Effects of Single Impurity Scattering on One-Dimensional Quantum-Effect Devices

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The potential for increased functionality and for continued device scaling underly the optimism for the future of quantum-effect electronics. These electron wave phenomena devices have shown very dramatic transport characteristics which could possibly be used in future circuits. However, in order for such practical applications to become a reality, the robustness of the individual devices against manufacturing defects and undesirable impurities must be well understood. Unfortunately, impurities will be most detrimental for one-dimensional (1D) structures which have recently shown very exciting and promising quantum-effects. We report on dramatic changes in the 1D quantum-effect features if only a *single* impurity exists in the device.

A split-gate dual electron waveguide device has recently demonstrated novel quantum-effect features in a variety of different implementations including two isolated 1D electron waveguides [1] and leaky 1D electron waveguides [2]. With such well understood characteristics, it is an ideal structure to study imperfections in 1D electronic systems. Since these devices are implemented in very high mobility AlGaAs/GaAs heterostructures, only a small number of impurities exist in the intrinsic device area. Therefore, we are sometimes able to measure a device in which one waveguide contains only very few impurities while the other waveguide is impurity-free. Using such a device we can compare in detail variations between an ideal 1D waveguide and a nonideal 1D waveguide.

The signature of a clean split-gate dual waveguide device is the observation of discrete $2e^2/h$ conductance steps for each waveguide as its electronic width is increased. The steps correspond to the opening of an additional propagation mode in the waveguide or, in a more electronic sense, the crossing of a subband through the Fermi level. A more unique feature of this device can be seen in the tunneling current leaking from the waveguides through the thin middle barrier. Here, we observe very strong oscillations as the tunneling current traces out the 1D density of states [2].

Using an asymmetric biasing scheme, we are able to sweep the conducting path of each waveguide sideways through the region between the split-gates. In this way, we have studied transport in different lateral regions of the waveguides for an L=0.5 μm, W=0.3 μm (waveguide dimensions) device. The impurity-free waveguide shows very sharp conductance steps and serves as an in-situ reference. The conductance steps in the other waveguide are clean and sharp as long as an impurity is not included in the channel. As the waveguide is opened to include one of the single impurities, an immediate and dramatic degradation in the conductance steps is observed. The effect of the impurity in the channel is to make the transmission probability energy dependent and less than unity, resulting in the observed degradation. By analyzing which $2e^2/h$ conductance step becomes distorted, we are able to pinpoint to within several hundred angstroms the location of two single impurities in the waveguide. One impurity lies very near the thin middle common barrier while the other impurity lies closer to the outer side barrier.

Even more dramatic effects of the single impurities are seen in the tunneling current flowing through the thin middle barrier. For the clean waveguide, we observe the familiar oscillations in the tunneling current corresponding to the sweeping of the 1D subbands through the Fermi level. However, in the other waveguide, which contains the two single impurities, the oscillations are completely washed out. The impurities cause mode mixing in their vicinities, thereby destroying the resolution of the discrete energy levels of the waveguide.

We have shown that a severe degradation in the quantum-effect features occurs when only a *single* impurity exists in the device. Such extreme sensitivity on device nonidealities has strong implications for the future of 1D quantum-effect electronics.

[1] Eugster et al., *Appl. Phys. Lett.* **60**, 642, 1992. [2] Eugster et al., *Phys. Rev. Lett.* **67**, 3586, 1991.

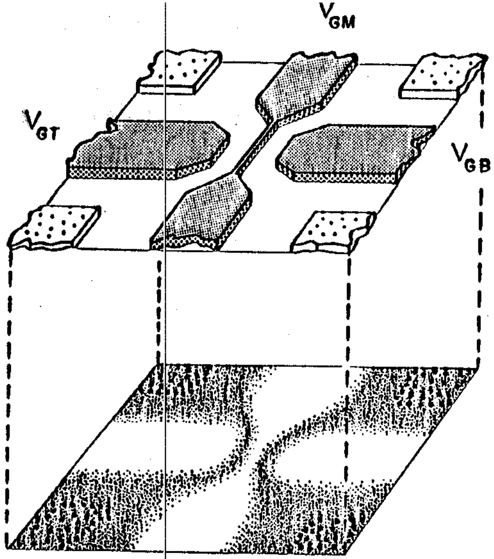

Fig. 1. Schematic of a split-gate dual electron waveguide device. Shaded regions represent electron concentration.

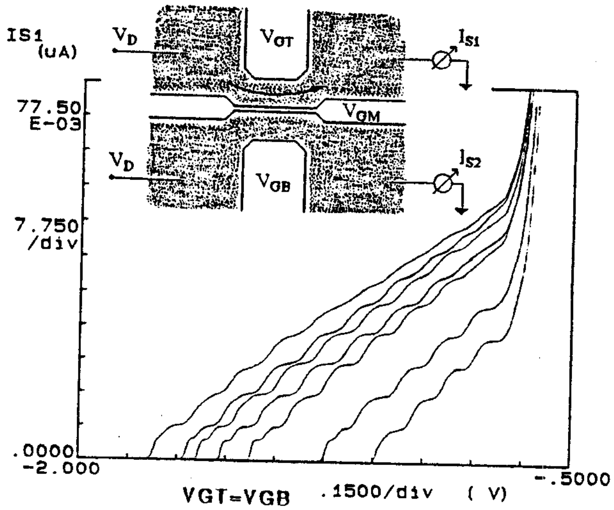

Fig. 2. Waveguide current for different lateral regions of the top clean waveguide (see inset) in an L=0.5 μm, W=0.3 μm device.

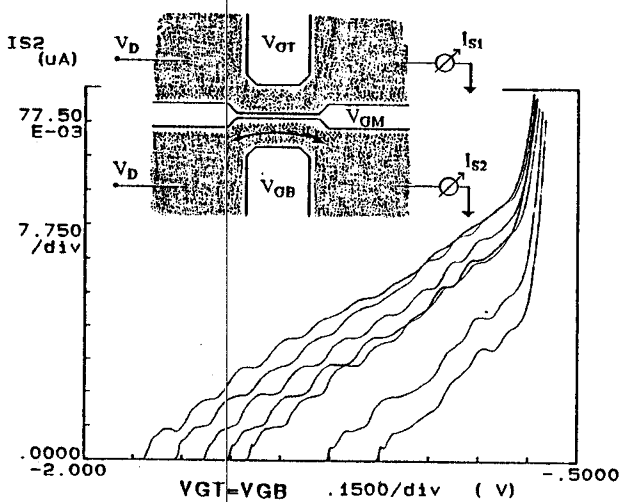

Fig. 3. Waveguide current for different lateral regions of the bottom dirtier waveguide in same L=0.5 μm, W=0.3 μm device as in Fig. 2.

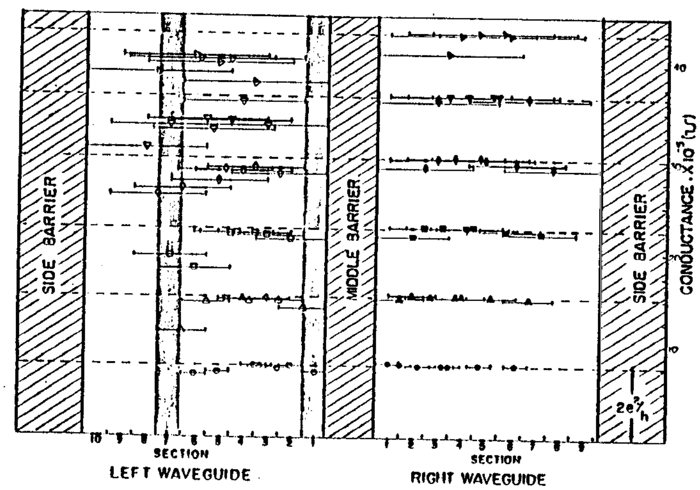

Fig. 4. Plotted conductance levels (of Figs. 2 and 3) for different sections of the waveguides. Shaded sections 1 and 7 in left (bottom) waveguide represent impurity locations. Conductance deviates dramatically from reference in these sections.

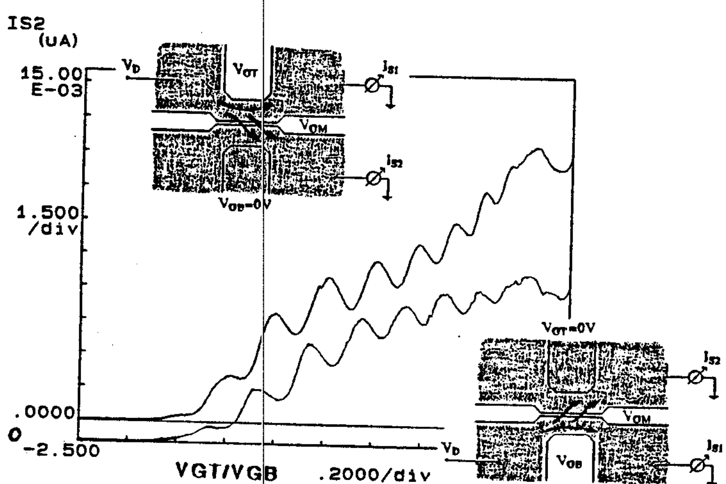

Fig. 5. Tunneling current for each waveguide in a completely clean L=0.2 μm, W=0.3 μm device in a leaky waveguide implementation.

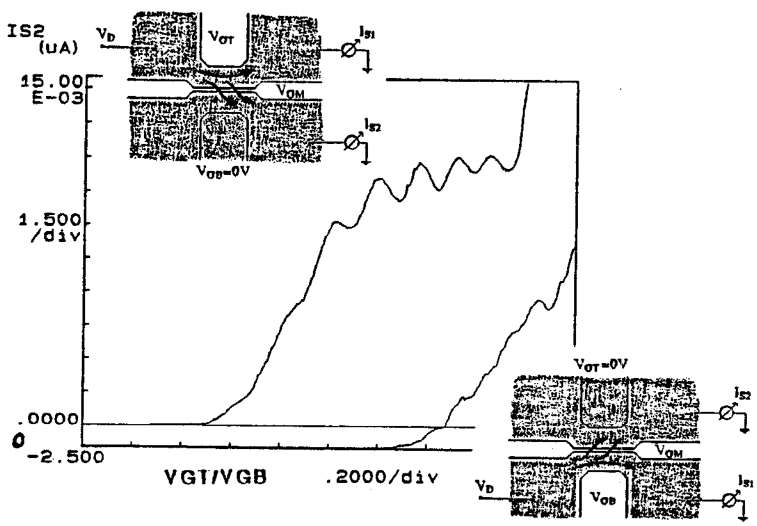

Fig. 6. Tunneling current for each waveguide in the impurity-affected L=0.5 μm, W=0.3 μm device.