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Electroluminescence spectroscopy in a high magnetic field of the ballistic-electron energy distribution in single-barrier heterostructures

R. Teissier,* J. J. Finley, M. S. Skolnick, and J. W. Cockburn
Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom

R. Grey, G. Hill, and M. A. Pate
Science and Engineering Research Council Central Facility for III-V Materials,
Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, United Kingdom

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A high-resolution electroluminescence study of the hot-electron energy distribution, and of the nature of the tunneling processes, in GaAs/Al$_x$Ga$_{1-x}$As single-barrier p-i-n diodes is reported. Application of quantizing magnetic fields permits electron injection from narrow, well-defined electron states into the collector region, even at high emitter density. As a result ballistic-electron peaks, accompanied by their LO-phonon cascade, are clearly resolved. Cross-barrier recombination is also observed. The energy distribution of the ballistic electrons is shown to reflect exactly that of the emitter electrons, even though the density is $\sim 10^5$ times lower, thus demonstrating that the two-dimensional to three-dimensional tunneling process is elastic and independent of the in-plane motion. The energy relaxation of the ballistic electrons is shown to be dominated by LO-phonon emission, with energy randomization by, e.g., carrier-carrier scattering playing no significant role.

Experimental access to nonequilibrium electron distributions is most important in order to achieve a soundly based understanding of the physics of high-speed semiconducting devices. All-electrical techniques have demonstrated the occurrence of quasiballistic transport in hot-electron transistors[1,2] and heterojunction-bipolar transistors.[3] On the other hand, optical techniques have proved very effective in studying the relaxation of optically injected electron populations in bulk semiconductors.[4,5] Recently Petersen, Frei, and Lyon[6] have observed electrically injected ballistic electrons in Al$_x$Ga$_{1-x}$As/GaAs heterodiodes, using electroluminescence (EL) spectroscopy.

In the present paper, we study by EL the relaxation of hot electrons injected from an n-type-doped emitter to a p-type-doped collector through a single Al$_x$Ga$_{1-x}$As barrier, with high magnetic field (B), parallel to the transport direction z. Without field, the emitter electrons are confined in the z direction by the triangular potential well in the accumulation layer [see Fig. 1(a)], and, because of their free motion in the (x,y) plane, they occupy the two-dimensional density of states over a width ε_f proportional to their sheet density. When a field $B\|z$ is applied, the motion in the (x,y) plane becomes quantized, leading to the formation of Landau levels (LL's). Thus the emitter electrons are confined in all directions and can only occupy discrete energy levels, as shown in Fig. 1. Such experimental conditions permit unambiguous conclusions to be reached as to the effects of tunneling and relaxation processes on the evolution of the measured hot-electron distribution from the initial equilibrium distribution in the emitter.

The EL technique relies on the observation at low temperature (2 K) of the recombination of hot electrons with neutral acceptors in the p-type-doped region of the structure.[4] Because of the strong localization of the hole on acceptor atoms (Bohr radius $a_0=21.3$ Å), recombination is allowed for a wide spread of electron wave vectors. When corrected for the energy dependence of the probability of recombination with acceptors, the EL spectra reflect exactly the actual electron-energy distribution integrated over the width of the collector, for electron energies below the intervalley transfer threshold of about 1.8 eV.[7] The probability $P(E)$ of recombination with neutral acceptors of a free electron of kinetic energy E and wave vector k can be determined accurately from the k component $M(k)$ of the acceptor wave function described in the effective-mass approximation, since

$$P(E)\propto|M(k)|^2$$

with

$$k=\frac{\sqrt{2m^*E}}{\hbar} \quad \text{and} \quad M(k)\propto\frac{1}{(1+a_0^2k^2)^2}.$$

The sample studied in the present paper is shown schematically in Fig. 1(a). It was grown by molecular-beam epitaxy and consisted of the following layers: n^+-type GaAs substrate, 1-μm $n=10^8$ cm^{-3} GaAs buffer, 500-Å $n=10^{17}$ cm^{-3} GaAs emitter, 500-Å $n=3\times10^{16}$ cm^{-3} GaAs emitter, 50-Å-undoped GaAs spacer, 100-Å Al$_{0.4}$ Ga$_{0.6}$As barrier, 50-Å-undoped GaAs spacer, 5000-Å $p=10^{17}$ cm^{-3} Be-doped GaAs collector, and 5000-Å p^+-type GaAs top contact. It was processed into mesas of 200 and 400 μm diameter. Annular top contacts crossed by metallized fingers at a pitch of 20 μm were employed to provide optical access to the diode while keeping in-plane inhomogeneties as low as possible. The samples were mounted in a superconducting magnet and studied at 2 K with $B\|z$. The EL signal was collected by an optical fiber and analyzed with a high stray light rejection triple grating spectrometer and a liquid-nitrogen-cooled charge-coupled-device camera.

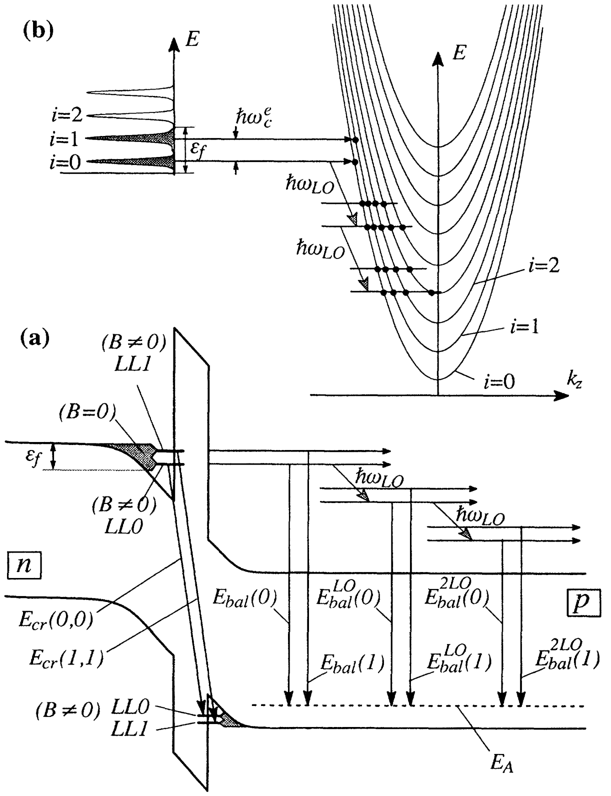

FIG. 1. (a) Schematic band diagram (not to scale) of the structure under forward bias. (b) The band dispersion in the 2D emitter and 3D collector regions. In the magnetic field, the 2D emitter accumulation layer is quantized into Landau levels (LL's) from which the ballistic electrons are injected. Two LL's are represented in the figure. In the collector, the ballistic population relaxes by emitting a cascade of LO phonons. It should be noted that the tunneling process conserves the in-plane motion (i.e., the LL number), while LO-phonon emission does not necessarily do so. The hot-electron distribution is measured from the study of the EL recombination of electrons with neutral acceptors in the p region.

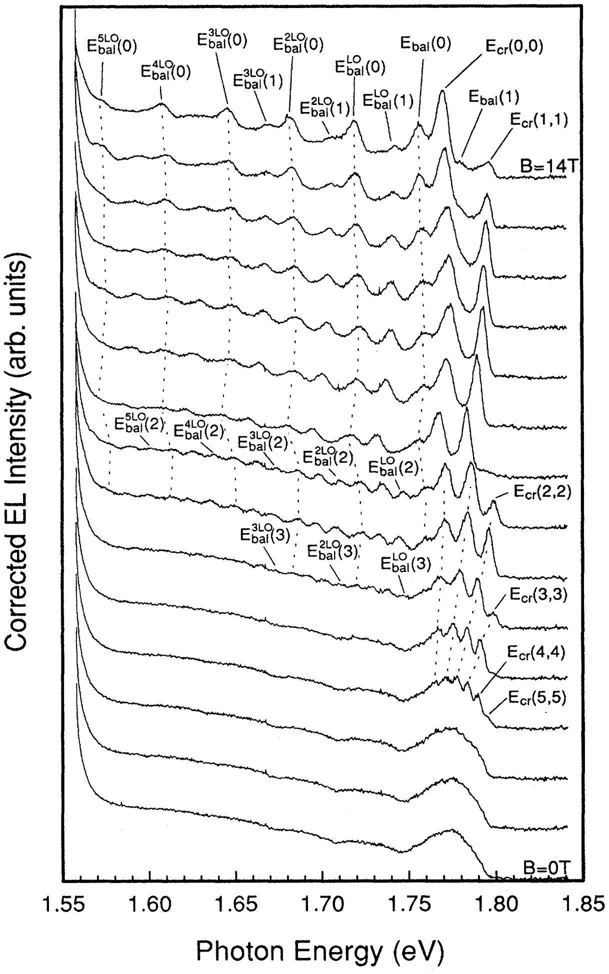

FIG. 2. EL spectra at a bias of 1.85 V and for the magnetic field between 0 and 14 T. The peak assignments are discussed in the text.

The EL spectra obtained when forward biased at 1.85 V, and for $B||z$ ranging from 0 to 14 T, are shown in Fig. 2. The spectra are corrected for the response of the system, for the energy dependence of reabsorption in the GaAs top contact, and for the recombination probability $P(E)$, as discussed above and in Refs. 7 and 8. The sharp increase in the EL signal below 1.57 eV is due to the high-energy tail of the recombination of thermalized electrons in the collector, whereas the weaker features present between 1.57 and 1.8 eV arise principally from the highly nonequilibrium distribution of electrons that have tunneled through the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ barrier. The 1.57–1.8-eV spectrum at $B=0$ is composed of a broad peak at $\sim$1.77 eV, followed by two barely resolved features at $\sim$36 and 72 meV to lower energy. In magnetic field $B||z$, the resolution of the spectra improves dramatically. Splitting into well-defined LL's is observed, providing clear proof for the contribution of a broad distribution of carriers, with free motion in the (x,y) plane, to the $B=0$ spectra.[9] For each LL i, we observe a series of lines labeled $E_{\mathrm{bal}}^{n\mathrm{LO}}(i)$ with $n=0$ to 5, evenly spaced by 36 meV. The series of peaks arises from a hot-electron population that relaxes by emitting a cascade of LO phonons ($\hbar\omega_{\mathrm{LO}} \approx 36$ meV).[4,6] The highest energy lines $E_{\mathrm{bal}}(i)$ of the series is attributed to the recombination with neutral acceptors of unrelaxed ballistic electrons, and the lines $E_{\mathrm{bal}}^{n\mathrm{LO}}(i)$, $n \geqslant 1$, to quasiballistic electrons that have emitted successively nLO phonons[10] (Fig. 1).

The degeneracy of a LL is $2eB/h$, including spin. As a result, with increasing B the number of populated LL's decreases, as observed in Fig. 2. At the same time, the splitting between LL's is proportional to B, with the result that the best resolved spectrum is obtained at the highest field of 14 T. This spectrum is dominated by recombination from the $i=0$ LL with a weaker contribution from the $i=1$ LL. In addition, one can see another group of lines labeled $E_{\mathrm{cr}}(i,i)$ in the higher-energy region of the spectra. We show below that these lines arise from cross-barrier recombination.

The energy splitting $\Delta(\mathrm{bal}) = E_{\mathrm{bal}}^{n\mathrm{LO}}(i) - E_{\mathrm{bal}}^{n\mathrm{LO}}(i-1)$ between quasiballistic lines arising from successive LL's found to be independent of both i and n, and is plotted in Fig. 3. $\Delta(\mathrm{bal})$ increases linearly with B and, using $\Delta(\mathrm{bal}) =$

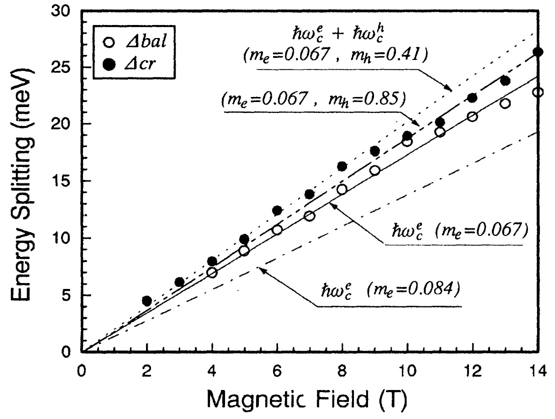

FIG. 3. Evolution with the magnetic field of the splitting between LL features in the ballistic [Δ(bal)] and cross-barrier [Δ(cr)] recombinations. Δ(bal) is equal to the emitter-electron LL splitting, whereas Δ(cr) has contributions from both the LL splitting of the emitter-electron and collector-hole accumulation layers.

$\hbar\omega_c^e=\hbar eB/m_e$ (ω_c^e being the electron-cyclotron frequency), corresponds to an effective mass $m_e=0.067\pm0.004m_0$, equal to the band-edge effective mass in GaAs. The splitting Δ(cr) between two consecutive $E_{\rm cr}(i,i)$ transitions is higher than $\hbar\omega_c^e$. This indicates that these transitions also involve free-hole levels,[11] which can only be the LL's of the hole-accumulation layer on the collector side of the barrier [see Fig. 1(a)]. Δ(cr) is then given by $\hbar\omega_c^e+\hbar\omega_c^h$, ω_c^h being the hole-cyclotron frequency. The hole LL energies and spacing are expected to vary in a highly nonlinear fashion with B, and to have a marked dependence on hole density (n_h).[12] Nevertheless, it is worth noting that, from Fig. 3, Δ(cr) $-$Δ(bal) gives $m_h=0.41\pm0.04m_0$ for $B\leqslant8$ T and $m_h=0.85\pm0.3m_0$ for $B>8$ T, which are in good agreement with the hole masses of $0.38m_0$ and $0.6m_0$ observed by Stormer *et al.*[13] in cyclotron-resonance experiments on a heterojunction with an n_h of 5×10^{11} cm^{-2} (the present n_h is $\sim7\times10^{11}$ cm^{-2} as shown below).

The LO-phonon cascade is not observed for the $E_{\rm cr}(i,i)$ lines, supporting their identification as cross-barrier recombination of the ith electron LL with the ith hole LL, since these transitions arise between equilibrium populations. The observation of the $E_{\rm cr}(i,i)$ peaks allows us a precise characterization of the emitter states. From the fields B_i at which the successive LL's are populated with decreasing field ($i=2$ at ≈7 T, $i=3$ at ≈5 T, etc.) as measured on the $E_{\rm cr}(i,i)$ features in Fig. 2, the carrier density of the electron population that contributes to the spectra can be deduced using $n_s^e=2ieB_i/h$.[9] The density in the hole-accumulation layer is expected to be very similar. For $V=1.85$ V, all the measured B_i are consistent with a density $n_s^e=7\times10^{11}$ cm^{-2}. This value is in very good agreement with that of 7.25 $\times10^{11}$ cm^{-2} deduced from oscillations observed in magnetotransport measurements.[14] By repeating the same procedure for various biases, we obtain, as shown on Fig. 4, a linear variation of n_s^e versus V, thus proving that the emitter states from which tunneling occurs are two dimensional (2D).

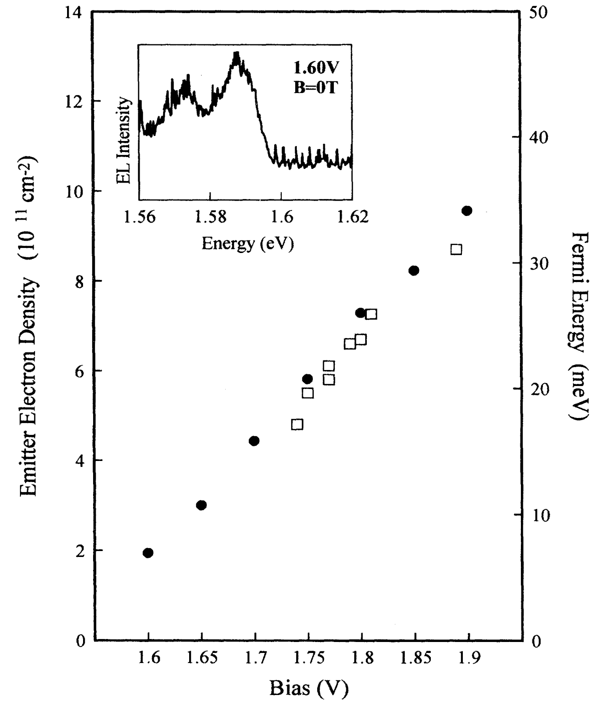

FIG. 4. Evolution with bias of the emitter-electron density determined by the Landau depopulation of the $E_{\rm cr}(i,i)$ features (squares) and by magnetotransport oscillations (circles) using the technique presented in Ref. 14. Inset: EL spectrum taken at a bias of 1.60 V and $B=0$. $E_{\rm cr}$ and $E_{\rm bal}$ can be resolved because of the small value of ε_f.

The electrons in the ith LL of the 2D emitter tunnel into the 3D collector and give rise to the $E_{\rm bal}^{n\rm LO}(i)$, $n=0,1,2,\ldots$, peaks [see Fig. 1(b)]. The number of LL peaks present in the quasiballistic features is always equal to the number of populated emitter LL's. Together with the fact that Δ(bal) is equal to $\hbar\omega_c^e$, this demonstrates that the tunneling process is elastic. As shown in Fig. 1(b), the presence of the LL structure in the ballistic-electron distribution is due to the energy conservation of the 2D emitter distribution, and not to the formation of LL's in the 3D collector, where free motion in the z direction leads to dispersion. This explains why we measure from the LL splitting in Fig. 3 an effective mass equal to the band-edge electron mass and not the value of $0.084m_0$ that, because of nonparabolicity, is expected at 250 meV above the conduction-band edge.[15] Furthermore, the quasiballistic lines corresponding to different fully populated LL's have very similar intensities. This shows further that the tunneling is equally probable for all the emitter LL's, and thus is independent of transverse momentum.

In addition, the initial ballistic-electron distribution is conserved in the successive phonon replicas. This demonstrates that LO-phonon emission is the dominant relaxation process, and that energy randomizing events such as carrier-carrier scattering are negligible. At 1.85 V, a value of the density of ballistic electrons $n_s^{\rm bal}\approx3\times10^6$ cm^{-2} is estimated from the current density of 3 A/cm^2 and an inelastic scattering time of 190 fs,[7] and is about 2×10^5 times less than n_s^e. Electron-electron scattering is not likely in our experiments, since it is only expected to be significant at areal densities $\geqslant 10^{11}$ cm^{-2}.[16] Electron-hole plasmon scattering, which becomes important at $p > 10^{18}$ cm^{-3},[5] can, however, explain the slight decrease of the peak-to-valley ratio in the quasiballistic features in the low-energy part of the spectra of Fig. 2.

At $B=0$ T, the value of $n_s^e \approx 7\times 10^{11}$ cm^{-2} at 1.85 V corresponds to a Fermi energy of 26 meV. From the discussion above, the width of the ballistic-electron distribution is also 26 meV, although only a small fraction of the available states is populated. These large widths account for the relatively poor resolution of the spectra taken at $B=0$. An application of high-magnetic field is necessary in order to remove the free-carrier broadening, and to reveal the contribution of the ballistic, quasiballistic, and cross-barrier recombinations. At lower applied bias, by contrast, the emitter density is less and both $E_{\rm bal}$ and $E_{\rm cr}$ contributions can be resolved without magnetic field, as shown in Fig. 4(b). Indeed, at this bias of 1.60 V, ε_f is only ~ 7 meV, as obtained from Fig. 4(a), and is significantly smaller than the splitting of 15 meV between the ballistic and the cross-barrier peaks.

In conclusion, the hot-electron energy distribution and cross-barrier recombination have been studied in magneto-EL on *p-i-n* tunnel structures. The application of a high-magnetic field permits high spectroscopic resolution (better than 5 meV) to be achieved, even for emitter Fermi energies of ~ 30 meV. The ballistic and quasiballistic electron distributions in the collector are shown to reflect exactly that of the emitter, with LL splittings characteristic of that of the band edge. This is shown to arise from the conservation of energy in the 2D to 3D tunneling process. Furthermore, clear evidence that the tunneling process is independent of the LL index, and hence of transverse momentum, has been presented. The dominance of LO-phonon energy relaxation of the ballistic distribution has been shown, with no significant energy randomization occurring even after the emission of up to five LO phonons. Finally, it should be noted that the study of cross-barrier recombination between 2D electron and hole gases separated by a tunnel barrier is, in principle, a high-sensitivity optical technique for studying the Coulomb interactions between spatially separated 2D systems.

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[*] Permanent address: Laboratoire de Microstructure et Microélectronique, CNRS, 196 av. Henri Ravera, 92225 Bagneux Cedex, France.

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