

# AlAs/GaAs tunnel emitter bipolar transistor

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We report the first microwave AlAs/GaAs tunnel emitter bipolar transistor utilizing nonequilibrium electron transport in the base. At an emitter current density of  $1 \times 10^5 \text{ A cm}^{-2}$ , current gain of greater than unity is measured up to a frequency of 40 GHz. dc current gains of 82 and 53 are measured for devices with emitter stripe widths of 9 and  $1.5 \mu\text{m}$ , respectively. Enhanced device scaling is made possible with the extremely high velocity in the thin base region.

There is interest in using heterojunction bipolar transistors for high-speed electronics applications.<sup>1,2</sup> However, low power devices require small device dimensions which often result in degradation of common emitter current gain.<sup>3,4</sup> The inability to scale down device size while maintaining device performance is considered to be a major problem with AlGaAs heterojunction bipolar transistors. In this letter we show that the current gain can be preserved in transistors with small emitter stripe width ( $W = 1.5 \mu\text{m}$ ) by using a tunnel emitter bipolar transistor (TEBT)<sup>5</sup> and without resorting to a sophisticated process technology specifically designed to improve lateral scaling.<sup>6</sup> In addition, we present the results of the first microwave measurements performed on a TEBT.

Transistor structures were grown by gas source molecular beam epitaxy on semi-insulating (001) oriented GaAs substrates. During growth the substrate temperature was  $580^\circ\text{C}$  and the gas source used was (thermally cracked) arsine. Figure 1 shows a schematic band diagram of a typical TEBT used in our study. Electrons in the  $n$ -type ( $1 \times 10^{18} \text{ cm}^{-3}$  Si impurity) GaAs emitter can tunnel through a 120-Å-thick AlAs barrier into a 500-Å-wide  $p$ -type ( $1 \times 10^{19} \text{ cm}^{-3}$  Be impurity) GaAs base. After traversing the base, electrons flow through the 5000-Å-thick  $n$ -type ( $5 \times 10^{16} \text{ cm}^{-3}$  Si impurity) collector depletion region before being collected in the 5000-Å-thick  $n^+$  layer forming the GaAs subcollector contact.

The wafers were fabricated into three level mesa structures using standard photolithographic and wet chemical etching techniques, allowing separate electrical contacts to emitter, base, and collector. Parallel conductivity between the emitter-base diode and the ohmic contacts was eliminated by using a selective spray etch ( $\text{H}_2\text{O}_2$  adjusted with  $\text{NH}_4\text{OH}$  to have a 7.05 pH) to define the emitter mesa. Ohmic contacts to emitter and collector were fabricated by rapid thermal annealing a NiGeAu alloy. Base contact was achieved by etching the AlAs tunnel barrier to expose the  $p$ -type GaAs base and then using a AuBe alloy. Transistors with various emitter stripe widths  $W = 1.5, 2, 3, 4,$  and  $9 \mu\text{m}$  were fabricated. In Fig. 2 we show typical common base and common emitter characteristics of a TEBT with  $W = 1.5 \mu\text{m}$ .

In Fig. 3 we plot common emitter current gain  $\beta$  as a

function of emitter stripe width  $W$  for a fixed emitter current density of  $2 \times 10^4 \text{ A cm}^{-2}$ . As may be seen,  $\beta = 82$  for  $W = 9 \mu\text{m}$  and decreases to  $\beta = 53$  for  $W = 1.5 \mu\text{m}$ . Previous scaling studies using standard heterojunction bipolar transistor structures show a factor of ten reduction in  $\beta$  over the same range of  $W$ .<sup>3,4</sup> The improved lateral scaling we observe in TEBTs may be understood as arising from extreme nonequilibrium electron base transport which has been reported in a similar structure.<sup>7</sup> It may be illustrated theoretically that ballistic, compared to diffusive, base transport results in a reduced nonradiative recombination cross section and volume.

For example, in a TEBT electrons are injected with energy  $E_i$  in a narrow beam normal to the emitter-base heterojunction plane. An electron injected over a potential step from a thermal distribution has an angular spread given approximately by  $\langle \theta \rangle \simeq \tan^{-1}(k_B T/E_i)^{1/2}$ . Tunnel injection reduces  $\langle \theta \rangle$  because tunneling probability is maximized for electrons moving perpendicular to the tunnel barrier. From the common emitter offset voltage and the experimental results of Ref. 7, we estimate  $E_i \simeq 400 \text{ meV}$  implying  $\langle \theta \rangle \lesssim 14^\circ$

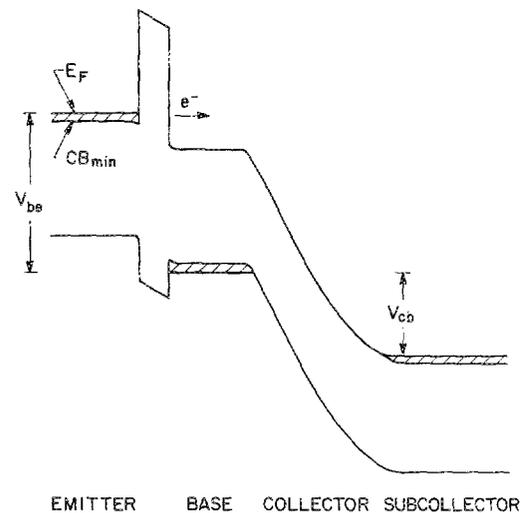


FIG. 1. Schematic band diagram of an  $n$ - $p$ - $n$  tunnel emitter bipolar transistor under bias. The conduction-band minimum  $CB_{\text{min}}$ , the electron quasi-Fermi level  $E_F$ , the emitter-base bias voltage  $V_{\text{be}}$ , and the base-collector bias voltage  $V_{\text{bc}}$  are indicated.

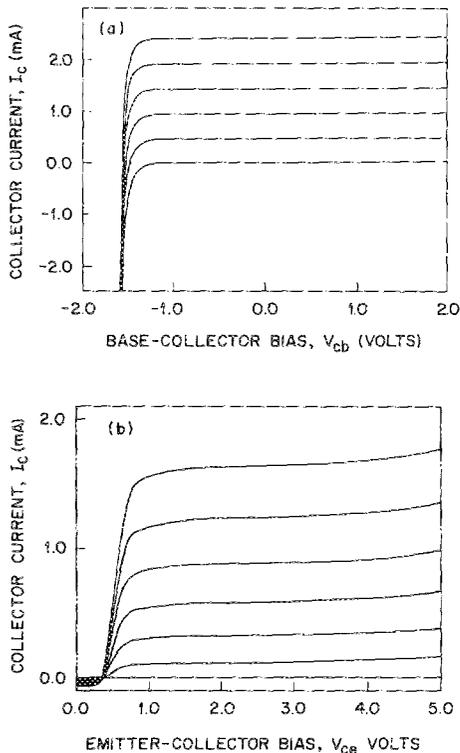


FIG. 2. Room-temperature common base (a) and common emitter (b) current gain characteristics of the device shown schematically in Fig. 1. Emitter stripe width is  $W = 1.5 \mu\text{m}$  and emitter area is  $6 \times 10^{-7} \text{cm}^2$ . Curves (a) were taken in steps of  $500 \mu\text{A}$ , beginning with an injected emitter current of zero. Curves (b) were taken in steps of  $10 \mu\text{A}$ , beginning with an injected base current of zero.

at room temperature. Compared to a diffusive transistor, the small value of  $\langle \theta \rangle$  in a TEBT results in a reduced interaction volume for nonradiative recombination. In a diffusive transistor, recombination can take place on the exposed base surface adjacent to the emitter stripe and in the extrinsic bulk base region. In the limiting case of extreme nonequilibrium electron transport across the base region there is a reduction in the interaction volume by a factor of approxi-

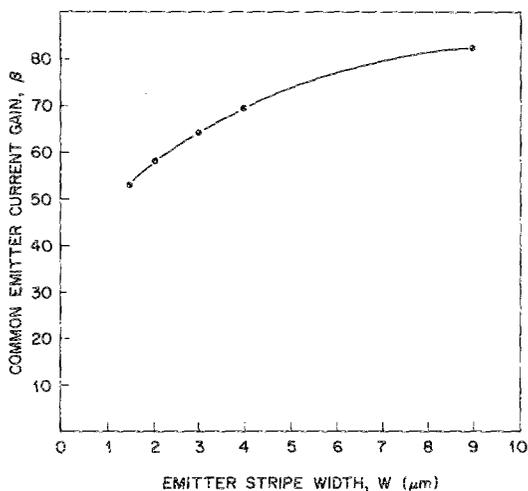


FIG. 3. Common emitter current gain as a function of emitter stripe width  $W$  for a constant emitter current density of  $j_e = 2 \times 10^4 \text{A cm}^{-2}$ .

mately  $\Delta_v = (eZ_b v_i^{\text{diffusive}} / 4\mu E_i)^{1/2}$ , where  $\mu$  is the mobility of minority carriers in the base of a diffusive transistor,  $v_i^{\text{diffusive}}$  is the diffusion velocity, and  $Z_b$  is the base thickness. As an example, for  $Z_b = 500 \text{\AA}$ ,  $\mu = 500 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ , a value of  $v_i^{\text{diffusive}}$  in GaAs of  $1 \times 10^7 \text{cm s}^{-1}$ , and if  $E_i = 400 \text{meV}$ , we obtain  $\Delta_v \approx 1/4$ . The reduction in  $\Delta_v$  associated with ballistic electron transport suggests improvement by a factor of 4 in lateral scaling is possible. Additional improvement in lateral scaling arises from a reduced cross section for nonradiative processes due to enhanced electron velocity (compared to  $v_i^{\text{diffusive}}$ ) in the transistor base.

It is well known that speed (current gain cutoff frequency) of a bipolar transistor is determined by the emitter-collector delay time  $\tau_{ec} = 1/2\pi f_T = r_e(C_e + C_c) + \tau_b + \tau_c + (R_{ec} + R_c)C_c$ , where  $C_e$  is the emitter capacitance,  $C_c$  the collector capacitance,  $\tau_b$  is the base transit time,  $\tau_c$  is the collector transit time,  $r_e$  is the dynamic emitter resistance, and  $R_{ec}$  and  $R_c$  are the emitter and collector series resistance, respectively. In the above relation for  $\tau_{ec}$  the term  $r_e(C_e + C_c)$  is current dependent since the dynamic emitter resistance  $r_e = nk_B T / I_e$ , where  $I_e$  is the emitter current and  $n$  is the junction ideality factor. In a conventional  $N$ - $p$  heterojunction emitter the maximum emitter current density is limited by the electron thermal velocity (typical diffusion velocity in AlGaAs is around  $3 \times 10^6 \text{cm s}^{-1}$ ) and the  $N$ -type impurity concentration  $N_e$  in the wide band-gap emitter. Therefore, at some current density  $j_e$ , the current gain  $\beta$  and cutoff frequency  $f_T$  will be limited by the electron supply (i.e., space-charge-limited current). In a conventional AlGaAs/GaAs heterojunction bipolar transistor with emitter impurity concentration  $N_e = 5 \times 10^{17} \text{cm}^{-3}$ ,  $j_e$  is limited to  $\sim 10^5 \text{A cm}^{-2}$ . On the other hand, in a TEBT  $j_e$  is not limited by supply of electrons because of the degenerately doped emitter contact layer and the high (nondiffusive) velocity in the tunnel barrier. Thus, at sufficiently high emitter current, a TEBT may have a smaller emitter charging time compared to a conventional bipolar structure.

We characterized the high-frequency small-signal performance of TEBTs at microwave frequency from 1 to 40 GHz with a vector network analyzer and millimeter wafer probes. Figure 4 shows the measured current gain  $|h_{21}|$  and maximum available power gain MAG as a function of fre-

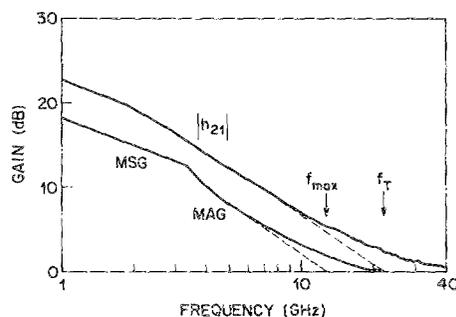


FIG. 4. Measured current gain  $|h_{21}|$ , maximum stable gain MSG, and maximum available gain MAG as a function of frequency for  $V_{cb} = 5 \text{V}$  and  $I_e = 6.4 \text{mA}$ . The TEBT has an emitter area of  $6 \times 10^{-8} \text{cm}^2$  and a maximum emitter current density of  $2.5 \times 10^5 \text{A cm}^{-2}$  before degradation of current gain.

quency. The device shows greater than unity current gain and available power gain up to a frequency of 40 and 20 GHz, respectively. The high-frequency tails in the measured current gain are due to large collector capacitance  $C_c$  and large series resistance from the non-self-aligned etched-mesa process. This also gives rise to a large charging time  $(R_{cc} + R_c + r_{cc})C_c$ , which limits  $f_T$ . Using a  $-20$  dB per decade roll-off slope, we obtain a current gain cutoff frequency  $f_T$ , of 21 GHz and a maximum frequency of oscillation  $f_{max}$  of 12 GHz. We note that improved  $f_T$  and  $f_{max}$  may be obtained by adopting self-aligned processing techniques which reduce the extrinsic collector capacitance and base resistance.<sup>1</sup> Further improvement of the frequency performance of a TEBT may be obtained by reducing the vertical dimension of the collector depletion region to reduce the transit delay  $\tau_c$ .

In conclusion, we have shown dramatically improved lateral device scaling using nonequilibrium minority-carrier transport in a tunnel emitter bipolar transistor and results of

the first microwave experiments on such a structure gave a measured current gain of greater than unity up to 40 GHz. Our results suggest that tunnel emitter bipolar transistors fabricated in materials such as AlGaAs, InGaAsP, or InAlGaAs may be of importance in high-speed electronic circuit applications.

<sup>1</sup>M. F. Chang, P. M. Asbeck, K. C. Wang, G. J. Sullivan, N. H. Sheng, J. A. Higgins, and D. L. Miller, IEEE Electron Device Lett. **EDL-8**, 303 (1987).

<sup>2</sup>T. Ishibashi and Y. Yamauchi, IEEE Trans. Electron Devices **ED-35**, 401 (1988).

<sup>3</sup>O. Nakajima, K. Nagata, H. Ito, T. Ishibashi, and T. Sugeta, Jpn. J. Appl. Phys. **24**, L596 (1985).

<sup>4</sup>M. F. Chang, P. M. Asbeck, D. L. Miller, and K. C. Wang, IEEE Electron Device Lett. **EDL-7**, 8 (1986).

<sup>5</sup>F. E. Najjar, D. C. Radulescu, Y. K. Chen, G. W. Wicks, P. J. Tasker, and L. F. Eastman, Appl. Phys. Lett. **50**, 1915 (1987).

<sup>6</sup>S. Tiwari, A. Ginzberg, S. Akhtar, S. L. Wright, R. F. Marks, Y. H. Kwark, and R. Kiehl, IEEE Electron Device Lett. **EDL-9**, 422 (1988).

<sup>7</sup>K. Berthold, A. F. J. Levi, J. Walker, and R. J. Malik, Appl. Phys. Lett. **52**, 2247 (1988).