homoepi (RMS = 8nm).

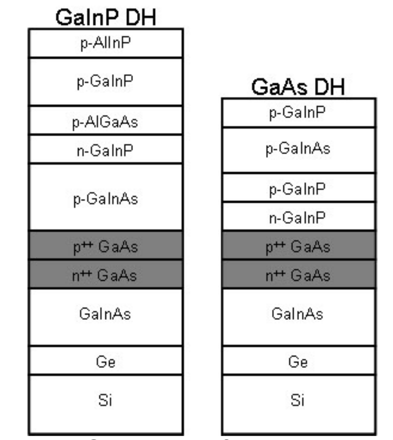

Fig. 3. Schematic of the two double heterostructures grown on Ge/Si templates.

III-V double heterostructures were grown on these Ge/Si templates; one with an AlGaAs/GaInP/AlGaAs active region, the other with a GaInP/GaAs/GaInP active region. These will be referred to as GaInP and GaAs double heterostructures (DH) respectively.

EXPERIMENTAL PROCEDURES

Ge/Si Templates

Ge/Si templates were fabricated using a co-implantation of H^+ and He^{2+} 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 producing a Ge/Si template and a Ge donor wafer. The Ge/Si templates were prepared for epitaxial growth with a modified CP4 etch to remove the residual damage from the implantation. Since the coefficient of thermal expansion mismatch between Ge and Si is quite large [3], the Ge donor wafers were also prepared for epitaxial growth using the same etch treatment to isolate the effects of surface morphology from those due to CTE mismatch-induced strain. Also, 200nm of Ge homoepitaxy was grown on some of the templates before III-V DH growth to enable us to study the effects of different types of surface morphologies. The homoepitaxy samples showed much rounder surface features when compared to the as-transferred and etched Ge/Si templates. In order to better understand the effects of our damage removal etch, Ge epi-ready substrates were etched under the same conditions as the templates. Ge epi-ready wafers with no processing were used as controls in all growths. The growth structures were designed to mimic two-junction solar cell structures (see Fig. 3).

The damage removal processing was analyzed using spectroscopic ellipsometry to measure the Ge film thickness as a function of etch time. Using the implant dose, we estimated the damaged region to be ~200nm thick. Good quality Ge homoepitaxy can be achieved on our templates with a 15s etch (see Fig. 4), thus confirming that our etch process is removing all of the damage.

RESULTS

AlGaAs/GaInP/AlGaAs Double Heterostructures

The GaInP DHs were shown to be optically active by mapping the photoluminescence (PL) over large areas of the transferred films (~6cm^2). The PL was measured using 50mW 488nm laser excitation for all GaInP DH samples. The collection slit width and pump power were not changed between samples, so the PL intensity is comparable among all samples (see Fig. 5). The DH on the Ge/Si template did show the lowest intensity, but it was still within an order of magnitude of the control sample. Since the Ge donor wafer sample shows a higher intensity, the CTE-mismatch is inducing non-catastrophic strain in the III-V growth. However, the surface morphology appears to be the dominant factor in the performance of

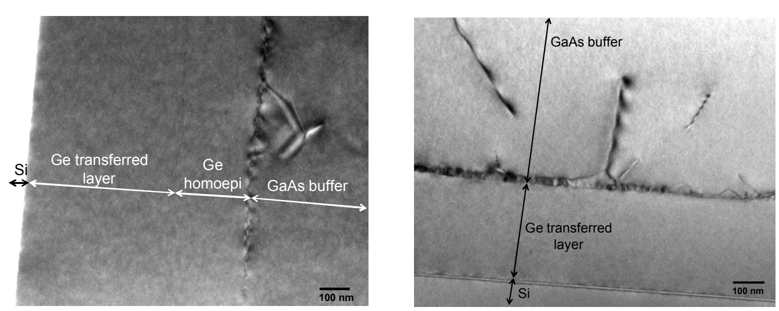

Fig. 4. Cross-sectional TEM images of III-V double heterostructures grown on Ge/Si templates.

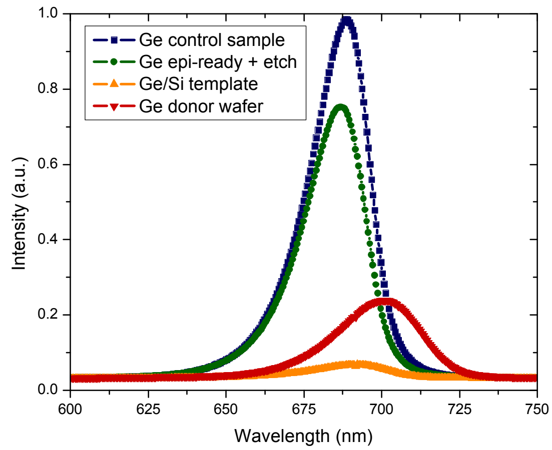

Fig. 5. Photoluminsecence spectra from GaInP active region grown on bulk epi-ready Ge, epi-ready Ge +etch, Ge/Si template, and the Ge donor wafer.

DH Type	Sample	Lifetime (ns)
GaInP	CIT Control	4.78
GaInP	Epi-ready + Etch	1.87
GaInP	Ge/Si Template	0.799
GaInP	Ge Donor Wafer	1.89
GaAs	Control	112
GaAs	Epi-ready + Etch	85.6
GaAs	Ge/Si Template	0.124
GaAs	Ge Donor Wafer	0.104
GaAs	Control (2)	188
GaAs	Ge/Si Template (2)	1.03

Table 1. Photoluminsecence intensity and peak position from the GaInP active region grown on bulk epi-ready Ge and the Ge/Si template.

these structures, since intensity of the donor wafer is only four times the template sample.

In order to quantitatively compare the performance of these samples, time-resolved photoluminescence (TRPL) measurements were performed on all of these samples (see Table 1). The TRPL measurements show that the template sample is of a high quality since it is only four times smaller than the control sample at ~1ns. Again, a factor of two is gained in the Ge donor wafer sample, showing that the surface morphology still needs to be improved.

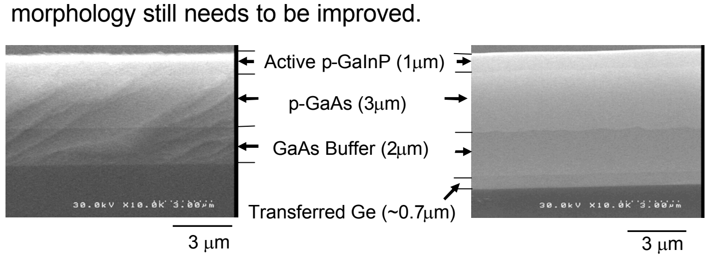

Fig. 6. Cross-sectional SEM images of GaInP active structure on epi-ready Ge (left) and Ge/Si template (right).

Cross-sectional SEM and TEM were used to better understand how the templates were affecting the material structure of the DHs. The cross-sectional SEM images of these structures show a slight roughening at the interfaces, which is most apparent at the GaAs buffer/p-GaAs interface (see Fig. 6). Cross-sectional TEM of these structures shows that all of the residual defects and damage from the ion implantation were successfully removed, so this is not the cause of the lower performance. In addition, the Ge homoepitaxy grown on templates is high quality with a good interface to the template layer (see Fig. 4). Therefore, the templates are useful for homoepitaxy, but the application to heteroepitaxy still needs to be improved. The miscut of the template samples may be imperfect after processing making it more difficult to grow high quality III-V materials. The GaAs buffer layer grown in the structures shows good bulk quality, though there is a high density of defects nucleating just at the surface of the template layer (see Fig. 4). Upon closer examination in high-resolution TEM, this appears to be caused by some degree of contamination on the surface, perhaps a residual oxide layer. Similar contamination can be seen on the bulk epi-ready Ge control sample. In addition, cathodoluminescence (CL) measurements taken on the template samples show the defect density to be ~8x10^{6}cm^{-2}, whereas the Ge donor wafer sample shows a dislocation density of ~1x10^{3}cm^{-2}. The epi-ready Ge that was exposed to the same etching procedures as the template samples shows an extremely low threading dislocation density in CL (~30cm^{-2}), but a dense cross-hatch pattern, which is typical for lattice-mismatched materials. This suggests that the surface morphology may be affecting the ordering in the GaInP, rather than just producing dislocations.

GaInP/GaAs/GaInP Double Heterostructures

The GaAs DHs were also optically active, but the peak intensity of the Ge/Si templates and the Ge donor

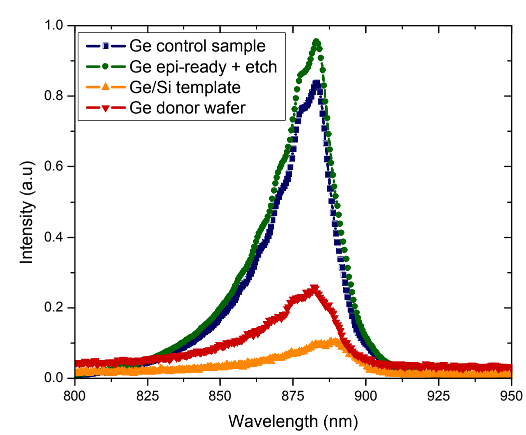

Fig. 7. Photoluminsecence spectra from GaInP active region grown on bulk epi-ready Ge, epi-ready Ge +etch, Ge/Si template, and the Ge donor wafer.

wafers was significantly lower than the control samples. The pump beam was the same as in the GaInP DHs, but the collection slits were adjusted between measurement of the two epi-ready samples and the Ge/Si template and donor wafer. The peak intensities of the template and donor wafers cannot be directly compared. They have been artificially increased to allow direct comparison of the peak positions and peak shapes. The peak position of the template sample is slightly red-shifted compared to all the other samples (see Fig. 7). The CTE-mismatch appears to be causing the peak shift since it is not in the donor wafer sample. However, as with the GaInP DHs, the surface morphology appears to dominate the intensity results. TRPL measurements of these samples show, though the PL intensity is quite low, the GaAs active region on the Ge/Si template has a lifetime of ~1ns (see Table 1).

GaInP/GaAs Two Junction Solar Cells

Preliminary two junction solar cells were grown on Ge/Si templates as well as Ge donor wafers and Ge control wafers. These initial cell results are without anti-reflective coating and without optimizing the growth parameters. Spectral response measurements were taken on the GaInP top cell and converted to external quantum efficiency (see Fig. 8). The Ge/Si template shows about the same overall quantum efficiency as the donor wafer giving us further proof that the surface preparation is dominating the performance of these devices, not the CTE-mismatch induced strain. However, there is some red response loss in the template sample denoting a lower diffusion length in the template sample. Initial light IV data shows promise for the template samples as the short circuit current is similar to the donor wafer sample (see Fig. 9).

CONCLUSIONS

Now that we have demonstrated reasonable top cell performance on Ge/Si template samples, the next step is to optimize the surface preparation. Chemical-mechanical polishing techniques should further improve the surface roughness of these templates.

Our transferred films performed very well mechanically in surviving X-TEM sample prep as well as the large thermal cycles required for metalorganic chemical vapor deposition, indicating that the Ge is covalently bonded to the Si and the CTE-mismatch is not catastrophic for normal processing conditions. These results show promise for the use of transferred Ge layers as epitaxial templates for GaAs-based semiconductor heterostructures on Si.

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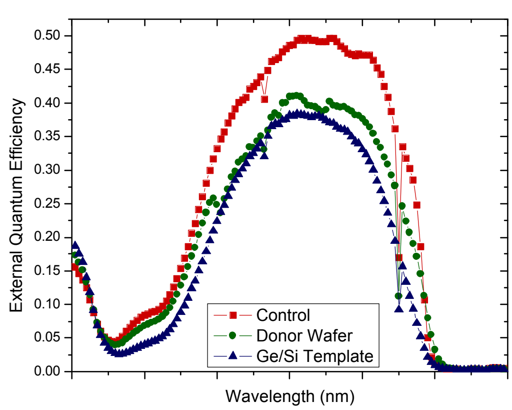

Fig. 8. External quantum efficiency of a GaInP cell grown as part of a two junction GaInP/GaAs solar cell on bulk epi-ready Ge, a Ge donor wafer, and a Ge/Si template.

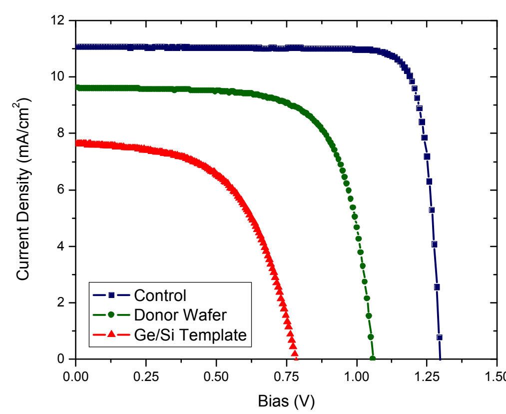

Fig. 9. Light I-V data for GaInP cells on bulk epi-ready Ge, a Ge donor wafer, and a Ge/Si template.