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

A. Zaslavsky, D. C. Tsui, M. Santos, and M. Shayegan
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

(Received 19 November 1990; accepted for publication 3 February 1991)

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.[1] 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,[2] research on planar DBRTS has led to the discovery of a number of interesting phenomena, including intrinsic bistability[3] and phonon-assisted tunneling.[4] 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[5] and by designing accumulation layers into DBRTS structures.[6] 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,[7] and deposition of narrow gates on 2D electron gas (2DEG).[8] 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.[9]

The structure is produced by liquid phase epitaxial (LPE) regrowth of a modulation-doping n-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ layer on an MBE-grown sample cleaved *in situ*.[10] The original MBE structure was grown on an n^+-GaAs substrate and had the following parameters: 6000 Å n^+-GaAs buffer layer (Si doped to 2×10^{17} cm^{-3}), 1 μm GaAs spacer, 50 Å $\mathrm{Al}_{0.35}\mathrm{Ga}_{0.65}\mathrm{As}$ barrier, 50 Å GaAs well, 60 Å $\mathrm{Al}_{0.35}\mathrm{Ga}_{0.65}\mathrm{As}$ barrier, 1 μm GaAs spacer, and 5000 Å n^+-GaAs top contact layer (3×10^{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 ~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[11]). 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-$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ was regrown on the freshly cleaved {110} surface at $T = 720$ °C. The melt composition was adjusted for Al content $x\approx0.35$ and doping density $N_d\approx10^{17}$ cm^{-3}, parameters we found to create a 2DEG of reproducible $n^{2D}\sim4\times10^{11}$ 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 $T = 4.2$ 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

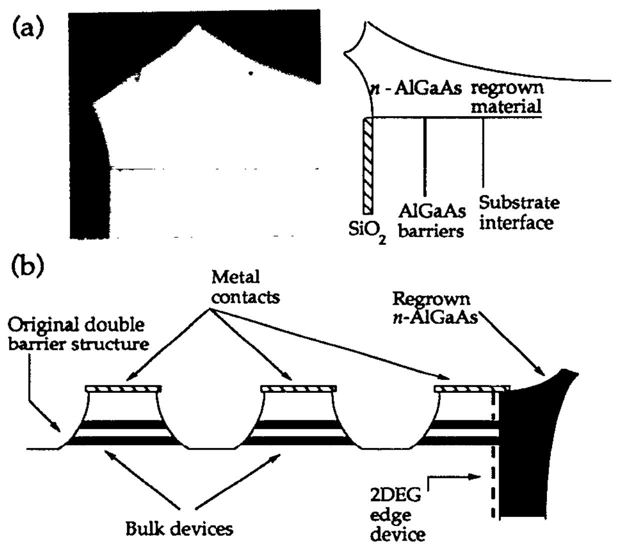

FIG. 1. (a) Cross-sectional photograph and diagram of the DBRTS after regrowth. (b) Schematic diagram of adjacent 2DEG and bulk devices, with $Al_xGa_{1-x}As$ regions shaded (not to scale).

$I(V)$ 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.

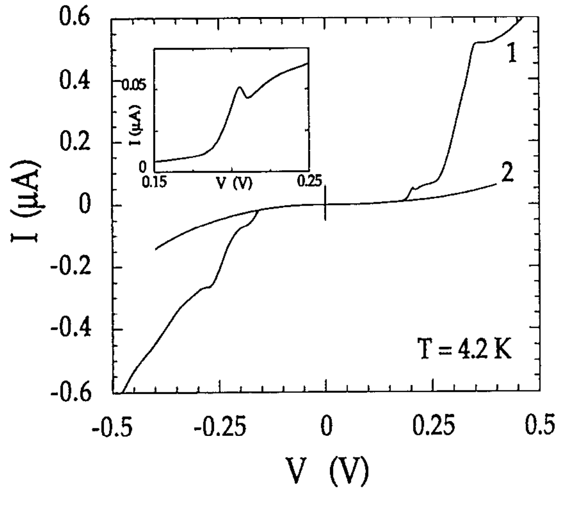

FIG. 2. $I(V)$ characteristics of the 2DEG (curve 1) and bulk (curve 2) devices at $T=4.2$ K. Inset contains an expanded view of the first resonant feature in the forward bias polarity of the 2DEG device.

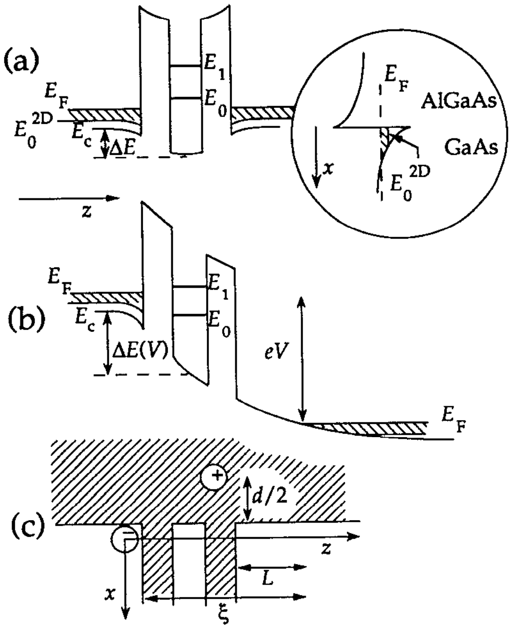

FIG. 3. (a) Schematic and diagram of the 2DEG DBRTS along the z axis at zero bias. Inset illustrates 2DEG band structure in the electrodes along the x axis. Occupied electron states are striped. (b) Band diagram along the z axis under bias V. (c) Schematic illustration of the "charged wire" model used to estimate the expected bias positions of the resonant $I(V)$ features. $Al_xGa_{1-x}As$ regions are striped, L labels the 2DEG collector depletion region. Negative (2D electrons accumulated at the emitter barrier) and positive (donors in regrown $Al_xGa_{1-x}As$ uncompensated by adjacent 2DEG) charges are modeled by wires (circles) located at the origin and $(\langle x\rangle+\xi/2, \langle x\rangle+d/2)$, respectively.

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-$Al_xGa_{1-x}As$ layer. The Al fraction of the device in Fig. 2 measured by band-gap photoluminescence is $x=0.35\pm0.02$. From calibration regrowth runs on cleaved GaAs epilayers we estimate the 2DEG density in our structure to be $n^{2D}=4.0\times10^{11}$ cm^{-2}. The donors can be modeled as a constant density of fixed positive charge extending $d=n^{2D}/N_d \sim 400$ Å into the n-$Al_xGa_{1-x}As$. The resulting electron distribution outside the barriers can be calculated by the usual techniques[12,13] and is illustrated in the inset of Fig. 3(a). At this density, electrons occupy the lowest 2D subband $E_0^{2D} \sim 60$ meV (all energies are referred to the bottom of the conduction band E_c at the GaAs/$Al_xGa_{1-x}As$ interface in the emitter, see Fig. 3) up to the Fermi level, $E_F - E_0^{2D} = 14$ meV, with electron states described by:

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

The electric field at the interface is $F_x = en^{2D}/\epsilon = 5.7\times10^4$ V/cm (ϵ is the dielectric constant) and the average penetration of the 2DEG wave function into the GaAs is $\langle x\rangle \sim 70$ Å.[13]

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 ΔE between E_c 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 ΔE. One-dimensional states in the well subbands are consequently described by:

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

where $E_i = E_z + E_i^{1D}$; $E_z = 70$ 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^{1D} 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_0^{2D} [the bottom of the emitter 2DEG electron distribution, see Figs. 3(a), 3(b)] with the 1D subbands in the well,[9] that is when $\Delta E(V) = E_i - E_0^{2D}$.

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[14] we know that V is dominated by two terms: potential drop in the double-barrier structure and in the collector depletion region. In our structure the positively charged donors in the regrown $Al_xGa_{1-x}As$ are spatially separated from 2DEG in the GaAs by $d/2 + \langle x \rangle = 270$ Å on average. We define the extent of the collector depletion region as L. The positive donor charge that is uncompensated by the adjacent 2DEG then forms a strip of width $\xi = B_1 + W + B_2 + L$ (B_i and W are the barrier and well widths). We can model this positive charge as a wire with a constant charge density of $en^{2D}\xi$ running through the center of the strip—see Fig. 3(c). The corresponding negative electron charge accumulated in the emitter can also be modeled as a wire of radius $\langle x \rangle$ carrying a charge density $-en^{2D}\xi$. Taking the center of this negatively charged wire as the origin, we can evaluate both the total voltage drop V and $\Delta E(V)$ by applying the standard formula for the potential created by two oppositely charged wires: $\varphi(\mathbf{r}) = -\lambda \ln(r_1/r_2)/2\epsilon$, where λ is the linear charge density on the wires and r_i are the distances to the wires. From Fig. 3(c) we have:

$$V = \varphi(\langle x \rangle, \langle x \rangle) - \varphi(\langle x \rangle + \xi, \langle x \rangle) \qquad (3a)$$

$$\Delta E(V) = \varphi(\langle x \rangle, \langle x \rangle) - \varphi(\langle x \rangle + B_1 + W/2, \langle x \rangle), \qquad (3b)$$

where B_1 is the first (emitter) barrier. If, to first order, we assume that F_x is the same in the well and the emitter, we have $E_0^{1D} \approx E_0^{2D}$ and these formulae predict $I(V)$ peaks due to resonant tunneling through the lowest 1D subband at $V = 200$ mV (forward bias) and $V \approx -150$ 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 new 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 $Al_xGa_{1-x}As$ is followed by another layer of n^+-GaAs which could serve as a gate.

We express our gratitude to E. J. Prinz for SiO_2 deposition, Dr. C. Petersen for photoluminescence measurements on the regrown n-$Al_xGa_{1-x}As$ used to verify the Al content, and Dr. S. Luryi and Dr. M. R. Frei for helpful discussions. This work was supported by ARO grant No. DAAL03-89-K-0036 and NSF grant No. ECS-8553110 and No. DMR-8921073.

[1] R. Tsu and L. Esaki, Appl. Phys. Lett. **22**, 562 (1973); L. L. Chang, L. Esaki, and R. Tsu, *ibid.* **24**, 593 (1974).

[2] E. R. Brown, T. C. L. G. Sollner, C. D. Parker, W. D. Goodhue, and C. L. Chen, Appl. Phys. Lett. **55**, 1777 (1989).

[3] V. J. Goldman, D. C. Tsui, and J. E. Cunningham, Phys. Rev. Lett. **58**, 1256 (1987).

[4] V. J. Goldman, D. C. Tsui, and J. E. Cunningham, Phys. Rev. B **36**, 7635 (1988).

[5] J. Smoliner, W. Demmerle, G. Berthold, E. Gornik, and G. Weimann, Phys. Rev. Lett. **63**, 2116 (1989).

[6] M. L. Leadbeater, E. S. Alves, L. Eaves, M. Henini, O. H. Hughes, A. Celeste, J. C. Portal, G. Hill, and M. Pate, Phys. Rev. B **39**, 3438 (1989).

[7] M. A. Reed, J. N. Randall, R. J. Aggarwal, R. J. Matyi, T. M. Moore, and A. E. Wetsel, Phys. Rev. Lett. **60**, 535 (1988)

[8] A. Palevski, M. Heiblum, C. P. Umbach, C. M. Knoedler, A. N. Broers, and R. H. Koch, Phys. Rev. Lett. **62**, 1776 (1989).

[9] S. Luryi and F. Capasso, Appl. Phys. Lett. **47**, 1347 (1985); **48**, 1693 (1986), Erratum.

[10] Regrowth of 2DEG on substrates cleaved inside an MBE chamber was recently reported by Loren Pfeiffer, K. W. West, H. L. Stormer, J. P. Eisenstein, K. W. Baldwin, D. Gershoni, and J. Spector, Appl. Phys. Lett. **56**, 1697 (1990).

[11] M. R. Frei and D. C. Tsui, Appl. Phys. Lett. **55**, 2432 (1989); A. Zaslavsky, M. R. Frei, and D. C. Tsui, *ibid.* **57**, 2455 (1990).

[12] D. Delagebeaudeuf and N. T. Linh, IEEE Trans Electron. Dev. **ED-29**, 955 (1982).

[13] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

[14] V. J. Goldman, D. C. Tsui, and J. E. Cunningham, Phys. Rev. B **35**, 9387 (1987).