

Carbon-doped base GaAs/AlGaAs heterojunction bipolar transistor grown by metalorganic chemical vapor deposition using carbon tetrachloride as a dopant source

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Carbon tetrachloride (CCl_4) has been used as a carbon doping source for the base region of a GaAs/AlGaAs Npn heterojunction bipolar transistor (HBT) grown by low-pressure metalorganic chemical vapor deposition (MOCVD). Transistors were fabricated and characterized for dc current gain, emitter-base junction ideality factor, base contact resistance, and external base resistance. Microwave characterization by S -parameter measurement was performed to determine the common emitter current gain and maximum available gain as a function of frequency. Transistors with the base contact area self-aligned to a $3 \times 10 \mu\text{m}$ emitter finger had a dc current gain as high as 50, an emitter-base junction ideality factor of $n = 1.2$, and a current gain cutoff frequency of $f_i = 26 \text{ GHz}$. Transistors of equal emitter area without self-alignment exhibited dc current gain as high as 86, $n = 1.2$, and $f_i = 20 \text{ GHz}$. A base contact resistance of $R_c = 2.85 \times 10^{-6} \Omega \text{ cm}^2$ and an external base sheet resistance of $R_s = 533.4 \Omega/\square$ were measured. These preliminary results indicate that carbon doping from CCl_4 may be an attractive substitute for Zn or Mg in GaAs/AlGaAs HBT structures grown by MOCVD.

In order to obtain GaAs/AlGaAs heterojunction bipolar transistors with high gain and high frequency response, a very thin ($< 1000 \text{ \AA}$), very heavily doped ($p > 1 \times 10^{19} \text{ cm}^{-3}$) p -type base layer is required.^{1,2} For GaAs/AlGaAs HBT structures grown by metalorganic chemical vapor deposition (MOCVD), Mg and Zn are commonly used acceptor impurities for the base layer, while Be is typically used for heavy p -type doping of GaAs grown by molecular beam epitaxy (MBE). Unfortunately, the large diffusion coefficients associated with these impurities can lead to p - n junction redistribution during crystal growth or subsequent high-temperature processing.³⁻⁵ p -type dopant diffusion has been shown to change the position of the base-emitter p - n junction relative to the position of the base-emitter GaAs/AlGaAs heterojunction, resulting in degraded HBT performance unless special set back doping layers are used.⁵

Carbon has been identified as an alternative acceptor to Mg, Zn, and Be.⁶⁻¹⁰ Carbon incorporates primarily as a substitutional acceptor on the column V sublattice, and is expected to have a much smaller diffusion coefficient than Mg or Zn.^{6,7,11,12} High carbon acceptor concentrations in GaAs have been obtained by MBE using carbon evaporated from a heated graphite source,¹³ and by atomic layer epitaxy (ALE) using carbon incorporation from trimethylgallium.¹⁴ To this date, the intentional addition of carbon to GaAs grown by MOCVD using a number of hydrocarbon sources has not been successful, or has led to films of low carbon content.^{7,8} However, carbon acceptor concentrations in excess of $1 \times 10^{19} \text{ cm}^{-3}$ have been obtained in low-pressure MOCVD-grown GaAs using CCl_4 as a doping source.¹⁰ Using CCl_4 , very thin, heavily doped p -type layers have been

grown with abrupt dopant turn-on and turn-off.^{10,12}

In this work, CCl_4 has been used as a carbon doping source for the base region of a GaAs/AlGaAs Npn HBT grown by low-pressure MOCVD. Transistors with the base contact area either self-aligned or non-self-aligned to a $3 \times 10 \mu\text{m}$ emitter finger were fabricated using wet chemical etching to expose the base and subcollector contact areas and liftoff techniques to pattern metallized areas. dc characterization was performed to determine the gain, base contact resistance, external base resistance, emitter-base ideality factor, and collector-base ideality factor of the transistors. Microwave S -parameter measurements were made to determine the common emitter current gain and the maximum available gain as a function of frequency.

The epitaxial structure was grown by low-pressure MOCVD in an Emcore GS3100 reactor on a 2° off (100) oriented undoped liquid-encapsulated Czochralski (LEC) GaAs substrate. The growth was carried out at a pressure of

TABLE I. Growth parameters for doping concentration, thickness, growth temperature, and Al composition of the HBT epitaxial structure. A growth temperature of 580°C was used for the base layer to maximize carbon incorporation from the CCl_4 . A 2 min growth pause under arsine was used to change the substrate temperature before and after the base layer.

Layer	Doping (cm^{-3})	Thickness (\AA)	T_G ($^\circ \text{C}$)	Material
Subcollector	$n = 1 \times 10^{18}$	5000	600	GaAs
Collector	$n = 5 \times 10^{16}$	5000	600	GaAs
Base	$p = 2 \times 10^{19}$	1000	580	GaAs
Emitter grade	undoped	300	760	GaAs- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$
Emitter	$N = 5 \times 10^{17}$	1400	760	$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$
Cap grade	$n = 1 \times 10^{18}$	300	760	$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As-GaAs}$
Cap	$n = 1 \times 10^{18}$	1000	760	GaAs

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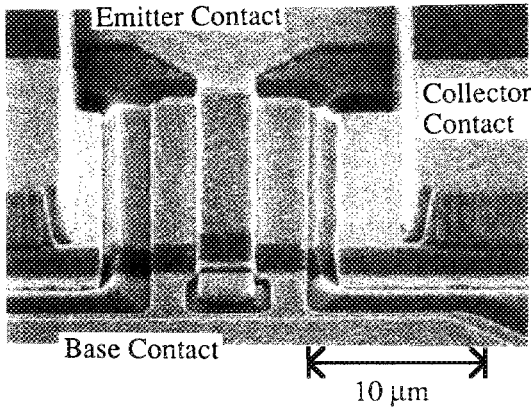


FIG. 1. Scanning electron micrograph of a completed self-aligned carbon-doped base HBT with a $3 \times 10 \mu\text{m}$ emitter finger.

100 Torr, substrate rotation rate of 1500 rpm, and H_2 flow rate of 9 slm. Trimethylgallium and trimethylaluminum were the group III growth precursors, and 100% arsine was the group V source. The carbon doping source was a 1500 ppm mixture of CCl_4 in H_2 , and n -type doping was obtained with a 1000 ppm mixture of H_2Se in H_2 . The parameters for doping concentration, thickness, growth temperature, and Al composition of the epitaxial structure are shown in Table I. A growth temperature of 580°C was used for the base layer to maximize carbon incorporation from the CCl_4 . A 2 min growth pause under arsine was used to change the substrate temperature before and after the base layer.

HBTs with the base metal contact area both self-aligned and non-self-aligned to a $3 \times 10 \mu\text{m}$ emitter finger were fabricated using wet chemical etching to expose the base and sub-collector, and metal liftoff to pattern the areas for contacts. The area for each device was defined by a $\sim 1\text{-}\mu\text{m}$ -deep mesa etch and an O^+ implant. Evaporation and liftoff of Pd/Ge/Au ($300 \text{ \AA}/400 \text{ \AA}/4000 \text{ \AA}$) for metallization of the collector and emitter contacts was followed by a low-temperature sinter under H_2 . Evaporation and liftoff of Pt/Ti/Au ($200 \text{ \AA}/1000 \text{ \AA}/1500 \text{ \AA}$) for metallization of the base contact was followed by a flash alloy. The conductivity of the sintered contacts was not affected by the flash alloy. For S -parameter measurements, two identical transistors were connected in parallel using air bridges. A scanning electron micrograph of

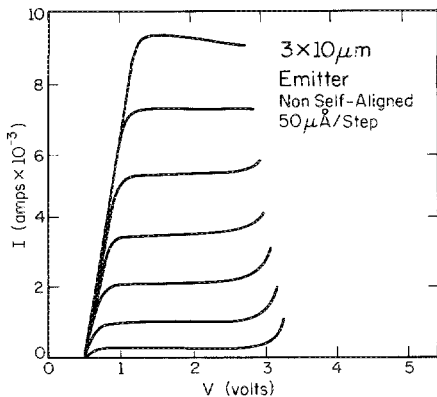


FIG. 2. Collector I - V characteristic of a non-self-aligned carbon-doped base HBT with a current gain as high as 86, a voltage offset of 400 mV, and a breakdown voltage of 3.3 V. The low breakdown voltage is caused by the doping of the collector layer ($n \sim 5 \times 10^{16} \text{ cm}^{-3}$) and the large current gain.

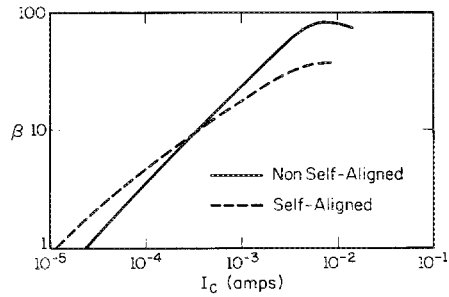


FIG. 3. Dependence of current gain on collector current for self-aligned and non-self-aligned HBTs.

a completed self-aligned device (top view) is shown in Fig. 1.

The collector I - V characteristic of carbon-doped base HBT is shown in Fig. 2. The $3 \times 10 \mu\text{m}$ emitter non-self-aligned transistors exhibit a current gain of 86. Self-aligned devices of the same size had a current gain as high as 50. A voltage offset of 400 mV was observed for both types of devices, and is believed to result from the difference in threshold voltage between the emitter-base and collector-base interfaces.¹⁵ The transistor breakdown voltage was $\sim 3.0 \text{ V}$ for both transistor types. The relatively low breakdown voltage is caused by the doping ($n \sim 5 \times 10^{16} \text{ cm}^{-3}$) of the collector layer and the large current gain. The base-emitter junction ideality factor was deduced from the p - n junction characteristics of devices tested with the collector open. A base-emitter junction ideality factor of $n = 1.2$ was obtained for both self-aligned and non-self-aligned transistors. The base-collector junction ideality factor for both self-aligned and non-self-aligned transistors, determined from gummel plots, is $n = 1.1$. The near-unity values indicate that the g - r currents in the emitter-base and collector-base junction depletion regions are small.

Using transmission line measurement (TLM) patterns, a base contact resistance of $R_c = 2.85 \times 10^{-6} \Omega \text{ cm}^2$ and an external base sheet resistance of $R_s = 533.4 \Omega/\square$ were measured. This external sheet resistance corresponds to a base doping of $p \sim 1.5 \times 10^{19} \text{ cm}^{-3}$.

The dependence of current gain on collector current is shown in Fig. 3 for both self-aligned and non-self-aligned HBTs. Both types of devices attain maximum current gain at approximately the same collector current. However, the self-aligned transistors have greater current gain at low collector

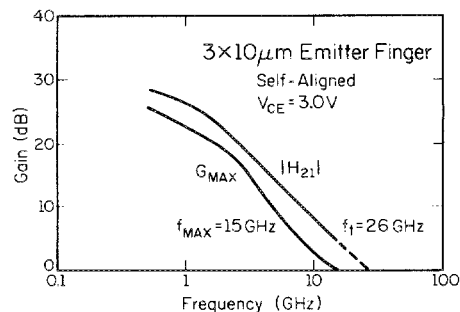


FIG. 4. Frequency dependence of the common emitter current gain (H_{21}) and maximum available gain (G_{max}), derived from S -parameter measurements, for self-aligned HBTs with $3 \times 10 \mu\text{m}$ emitter fingers. Assuming a 6 dB/octave rolloff from the measured values, $f_1 = 26 \text{ GHz}$ and $f_{\text{max}} = 15 \text{ GHz}$ were obtained.

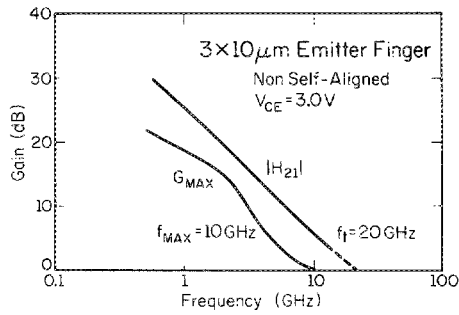


FIG. 5. Frequency dependence of the common emitter current gain (H_{21}) and maximum available gain (G_{MAX}), derived from S -parameter measurements, for non-self-aligned HBTs with $3 \times 10 \mu\text{m}$ emitter fingers. Assuming a 6 dB/octave rolloff from the measured values, $f_t = 20 \text{ GHz}$ and $f_{\text{max}} = 10 \text{ GHz}$ were obtained.

current. The difference in the slopes of the β vs I_c characteristics is due to differences in the actual emitter-base junction area caused by undercutting of the wet chemical etch in the fabrication of the self-aligned devices. The reduced junction area results in increased current density in the self-aligned HBTs. The higher peak current gain in the non-self-aligned HBTs may result from less recombination of emitter current at the base contact metal.¹⁶ The self-aligned device, with less lateral separation between the base contact and the emitter-base junction, will experience larger recombination currents.

Microwave performance of the HBTs was characterized by S -parameter measurement of two transistors connected in parallel and contacted with Cascade probes using an HP 8510 calibrated with standards on alumina substrates. The frequency dependence of the common emitter current gain (H_{21}), and the maximum available gain (G_{max}), derived from the S -parameter measurements, are shown for the self-aligned and non-self-aligned HBTs in Figs. 4 and 5, respectively. The transistor bias was set at $V_c = 3.0 \text{ V}$ for all measurements, while the current density was $J_c \approx 6.0 \times 10^4 \text{ A/cm}^2$. By assuming a 6 dB/octave rolloff from the measured gain values, a cutoff frequency of $f_t = 26 \text{ GHz}$ for the self-aligned HBTs was obtained, while $f_t = 20 \text{ GHz}$ for the non-self-aligned transistors. The frequency at which the maximum available gain reached unity was $f_{\text{max}} = 15 \text{ GHz}$ for the self-aligned devices and $f_{\text{max}} = 10 \text{ GHz}$ for the non-self-aligned devices. The higher frequency operation of the self-aligned device arises from reduced external base resistance.

In conclusion, CCl_4 has been used as a carbon doping source for the base region of a GaAs/AlGaAs Npn HBT grown by low-pressure MOCVD. Transistors with a $3 \times 10 \mu\text{m}$ emitter finger self-aligned to the base contact had dc

current gain as high as 50 and a current gain cutoff frequency of $f_t = 26 \text{ GHz}$. Transistors of equal emitter area without self-alignment had dc current gain as high as 86 and $f_t = 20 \text{ GHz}$. Both types of devices exhibited low base contact resistance and external base sheet resistance, as well as excellent ideality factors for the emitter-base and collector-base junctions. Improved gain and frequency response may be obtained in future devices by heavier carbon doping of the base region, and lighter n -type doping of the collector layer. These preliminary results indicate that carbon doping from CCl_4 may be an attractive substitute for Zn or Mg in GaAs/AlGaAs HBT structures grown by MOCVD.

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