InP/InGaAs Heterojunction Bipolar Transistors Grown by Gas-Source Molecular Beam Epitaxy with Carbon-Doped Base

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Abstract—**The first N-p-n InP/InGaAs heterojunction bipolar transistors (HBT's) with p-type carbon doping in InGaAs are reported. P-type carbon doping in the InGaAs base has been achieved by gas-source molecular beam epitaxy (GSMBE) using carbon tetrachloride (CCl_4) as the dopant source. The resulting hole concentration in the base was 1×10^{19} cm^{-3}. HBT's fabricated using material from this growth method display good *I-V* characteristics with dc current gain above 500. This verifies the ability to use carbon doping to make a heavily p-type InGaAs base of an N-p-n HBT.**

HBT technology has received much attention for use in high-speed digital circuits and high-efficiency microwave devices. The InP/InGaAs HBT has advantages over HBT's in other material systems: high electron mobility, low turn-on voltage v_{be}, low surface recombination velocity as compared to GaAs, and use of the same substrates as sources and detectors of 1.3–1.55-μm wavelength radiation favored in optoelectronics.

A widely used acceptor dopant used in InP/InGaAs HBT's is beryllium. Although beryllium can attain high doping levels, it is limited by its concentration-dependent diffusivity, which at high doping levels may significantly degrade device performance. There are reports of severe diffusion problems in the AlGaAs/GaAs system [1] and with some InGaAs-base devices [2]. With high-temperature aging of beryllium-doped AlGaAs/GaAs HBT's, changes can occur in the base–emitter junction because of the high diffusion coefficient of beryllium, resulting in a decreased lifetime for these devices under bias.

To overcome the problem of beryllium diffusion, the use of carbon as an acceptor has been recently studied. In GaAs, carbon has high acceptor efficiency, and low diffusivity, $< 10^{-16}$ cm$^2 \cdot$ s^{-1} at 950°C [3]. This value of diffusion coefficient is at least three orders of magnitude smaller than the value for beryllium. Thus, HBT structures can be designed without undoped setback layers to accommodate the diffusion of base dopants. Also, the low diffusion coefficient of carbon allows more flexible device processing and more reliable devices. AlGaAs/GaAs HBT's that take advantage of carbon doping have shown excellent results [4].

Carbon had been thought to be amphoteric in $In_{0.53}Ga_{0.47}As$ [5], yielding highly compensated n-type or p-type conductivity in MBE-grown materials. Initial HBT results with carbon-doped InGaAs bases (lattice-matched to InP) had low hole concentrations. Since then, carbon-doped InGaAs with hole concentration of 1×10^{19} cm^{-3} was reported by Abernathy *et al.* [3] using trimethylgallium (TMG) in a nitrogen carrier as a source for gallium and carbon, and elemental indium and arsenic effusion cell sources, suggesting hydrogen had a role in carbon incorporation or acceptor activity. Chin *et al.* [6] used carbon tetrachloride (CCl_4) as a carbon source in gas-source molecular beam epitaxy (GSMBE, with hydrides used for the group V material supply), thereby removing the limit on doping level posed by using a growth source (TMG) as the carbon source. A 420°C post-growth anneal gave a bulk hole density of 5×10^{19} cm^{-3}, implicating reversible acceptor passivation as the role of hydrogen (incorporated from the hydrogen carrier gas for the CCl_4 or more likely from the cracked arsine). This hole concentration for InGaAs (lattice-matched to InP) represents significant progress with respect to work reported by Shirakashi *et al.* [7]. While reactivation of hydrogen passivated zinc acceptors in InGaAs has been observed in this temperature range [8], the lower solubility and diffusivity of hydrogen in n-type semiconductors could limit the observed activation of carbon in n-p-n structures. Independent control of alloy composition and high p-type activation of a nondiffusive dopant in thin layers remained to be exploited in a device context.

This paper reports the first successful InP/InGaAs HBT, lattice-matched to InP, with carbon doping. The devices have high current gain, which illustrates carbon's utility as an acceptor in the thin InGaAs base.

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The HBT structure was grown using an Intervac GSMBE system. AsH_3 and PH_3 were used as the sources for the Group V elements. The epitaxial layer structure grown consists of an n^+ (1×10^{19} cm^{-3}) 5000-Å InGaAs subcollector, an n^- (2×10^{16} cm^{-3}) 3000-Å InGaAs collector, a p^+ (6×10^{19} cm^{-3} nominal concentration of carbon atoms) 500-Å InGaAs base, an n (5×10^{17} cm^{-3}) 800-Å InP emitter, an n (2×10^{18} cm^{-3}) 500-Å InP emitter, and an n^+ (1×10^{19} cm^{-3}) 300-Å InGaAs cap layer. For the InGaAs base, the growth temperature was 420°C and the carbon concentration from the CCl_4 flux is 6×10^{10} cm^{-3} (although this is not necessarily the resulting hole concentration, as will be explained later). The design of this HBT did not use setback layers. The structure was grown on Fe-doped, 2-in-diameter semi-insulating InP substrates.

HBT's with large-area emitters were fabricated with a self-aligned emitter process. The emitter metal was used as an etch mask to etch down to the base layer. Access to the base layer was obtained by using selective wet etching, removing the InGaAs cap with H_2SO_4:H_2O_2:H_2O (1:1:20) and the InP emitter with H_3PO_4:HCl (1:1). Base contacts were made by evaporating AuZn; the collector contacts were made by etching down to the subcollector using the above InGaAs selective wet etch and evaporating AuGe. All contacts to the different layers were not annealed. The devices were isolated by mesa etching to the subcollector using the selective InGaAs etch.

To explore the effect of post-growth annealing, one set of devices was fabricated on unannealed material. Another set of devices was fabricated on material with a preprocessing anneal of 420°C for 2 min using rapid thermal annealing in a forming gas ambient. In p-type InGaAs single layer experiments, such anneals lead to increased "activation" of the carbon dopant, which should result in decreased base sheet resistance in HBT's. The base sheet resistance was measured using standard transmission line measurements. The unannealed sample had a base sheet resistance of 2 kΩ/sq, compared to 2.3 kΩ/sq for the annealed sample. Using an estimated hole mobility of 70 $cm^2/V \cdot s$ derived from Hall measurements on separate samples (which agrees with the value reported for other acceptors in the literature [9]), the base sheet resistance leads to a hole concentration of 1×10^{19} cm^{-3} (a value believed to be accurate to within 30%). The negligible improvement in the base sheet resistance and the lower than expected value for base doping might be understood on the basis of the following argument. Chin *et al.* [6] speculated that a mechanism limiting the carbon activation is the presence of hydrogen introduced during the growth process. With this assumption, preprocess annealing may not increase the amount of carbon activated since the n-type emitter and cap layer could trap the hydrogen in the base layer. The higher hole concentration in this HBT structure, compared to single layer InGaAs in [6] prior to annealing, can be explained by diffusion of hydrogen from the base occurring during the growth of the InP emitter, until the n-type emitter is thick enough to act as a barrier to hydrogen diffusion.

Fig. 1 shows a typical Gummel plot for a 75×75-μm^2 emitter area HBT. The dc current gain has a maximum value of 546 and the maximum value of incremental current gain h_{fe} is 846. The measured ideality factor for the collector current is 1.0 and base current ideality factor is 2.5. There is a region of the base current at low values of base-emitter voltage which shows negative resistance behavior, similar to that seen in Esaki tunnel diodes. The high ideality factor of the base current and the negative resistance behavior is indicative of tunneling through the base-emitter junction. Further study of this effect is currently being pursued. There is also a decrease in the current gain seen at high values of collector current. It is believed this is due to saturation of the collector current. Current obtained by further increasing the base-emitter voltage only leads to increased base current, resulting in decreased current gain.

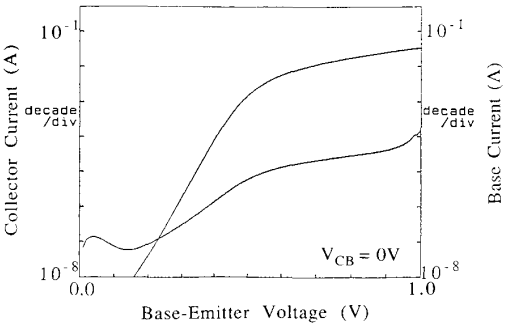

Fig. 1. Gummel plot of carbon-doped HBT.

The common emitter characteristic of a typical carbon-doped HBT is shown in Fig. 2. There is a low value of collector-emitter breakdown voltage BV_{CEO}. BV_{CEO} and the collector-base breakdown voltage BV_{CBO} were defined as the voltages which caused the collector current to reach a value of 100 μA, in the common-emitter and common-base mode, respectively. The respective values obtained for BV_{CEO} and BV_{CBO} are 1.16 and 5.34 V. BV_{CEO} is related to BV_{CBO} by the equation

$$BV_{CEO} = BV_{CBO}\left(\frac{1}{1 + h_{fe}}\right)^{1/n} \tag{1}$$

where h_{fe} is the incremental current gain and n is a phenomenological constant used to relate the avalanche multiplication factor to the base-collector breakdown voltage. The value of n appropriate to InGaAs is not accurately known. An estimate of n can be obtained from reported values of ionization rates versus electric field for InGaAs [10]. These were used to numerically calculate the ionization integral as a function of voltage [11]. Fitting these values for InGaAs with the collector doping used here yielded an n value in the range of 5-6 for InGaAs. Using (1) and the value for h_{fe} at 100 μA (276), BV_{CEO} is calculated to be about 2.0 V, in reasonable accord with the experimental value of BV_{CEO}. The low value of BV_{CEO} can thus be partially attributed to the high current gain, even at low current, of this device.

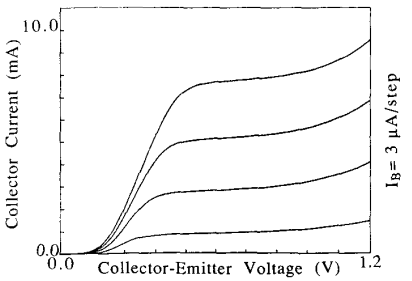

Fig. 2. Common-emitter characteristic of carbon-doped HBT with emitter area of 75 × 75 μm^2.

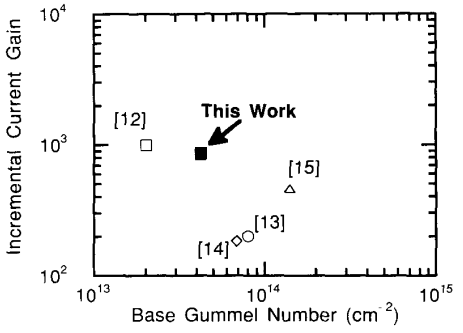

Fig. 3. Plot of small-signal current gain versus base Gummel number at about J_c = 1000 A/cm^2 for this work and for several reported transistors.

It is of interest to compare the incremental current gain of this device with previously reported values. The incremental current gain for HBT's is typically inversely proportional to the Gummel number in the base to some power between 1 and 2 depending on the physical origin of the base current. Fig. 3 shows a plot of h_{fe} as a function of the base Gummel number for several previously reported InP/InGaAs HBT's. The value obtained for the carbon-doped device is comparable for devices with a similar Gummel number based on interpolation of previous results for InGaAs-base devices. This indicates a low minority-carrier recombination rate for this material, despite its low growth temperature and significant density of unactivated carbon atoms.

In conclusion, the feasibility of using carbon doping in the base of InP/InGaAs HBT's has been demonstrated. The device displayed excellent current gain, but relatively high base sheet resistance. The hole concentration in the base was 1×10^{19} cm^{-3}, indicating that high hole concentrations are achievable in InGaAs with carbon. The fact that preprocessing annealing did little to improve the base sheet resistance supports the theory of hydrogen passivation being the dominant mechanism inhibiting carbon activation in InGaAs. Further study is in order, to optimize conditions to fully take advantage of this growth method for use in high-speed devices.

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References

[1] D. L. Miller and P. M. Asbeck, "Be redistribution during growth of GaAs and AlGaAs by molecular beam epitaxy," *J. Appl. Phys.*, vol. 57, pp. 1816-1822, 1985.

[2] W. Lee and C. G. Fonstad, "$In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ abrupt double heterojunction bipolar transistors," *IEEE Electron Device Lett.*, vol. EDL-7, pp. 683-685, 1986.

[3] C. R. Abernathy *et al.*, "Carbon doping of III-V compounds by MOMBE," *J. Cryst. Growth*, vol. 105, pp. 375-382, 1990.

[4] G.-W. Wang *et al.*, "High performance MOCVD-grown AlGaAs/GaAs heterojunction bipolar transistors with carbon-doped base," *IEEE Electron Device Lett.*, vol. 11, pp. 241-243, 1990.

[5] M. Kamp *et al.*, "Carbon incorporation in MOMBE-grown $Ga_{0.47}In_{0.53}As$," *J. Cryst. Growth*, vol. 95, pp. 154-157, 1989.

[6] T.-P. Chin, P. D. Kirchner, J. M. Woodall, and C. W. Tu, "Highly-doped p-type $Ga_{0.5}In_{0.5}As$ and $Ga_{0.5}In_{0.5}P$ by carbon tetrachloride in gas source molecular beam epitaxy," *Appl. Phys. Lett.*, vol. 59, pp. 2865-2867, 1991.

[7] J.-I. Shirakashi *et al.*, "P-type carbon-doped InGaAs grown by metalorganic molecular beam epitaxy," *Japan. J. Appl. Phys.*, vol. 30, pp. L 1609-L 1611, 1991.

[8] B. Theys *et al.*, "Hydrogen neutralization of dopant in p-type $Ga_{0.47}In_{0.53}As$," *Physica B*, vol. 170, pp. 421-425, 1991.

[9] A. Le Corre *et al.*, "Influence of oxygen incorporation on beryllium-doped InGaAs grown by molecular beam epitaxy," *Appl. Phys. Lett.*, vol. 51, pp. 1597-1599, 1987.

[10] T. P. Pearsall, "Impact ionization rates for electrons and holes in $Ga_{0.47}In_{0.53}As$," *Appl. Phys. Lett.*, vol. 36, pp. 218-220, 1980.

[11] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. New York: Wiley, 1981, p. 100.

[12] R. N. Nottenburg, H. Temkin, M. B. Panish, R. Bhat, and J.-C. Bischoff, "InGaAs/InP double-heterostructure bipolar transistor with near-ideal β versus I_c characteristic," *IEEE Electron Device Lett.*, vol. EDL-7, pp. 643-645, 1986.

[13] R. N. Nottenburg, Y.-K. Chen, M. B. Panish, R. Hamm, and D. A. Humphrey, "High-current-gain submicrometer InGaAs/InP heterostructure bipolar transistors," *IEEE Electron Device Lett.*, vol. 9, pp. 524-526, 1988.

[14] T. Makimoto, K. Kurishima, T. Kobayashi, and T. Ishibashi, "InP/InGaAs double-heterojunction bipolar transistors grown on (100) Si by metalorganic chemical vapor deposition," *IEEE Electron Device Lett.*, vol. 12, pp. 369-371, 1991.

[15] D. Ritter, R. A. Hamm, A. Feygenson, and M. B. Panish, "Diffusive base transport in narrow base $InP/Ga_{0.47}In_{0.53}As$ heterojunction bipolar transistors," *Appl. Phys. Lett.*, vol. 59, pp. 3431-3433, 1991.