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GaInP/GaAs dual junction solar cells on Ge/Si epitaxial templates

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Large area, crack-free GaInP/GaAs double junction solar cells were grown by metal organic chemical vapor deposition on Ge/Si templates fabricated using wafer bonding and ion implantation induced layer transfer. Photovoltaic performance of these devices was comparable to those grown on bulk epi-ready Ge, demonstrating the feasibility of alternative substrates fabricated via wafer bonding and layer transfer for growth of active devices on lattice mismatched substrates. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2887904]

State-of-the-art high-performance multijunction solar cells are tandem monolithic devices. As such, these devices are limited in their ultimate performance by lattice matching requirements for monolithic growth processes. Though lattice-mismatched multijunction solar cells have been grown with metamorphic growth techniques,[1–5] they are limited to a relatively small range of lattice mismatch in the metamorphic buffer layers.

In multijunction solar cells, monolithic epitaxial integration involves several requirements. First, all materials in the structure must be approximately lattice matched. This ensures that the quality of the active regions are high enough to enable efficient carrier extraction. In addition, the monolithic nature requires these devices to have only two terminals, and based on Kirchhoff's Law, all subcells must operate at the same current. Therefore, an ideal device would divide the solar spectrum power between the subcells evenly. Unfortunately, optimal band gaps for spectrum splitting are not generally in lattice matched materials. As a result, current designs compromise ideal spectrum splitting to achieve lattice matched devices.

In lattice matched GaInP/GaAs/Ge multijunction cells, the Ge cell is significantly overpowered. A third junction with a band gap of approximately 1 eV would enable significantly higher efficiency. This is the primary motivation behind the metamorphic growth efforts in multijunction solar cells.[2–4] Improving current matching between subcells enhances the performance of the entire device. Thick buffer layers are required in metamorphic growth to achieve full relaxation of lattice mismatch induced strain enabling the growth of high quality active regions. The current solar cell with the world record efficiency is a metamorphic triple junction GaInP/GaAs/Ge cell.[6]

Alternatively, wafer bonding can accommodate any amount of lattice mismatch at the bond interface because this interface is incoherent rather than the forced coherency of an epitaxially grown interface. Wafer bonding and layer transfer is an enabling technology for the realization of a four-junction solar cell with band gaps close to the calculated optimal band gaps. A prototypical wafer bonded four-junction would consist of GaInP/GaAs/InGaAsP/InGaAs (1.9/1.42/1.05/0.72 eV) using layer transfer and wafer bonding to combine the GaInP/GaAs dual junction grown on a GaAs or Ge template with the InGaAsP/InGaAs grown on an InP/Si template. For this structure to be viable, we must have Ohmic contacts at the bonded interfaces and good quality epitaxial growth on the bonded templates.

In the present work, we will discuss progress on the top dual junction cell grown on Ge/Si epitaxial templates. High performance bottom cells grown on InP/Si templates and low-resistance bonded interfaces have been discussed previously.[7,8] The bonded templates were fabricated with wafer bonding and ion implantation induced layer transfer.[9,10] This technique allows careful control of transferred film thickness and guarantees high-quality single crystal thin films in direct contact with the handle substrate. This is in contrast to previous work to grow III-V devices on Si substrates, which required buffer layers to minimize the defect generation in the active devices.[11–13]

The first step in fabrication of these epitaxial templates is to implant a Ge wafer with H^+ at 180 keV and a dose of $1 \times 10^{17}\ \mathrm{cm}^{-2}$. Next, wet chemical cleaning removes organic and particulate contaminants from both the oxidized Si and Ge wafers. We employ a SiO_2 bonding layer for thermal stability of the transferred film. Just before initiating the bond, both substrates are plasma activated. A Suss Microtech SB-6e bonder initiates the bond at a temperature of 200 °C.

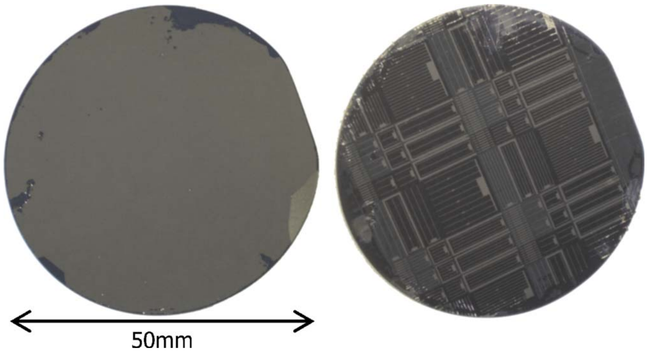

FIG. 1. (Color online) Optical micrographs of a full 50 mm Ge/Si template made with layer transfer and wafer bonding (left) and GaInP/GaAs solar cells grown on a Ge/Si template (right).

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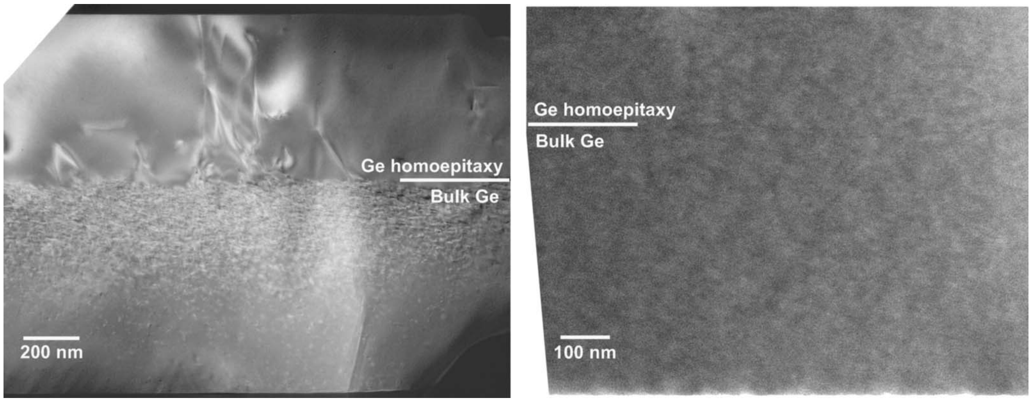

FIG. 2. Cross-sectional transmission electron microscopy images of Ge homoepitaxy on a Ge/Si template without damage removal (left) and with damage removal (right). The white line is at the interface of the substrate and the homoepitaxy.

The bonded pair was then annealed at 250–350 °C under >1 MPa pressure to induce exfoliation and strengthen the bond between the two wafers. The Ge layer transferred to the Si substrate is approximately 1.4 μm thick. Thus far, we have shown up to full 2 in. wafer layer transfer of Ge on Si, as shown in Fig. 1.

The RMS roughness of these films after layer transfer is approximately 25 nm and the ion implantation induced damaged layer extends approximately 200 nm into the film. Removal of the damaged material and abatement of the surface roughness are crucial to enabling high quality epitaxial growth on these substrates. A dilute CP-4 ($HF:HNO_3:CH_3COOH$) wet etch removes the damaged layer. Touch polish with a Logitech PM5 chemical mechanical polisher minimizes the surface roughness further. Final RMS roughness of the Ge/Si templates is ~0.5 nm. Figure 2 shows cross-sectional transmission electron microscopy (X-TEM) images of Ge homoepitaxy on Ge/Si templates with and without damage removal. Removal of the ion implantation induced lattice damage produced substrates that are viable for high quality epitaxial growth.

To examine the potential of these substrates for use in heteroepitaxy of high quality III-V materials, dual junction GaInP/GaAs solar cells were grown using Ge/Si epitaxial templates. Figure 3 shows a schematic of the structure. Spectrolab performed all cell growth and processing. Light current-voltage (*I-V*) performance was measured under AM1.5D illumination before and after an antireflective (AR) coating was applied to the devices (Fig. 4). The light *I-V* data show comparable short circuit current between some control devices grown on a bulk Ge substrate and some devices grown on a Ge/Si template. However, open circuit voltage is slightly lower (1.97–2.08 V versus 2.16 V) in the devices

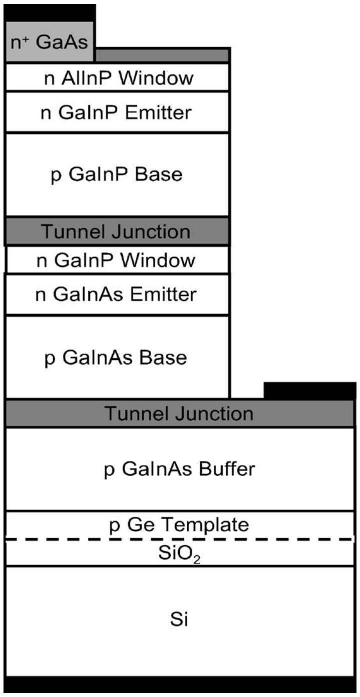

FIG. 3. Schematic cross section of the dual junction solar cell grown and processed by Spectrolab. The bonded interface is shown by a dashed line.

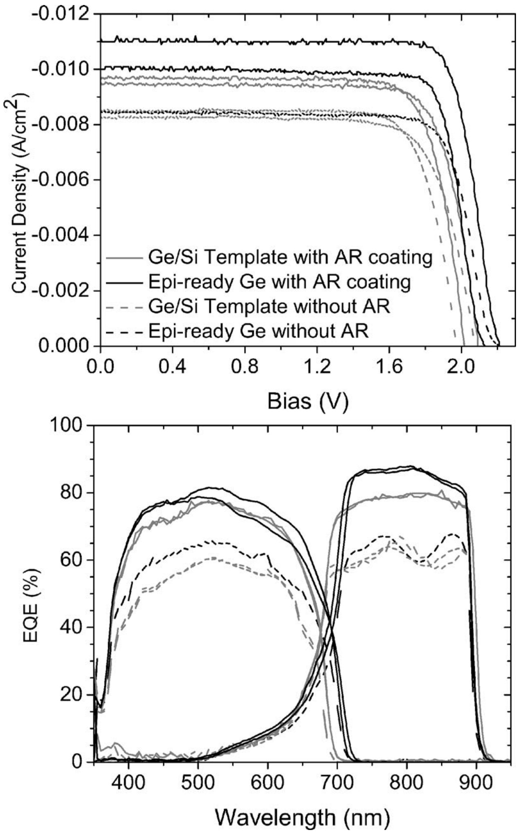

FIG. 4. Photovoltaic *I-V* curves (top) and spectral response (bottom) for the GaInP/GaAs solar cells grown on Ge/Si epitaxial templates and on a bulk epi-ready Ge substrate.

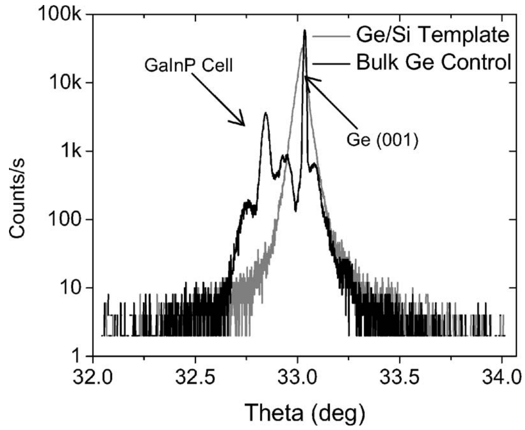

FIG. 5. High-resolution x-ray diffraction rocking curves for the GaInP/GaAs solar cells grown on Ge/Si epitaxial templates and on a bulk epi-ready Ge substrate.

grown on the Ge/Si template. Overall, the device performance is comparable to the control with no loss in fill factor (FF) compared with the control (FF=0.79). 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%.

Spectral response measurements (Fig. 4) indicate the GaInP cell band gap has shifted approximately 60 meV from ~1.74 to ~1.8 eV. This shift in the band gap is due to a change in GaInP composition. The Ge substrate used for the control sample in these growths was (100) oriented with a miscut of 6° toward the ⟨011⟩ orientation, whereas the Ge wafer used to make the Ge/Si template was (100) oriented with a miscut of 9° toward the ⟨011⟩ orientation. Higher miscut substrates have lower In composition for the same growth conditions.[14] Shown in Fig. 5 is the high resolution X-ray diffraction data for the control sample and the Ge/Si template sample. The scan on the control sample shows the top cell to be compressively strained 691 s, which corresponds to an indium composition of about 53%, assuming it is 100% strained. On the other hand, the Ge/Si sample is lattice matched, which corresponds to an indium composition of 49.5%. Increasing indium composition by 3.5% decreases the band gap by ~64 meV,[15] which correlates well with spectral response measurements.

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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