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Evidence for population inversion in excited electron states of a double barrier resonant tunneling structure

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We report evidence for a population inversion between excited electron states of the quantum well of a GaAs-AlGaAs double barrier resonant tunneling structure (DBRTS). The relative populations of the states are determined by photoluminescence spectroscopy of the tunneling electrons in the structure. When the DBRTS is biased at the fourth electron resonance, the population of the $n=4$ confined level is found to be greater than that of the $n=3$ state. We show that such a population inversion is consistent with a rate equation analysis of the relative populations of the two levels when electrons tunnel into $n=4$.

During the last 20 years, there have been a variety of proposals to achieve a population inversion between electron energy levels in semiconductor low dimensional structures, based on the ability to manipulate independently the populations of individual levels in such structures.[1–4] For example, variation of quantum well (QW) width permits modification of interlevel scattering rates, whereas rates of filling and emptying of the levels by tunneling can be altered by changing barrier widths. However, in spite of this effort, a report of population inversion in such a device structure is lacking up to the present time. In this letter we report the results of photoluminescence (PL) experiments which provide evidence for a population inversion between the $n=4$ (E4) and $n=3$ (E3) levels of the 200-Å-wide QW of a GaAs-AlGaAs double barrier resonant tunneling structure (DBRTS). We show that such a population inversion is consistent with a rate analysis of the excited state populations, since the electron-optic phonon scattering rate is greater for E3–E2 transitions than for E4–E3 transitions.

The DBRTS was grown by molecular beam epitaxy and comprised: n^+GaAs substrate, 0.5 μm $n=1.5\times10^{18}$ cm^{-3} GaAs, 0.5 μm 2×10^{17} cm^{-3} GaAs, 100 Å undoped GaAs, 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, 0.75 μm $n=2\times10^{17}$ cm^{-3} GaAs, 0.25 μm $n=1\times10^{18}$ cm^{-3} GaAs top contact. The structure was processed into mesas with annular contacts. PL was excited by a He-Ne laser, using a power density of around 1 W cm^{-2} which produced negligible perturbation of the I-V characteristics. The I-V characteristic obtained at $T=5$ K is shown in Fig. 1(a). Electron tunneling resonances are observed at 0.05, 0.18, 0.40, and 0.68 V.

When positive bias is applied, photocreated minority holes are driven from the top contact to the collector barrier. They then tunnel into the QW, where they can recombine with electrons to generate PL. Throughout the bias range of the experiment the most intense PL from the QW arises from recombination of E1 electrons with $n=1$ (HH1) heavy holes (E_{11h} recombination). At biases beyond the onset of the E2 resonance, E2-HH1 (E_{21h}) recombination is expected to occur at 1.551 eV. For most of this bias range, the E_{21h} PL is obscured by overlap with the high energy tail of the strong GaAs band-edge PL. However, at the peak of the E2 resonance (~0.17 V) a weak shoulder at 1.554 eV becomes discernible on the GaAs high energy tail, due to E_{21h} recombination.

At a bias of around 0.25 V, close to the onset of the E3 resonance, an additional PL peak emerges at an energy of 1.596 eV. This peak, which is about 10^4 times less intense than the E_{11h} peak, is attributed to E3-HH1 (E_{31h}) recombina-

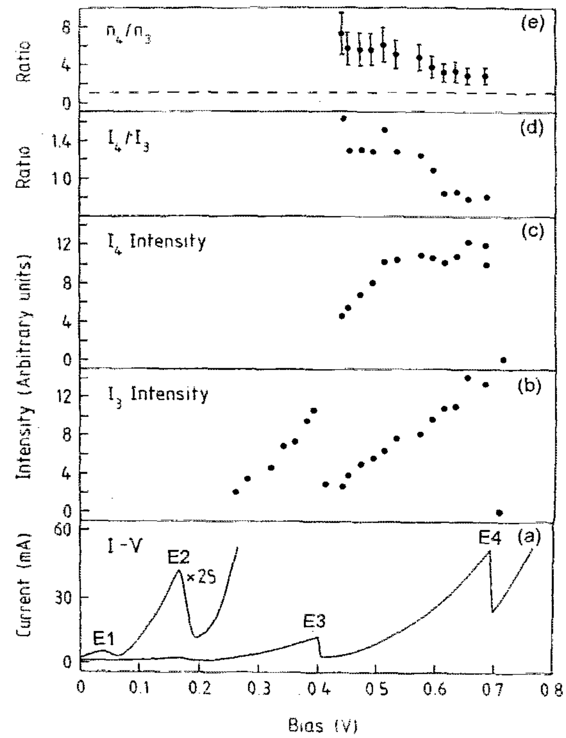

FIG. 1. (a) Current-voltage characteristic (5 K) showing E1, E2, E3, and E4 electron tunneling resonances. (b) E3-HH1 PL intensity (I_3) vs bias in the bias range of the E3 and E4 resonances. (c) E4-HH1 PL intensity (I_4) vs bias in the bias range of the E4 resonance. (d) I_4/I_3 vs bias. (e) n_4/n_3 population ratio vs bias.

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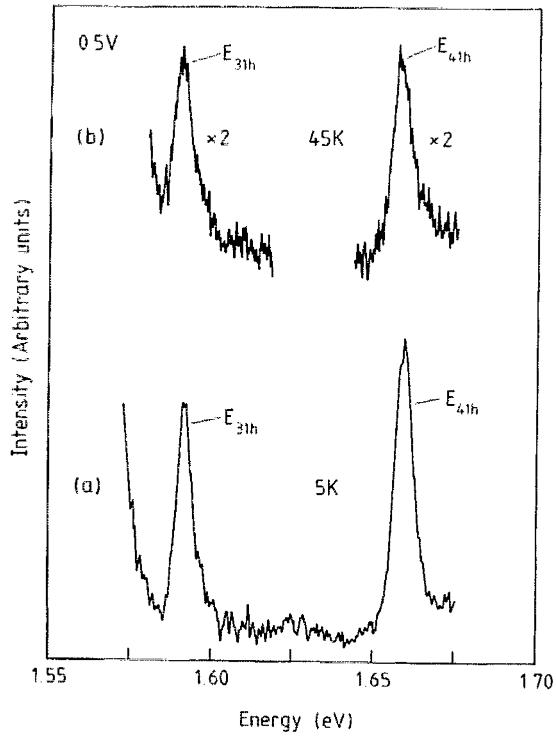

FIG. 2. (a) PL spectrum obtained at a bias of 0.5 V and a temperature of 5 K showing E_{31h} and E_{41h} recombination. (b) As (a), but at $T=45$ K.

tion, calculated to occur at 1.593 eV. The integrated intensity (I_3) of this peak is plotted versus bias in Fig. 1(b). At the onset of the E4 resonance ($V\sim 0.44$ V), a further PL peak is observed at 1.660 eV, due to E4-HH1 (E_{41h}) recombination (calculated to occur at 1.650 eV). The integrated intensity of the E_{41h} peak is plotted against bias in Fig. 1(c).

A representative PL spectrum in the 1.55–1.70 eV region, obtained at a bias of 0.5 V, is shown in Fig. 2(a). The I_4/I_3 ratio, which is subject to an experimental uncertainty of $\pm 15\%$, is plotted versus bias in Fig. 1(d). The population ratio of E4 and E3, n_4/n_3, is determined from I_4/I_3 using the relation

$$(\alpha/\beta)(I_4/I_3)=(n_4/n_3)(f_4/f_3), \tag{1}$$

where α $(=1.2\pm 0.1)$[5] accounts for the greater absorption of E_{41h} than E_{31h} PL in the GaAs top contact, β $(=1.6\pm 0.1)$ is the correction factor for the response of the spectrometer/detector system and f_4/f_3 is the ratio of the oscillator strengths for E_{41h} and E_{31h} transitions at the electric field of interest.

Equation (1) assumes that the entire electron distributions in both E3 and E4 are probed by HH1 holes. Assuming conservation of transverse wave vector, k_{xy}, this means that the maximum k_{xy} of the holes must be at least as large as the maximum k_{xy} of electrons in E3 and E4 if Eq. (1) is to be valid. We estimate a HH1 hole temperature of around 10 K, based on published cooling rates for holes in GaAs QWs[6] and a HH1 hole lifetime $\geqslant 10$ ns.[7] Using the Luttinger Hamiltonian to calculate the HH1 dispersion relation for our potential, we obtain a maximum k_{xy} of $\sim 7.5\times 10^5$ cm^{-1} for HH1 holes at 10 K. For an electron effective mass of 0.067 m_0, the above condition requires that E3 and E4 electrons relax to within about 3 meV of the bottom of their respective subbands. Any higher energy electrons may be detected in PL by raising the temperature of the sample in order to provide a thermal population of holes at increased k_{xy}. The presence of any high energy electron distributions would then lead to broadening of the E_{31h} and E_{41h} PL peaks. If different E3 and E4 distributions were probed, this would result in changes in the I_4/I_3 ratio as the temperature was raised. In order to check the validity of Eq. (1) we therefore studied PL at higher temperatures. The I_4/I_3 ratio at 0.5 V remained at a value of 1.5 ± 0.1 as the sample temperature was raised from 5 to 45 K (above 45 K the E_{31h} signal became difficult to resolve from the GaAs band-gap PL). A representative spectrum, taken at a bias of 0.5 V and $T=45$ K is shown in Fig. 2(b). At a lattice temperature of 45 K, the thermal distribution of holes (4 meV) will probe electron energies up to 12 meV from the subband minima. Since our experiments revealed no discernible broadening nor any changes in relative intensity of the PL peaks, we conclude that the 5 K measurements probe the entire E3 and E4 distributions, and that Eq. (1) is valid for the calculation of the n_4/n_3 ratio.

The oscillator strengths were calculated from solutions to the Schrödinger equation for the QW potential in the presence of an electric field. Since the states are not true bound states, but tunneling resonances, plane wave boundary conditions were used on the low energy side of the structure. Electric field values were obtained by comparing the bias dependence of the E_{11h} peak position with the calculated electric field dependence of the E_{11h} energy due to the quantum confined Stark effect.[8] In general, the oscillator strengths will depend on in-plane wave vector for $k_{xy}>0$.[9] However, we have calculated, using the HH1 dispersion relation for our potential, that there is little change in either f_3 or f_4 for k_{xy} up to about 4% of the Brillouin zone boundary wave vector. For instance, at a bias of 0.5 V the f_4/f_3 ratio at $k_{xy}=1.5\times 10^6$ cm^{-1} (the maximum wave vector probed by HH1 holes at 45 K) is calculated to be only 10% greater than the value at $k_{xy}=0$, For the range of k space probed by the 10 K hole population ($k_{xy}\leqslant 7.5\times 10^5$ cm^{-1}), the variations are even smaller, and are therefore ignored in our calculations.

The f_4/f_3 ratio was calculated in this way throughout the bias range of the E4 resonance, increasing from a value of 0.21 ± 0.04 at 0.44 V to 0.28 ± 0.05 at the peak of the resonance. The uncertainty in f_4/f_3 is due to estimated uncertainties in material parameters and in the determination of the electric field. Band bending due to charge buildup in the QW was ignored in the calculations of f_4/f_3. The majority of the charge buildup occurs in the E1 level, the E1 population being of the order of 10^4 times greater than those of the excited states. Inclusion of band bending arising from an electron density in E1 of 10^{11} cm^{-2} on resonance[10] leads to a decrease in the f_4/f_3 values (and a corresponding increase in n_4/n_3) of $\sim 20\%$.

The values of n_4/n_3 obtained from Eq. (1) are plotted in Fig. 1(e). It is apparent that $n_4>n_3$ throughout the bias range of the E4 resonance, suggesting that a population inversion is

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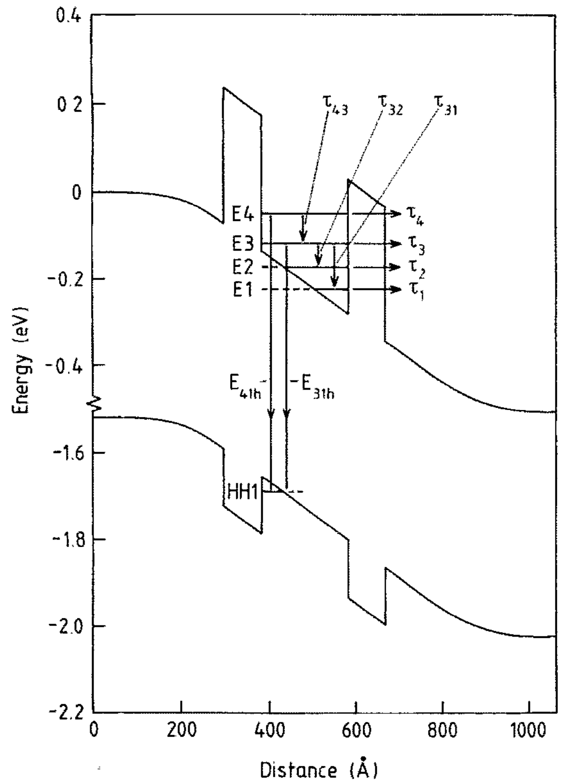

FIG. 3. Schematic band-edge diagram of the DBRTS at a bias of 0.5 V. The tunneling-out times (τ_1–τ_4) from the QW levels are indicated, as are the relevant intersubband scattering times, τ_{43}, τ_{32}, and τ_{31}.

obtained between E4 and E3 when electrons tunnel into E4. We now show that such a population inversion is consistent with a rate analysis of the populations of E3 and E4 when the structure is biased at the E4 resonance.

As indicated in Fig. 3, when electrons tunnel into E4 they can subsequently either tunnel directly out of the QW, or scatter down to lower QW levels before tunneling out. With the DBRTS biased at the E4 resonance, the E3 population obeys the following rate equation:[11]

$$\frac{dn_3}{dt}=\frac{n_4}{\tau_{43}}-\frac{n_3}{\tau_3}-\frac{n_3}{\tau_{32}}-\frac{n_3}{\tau_{31}}-\frac{n_3}{\tau_{R3}}, \tag{2}$$

where τ_{43}, τ_{32}, and τ_{31} are the scattering times from E4 to E3, E3 to E2, and from E3 to E1 respectively, τ_3 is the tunneling-out time from E3, and τ_{R3} is the characteristic time for recombination with HH1 holes. The intersubband scattering time for subband spacings greater than the LO phonon energy ($\hbar\omega_{\mathrm{LO}}=36$ meV) is ~0.5 ps,[12] whereas τ_3 is calculated to be ~250 ps at a bias of 0.5 V, and τ_{R3} will very likely be greater than 10 ns.[7] Thus, the tunneling-out and recombination terms may be neglected in comparison with the intersubband scattering terms in Eq. (2), to give, in the steady state

$$n_4/n_3=(\tau_{43}/\tau_{32})+(\tau_{43}/\tau_{31}). \tag{3}$$

LO phonon scattering of electrons between parallel, parabolic subbands separated by energy ΔE requires the participation of a phonon of wave vector $q\propto(\Delta E-\hbar\omega_{\mathrm{LO}})^{1/2}$. Since the strength of the Fröhlich interaction between electrons and LO phonons decreases with increasing q,[12] the scattering time is expected to increase with ΔE. Thus, τ_{43} ($\Delta E=67$ meV)$>\tau_{32}$($\Delta E=47$ meV) giving, from Eq. (3), $(n_4/n_3)>1$, consistent with the observed population inversion.[13] Using the model of Ref. 12 we have calculated values for the scattering times in Eq. (3), using appropriate form factors for the transitions involved, and obtain $n_4/n_3\sim2.3$, in good agreement with our measurements.

In conclusion, we have studied PL from the E3 and E4 excited states of the QW of a DBRTS under bias. Analysis of the PL has shown that the relative intensities of the $E_{3\mathrm{lh}}$ and $E_{4\mathrm{lh}}$ signals correspond to a higher population of electrons in E4 than in E3 when the structure is biased at the E4 resonance. We have shown that such a population inversion is consistent with the results of a rate analysis of the relative populations of E3 and E4 in this bias range.

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