High efficiency InGaAs solar cells on Si by InP layer transfer

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InP/Si substrates were fabricated through wafer bonding and helium-induced exfoliation of InP, and InGaAs solar cells lattice matched to bulk InP were grown on these substrates using metal-organic chemical-vapor deposition. The photovoltaic characteristics of the InGaAs cells fabricated on the wafer-bonded InP/Si substrates were comparable to those synthesized on commercially available epiready InP substrates, thus providing a demonstration of wafer-bonded InP/Si substrates as an alternative to bulk InP substrates for solar cell applications. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2753751]

Engineered substrates consisting of thin films of InP on Si handle substrates (InP/Si substrates) have the potential to significantly increase performance while reducing the cost and weight of compound semiconductor solar cells relative to those fabricated on bulk InP substrates. InGaAs solar cells on InP have superior performance to Ge cells at photon energies greater than 0.7 eV. The current record efficiency cell for 1 sun illumination was achieved using an InGaP/GaAs/InGaAs triple-junction cell design with an In-GaAs bottom cell.[1] Thermophotovoltaic cells from the In-GaAsP family of III-V materials grown epitaxially on InP substrates would also benefit from such an InP/Si substrate.[2]

Additionally, a proposed four-junction solar cell, fabricated by joining subcells of InGaAs and InGaAsP grown on InP with subcells of GaAs and AlInGaP grown on GaAs through a wafer-bonded interconnect, would enable the independent selection of the subcell band gaps for well developed materials grown on lattice matched substrates.[3,4] Substitution of InP/Si substrates for bulk InP in the fabrication of such a four-junction solar cell could significantly reduce the substrate cost, as described below.

The direct heteroepitaxial growth of InP thin films on Si substrates has not produced the low dislocation-density high quality layers required for active InGaAs/InP in optoelectronic devices due to the ~8% lattice mismatch between InP and Si.[5] Wafer bonding, on the other hand, is not subject to lattice matching limitations associated with epitaxial growth, and defects caused by the lack of crystallographic registry are isolated to the wafer-bonded interface. Thus, provided the wafer-bonded interface does not play an active role in the operation of the device, the independent materials and de-

vices fabricated in them can, in principle, have performance typical of devices made on or in the bulk material.

Layer transfer of a high quality single crystal InP film onto a Si bulk substrate can be accomplished through wafer bonding of InP to Si and exfoliation of a thin film from the InP donor wafer induced by implantation of light elements such as hydrogen and helium, as described in depth in Refs. 6 and 7. Because only a few microns of InP are consumed in the transfer of a film and subsequent reclaim of the InP donor substrate, a single InP wafer could be reused repeatedly to generate many InP/Si substrates, thus reducing the material cost of InP in devices grown on those substrates. In this letter, we describe the fabrication of wafer-bonded InP/Si substrates and report the results from the first known demonstration of InGaAs solar cell fabrication on the InP/Si engineered substrates.

InP (001) donor substrates and thermally oxidized Si (001) handle substrates were used for the fabrication of InP/Si substrates for the growth of InGaAs solar cell test structures. The SiO$_2$ film at the bonded interface was found to improve the thermal stability relative to structures fabricated with a direct semiconductor-semiconductor bond. The first step in the InP/Si substrate fabrication was the ion implantation of the InP donor wafer with He$^+$ at an energy between 115 and 180 keV to a dose of at least 1.0×10^{17} cm^{-2}. Prior to wafer bonding, the surfaces of both the InP donor and the Si handle substrates were prepared by wet chemical cleaning to remove organic and particulate contaminations, followed by activation of the bonding surfaces with an atmospheric pressure plasma exposure. Bonding between the InP donor and the Si handle was then initiated at a temperature of 150 °C or greater. The two substrates were then annealed under uniaxial pressure of at least 1 MPa to promote the formation of covalent bonds between the InP and Si substrates and induce the exfoliation of a thin layer

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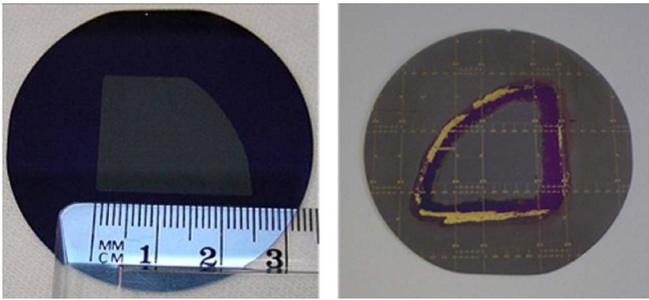a)Electronic mail: tanabe@caltech.edu
b)Electronic mail: haa@caltech.edu

FIG. 1. (Color online) Optical micrographs of (left) a layer-transferred InP/Si substrate; one-quarter of a 50 mm diameter InP layer was transferred onto a 50 mm diameter Si substrate, and (right) InGaAs solar cells grown on an InP/Si substrate.

FIG. 3. Schematic cross-sectional view of the InGaAs solar cell grown on the InP/Si substrates.

($\sim$900 nm) of InP thus forming the InP/Si substrate. A typical image of an InP/Si substrate fabricated by transferring a thin InP film to a Si substrate with a SiO$_2$ bonding layer is shown in Fig. 1 (left). The film was transferred from an InP substrate implanted with He$^+$ to a dose of 1.0×10^{17} cm^{-2} at an energy of 180 keV.

This ion implantation induced exfoliation process results in lattice damage in the transferred film with the peak of that damage roughly coinciding with the exfoliated region. Thus, in the as-transferred InP/Si structure, there is a distribution of lattice defects with a peak at the surface of the transferred film decreasing to a minimum defect density in the material adjacent to the bonded interface. Figure 2 shows a representative cross-sectional transmission electron (XTEM) micrograph of a film transferred from InP implanted with 115 keV He$^+$ to a dose of 1.0×10^{17} cm^{-2}. The inset selected area diffraction pattern shows that the InP adjacent to the bonded interface is single crystalline. Close inspection of the defect structure using high-resolution XTEM imaging shows that the strain contrast apparent in Fig. 2 is caused both by extended defects that can be directly imaged and point defects such as vacancies and interstitials. For the InP/Si substrates used for the growth of InGaAs solar cells, the damaged surface region of the as-transferred InP film was removed, leav-
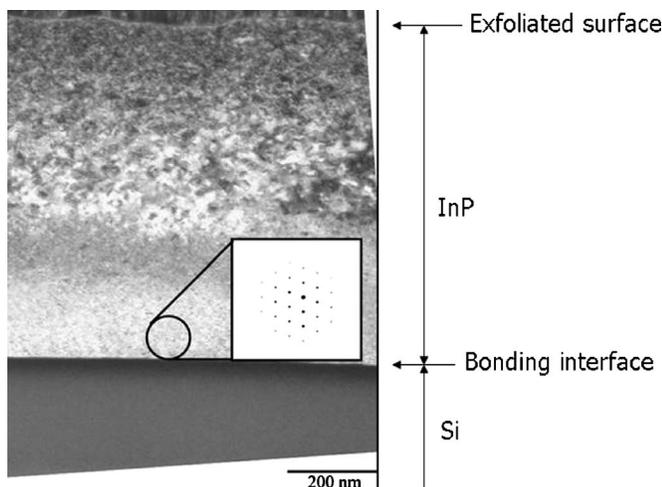
ing a film of $\sim$400 nm thickness. The transferred InP films were thinned using a combination of inductively coupled plasma reactive ion etching for damage removal and a wet chemical etch for surface smoothing.

To test the performance of III-V compound, active photovoltaic device layers grown on the wafer-bonded InP/Si substrates in functional solar cell structures, single-junction InGaAs solar cells were grown both on InP/Si substrates and commercial bulk epiready InP (001) substrates as a reference by metal-organic chemical-vapor deposition. Each of the solar cells had a n-type InGaAs emitter and a p-type InGaAs base with a band gap energy of 0.74 eV, nominally lattice matched to (001) InP. Although we have not investigated the strain in these epitaxial InGaAs layers in detail yet, it is supposed that they are under tensile strain due to the difference in thermal expansion between InP and Si from the analysis with a similar heterostructure in Ref. 6. The cells were designed to enable convenient and low-resistance contact to both base and emitter through the top surface of the cell. A schematic of the InGaAs cell structure is shown in Fig. 3. The cell consists of a 1 μm thick InP buffer layer doped n type with a target carrier concentration of 1×10^{19} cm^{-3} that functions as a current spreading layer for lateral back side contact. Back side and front side contacts were made using Ti/Au contacts on an InGaAs doped n type with a target carrier concentration of 1×10^{19} cm^{-3}. An In-GaAs tunnel-junction was used to switch the carrier type from the p type in the base to n type in the back side contact structure, allowing the front and back contacts to be fabricated with a single lithographic process. The remainder of the structure was typical of a single-junction InGaAs cell. No antireflective coating was used in the fabrication of the test cells. A typical image of the InGaAs solar cells grown on the InP/Si substrate is shown in Fig. 1 (right).

Light current-voltage (I-V) characteristics of the 4 mm^2 InGaAs cells grown on the InP/Si templates and on bulk InP (001) substrates were measured under AM1.5 Global illumination truncated at 850 nm by a long-pass filter, to mimic the optical configuration of subcells under a GaAs cell. The resulting I-V data are shown in Fig. 4. The device parameters for the InGaAs cell grown on the wafer-bonded InP/Si substrate were J_{sc}=24.9 mA cm^{-2}, V_{oc}=0.30 V, and FF=0.66,

FIG. 2. Cross-sectional transmission electron microscope image of an InP/Si substrate fabricated using InP implanted with 115 keV He$^+$ to a dose of 1.0×10^{17} cm^{-2} showing the strain contrast caused by defects created during ion implantation, and (inset) selected-area diffraction image indicating that the InP adjacent to the bonded interface (within $\sim$200 nm) is crystalline.
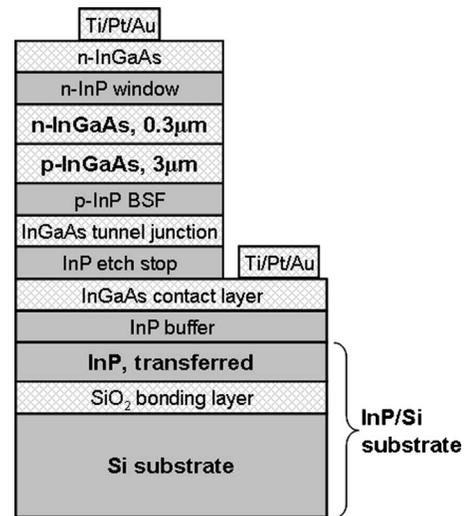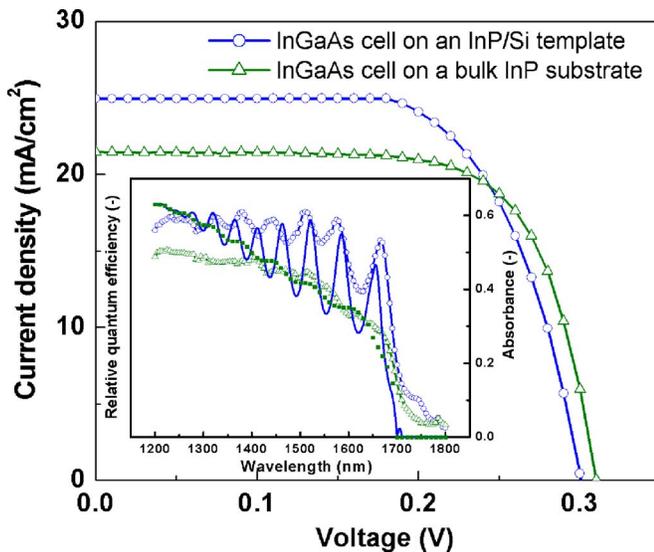
FIG. 4. (Color online) Light *I-V* curves and (inset) spectral responses for the InGaAs solar cells grown on an InP/Si substrate and on a commercial epiready InP substrate. The *I-V* measurements were performed under AM1.5G illumination truncated at 850 nm. The calculated absorbances for InGaAs/InP/SiO$_2$/Si (solid line) and InGaAs/InP (dot line) structures are also plotted in the inset.

where J_{sc}, V_{oc}, and FF are short-circuit current, open-circuit voltage, and fill factor, respectively. This performance corresponds to an energy conversion efficiency of 13.6% based on the irradiation power density of 36.3 mW/cm^2 for the AM1.5 Global illumination truncated at 850 nm. This performance was comparable to that of the InGaAs cells grown on bulk InP (001) substrates, $J_{sc}=21.5$ mA cm^{-2}, $V_{oc}=0.31$ V, and FF=0.70. Figure 4 (inset) shows the spectral responses for the InGaAs solar cells grown on the InP/Si substrate and a bulk InP substrate. The larger J_{sc} and the higher quantum efficiency for the cell grown on the InP/Si substrate are attributed to enhanced light trapping effects in the wafer-bonded cell structure, due primarily to reflection at the bonding interfaces. The reflectivity of the InP/SiO$_2$/Si interface is estimated to be ~0.45 at maximum in the IR range for normal incidence due to the large refractive index differences at the InP/SiO$_2$ and SiO$_2$/Si interfaces compared to a reflectivity at the InGaAs/InP interface of less than 0.005. Light trapping effects might also be enhanced by the slightly rougher top surface for cells grown on InP/Si substrates, attributable to the increased roughness of the InP/Si substrate growth surface (~10 nm rms), relative to the bulk, epiready InP (001) substrates (<1 nm rms).[8,9] The enhanced photocurrent and the oscillatory variation of the spectral quantum efficiency for the InGaAs cell on the InP/Si substrate were well modeled by a simple one-dimensional optical calculation of the absorbance of the InGaAs layer in the InGaAs/InP/SiO$_2$/Si structure relative to the InGaAs/InP reference structure, as shown in the inset of Fig. 4. No significant band gap shift was caused by the InP/Si substrate structure, as indicated by the spectral response. These light

I-V characteristics and spectral response results indicate that InP/Si substrates are promising alternative substrates to InP bulk wafers for InGaAs solar cell fabrication. The obtained J_{sc} of 24.9 mA cm^{-2} for the InGaAs cell on the InP/Si substrate is large enough to current match to state-of-the-art InGaP/GaAs two-junction cells.[10,11] This InGaAs cell is therefore a strong candidate for the bottom cell of an ultra-high efficiency three-junction cell with its significantly higher V_{oc} than the conventional Ge bottom cell.[12–14]

In this letter, we demonstrated InGaAs solar cell fabrication on layer-transferred InP/Si substrates. Such InP/Si substrates could be used as substrates for InGaAsP/InGaAs dual-junction solar cells lattice matched to InP as well as conventional InP single-junction cells. Ultimately, InP/Si substrates are extendable for fabrication of ultrahigh efficiency four-junction AlInGaP/GaAs/InGaAsP/InGaAs cells via a direct bond interconnect between subcell structures of InGaAsP/InGaAs grown on InP/Si and AlInGaP/GaAs grown on GaAs to form the overall four-junction cell structure.

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