High-purity InP grown on Si by organometallic vapor phase epitaxy

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We have grown by organometallic vapor phase epitaxy high-purity InP on Si substrates using a GaAs intermediate layer. The InP layers exhibit residual electron concentration as low as 5×10^{14} cm^{-3} and electron mobilities as high as 4000 and 25 000 cm^2/V s at 300 and 77 K, respectively. The achieved InP quality is dependent on the GaAs intermediate layer thickness. These excellent electrical properties are due to high crystal qualities as evidenced by x-ray rocking curve half width as low as 215 arcsec and defect densities on the order 10^8 cm^{-2}. *p/n* junctions, with ideality factors as low as 1.6 and low leakage currents, confirm the device quality of this material.

Heteroepitaxial growth of InP on Si continues to be a subject of intense investigation because of the potential of integration of optical and other III-V devices with Si-based electronic devices on the same chip. Monolithic integration of Si and III-V devices is desirable for a variety of applications, such as optical communications and optical control of Si devices in fly-by-light systems for avionics, radars, and flight control.

Two III-V on silicon materials have been studied more than others; GaAs-on-Si and InP-on-Si. Of these two, InP-on-Si is of interest because optical sources and detectors can be fabricated with it, and because of the close thermal expansion match between InP and Si.[1,2] This allows the growth of thick layers of InP on Si without cracking and with a reduction of thermal stress-related defects. Recent results on long-life lasers and photodetectors on InP-on-Si have confirmed these expectations.[3,4] Despite these device results, high purity, and high mobility InP-on-Si with properties approaching those of InP have not yet been demonstrated.

We report here the growth of high-purity, high mobility InP-on-Si by organometallic vapor phase epitaxy (OMVPE). We also outline the conditions necessary for the growth of InP-on-Si with high crystalliine qualities needed for excellent optical, electrical, and *p/n* junction characteristics.

These layers were grown by organometallic vapor phase epitaxy. A layer of GaAs was first grown on Si by low-pressure OMVPE, followed by InP grown in a separate system at atmospheric pressure. The reactants for the GaAs growth were trimethylgallium and arsine, while for the InP trimethylindium and phosphine were used. For the *p/n* junctions, the *p* layers were doped with zinc using diethylzinc. Layers grown for Hall measurements were grown on 50 Ω cm *p*-type Si while the ones for the *p/n* junctions were on n^+-Si substrates. A typical growth sequence for both GaAs and InP involves growth of a thin layer at low temperatures (~400 °C), growth of the epilayer at 600–650 °C.

We evaluated the crystal qualities of the InP epitaxial layers (using x-ray diffraction) that were grown on GaAs/Si substrates with GaAs thicknesses ranging from 200 Å to 1 μm. Figure 1(a) show a typical rocking curve for 3 μm InP grown on 1 μm GaAs/Si substrates. Materials grown with thinner GaAs intermediate layers have larger InP rocking curve half widths. The separation of the InP and Si peaks is also smaller for the InP-on-Si layer with the thinner intermediate layer. This indicates that this material is under a higher stress than the more optimized layer. The stress for the layers with 1 μm GaAs intermediate layers is estimated to be as low as 1.3×10^9 dynes/cm^2.

Figure 1(b) further shows that the rocking curve full width at half maximum (FWHM) decreased with increasing GaAs and InP thickness. From this, it can be concluded that the higher the GaAs thickness, the better the quality of the InP grown on it, since the rocking curve FWHM correlates with the defect density of the material. Further study is required to identify the optimum GaAs thickness. However, we believe 1 μm of GaAs is sufficient to optimize the InP quality since the GaAs layer quality is optimized after 0.5 μm growth. We also found that the rocking curve FWHM decreased with post-growth annealing of the InP layer at 750–800 °C for 10 min. It decreased from 363 arcsec for layers annealed at 750 °C to 215 arcsec for layers annealed at 800 °C for 6 μm InP epitaxial layers. These half widths are the lowest that we are aware of for InP layers of similar thickness grown on Si.

Transmission electron microscopy (TEM) was used to examine these layers and showed no evidence of stacking

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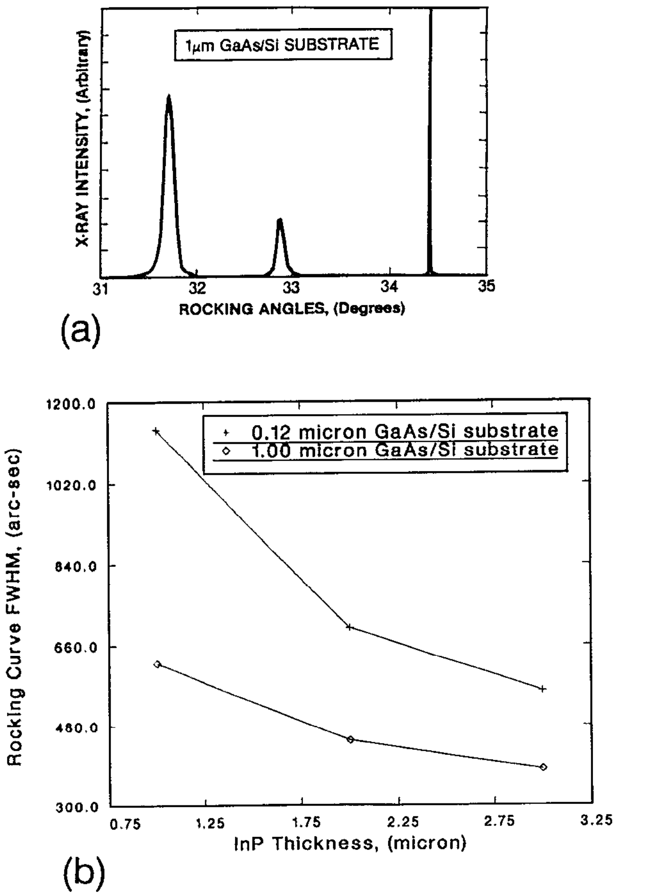

FIG. 1. Crystal properties of 3 μm InP on 1 μm GaAs/Si substrates. (a) X-ray diffraction rocking curve, (b) variation of rocking curve linewidth with GaAs/Si and epitaxial InP thicknesses.

faults. Defect densities as low as 10^8 cm^{-2} were estimated from the TEM micrographs. Etch pit densities (EPDs) were determined from HBr: H_3PO_4 acid delineation and were as low as 10^6 cm^{-2}. The discrepancy between the EPD and TEM values may be due to incomplete delineation of the variety of the defects in the InP by the HBr: H_3PO_4 solution.

The electrical properties of our InP-on-Si were assessed by Hall measurement and differential Hall profiling. The room-temperature Hall mobility values were 710, 3300, and 3000 cm^2/V with corresponding electron concentrations of 5×10^{15}, 2.5×10^{15}, and 4×10^{15} cm^{-3} for 1, 3, and 6 μm InP layers on 1 μm GaAs/Si substrates. The 77 K electron mobility was as high as 25000 cm^2/V s for 6-μm-thick layers. The electron mobility of a 2 μm InP layer grown on InP in the same system and using the same reactant is 4300 and 31 000 cm^2/V s at 300 and 77 K, respectively, with electron concentration of 6.2×10^{14} cm^{-3}. Therefore the InP layers grown on Si have electrical properties that are close to those of InP control layers grown on bulk InP substrate. When purer metalorganics were used, the electron concentration of InP grown on Si were as low as 6.2×10^{14} cm^{-3}.

Differential Hall profiling not only confirms these results, but shows that the 300 K electron mobility in

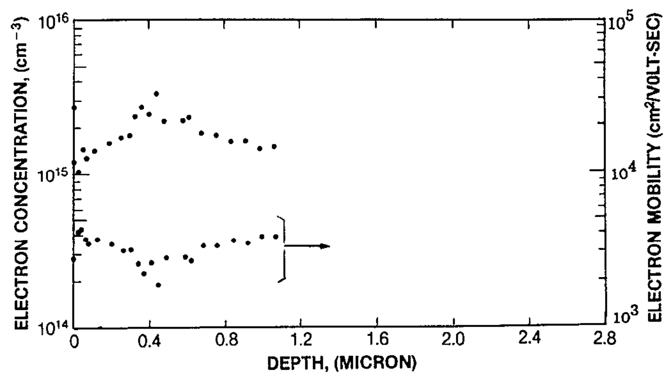

FIG. 2. Electron mobility and concentration profiles of InP-on-Si at 300 K as determined from differential Hall measurements.

theInP-on-Si layer is as high as 4000 cm^2/V s (Fig. 2). The slight variation in mobility in Fig. 3(a) is responsible for the lower average electron mobilities determined from Hall measurements. The electron mobilities does not decrease with depth as drastically as has been reported for InP-on-Si grown by gas source molecular beam epitaxy (MBE).[5] The electrical properties of these InP-on-Si are the best reported to date.

The InP/GaAs/Si layers show good optical properties that are comparable to control material grown on InP substrates. As Fig. 3 shows, the photoluminescence spectra for

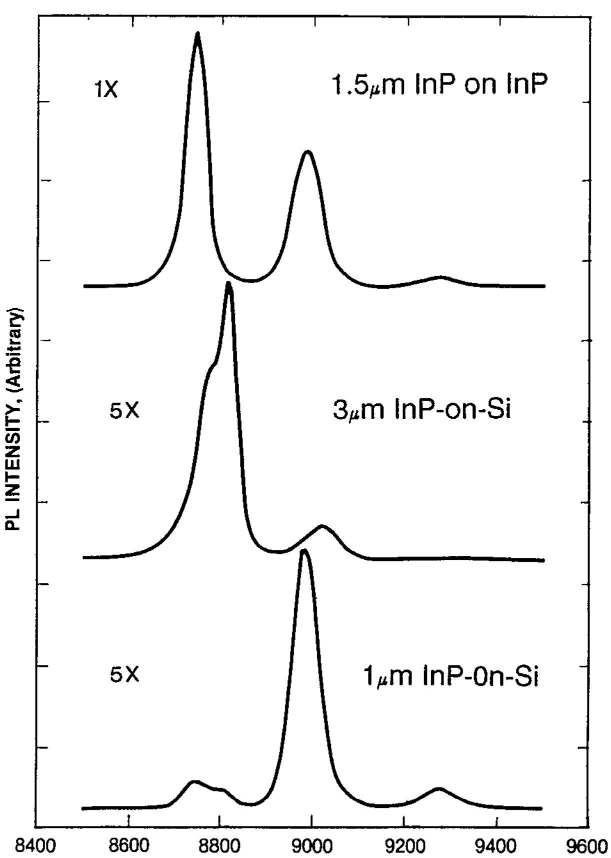

FIG. 3. Photoluminescence spectra of InP-on-Si at 10 K.

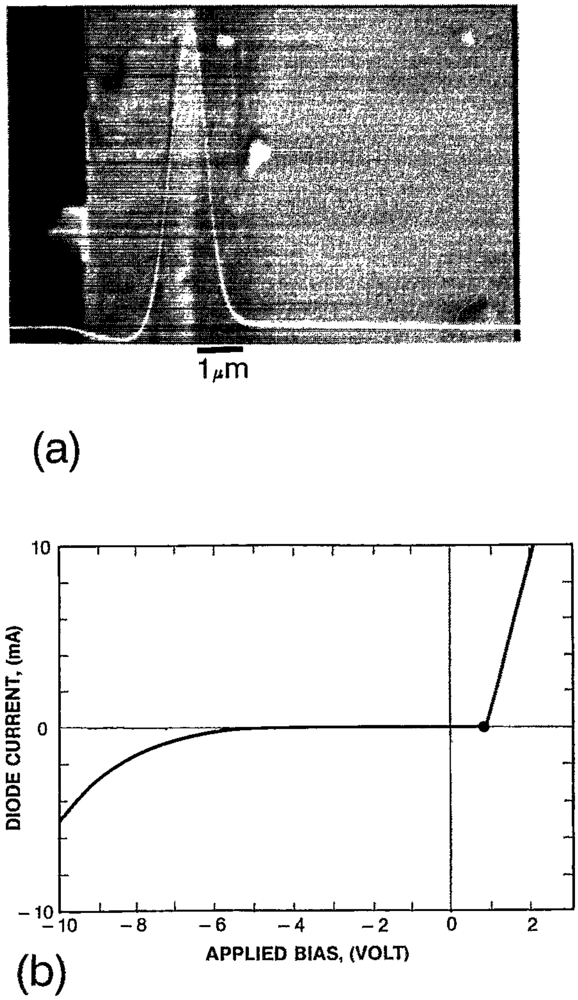

FIG. 4. Junction properties of 1 μm p^+ InP/2 μm *n*-InP grown on GaAs/Si. (a) SEM micrograph and EBIC scan of junction cross section, (b) *I-V* characteristic of the *p/n* junction.

the InP-on-Si at 10 K exhibit bound exciton and acceptor-related emissions at the same energy as the InP layer grown on InP. This indicates that there is little built-in stress in this material unlike typical GaAs-on-Si results, perhaps because of the better thermal expansion match between InP and Si.

Finally, the device quality of the material was evaluated by growing *p/n* junctions. Figure 4(a) shows the scanning electron microscope (SEM) micrograph of a 1 μm p^+-InP/2 μm *n*-InP layer grown on a 1 μm GaAs/Si substrate. The superimposed electron beam induced current (EBIC) trace shows a sharp *p/n* junction. The minority-carrier diffusion length was estimated from the EBIC trace to be 1.6 μm which is lower than the 3 μm typically measured for low threshold laser structures grown on InP. The *p/n* junctions have an ideality factor of 1.6 as estimated from the current-voltage (*I-V*) characteristic in Fig. 4(b).

In summary, we have grown high-purity InP-on-Si using GaAs intermediate layers, with electron mobilities as high as 4000 $cm^2/V\,s$ and 25 000 $cm^2/V\,s$ at 77 K which are the best reported so far for this kind of material. We have shown that these excellent electrical results were enabled by high crystal qualities of the InP films as evidenced by rocking curve FWHMs as low as 215 arcsec and defect densities on the order of 10^8 cm^{-2}. *p/n* junctions with ideality factors as low as 1.6 confirm the device quality of this material.

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