

## InGaAs/InP double heterostructures on InP/Si templates fabricated by wafer bonding and hydrogen-induced exfoliation

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Hydrogen-induced exfoliation combined with wafer bonding has been used to transfer  $\sim 600$ -nm-thick films of (100) InP to Si substrates. Cross-section transmission electron microscopy (TEM) shows a transferred crystalline InP layer with no observable defects in the region near the bonded interface and an intimately bonded interface. InP and Si are covalently bonded as inferred by the fact that InP/Si pairs survived both TEM preparation and thermal cycles up to 620 °C necessary for metalorganic chemical vapor deposition growth. The InP transferred layers were used as epitaxial templates for the growth of InP/In<sub>0.53</sub>Ga<sub>0.47</sub>As/InP double heterostructures. Photoluminescence measurements of the In<sub>0.53</sub>Ga<sub>0.47</sub>As layer show that it is optically active and under tensile strain, due to differences in the thermal expansion between InP and Si. These are promising results in terms of a future integration of Si electronics with optical devices based on InP-lattice-matched materials. © 2003 American Institute of Physics. [DOI: 10.1063/1.1637429]

Applications of InP-based materials are numerous, and thus integration of InP on Si may enable realization of powerful integrated III–V-on-Si systems. InP and its lattice matched quaternary counterpart In<sub>1-x</sub>Ga<sub>x</sub>As<sub>y</sub>P<sub>1-y</sub> are direct gap semiconductors, which have high carrier mobilities, therefore finding applications in lasers, multijunction solar cells<sup>1</sup> and high-speed devices. Additionally, they cover the low dispersion and minimum loss wavelengths for optical fiber communication at 1.3 and 1.5  $\mu\text{m}$ , respectively, making them attractive materials for fabricating semiconductor lasers and detectors for telecommunications applications. However, InP is mechanically fragile, is not available in large substrates, and is expensive. Integrating InP thin films on Si substrates improves its mechanical strength and may also allow InP integration on large substrates by a process of tiling transferred thin films. Most importantly, a viable approach to InP/Si may enable cost-effective integration of infrared optoelectronic devices with well-established silicon electronics.

Because InP and Si have a large lattice mismatch (8.1%), heteroepitaxial growth on Si has not yet been able to produce the high quality electronic material needed in optoelectronic devices, since the dislocation density is typically  $10^7 \text{ cm}^{-2}$ . In some cases densities of  $10^5 \text{ cm}^{-2}$  can be reached by conformal growth, but this is only possible on very small areas.<sup>3</sup> Other methods have been attempted to circumvent the restrictions of heteroepitaxial growth. However, most of these processes require an entire substrate to be consumed.<sup>4</sup> Direct wafer bonding of III–V semiconductors to Si has been previously demonstrated.<sup>5,6</sup> However, it would be more desir-

able to have a method for InP/Si integration in which the InP substrate can be repeatedly reused, rather than consuming one InP substrate per active InP-based device layer. Hydrogen-induced exfoliation and layer transfer has shown to be a successful method for Si film fabrication, which has motivated work on hydrogen-induced exfoliation of III–V semiconductors.<sup>7</sup> By wafer bonding and hydrogen-induced layer transfer, a single InP substrate could be reused and implanted repeatedly allowing one InP bulk substrate to transfer many InP films, thus reducing the cost of InP/Si substrate fabrication. In this letter, we present results of the structural and epitaxial template properties of InP/Si heteroepitaxial templates fabricated by wafer bonding and hydrogen-induced layer transfer.

InP wafers were implanted at room temperature with 80 keV H<sup>+</sup> to a dose of  $2 \times 10^{17} \text{ cm}^{-2}$ . Following implantation, both the implanted InP and Si substrates were coated with photoresist to protect the bonding surfaces from scratches and particles. The substrates were then cleaved into  $\sim 1\text{--}3 \text{ cm}^2$  samples. The photoresist was removed and the samples were ultrasonically cleaned with acetone and methanol followed by de-ionized water to leave a smooth, particle-free surface. The surface was then rendered hydrophobic with 10% HF/H<sub>2</sub>O solution. Contact-mode, atomic-force microscopy (AFM) measurements showed that the surface roughness of both InP and Si is less than 0.5 nm rms, which enables intimate contact between the bonding surfaces. Bonding between the InP and Si samples is then initiated by contact at room temperature in an atmospheric ambient. The room temperature bonded samples were then annealed under nitrogen ambient to a temperature of  $\sim 225 \text{ °C}$  under a uniaxial pressure of  $\sim 0.5 \text{ MPa}$  to initiate hydrogen-induced layer exfoliation and layer transfer. By careful control of

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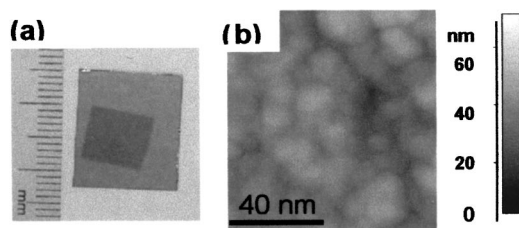


FIG. 1. (a) Optical micrograph of a  $\sim 1$  cm<sup>2</sup> transferred InP layer on Si. (b) Contact mode atomic force microscopy image of the surface.

surface contamination and pressure uniformity, a complete layer transfer has been repeatedly demonstrated.

Figure 1(a) shows an optical image of a  $\sim 1$  cm<sup>2</sup> InP transferred area. The as-transferred surface of the InP exhibits a 9–10 nm rms roughness, as measured by AFM and illustrated in Fig. 1(b). Micrographs of (110)-oriented cross sections obtained by cross-sectional transmission electron microscopy (TEM) are shown in Figs. 2(a)–2(c). A high-resolution image of the interface in Fig. 2(b) indicates intimately bonded InP/Si interfaces. This, together with the ability of the sample to survive the TEM sample preparation process, suggests that InP and Si are covalently bonded. The image reveals the presence of a 4-nm-thick amorphous layer at the interface. Studies on wafer-bonded InP/Si samples by Fourier-transform infrared spectroscopy suggest that water adsorbed at the bonded interface reacts upon annealing to 300 °C to form an interfacial layer of InPO<sub>x</sub>.<sup>8</sup> This behavior is consistent with previous work that shows that HF treated InP surfaces do not form a stable hydride passivation layer and are rapidly oxidized forming a surface to which water readily adsorbs.<sup>9</sup> A dark-field cross-sectional (110) zone-axis TEM image [Fig. 2(a)] shows a 400-nm-thick, low-defect single crystal InP region next to the bonded interface. Figure 2(c) indicates, however, that a 200-nm-thick region nearest to the transferred InP surface appears dark in the bright-field image indicating a large defect density in this region, presumably due to damage from the implantation process.

The suitability of the as-cleaved InP transferred layer as a template for InP epitaxial growth was investigated by growing a lattice-matched InP/In<sub>0.53</sub>Ga<sub>0.47</sub>As/InP double heterostructure with atmospheric-pressure metalorganic vapor-

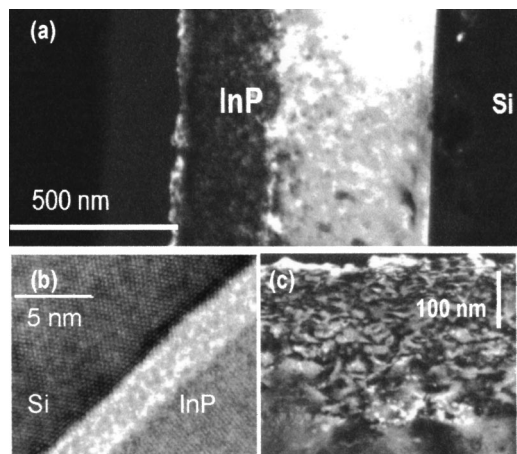


FIG. 2. (a) Dark-field image of a transferred layer of InP on Si. (b) High-resolution electron transmission micrograph of the interface of InP with Si. (c) TEM micrograph of the damaged InP surface.

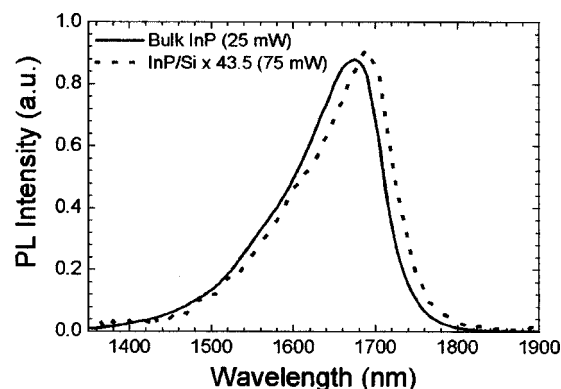


FIG. 3. InP/In<sub>0.53</sub>Ga<sub>0.47</sub>As/InP double heterostructure photoluminescence spectra from a bulk InP control wafer and an InP/Si wafer bonded heterostructure.

phase epitaxy. The double heterostructure was grown simultaneously on an (100)InP/(100) Si structure and also on a bulk (100) InP control wafer at 620 °C. The V/III ratio was  $\sim 120$  for the growth of InP and  $\sim 10$  for In<sub>0.53</sub>Ga<sub>0.47</sub>As. The growth rate was in both cases 100 nm/min. Each layer of the double heterostructure is 1000 nm thick. Photoluminescence spectra, shown in Fig. 3, were measured at room temperature with a 1064 nm pump wavelength with a 10  $\mu$ m diameter spot. A pump power of 25 mW was used on the control sample whereas a pump power of 75 mW was used for the double heterostructure grown on the transferred InP/Si. For purposes of comparing the line shape of the photoluminescence, the peak intensity of the spectrum from the wafer-bonded sample was normalized to that of the bulk InP control. The normalization factor was 43.5, indicating a much weaker photoluminescence intensity for the In<sub>0.53</sub>Ga<sub>0.47</sub>As grown on the InP template. We attribute this to the fact that the surface of the transferred InP has a high density of dislocations resulting from residual ion implantation damage, as seen in Fig. 2(c). We anticipate that the defect density may be reduced by removal of the damaged layer. Importantly, the underlying InP layer appears to be defect-free, within the resolution of cross-sectional transmission electron microscopy, despite thermal cycling to 620 °C of the InP/Si structure during epitaxial growth. Work on the improvement of the surface quality by chemical-mechanical polishing is in progress. The band edge photoluminescence peak has the same shape in both samples, but a slight bandgap shift of  $\sim 15$  nm to longer wavelengths is observed for the In<sub>0.53</sub>Ga<sub>0.47</sub>As grown on InP/Si, with respect to the control sample. This effect can be attributed to tensile strain in the grown films arising from the coefficient of thermal expansion mismatch of the InP and the underlying Si substrate. Indeed, as calculated by Kuo *et al.*<sup>10</sup> such a shift would correspond to a tensile strain of  $\sim 0.075\%$ . Based on the thermal expansion coefficients of InP and Si,<sup>11</sup> the strain of an InP film on Si at room temperature as a function of the bonding temperature of InP/Si pairs was calculated and is depicted in Fig. 4. This result suggests that the zero stress condition for the InP/Si interface is set by the onset of covalent bonding at 400 °C or higher, and thus the InP template is tensile strained about  $\sim 0.07\%$ .

In conclusion, we have shown that integration of (100)

InP thin films on (100) Si is possible by wafer bonding and

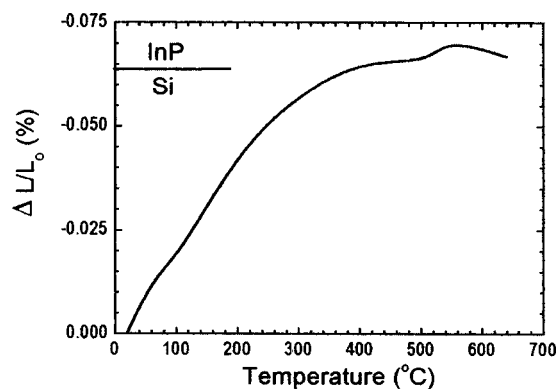


FIG. 4. Strain of a InP film on Si at room temperature as a function of bonding temperature.

hydrogen-induced exfoliation. The resulting InP layers are crystalline. Films survived TEM preparation and thermal cycles up to 620 °C necessary for metalorganic chemical vapor deposition growth, indicating that the InP is covalently bonded to the Si substrate. Moreover, the films were used successfully as epitaxial templates for the growth of optically active InP/In<sub>0.53</sub>Ga<sub>0.47</sub>As/InP double heterostructures. These results show promise for the use of transferred InP layers as epitaxial templates for the growth of InP-based semiconductor heterostructures on Si.

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