Observation of ballistic transport in double-barrier resonant-tunneling structures by electroluminescence spectroscopy

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We report a direct observation by electroluminescence (EL) spectroscopy of ballistic-electron transport in double-barrier resonant-tunneling $GaAs/Al_xGa_{1-x}As$ p-i-n diodes. The samples studied contain two confined electron states ($e1$ and $e2$) and consequently two resonances in the current versus bias characteristic. When biased for electron tunneling through $e2$, an analysis of EL intensities permits a quantitative determination of the ratio (1:16 and 1:203 for the two samples studied) of the ballistic current flowing directly through $e2$ to the current flowing sequentially through $e1$.

Since the first studies on double-barrier resonant-tunneling structures (DBRTS),[1] the nature of the tunneling process in these structures has been much discussed.[2] Recent optical[3,4] and magnetotransport[5] experiments have demonstrated that a significant fraction of the tunneling current is sequential, with electrons undergoing inelastic scattering in the quantum well (QW) of the DBRTS before tunneling out of the structure. In this paper, we report the direct observation of ballistic-electron transport in a DBRTS. The ballistic electrons, which tunnel through the structure without undergoing any energy relaxation, are observed using electroluminescence (EL) spectroscopy.

The experiments were carried out at 2 K on DBRTS embedded in p-n junctions, using the ballistic-electron luminescence spectroscopy (BELS) described by Petersen and co-workers.[6,7] This technique relies on the fact that hot electrons injected into a p-type region can generate EL by recombining with neutral acceptors. The samples were grown by molecular-beam epitaxy, and comprised the following layers: n^+-type GaAs substrate, 1-μm $n=1\times10^{18}$ cm^{-3} GaAs, 1000-Å $n=1\times10^{17}$ cm^{-3} GaAs emitter, 50-Å undoped GaAs spacer, 80-Å $Al_{0.4}Ga_{0.6}As$ barrier, 70-Å GaAs QW for sample 1 or 80-Å GaAs QW for sample 2, 80-Å $Al_{0.4}Ga_{0.6}As$ barrier, 50-Å undoped GaAs spacer, 1000-Å $p=5\times10^{17}$ cm^{-3} Be-doped GaAs collector, and 9000-Å $p=1\times10^{18}$ cm^{-3} GaAs. The structures were processed into 100-μm-diameter mesas with Ohmic annular top contacts.

As shown in Fig. 1(a), the diodes exhibit two main resonances in the current versus forward bias characteristics, corresponding to resonant tunneling of electrons through the first ($e1$) and second ($e2$) confined electron levels in the QW. We also observe weaker resonances due to hole tunneling from the p-type GaAs layer to the $n=1$ light-hole (lh1), $n=2$ heavy-hole (hh2), and $n=3$ heavy-hole (hh3) QW states, as labeled in Fig. 1(a). These attributions are made by comparison with the calculated positions of hole resonances, and by comparison with previous work on DBRTS in p-n junctions.[8,14] The shoulder observed at 1.66 V is due to oscillations of the diode in this negative-differential-resistance region. Under bias, EL recombination of electrons from $e1$ (and also from $e2$ at the second resonance) with hh1 can be clearly seen, as described in a previous paper.[8] In order to perform BELS measurements, we increased the sensitivity of

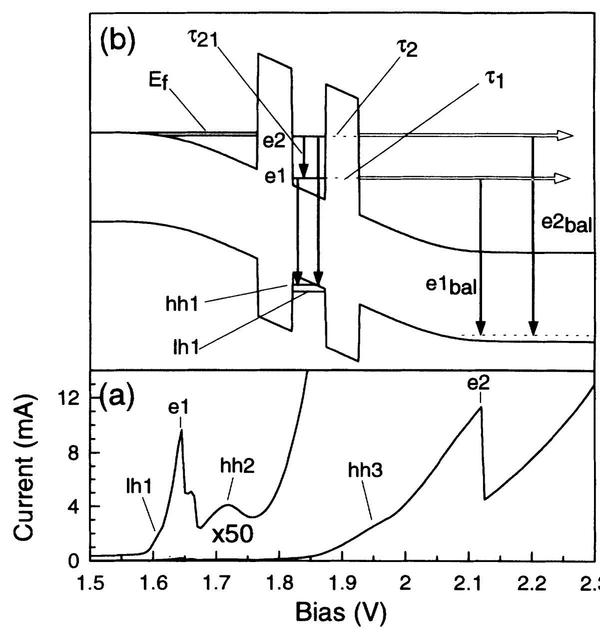

FIG. 1. (a) Current vs bias characteristic for sample 1 (70-Å QW). (b) Schematic band diagram for forward bias at the second resonance, showing the different transport and recombination processes. τ_1 and τ_2 are the tunneling out times from $e1$ and $e2$, respectively, and τ_{21} is the intersubband relaxation time.

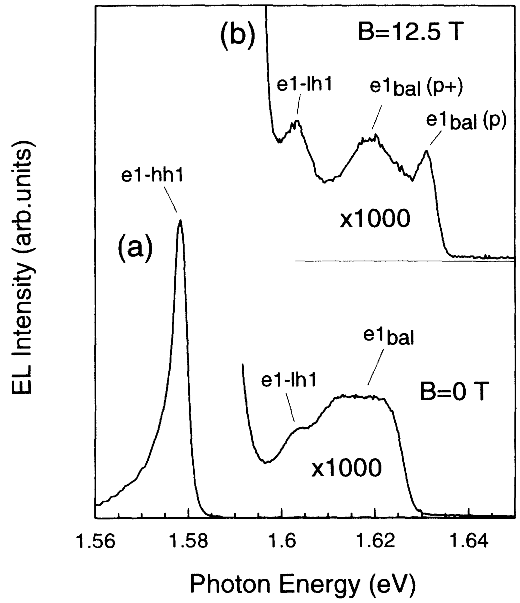

FIG. 2. (a) EL spectrum of sample 1 at the first resonance (1.65 V) and zero magnetic field. $e1$-hh1 and $e1$-lh1 QW lines and the $e1_{\rm bal}$ ballistic-electron peak are observed. (b) EL spectrum at the same bias but with 12.5-T magnetic field applied parallel to the transport direction.

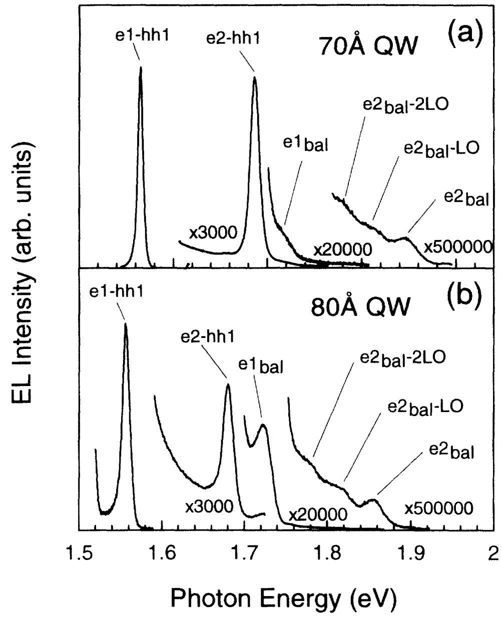

FIG. 3. EL spectra of sample 1 (a) and sample 2 (b) when biased at the second resonance (2.10 V).

our experimental setup by almost three orders of magnitude, by using a liquid-nitrogen-cooled charge-coupled-device detector array together with a triple spectrometer with high stray light rejection.

Figure 2(a) shows the EL spectrum of sample 1 (70-Å QW) biased at the peak of the first resonance (1.65 V). The most intense EL arises from the fundamental $e1$-hh1 transition in the QW at 1.578 eV. However, the most important feature of the spectrum for the present work is the weaker line ($e1_{\rm bal}$) around 1.62 eV. In contrast with the QW peaks, which show a very small quantum-confined Stark shift to lower energy with increasing bias, $e1_{\rm bal}$ shifts towards higher energy as bias is increased. This behavior strongly suggests that the $e1_{\rm bal}$ peak arises from the recombination of ballistic electrons flowing out of the DBRTS with neutral acceptors in the p-type GaAs region, as an increase in the electric field results in an increase in the transition energy [see the schematic diagram in Fig. 1(b)].

This attribution of the $e1_{\rm bal}$ peak is confirmed by the behavior of similar peaks ($e1_{\rm bal}$ and $e2_{\rm bal}$) in the spectra taken at the second resonance [Figs. 3(a) and 3(b) for samples 1 and 2, respectively]. As observed at the first resonance, both $e1_{\rm bal}$ and $e2_{\rm bal}$ shift towards higher energy as the bias is increased to the peak of the resonance (Fig. 4). Furthermore, the energy separation of $e1_{\rm bal}$ and $e2_{\rm bal}$ (141 and 125 meV for samples 1 and 2, respectively) is very close to the $e2$-$e1$ separation measured from the QW luminescence (140 and 122 meV) for samples 1 and 2, respectively), and remains constant as the bias is varied. In addition, at about 36 and 72 meV below the $e2_{\rm bal}$ line, phonon replicas of $e2_{\rm bal}$ are clearly observed. The occurrence of such LO phonon replicas is a characteristic signature of hot-electron recombination.[6,7,10]

From this evidence we conclude that $e1_{\rm bal}$ and $e2_{\rm bal}$ are due to the recombination with neutral acceptors of ballistic electrons tunneling out from $e1$ and $e2$, respectively, the $e2_{\rm bal}$-LO and $e2_{\rm bal}$-2LO replicas arising from electrons which emit one or two LO phonons ($\hbar\omega_{\rm LO}=36$ meV), respectively, before recombining.

In addition to the ballistic-electron features, we also observe the $e2$-hh1 and $e1$-hh1 QW transitions at the second resonance, the $e2$ level being populated directly by electrons tunneling from the emitter. The observation

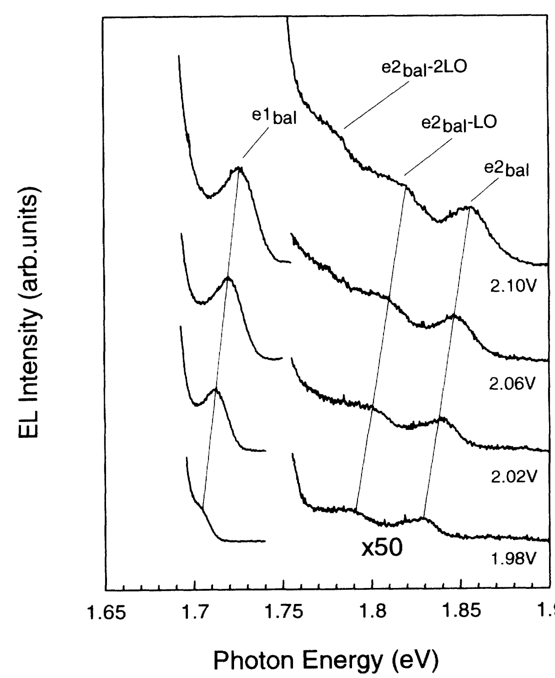

FIG. 4. Evolution with increasing bias of the $e1_{\rm bal}$ and $e2_{\rm bal}$ lines for sample 2 at the second resonance.

of $e1_{\rm bal}$ and $e1$-hh1 in this bias range shows that $e1$ is also populated at the second resonance, and proves that sequential tunneling and electron relaxation from $e2$ to $e1$ occurs. It should be noted that while the ballistic electrons which tunnel through $e1$ and $e2$ at the first and second resonance, respectively, do not experience any inelastic scattering during tunneling, it is not possible to confirm that these electrons undergo a coherent tunneling process. This is because these experiments provide no means to detect whether or not the ballistic electrons have experienced any elastic-scattering events, which would break the phase coherence of the tunneling wave function.

Analysis of the relative intensities of the $e1_{\rm bal}$ and $e2_{\rm bal}$ lines allows us to determine the relative contributions of electrons tunneling directly through $e2$ (J_2) or sequentially through $e1$ (J_1) to the total tunneling current at the second resonance. The luminescence intensity of a current density J of monoenergetic hot electrons with kinetic energy E_c, which recombine with neutral acceptors is given by

$$I^{\rm EL} \propto J|M(k_c)|^2\tau(E_c) , \tag{1}$$

where $\tau(E_c)$ is the inelastic-scattering time, k_c is the wave vector of the hot electrons, $M(k)$ is the k component of the acceptor wave function, which is given in the effective-mass approximation by[9,10]

$$M(k) \propto (1+a_0^2k^2)^{-2} , \tag{2}$$

and $a_0=21.3$ Å is the Bohr radius of the Be acceptor levels.[11] We then deduce the ratio J_1/J_2,

$$\frac{J_1}{J_2}=\frac{I_1^{\rm EL}}{I_2^{\rm EL}}\frac{\tau(E_{c2})}{\tau(E_{c1})}\frac{|M(k_{c2})|^2}{|M(k_{c1})|^2} , \tag{3}$$

where $E_{ci}=\hbar^2k_{ci}^2/2m^*=E_{ei_{\rm bal}}-(E_g-E_{A^0})$; $E_{ei_{\rm bal}}$ is the observed EL ballistic energy, $E_g=1.519$ eV the GaAs band-gap energy, and $E_{A^0}=28$ meV the Be-acceptor binding energy. The measured EL intensities are corrected for the spectral response of the experimental setup and for reabsorption in the GaAs top contact.[8] We measured $I_I^{\rm EL}/I_2^{\rm EL}=92$, which gives $J_1/J_2=16$ for sample 2.[12] Following a similar procedure for sample 1, we obtain $I_I^{\rm EL}/I_2^{\rm EL}=16$ and $J_1/J_2=2.3$. The smaller J_1/J_2 ratio for sample 1 arises since the $e2$ level is closer to the top of the collector barrier because of the smaller QW width. This leads to a higher probability for tunneling out of $e2$, whereas the intersubband scattering probability remains almost the same as for sample 2. Indeed in a simple description where we neglect recombination processes, we have [see Fig. 1(b)]

$$\frac{J_1}{J_2}\approx\frac{\tau_2}{\tau_{21}} \quad \text{and} \quad R=\frac{J_1/J_2(\text{sample 2})}{J_1/J_2(\text{sample 1})}\approx\frac{\tau_2(\text{sample 2})}{\tau_2(\text{sample 1})} . \tag{4}$$

For the conditions of resonance and using a barrier height of 385 meV, a WKB calculation gives τ_2(sample 1)=23 ps and τ_2(sample 2)=88 ps, which leads to a ratio $R=3.8$, which is in reasonably good agreement with the value $R=7$ obtained from the above analysis. In both samples, however, the main result is that at the second resonance most of the current flows sequentially through the electron ground state in the QW. Our previous determination[8] of $J_1/J_2=0.3$ from analysis of the QW EL signals was much less reliable since it relied on calculation of absolute values of τ_1 and τ_2 for a particular sample.

In the bias range of the first resonance, the $e1_{\rm bal}$ peak for structure 1 has a flat-topped line shape and a low-energy shoulder at 1.602 eV [Fig. 2(a)]. The latter feature, which remains fixed in energy as bias is varied and is not observed in similar experiments on π-i-n diodes with a single barrier is due to recombination of $e1$ electrons with lh1 holes in the QW. This transition is calculated to occur at 1.601 eV. The nature of the $e1_{\rm bal}$ peak is clarified by measuring EL spectra with a magnetic field applied parallel to the transport direction ($B\|z$). Application of the magnetic field results in the formation of Landau levels, thus removing free-carrier broadening from the transverse-energy distribution of the tunneling electrons, probably arising from the spread of transverse kinetic energies of the electrons in the QW.

A typical EL spectrum, obtained at a magnetic field ($B\|z$) of 12.5 T, is shown in Fig. 2(b). The spectrum shows that the flat top of the $e1_{\rm bal}$ peak at zero magnetic field arises principally from the superposition of two closely spaced peaks, which become resolved as free-carrier broadening is removed by the applied field.[15] We attribute these peaks to recombination of ballistic electrons with neutral acceptors in different regions of the sample, the lower-energy peak being due to recombination in the p^+ top contact, and the higher-energy feature arising from recombination in the more lightly doped collector of the structure. These attributions are consistent with the ballistic length of about 900 Å in $p=5\times10^{17}$ cm^{-3} GaAs for electrons with kinetic energy of 200 meV.[13] For such values of the ballistic length, EL recombination from both the 1000-Å-thick $p=5\times10^{17}$ cm^{-3} collector region and the p^+ contact region is expected. Anyway, the main result is that this change in the shape of $e1_{\rm bal}$ with an applied magnetic field tends to show that a broad electron distribution is tunneling through the DBRTS. However, we cannot make a more quantitative conclusion here. Detailed studies of the ballistic-electron line shape in single- and double-barrier structures are currently in progress and will be discussed in a future publication.

In summary, we have shown that EL spectroscopy permits a direct observation of ballistic-electron tunneling in DBRTS. In structures containing two quasiconfined electron states, which are biased for electron tunneling into the $e2$ level, analysis of the relative intensities of the EL peaks arising from recombination of electrons injected into the p-type region from $e1$ and $e2$ shows that, in this bias range, most of the current arises from sequential tunneling.

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[12]The major contribution to the correction to $I_1^{\mathrm{EL}}/I_2^{\mathrm{EL}}$ in order to obtain J_1/J_2 arises from the ratio $|M(k_{c1})|^2/|M(k_{c2})|^2$ (5.2 and 4.7 for samples 1 and 2, respectively). This ratio can be calculated accurately using Eq. (2) as demonstrated in Ref. 10. The inelastic scattering times $\tau(E_c)$ in the collector are determined by both LO phonon emission times (τ_{LO}) and intervalley scattering times (τ_{sc}). τ_{LO} will vary only very slightly between the $e1_{\mathrm{bal}}$ and $e2_{\mathrm{bal}}$ electrons, and τ_{sc} decreases with increasing energy, again as shown in the hot-electron photoluminescence experiments of Ref. 10. From these results we get $\tau(E_{c1})/\tau(E_{c2})=1.35$ and 1.24 for samples 1, and 2 respectively.

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