Electroluminescence and impact ionization phenomena in a double-barrier resonant tunneling structure

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Electroluminescence (EL) due to impact ionization in the high field region of a double-barrier resonant tunneling structure is reported. Knowledge of the charge distribution in the structure enables a detailed analysis to be made of the impact ionization rate as a function of electric field. Large peak-to-valley ratios of 15:1 in the EL emission intensity from the quantum well active region are observed.

The first observation of electroluminescence (EL) in a double-barrier resonant tunneling structure (DBRTS) is reported. The EL emission in the *n*-type GaAs/(AlGa)As DBRTS arises from recombination between electrons in the quantum well (QW) active region and the GaAs contacts, and holes generated by impact ionization (II) in the high-field collector region. Radiative recombination is a very sensitive technique to measure the hole generation rate and allows II phenomena to be investigated at electric fields close to threshold, as demonstrated in recent work on single-barrier GaAs/(AlGa)As structures.[1,2] DBRTS are well suited to the study of II phenomena since electrons are injected at defined, nearly monoenergetic energies into the high-field region of the devices. Furthermore, the charge and electric field distributions can be determined accurately from magnetotransport[3,4] and photoluminescence (PL),[5] enabling a precise analysis of the electron dynamics and II phenomena to be performed.

An asymmetric DBRTS, which has one thick and one thin tunnel barrier, was employed.[6] It comprised the following layers: n^+-GaAs substrate, 1 μm GaAs 2×10^{18} cm^{-3}, 50 nm GaAs 1×10^{17} cm^{-3}, 50 nm GaAs 1×10^{16} cm^{-3}, 3.4 nm GaAs undoped spacer layer, 5.7 nm $Al_{0.4}Ga_{0.6}As$ barrier, 5.9 nm GaAs (QW), 14.1 nm $Al_{0.4}Ga_{0.6}As$ barrier, 3.4 nm GaAs undoped spacer layer, 50 nm GaAs 1×10^{16} cm^{-3}, 50 nm GaAs 1×10^{17} cm^{-3} and 500 nm GaAs 2×10^{18} cm^{-3} top contact. The layers were processed into 100-μm-diam mesas with annular contacts to allow optical access. In the following, reverse bias corresponds to electron flow from the substrate to the top contact, with the 14.1 nm barrier on the collector side, as shown in Fig. 1 at a bias of 3 V. The incorporation of the thick barrier, with low transmission probability, is crucial for the study of the II and EL phenomena. It enables the high fields for II to be achieved without excessive current flow. In addition, it leads to very large charge buildup in the well on resonance ($\sim1\times10^{12}$ cm^{-2}) and to strongly enhanced EL from the QW.

The $I(V)$ characteristics in reverse bias reveal two resonant peaks at 0.3 and 3.1 V, corresponding to electrons tunneling from the two-dimensional electron gas, adjacent to the emitter barrier, into the first and second quasi-bound states of the QW. Figure 2(a) shows the $I(V)$ characteristics at the second resonance. Between 2.8 and 3.1 V the structure is intrinsically bistable due to the different charge states of the well, between the on and off-resonance states.[6,7] For biases above 2.6 V, at the onset of significant current flow, EL emission is observed. The EL at 4 K is composed of three spectral features peaking at 1.572, 1.515, and 1.493 eV, as shown in Figs. 3(a), 3(b) for the on-and off-resonance states at 3.0 V. The 1.572 eV emission (labeled QW) arises from electron-hole recombination in the QW, whereas the 1.515 and 1.493 eV bands are due to electron-hole (e-h) and electron-neutral acceptor (e-Å) recombination in the GaAs emitter.

The electrons which participate in the EL arise (i) for the QW signal, from the electron charge which builds up in the well; (ii) for the GaAs signal, from the n^+ doping in the emitter contact. The minority-carrier holes are created by II due to high-energy electrons injected through the tunnel barriers into the high-field region. Electrons which

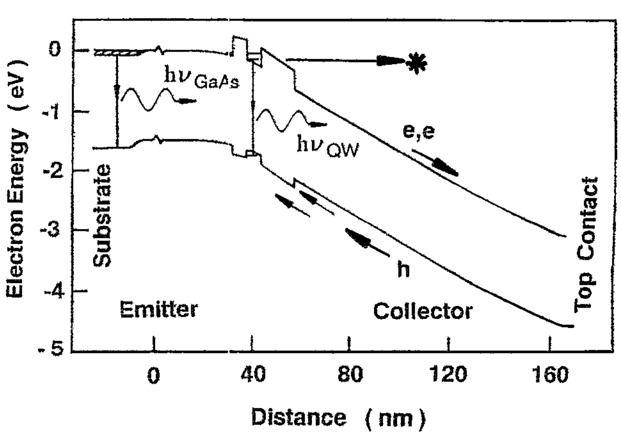

FIG. 1. Calculated conduction- and valence-band edge profiles at 3 V bias on the second tunneling resonance. The star at 50 nm beyond the thick barrier indicates the minimum distance a ballistic electron must travel in order to gain $1.5E_g$ of energy and give rise to impact ionization.

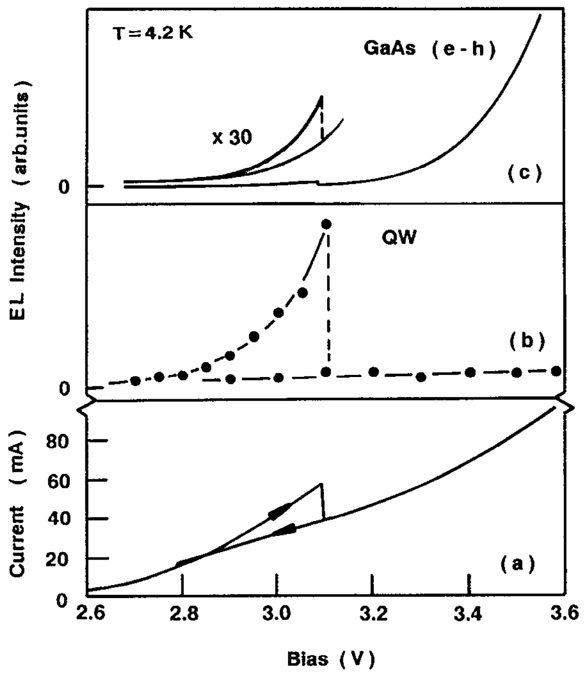

FIG. 2. (a) Current, (b) QW EL intensity, and (c) GaAs e-h EL intensity as a function of bias at the second resonance at 4 K.

gain more than $\sim 1.5\ E_g$ (E_g is the GaAs band gap of 1.5 eV) of energy in the depletion region can cause II;[8] the high-energy electron relaxes to near the GaAs band edge by exciting an electron-hole pair across the band gap in a process conserving energy and momentum.[8] The electrons and holes created drift apart in the high-field region (see Fig. 1). The holes drift towards the collector barrier where they can (i) form a low density hole gas ($n_s \leqslant 10^9$ cm^{-2}) and then tunnel into the QW or into the emitter region, or

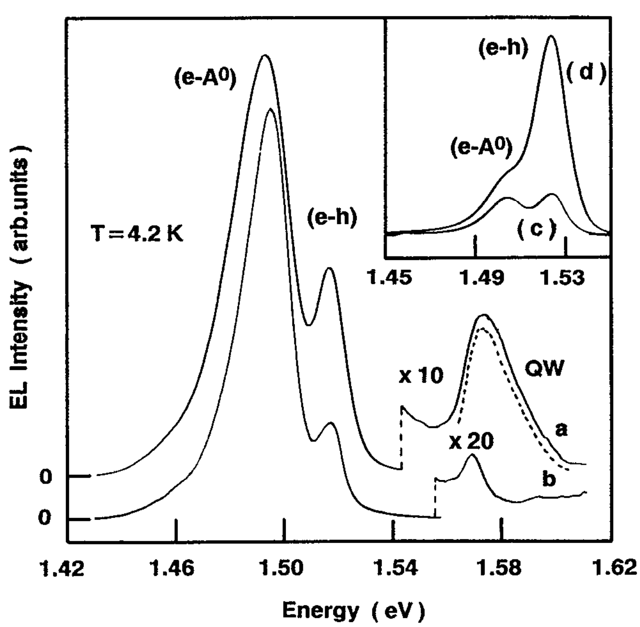

FIG. 3. EL spectra (4 K) at 3 V bias in the (a) on and (b) off resonance states. The inset shows the e-Å and e-h bands at (c) 3.3 V and (d) 3.6 V.

(ii) pass directly over the relatively small valence-band potential discontinuity (~ 150 meV) into the n^+-GaAs emitter region.[9] The holes which tunnel into the QW either recombine with the high density of electrons which builds up on resonance, giving rise to the QW EL signal, or tunnel out through the thin emitter barrier. These holes, together with the much higher density ($\sim$ten times greater[9]) of holes which pass directly into the emitter region lead to the 1.515 and 1.493 eV GaAs emission peaks.

Figures 3(a) and 3(b) (1.560–1.600 eV region) show the QW EL spectra at 3.0 V for the on- and off-resonance states. The on-resonance state [Fig. 3(a)] has $\sim$four times higher intensity and is a factor of 3 broader than the off-resonance spectrum in Fig. 3(b). Such broadening has been observed in photoluminescence (PL) studies and is due to band filling arising from the charge buildup (n_w^e) in the QW on resonance.[5] n_w^e can be determined from line shape fitting to the spectrum.[5] The best fit to Fig. 3(a) is shown by the dashed curve obtained for $n_w^e = 7.2 \times 10^{11}$ cm^{-2} (Fermi energy of 27 meV) and an electron temperature of 40 K. Further confirmation of the n_w^e values is obtained from magneto-optical studies.[5,10] The charge density (n_a^e) in the emitter accumulation layer can be measured accurately using magnetocapacitance (e.g., $n_a^e = 7 \times 10^{11}$ cm^{-2} at 3.0 V).[6] With the knowledge of both n_w^e and n_a^e, the charge distribution through the device is known precisely and so the potential drops and electric fields can be calculated by solution of Poisson's equation. Figure 1 is the result of such a calculation at 3.0 V bias, in the on-resonance state.

The EL intensity as a function of bias [$I_{\rm EL}(V)$] is shown in Fig. 2(b) for the 1.572 eV QW signal.[11] $I_{\rm EL}(V)$ exhibits hysteresis over the same voltage range as the current, though with a much higher peak-to-valley ratio of 15:1 [1.4:1 for $I(V)$ in Fig. 2(a)]. The large ratio arises since $I_{\rm EL}(V)$ is a function of both the electron (n_w^e) and hole (n_w^h) densities in the well. Tunneling out through the 5.7 nm barrier provides a loss channel for holes in the QW, which competes with radiative recombination. Under these circumstances, $I_{\rm EL}$ is proportional to n_w^e as well as n_w^h (the "nonradiative" limit).[12] n_e^w changes from 8×10^{11} to $< 10^{11}$ cm^{-2} between the on- and off-resonance states at 3.1 V, thus accounting very plausibly for the large peak-to-valley ratio for $I_{\rm EL}(V)$.

Figure 2(c) shows $I_{\rm EL}(V)$ for the GaAs band gap (e-h) EL. It exhibits a nearly exponential increase with bias, a characteristic signature of II. There is a marked region of hysteresis with a similar peak-to-valley ratio to that of $I(V)$ in Fig. 2(a). The recombination for the (e-h) signal occurs in the GaAs emitter region, where the electron density is independent of bias. Thus $I_{\rm EL}(V)$ is controlled only by the hole generation rate in the II process. The (e-Å) signal shows a much less rapid increase with bias than (e-h), (see inset to Fig. 2) due to saturation of the ionized acceptor centers. A careful measurement of the absolute EL intensity was carried out by comparison of $I_{\rm EL}$ with that of a calibrated light-emitting diode, emitting in the same wavelength band. From this calibration, the internal quantum efficiency (η) (number

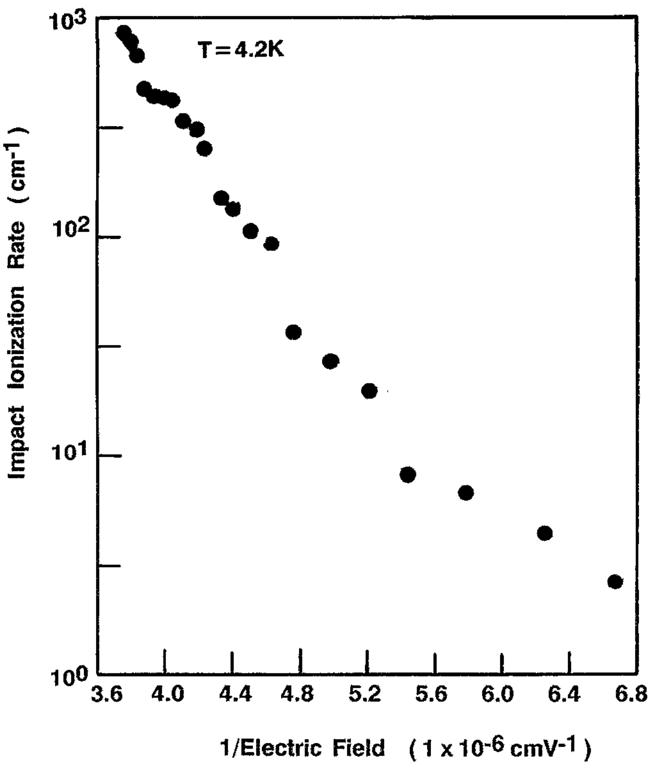

FIG. 4. Impact ionization rate (α) as a function of (electric field)$^{-1}$.

of photons emitted per electron reaching the collector) of the DBRTS was obtained,[13] after allowance for the fraction of the EL (1.35%) emitted through the top surface of the GaAs. A value for η of 0.6% was deduced in this way, at 3.6 V applied bias.

To determine the II rate, both the electric field in the depletion region and the length (d) over which II is energetically possible, must be determined. The Poisson's equation solution shows that a ballistic electron (see Fig. 1) can only gain the $1.5E_g$ of energy required for II above 2.6 V, in agreement with experiment. At higher biases, d is given by the length in the high-field region from the point at which II is energetically possible, represented by the star in Fig. 1, to the onset of the low-field, heavily doped contact layer.[14] The II rate, α, is obtained from $\eta = 1 - e^{-\alpha d}$ ($=\alpha d$ since $\eta < 1$). The relatively small value of η of 0.006 (and hence αd) implies that the structure is not operated in the current multiplication regime. The values for α determined in this way are plotted in Fig. 4, as a function of (average electric field)$^{-1}$ over the distance d. The absolute value for α of $\sim 10^3$ at 3.8×10^{-6} cm/V (3.6 V bias) agrees within a factor of 3, less than the uncertainty of the present work,[13] with that reported by Bulman *et al.* from current multiplication measurements.[15] In their EL measurements on GaAs-(AlGa)As single-barrier structures, Snow *et al.*[1] found comparable values of α to those in Fig. 4 at electric fields approximately a factor of two smaller,[16] in marked disagreement with the results of Bulman *et al.*[15] (and the present work). This led Snow *et al.* to deduce an anomalously high value[17] of 112 Å for the mean free path for LO phonon emission, perhaps because of underestimate of the electric field in their structure.

In summary, electroluminescence and II in DBRTS have been reported. Large peak-to-valley ratios in $I_{EL}(V)$ from the QW have been observed. Impact ionization rates in good agreement with those reported from current multiplication have been deduced.

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