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LETTER TO THE EDITOR

Observation of space-charge build-up and thermalisation in an asymmetric double-barrier resonant tunnelling structure

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Abstract. By means of a study of magnetoquantum oscillations in the differential capacitance, we have observed the thermalisation of the space charge stored dynamically in the quantum well of an asymmetric double-barrier resonant tunnelling heterostructure based on n-GaAs/(AlGa)As. Fourier analysis of the oscillations was used to monitor the charge build-up in both the emitter accumulation layer and in the well. The storage time of an electron in the well was found to be $\simeq 0.5\ \mu s$. The resonant tunnelling is truly sequential rather than coherent.

The occurrence of intrinsic bistability in the current—voltage characteristics of asymmetric double-barrier structures (DBSs) based on n-type GaAs/(AlGa)As has recently been reported [1, 2]. Intrinsic bistability arises from an electrostatic feedback effect associated with the build-up of electronic charge in the quantum well between the barriers when resonant tunnelling occurs. Although intrinsic bistability is well founded theoretically [3, 4], earlier reports of its observation proved controversial [5–7]. Our structure [1] was prepared with barriers of different thicknesses. A large build-up of charge in the well is expected at resonance when electrons are injected through the thinner (emitter) barrier and are inhibited from tunnelling out due to the lower transmission coefficient of the thicker (collector) barrier. In this letter we report how studies of magneto-oscillations in the differential capacitance can be used to monitor both the space-charge build-up in the quantum well and in the accumulation layer of the emitter contact. In contrast to previous studies of magnetoquantum oscillations in symmetric DBSs [8, 9], we find that the quasi-Fermi level of the electrons stored in the well lies significantly below the Fermi level of the electrons in the emitter accumulation layer. We attribute this to energy relaxation of the stored charge distribution which will occur if the electron storage time in the quantum well is sufficiently long. Estimates of this storage time obtained experimentally and theoretically are consistent with this hypothesis. The resonant tunnelling process in our asymmetric DBS is thus truly sequential [10] rather than coherent.

Our asymmetric structure consisted of the following layers in order of growth from the n^+-GaAs substrate: (i) $2\ \mu m$ GaAs, doped to $2 \times 10^{18}\ cm^{-3}$, (ii) 50 nm GaAs, $10^{17}\ cm^{-3}$, (iii) 50 nm GaAs, $10^{16}\ cm^{-3}$, (iv) 3.3 nm GaAs, undoped, (v) 8.3 nm $Al_{0.4}Ga_{0.6}As$, undoped (thin barrier), (vi) 5.8 nm GaAs, undoped (well), (vii) 11.1 nm

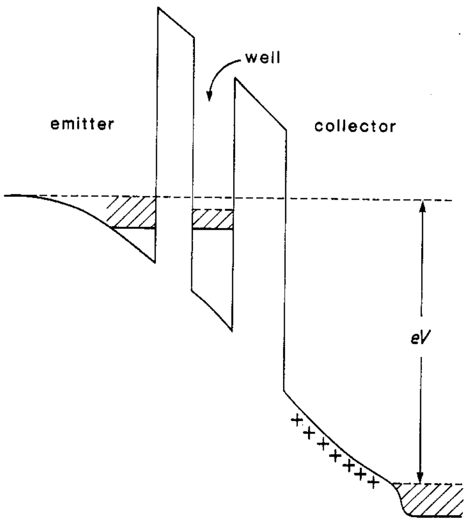

Figure 1. Conduction-band profile under applied voltage V showing bound-state levels (full lines) in emitter and well and quasi-Fermi levels (broken lines).

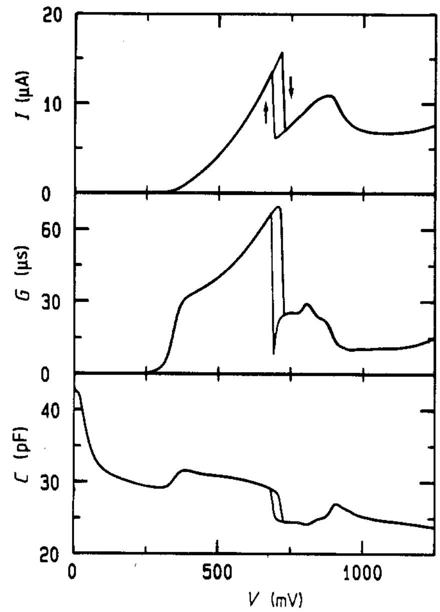

Figure 2. Voltage dependence of DC current I, AC capacitance C, and parallel conductance G measured at 1 MHz and 4 K.

$Al_{0.4}Ga_{0.6}As$, undoped (thick barrier), (viii) 3.3 nm GaAs, undoped, (ix) 50 nm GaAs, 10^{16} cm^{-3}, (x) 50 nm GaAs, 10^{17} cm^{-3}, (xi) 0.5 μm GaAs, 2×10^{18} cm^{-3}, top contact. The layers were processed into mesas of diameter 200 μm. The conduction-band profile with the top contact biased positively is shown in figure 1. In the lightly doped layer of the emitter contact, a bound state is formed in the accumulation region adjacent to the barrier and, at liquid helium temperatures, the associated two-dimensional electron gas (2DEG) is degenerate. The accumulation potential may be modelled satisfactorily using a variational solution [11] for the bound-state wave function. At a bias of 330 mV, the electric field in the emitter barrier is 29 kV cm^{-1} and the width of the accumulation region is $\simeq$14 nm. In the remainder of this layer ($\simeq$36 nm) the Fermi level is close to the conduction-band edge since the doping density (10^{16} cm^{-3}) is close to the Mott metal–insulator transition. However, this does not give rise to an important series resistance, as is also shown by previous studies [12] of similarly doped single-barrier structures.

The current–voltage characteristic for our asymmetric DBS at 4 K is given in figure 2. This shows clearly the threshold for resonant tunnelling at V_{th} = 330 mV, the turn-off at V_p = 725 mV where the current peaks, and the region of intrinsic bistability. In the sequential theory [10, 4], resonant tunnelling is regarded as two successive transitions from the emitter into the well and then from the well into the collector contact. The transverse components of momentum and hence transverse kinetic energy are conserved in the tunnelling process. Total energy is also conserved so resonant tunnelling occurs when the energies of the bound states in the accumulation layer and quantum well essentially coincide. However, because of finite level widths, the tunnelling rate from emitter into well will be a sharply peaked resonant function of the voltage drop across the emitter barrier. The observed resonant tunnelling range V_{th} to V_p corresponds to climbing up this resonance peak. It is the screening effect of the charge build-up in the quantum well (electrostatic feedback) that is responsible for the extended voltage range over which resonant tunnelling is observed in the $I(V)$ curve and the appearance of current bistability [4]. When the applied voltage is increased, only a very small voltage change across the emitter barrier is needed to charge up the well and, due to the screening effect of this charge, almost all the extra voltage drop occurs across the collector barrier and depletion layer. When biased in the opposite direction, a very sharp maximum in the $I(V)$ curve is observed [1] since in this case (thin collector barrier) there is little charge build-up and electrostatic feedback is negligible. The bistability does not then appear.

Conservation of transverse kinetic energy in resonant tunnelling requires the Fermi levels in the accumulation layer and quantum well to coincide. But the theory of resonant tunnelling [4] shows that the states of transverse motion in the well are only partially occupied, since the occupancy is determined dynamically by the balance between the transition rates into and out of the well. However, if the energy relaxation time is much less than the charge storage time in the well, the electron distribution will be able to thermalise to the lattice temperature and establish a well-defined quasi-Fermi level below that in the emitter contact. This is the situation illustrated in figure 1. The Fermi energy of a thermalised 2DEG in the quantum well is less than the Fermi energy of the 2DEG in the accumulation layer since the bound-state levels essentially coincide during resonant tunnelling.

We have investigated this possibility by studying magneto-oscillations in the capacitance of the structure for a magnetic field $\boldsymbol{B}$ applied perpendicular to the plane of the barrier interfaces. In this geometry, the states of transverse motion of a degenerate 2DEG (in emitter or well) are quantised into Landau levels. Theoretically, oscillations with a definite period $\Delta(1/B)$ in $1/B$ arise from a modulation of the charge when Landau levels pass through the quasi-Fermi level. This charge modulation affects the distribution of electric potential and screening lengths, and hence modulates the capacitance of the device. The frequency of the oscillations, $B_f = (\Delta(1/B))^{-1}$, is thus related to the Fermi energy E_F by $B_f = m^* E_F / e\hbar$, where m^* is the effective mass. For fully, as opposed to partially, occupied states $E_F = \hbar^2 \pi n / m^*$, where n is the areal electron density. This gives

$$n = 2eB_f/h. \tag{1}$$

The voltage dependence of the differential capacitance C and parallel conductance $G = 1/R$ are also plotted in figure 2. The differential parameters were measured at 1 MHz with a modulation of 3 mV using a Hewlett–Packard 4275A *LCR* meter in the mode that analyses the impedance of a device as a capacitor C and parallel resistor R. Between 10 kHz and 2 MHz, these parameters are also independent of measurement frequency. Figure 3 shows typical oscillatory structure in the variation of capacitance with magnetic field. Similar oscillations are also observed in the current I and conductance G, but are less well defined. However, the capacitance measurements have higher sensitivity when the tunnel current is low. To reveal more clearly multi-periodic behaviour we have Fourier analysed the experimental capacitance traces. The distributions of magneto-oscillation frequencies B_f thus obtained are shown in figure 4 for different applied voltages.

Below the threshold voltage V_{th}, there is a single peak in the magneto-oscillation spectrum. This peak is clearly associated with the 2DEG in the emitter accumulation layer, since the corresponding areal density n_a, obtained from equation (1), increases

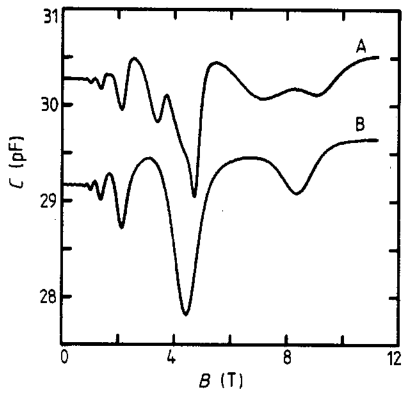

Figure 3. Magneto-oscillations in differential capacitance C versus magnetic field B for applied voltages of (curve A) 600 mV and (curve B) 300 mV.

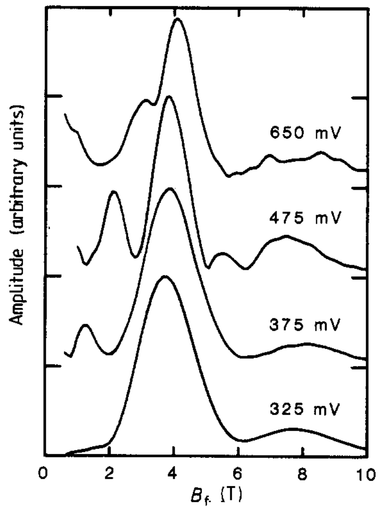

Figure 4. Amplitude of frequency distribution versus magneto-oscillation frequency B_f for different applied voltages.

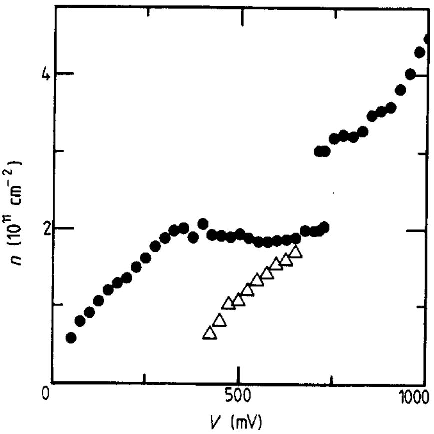

Figure 5. Areal density n versus voltage V for charge in emitter n_a (full circles), and well n_w (triangles).

steadily with voltage up to V_{th} as shown in figure 5. Moreover, the static capacitance values, given by the ratio of total accumulation charge to applied voltage, are in good agreement with the AC values shown in figure 2 and are consistent with our theoretical modelling of the potential distribution across the heterostructure. We have also investigated the magneto-oscillations when the magnetic field is tilted at an angle θ to the normal to the layers. Up to $\theta = 40°$, the form of the oscillations as a function of $B \cos \theta$ is largely unchanged. This confirms the two-dimensional nature of the electrons in the emitter accumulation layer.

Between V_{th} and V_p, this magneto-oscillation frequency is independent of voltage (figure 4), and, within experimental error, the accumulation density n_a remains constant at $2 \times 10^{11}\ \mathrm{cm}^{-2}$. Hence the electric field and voltage drop across the emitter barrier remain virtually unchanged in this range, which is consistent with our model of resonant tunnelling between bound states in the emitter and quantum well. Also in the resonant tunnelling region, a second, weaker peak appears in the magneto-oscillation spectrum (figure 4). The frequency of this peak gives an areal density n_w, from equation (1), which increases throughout this range and approaches n_a at the voltage V_p for maximum current (figure 5). We attribute this peak to a thermalised degenerate charge distribution stored in the quantum well. The equality of n_a and n_w at $V = V_p$ is to be expected theoretically since the peak transition rate into the well is much greater than the decay rate out of the well through the collector barrier. The dynamically determined occupancy of the states in the well is then close to unity and energy relaxation has little effect on the electron distribution.

This thermalisation is confirmed by comparing the lifetime τ_c of the electrons in the well with the energy relaxation rate. The lifetime τ_c is limited by tunnelling through the collector barrier and is related to the current density by $J = n_w e/\tau_c$ [4]. At the resonance peak ($J \simeq 0.06\ \mathrm{A\ cm^{-2}}$, $n_w \simeq 2 \times 10^{11}\ \mathrm{cm}^{-2}$) this gives $\tau_c \simeq 0.6\ \mu\mathrm{s}$. The energy relaxation must be via spontaneous emission of acoustic phonons since the temperature is low (4 K) and the electron kinetic energies ($E_F \simeq 7$ meV) are too small for optic-phonon processes. An estimate of the emission rate τ^{-1} from the deformation potential gives $\tau_{ph} \simeq 10^{-9}$ s for a well width of 5.8 nm. This is indeed much shorter than τ_c. We note that electron–electron scattering is not important here since the phonon emission rate is sufficiently large to thermalise the electron distribution to the lattice temperature within the available time τ_c.

When V increases above V_p a transition occurs in which charge is expelled from the well with a consequent redistribution of potential and resonant tunnelling can no longer occur. This results in a step-wise increase in the accumulation layer density to $n_a \simeq 3 \times 10^{11}\ \mathrm{cm}^{-2}$, as shown in figure 5. For $V > V_p$ only a single magneto-oscillation period is observed. The different charge states of the device on the high- and low-current parts of the hysteresis loop are also clearly shown by the different magneto-oscillation frequencies observed. In the opposite bias direction, only one series of magneto-oscillations, due to the emitter accumulation layer, is observed. The corresponding sheet density increases smoothly with voltage showing that, in this case, there is little charge build-up in the well [1]. We note here that the broad maximum in $I(V)$ above the current bistability is due to inelastic tunnelling processes which have been previously observed and discussed elsewhere [13].

The principal features of the $C(V)$ curve of figure 2 can also be understood in terms of our model. We may regard the DBS as two parallel plate capacitors C_1 (emitter barrier and accumulation layer) and C_2 (collector barrier and depletion layer) connected in series. The charge on the common central plate corresponds to the charge stored in the quantum well. The steep fall in capacitance at low voltages is due to the rapid increase in depletion length in the lightly doped ($10^{16}\ \mathrm{cm}^{-3}$) collector layer, which decreases C_2. The slower decrease for $V > 50$ mV is due to the less rapid rate of depletion of the layer doped to $10^{17}\ \mathrm{cm}^{-3}$. However, the most notable features are the sharp increase in capacitance at V_{th} and subsequent fall at V_p. When the bound states of the accumulation layer and quantum well are on resonance, the voltage drop across C_1 is essentially constant. An increase in applied voltage therefore appears almost entirely across C_2. The measured differential capacitance is thus $C \simeq C_2$ in the resonant tunnelling region, whereas off-resonance $C = C_1C_2/(C_1 + C_2) < C_2$.

This quasi-static argument is not obviously applicable at 1 MHz, where the measurements of differential capacitance were made. In a small-signal analysis [14] based on the sequential theory of resonant tunnelling, C_1 and C_2 have parallel resistors R_1 and R_2 respectively. R_1 allows electrons tunnelling from the emitter to charge the quantum well, whilst R_2 allows the stored charge to leak through the collector barrier. Our previous argument is equivalent to the assumption that, during resonant tunnelling, R_1 becomes very small and effectively short-circuits C_1, with the consequence that the measured capacitance $C \simeq C_2$. By identifying the time constant R_2C_2 with the storage time τ_c we have $\tau_c = R_2C_2 \simeq RC$ during resonance. The values shown in figure 2 give $\tau_c \simeq 0.4\ \mu s$ at V_p, which is consistent with our previous estimate from the DC current and charge. An approximate theoretical estimate of τ_c can be made by calculating the attempt rate (obtained from the energy of the bound state above the bottom of the well $\simeq$ 68 meV) and the transmission coefficient of a rectangular barrier (conduction-band offset $\simeq$ 320 meV). This gives $\tau_c \simeq 1\ \mu s$. Under bias, a smaller value is expected since the average collector-barrier height is then decreased. Measurements of the tunnelling escape time from the quantum well of a DBS have also been made by studying the temporal decay of photoluminescence [15]. However, the optical determination of τ_c is limited to thin-barrier structures for which τ_c is less than the radiative recombination time, $\tau_r \simeq 0.5$ ns. In our asymmetric structure, it is the thick collector barrier that gives rise to the long τ_c.

In conclusion, we have observed the build-up of a thermalised charge distribution in the quantum well of a suitably asymmetric DBS. The storage time of an electron in the well was found to be $\simeq 0.5\ \mu s$, which is considerably longer than the energy relaxation time. The tunnelling process is thus truly sequential.

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In this paper the bias direction for occurrence of intrinsic bistability was referred to as reverse bias. *See also*

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