High-field transport in GaAs transistors

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Resonant tunneling is used to explore the dynamics of electron transport in the electric field of reverse-biased GaAs *n-p-n* heterojunction bipolar transistor collectors. Extreme velocity overshoot is observed in a fraction of a percent of electrons which are accelerated ballistically in the Γ valley to energies greater than 1.5 eV. In addition, we show that $\Gamma-X$ valley transfer is the dominant scattering mechanism for high-energy Γ valley electrons.

In a "ballistic" electron transistor charge transport across the base *and* collector depletion region involves little or no inelastic scattering. Recently we were able to demonstrate[1] that, in agreement with theory,[2] nonequilibrium conduction-band electrons can traverse the base of a GaAs *n-p-n* heterojunction bipolar transistor without suffering significant scattering. The purpose of this letter is to show that electrons can transverse the collector depletion region ballistically and that there exists an optimum base/collector bias above which intervalley scattering dominates collector transport.

The transistor structures used in this study were grown by molecular beam epitaxy on semi-insulating ⟨001⟩ oriented GaAs substrates at a substrate temperature of 600 °C. Minimally As-stabilized growth conditions were optimized to yield smooth and abrupt GaAs/AlAs interfaces as determined by reflection high energy electron diffraction (RHEED). The absolute growth rates were monitored *in situ* using RHEED intensity oscillations.

Figure 1 shows a schematic band diagram of a typical structure under bias. Electrons in the *n*-type (3×10^{17} cm^{-3} Si impurity) Al$_{0.3}$Ga$_{0.7}$As emitter are injected into the 1500-Å-thick *p*-type (3×10^{18} cm^{-3} Be impurity) GaAs base. The injected electrons rapidly scatter, lose energy, and diffuse across the thick base with an average energy a few meV above the conduction-band minimum. After traversing the base, the electrons are transmitted through the collector via quantized electronic states due to the presence of a resonant tunnel structure in the undoped collector depletion region. The 20-Å-thick AlAs tunnel barrier close to the *p*-type base is separated by a 100 Å $<Z_c<$ 600 Å thick layer of GaAs from a 45-Å-thick AlAs barrier. The 45-Å-thick AlAs barrier is grown adjacent to the *n*-type (3×10^{18} cm^{-3} Si impurity) collector contact layer.

The wafers were fabricated into two level mesa structures using photolithographic and wet chemical etching techniques. Separate ohmic electrical contact to emitter and collector was achieved by rapid thermal annealing of a NiGeAu alloy and base contact was made by using a AuBe alloy. The smallest completed transistor structures had an emitter area of 6×10^{-6} cm^2 and the largest had an emitter area of 8×10^{-5} cm^2.

In Fig. 2 we show typical common base and common emitter current-voltage characteristics for the device sketched in Fig. 1 with $Z_c = 150$ Å. As may be seen in Fig.

2(b), breakdown occurs for $V_{ce} \sim 4$ V which corresponds to an electric field $\sim 10^6$ V cm^{-1} in the collector. These high breakdown fields are possible because small Z_c reduces the ionization volume. In similar structures with $Z_c \gtrsim 1000$ Å we observe breakdown at electric fields of less than 3×10^5 V cm^{-1}.

In Fig. 2 resonances in the current-voltage characteristics are indicated by arrows and are clearly visible over a wide range of voltage bias. In Fig. 2(a) the derivative of the collector current, dI_c / dV_{bc}, indicates the presence of resonances for $V_{bc} \lesssim + 1.3$ V. Careful modeling, taking into account depletion in the *p*-type base and *n*-type collector, allows an accurate value for the maximum energy E_i^{max} attained by the Γ valley electron in region Z_c to be plotted on the upper horizontal axis in Fig. 2(a). As may be seen from the figure, the highest energy resonance occurs for E_i^{max} greater than 1.5 eV. This is direct evidence that a few ($\sim 0.2\%$) of the initially injected electrons can be accelerated in strong electric fields ($\sim 8 \times 10^5$ V cm^{-1}) to energies of around 1.5 eV without scattering. Qualitatively similar results (with less pronounced structure) are obtained when the sample is maintained at a temperature $T = 300$ K. Other samples with wider well width, 150 Å $< Z_c \lesssim$ 450 Å, also show resonances for $E_i^{max} \lesssim 1.3$ eV.

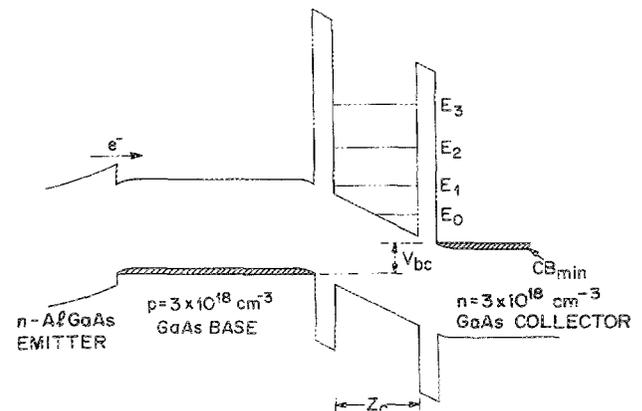Our results demonstrate that extreme velocity over-

FIG. 1. Schematic band diagram of an *n-p-n* heterojunction bipolar transistor with a resonant tunnel collector under bias. The conduction-band minimum CB$_{min}$, the base collector bias voltage V_{bc}, and the resonant tunnel well width Z_c are indicated.
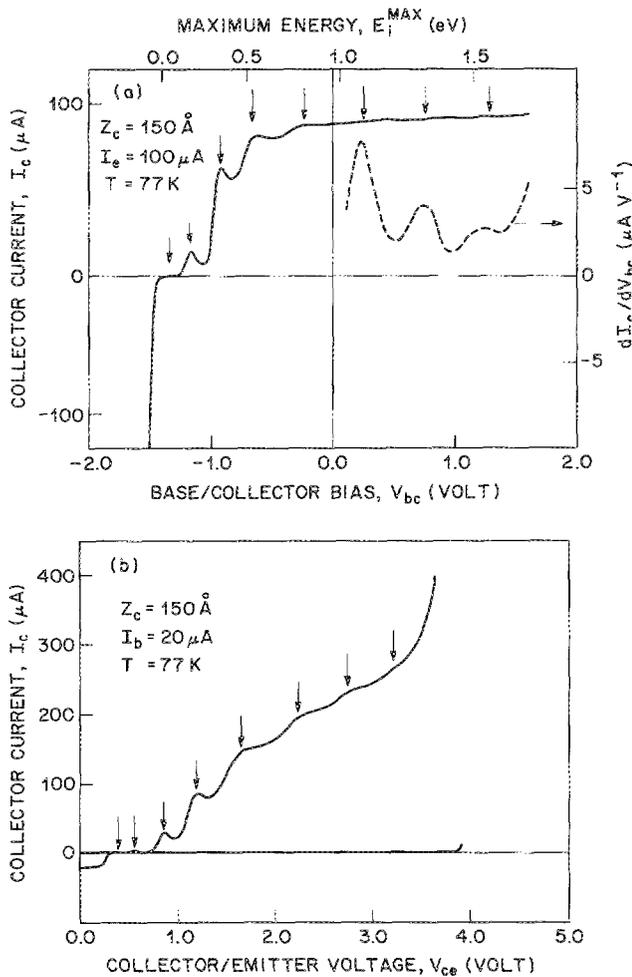
MAXIMUM ENERGY, E_i^{MAX} (eV)

FIG. 2. (a) Common base and (b) common emitter current gain characteristics at $T = 77$ K of the device shown schematically in Fig. 1. Emitter area is 6×10^{-6} cm². The arrows indicate the position of resonances in the collector current I_c. The resonant tunnel well width Z_c emitter current I_e and base current I_b are indicated.

FIG. 3. Conductance dI/dV_{bc} as a function of base/collector bias V_{bc} for a sample with $Z_c = 600$ Å. Measurements were taken in the common base configuration with emitter currents $I_e = 0$ μA and $I_e = 100$ μA (emitter current density $j_e = 17$ A cm^{-2}). The sample was maintained at a temperature of $T = 77$ K.

width, Z_c, and consequent reduction in probability of being scattered by longitudinal optical phonons. The average time the electron spends in the well decreases because the tunneling probability through the collector barrier increases and the average velocity through the structure increases with increasing E_i^{max}.

For a maximum electron energy, $E_i^{max} \gtrsim E_{\Gamma L} \simeq 0.3$ eV scattering from the Γ valley to the L valley is possible but has a small effect on the oscillation amplitude. However, when $E_i^{max} \gtrsim E_{\Gamma X} \simeq 0.5$ eV the oscillation amplitude is significant-

shoot ($v_i^{max} > 1.2 \times 10^8$ cm s^{-1}) is possible for a small fraction of electrons accelerated in a large electric field. However, we think the most surprising fact is that electrons can be accelerated ballistically to energies greater than 1.5 eV which is almost the width in energy of the GaAs conduction band, $E_{bw} = 1.85$ eV. E_{bw} is the absolute maximum kinetic energy a conduction-band electron can be accelerated to without scattering.[3] Our experiments show that nonequilibrium electrons can approach this fundamental limit to ballistic transport.

It is clear from Fig. 2(a) that with increasing E_i^{max} the resonant amplitude increases, reaches a maximum, and then decreases. To explore this phenomenon in more detail we measured conductance oscillations as a function of base/collector bias[4] V_{bc} for a number of our samples. In Fig. 3 we show results obtained for a typical sample with $Z_c = 600$ Å measured at a temperature of 77 K. For the purpose of discussion, in Fig. 4 we plot the oscillation amplitude as a function of E_i^{max}. The initial increase in amplitude with increasing E_i^{max} may be understood as due to a decrease in the average time spent by an electron in the quantum well of
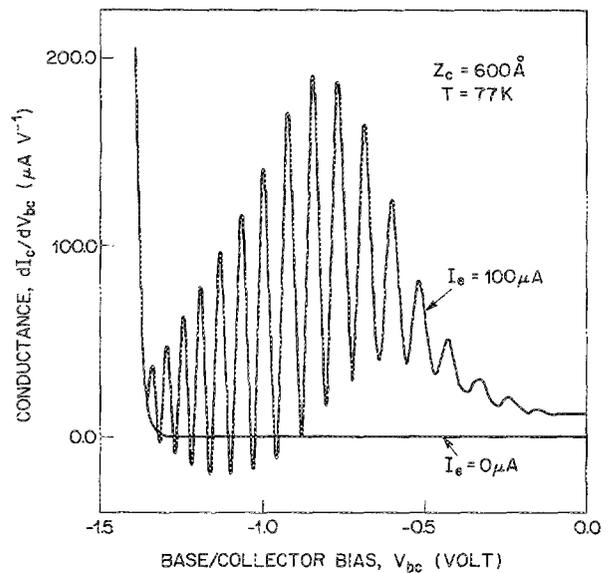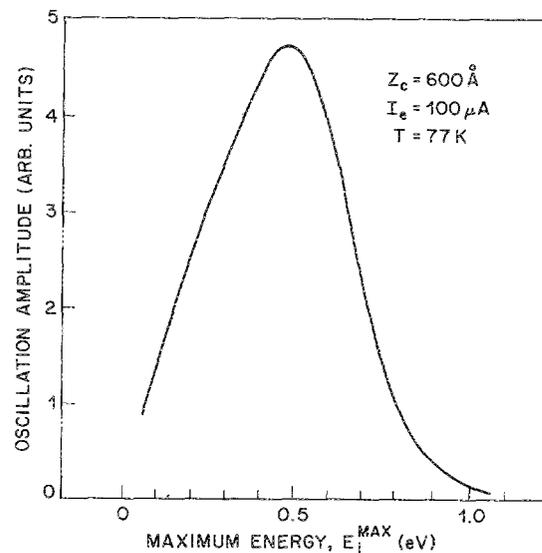

FIG. 4. Oscillation amplitude as a function of E_i^{max} for a sample with $Z_c = 600$ Å. Measurements were taken in the common base configuration with an emitter current, $I_e = 100$ μA (emitter current density $j_e = 17$ A cm^{-2}). The sample was maintained at a temperature of $T = 77$ K.

ly damped. This immediately suggests that Γ–X valley scattering is the dominant mechanism responsible for the observed suppression in amplitude. We have calculated the curve shown in Fig. 4 using the known bulk values of longitudinal optic phonon scattering rate, $1/\tau_{LO}$, and the functional form of Γ to X intervalley scattering rate and Γ to L intervalley scattering rate,[5] with relative scattering strength as a variable. The most sensitive parameter in the model is the ratio of intervalley scattering strengths $(1/\tau_{\Gamma X})/(1/\tau_{\Gamma L})$. Agreement with our experimental data is obtained if the ratio of intervalley scattering rates for an electron of energy 0.58 eV is $(1/\tau_{\Gamma X})/(1/\tau_{\Gamma L}) \sim 3$. We note that this ratio of intervalley scattering rates for nonequilibrium electron transport is close to the value obtained from recent optical experiments.[6]

Our results have consequences for the design of bipolar transistors which utilize ballistic electron transport in the collector and field-effect transistors using velocity overshoot between source and drain. Since $1/\tau_{\Gamma X}$ is much more important than $1/\tau_{\Gamma L}$, optimum ballistic transport occurs for small Z_c and in an electric field such that $E_i^{\max} \gtrsim E_{\Gamma X}$. In addition, and in qualitative agreement with Monte Carlo calculations,[7] other semiconductors with larger $E_{\Gamma X}$, such as $In_{0.53}Ga_{0.47}As$ ($E_{\Gamma X} = 1.1$ eV) and InAs ($E_{\Gamma X} = 1.8$ eV), will exhibit improved high-field ballistic transport/velocity overshoot compared to GaAs.

Finally, we note that there have been reports of hysteresis in the position of peaks in the current-voltage characteristics of resonant tunnel junctions.[8,9] This hysteresis may be due to a space charging effect[8] and so should depend on current density, or the hysteresis may arise from the external measurement circuit.[9] Unlike previous resonant tunnel structures, we can alter the collector current density independently of the base/collector bias, V_{bc}. For collector current densities greater than around 100 A cm^{-2} we observed hysteresis in the position of resonant peaks. However, the magnitude of the hysteresis (area inside the hysteresis loop) varied nonmonotonically with increasing current density and depended on external circuit measurement parameters such as voltage sweep rate. This suggests that the dominant cause of the hysteresis we observe is due to the external measurement circuit.

In summary, a small number of the initially accelerated electrons in the conduction band of GaAs can attain energies greater than 1.5 eV without scattering. However, because Γ–X scattering is the dominant inelastic mechanism in GaAs, most electrons transfer into the X valley when they have an energy $E_i > E_{\Gamma X}$.

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