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Electroluminescence spectroscopy of intervalley scattering and hot-hole transport in a GaAs/Al$_x$Ga$_{1-x}$As tunneling structure

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We have carried out an investigation by electroluminescence (EL) spectroscopy of hot-electron and -hole transport in a *p-i-n* GaAs/Al$_{0.35}$Ga$_{0.65}$As single-barrier tunneling structure at high electric fields (~150 kV cm^{-1}). We observe EL arising from hot electrons in the *p*-type collector which reenter the Γ conduction-band valley from the *L* minimum. Analysis of the EL spectra provides an estimate of the relative Γ-*L* scattering rates by longitudinal and transverse phonon emission. In addition we observe EL due to recombination of hot holes injected into the spin-orbit split-off valence band of the *n*-type emitter region. Measurement of the pressure dependence of the EL spectra permits unambiguous identification of these spectral features. [S0163-1829(96)05732-3]

Hot-carrier transport plays an important role in the operation of many semiconductor devices, such as Gunn oscillators, heterojunction bipolar transistors, and avalanche photodiodes. In 1989, Petersen, Frei, and Lyon[1] demonstrated that electroluminescence (EL) spectroscopy could be used to study energy relaxation processes in hot-electron populations in *p-n* GaAs/Al$_x$Ga$_{1-x}$As heterostructures. Such hot-electron EL spectroscopy has subsequently been used to determine ballistic lengths and conduction-band offsets in GaAs/Al$_x$Ga$_{1-x}$As structures,[2] and to provide precise information on the nature of the tunneling process in single- and double-barrier structures.[3–5] In the present paper we report the results of hot-electron EL experiments carried out to investigate hot-carrier transport at high electric fields in a *p-i-n* GaAs/Al$_x$Ga$_{1-x}$As single-barrier tunneling structure. The structure has a 220-Å-wide Al$_{0.35}$Ga$_{0.65}$As barrier, allowing electric fields of up to 150 kV cm^{-1} to be applied without excessive current flow. This has enabled us to carry out the first spectroscopic study of Γ-*L* intervalley scattering in a semiconductor device under operating conditions. In addition, we observe clear evidence for quasiballistic hole transport, and for the involvement of confined barrier *X* states in the tunneling process.

Experiments were carried out at a temperature of 4.2 K and at hydrostatic pressures of up to 12.5 kbar. The variation of the EL spectra with pressure permits unambiguous attribution of the observed features. The structure was grown by molecular-beam epitaxy on an n^+ GaAs substrate, and comprised the following layers: 1 μm $n=1\times10^{18}$ cm^{-3} GaAs, 500 Å $n=1\times10^{17}$ cm^{-3} GaAs, 500 Å $n=3\times10^{16}$ cm^{-3} GaAs emitter, 50 Å undoped GaAs spacer, 220 Å undoped Al$_{0.35}$Ga$_{0.65}$As barrier, 50 Å undoped GaAs spacer, 0.5 μm $p=1\times10^{17}$ cm^{-3} GaAs collector, and 0.5 μm $p=2\times10^{18}$ cm^{-3} GaAs top contact. The wafer was processed into circular mesas 200 or 400 μm in diameter. Measurements were carried out with the samples mounted in a Unipress liquid pressure cell, fitted with a sapphire window for optical access. Petroleum extract was used as the pressure transmitting medium, and the pressure changed at room temperature. The cell was immersed in liquid helium and the luminescence from the sample was transmitted via optical fibres to a triple grating spectrometer fitted with a liquid nitrogen cooled charge-coupled-device detector array.

At forward biases in excess of the flat band voltage (~1.51 V at atmospheric pressure), electrons (holes) are injected through the Al$_x$Ga$_{1-x}$As barrier into the *p*-type (*n*-type) region of the structure, where they recombine with majority carriers to generate EL. By far the most intense EL arises from near band-edge electron-hole and electron-neutral acceptor recombination in the *n*- and *p*-doped re-

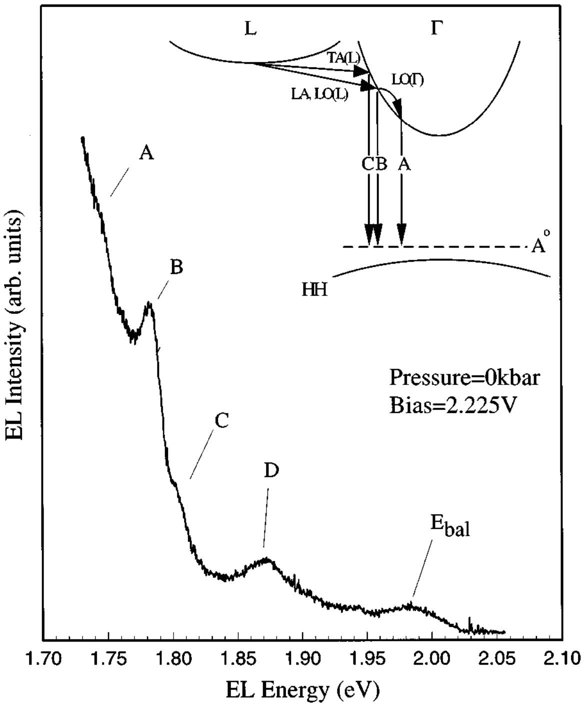

FIG. 1. Typical EL spectrum in the 1.7–2.1 eV energy range, obtained at a bias of 2.225 V. The features shown are of the order of 10^6–10^7 times less intense than the GaAs band-edge EL. The inset illustrates the recombination processes that produce the EL features *A*, *B*, and *C*.

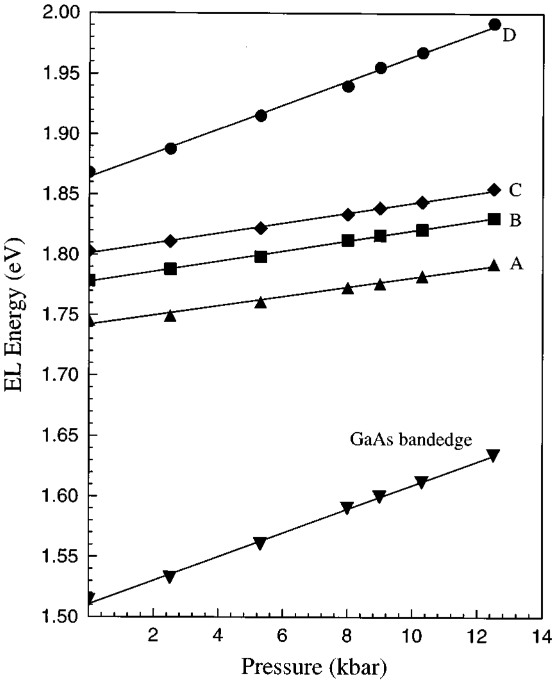

FIG. 2. EL energy vs hydrostatic pressure for peaks *A*, *B*, *C*, and *D* in Fig. 1(a). Also shown is the pressure dependence of the GaAs band-edge EL.

gions, respectively. The EL features of interest in the present work, however, occur in the 1.7–2.1-eV energy range, and are of the order of 10^6–10^7 times less intense than the near band-edge EL. Figure 1 shows a typical high-energy EL spectrum, obtained at atmospheric pressure with a bias of 2.225 V applied to the structure. The highest-energy peak in the spectrum (E_{bal}) arises from the recombination of ballistic electrons with acceptor-bound holes in the collector region. The energy of this peak increases monotonically with device bias. By contrast, the peak positions of the other spectral features are bias independent. We attribute the peaks labeled *A*, *B*, and *C* in Fig. 1 to the recombination with neutral acceptors of electrons which reenter Γ from the *L* minimum after having undergone intervalley scattering in the collector region (the origin of peak *D* is discussed below). Similar recombination of reentrant *L* electrons has previously been observed in hot-electron photoluminescence (PL) experiments.[6,7] The origins of peaks *A*, *B*, and *C* are illustrated in Fig. 1. Peak *B*, at 1.79 eV, is the most intense of the three and arises from electrons which reenter Γ with the emission of *L*-point LA ($\hbar\omega \approx 26$ meV) or LO ($\hbar\omega \approx 28$ meV) phonons.[8] The weaker peak *A*, 36 meV lower in energy than *B*, is due to electrons from the above reentrant population which emit a zone center LO phonon in the Γ valley before recombining. The peak marked *C* arises from electrons that have reentered Γ with the emission of *L*-point TA phonons ($\hbar\omega \approx 8$ meV).[9] These identifications are consistent with the bias independence of the peak positions, as the EL energies are expected to depend only on the energy separation $\Delta E_{\Gamma L}$ of the Γ and *L* conduction-band valleys. At atmospheric pressure our EL measurements give $\Delta E_{\Gamma L} = 324 \pm 4$ meV at 4.2 K, in excellent agreement with previous measurements by other workers.[6,7,10,11]

The above attributions of the EL features are further confirmed by the pressure dependence of their peak positions, shown in Fig. 2. Peaks *A*, *B*, and *C* all display a pressure coefficient of 4.1 ± 0.1 meV/kbar, as expected for states with *L* symmetry.[12,13] In conventional PL studies of the pressure dependence of the conduction-band minima in GaAs, luminescence from the *L* valley is not observed, since the conduction-band minimum is always at either the Γ ($P \leqslant 40$ kbar) or the *X* ($P \geqslant 40$ kbar) point.[10] The present technique provides a method to measure directly the pressure coefficient of the *L* valley in GaAs by luminescence spectroscopy.

The role of the various phonon modes in intervalley scattering has been investigated theoretically by a number of workers.[14–16] Birman, Lax, and Loudon[14] calculated the selection rules for scattering between the Γ and *L* minima of the Brillouin zone, and showed that in GaAs, only LA and LO phonons possess the correct symmetry to take part in the scattering process. Subsequent work has, however, shown that when the initial or final state has a finite wave vector in Γ (as it must in order for energy to be conserved), then *L*-Γ scattering may proceed by the emission of transverse as well as longitudinal phonons.[15,16] This is consistent with our results, and those of Mirlin *et al.*,[6] which clearly show that TA phonons are involved in the *L*-Γ scattering process.

From our EL spectra we can estimate the relative *L*-Γ scattering times by LO-LA and TA phonon emission. Since peaks *B* (LO-LA phonon emission) and *C* (TA phonon emission) originate from the same *L* population, their relative intensity is given by $I_B/I_C = \tau_T/\tau_L$, where τ_T^{-1} and τ_L^{-1} are the *L*-Γ scattering rates by TA and LO-LA phonon emission, respectively. From our EL spectra we obtain $\tau_L^{-1} \approx 20\tau_T^{-1}$. We observe no systematic variation of the relative scattering

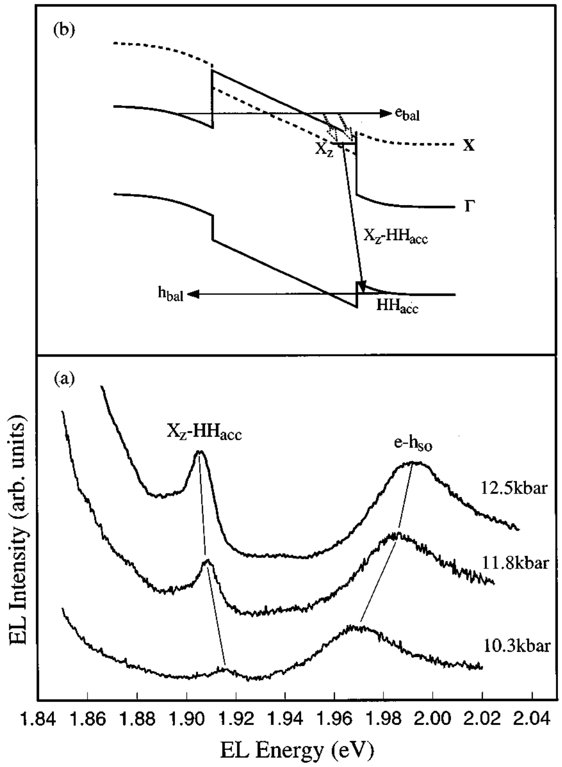

FIG. 3. (a) EL spectra showing the emergence of the X_z-HH$_{acc}$ peak at pressures above 10 kbar. (b) Schematic band-edge diagram to illustrate the origins of the X_z-HH$_{acc}$ and e-h_{so} peaks. Tunneling electrons (e_{bal}) scatter into the lowest confined X_z state in the barrier and recombine with holes in the collector accumulation layer to produce the X_z-HH$_{acc}$ EL, while ballistic holes (h_{bal}) are injected into the spin-orbit split off valence band in the emitter, from where they recombine to generate the e-h_{so} feature.

rates with either bias or pressure. The scattering rate due to the emission of intervalley phonons of energy $\hbar\omega$ is related to the L-Γ deformation potential ($D_{\Gamma L}$) by[17] $\tau^{-1} \propto D^2_{\Gamma L}/\hbar\omega$. Our measurements therefore indicate that the deformation potential for L-Γ scattering by TA phonon emission [$D_{\Gamma L}$(TA)] is around 8 times smaller than that for longitudinal phonon emission [$D_{\Gamma L}(L)$]. This is in reasonable agreement with the calculations of Zollner, Gopalan, and Cardona,[16] who found $D_{\Gamma L}(L) \approx 3D_{\Gamma L}(\mathrm{TA})$. Further discussions on the determination of intervalley scattering rates will be presented in a future publication.

We now consider the origin of peak D in Fig. 1(a). This peak, whose position is bias independent, has a pressure coefficient of 10.1 meV/kbar, very similar to that of the GaAs band-edge luminescence (10.0 meV/kbar). This indicates unambiguously that this peak arises from recombination of carriers originating from the Γ point of the Brillouin zone. Although this peak is too low in energy to arise from band-edge recombination in the Al$_{0.35}$Ga$_{0.65}$As barrier [peak energy of 1.87 eV compared with E_g(Al$_{0.35}$Ga$_{0.65}$As)~2.05 eV at atmospheric pressure], samples having 30% and 40% Al barriers were studied in order to investigate the possibility of peak D arising from recombination of electrons at the Γ minimum in the barrier with either holes from the collector accumulation layer, or with deep impurity states. Within experimental error, peak D was found to be in an identical position in all three samples, and therefore cannot arise from recombination of Γ electrons in the barrier region.

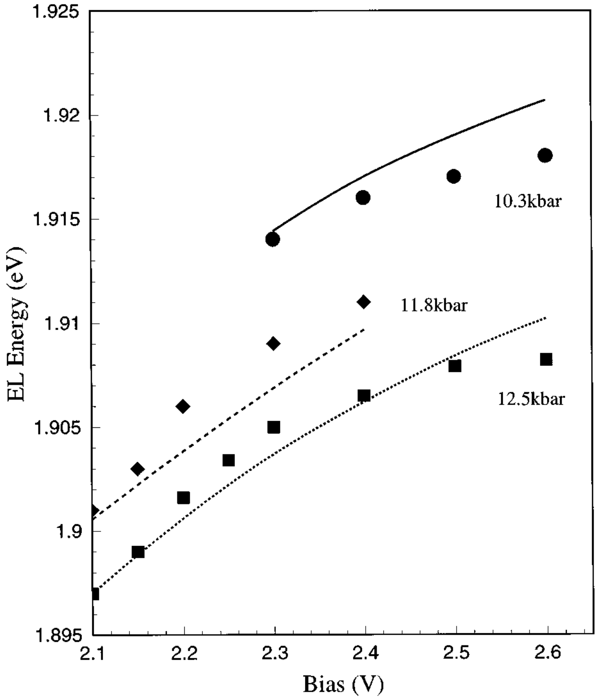

FIG. 4. Bias dependence of the X_z-HH$_{acc}$ peak at hydrostatic pressures of 10.3 (●), 11.8 (◆), and 12.5 (■) kbar. The results of envelope function calculations of the bias dependence of the peak position at each pressure are shown by the solid (10.3 kbar) dashed (11.8 kbar), and dotted (12.5 kbar) lines.

The only other possible attribution of peak D is to the recombination of Γ electrons in the emitter region of the structure with holes in the spin-orbit split-off valence band (e-h_{so} recombination). Such recombination has previously been observed in PL spectroscopy by Zakharchenya *et al.*[18] In the present experiment, the split-off valence band in the emitter is populated by high-energy ballistic holes injected through the barrier from the hole accumulation layer on the p-type side of the structure [Fig. 3(b)]. The energy of peak D is 355 meV above the band-edge EL, in very good agreement with previous measurements of the spin-orbit splitting in GaAs.[18,19] The similarity of the pressure coefficient of peak D to that of the band-edge EL is consistent with the weak pressure dependence of the spin-orbit coupling.[12,20] The observation of e-h_{so} EL provides a potential means to study ballistic hole transport in p-i-n device structures.

At pressures in excess of 10 kbar, an additional EL peak emerges in the 1.895–1.920-eV energy range [Fig. 3(a)]. The origin of this feature is illustrated in Fig. 3(b). At these higher pressures the Al$_{0.35}$Ga$_{0.65}$As barrier band gap is indirect, with the X conduction-band minima lying below Γ. A quantum well is thus formed in the X conduction-band profile of the structure, leading to the formation of quasiconfined X_z and X_{xy} states in the barrier. Electrons tunneling from the emitter accumulation layer scatter into the confined X states and then relax to the lowest X_z state from where they recombine with heavy holes from the collector accumulation layer to generate EL (X_z-HH$_{acc}$ recombination).

Due to the spatial separation of the X_z electron and HH_{acc} hole wave functions, the X_z-HH_{acc} transition energy increases with bias. The bias dependence of the X_z-HH_{acc} EL peak position for pressures of 10.3, 11.8, and 12.5 kbar is plotted in Fig. 4. The observed peak positions are in very good agreement with the results of envelope function calculations of the transition energies, also shown in Fig. 4. The transition energies were calculated as a function of electric field in the barrier, using Shubnikov–de Haas–like magnetotransport measurements[21] to calibrate device bias against electric field. The importance of confined X states in tunneling through indirect band-gap AlAs barriers has been clearly demonstrated in previous work by means of transport measurements[5,22] and EL spectroscopy.[5] The present work shows that at high electric fields, such states can also be involved in tunneling through $Al_xGa_{1-x}As$ barriers when the X minimum lies only slightly below Γ (we calculate the Γ-X separation to be ~50 meV at 10 kbar).

In summary, we have used EL spectroscopy to study vertical transport at high electric fields in a $GaAs/Al_{0.35}Ga_{0.65}As$ p-i-n single-barrier tunneling structure at hydrostatic pressures of up to 12.5 kbar. We observe EL peaks arising from the recombination with neutral acceptors of electrons which reenter the Γ conduction-band valley from the L minimum in the collector, with the emission of L-point longitudinal and transverse phonons. From the relative intensities of the EL peaks, we estimate that the intervalley scattering rate by longitudinal phonon modes is ~20 times greater than for scattering by transverse acoustic phonon emission. We also observe EL arising from recombination of hot holes, which are injected from the collector accumulation layer into the spin-orbit split-off valence band of the emitter region. The attribution of all these features is confirmed by measurements of the pressure dependence of their peak positions. At pressures beyond 10 kbar, luminescence is observed arising from recombination of electrons from quasiconfined X_z states in the indirect band-gap barrier with holes from the collector accumulation layer.

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[9] At the electric fields applied in these experiments, electrons enter the collector with sufficient energy to scatter to the X valley as well as to L. However, no EL is observed arising from recombination of electrons reentering Γ from X. This is consistent with expectations, since X electrons are much more likely to scatter to L than reenter Γ, due to the higher density of states in the L valley.

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