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InP/InGaAs Double Heterojunction Bipolar Transistors Grown on Si Substrates

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We report, for the first time, the successful fabrication of InP/InGaAs double heterojunction bipolar transistors grown on Si substrates by metalorganic chemical vapor deposition. When the InP buffer layer on Si is thick enough, the transistors exhibit high current gains over 250 and their ideality factor is 1.3; these values are comparable to those in transistors grown on InP substrates.

Much attention has been paid to growing III-V compound semiconductors on Si substrates because the use of Si substrates offers many advantages, including high-thermal conductivity, large-area, low-cost wafers, and mechanical durability. Up to now, most of works involving III-V compound semiconductor heteroepitaxy on Si substrates have focused on the growth of GaAs on Si, and many GaAs-based devices have been fabricated on Si [1)-3)]. Compared with the growth of GaAs on Si, the growth of InP on Si has not been widely studied. There are a few reports covering InP-based optical devices fabricated on Si [4)-6)] but none dealing with electronic devices to our knowledge. One of the reasons is the larger lattice mismatch that exists in the InP on Si system than in the GaAs on Si system. However, in InGaAsP/InP light emitting diodes grown on InP substrates, dislocations do not act as strong nonradiative centers, in contrast to GaAs or AlGaAs optical devices[7)]. If the dislocations due to the larger mismatch do not degrade the device performance significantly in the InP system, it appears that InP-based electronic devices on Si substrates would exhibit good characteristics.

One of the promising InP-based electronic devices is the InP/InGaAs heterojunction bipolar transistor (HBT). It has great potential for microwave and high-speed digital applications. Some opto-electronic integrated circuits have already been developed incorporating HBT's. As InP has a very high electron saturation drift velocity, InP/InGaAs double heterojunction bipolar transistors (DHBT's) are also very suitable as microwave power devices. When utilizing HBT's as power devices, the major concern is the temperature rise during operation which is mostly determined by the thermal-spreading resistance of the substrate material. InP substrates have greater thermal conductivity than GaAs, so replacing the substrates with Si further extends the possibile power handling capability. In this paper, the successful fabrication of InP/InGaAs DHBT's grown on Si substrates by metalorganic chemical vapor deposition (MOCVD) is reported for the first time.

The Si substrates used were p-type (boron doped) FZ grown wafers with resistivity of 5000 Ohm-cm, oriented 2 degrees off the (100) plane towards the

[110] direction. Epitaxial layers for the DHBT's were grown on the Si substrate with a thin GaAs buffer layer; the buffer layer usage is expected to result in better quality in the InP on Si system[8),9)]. The two-step growth process[10)] was applied for the InP layer on GaAs on Si.

Figure 1 shows a schematic InP/InGaAs DHBT structure on Si. To achieve a high gain in this DHBT structure, it is necessary to reduce the effect of the conduction-band barrier formed in the base/collector junction on the InP collector side, which degrades the base transport factor[11)]. In this experiment, a 400-Å thick undoped InGaAs layer and a 200-Å N^+-InP layer ($N_D=1x10^{18}$ cm^{-3}) were inserted between the p^+-InGaAs base and the undoped InP collector. Under the optimal two-step growth condition, the 5000-Å thick InP buffer layer was grown on GaAs surfaces. Then the DHBT structure was grown at 550°C. InGaAs layers were grown using trimethylindium, triethylgallium and arsine. Here, n-type and p-type layers were doped with Si and Zn using silane and dimethylzinc, respectively.

For comparison, Fe-doped semi-insulating (100) InP wafers with the same epitaxial layers were processed under the same growth condition concurrently with the Si and GaAs wafers. Figure 2 shows common emitter current gain (h_{FE}) versus collector current density (J_C) for DHBT's on Si, GaAs and InP each with a 12x12 μm^2 emitter area. The ideality factors for base current are 1.8 and 1.5, for the devices on Si and GaAs. These values fairly agree with the values obtained for emitter-base diodes. While h_{FE} increases with J_C for DHBT's on Si and GaAs, it is relatively independent of J_C for DHBT on InP. This difference indicates that the dislocations are responsible for the increase in generation-recombination current at the devices on the Si and GaAs substrates. The maximum h_{FE} is, however, nearly equal for all cases. These results indicate that the dislocations increase only slightly the recombination current at the neutral base region. It has been reported that the dislocations increase the recombination current both at the neutral base region and at the emitter-base interface for the AlGaAs/GaAs HBT's on Si[12)]. The effect of dislocations in the InP/InGaAs system is found to be different from that in the AlGaAs/GaAs system.

Figure 3 shows h_{FE} versus J_C for the DHBT's on Si substrates when the InP buffer layer thickness is varied from 0.5 µm to 4 µm. The DHBT structure is similar to that illustrated in Fig.1, but the base doping concentration and thickness are $1.5x10^{19}$ cm^{-3} and 700 Å, respectively. As the InP buffer layer thickness increases from 0.5 µm to 4 µm, the ideality factor decreases from 1.7 to 1.3 and approaches to that of devices on InP (n=1.2). The device on the 4 µm-thick InP buffer layer exhibits current gains over 250 and its ideality factor is 1.3, which are comparable to those in devices on InP substrates. These results indicate that the the 4 µm-thick InP layer on Si is good enough for DHBT's on Si substrates even though the dislocation density might be $>10^7$ cm^{-2}.

In summary, InP/InGaAs DHBT's were grown by MOCVD on Si substrates for the first time. The DHBT's exhibited high current gains over 250 and an ideality factor of 1.3, which are comparable to those in DHBT's on InP substrates. The dislocations have not significantly increased the recombination current at the neutral base region, but have increased the generation-recombination current at the emitter-base interface. The effect of dislocations on device performance is considerably different from the case of AlGaAs/GaAs HBT's on Si substrates. It was proved that InP/InGaAs HBT's grown on Si substrates can achieve high performance.

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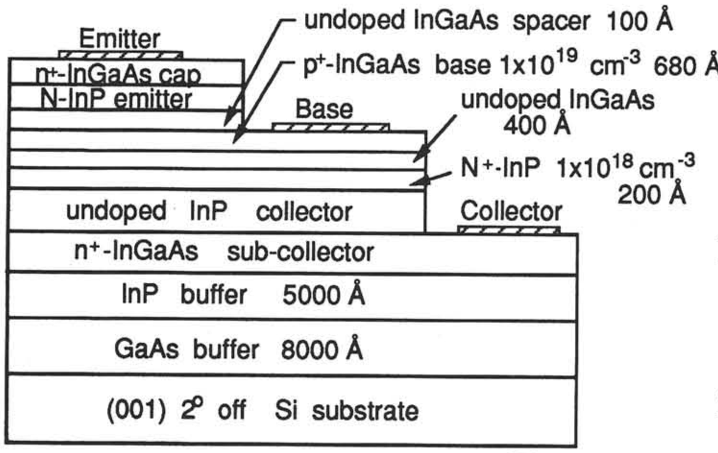

Fig.1: Schematic InP/InGaAs DHBT structure on Si.

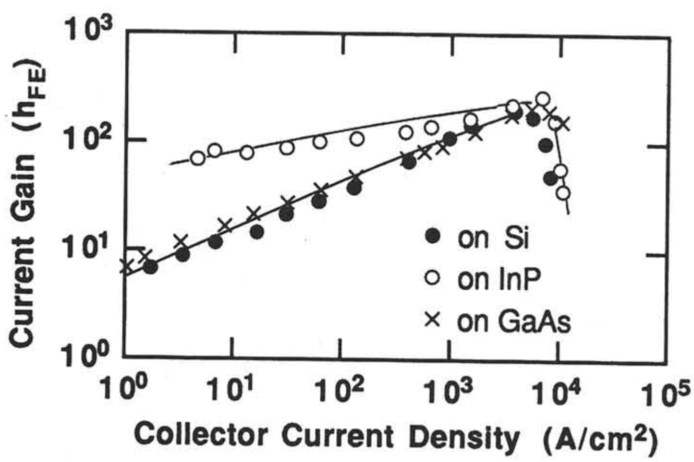

Fig.2: Common emitter current gain (h_{FE}) versus collector current density (J_C) for DHBT's on Si, GaAs and InP.

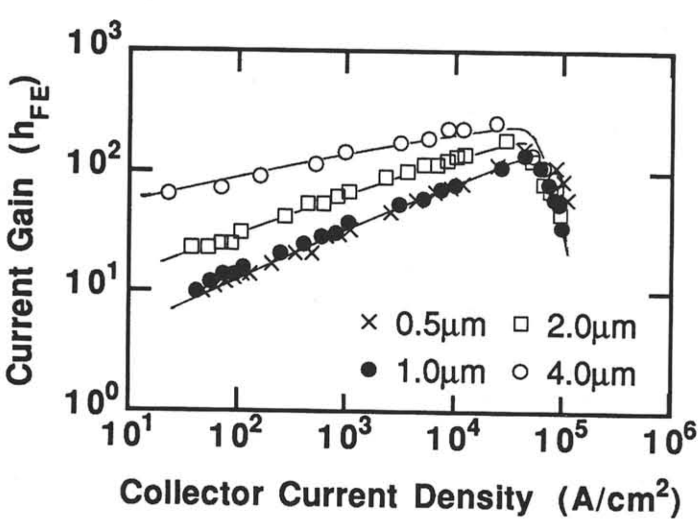

Fig.3: h_{FE} versus J_C for DHBT's on Si when the InP buffer layer thickness is varied from 0.5 μm to 4 μm.

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