

# 1D to 1D Tunneling in a Dual Electron Waveguide Device

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We report the first unambiguous observation of controlled electron tunneling between two closely spaced one-dimensional (1D) electron waveguides. This represents a significant step forward towards the realization of a quantum field-effect electron directional coupler (QFED) [1].

An electron waveguide is essentially a one-dimensional (1D) electronic channel through which electrons travel without scattering. Discrete quantum-mechanical modes which correspond to the 1D subbands arise due to the lateral confining potential. Recent experimental work has unmistakably proven the existence of electron waveguiding through the observation of quantized conductance [2,3] and tunneling oscillations [4] in short 1D devices.

With the ultimate goal of implementing an electron directional coupler, we have been working for a few years on a dual electron waveguide device. In this device, two closely spaced 1D channels are electrostatically formed by negatively biasing three gates patterned in a split-gate fashion on top of an AlGaAs/GaAs modulation-doped heterostructure. In a split-gate scheme, the 2D electron gas (2DEG) is depleted underneath the gates leaving a narrow conducting channel in between. In our approach, the two side-gates are used to define the outer boundaries of the two waveguides and the middle-gate is used to establish the thin common barrier separating the waveguides. Independent access to the three gates allows control over the width and carrier concentration of the individual waveguides (which determines the number of occupied modes in each waveguide) as well as the proximity and interaction of the waveguides with each other.

We have fabricated a variety of dual electron waveguide devices with different lengths  $L$  and widths  $W$  on an AlGaAs/GaAs heterostructure ( $N_s = 4 \times 10^{11} \text{ cm}^{-2}$  and  $\mu = 1.2 \times 10^6 \frac{\text{cm}^2}{\text{V-sec}}$  at 4 K). The key feature in these devices is the 30 nm wide middle gate fabricated using a single-pass e-beam lithography technique. Such a thin gate is required to achieve significant tunneling. The middle gate is widened outside of the coupled region to prevent interaction outside the waveguiding region. Device processing consists of mesa isolation, ohmic contact formation to allow individual access to the input and output of each waveguide, and a combination of UV and e-beam lithography for gate formation.

In our measurements, a middle-gate voltage  $V_{GM}$  is set to establish a thin tunneling barrier between the two waveguides. A drain-source voltage is fixed between the input of one waveguide and the output of the other waveguide. We modulate the width of only one of the waveguides using the appropriate side-gate voltage  $V_{GT}$  ( $V_{GB}$ ) while the other waveguide is set at a certain width by the other side-gate voltage  $V_{GB}$  ( $V_{GT}$ ). The tunneling current between the two halves of the device is measured. We report on the tunneling characteristics of an  $L=1.0 \mu\text{m}$ ,  $W=0.4 \mu\text{m}$  dual electron waveguide device at  $T=1.6 \text{ K}$ .

There are three distinct regimes in the tunneling current dependence with  $V_{GT}$  and  $V_{GB}$ . A 1D to 2D regime exists when only one waveguide is implemented while the other waveguide is not yet formed (there is a 2D gas). In this regime, tunneling oscillation ridges characteristic of the subband structure in the waveguide are observed [4]. In a similar manner, a 2D to 1D regime, in which a waveguide is formed on the other half of the device, shows tunneling oscillation ridges characteristic of the subband structure in that waveguide. A 1D to 1D regime is established when two electron waveguides are implemented. The tunneling current should now be sensitive to the alignment of the subbands in the two electron waveguides. In this regime, we observe bumps in the tunneling current as a function of both side-gate voltages as the individual subbands line up between the two waveguides. This is unmistakable proof that 1D to 1D tunneling is taking place.

In summary, we have observed tunneling between two 1D electron waveguides. These results constitute the first observation of 1D to 1D tunneling in any electronic system.

[1] del Alamo and Eugster, *Appl. Phys. Lett.* **56**, 78, (1990). [2] van Wees et al., *Phys. Rev. Lett.* **60**, 848, (1988). [3] Wharam et al., *J. Phys. C* **21**, L209, (1988). [4] Eugster and del Alamo, *Phys. Rev. Lett.* **67**, 3586, (1991).

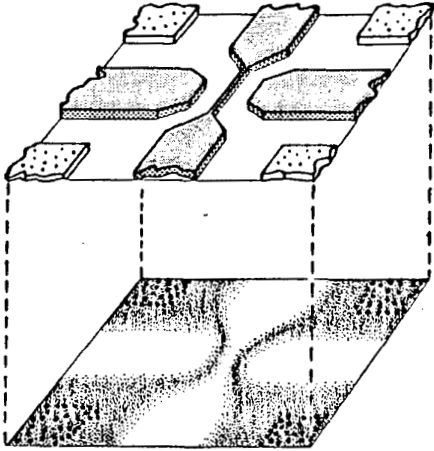


Fig. 1. Conceptual picture of dual electron waveguide device. Shaded region represents electron concentration at the heterointerface.

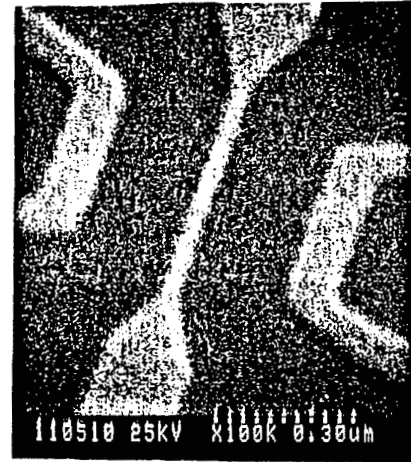


Fig. 2. SEM of split-gates of dual electron waveguide device.

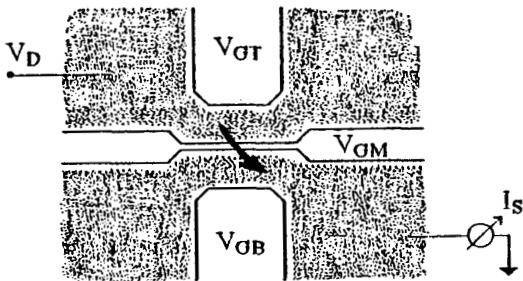


Fig. 3. Bias schematic for 1D to 1D tunneling regime.

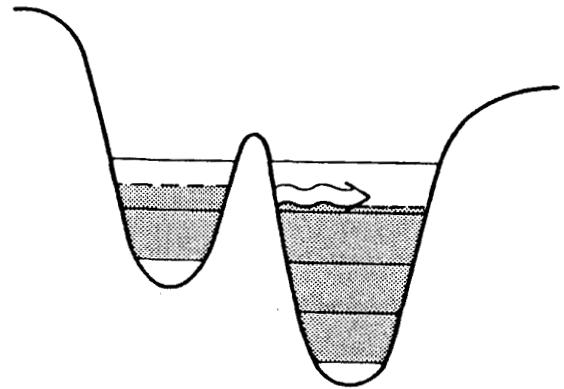


Fig. 4. Energy cross-section of the two 1D electron waveguide.

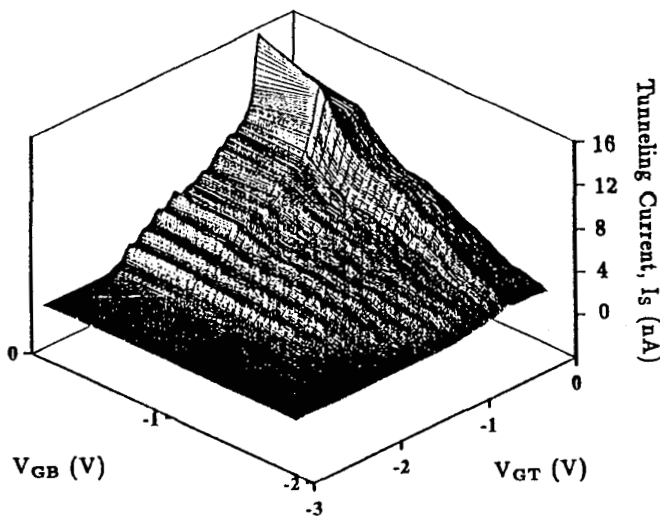


Fig. 5. Tunneling current as a function of top and bottom gate bias.

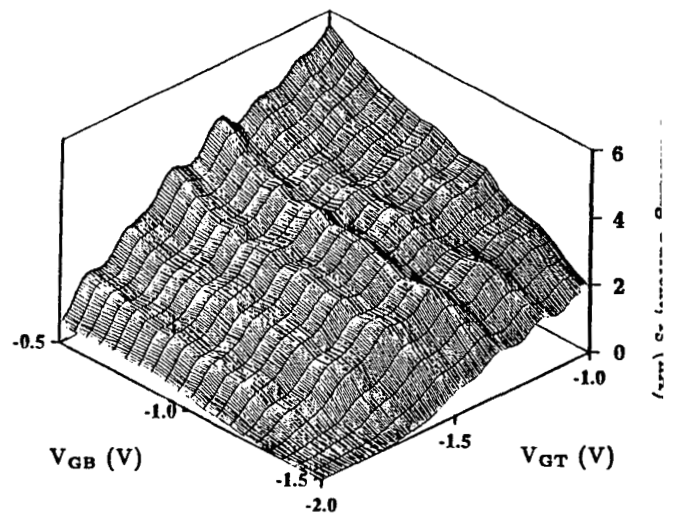


Fig. 6. Expansion of the 1D to 1D tunneling regime in Fig. 5. The observation of bumps constitutes unmistakable evidence of 1D to 1D tunneling.