Electroluminescence from the base of a GaAs/AlGaAs double heterojunction bipolar transistor

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We have measured the electroluminescence spectrum of a double heterojunction bipolar transistor and found that a potential well formed at the base-collector junction acts as a preferential trap of low-energy electrons in the base. At high injection current densities the trap saturates. The subsequent buildup of carriers in the base changes the transistor turn-on characteristics.

Information on the dynamics of injected nonequilibrium electron transport in submicron semiconductor devices has been obtained using "hot-electron spectroscopy".[1] More recently this electrical measurement technique has been used to explore base transport dynamics in GaAs/AlGaAs *n-p-n* double heterojunction bipolar transistors (DHBT's).[2] In addition to investigating transport properties by purely electrical means, electroluminescence from charge carriers has been used to study emitter injection efficiency[3] and carrier transport in the base of a GaAs transistor.[4] In this letter we present new results on the relaxation of nonequilibrium electrons trapped in the base of a DHBT by measuring the electroluminescence spectrum as a function of collector barrier energy.

The devices used in our study are AlGaAs/GaAs DHBT's grown by molecular beam epitaxy to have a band profile similar to that shown in Fig. 1(a). They consist of an $Al_{0.31}Ga_{0.69}As$ emitter and an $Al_{0.35}Ga_{0.65}As$ collector doped 2×10^{17} cm^{-3} *n* type with Si and a 900-Å-wide GaAs base doped 2×10^{18} cm^{-3} *p* type with Be. The base/collector

heterojunction includes a 50-Å compositional grading to reduce quantum mechanical reflection of hot electrons arriving at the collector. The wafers were fabricated into two level mesa structures using standard chemical etching techniques[1] allowing electrical contact to emitter, base, and collector. These devices typically have common emitter current gains β of over 50 at a temperature of 300 K increasing to greater than 500 at 100 K.

In our experiments a DHBT was maintained at a temperature of 5 K to avoid thermal effects. The emitter was biased negative with respect to the base at ground potential to inject electrons into the *p*-type base with a nonequilibrium momentum distribution sharply peaked normal to the plane of the AlGaAs/GaAs heterojunction [see Fig. 1(a)]. These injected electrons, of initial energy $E_i \simeq 200$ meV above the conduction-band minimum CB$_{min}$, of the base may lose energy by either exciting longitudinal optic phonons or electron-hole pairs in the Fermi sea of holes. They may also randomize their momentum via elastic collisions with ionized impurities in the *p*-type base. Spectroscopic information
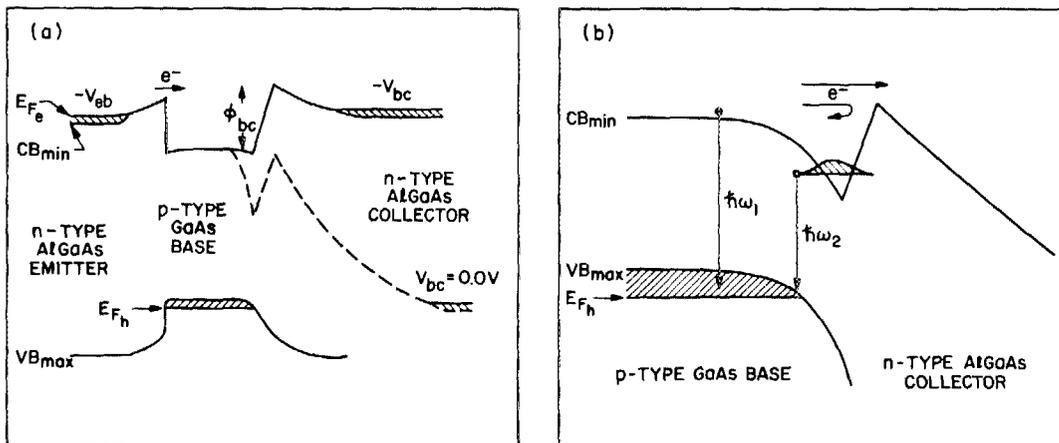

FIG. 1. (a) Schematic band diagram of an *n-p-n* AlGaAs/GaAs DHBT under bias. The conduction-band minimum CB$_{min}$, the valence-band maximum VB$_{max}$, the hole quasi-Fermi level E_{F_h}, the electron quasi-Fermi level E_{F_e}, and the collector barrier energy ϕ_{bc} are indicated. (b) Schematic band diagram of the base-collector junction indicating above-band-gap $\hbar\omega_1$ and sub-band-gap, $\hbar\omega_2$ radiative recombination from electrons trapped in the base. The exponentially decaying wave function of electrons trapped in the base-collector triangular potential well is also shown.

on the momentum distribution of hot electrons arriving at the collector barrier is obtained electrically by measuring the change in current, dj_c/dV_{bc}, across the barrier as a function of barrier energy, ϕ_{bc}. Since an approximately linear variation in ϕ_{bc} is achieved by applying a negative bias $-V_{bc}$ to the collector with respect to the base at ground potential, measuring dj_c/dV_{bc} as a function of V_{bc} gives the "hot-electron spectrum".[1] Unfortunately, using this electrical measurement technique, all information about electrons which cannot surmount the barrier and are trapped in the base is lost. However, we can study the relaxation of these nonequilibrium electrons by measuring the luminescence spectrum of hot electrons recombining with holes in the base as a function of V_{bc} and hence ϕ_{bc} as shown schematically in Figs. 1(a) and 1(b).

When the collector is biased negative ($V_{bc} = -1.5$ V) such that ϕ_{bc} is greater than the injection energy E_i, all the injected electrons are trapped in the base region. These electrons rapidly scatter [scattering time less than ~ 0.1 ps (Refs. 4 and 5)] in the base before radiatively recombining with the holes [recombination time greater than ~ 100 ps (Ref. 5)]. Because the transition probability for electron-hole recombination is essentially frequency independent for energies greater than the band gap E_g, the energy spectrum of above-band-gap radiation is a measure of the energy distribution of the nonequilibrium electrons. If the scattered electrons may be described in terms of an effective electron temperature (the usual assumption in hot-electron luminescence experiments[5,6]), then a plot of the logarithm of intensity with photon energy gives the effective electron temperature of the hot-electron distribution. For the situation when $\phi_{bc} > E_i$ this procedure gives an effective temperature $T_e \sim 60$ K for electrons in the base as shown in Fig. 2(a). With increasing V_{bc}, the barrier ϕ_{bc} decreases, and the effective electron temperature T_e increases linearly up to a maximum of ~ 100 K for $\phi_{bc} \lesssim 0$ eV. However, as ϕ_{bc} is reduced to zero some curvature appears in the logarithmic plot suggesting a breakdown of the effective electron temperature concept. Nevertheless, for the purpose of discussion, we use T_e as an approximate measure of the high-energy portion of the electron distribution.

We can relate this apparent increase in T_e to the presence of a triangular quantum well at the base-collector interface[2] which acts as a preferential trap for electrons close in energy to the conduction-band minimum. Low-energy electrons are extracted from the distribution arriving at the collector barrier thereby increasing the apparent T_e of the distribution contributing to above-band-gap radiation. Electrons trapped in the quantum well have exponentially decaying wave functions which overlap with unoccupied electron (hole) states in the GaAs valence band giving rise to optical transitions in which photons of energy less than E_g are emitted. This situation is illustrated in Fig. 1(b) in which above-band-gap transitions are indicated by $\hbar\omega_1$ and sub-band-gap transitions by $\hbar\omega_2$.

The measured variation of sub-band-gap radiation with increasing V_{bc} (decreasing ϕ_{bc}) is shown in Fig. 2(b). As may be seen the peak intensity of the sub-band-gap radiation shifts to lower energy with decreasing ϕ_{bc} for fixed emitter current j_e. This occurs because with decreasing ϕ_{bc} the depth of the quantum well increases so that the lowest energy electron states of the well are separated in energy from the valence-band hole states by a reduced amount. In fact, by varying V_{bc} the peak position can shift by more than 60 meV (which is similar to the largest observed electric field induced shifts in photoluminescence experiments on single quantum well structures[7]). The intensity of the sub-band-gap radiation also decreases with decreasing ϕ_{bc} due to reduction in overlap between trapped electron states and valence-band hole states and an enhanced electron tunneling probability through the collector barrier which reduces the carrier concentration in the well. Eventually, for $\phi_{bc} \lesssim 0$ eV the transistor has turned on and little radiation is emitted because nearly all the injected electrons are collected, very few electrons recombine in the base (a fact which is reflected in the high β values for these devices).

In Fig. 3 the luminescence spectra for two emitter currents j_e at a fixed value of $V_{bc} = -0.7$ V are shown. As may be seen, the above-band-gap contribution to the spectrum is almost unchanged, except in overall intensity, upon increasing j_e by an order of magnitude. However, with increasing emitter current the peak in sub-band-gap radiation increases
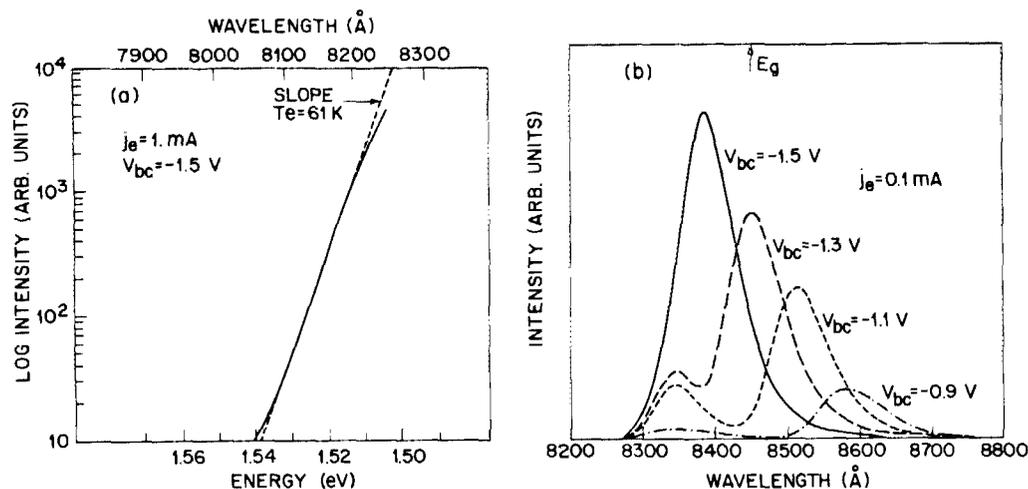

FIG. 2. (a) Logarithm of luminescence intensity with energy for a DHBT sample with a 900-Å base width doped $p = 2 \times 10^{18}$ cm^{-3} and $V_{bc} = 1.5$ V. (b) The variation of the luminescence spectrum with wavelength obtained from the DHBT sample used in (a) for the indicated values of V_{bc}.
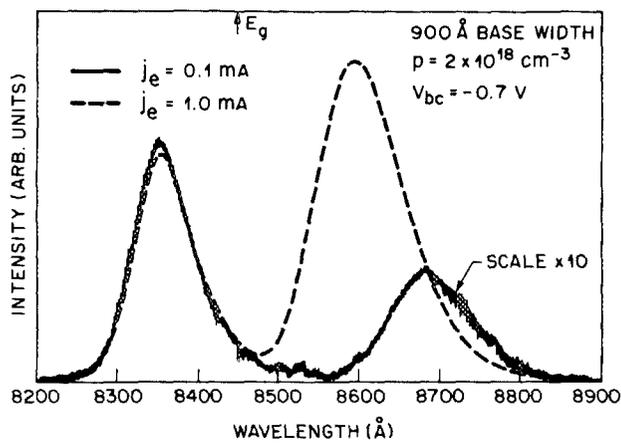
FIG. 3. Change in the luminescence spectrum for the sample in Fig. 2 for two different values of j_e and fixed V_{bc}.

FIG. 4. Plot of the logarithm of dj_c/dV_{bc} with V_{bc} for the indicated injection currents j_e. In the hot-electron spectrum both the injection energy E_i and the conduction-band minimum CB_{min} are shown.

in relative intensity and shifts to higher energy. This is consistent with our model; since an electron's radiative recombination time is longer than the time taken to trap an electron in the quantum well more electrons are trapped by the quantum well and the well fills. The observed saturation in the quantum well is a nonlinear effect and is the precursor to a change in the transistor turn-on characteristics.

At high current densities the occupation, observed in the electroluminescence spectrum, of conduction-band electron states in the base influences the turn-on characteristics of the transistor and changes the character of the hot-electron spectrum, with apparently more electrons being collected at greater ϕ_{bc}. This effect is most easily illustrated by measuring hot-electron spectra of a DHBT with a narrower base width where saturation effects occur at lower current densities. In Fig. 4 we plot the logarithm of dj_c/dV_{bc} with V_{bc} for a DHBT in which all parameters other than a 300-Å base width are the same as for the 900-Å base width sample. At a low injection current of $j_e = 0.1$ mA (~ 1 A cm^{-2}) we are in the linear regime (doubling the injection current gives the same spectrum scaled by a factor of 2). At injection currents of ~ 1 mA (~ 10 A cm^{-2}) and greater we enter the nonlinear regime with more electrons being collected at greater ϕ_{bc}. However, this nonlinear effect does not reflect the hot-electron distribution arriving at the collector of a fully turned-on transistor (when $\phi_{bc} \lesssim 0$ eV no accumulation occurs in the base). In this situation the true distribution is determined by performing hot-electron spectroscopy at low current densities ($\lesssim 10$ A cm^{-2} for 900 Å base width samples) in a regime where the accumulation of hot electrons in the base has a negligible effect.

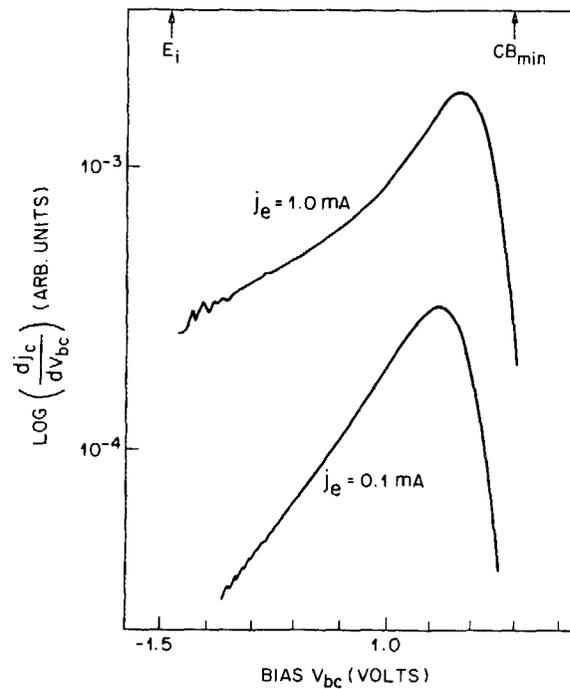In conclusion, electroluminescence has been used to probe the dynamics of nonequilibrium electrons trapped in the base of a DHBT. Our experiments have revealed that the quantum well formed at the base/collector interface acts as an efficient, preferential trap for low-energy electrons in the base. In addition, at high current densities, the accumulation of electrons in the quantum well saturates and electrons trapped in the base alter the turn-on characteristics of the transistor modifying the hot-electron spectrum.

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