Resonant tunneling of two-dimensional electrons into one-dimensional subbands of a quantum wire

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Liquid phase epitaxy regrowth on the edge of in situ cleaved substrates is employed to create a vertical two-dimensional electron gas in a double-barrier tunneling potential. Resonant tunneling of two-dimensional electrons through one-dimensional quantum wire subbands is unambiguously identified by negative differential resistance features in the transport characteristics. The bias positions of these features agree with simple tunneling theory estimates based on conservation laws and the calculated band alignment in the structure under bias.

Resonant tunneling into quantum states of reduced dimensionality has attracted much interest since the original proposal and realization of the double-barrier resonant tunneling structure (DBRTS) by Esaki and co-workers. The standard experimental system employed in this research has been the planar DBRTS diode grown by molecular beam epitaxy (MBE), where the tunneling occurs from a three-dimensional (3D) density of states in the emitter into two-dimensional (2D) subbands confined by the double-barrier potential. In addition to the basic properties of negative differential resistance (NDR) regions in the current-voltage $I(V)$ characteristics and the possibility of high-speed operation, research on planar DBRTS has led to the discovery of a number of interesting phenomena, including intrinsic bistability and phonon-assisted tunneling. At the same time, various techniques have been employed to create other systems involving tunneling between states of different dimensionalities. Thus, 2D to 2D tunneling systems have been achieved in planar MBE devices both by modulation-doping techniques and by designing accumulation layers into DBRTS structures. Tunneling systems with confinement in directions other than the growth axis have been realized by various microfabrication techniques, including etching narrow cylinders from DBRTS structures with resulting 1D to 0D (quantum dot) tunneling, and deposition of narrow gates on 2D electron gas (2DEG). The latter technique produces smooth confining potentials in the tunneling direction, however, preventing the formation of sharp, well-separated subbands that produce strong resonant features in the $I(V)$. In this letter we report the use of liquid phase epitaxy (LPE) regrowth on the edge of MBE substrates cleaved in situ to create a vertical 2DEG in a sharp, MBE-quality double-barrier potential. In the resulting tunneling structure 2D electrons tunnel through well-defined 1D quantum wire subbands, leading to the appearance of NDR features in the $I(V)$ curve. The positions of these features agree with simple resonant tunneling theory estimates based on conservation of energy and transverse momentum.

The structure is produced by liquid phase epitaxial (LPE) regrowth of a modulation-doping $n\cdot Al_{0.35}Ga_{0.65}As$ layer on an MBE-grown sample cleaved in situ. The original MBE structure was grown on an $n^+\cdot GaAs$ substrate and had the following parameters: 6000 Å $n^+\cdot GaAs$ buffer layer (Si doped to $2 \times 10^{17}$ cm$^{-3}$), 1 μm GaAs spacer, 50 Å $Al_{0.35}Ga_{0.65}As$ barrier, 50 Å GaAs well, 60 Å $Al_{0.35}Ga_{0.65}As$ barrier, 1 μm GaAs spacer, and 5000 Å $n^+\cdot GaAs$ top contact layer ($3 \times 10^{17}$ cm$^{-3}$). The barriers, well, and spacer layers were all nominally undoped. The 1-μm-wide spacer layers were designed to add a large series resistance to the planar DBRTS structure, shifting any resonant tunneling features arising from bulk transport far towards higher bias. As a result, ordinary planar DBRTS fabricated from this material exhibited smooth, low-current $I(V)$ curves up to 0.8 V bias in both polarities.

Before LPE regrowth, the sample was covered with $\sim 5000$ Å of SiO$_2$ to prevent growth on the top surface and positioned vertically in a slot in the graphite slider (a description of our LPE system is available elsewhere). By pushing the slider forward in the graphite boat the sample was cleaved in situ and moved under the regrowth melt. A 5-10-μm-thick layer of the Sn-doped $n\cdot Al_{0.3}Ga_{0.7}As$ was regrown on the freshly cleaved {110} surface at $T = 770 \degree C$. The melt composition was adjusted for Al content $x \approx 0.35$ and doping density $N_d \approx 10^{17}$ cm$^{-3}$. Parameters we found to create a 2DEG of reproducible $n^{2D} \sim 4 \times 10^{11}$ cm$^{-2}$ density on both planar and cleaved substrates in our LPE system. A cross-sectional photograph of the sample after removal from the chamber is shown together with a schematic diagram in Fig. 1(a). After etching off the SiO$_2$, a 40 μm period grating of AuGe contact metal (14 μm stripes, 26 μm spaces) was deposited parallel to the cleaved edge and alloyed at 400 °C for 2 min. The contact stripes were isolated from one another by etching or scribing. This created parallel devices of approximately the same size as the edge device with 2DEG, as shown in Fig. 1(b), making it possible to compare the tunneling of 2DEG through a quantum wire in the edge device with bulk tunneling in adjacent, identically processed devices. The back contact was made to the $n^+$ substrate. All measurements were taken at $T = 4.2 \degree K$.

A comparison of the $I(V)$ curves of the edge 2DEG device and a representative bulk device is shown in Fig. 2. The bulk device (curve 2) shows a smooth current rise with no features whatever up to $V = 0.8$ V applied bias in both polarities. The edge device (curve 1) follows the bulk...
FIG. 1. (a) Cross-sectional photograph and diagram of the DBRTS after regrowth. (b) Schematic diagram of adjacent 2DEG and bulk devices, with Al$_x$Ga$_{1-x}$As regions shaded (not to scale).

$I(V)$ characteristic until a threshold bias $V_t$ is reached, whereupon the current rises sharply. In the forward bias (top contact biased positive with respect to the substrate) $V_t \approx 175$ mV, in reverse bias $V_t \approx -145$ mV. After the threshold, the reverse bias $I(V)$ exhibits clear features at $V = -175$ mV and $V = -240$ mV. The forward bias $I(V)$ also exhibits strong features at $V = 205$ mV and $V = 350$ mV, with the first feature exhibiting definite NDR behavior (see inset of Fig. 2 for an expanded view). Since the bulk $I(V)$ in this bias range is perfectly smooth, the appearance of strong $I(V)$ features and particularly NDR regions provides unambiguous evidence of resonant tunneling from the 2DEG into 1D subbands of the quantum wire.

In order to calculate the expected positions of the tunneling features in the $I(V)$ characteristics of our tunneling system, we estimate the energy-momentum distribution of tunneling electrons in the emitter electrode, together with the energy positions of 1D subbands in the well, and the alignment of the emitter and 1D subband states under applied bias. Outside the barriers, we have a modulation-induced 2DEG subband, with electrons transferred from the regrown n-Al$_x$Ga$_{1-x}$As layer. The Al fraction of the device in Fig. 2 measured by band-gap photoluminescence is $x = 0.35 \pm 0.02$. From calibration regrowth runs on cleaved GaAs epilayers we estimate the 2DEG density in our structure to be $n_{2D} = 4.0 \times 10^{11}$ cm$^{-2}$. The donors can be modeled as a constant density of fixed positive charge extending $d = n_{2D}/N_d = 400$ Å into the n-Al$_x$Ga$_{1-x}$As. The resulting electron distribution outside the barriers can be calculated by the usual techniques and is illustrated in the inset of Fig. 3 (a). At this density, electrons occupy the lowest 2D subband $E_{0}^{2D} \approx 60$ meV (all energies are referred to the bottom of the conduction band $E_C$ at the GaAs/Al$_x$Ga$_{1-x}$As interface in the emitter, see Fig. 3) up to the Fermi level, $E_F - E_{0}^{2D} = 14$ meV, with electron states described by:

$$F(k_x, k_z) = E_0^{2D} + \hbar^2(k_x^2 + k_z^2)/2m^*.$$  (1)

The electric field at the interface is $F_x = en_{2D}/\varepsilon = 5.7 \times 10^4$ V/cm ($\varepsilon$ is the dielectric constant) and the average penetration of the 2DEG wave function into the GaAs is $\langle x \rangle \sim 70$ Å.
At zero bias, electrons accumulate almost symmetrically near the barriers to compensate the positively charged donors opposite the barriers and well. This produces an electric field along the z axis and creates a potential difference $\Delta E$ between $E_i$ in the emitter and the center of the well, as shown in Fig. 3(a). Applying bias between the 2DEG electrodes further lowers the center of the well with respect to the emitter, increasing $\Delta E$. One-dimensional states in the well subbands are consequently described by:

$$E_i(k_y) = -\Delta E(V) + E_i + k_y^2/2m^*,$$

(2)

where $E_i = E_z + E_i^{ID}$, $E_z = 70 \text{ meV}$ is the quantization energy along the z axis due to the double-barrier potential (only the lowest level is relevant in our bias range); and $E_i^{ID}$ are the subband energies due to the confinement by electric field $F_x$ in the well.

The potential distribution in the tunneling direction under applied bias is shown schematically in Fig. 3(b). As $V$ is increased, the ID subbands are shifted down and eventually align with the emitter states occupied by 2DEG. At this point the resonant tunneling current, which conserves both energy and transverse momentum $k_y$, begins to flow. The resonant current peaks in $I(V)$ occur whenever the applied bias aligns $E_i^{ID}$ with the lower 2DEG electron distribution, see Figs. 3(a), 3(b)) with the ID subbands in the well,

$$\Delta E(V) = E_i - E_i^{ID}.$$

A rigorous evaluation of the band alignment in our structure requires a self-consistent solution of Poisson and Schrödinger equations in two dimensions, but a simple estimate of the relation between the total bias $V$ and $\Delta E(V)$ can be obtained as follows. From measurements and self-consistent calculations on planar DBRTS devices

$$E_i^{ID} = -\left(\frac{\pi}{2}\right)^2 \frac{e^2}{2\epsilon r_i} = \frac{e^2}{2\epsilon r_i} = \frac{e^2}{2\epsilon D},$$

where $r_i$ is the first (emitter) barrier. If, to first order, we assume that $E_i^{ID}$ is the same in the well and the emitter, we have $E_i^{ID} \approx E_i^{DB}$ and these formulae predict $I(V)$ peaks due to resonant tunneling through the lowest 1D subband at $V = 200 \text{ mV}$ (forward bias) and $V = -150 \text{ mV}$ (reverse bias), with the asymmetry arising from unequal barrier widths. Considering the simplicity of the model these numbers are in reasonable agreement with the experimental results of Fig. 2. We note that our approach requires only the values of $n^{2D}$, $N_D$, and DBRTS parameters to estimate the bias positions of tunneling features in $I(V)$.

In conclusion, we have employed a novel technique—regrowth on the edge of an MBE structure cleaved in situ inside the LPE chamber—to produce a resonant tunneling structure in which electrons tunnel from a modulation doping-induced 2DEG into a 1D quantum wire. The 2D to 1D tunneling process is unambiguously identified by the appearance of NDR features in the $I(V)$ characteristics of the device. The position of the $I(V)$ features is in reasonable agreement with a simple model in which tunneling is determined by energy and momentum conservation together with the estimated alignment of the emitter and well subbands under bias. Finally, we note that a three-terminal device along the lines of Ref. 9 can be realized using our regrowth-on-edge technique if the layer of Al$_x$Ga$_{1-x}$As is followed by another layer of $n^+$-GaAs which could serve as a gate.

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