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Electroluminescence recombination from excited-state carrier populations in double-barrier resonant-tunneling structures

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Electroluminescence recombination arising from electrons in both the $n=1$ and $n=2$ confined levels ($E1$ and $E2$) of the quantum well of a GaAs-$\mathrm{Al_{0.4}Ga_{0.6}As}$ p-n junction double-barrier resonant-tunneling structure is reported. At the $E2$ resonance, study of the relative intensities of the $E2$ to $E1$ electroluminescence permits a quantitative determination of the relative populations (1:300) of the two levels. From this the ratio of the $E1$ tunneling time to the intersubband scattering time is deduced. Despite the small population of $E2$, we show that a significant fraction of the on-resonance current still arises from tunneling through this state.

Optical spectroscopy has been shown recently to be a powerful technique for the study of transport in double-barrier resonant-tunneling structures (DBRTS).[1-5] Photoluminescence (PL) intensity[1] and PL line-shape analysis,[2] magneto-optical studies,[2] PL excitation spectroscopy,[3,4] and differential absorption spectroscopy[5] (DAS) have all been employed to study charge build up in the quantum wells (QW's) of DBRTS. Sequential tunneling has been demonstrated from the observation of PL from electrons in the $n=1$ subband ($E1$) when the structures are biased for tunneling into the $n=2$ confined level ($E2$).[2,6,7]

In the present paper, electroluminescence (EL) recombination from the QW's of $\mathrm{Al_{0.4}Ga_{0.6}As}$-GaAs-$\mathrm{Al_{0.4}Ga_{0.6}As}$ DBRTS embedded in GaAs p-n junctions is reported. By comparison with PL studies of conventional n-i-n DBRTS, where the holes are supplied by photoexcitation,[1-3] in a p-i-n structure the holes are already present in the doped p^+ region. When bias is applied, both electron and hole tunneling can occur through the double-barrier region, and lead to EL recombination in the QW.[8]

The experiments were carried out on structures with QW's of width 70 and 80 Å which contain two confined electron levels. When biased for electron tunneling into $E1$, EL recombination between $E1$ electrons and $n=1$ heavy holes (HH1) ($E_{11\mathrm{h}}$ recombination) is observed. On increasing the bias to the second ($E2$) resonance, $E2$ electron, HH1 ($E_{21\mathrm{h}}$) recombination is also seen. This work represents a significant advance over that reported previously where only $E_{11\mathrm{h}}$ PL was detected. Higher sensitivity to weak signals is obtained in EL compared to PL studies; the background is zero and any optical signal detected must result from recombination in the device under study.

The structures studied were grown by molecular-beam epitaxy, and were of the following design: n^+-type GaAs substrate, 1-μm $n=1\times10^{18}$ cm^{-3} GaAs, 1000-Å $n=1\times10^{17}$ cm^{-3} GaAs, 50-Å undoped GaAs spacer, 80-Å $\mathrm{Al_{0.4}Ga_{0.6}As}$ barrier, 70- or 80-Å GaAs QW, 80-Å $\mathrm{Al_{0.4}Ga_{0.6}As}$ barrier, 50-Å undoped GaAs spacer, 1000-Å $p=5\times10^{17}$ cm^{-3} GaAs, and 9000-Å $p=1\times10^{18}$ cm^{-3} GaAs. The structures were processed into 100-μm-diam mesas with annular top contacts for the collection of the EL. All the measurements were carried out with the samples immersed in liquid helium at 4.2 K.

The structures showed negligible current flow for $V<1.5$ V, the flat-band condition. A forward bias of 1.5 V on the p-n junction corresponds to zero bias in a conventional n-i-n DBRTS. The I-V characteristic for the DBRTS with a 70-Å QW is shown in Fig. 1(a). Two main resonances are observed at 1.65 and 2.1 V and arise from electron tunneling into the $E1$ and $E2$ levels of the QW. These identifications are obtained by comparison with an n-i-n DBRTS with 80-Å barriers, and an 80-Å QW (Ref. 2), where very similar I-V characteristics were observed. The weak shoulders at 1.62 and 1.95 V very likely arise from hole resonant tunneling through the LH1 and LH2 levels of the QW.[9,10] The hole resonances are identified from the calculated confinement energies of the electron and hole levels, and from comparison with the known biases of the $E1$ and $E2$ resonances.

A series of EL spectra covering the bias ranges of the $E1$ and $E2$ resonances is shown in Fig. 2. EL is first observed at $\sim$1.6 V, close to the onset of the $E1$ and LH1 resonances. The spectrum in Fig. 2(i), taken at 1.60 V, peaks at 1.579 eV. The $E_{11\mathrm{h}}$ peak is calculated to occur at E_g(GaAs) (1.519 eV)+$E1$ (48 meV)+HH1 (13 meV) $-E_x$ (8 meV)=1.572 eV (E_x is the exciton binding energy). This is close to the observed value of 1.579 eV.

The $E_{11\mathrm{h}}$ peak is observed throughout the bias range from 1.6 to 2.3 V [left-hand side, Figs. 2(i)-2(vi)]. At the onset of the $E2$ resonance, EL recombination is also observed at $\sim$1.715 eV [right-hand side, Fig. 2(iv)].[11] The 1.715-eV emission, which is approximately 10^4 times weaker than that due to $E_{11\mathrm{h}}$, corresponds to $E_{21\mathrm{h}}$ recombination. At 1.9 V the separation between the $E_{21\mathrm{h}}$ and E_{11h} emission peaks is 143 meV ($1.716-1.573$ eV), close to the calculated $E2$-$E1$ separation of $195-48=147$

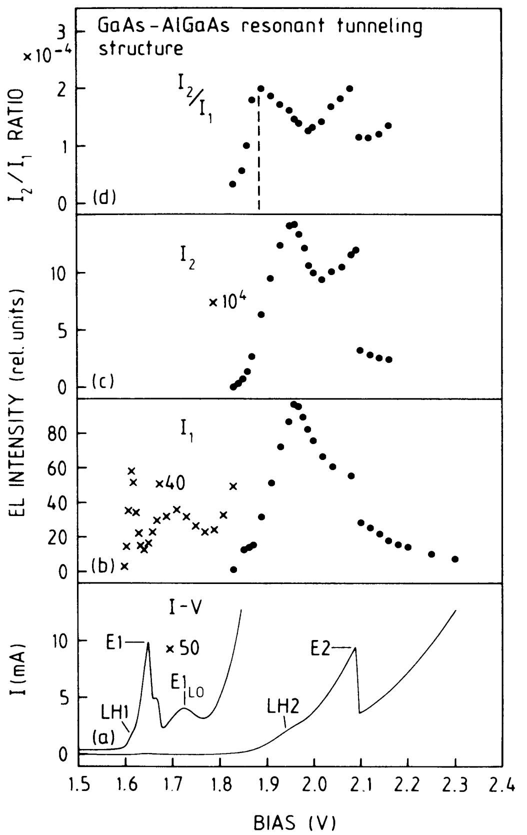

FIG. 1. (a) Current-voltage characteristics (4.2 K) showing $E1$ and $E2$ tunneling resonances at 1.65 and 2.09 V, respectively. 1.5 V corresponds to the flat-band voltage of the *p-n* junction. The weak shoulder at 1.62 V is ascribed to the LH1 resonance. (b) $E1$-HH1 EL intensity (I_1) vs bias. The intensities represented by the crosses are multiplied by a factor of 40. (c) $E2$-HH1 EL intensity (I_2) vs bias. (d) Ratio of I_2/I_1 EL intensities vs bias. The vertical dashed line at 1.9 V signifies the onset of the region above 1.9 V where the I_2/I_1 ratio is not affected by the nonzero $E1$ population below the $E2$ resonance.

meV, confirming the identification of the 1.715-eV peak. At the $E2$ resonance, electrons tunnel into the $n=2$ electron state. As shown in Fig. 3, they can then either tunnel directly out of the well (rate $1/\tau_2$) or they can undergo intersubband scattering (rate $1/\tau_i$) by rapid LO phonon emission to $E1$, accumulate in $E1$, and then tunnel out of the well (rate $1/\tau_1$).

The E_{11h} and E_{21h} integrated intensities (I_1 and I_2, respectively) are plotted as a function of bias in Figs. 1(b) and 1(c). Between 1.6 and 1.85 V only E_{11h} is observed. A sharp peak in I_1 is observed at 1.62 V, corresponding to the shoulder seen in *I-V* arising from tunneling into LH1. The EL intensity is controlled by both the electron and hole populations in the QW,[1,2,8] and so resonances due to both electron and hole tunneling are expected.[8] The results in Figs. 1(a) and 1(b) show that the EL intensity is a much more sensitive function of the hole population in the QW than the tunnel current, in agreement with previous PL results.[12,13] No feature corresponding to the $E1$ resonance in *I-V* [Fig. 1(a)] is seen in Fig. 1(b). This is not well understood, but in the 80-Å well sample I_1 does peak

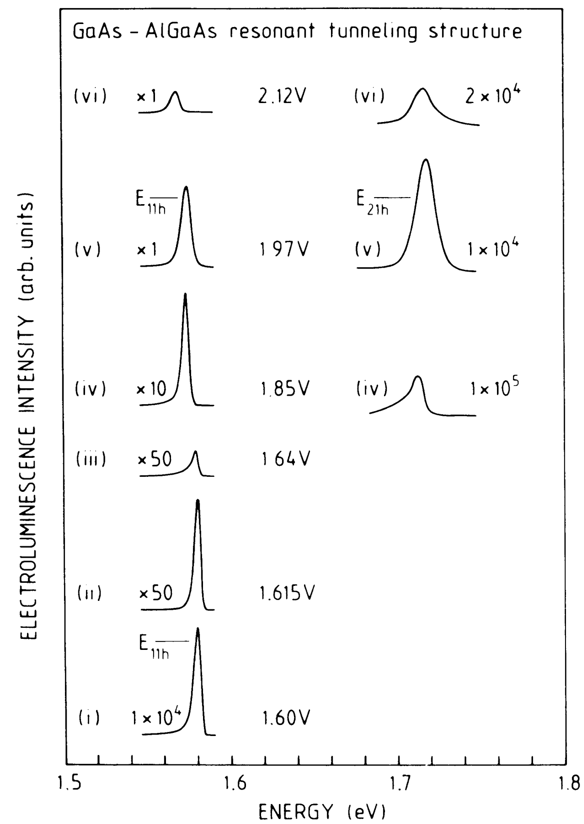

FIG. 2. EL spectra at 4.2 K as a function of bias. $E1$-HH1 is presented in the left half of the figure and $E2$-HH1 in the right half. Between 1.60 and 1.64 V [(i)-(iii)] only $E1$-HH1 EL is observed. Beyond the onset of the $E2$ resonance at 1.86 V both $E1$-HH1 and $E2$-HH1 signals are seen [(iv)-(vi)].

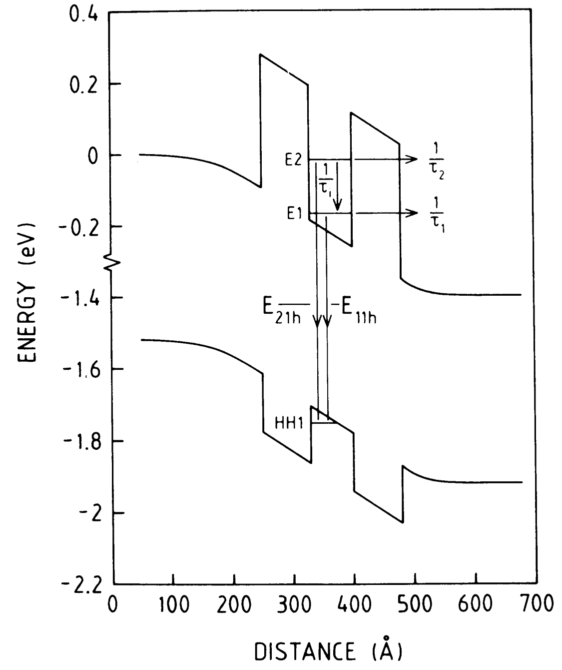

FIG. 3. Schematic diagram of the DBRTS at 2.0 V applied bias. The rates for tunneling out from $E2$ and $E1$ ($1/\tau_2$ and $1/\tau_1$) and the intersubband scattering rate $1/\tau_i$ are indicated.

at the $E1$ resonance. It is most likely that the $E1$ resonance in I_1 in the 70-Å QW is suppressed by the rapidly decreasing hole population in this bias range.

We now direct attention to the behavior of the EL intensities (I_1,I_2) in Figs. 1(b) and 1(c) beyond 1.85 V. A good correlation between $I_1(V)$ and $I_2(V)$ is seen in Figs. 1(b) and 1(c). Both show a very strong increase at 1.85 V, the onset of the $E2$ resonance in I-V in Fig. 1(a). For $V<1.85$ V, I_2 is zero. By contrast I_1 is nonzero in the 1.68–1.85 V region due to the occurrence of inelastic tunneling [the broad peak at 1.72 V in Fig. 1(a) is due to LO phonon-assisted tunneling]. Both I_1 and I_2 peak at ~ 1.97 V before decreasing towards the cutoff of the resonance at ~ 2.1 V. The peak in I_2 and I_1 occurs at 1.97 V, even though the electron populations must increase up to the cutoff of the resonance at 2.1 V, because of the decreasing HH1 population beyond 1.97 V. An analogous result was found in PL on the very similar *n-i-n* structure of Ref. 2 beyond 0.4 V. As explained in Ref. 2, beyond 0.4 V (1.9 V for a *p-i-n* structure) holes which tunnel through the first barrier have sufficient energy to pass directly over the top of the second barrier without capture by the QW.

The ratio I_2/I_1, in the region of the second resonance, is plotted in Fig. 1(d). The values below 1.9 V are affected by the fact that I_1 is nonzero at lower biases where E_2 tunneling cannot occur and $I_2=0$ [the region to the left of the dashed vertical line of Fig. 1(d)]. In the main region of interest from 1.9 to 2.2 V the I_2/I_1 ratio varies by less than a factor of 1.7 with a minimum value of 1.2×10^{-4} at 2.0 V. A very similar value is found for the 80-Å QW DBRTS. Since both E_2 and E_1 electrons recombine with HH1 holes, the ratio I_2/I_1 is independent of the hole population, and is given by

$$\frac{I_2}{I_1}=\frac{n_2}{n_1}\frac{f_2}{f_1}, \tag{1}$$

where n_2 and n_1 are the $E2$ and $E1$ populations, respectively, and f_2/f_1 is the ratio of oscillator strengths for E_{21h} to E_{11h} transitions.[14] The f_2/f_1 ratio was calculated from a solution of Schrödinger's equation for the QW, using electric-field values obtained from solution of Poisson's equation. At 2.0-V bias f_2/f_1 is calculated to be 0.08, increasing to 0.1 at 2.1 V. Some absorption of the EL will occur in the top GaAs contacts. This is a small effect, but will lead to attenuation of I_2 relative to I_1 by a factor of about 2.[15] Using the 2.0-V values of $I_2/I_1=1.2\times10^{-4}$ (2.4×10^{-4} after accounting for GaAs attenuation) and $f_2/f_1=0.08$, n_2/n_1 is obtained from Eq. (1) to be 3×10^{-3}.

When the structure is biased at the $E2$ resonance, n_1 and n_2 are determined by the following rate equations:

$$\frac{dn_2}{dt}=G-\frac{n_2}{\tau_2}-\frac{n_2}{\tau_i}-\frac{n_2}{\tau_{R2}}, \tag{2}$$

$$\frac{dn_1}{dt}=\frac{n_2}{\tau_i}-\frac{n_1}{\tau_1}-\frac{n_1}{\tau_{R1}}, \tag{3}$$

where G is a "generation" rate for n_2 electrons determined by tunneling in from the emitter contact τ_2, τ_1, and τ_i were defined earlier (see Fig. 3), and $(\tau_{R2})^{-1}$ and $(\tau_{R1})^{-1}$ are radiative recombination rates. In the steady state, from Eq. (3),

$$\frac{n_2}{\tau_i}-\frac{n_1}{\tau_1}-\frac{n_1}{\tau_{R1}}=0, \tag{4}$$

and so $n_2/n_1=\tau_i(1/\tau_1+1/\tau_{R1})$. Electrons relax from $E2$ to $E1$ by rapid LO phonon intersubband scattering at a rate $1/\tau_i\sim2\times10^{12}$ sec^{-1}.[16] Using the deduced value of n_2/n_1 of 3×10^{-3}, $1/\tau_1+1/\tau_{R1}$ is thus found to be 6×10^9 sec^{-1}. At the probable carrier densities in the well ($<10^{10}$ cm^{-2} for at least one of the carriers away from the peak of resonance) τ_{R1}^{-1} will very likely be $<10^8$ sec^{-1}, and can be neglected relative to τ_1^{-1}.[17] As a result τ_1^{-1} is found to be 6×10^9 sec^{-1}. Calculated values for τ_1^{-1} are extremely sensitive to the barrier width and height employed. For example, for $d=80$ Å, we obtain a value for τ_1^{-1} of 1.1×10^9 sec^{-1}, from the calculated width of the E_1 resonance at 2.0 V applied bias, increasing to 4.6×10^9 sec^{-1} for $d=70$ Å. Bearing in mind this sensitivity to the input parameters we conclude that the experimental value of τ_1^{-1} of 6×10^9 sec^{-1} is in very reasonable agreement with the calculated values, and provides confidence in the analysis of I_2/I_1 intensities.

The rate equations show that the n_2/n_1 population ratio is determined by τ_i/τ_1. n_2/n_1 is small ($\sim3\times10^{-3}$) due to the rapid intersubband scattering by LO phonons ($\hbar\omega\sim36$ meV) between states ~150 meV apart in energy. By contrast the absolute values of n_2 and n_1 are also determined by the tunneling in (G) and tunneling out $(1/\tau_2)$ rates from $E2$ [see Eq. (2)]. We calculate $1/\tau_2$ to be 1×10^{12} sec^{-1}, for $d=80$ Å at 2-V bias. The ratio of the $E2$ to $E1$ current densities is given by $J_2/J_1=(n_2/n_1)(\tau_1/\tau_2)$, which is ~3 for $n_2/n_1=3\times10^{-3}$, $\tau_1/\tau_2\approx10^3$. Thus, even though the n_2/n_1 ratio is very small it is clear that a significant part of the tunnel current is carried by tunneling through the $E2$ state, with the rest being transported by a sequential process via $E1$.[18]

The above analysis of the I_2/I_1 and n_2/n_1 ratios has been performed at 2.0-V applied bias. The reason for the rapidly increasing I_2/I_1 ratio for $V=1.86$ to 1.90 V has been discussed earlier. The decrease of I_2/I_1 from 1.9 to 2.0 V is not well understood. However, beyond 2.0 V, where I_2/I_1 increases by a factor of 1.7 from 2.0 to 2.1 V, the increase can be understood in terms of the decreasing value of τ_1 with bias [see Eq. (1) and (4)], and of the expected increase of f_2/f_1 with bias. We calculate a decrease of τ_1 by a factor of 2, from 2 to 2.1 V. This is a larger variation than that expected for the increase of the f_2/f_1 ratio (of a factor of 1.3) over the same bias range, and can account at least qualitatively for the increase in I_2/I_1 observed in Fig. 1(d). When the device goes off resonance at 2.1 V, I_2/I_1 decreases again. This is expected since the electric field across the collector barrier will decrease, and hence τ_1 will increase as charge is ejected from the well between the off- and on-resonance states.

Related results have been reported by Grahn *et al.* in PL experiments on GaAs-AlAs superlattices.[14] In those experiments tunneling occurred by a sequential process from $E1$ to $E2$ of adjacent wells, followed by intersubband scattering from $E2$ to $E1$ and then tunneling to $E2$ in the next well.[19] The present case is much more straightforward to analyze since tunneling through only one QW is involved.

To conclude, EL recombination from the ground and first excited electron state of the QW of a *p*-*n* junction DBRTS has been reported. Study of the relative intensities of $E2$ to $E1$ recombination at the $E2$ resonance has permitted the ratio of the $E1$ tunneling time to the intersubband scattering time to be deduced. In spite of the small $E2$ population deduced, a significant fraction of the on-resonance current is carried by tunneling through $E2$, with the rest being transported by sequential processes via $E1$.

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