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InP/InGaAs DOUBLE HETEROJUNCTION BIPOLAR TRANSISTORS INCORPORATING CARBON-DOPED BASES AND SUPERLATTICE GRADED BASE–COLLECTOR JUNCTIONS

R. C. Gee, C. L. Lin, C. W. Farley, C. W. Seabury, J. A. Higgins, P. D. Kirchner, J. M. Woodall and P. M. Asbeck

Indexing terms: Bipolar devices, Transistors, Semiconductor devices and materials

High performance InP/InGaAs double heterojunction bipolar transistors (DHBTs) incorporating carbon-doped bases and graded base–collector junctions implemented using a short period superlattice were grown by gas source MBE (GSMBE). Base hole concentrations up to $1\cdot6 \times 10^{19}\,cm^{-3}$ were obtained, using CCl_4 as the dopant source. Transistors with $2 \times 10\,\mu m^2$ emitters achieved f_t and f_{max} values up to 76 and 82 GHz, respectively. These devices demonstrate state of the art values of f_{max}.

Introduction: InP/InGaAs heterojunction bipolar transistors (HBTs) have a number of potential advantages over GaAs-based HBTs including: higher electron mobility and electron transient velocity overshoot, lower base–emitter turn-on voltage and commonality of substrate (InP) with 1·3 and $1\cdot55\,\mu m$ photonic devices. To achieve high base doping concentrations without diffusion of the base dopant, the use of carbon as a *p*-type dopant in InP/InGaAs HBTs has recently received attention [1, 2], although high microwave performance has not yet been demonstrated.

A disadvantage of InP/InGaAs HBTs is the low breakdown voltage associated with the use of an InGaAs collector, which limits the usefulness of these devices in high power or voltage applications. Implementing double heterojunction bipolar transistors (DHBTs) using InP as the collector should increase the breakdown voltage. Problems associated with the conduction band spike formed at the base–collector heterojunction can be reduced by grading the composition between the base and collector. Conventionally, this requires the use of GaInAsP whose composition must be carefully controlled to maintain lattice matching.

We report here InP/InGaAs DHBTs incorporating carbon-doped bases grown using CCl_4 with GSMBE. InP collectors were used; grading at the base–collector junction was achieved by a short period superlattice. The use of GSMBE is a convenient way of achieving carbon-doped, *p*-type InGaAs and short period superlattices used to grade the base–collector junction. Microwave characterisation demonstrated high performance, making the devices promising for use in high power, high speed circuits.

Device structures and fabrication: Carbon-doped InP/InGaAs DHBTs were produced using an Intevac GSMBE system [1, 3]. Two DHBT structures were grown with varying base thicknesses. Structure A1 consisted of an n^+ ($10^{19}\,cm^{-3}$) 4000 Å InGaAs subcollector, an n^+ ($3 \times 10^{18}\,cm^{-3}$) 500 Å InP collector, an n ($6 \times 10^{16}\,cm^{-3}$) 3000 Å InP collector, an n ($6 \times 10^{16}\,cm^{-3}$) 600 Å grading region, a p^+ ($2\cdot5 \times 10^{19}\,cm^{-3}$ nominal concentration of carbon atoms) 600 Å InGaAs base, an n ($5 \times 10^{17}\,cm^{-3}$) 1500 Å InP emitter, an n ($2 \times 10^{18}\,cm^{-3}$) 500 Å InP emitter and an n^+ ($10^{19}\,cm^{-3}$) 500 Å InGaAs cap layer. Structure B1 is identical to structure A1 except the base thickness is 1200 Å. These structures did not include intentional setback layers. The DHBT structures were grown on Fe-doped, 3 inch diameter semi-insulating InP substrates. These structures incorporated a growth interruption for an *in situ* anneal at 400°C for 5 min without arsine overpressure prior to the deposition of the InP emitter layer, which in previous work with single-layer, carbon-doped InGaAs enhanced carbon activation [3]. Good surface morphology of the entire structure indicated there was little surface degradation due to the *in situ* annealing.

The chirped superlattice used to grade the base–collector junction employed alternating layers of InGaAs and InP over a distance of 600 Å, which allows for an electric field as low as 40 kV/cm to be supported before the spike at the base–collector junction hinders the flow of electrons. There were 10 superlattice periods, each 60 Å thick. The thickness of the InGaAs layer decreased from 55 Å at the interface of the base–collector junction to a thickness of 5 Å at the end of the grading region. Conversely, the thickness of the InP layers was increased from 5 to 55 Å at the end of the grading region.

Small emitter area devices were fabricated using a selfalignment technique that is a derivative of the 'dual liftoff' technique used for GaAs-based HBTs [4]. Ti/Pt/Au was used for low resistance ohmic contacts and these contacts were not annealed. Isolation was achieved by mesa etching down to the semi-insulating InP substrate and planarisation was achieved using polyimide and SiO.

Results and discussion: In previous work with carbon-doped InP/InGaAs HBTs, the effective base doping deviated from the carbon concentration due to hydrogen passivation of the carbon dopant [1, 2]. Transmission line measurements were used to determine the effective carrier concentration in the base. The base sheet resistance was 1050 Ω/□ for structure A1 and 500 Ω/□ for structure B1. Assuming a hole mobility of $65\,cm^2/Vs$ [5], the effective acceptor concentration is $1\cdot6 \times 10^{19}\,cm^{-3}$ for both structures. The specific contact resistivity for devices from structure A1 and structure B1 was $1\cdot7 \times 10^{-6}\,\Omega cm^2$ and $3\cdot2 \times 10^{-6}\,\Omega cm^2$, respectively. SIMS profiles of the base layer showed carbon concentrations of $2\cdot1 \times 10^{19}\,cm^{-3}$ for structure A1 and $2\cdot5 \times 10^{19}\,cm^{-3}$ for structure B1. These hole concentrations are significantly higher than in previous work with carbon-doped InP/InGaAs HBT structures [1, 2], although further improvements in dopant activation may still be achievable.

The current gain of $70 \times 70\,\mu m^2$ emitter area devices from structure A1 was 100 and 25 for structure B1. The current gain dependence with base thickness is consistent with current gain limited by base recombination. Gummel plots indicated there was no diffusion of the acceptor dopant into the wide bandgap InP emitter. Devices fabricated from both structures had a common-emitter breakdown voltage, BV_{CEO}, of 5 V and a common-base breakdown voltage, BV_{CBO}, of 8 V. These values were defined as the voltage necessary to induce $100\,\mu A$ of collector current in these devices. These values of breakdown voltage are comparable to previously reported values for InP-based DHBTs [6–9].

RF characterisation of devices with a single emitter finger of $2 \times 10\,\mu m^2$ biased in the common-emitter mode was performed using a Cascade microwave probe station and HP 8510 network analyser. Fig. 1 shows the measured RF data for a device with 1200 Å base. The bias conditions for these measurements were a base–collector reverse bias of 2·0 V and collector current of 38 mA for structure A1 and 42·5 mA for structure B1. Structure A1 had measured maximum values of f_t of 76 GHz and f_{max} of 82 GHz, and structure B1 had f_t values of 66 GHz and f_{max} of 83 GHz. Although high, f_t is somewhat lower than expected possibly due to high emitter resistance and high base-collector capacitance from the relatively high collector doping (which contributed an estimated 0·4 ps to the emitter–collector delay). The lower f_t for sample B1 is consistent with the expected larger base transit time than for A1. Fig. 2 shows a comparison of reported values of f_{max} for beryllium-doped InP/InGaAs DHBTs with the values reported in this work as a function of base Gummel number.

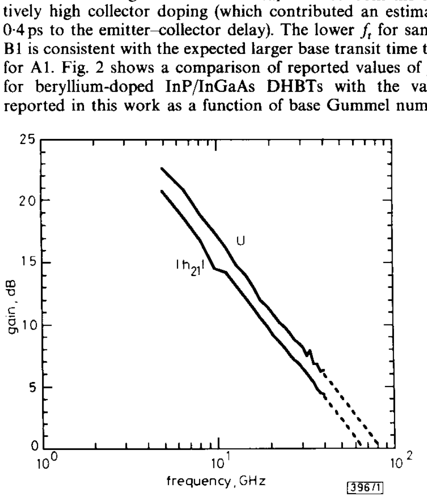

Fig. 1 *$|h_{21}|$ and unilateral gain as functions of frequency for 2 × 10 μm² transistor with 1200 Å base*

Extrapolations are at a slope of −20 dB/decade; V_{CB} = 2·0 V and I_C = 42·5 mA

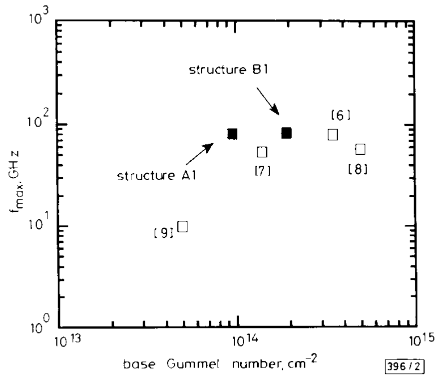

Fig. 2 *f_{max} as function of base Gummel number for this work and various reported values for beryllium-doped InP/InGaAs DHBTs*

The results of this work are comparable to the expected microwave performance for a beryllium-doped InP/InGaAs DHBT with similar base Gummel number. Values of f_{max} in this work are the highest reported for InP-based DHBTs [6].

For both structures, f_t started to roll off at a collector current density of 2·0 × 10^5 A/cm². Assuming that the roll-off of f_t was due to the Kirk effect, the effective electron velocity is estimated to be 7 × 10^6 cm/s for both devices. This value for the effective electron velocity sets a lower limit, because f_t roll-off may be due to a mechanism other than the Kirk effect. This electron saturation velocity indicates that the chirped superlattice used to grade the base–collector junction has little effect on electron transport.

Conclusion: Carbon-doped InP/InGaAs DHBTs with short period superlattice graded base–collector junctions grown by GSMBE using CCl_4 can achieve high microwave performance. Further improvements in the *in situ* annealing conditions would be expected to improve the microwave characteristics. The breakdown voltage and effective electron velocity were evaluated and indicate that the use of the chirped superlattice in the collector is an effective way of grading the base–collector junction of high performance InP/InGaAs DHBTs. These devices show much potential for use in high speed microwave circuits.

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R. C. Gee and P. M. Asbeck (*Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92093-0407, USA*)

C. L. Lin, P. D. Kirchner and J. M. Woodall (*IBM Research Division, T. J. Watson Research Center, Yorktown Heights, NY 10598, USA*)

C. W. Farley, C. W. Seabury and J. A. Higgins (*Rockwell International Science Center, Thousand Oaks, CA 91360, USA*)

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VERY BROADBAND DISTRIBUTED AMPLIFIER TO 75 GHz

J. Braunstein, P. J. Tasker, A. Hülsmann, M. Schlechtweg, K. Köhler, W. Bronner and W. Haydl

Indexing terms: Amplifiers, Traveling wave semiconductor amplifiers, MODFETs

Distributed amplifiers were fabricated successfully with a gain of 8 dB ± 1 dB in the frequency range 5–75 GHz measured on-wafer. The associated input and output matching is better than −10 dB. To the authors' knowledge this is a new performance record, not only for GaAs based circuits but also for InP based MMICs. The MMICs were realised in coplanar waveguide technology.

Introduction: Distributed amplifiers are of particular interest in all broadband systems, e.g. measurement systems. Fabrication at short gate lengths is rather difficult because of non-uniform transistor performance over the wafer and therefore