Observation of charge storage and intersubband relaxation in resonant tunneling via a high sensitivity capacitive technique

E. F. Schubert, Federico Capasso, and A. L. Hutchinson
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

S. Sen
Department of Electronics Science, University College of Science, Calcutta 700 009, India

A. C. Gossard
Department of Materials Science and Engineering, University of California, Santa Barbara, California 93106

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In suitably designed resonant tunneling double barriers the capacitance-voltage curve exhibits well-defined features corresponding to the charging and discharging of the quantum well. From the bias dependence of the electron density in the well we find that in our thick parabolic wells, electrons tunneling into the excited states relax to the lowest subband and sequentially tunnel out. Our experiments allow us to obtain the charge density accumulated in the well and the tunneling escape rate of electrons out of the well.

In recent years there has been an increasing interest in resonant tunneling (RT) through double barriers.[1] Charge bulidup in the well plays a crucial role in determining the time evolution of RT and phenomena such as bistability.[2]

In the present work we have exploited a capacitive technique to directly measure the storage of electrons in the well during RT as a function of bias. These measurements yield important information on the dynamics of the tunneling process, on phenomena such as scattering and energy relaxation in the well and, coupled with current density data, allow us to evaluate tunneling escape rates. Recently the bistability of RT structures was investigated by magnetocapacitance measurements.[3] The authors used magnetoquantum oscillations in the differential capacitance to investigate space-charge buildup in the well.[3]

The double-barrier structures with a parabolically shaped well were grown in a Varian Gen. II system on Si-doped n^+- substrates. The epitaxial layer sequence consists of an n^+-GaAs buffer layer (5000 Å, 1×10^{18} cm^{-3}), a 30-Å-thick AlAs layer, the parabolic well, again a 30-Å-thick AlAs layer and finally a Si-doped GaAs top layer (4000 Å, 1×10^{18} cm^{-3}). The AlAs barriers and the parabolic well are undoped. The parabolic well is 380 Å wide and is realized by gradually changing the alloy composition from $x = 30\%$ adjacent to the bottom AlAs barrier to $x = 0\%$ in the center of the well again to $x = 30\%$ adjacent to the top AlAs barrier. The band diagram of the RT structure is shown in Fig. 1(a). The grading was achieved by chopping the molecular beams of $Al_{0.30}Ga_{0.70}As$ and GaAs with a chop period of 15 Å to obtain the desired alloy composition ranging between $0\leqslant x\leqslant30\%$, as described by Sen *et al.*[4] Mesas of $\phi = 75$ μm are photolithographically defined on the samples. Capacitance-voltage (*C-V*)(f= 10 MHz) and current-voltage (*I-V*) measurements are performed with Hewlett–Packard parameter analyzer 4145B and the Impedance/Gain-Phase analyzer 4194A. The samples are immersed into liquid He at 4.2 K.

I-V characteristic of the parabolic well structure is shown in Fig. 1(b). The figure reveals four resonances in the bias range 0–0.5 V. The substrate contact is positively biased with respect to the epitaxial layer contact, i.e., the charge carriers flow from the top epitaxial layer through the double barrier to the substrate. The lowest resonance, i.e., for tunneling of electrons into the ground state of the parabolic well is referred to as the $n = 0$ resonance. The resonances occur at biases of 40 mV ($n = 0$), 140 mV ($n = 1$), 270 mV ($n = 2$), and 440 mV ($n = 3$). The separation increases from 100 mV (between $n = 0$ and $n = 1$) to 130 mV and to 170 mV (between the $n = 2$ and $n = 3$). Naively, a constant spacing is expected between the resonances due to the harmonical nature of the states in a parabolic quantum well. However, an increase in separation can be understood on the basis of the AlAs barriers, which further increase the energy of states with increasing quantum number.[4] The series resistance of 80 Ω (see below) is too small to explain the increasing voltage spacing between resonances.

The *C-V* curve at 4.2 K of a RT structure with a parabolic well is shown in Fig. 2(a). The capacitance has a

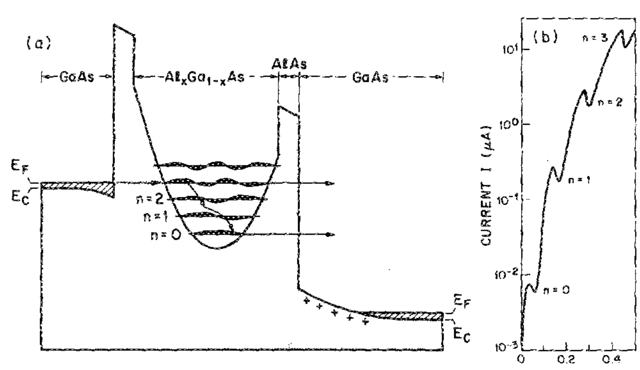

FIG. 1. (a) Schematic illustration of the conduction-band diagram of a resonant tunneling structure with a parabolic well. The two tunneling processes, elastic (energy conserved) and inelastic (electron undergoes energy relaxation in the well), are indicated by arrows. (b) Current-voltage characteristic of an $Al_xGa_{1-x}As$/GaAs parabolic well resonant tunneling structure at $T = 4.2$ K. Four resonances, $n = 0$ to $n = 3$, are observed.

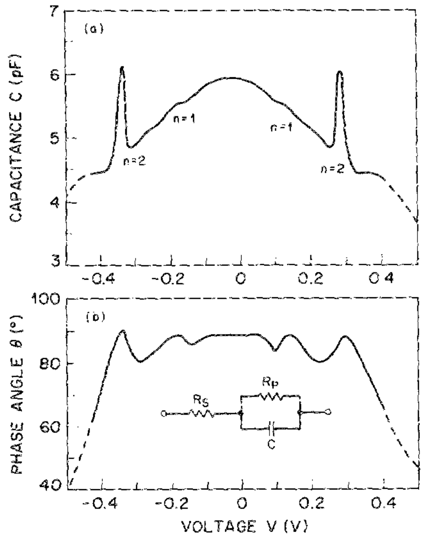

FIG. 2. (a) Capacitance-voltage characteristic of a resonant tunneling structure with parabolic well at $T = 4.2$ K. A shoulder and a peak are observed at the $n = 1$ and $n = 2$ resonance, respectively. (b) Phase angle between current and voltage measured at a frequency of 10 MHz.

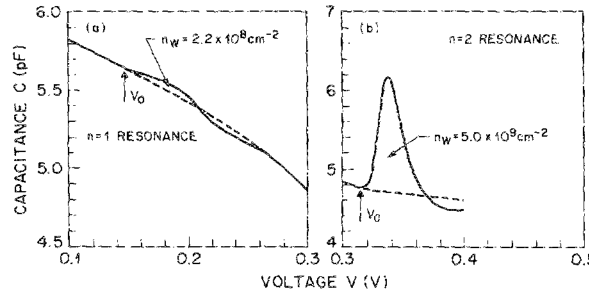

FIG. 3. Capacitance-voltage curve at 4.2 K in the vicinity of the (a) $n = 1$ and (b) $n = 2$ resonance. The maximum charge densities are 2.2×10^8 cm^{-2} and 5.0×10^9 cm^{-2} for the $n = 1$ and $n = 2$ resonance, respectively.

clear structure at voltages which correspond to the $n = 1$ and $n = 2$ resonance. Especially at the $n = 2$ resonance a strong peak in the capacitance is observed. It is a result of charge pile-up in the well during RT. This accumulation is maximum at the peaks of the I-V characteristic.

The phase angle between current and voltage is shown in Fig. 2(b). The inset shows the equivalent circuit model of a RT structure.[5] The series resistance R_s is obtained from impedance measurements for 100 Hz $\leqslant f \leqslant$ 15 MHz. R_s [see Fig. 2(b)] is then obtained from the best fit between measured and calculated impedance. The series resistance R_s is determined to be 80 Ω. Near the peak of the I-V characteristic the magnitude of the (parallel) double-barrier dynamic resistance, R_p, $[\equiv (dI/dV)^{-1}]$, is relatively small. In order to measure the parallel capacitance C the total impedance of the structure must be determined by the capacitor, i.e., $R_s \ll R_p$ and $R_p \gg (\omega C_p)^{-1}$, i.e., the phase angle must be close to 90°. As an example, we evaluate the differential resistance at the $n = 1$ and $n = 2$ peak and obtain $R_p = 150$ kΩ and 20 kΩ, respectively. With $C = 6$ pF and $f = 10$ MHz we obtain a reactance of 2600 Ω. With $R_s = 80$ Ω the above inequalities are satisfied.[6] Furthermore, the phase angle of $\cong 90°$ obtained for small voltages demonstrates that the leakage current is small.

The capacitance of a system is defined as $C = dQ/dV$, where Q is the charge and V is the voltage applied to the system. The charge of a resonant tunneling structure is given by either the positive donor charge at the anode side or the negative accumulation charge at the cathode side plus the negative charge in the well (see Fig. 1 for illustration). The total capacitance is then given by $C_t = \Sigma dQ/dV$, where $\Sigma\, dQ$ is the sum of the accumulation layer charge and the charge in the well. For small charge densities in the well (as compared to the accumulation charge) the total capacitance per unit area can be written as

$$C_t = \frac{dQ_{ac}}{dV} + \frac{dQ_{QW}}{dV} \cong C_{ac}(V) + \Delta C(V), \qquad (1)$$

where Q_{ac} and Q_{QW} is the charge per unit area in the accumulation layer and the quantum well, respectively. The equation indicates that any small deviation of the capacitance, $\Delta C(V)$, from the capacitance $C_{ac}(V)$, can be attributed to the charge in the well. The capacitance $C_{ac}(V)$ is the capacitance of the structure in the absence of any charge storage in the well. Charge accumulation effects in the well are observable in the capacitance curves when the bias exceeds V_0 (see Fig. 3). The additional charge accumulated in the well as the bias is increased from V_0 to V can be obtained from Eq. (1):

$$n_w(V) - n_w(V_0) = \frac{1}{e} \int_{V_0}^{V} \Delta C dV. \qquad (2)$$

At the bias V_0 the charge in the well is relatively small as compared to the charge in the well at the resonance peak. Note that the disparity of the charge in the well off resonance and on resonance is indicated by the large change between the current at $V = V_0$ and the peak current. The relative error in determing the charge according to Eq. (2) is estimated to be a factor of $\leqslant 2$ and is determined by the charge in the well at V_0, i.e., $n_w(V_0)$. We estimate the sensitivity of the technique to be in the 10^8 cm^{-2} range. In the following we assume $n_w(V_0)$ to be zero.

The measured C-V curve of the resonant tunneling structure in the vicinity of the $n = 1$ resonances is shown in Fig. 3(a). The maximum charge denity as determined from Eq. (2) is $n_w = 2.2 \times 10^8$ cm^{-2}.

As the voltage increases further (> 0.2 V) the capacitance drops rapidly, indicating a decrease of the charge density in the parabolic well. The capacitance excursions are quite symmetric with respect to the base-line capacitance $[\simeq C_{ac}(V)]$ shown as a dashed line in Fig. 3(a).

The C-Vcharacteristic in the vicinity of the $n = 2$ resonance is shown in Fig. 3(b). A clearly developed capacitance peak is observed at the resonance. The maximum carrier density in the well is obtained as $n_w = 5.0 \times 10^9$ cm^{-2}. The charge density is approximately a factor of 20 larger than in the case of the $n = 1$ resonance.

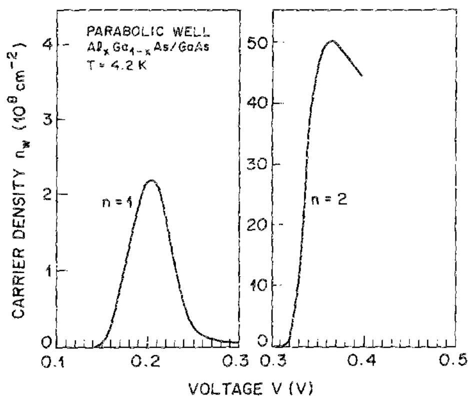

FIG. 4. Evolution of the charge density in the well with voltage for the $n = 1$ and $n = 2$ resonance.

The evolution of the carrier density with applied voltage is shown in Fig. 4 for the $n = 1$ and the $n = 2$ resonance. For the $n = 1$ resonance, the well is emptied for voltages higher than the resonance voltage. The charge density does not approach zero for the $n = 2$ resonance. This residual charge in the well is necessitated by the continuing large current density for voltages higher than the $n = 2$ resonance.

The tunneling process manifests itself macroscopically as a current through the structure. Through a simple rate equation argument the steady-state RT current can be written as

$$j = en_w/\tau, \tag{3}$$

where n_w is the sheet carrier density in the well and $1/\tau$ the electron tunneling rate out of the well. The latter can be well approximated by[7]

$$1/\tau = (E_n/h) T_n, \tag{4}$$

where E_n is the energy of the bottom of the nth subband and T_n is the tunneling probability through the exit barrier for an electron in the nth subband.

The large difference between the stored charge densities at the two resonances ($n_2/n_1 \sim 20$) provides direct information on the nature of the tunneling process. Let us recall that when the width of the incident electron distribution (i.e., the quasi-Fermi energy in the emitter) is much wider than the resonance widths the current density is not determined by the overall resonant transmission but by the emitter barrier transmission (i.e., the barrier with the smaller transmission probability), as shown by Weil and Vinter.[8] Thus if the tunneling process through the double barrier does not involve a change of the carrier energy, the tunneling current would increase exponentially with energy, while the lifetimes would exponentially decrease. The product $n_w = j\tau$ would therefore remain nearly constant, *independent of the quantum number n*. This is in direct contrast with our experiments which give unambiguously $n_2 \gg n_1$. These data must imply therefore that electrons tunnel inelastically through the double barrier.

More information on the energy relaxation process in the well and on the tunneling dynamics can be obtained by combining the current density data with the measurements of n_w. The mean lifetime in the well τ can be determined from the measured current density j and charge density n_w in the well, using Eq. (4). A striking result of this estimation is that the mean lifetime is approximately constant, independent of the quantum number n. In fact from the peak j and n_w of the $n = 1$ and $n = 2$ resonances ($j_1 = 5.7 \times 10^{-3}$ A/cm^2, $j_2 = 6.8 \times 10^{-2}$ A/cm^2, $n_{w,1} = 2.2 \times 10^8$ cm^{-2} and $n_{w,2} = 5.0 \times 10^9$ cm^{-2}) one obtains $\tau_1 = 6.2$ ns and $\tau_2 = 11.8$ ns. The two times τ_1 and τ_2 agree within a factor of 2. This discrepancy is not significant and is expected considering the uncertainty [$\simeq n_w(V_0)$] in the determination of the charge densities. This result demonstrates that the escape rate is independent of the electron energy and represents strong evidence that the electrons tunnel out from the lowest subband after undergoing scattering and energy relaxation in the well [Fig. 1(a)]. This is simply understood by noting that the scattering rate τ_{ph}^{-1} ($\sim 10^{13}$ s^{-1}) by emission of optical phonons (absorption is negligible at the temperatures of our experiments) is orders of magnitude greater than $1/\tau_1$, $1/\tau_2$.

It is interesting to note that the tunneling escape time τ_0 out of the ground-state subband, calculated from Eq. (4), is an order of magnitude larger than the experimental τ's. This discrepancy can be understood in terms of the unavoidable interface roughness present in layers grown by molecular beam epitaxy, as recently shown by Leo and MacDonald.[9]

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