

# dc performance of ballistic tunneling hot-electron transfer amplifiers

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We present new experimental results of ballistic electron transport through thin  $n^+$ -GaAs layers. Measurements were done on tunneling hot-electron transfer amplifier devices composed of GaAs and AlGaAs layers. In devices with GaAs active regions (bases) of 300 and 800 Å, collisionless or ballistic transport was observed. By performing hot-electron energy spectroscopy we found that the collected ballistic distributions were similar in shape but differed in magnitude. This suggests the existence of a strong scattering mechanism which randomizes the otherwise ballistic electrons. The maximum differential current transfer ratio  $\alpha$  was 0.9 in devices for which about 75% of the injected current traversed the base ballistically. The presence of ballistic transport has also allowed the measurement of the AlGaAs barrier height through observation of the onset of current collection in the devices. Barrier heights higher than those recently reported have been measured. In addition we show the effects of grading the collector barrier. The most noted effect in these cases was a higher transfer ratio.

In high-speed electronics, horizontal devices such as the field-effect transistor constitute the majority. There, the contacts are deposited on a flat surface and current transport is just underneath the surface. Since submicron lateral dimensions are difficult to achieve, vertical devices such as the bipolar transistor, where the transport is perpendicular to the layers, are usually faster. However, an important speed limitation of a bipolar switching transistor, results from the storage time of the injected minority carriers<sup>1</sup> in the active region (base) of the device. A vertical unipolar device thus looks attractive. A few of these devices have been recently reported on: the permeable base transistor<sup>2</sup> and the vertical field-effect transistor,<sup>3</sup> where thermal electrons are injected into the active layer; the planar doped barrier transistor<sup>4</sup> and the tunneling hot-electron transfer amplifier (THETA) transistor,<sup>5-7</sup> which utilize injected hot, nonequilibrium electrons. In the latter cases the transit time through the device is the shortest possible. Recently the hot-electron devices have been used as "electron energy spectrometers,"<sup>6-9</sup> and have in particular demonstrated the existence of ballistic transport in semiconductors.<sup>9</sup>

We report here new results of a differential transfer ratio  $\alpha$  as high as 0.9 in THETA devices. The effects of base width and doping levels on the ballistic current transport are presented. Through observation of the onset of current collection above the collector barrier, the height of this potential barrier is determined. The measured heights are larger than the recently accepted value of the conduction-band discontinuity.<sup>10</sup> This discrepancy may be in part due to the existence of uncontrollable negative charges in the AlGaAs barriers.<sup>11</sup> In addition we will discuss the effect of grading the collector barrier on device characteristics.

The detailed structure, the fabrication procedure, and the principles of operation of the THETA device have recently been reported.<sup>5,7,9</sup> Briefly, the molecular beam epitaxy (MBE)-grown structure is composed of two undoped AlGaAs barrier layers between three heavily doped GaAs layers (emitter, base, and collector). One barrier is made very thin ("emitter barrier," about 100 Å thick), thus enabling direct tunneling from emitter to base. The second barrier is made thicker ("collector barrier," 500–1000 Å thick),

to prevent tunneling. The central GaAs layer (base) serves as a common electrode for the two AlGaAs barriers. When a negative voltage  $V_{BE}$  is applied to the emitter with respect to the base, electrons tunnel through the emitter and emerge into the base with an energy of approximately  $eV_{BE}$  with respect to the Fermi level  $\xi$  in the base (thus being "hot electrons"). They tunnel quasi-monoenergetically with an energy spread of about 50 meV. If the width of the base is on the order of the mean free path between scattering events, a fraction of the hot electrons will traverse the base ballistically and surmount the collector barrier. This is possible if  $eV_{BE} + \xi > \Phi_C$ , where  $\Phi_C$  is the collector barrier height, which is ideally equal to the conduction-band discontinuity  $\Delta E_C$  at the GaAs-AlGaAs heterointerface.

Major loss mechanisms that reduce the differential transfer ratio  $\alpha \equiv dI_C/dI_E$ , where  $I_C$  and  $I_E$  are the collector and emitter currents, respectively, are electron-phonon and electron-electron scatterings, and quantum mechanical reflections at the base-layer collector-barrier interface. Device operation at room temperature in this system of materials is impossible because of the large thermionic currents resulting from electrons surmounting the barriers. As the temperature is reduced below 140 K, the thermionic leakage currents become negligible, electron-phonon scattering events reduce, and  $\alpha$  increases.

Structures with tunneling barriers 100 Å wide and collector barriers 1000 Å wide were fabricated using an Al mole fraction of  $x = 0.3$ . The collector barrier was graded over 60 Å to  $x = 0.1$  at the interface with the base. The base widths were 300 and 800 Å and the GaAs layers were doped to a level of  $1 \times 10^{18} \text{ cm}^{-3}$ . Hot-electron energy spectroscopy was performed on these structures.<sup>8,9</sup> Spectroscopy is done by applying a negative voltage to the collector with respect to the base. This raises the collector barrier height on the collector side, thus preventing the collection of the part of the electron distribution which is below the top of the barrier.<sup>7,9</sup> The span of the electron energy distribution above the unbiased collector barrier is indicated by the collector current tail at negative  $V_{CB}$ . The part of the distribution which is below the barrier top can be estimated by the gradual increase of  $I_C$  for positive collector voltage which lowers the collector bar-

rier height. The component of the momentum distribution which is normal to the layers, as a function of the energy associated with the normal direction at the collection point ("normal energy"), is derived from  $dI_C/dV_{CB}$  for  $V_{CB} < 0$ .<sup>9</sup> Since the electron velocity does not change markedly over the range of the distribution width, the electron distribution is quite similar to the momentum distribution. Ballistic transport is clearly evident in devices with a base width of 800 Å (Fig. 1). Narrow distributions (50–60 meV at half-maximum) with peak positions that nearly coincide with the Fermi level in the emitter are measured, a clear characteristic of ballistic transport. As the base width reduces from 800 to 300 Å, the fraction of the injected current that traverses the base ballistically increases from about 15% to 30%, although the distribution shape and width stay nearly unchanged (see Fig. 1). This clearly indicates that most scattering events randomize the velocities or involve large energy relaxation effects, removing the scattered electrons completely from the collected energy distribution. A loss mechanism which involves scattering of hot electrons by coupled modes of phonons and plasmons has been proposed,<sup>8,12</sup> but clear experimental evidence has not yet substantiated this. The sharpness of the collected distribution indicates that the AlGaAs barrier in the collector acts as an almost ideal dielectric with very little alloy or other scattering mechanisms. The rate at which the ballistic fraction increases with decreasing base width does not indicate a constant mean free path. If for the transfer we assume an inverse exponential dependence on the width, data from devices with base widths of 800 and 300 Å yield mean free paths of

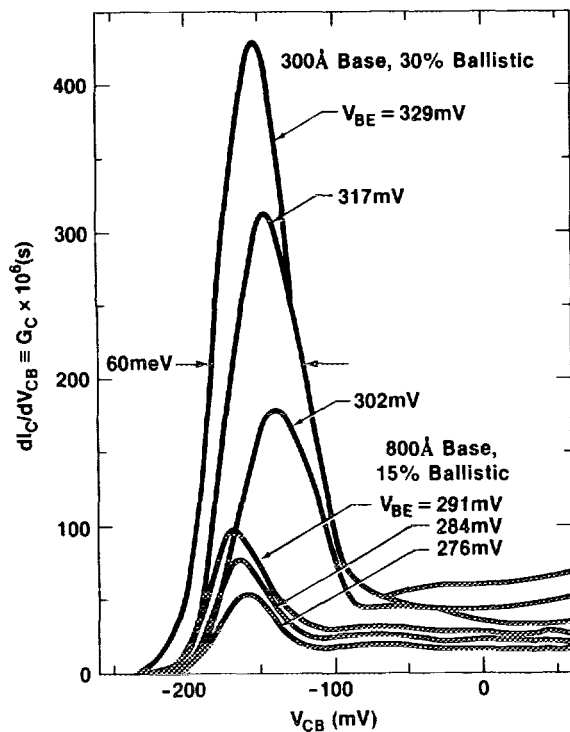


FIG. 1. Energy distributions of the ballistic electrons in two similar THETA devices. Both devices have a doping level of  $1 \times 10^{18} \text{ cm}^{-3}$ , Al mole fraction 0.32, and emitter and collector barriers are 100 and 1000 Å, respectively. Only base widths differ, one being 300 Å and the other 800 Å. Note the similarity in the collected energy distributions of the devices. The difference in the peak positions results from the slight difference of the Al mole fraction in the collector barrier of the two devices.

420 and 250 Å, respectively. This could result from modification of the scattering mechanism by quantization that must take place in the thin base.

Collection is only possible when  $eV_{BE} + \xi > \Phi_C$ . Transport across the base is severely reduced when  $eV_{BE} + \xi > E_{\Gamma L}$ , where  $E_{\Gamma L} \approx 0.3 \text{ eV}$  is the energy separation between the  $\Gamma$  and  $L$  valley minima.<sup>13</sup> This is due to electron transfer from  $\Gamma$  to  $L$  states that leaves only  $\approx 50 \text{ meV}$  energy window for ballistic transport in the above devices. Devices with a collector barrier height of about 140 meV have been fabricated (corresponding to an Al mole fraction of about 0.16), thus increasing the available energy window for ballistic transport to about 160 meV. In addition, by reducing the doping level to  $7 \times 10^{17} \text{ cm}^{-3}$  in those devices and having a 300-Å-wide base, the ballistic fraction of the injected current (measured at  $V_{CB} = 0$ ) increased to 75%. The maximum attained differential  $\alpha$  increased to 0.9 at injection energies just below these corresponding to the  $L$  valley minima. We infer a ballistic mean free path in these devices of about 1000 Å, a surprisingly large value that could be related in part to the larger energy window available for transport. At higher injection energies for which transfer into the  $L$  valleys does take place, the maximum decrease in  $\alpha$  is some 10%–15%.<sup>13</sup> This reduces the differential current gain  $\beta \equiv dI_C/dI_B$  from 9 to about 3.

An added feature of a ballistic THETA device is its ability to determine the collector barrier height (which is ideally the conduction-band discontinuity at the GaAs-AlGaAs heterointerface). At 4.2 K, when the Fermi level of the emitter is aligned with the collector barrier top, a fairly abrupt onset in  $\alpha$  is observed. The collector barrier height is then found by adding the Fermi level in the base,  $\xi$ , to  $eV_{BE}$  at the onset of  $\alpha$ . Since quantized energy levels are formed in the thin base, the potential distribution in the base is difficult to calculate self-consistently and some uncertainty exists in determining  $\xi$ . Figure 2 gives a few examples of onsets in the  $\alpha$ 's for different devices at  $V_{CB} = 0$  and 0.2 V and the corresponding Al mole fractions of the collector barriers. For example, for Al mole fraction  $x = 0.32$ , barrier heights are estimated to be between 300 and 335 meV (for  $V_{CB} = 0$ ) for three different devices, while for  $x = 0.16$  the barrier height is 140 meV (the  $\xi$ 's are estimated for the particular doping level and base width in each device with some 10 meV uncer-

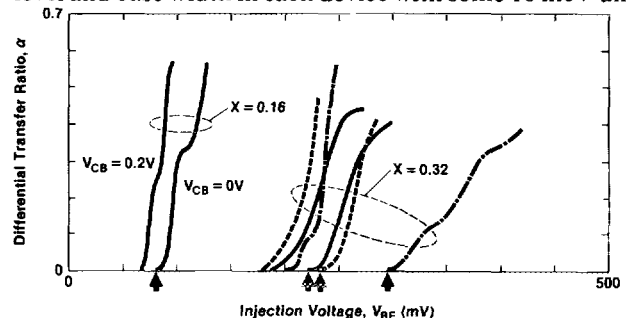


FIG. 2. Onset of  $\alpha$  for different devices, all with a 300-Å-wide base, with and without an applied positive collector-base voltage, measured at 4.2 K. The onsets for  $V_{CB} = 0$  (marked by the arrows) give the collector barrier heights above the Fermi level in the base. The other curve for each device is measured at  $V_{CB} = 0.2 \text{ V}$ . All devices have a graded region in the collector barrier of 60 Å, except the one with the highest onset which has a graded region of 200 Å. The doping of the devices is in the range  $7 \times 10^{17}$ – $1.5 \times 10^{18} \text{ cm}^{-3}$ .

tainty). Apparently our results indicate larger band discontinuities  $\Delta E_C$  (meV)  $\simeq (870\text{--}1050)x$  than those given by the recently accepted rule<sup>10</sup>  $\Delta E_C$  (meV)  $\simeq 830x$ . These results could be related to the existence of negative charges in the AlGaAs barrier<sup>11</sup> which have been reported at concentrations as high as  $2 \times 10^{16} \text{ cm}^{-3}$ . In our 1000-Å-wide barriers, such a negative charge contribution will give rise to some additional 40 meV to the top of the barrier. However, even the lowest values deduced for the barrier heights lead approximately to  $\Delta E_C/\Delta E_V \simeq 70:30$  rather than the recently reported ratio of 60:40 (Ref. 10).

The collector barrier is commonly graded in order to reduce the quantum mechanical reflections and to allow the reduction of the barrier height with the increase of  $V_{CB}$  (as demonstrated by the shifts in the onsets of  $\alpha$ 's shown in Fig. 2). To demonstrate the effects of collector barrier grading on the device performance, two similar THETA devices were fabricated. Their structural parameters are as follows: Al mole fraction in both barriers is 0.32, emitter and collector barriers are 100 and 1000 Å thick, respectively, and base width is 1000 Å with a doping level of  $2 \times 10^{17} \text{ cm}^{-3}$ . Figure 3(a) shows the characteristics of the device for which the Al concentration is graded down toward the base over about 200 Å, while Fig. 3(b) is that of the device with an abrupt barrier. The "graded" device exhibits a maximum  $\alpha$  of 0.7, its output differential resistance  $R_0 \simeq 36 \text{ k}\Omega$ , and the collector breakdown voltage  $V_{BE} \simeq 0.9 \text{ V}$ . Similarly for the abrupt device,  $\alpha = 0.3$ ,  $R_0 \simeq 250 \text{ k}\Omega$ , and  $V_{BR} \simeq 1.2 \text{ V}$ .

The different characteristic of the graded device is mainly due to the reduction of the collector barrier height as  $V_{CB}$  increases. This results in reduced quantum mechanical reflections and additional collection of quasi-ballistic electrons. Note that due to the relatively low doping level in these devices, most of the applied voltage  $V_{BE}$  is distributed across the accumulation layer in the emitter ( $\eta_E$ ) and the partial depletion layer in the base ( $\eta_B$ ), thus leaving only a relatively small fraction of the applied voltage across the AlGaAs tunneling barrier. For example, in order to inject a few microamperes into the base, the voltage across the 100-Å AlGaAs barrier should be about 0.16 V. This will necessitate

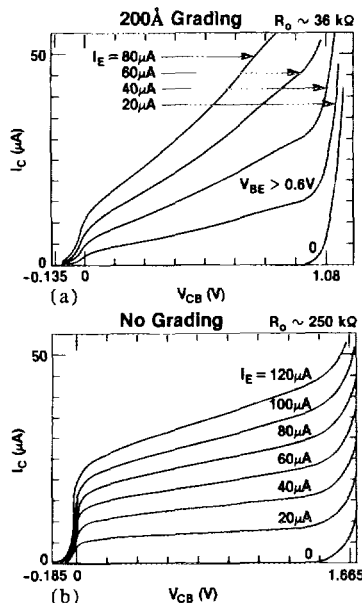


FIG. 3. Output characteristics of two THETA devices with a 1000-Å-wide base in a common base configuration with (a) a 200-Å graded collector barrier, and (b) an abrupt collector barrier. The graded barrier yields a lower breakdown voltage, a lower differential output resistance, but a larger  $\alpha$ . No ballistic transport is evident in these devices because of the high injection energies.

a  $V_{BE}$  of 0.64 V since  $\eta_E \simeq 0.08 \text{ V}$  and  $\eta_B \simeq 0.4 \text{ V}$ . Thus the injection energies are always well above the  $L$  and  $X$  satellite valley minima, inhibiting ballistic transport.<sup>13</sup>

The tails of the collector currents at negative  $V_{CB}$  represent the high-energy part of the electron distribution above the collector barrier. It is clearly evident from Fig. 3 that ballistic transport does not occur in these devices. A distribution width of more than 200 meV with a peak located at about 40–70 meV above the Fermi level in the base was deduced, assuming the arriving electrons are in the  $\Gamma$  states.<sup>7</sup> The large loss of "normal energy" indicates strong relaxation effects associated with either energy or momentum relaxation. This conclusion is not unique since a similar behavior could also be obtained if the electrons were  $L$  electrons encountering a potential barrier in the collector barrier of about 100 meV; such a potential barrier does arise from the discontinuity of  $L$  bands in the base collector-barrier interface.<sup>13</sup>

In summary, we have reported new measurements on tunneling hot-electron transfer amplifier or THETA devices. About 75% of the injected current traversed ballistically a 300-Å base doped to a level of  $7 \times 10^{17} \text{ cm}^{-3}$  at 4.2 K, with a calculated mean free path of about 1000 Å. While the ballistic fraction of the injected current decreased with increasing base width, the width of the ballistic peak remained at 50–60 meV regardless of the base width, suggesting a strong momentum redistribution or a severe energy loss occurring for the fraction of those electrons that did scatter. Barrier heights for AlGaAs barriers higher than the known band discontinuities between GaAs and AlGaAs have been measured. This could be in part due to the presence of uncontrollable negative charges in the AlGaAs barriers. The grading of the collector barrier increases the maximum gain, but decreases the maximum operating voltage and the output differential resistance of the devices.

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<sup>1</sup>S. M. Sze, *Physics of Semiconductor Devices*, 2nd. ed. (Wiley, New York, 1981), Chap. 3.5.

<sup>2</sup>C. O. Bolzer and G. D. Alley, *IEEE Trans. Electron Devices* **ED-27**, 1128 (1980).

<sup>3</sup>U. Mishra, P. A. Maki, J. R. Wendt, W. Schaff, E. Kohn, and L. F. Eastman, *Electron. Lett.* **20**, 145 (1984).

<sup>4</sup>R. J. Malik, M. A. Hollis, L. F. Eastman, D. J. Woodard, C. E. C. Wood, and T. R. AuCoin, *Proceedings of the Conference on Active Microwave Devices*, Cornell University, 1981, unpublished.

<sup>5</sup>M. Heiblum, *Solid State Electron.* **24**, 343 (1981).

<sup>6</sup>N. Yokoyama, K. Imamura, T. Ohshima, H. Nishi, K. Kondo, and H. Hiyamizu, in *Technical Digest of the International Electron Device Meeting*, San Francisco, 1984, p. 532 (unpublished).

<sup>7</sup>M. Heiblum, D. C. Thomas, C. M. Knoedler, and M. I. Nathan, *Appl. Phys. Lett.* **47**, 1105 (1985).

<sup>8</sup>A. F. J. Levi, J. R. Hayes, P. M. Platzman, and W. Wiegmann, *Phys. Rev. Lett.* **55**, 2071 (1985).

<sup>9</sup>M. Heiblum, M. I. Nathan, D. C. Thomas, and C. M. Knoedler, *Phys. Rev. Lett.* **55**, 2200 (1985).

<sup>10</sup>For example, J. Batey and S. L. Wright, *J. Appl. Phys.* **59**, 200 (1986).

<sup>11</sup>T. W. Hickmott, P. M. Solomon, R. Fischer, and H. Morkoç, *J. Appl. Phys.* **57**, 2844 (1985).

<sup>12</sup>M. A. Hollis, S. C. Palmateer, L. F. Eastman, N. V. Dandekar, and P. M. Smith, *IEEE Electron Device Lett.* **EDL-4**, 440 (1983).

<sup>13</sup>M. Heiblum, E. Calleja, I. M. Anderson, W. P. Dumke, C. M. Knoedler, and L. Osterling, *Phys. Rev. Lett.* **56**, 2854 (1986).