Electroluminescence of Ballistically Injected Electrons in AlGaAs/GaAs Heterodiodes

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We have observed hot-electron electroluminescence in AlGaAs/GaAs heterodiodes. The resolution provided by the luminescence technique allows ballistically launched electrons to be clearly distinguished from those that have emitted one or more longitudinal-optical phonons. The electroluminescence consists of a series of peaks spaced by one-LO-phonon energy whose width is in agreement with a calculation of the energy distribution of the injected electrons. The position of the ballistic peak provides a new way to accurately measure the conduction-band offset in semiconductor heterostructures.

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Ballistic transport of electrons in semiconductors has been observed recently in three terminal "hot-electron transistors" (HET's) fabricated by molecular-beam epitaxy.[1-4] These devices are similar in concept to the hot-electron camel-back transistor originally proposed and fabricated by Shannon,[5] in which a potential step at the emitter injects hot electrons into the base and a potential barrier at the collector energetically analyzes those electrons that have crossed the base region. Malik *et al.*,[1] Hayes, Levi, and Wiegmann,[2] and Levi *et al.*[3] fabricated planar-doped barrier HET's in GaAs and observed a relatively broad peak in the energy spectra which was attributed to ballistic transport. Heiblum *et al.*[4] have incorporated an AlGaAs tunnel barrier in the emitter to obtain a narrow initial energy distribution for the injected carriers and, consequently, produced a ballistic peak that was sharper than that of the planar-doped barrier HET. In these experiments, and more recently in two-dimensional lateral devices, oscillations with a period corresponding to the longitudinal-optical (LO) phonon energy (≈ 36 meV in GaAs) were observed when low-energy ($E < \hbar\omega_{\rm LO}$) collected electrons were studied as a function of injection energy.[6-8] However, the all-electrical techniques have not been able to directly analyze the high-energy ($E \gg \hbar\omega_{\rm LO}$) injected electron distribution with sufficient resolution to separate true ballistic electrons from those that have emitted one or more optical phonons.

Previously, Mirlin *et al.*[9] pioneered a low-temperature photoluminescence technique whereby optically injected hot electrons recombine with neutral acceptors in *p*-type GaAs. This technique allows the direct observation of unrelaxed hot electrons and hot-electron relaxation via LO-phonon emission, but suffers from broadening due to heavy-hole band warping and extraneous peaks due to light-hole excitation.

In this Letter we demonstrate a new technique for the direct observation of electrically injected hot electrons in GaAs. The electrons are injected from *n*-type AlGaAs into *p*-type GaAs at low temperatures and high-energy electroluminescence from hot-electron–neutral-acceptor recombination yields the hot-electron distribution (Fig. 1). Luminescence provides sufficient resolution to observe a peak due to unrelaxed electrons followed by a series of lower-energy peaks corresponding to electrons that have emitted optical phonons.[10] The valence-band structure does not complicate the spectra since optical excitation is avoided.

The devices used in the present experiments were grown by conventional liquid-phase epitaxy (LPE). The devices consist of a 3-μm-thick *p*-type GaAs:Ge layer followed by a 0.5-μm-thick nominally undoped AlGaAs layer, and a 0.5-μm cap layer of *n*-type AlGaAs:Sn. Samples with *p*-type doping densities from 1.0×10^{17} to 8.5×10^{17} cm^{-3} have been studied. Low-frequency capacitance-voltage measurements were used to determine the *i*-layer doping density of about 3.0×10^{16} cm^{-3} (*n* type). Approximately the same aluminum mole fraction of 0.30 and AlGaAs *n*-type doping of 2.0×10^{17} cm^{-3} have been used in all of the samples. A *p-i-n* heterodiode is formed by etching the AlGaAs from half of the sample to expose the GaAs layer, and subsequently alloying indium contacts into the unetched AlGaAs surface and the etched GaAs surface. A schematic cross

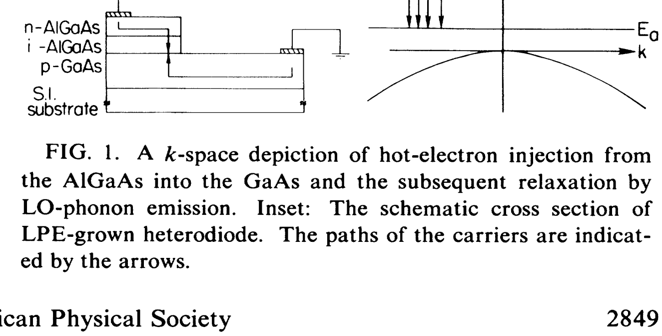

FIG. 1. A *k*-space depiction of hot-electron injection from the AlGaAs into the GaAs and the subsequent relaxation by LO-phonon emission. Inset: The schematic cross section of LPE-grown heterodiode. The paths of the carriers are indicated by the arrows.

section of the device is shown in the inset of Fig. 1.

The devices were mounted in an immersion-type optical cryostat and were held near liquid-He temperatures during measurements. The luminescence was analyzed by a high throughput triple spectrometer and the entire spectrum was detected in parallel by a Si charge-coupled-device array. The high sensitivity afforded by this detector was important for the observation of the weak high-energy luminescence. Standard low-temperature photoluminescence was used to determine both the mole fraction of Al in the AlGaAs and the Ge acceptor level in the GaAs.

Electroluminescence results from two samples are shown in Figs. 2 and 3. A series of peaks, each spaced by an LO-phonon energy can be clearly seen. The more heavily doped sample (sample *A*) exhibits three peaks (the ballistic electron peak followed by peaks corresponding to electrons which have emitted one or two LO phonons); further peaks cannot be resolved as the background intensity becomes too high. In contrast, the more lightly doped sample (sample *B*) exhibits four well-defined peaks. Subsequent peaks are obscured by the high-energy tail of the band-gap luminescence as each subsequent peak is closer to the gap. Our results are consistent with previous hot photoluminescence data,[9,11] where clear phonon emission peaks could not be detected above an acceptor concentration of 1.0×10^{18} cm^{-3}. The disappearance of the peaks was attributed to collisions of hot electrons with holes, either free or localized at acceptors, that become important at high-acceptor concentrations.

No significant temperature dependence of the hot electroluminescence was seen between 4.2 and approximately 35 K; at higher temperatures the intensity decreased as the acceptors began to ionize. To avoid excessive heating of the samples, a simple pulsed constant-current source was used. Nearly all the emitted light (band gap as well as hot luminescence) came from a narrow region immediately adjacent the etch line delineating the two halves of the diode. Since the *p*-layer resistance increases significantly as the acceptors freeze out, the electron current flows in the *n*-type AlGaAs as far as possible (the etch line) before injecting into the GaAs. The electron and hole current paths are shown in the inset of Fig. 1.

The measured full width of the peaks at their half maximum amplitude, FWHM, is approximately 15 meV for both samples. Broadening due to the phonon dispersion will be negligible since the optical phonons are nearly dispersionless near the zone center. Lateral inhomogeneities in the barrier height are another possible cause of broadening and were investigated experimentally by using the slits of the spectrometer to sample different sections of the device. The peak energies exhibited a small shift, approximately 3-4 meV, indicative of only slight compositional inhomogeneity across the sample.

The largest component of the linewidth is introduced by electron injection from the AlGaAs into the GaAs. Assuming a simple triangular AlGaAs depletion barrier under forward-bias conditions at low temperatures, the tunnel current was calculated using the WKB method. The tunneling probability, including the conservation of wave vector parallel to the interface, is given (in the WKB approximation) by

$$T(E,E_{\parallel})=\exp\left(-\frac{4}{3}\frac{(2m^*)^{1/2}}{|\mathbf{E}|q\hbar}(E_{\mathrm{DB}}+2E_{\parallel}-E)^{3/2}\right), \tag{1}$$

where E is the total electron kinetic energy, $E_{\parallel}$ is the component corresponding to wave vectors parallel to the junction, E_{DB} is the forward-bias depletion barrier (Fig.

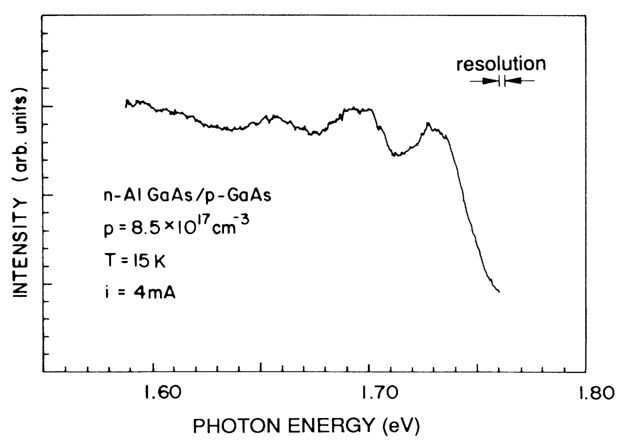

FIG. 2. Hot electroluminescence spectra obtained from device *A* under forward bias at low temperature. Three peaks are seen, separated in energy by one LO phonon. The highest-energy peak corresponds to an unrelaxed ballistic electron.

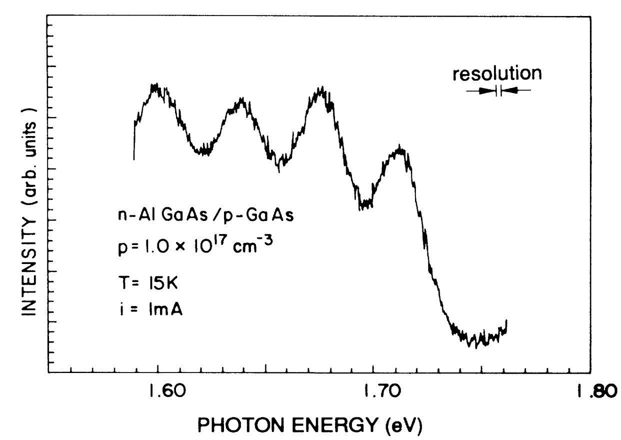

FIG. 3. Hot electroluminescence spectra obtained from device *B* under forward bias at low temperature. In this case, the lighter doping permits four clear peaks to be observed (see text).

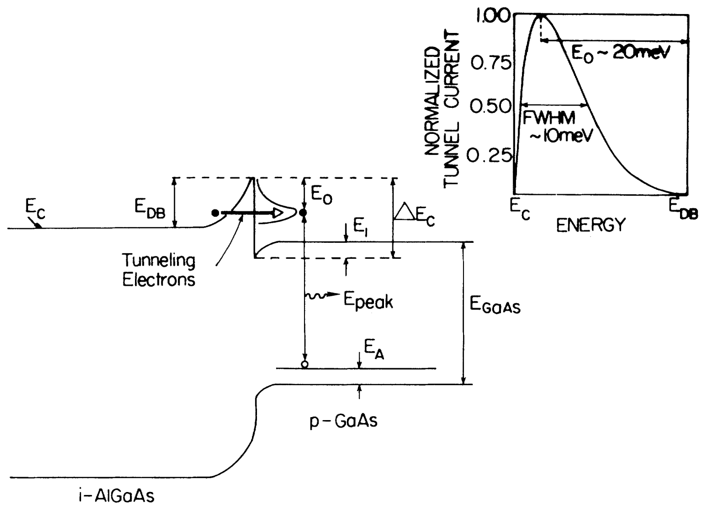

FIG. 4. The low-temperature forward-bias diode band bending. The depletion barrier on the AlGaAs side (not to scale) and associated tunnel current are shown. Inset: A plot of the tunnel current-energy distribution calculated using the WKB method.

4), and **E** is the depletion electric field. The tunneling current density is given by

$$J(E)=\frac{qm^*}{2\pi\hbar^3}F(E)\int_0^E T(E,E_\parallel)dE_\parallel\,, \tag{2}$$

where $F(E)$ is the Fermi distribution. The tunnel current was calculated by self-consistently matching the current density obtained from (2) to the measured current density. Results for sample A are shown in the inset of Fig. 4. The calculated maximum of the current distribution is approximately 20 meV below the top of the depletion barrier, and the FWHM of the distribution is 10 meV. Similar results are obtained for sample B.

The tunneling current was compared to the thermionic current (evaluated from the relationship of Chang[12]) and at low temperatures the tunneling component of the current is roughly 2 orders of magnitude larger than the thermionic component. Hence the tunnel process determines the shape of the injected-carrier distribution in our devices. The broadening due to tunnel injection combined with the broadening from the observed compositional inhomogeneity accounts very well for the measured peak linewidths.

The highest-energy luminescence peak in the GaAs has an energy corresponding to the minimum of the AlGaAs conduction band and thus provides a new method for determining the GaAs/AlGaAs conduction-band offset. The conduction-band offset is given by

$$\Delta E_C = E_{\text{peak}} + E_A + E_0 + E_1 - E_{\text{GaAs}}\,, \tag{3}$$

where E_{peak} is the photon energy, E_{GaAs} is the GaAs band gap, E_A is the acceptor energy, E_0 is the offset due to the electron tunneling, and E_1 is the small forward-bias band bending on the p side (Fig. 4). The radiative recombination of the hot electrons with neutral acceptors occurs outside of the junction depletion region on the GaAs p side and for unambiguous results this region needs to be small when compared to the inelastic scattering length. This condition is easily satisfied in our samples as the p-side equilibrium depletion width (which decreases significantly under forward bias) is 60 Å for device A and 280 Å for device B, while the scattering length (assuming an electron velocity of $\sim 1\times10^8$ cm/sec and a phonon scattering time of 100–200 fsec[9,11,13]) is on the order of 1000 Å. Figure 5 indicates the conduction-band offset versus mole fraction of alumi-

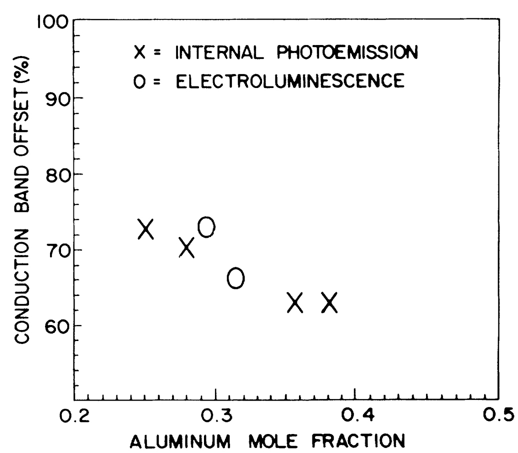

FIG. 5. Band-offset determination. The mole fraction of aluminum is plotted against the ratio of the conduction-band offset to the total band-gap difference. Current data are represented by ○, while data from internal photoemission results (see Ref. 11) are indicated by ×.

num for both samples along with previous internal photoemission results.[14] Our new results are in good agreement with those earlier measurements.

In summary, we have directly observed true ballistic injection of electrons into *p*-type GaAs in *n*-type AlGaAs/*p*-type GaAs heterodiodes. The width of the injected distribution is determined primarily by tunneling through the depletion barrier on the AlGaAs side of the diode and is narrow enough to allow us to study the relaxation mechanisms of these highly energetic electrons. By measuring the distribution with luminescence we have sufficient energy resolution to clearly show hot-electron energy loss to LO phonons and to electron-hole scattering. This technique is a powerful new probe of highly nonequilibrium transport in semiconductors.

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