Field-induced resonant tunneling between parallel two-dimensional electron systems

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Resonant tunneling between two high-mobility two-dimensional (2D) electron systems in a double quantum well structure has been induced by the action of an external Schottky gate field. Using one 2D electron gas as source and the other as drain, the tunnel conductance between them shows a strong resonance when the gate field aligns the ground subband edges of the two quantum wells.

Resonant tunneling (RT) has by now been observed in a wide variety of semiconductor systems.[1] The commonest configuration, the so-called double-barrier structure, typically consists of a single GaAs quantum well sandwiched between two AlGaAs barriers. Above and below the barriers are heavily doped GaAs regions serving as source and drain. Application of a dc bias voltage can induce RT via the energy levels within the quantum well. In this case the tunneling is between two three-dimensional (3D) conductors with a two-dimensional (2D) system providing an intermediate state.

In the present work resonant tunneling between two-dimensional electron gases (2DEGs) confined in quantum wells separated by a thin barrier layer[2] is investigated. Unlike 3D-2D tunneling, in this 2D-2D case conservation of in-plane momentum allows tunneling only when the quantum well subbands are closely aligned.[3] By establishing independent electrical connection[4] to the individual 2DEGs, the tunnel conductance between them can be directly measured. An important aspect here is the ability to resonantly control the tunneling by application of an external gate electric field. This allows a sweep of the subbands past one another.

The samples employed are modulation-doped double quantum well (DQW) structures. Two 140-Å-wide GaAs wells separated by an undoped 70 Å AlAs barrier[5] are embedded in the alloy $Al_{0.3}Ga_{0.7}As$. Doping[6] with Si δ layers 700 Å above and 900 Å below the DQW populates the ground subband of each quantum well with a 2DEG of nominal density 1.5×10^{11} cm^{-2} and mobility 8×10^{5} cm^2/V s. These parameters are determined by conventional magnetotransport on the individual 2DEGs.

Electrical connection to the individual 2DEGs is accomplished using a selective depletion scheme.[4] Diffused In contacts are made at the ends of a photolithographically defined mesa, as schematically depicted in the inset to Fig. 1. These contacts simultaneously connect to both 2DEGs. For each In contact a pair of Al Schottky gates is evaporated on the top and bottom of the sample. (The entire 5×5 mm sample is first thinned to ~55 μm by chemically removing most of the substrate.) For illustrative purposes, only one member of each pair is shown in the figure, the top gate on arm 1 and the bottom gate on arm 2. An appropriate negative bias voltage applied to one of the top gates (relative to the associated In contact) can deplete the top 2DEG without materially affecting the bottom 2DEG. Similarly, a back gate can be used to locally deplete the bottom 2DEG while not affecting the top 2DEG. Thus, either of the In contacts can be made to connect the central mesa region through either one, or both, of the 2D channels.

Two additional gates are deposited. On top of the sample a 50-μm-wide gate is applied across the equally wide central bar of the mesa. This gate is referred to as the "tunnel gate". Biasing this gate not only alters the upper 2DEG density, but also changes the relative alignment of the subband edges in the two quantum wells. In addition, a much larger back-side gate is deposited underneath most of the central region of the mesa.

Figure 1 displays two measurements of the conductance $G_{1,2}$ between contacts 1 and 2 as a function of bias V_t on the tunnel gate. In the upper trace all other gates are unbiased, yielding the "parallel" configuration common to

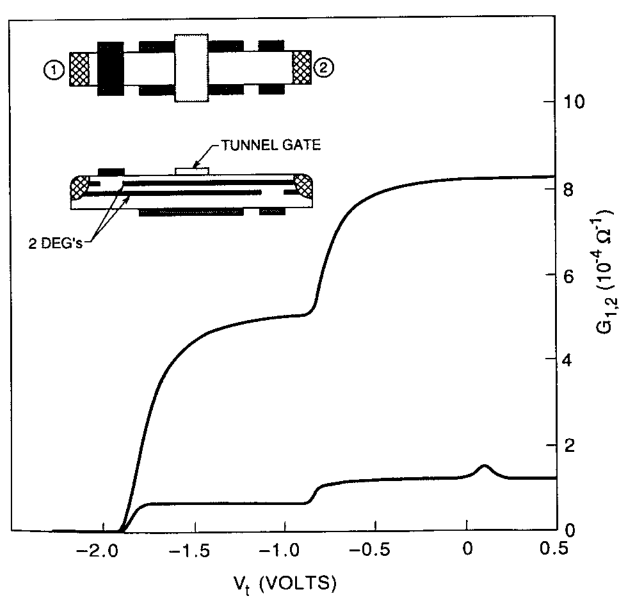

FIG. 1. Upper inset: A schematic view of the mesa layout and an idealized cross section through the DQW. The mesa (open), gates (shaded), and contacts (cross-hatched) are shown. The cross section depicts the "tunnel" configuration. Bottom gate on arm 1 and top gate on arm 2 are omitted for clarity. Data: Conductance $G_{1,2}$ vs tunnel gate bias V_t at 1.5 K. Upper trace taken in "parallel" configuration, lower trace obtained in "tunnel" configuration. Note resonant feature near $V_t = 0.1$ V.

most transport studies on multilayer 2D electron systems. The conductance is measured at 1.5 K using 0.1 mV, 27 Hz excitation. (Reducing the temperature or the drive level further has no effect on any of the results to be discussed.) Note the two-step structure. For $0 < -V_t < 0.9$ V both 2DEGs are conducting between contacts 1 and 2. As $-V_t$ exceeds ~0.9 V, the upper well under the tunnel gate depletes. As long as $-V_t < 1.9$ V, the current is flowing almost entirely through the lower well. (Due to tunneling however, a small current will also be present in the upper well.) For $-V_t > 1.9$ V both 2DEGs are severed and $G_{1,2} = 0$.

For the lower trace in Fig. 1 the top gate on arm 1 and the bottom gate on arm 2 are biased to deplete the upper and lower quantum wells, respectively. With these gate biases, contact 1 connects to the central region of the mesa via the lower 2DEG and contact 2 via the upper 2DEG. In this "tunnel configuration", shown in the inset to Fig. 1, the observed conductance $G_{1,2}$ is dominated by the tunneling resistance between the quantum wells in the central region of the mesa. As the data in Fig. 1 reveal, the basic two-step dependence on V_t is still observed. This is because tunneling occurs both "downstream" and "upstream" of the tunnel gate. Depleting the upper 2DEG ($-V_t$~0.9 V) removes the upstream part, and the conductance is roughly halved. As expected, the overall magnitude of the conductance is considerably less than that obtained in the parallel configuration. Most important however, is the small bump in the data near $V_t = 0.1$ V. This feature represents field-induced resonant tunneling between the 2DEGs under the tunnel gate.

To further examine the resonant feature near $V_t = 0.1$ V, an additional electric field is applied using the large back-side gate. This has two primary effects. First, it will shift the position of the resonance to a different V_t value. As discussed below, the condition for RT is aligned subband edges in the two quantum wells. In this quasi-equilibrium measurement this is equivalent to equal densities[7] for the 2DEGs. A back-side bias voltage V_b will change the density n_b of the bottom 2DEG and RT will occur only when the top 2DEG density is made equal to it. Secondly, a back-side bias will change the amount of "background" tunneling throughout the backgated region. Depending on the difference in the 2DEG densities at $V_b = 0$, the background tunneling can initially either increase or decrease. At large enough $|V_b|$ however, the tunneling rate will decrease since the 2DEG densities will become unequal, i.e., there will be substantial band bending and the subband edges will not match. Since the tunnel gate can be used to *locally* restore subband alignment, the peak-to-valley ratio of the field-induced RT can be enhanced.

Figure 2(a) displays a series of $G_{1,2}$ vs V_t characteristics for different biases V_b applied to the back-side gate. Both effects just discussed are observed. The RT peak position moves in linear proportional to V_b. For positive V_b the background immediately begins to fall. As V_b goes negative from zero the background first rises, but then falls as $-V_b$ increases further. This behavior is consistent with

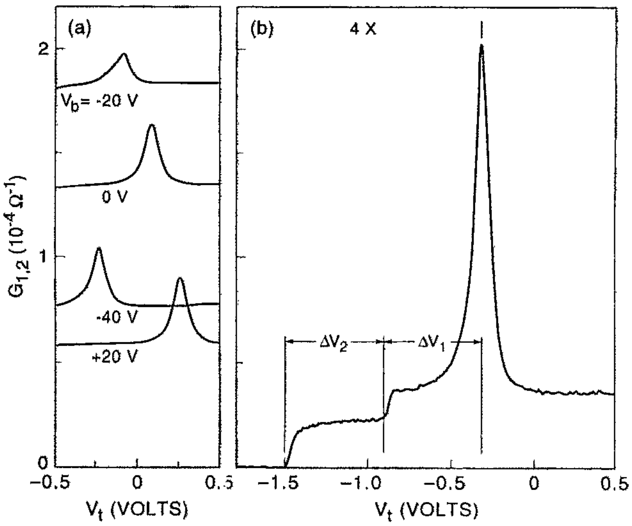

FIG. 2. (a) Conductance $G_{1,2}$ vs V_t in region around RT peak for various bias voltages V_b applied to the large back gate. (b) Optimized RT peak, $V_b = -50$ V. Back gate on arm 1 biased to -60 V to further suppress background tunneling. Vertical axis magnified four times.

the fact that the RT peak for $V_b = 0$ occurs at $V_t > 0$, i.e., at $V_b = 0$ the lower 2DEG has slightly higher density than the upper 2DEG.

Further enhancement of the RT peak can be obtained by biasing the otherwise unused back gate on arm 1. The fringing field from this gate helps to suppress background tunneling in the uncovered area between this gate and the large back gate. (This gate, omitted from Fig. 1, lies directly beneath the top gate on arm 1.) Figure 2(b) shows one such trace; even higher peak-to-valley ratios (>10) have on occasion been obtained.

Tunneling between two ideal 2D systems is highly constrained by the conservation of in-plane momentum. If complete conservation holds, then tunneling is possible only when near-perfect[3] alignment of the subband edges in the two quantum wells exists. To allow for a breaking of momentum conservation or the presence of other broadening effects (e.g., well width fluctuations) we introduce a shape function $f(\Delta E_0)$. We take f to be peaked when ΔE_0, the energy difference between the ground subband edges of the two quantum wells, is zero. In the tunnel configuration, the excitation voltage, V_{ex}, is closely equal to $\Delta\mu/e$, the difference in chemical potential between two 2DEGs. At low temperatures ($T \ll T_F$) the tunnel current flowing is

$$I = \alpha e V_{ex} D_0 f(\Delta E_0). \tag{1}$$

In this equation D_0 is the 2D density of states and α is a constant. The definition of the relevant energies is illustrated in Fig. 3(a). Taking n_t and n_b to be the 2D densities of the top and bottom 2DEGs we have

$$\Delta E_0 = eV_{ex} + (n_b - n_t)/D_0. \tag{2}$$

For small enough V_{ex}, the condition $\Delta E_0 = 0$ is equivalent to $n_t = n_b$; i.e., equal 2D densities[7] will produce a maximum in the conductance $G_{1,2} = I/V_{ex}$. For these measurements,

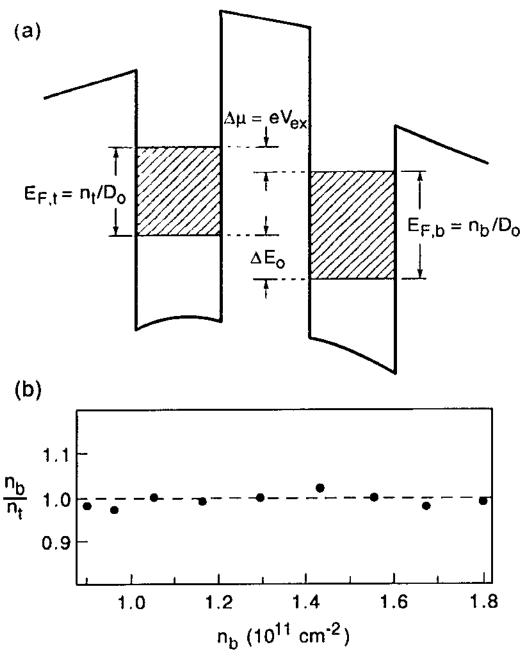

FIG. 3. (a) Simplified conduction-band diagram defining various energies. (b) Ratio of 2DEG densities at resonance vs bottom 2DEG density.

the excitation voltage contains no dc component and is small (0.1 mV) on the scale of the Fermi energies E_F (typically a few meV) of the 2DEGs. It is also several times smaller than the observed broadening of the tunnel peak (i.e., the f function). This is known since the conversion between applied V_t and Fermi energy change in the 2DEGs can be directly obtained from the $G_{1,2}$ vs V_t characteristic. The two steps in the data herald the depletion of the 2DEGs and hence the reduction of the relevant Fermi energies to zero. For the upper quantum well the "lever arm" factor is found to be $\Delta eV_t/\Delta E_{Ft} \approx 180$. This reveals the RT peak widths to be around 0.5 meV, about 10% of the typical Fermi energies.

Using the depletion steps in the $G_{1,2}$ vs V_t characteristic, we can estimate both 2DEG densities and thus the subband alignment at resonance. Defining ΔV_1 and ΔV_2 as in Fig. 2(b), the charge density of the top 2DEG at resonance is $C_t \times \Delta V_1$, with C_t the capacitance of the tunnel gate to the top 2DEG. Similarly the bottom well density is $C_b \times \Delta V_2$, with C_b the capacitance to the bottom 2DEG (assuming the top 2DEG is depleted). For this sample $C_t \sim 0.6$ pF and $C_t/C_b = 1.05$. Figure 3(b) shows the ratio n_b/n_t at resonance plotted against n_b. The closeness of these ratios to unity supports our assertion that the tunneling is strongest when the subband edges are aligned. We note however, that systematic shifts of these ratios away from unity, by as much as 15%, are sometime observed. While this is not understood at present, even a 15% uncertainty in the n_b/n_t ratio would imply a subband mismatch of only 0.7 meV. Furthermore, this method for estimating the resonant densities is likely subject to some systematic error. It ignores, for example, fringe field effects and the fact that a 2D electron system cannot fully screen an electric field owing to its finite density of states.[8]

There are several possible sources of the observed broadening ($\Gamma \sim 0.5$ meV) of the RT peak. The most obvious is a breakdown of momentum conservation. Assuming that is the sole mechanism, then the observed Γ values correspond to scattering wave vectors on the order of 5% of the Fermi wave vector. Although the barrier layer is undoped, scattering may arise from interface defects or the remote ionized Si donors. The mobility of the individual 2DEGs ($\sim 8 \times 10^5$ cm^2/V s) implies large-angle scattering times around $\tau \sim 30$ ps and thus energy uncertainties $\hbar/\tau$ of order only 0.02 meV. This is an underestimate, however, since the small-angle scattering time may be substantially less than τ.

Inhomogeneities suggest other broadening mechanisms. An example are fluctuations in the quantum well width L. These will produce fluctuations in the subband energies of order $\delta E_0/E_0 \sim 2 \times \delta L/L$. Even a single monolayer step ($\delta L \sim 2.8$ Å) will produce a subband energy shift of roughly $\delta E_0 \sim 1$ meV, the same order as the observed broadening Γ. Further experiments are required to fully elucidate the operative broadening mechanism.

In conclusion, we have demonstrated field-induced resonant tunneling between two high-mobility 2D electron gases. These observations provide insight into the physics of 2D-2D tunneling and may have interesting device implications as well.

It is a pleasure to thank T. J. Gramila, H. L. Stormer, and F. Capasso for useful discussions.

[1] For a review see F. Capasso, ed., "Physics of Quantum Electron Devices," *Springer Series in Electronics and Photonics* (Springer, Berlin, 1990), Vol. 28.

[2] The first 2D-2D tunneling conductance experiments were reported by J. Smoliner, E. Gornik, and G. Weimann, Appl. Phys. Lett. **52**, 2136 (1988).

[3] Strictly speaking one cannot speak of the subbands of the individual quantum wells. For the coupled DQW the minimum width of the tunneling resonance is set by the symmetric-antisymmetric gap at flatband. This is less than 0.01 meV for our sample.

[4] J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Appl. Phys. Lett. **57**, 2324 (1990).

[5] A pure AlAs barrier opens the possibility of $\Gamma - X$ tunneling. Whether $\Gamma - \Gamma$ or $\Gamma - X$ tunneling dominates is not important to this letter.

[6] L. N. Pfeiffer, E. F. Schubert, K. West, and C. Magee (unpublished).

[7] This is not true of an interlayer dc bias is applied. Then "hot" electron RT can be observed; J. P. Eisenstein (unpublished).

[8] By observing the depletion (via the tunnel gate) of the top 2DEG for various bias voltages applied to the large back gate, we conclude this penetration effect does not exceed 4%. See, however, Serge Luryi, Appl. Phys. Lett. **52**, 501 (1988).