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Pseudomorphic InGaAs base ballistic hot-electron device

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We report the first successful incorporation of a pseudomorphic InGaAs base in a ballistic hot-electron device. The device, with a 28-nm-thick $In_{0.15}Ga_{0.85}As$ base, had a collector-base breakdown voltage of 0.55 V and a maximum current transfer ratio of 0.89 at 4.2 K, considerably higher than the 0.75 in a comparable GaAs-base device. Electron energy spectroscopy measurements revealed that at least 30% of the injected electrons traversed the InGaAs base ballistically, causing a strong modulation in the injected currents into the quantized base. The Γ-L valley separation in the strained $In_{0.15}Ga_{0.85}As$ was estimated to be about 410 meV.

We have recently reported on the dc performance of GaAs tunneling hot-electron transfer amplifier (THETA) devices and the direct evidence of ballistic electron transport through thin n^+-GaAs layers.[1,2] In a typical THETA device with a 30-nm-wide n^+-GaAs base doped to $\sim 1\times 10^{18}$ cm^{-3}, about 30% of the injected current was observed to traverse the base ballistically, while the maximum differential current transfer ratio (α_M) was 0.75 at low temperatures.[2] By reducing the collector barrier height and thus increasing the available window for ballistic transport an $\alpha_M = 0.9$ was achieved.[1] However, the small collector barrier height limited the maximum allowed collector-base voltage without collector leakage to less than 0.3 V.

In this letter, we report the first successful incorporation of a 28-nm-wide n^+-$In_yGa_{1-y}As$ ($y = 0.15$) pseudomorphic layer as the base in the THETA device. This device is expected to suffer less from transfer to the L valleys due to a larger Γ-L valley separation. At the same time, the increased conduction-band discontinuity between AlGaAs and InGaAs enables us to reduce the AlAs mole fraction in the collector barrier for the same collector-base breakdown voltage. This tends to improve the quality of the AlGaAs and reduce the scattering of hot electrons in the collector barrier. Indeed we have found in the novel device a collector-base breakdown voltage of 0.55 V for an AlAs mole fraction of 0.15, and a maximum differential current transfer ratio $\alpha_M \simeq 0.89$ at 4.2 K.

The InGaAs pseudomorphic structures were grown by molecular beam epitaxy (MBE) on (100) n^+-GaAs substrates. Figure 1 describes the energy-band diagram of the device under normal bias conditions in a common-base configuration (CBC). The tunnel injector on the left is formed from a thin $Al_xGa_{1-x}As$ layer (10 nm, undoped, $x = 0.28$) which is sandwiched between an n^+-GaAs emitter and a 28-nm-thick n^+-$In_yGa_{1-y}As$ ($y = 0.15$) base which is doped to 1.1×10^{18} cm^{-3}. Another undoped $Al_xGa_{1-x}As$ layer (70 nm, $x = 0.15$) between the base and the n^+-GaAs collector layer forms the collector barrier, thus preventing the equilibrium electrons in the base from entering the collector. The AlAs mole fraction in the collector barrier is graded down to $x = 0.07$ over the last 10 nm on the base side to reduce the quantum mechanical reflections of the incoming hot electrons.

The measured output characteristics, I_C-V_{CB}, in a CBC at 4.2 K are shown in Fig. 2(a). These characteristics are very similar to those of a bipolar transistor. Due to the larger conduction-band discontinuity, the collector-base breakdown voltage (V_{CBM}) is about 0.55 V compared to $V_{CBM} \simeq 0.3$ V in the GaAs device with similar AlAs mole fraction in the collector barrier. The differential current transfer ratio-injection voltage characteristics, $dI_C/dI_E - V_{BE}$, of the same device are shown in Fig. 2(b). Note that the device has $\alpha_M \sim 0.89$ (0.87 at 77 K) that is substantially higher than $\alpha_M \sim 0.75$ in the GaAs devices with similar base doping and thickness.[2] Note also the resonances evident in the curves which are related to quantum mechanical interference of the ballistic electrons in the thin base and will be discussed later. We attribute the higher α_M to the larger Γ-L energy separation $E_{\Gamma L}$ in the strained InGaAs base.

When the injection energy is high enough, some of the ballistic electrons transfer to the L valleys in the base, resulting in a decrease in the current gain α. This was seen before in the GaAs THETA devices.[3] In the pseudomorphic InGaAs-base device, only a slight decrease in α is observed at high injection energies [Fig. 2(b)]. The value for $E_{\Gamma L}$ in

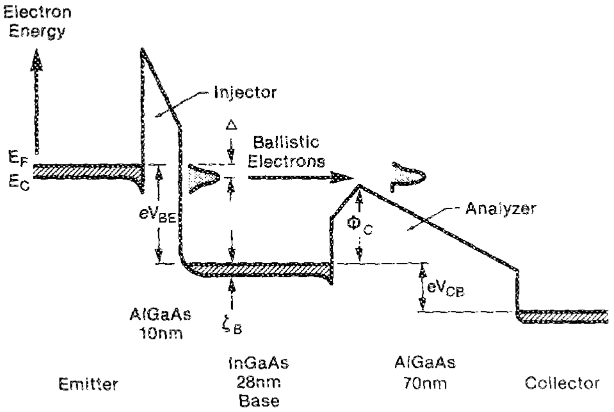

FIG. 1. Schematic diagram of the conduction band of a THETA device under forward bias operation.

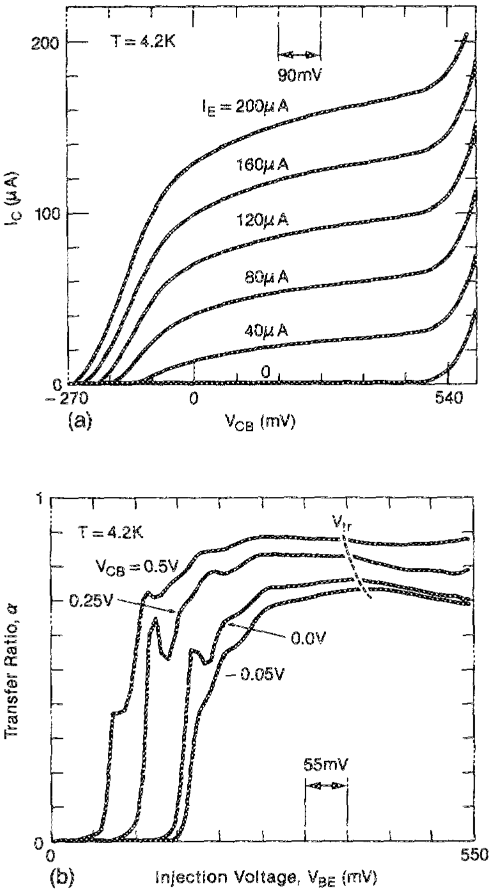

FIG. 2. Output current-voltage characteristics of the device at 4.2 K. The parameter is the injection current I_E. (b) The differential current gain α vs the injection voltage V_{BE} at 4.2 K. V_{tr} is the threshold voltage for the L-valley transfer.

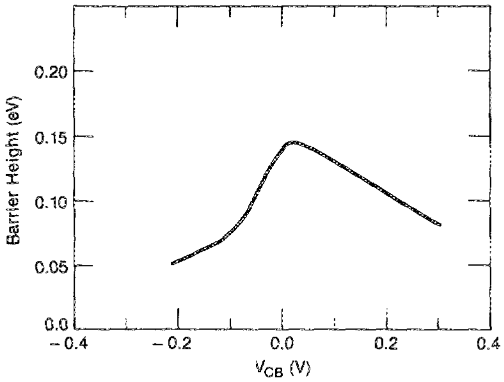

FIG. 3. Barrier height as a function of biasing voltage for an AlGaAs collector barrier, obtained by thermionic emission analysis of temperature-dependent current-voltage characteristics.

the strained base can be estimated from the value of $V_{BE} = V_{tr}$ where α starts decreasing. If this point is associated with the Fermi level in the emitter being one phonon energy above the bottom of the L band, then

$$E_{\Gamma L} \sim qV_{tr} + \zeta_B - E_{ph} - qV_{BB'} ,$$

where ζ_B is the Fermi energy in the base, E_{ph} the optical phonon energy at the edge of the Brillouin zone, and $V_{BB'}$ the voltage drop due to the parasitic base resistance. We estimate a Γ-L valley separation of about 410 meV (compared to 290 meV in GaAs[3]). This is somewhat bigger than ~370 meV predicted by the virtual crystal approximation.

Employing the "electron energy spectroscopy" technique,[1] the application of V_{CB} causes the potential height of the collector barrier above the Fermi level in the base, Φ_C, to change, thus affecting the collector current density J_C. The energy distribution associated with the perpendicular momentum (normal energy distribution) can be approximated by $(1/q\eta)(dJ_C/dV_{CB})$, where $\eta = (1/q)(d\Phi_C/dV_{CB})$ is a proportionality factor.[1] Since the potential shape of the collector barrier is complicated by barrier parameters that are difficult to control (unintentional charges,[4] Si segregation,[5] and the shape of the composition grading), the barrier height as a function of V_{CB} was determined from the activation energy for thermionic emission. In the temperature range 100 K < T < 180 K, the linearities of $\ln(J_C/T^2)$ vs $(1/T)$ plots were good and the effective Richardson constant A^* was 0.8–1.2. The results in Fig. 3 show a linear dependence of the collector barrier height, Φ_C, on V_{CB} in the range greater than 40 mV. Since $\eta = 0.23$ in the range of our spectroscopy measurements (ideally it should be 10 nm/70 nm ~ 0.14), $G_C = dI_C/dV_{CB}$ and the true hot-electron distribution are linearly scaled and are similar in shape. G_C curves for injection energies qV_{BE} = 150–170 meV are plotted in Fig. 4. A clear ballistic behavior is observed. The peak positions in G_C track exactly the injection energy qV_{BE} and are at $qV_{BE} - \Delta$ (the "ballistic condition") where $\Delta \sim 25$ meV (Ref. 6) is the displacement of the normal energy distribution peak below the Fermi level in the emitter (Fig. 1). The ballistic fraction of the electrons that cross the AlGaAs analyzer peak is estimated at about 30% of the injected current.

The ballistic transport maintains the phase coherence of the electrons and thus interference effects in the base can take place. This resulted in resonances in the tunneling currents into the base as shown in Fig. 5. The tunneling conductance is expected to reach a peak whenever the peak of the normal energy distribution, at $qV_{BE} - \Delta$, crosses the bottom

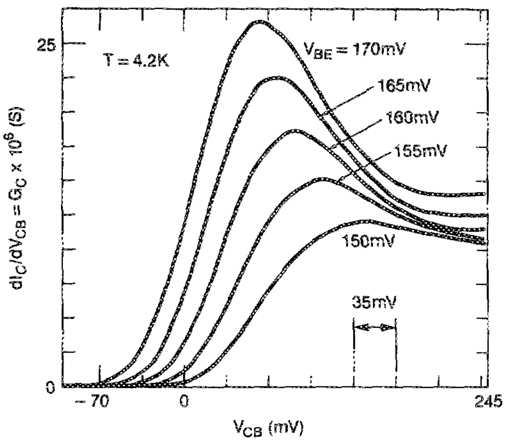

FIG. 4. Differential output conductance G_C as a function of the collector-base voltage. The parameter is the injection voltage V_{BE}. The value of G_C is proportional to the number of ballistic electrons.

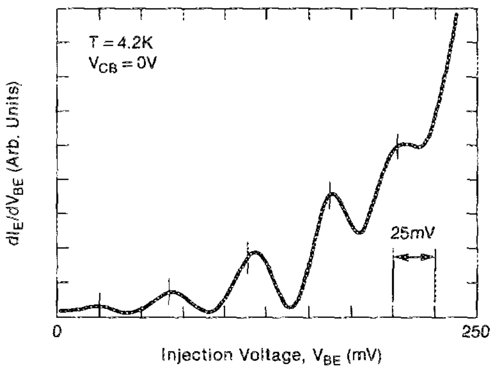

FIG. 5. Derivative of the measured injected current I_E with respect to base-emitter injection voltage V_{BE} for $V_{CB} = 0$ at 4.2 K. Each peak corresponds to a crossing of a subband minimum in the base. The calculated peak positions are marked by the vertical bars for comparison.

of a quasi-2D electron band formed in the base. We have estimated these conductance peak positions by solving the Schrödinger equation in the $In_{0.15}Ga_{0.85}As$ base assuming $m^* = 0.060m_e$, where m_e is the free-electron mass, and a nonparabolicity parameter $\alpha = 0.72$ eV^{-1} obtained from the virtual crystal approximation,[7] and noted them in Fig. 5. Even though this is not a self-consistent solution for the Poisson and Schrödinger equations,[8] it still gives a very good agreement with the experimental results. Note also that the observed strong peaks in Fig. 5 are another indication of the large fraction of ballistic electrons.

In summary, we report on the first successful demonstration of a pseudomorphic n-type InGaAs base THETA device. The maximum current transfer ratio was 0.89 at 4.2 K (0.87 at 77 K), and the minimum ballistic fraction was about 30%, detected by an energy spectroscopy technique. The relatively high gain was attributed mainly to the greater Γ-L energy separation.

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[7] The conduction-band nonparabolicity is accounted for via $E(k) = (\hbar^2 k^2/2m^*)(1 - \alpha\hbar^2 k^2/2m^*)$, where $E(k)$ is the kinetic energy in the Γ Band and α is the nonparabolicity parameter. The value for α in $In_{0.15}Ga_{0.85}As$ was approximated from a linear interpolation between $\alpha = 0.55$ eV^{-1} in GaAs and $\alpha = 1.167$ eV^{-1} in $In_{0.53}Ga_{0.47}As$.

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