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Cross-barrier recombination in a GaAs/AlGaAs double-barrier resonant tunneling structure

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We report the observation by photoluminescence (PL) spectroscopy of cross-barrier recombination between spatially separated two-dimensional electron and hole gases confined respectively in the quantum well (QW) and collector accumulation layer of a GaAs/AlGaAs double-barrier resonant tunneling structure. At the onset of the $n=3(E3)$ resonance in the current–voltage characteristic, the energy of the cross-barrier transition E_{cr} is found to coincide with that of the PL peak arising from recombination of electrons from the $E3$ confined level in the QW with $n=1$ confined hole states (E_{3lh} recombination). Similarly, at the onset of the $E4$ resonance, $E_{cr} \approx E_{4lh}$. We show that this behavior arises as a consequence of the symmetrical potential distribution within the structure at the onsets of the resonances. © *1996 American Institute of Physics.* [S0021-8979(96)07110-3]

Optical spectroscopy is well established as a powerful probe of vertical transport in semiconductor heterostructures. In particular, photoluminescence (PL) and electroluminescence (EL) spectroscopies have been successfully used to study tunneling[1–4] and ballistic transport[5,6] in single- and double-barrier tunneling structures. In double-barrier resonant tunneling structures (DBRTS), optical spectroscopy is usually employed to investigate recombination between carriers in the quasiconfined electron and hole states of the quantum well (QW) of the device. Such experiments yield direct information on the absolute[2] and relative[3,4] populations of the QW levels, and on the nature of the tunneling process.[2,3] In this communication we report the investigation by PL spectroscopy of spatially indirect recombination of confined QW electrons with holes in the collector accumulation layer of a conventional, symmetric DBRTS. Similar cross-barrier recombination has been previously reported in single-[6] and triple-[7] barrier structures, and also in a highly asymmetric DBRTS, specifically designed for enhanced overlap of the spatially separated wave functions.[8] The study of such transitions provides a means to obtain detailed information on the potential profile within the structure, and also to investigate coupling between confined, spatially separated electron and hole gases.

The DBRTS was grown by molecular-beam epitaxy on an n^+ GaAs substrate, and comprised the following layers: 0.5 μm $n=1.5\times10^{18}$ cm^{-3} GaAs; 0.5 μm $n=2\times10^{17}$ cm^{-3} GaAs emitter; 100 Å undoped GaAs spacer; 85 Å undoped $Al_{0.33}Ga_{0.67}As$ barrier; 200 Å undoped GaAs QW; 85 Å undoped $Al_{0.33}Ga_{0.67}As$ barrier; 100 Å undoped GaAs spacer; 0.75 μm $n=2\times10^{17}$ cm^{-3} GaAs collector; 0.25 μm $n=1\times10^{18}$ cm^{-3} GaAs top contact. The structure was processed into circular mesas with annular contacts to allow optical access. All measurements were taken with the samples immersed in liquid helium at 2 K. Analysis and detection of the very weak excited state and cross-barrier luminescence signals were facilitated by means of a high stray light rejection triple-grating spectrometer fitted with a liquid-nitrogen-cooled charge-coupled-device (CCD) detector array. PL was excited by a HeNe laser using a power density of about 1 W cm^{-2}, which produced negligible perturbation of the $I-V$ characteristics. The structure displays resonances in $I-V$ at forward biases (top contact positive relative to substrate) of 0.05, 0.18, 0.40, and 0.68 V, due to electrons tunneling from the emitter into the $E1$, $E2$, $E3$, and $E4$ confined QW levels respectively. The 2 K $I-V$ characteristic in the bias range of the $E2-E4$ resonances is shown in Fig. 1(a).

Under forward bias, photocreated holes from the top contact of the structure tunnel into the $n=1$ (HH1) level of the QW where they recombine with electrons in the ground and excited QW confined states to generate PL. Analysis of the intensities of the PL arising from the various QW transitions allows the relative populations of the confined electron levels to be determined, as discussed in detail in Refs. 3 and 4. Due to the predominantly sequential nature of the tunneling process[2–5] the most intense PL arises from $E1$–HH1 (E_{1h}) recombination, even when the structure is biased for tunneling into excited electron states of the QW.

Figure 2 shows a series of PL spectra in the 1.58–1.70 eV region, obtained at biases in the range of the $E3$ and $E4$ resonances. The strongest features in this region arise from $E3$-HH1 (E_{3lh}) and $E4$-HH1 (E_{4lh}) recombination. These peaks are approximately 10^4 times less intense than the E_{1lh} PL. For all biases beyond the onset of the $E4$ resonance, the intensity I_4 of the E_{4lh} line is similar to that of the E_{3lh} line I_3, with $I_3 < I_4$ at around 0.5 V. This observation, which occurs despite the fact that the E_{3lh} transition has the greater oscillator strength throughout the bias range of the experiment, is a consequence of a population inversion which occurs between $E4$ and $E3$ when the structure is biased for

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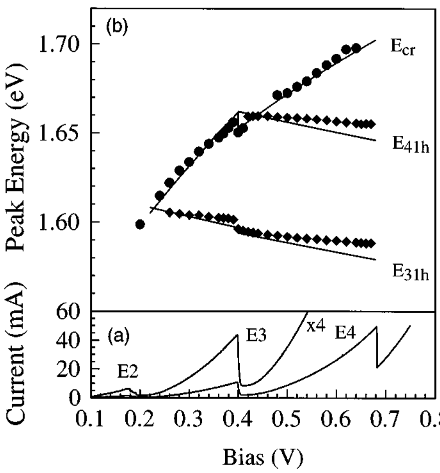

FIG. 1. (a) 2 K current–voltage ($I-V$) characteristic of the structure, showing $E2$, $E3$, and $E4$ electron tunneling resonances. (b) Measured (symbols) and calculated (solid lines) energies of the E_{3lh}, E_{4lh}, and E_{cr} transitions vs bias.

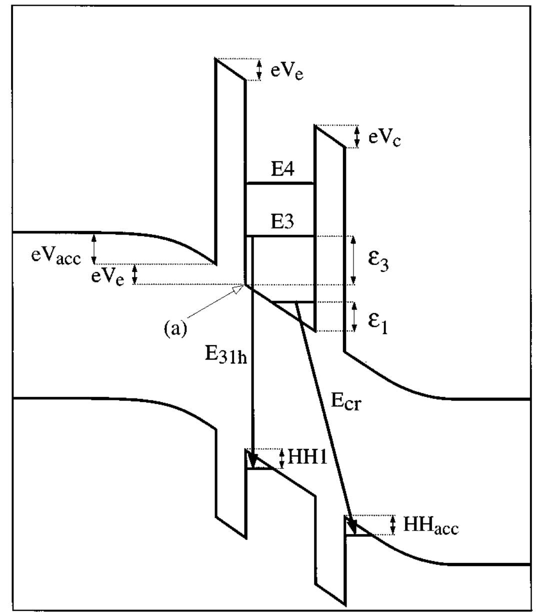

FIG. 3. Schematic band diagram of the structure biased at the onset of the $E3$ resonance, showing E_{3lh} and $E1$-HH_{acc} cross-barrier recombination. The $E2$ level has been omitted for clarity.

tunneling into $E4$. This is discussed fully in Ref. 4. The signal to noise ratio of the spectra in Fig. 2 is considerably greater than for those presented in Ref. 4, due to the high stray light rejection and sensitivity of the spectrometer/detector system used in the present work. This enables the line shapes of the excited state peaks to be observed in much greater detail. For instance, near the peaks of the $E3$ and $E4$ resonances in $I-V$, the E_{3lh} and E_{4lh} lines develop pronounced exponential high-energy tails (as seen in Fig. 2) indicative of recombination between thermalized carrier populations having effective temperatures greater than that of the lattice.[9]

This increased sensitivity also permits the observation of the weak features labeled E^*_{4lh} and E_{cr} in Fig. 2. E^*_{4lh} emerges at the onset of the $E4$ resonance in $I-V$, and is approximately 36 meV lower in energy than E_{4lh}, irrespective of bias. This peak is identified as a LO phonon satellite of E_{4lh}

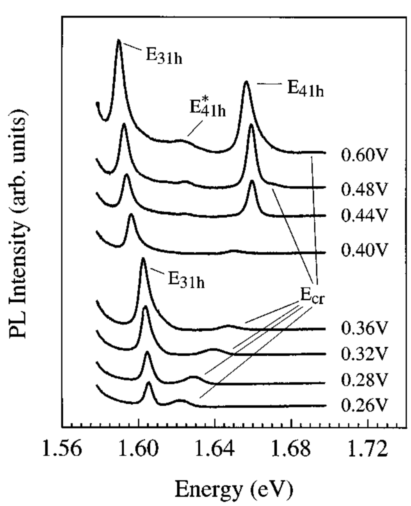

FIG. 2. PL spectra obtained in the 1.58–1.70 eV energy range for biases between the onset of the $E3$ resonance and the peak of the $E4$ resonance.

($\hbar\omega_{LO} \approx 36$ meV in GaAs). The primary feature of interest in the present work, however, is the feature labeled E_{cr} in Fig. 2. In contrast to the E_{3lh}, E_{4lh}, and E^*_{4lh} peaks, which decrease in energy due to the quantum confined Stark effect as bias is increased, E_{cr} moves to progressively higher energy with increasing bias. This indicates that E_{cr} arises from recombination between spatially separated electron and hole distributions, the transition energy increasing as the potential difference between the electron and hole states is raised. In the DBRTS studied, such a transition could occur between either

(a) electrons from the emitter region and holes from the confined HH1 level in the QW (E_{acc}-HH1 recombination) or
(b) electrons from the $E1$ QW level and holes from the collector accumulation layer ($E1$-HH_{acc} recombination, see Fig. 3).

The attribution to E_{acc}-HH1 recombination can, however, be excluded from consideration of the physics of the resonant tunneling process. For example, as the bias is increased from the onset to the peak of the $E3$ resonance, E_{cr} peak moves by approximately 40 meV to higher energy [Fig. 1(b)]. If the E_{acc}-HH1 attribution were correct this implies a movement of the QW levels relative to the emitter by 40 meV also. The precise nature of the emitter states from which tunneling occurs [three dimensional (3D) or two dimensional (2D)] is not known. However, if the emitter states are predominantly 3D, then for 3D (emitter) –2D (well) tunneling, the $E3$ level cannot move relative to the emitter by more than the emitter Fermi energy E_F over the bias range of the resonance.[10] E_F is only equal to ~18 meV, as determined by the emitter doping level of 2×10^{17} cm^{-3}, and thus the E_{acc}-HH1 attribution can be excluded. For the 2D (emitter)

−2D (QW) case, true resonant tunneling with conservation of energy and lateral momentum only occurs when the $E3$ level is aligned with the confined 2D level in the emitter accumulation layer.[11] The structure remains on resonance over a finite range of bias due to space charge buildup in the QW of the DBRTS; $E3$ remains pinned in energy relative to the accumulation layer, together with the rest of the QW levels over the bias range of the resonance, thus precluding the E_{acc}-HH1 attribution for the 2D−2D case also.[12]

The $E1$-HH_{acc} attribution for E_{cr} is by contrast fully consistent with the expected variation of the potential distribution within the device at both the third and fourth resonances. The observed energies for the E_{3lh}, E_{4lh}, and E_{cr} peaks are plotted versus bias in Fig. 1(b). The peak positions show excellent agreement with the results of Poisson−Schrödinger equation simulations of the transition, indicated by the solid lines in Fig. 1(b). In the calculations, the electron density n_s in the QW was taken to be 1×10^{11} cm^{-2} and 1.5×10^{11} cm^{-2}, respectively, at the peaks of the $E3$ and $E4$ resonances, and to vary linearly with bias from the onsets to the peaks of the resonances.[2,10] The QW $E3$ and $E4$ levels are found to move relative to the emitter by less than 20 meV within the bias range of the respective resonances, consistent with the device remaining on resonance, as required. The space-charge buildup in the QW increases the potential drop over the collector barrier relative to that across the emitter barrier and leads to the stronger variation of $E1$-HH_{acc} with bias relative to E_{acc}-HH1, which in turn is consistent with the device remaining on resonance. It is notable in both the experiment and simulations that E_{cr} decreases slightly in energy when the device goes off resonance at 0.4 V. The physical reason for this is that when the device goes off resonance, the charge buildup in the QW goes to zero, and the emitter charge increases to maintain self-consistency. For a given applied bias this leads to a small decrease in the potential drop across the collector barrier, and hence to a small decrease in the $E1$-HH_{acc} (E_{cr}) energy, as observed.

At the onset biases of the third and fourth resonances, the position of the E_{cr} peak coincides within 10 meV with that of E_{3lh} and E_{4lh}, respectively. This can be understood by reference to the schematic band diagram shown in Fig. 3. At the onset of the third resonance, the $E3$ energy ϵ_3, relative to position (a) in Fig. 3, may be written as $\epsilon_3=e(V_{acc}+V_e)$, where V_{acc} is the potential drop across the emitter accumulation layer and V_e is the potential drop across the emitter barrier. Thus, neglecting the small (∼6 meV) exciton binding energy, $E_{3lh}=E_g+e(V_{acc}+V_e)+\mathrm{HH1}$, where E_g is the band gap of GaAs. The energy of the E_{cr} transition is given by $E_{cr}=E_g+\epsilon_1+eV_c+\mathrm{HH}_{acc}$, where V_c is the potential drop across the collector barrier. The difference between the E_{3lh} and E_{cr} transition energies is then given by

$$E_{3lh}-E_{cr}=(eV_{acc}-\epsilon_1)+(\mathrm{HH1}-\mathrm{HH}_{acc})+e(V_e-V_c). \quad (1)$$

The calculations give $eV_{acc}=40$ meV and $\epsilon_1=37$ meV at the onset of the $E3$ resonance, and thus $eV_{acc}\approx\epsilon_1$. Furthermore, at the onset of the resonance, with $n_s=0$, the electric field in the structure is constant and we expect $V_e=V_c$, and also $\mathrm{HH1}\approx\mathrm{HH}_{acc}$ (=29 meV in the calculations). Thus, we expect $E_{3lh}-E_{cr}\approx0$ at the onset of the $E3$ resonance, as observed. Similar reasoning explains the coincidence of E_{cr} and E_{4lh} at the onset of the $E4$ resonance further substantiating our assignment of E_{cr}.

In summary, we have used PL spectroscopy to investigate cross-barrier recombination between electrons from the $E1$ quantum-well level of a DBRTS and holes from the collector accumulation layer. When the structure is biased at the onsets of the $E3$ and $E4$ resonances, the energy of the cross-barrier luminescence coincides with the peak positions of the E_{3lh} and E_{4lh} transitions, respectively. We have shown that this arises as a consequence of the constant electric field within the structure at the onsets of the resonances. The main contribution to the variations of the E_{cr} peak position with bias arises from the change in the potential drop across the collector barrier. Analysis of the bias dependence of the E_{cr} peak position thus provides a sensitive method to probe the potential distribution within a double-barrier structure.

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[12] If tunneling is 2D−2D but without conservation of lateral momentum, then the well levels can move relative to the emitter, but only by the emitter Fermi energy, as in the 3D−2D case.