saturate just above the unstrained Si saturation velocity 1 $\times 10^7$ cm/s. The calculated low-field (1 kV/cm) drift mobility data agree very well (over the whole calculated temperature range) with the highest Hall mobilities measured by [1] and [2] on thin (15–20 nm) modulation-doped Si channels on relaxed $Si_{1-x}Ge_x$ ($x = 25$–30%) buffers.

Our results demonstrate significant improvements of the in-plane electron drift velocity in strained Si on $Si_{1-x}Ge_x$ compared to bulk Si in the low-field and the high-field regions both at 300 and 77 K. This advantage should contribute considerably to the high-performance potential of devices based on modulation-doped Si/SiGe heterostructures such as n-channel quantum-well MODFET's and MOSFET's.

[1] F. Schäffler *et al.*, *Semicond. Sci. Technol.*, vol. 7, p. 260, 1992.
[2] Y. J. Mii *et al.*, *Appl. Phys. Lett.*, vol. 59, p. 1611, 1991.
[3] J. C. Sturm *et al.*, private communication, Sept. 1991.
[4] K. Ismail *et al.*, *Appl. Phys. Lett.*, vol. 58, p. 2117, 1991.
[5] U. König *et al.*, *Electron. Lett.*, vol. 28, p. 160, 1992.
[6] C. Jacoboni and L. Reggiani, *Rev. Mod. Phys.*, vol. 55, p. 645, 1983.
[7] C. Smith and M. E. Jones, *Superlattices and Microstruct.*, vol. 4, p. 391, 1988, have reported calculations for mobilities in the low-field range.
[8] R. People, *IEEE J. Quantum Electron.*, vol. QE-22, p. 1696, 1986.
[9] M. Rieger, thesis, Technical University Munich (Prof. P. Vogl), 1991.
[10] Canali *et al.*, *Phys. Rev. B*, vol. 12, p. 2265, 1975.

IIB-1 A New Single Electron Transistor—S. Y. Chou and Y. Wang, Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455 (612) 625-1316.

We propose and demonstrate a new single-electron transistor (SET) where the drain current is controlled by a single electron. The new SET is similar to a GaAs/AlGaAs heterostructure modulation-doped FET, except that it has a split gate which electrostatically squeezes a 2D channel into a 1D channel, and it also has a nanoscale metal bar inside the gate gap to form a potential barrier in the 1D channel. At certain gate voltages, a single electron can be "stopped" inside the 1D channel by the potential barrier, and due to Coulomb repulsion this electron "blocks" the current flow from the source of the FET to the drain (Coulomb Blockade). Therefore, the drain current of the SET will oscillate with the gate voltage giving strong negative differential resistances, instead of being a linear function of gate voltage as that in a conventional FET operated in the linear regime.

The SET's with gate gaps of 50 and 100 nm were fabricated using MBE and ultra-high resolution e-beam lithography. As the gate voltage was swept at low temperatures, for a SET with a 50-nm gate gap, more than 10 periodic oscillation peaks in the drain current were observed before the onset of the first $2e^2/h$ plateau. Similar periodic conductance oscillations were observed in a SET with a 100-nm gate gap. The oscillation periods were 15 and 9 mV for devices with gate gaps of 50 and 100 nm, respectively. The oscillation peaks were so strong that they could be seen without the use of a lock-in amplifier, and they persisted after thermal cycling and photon excitation. These oscillations were not observed in the FET's that have a split gate without a metal bar in the gate gap.

Further measurements showed that the oscillation period in the gate voltage corresponds to the gate voltage needed to put a single electron into the 1D channel. The shape of the oscillation peak can be well fitted by the derivative of the Fermi–Dirac distribution, indicating the peak width is caused by thermal broadening of a sharp energy level. A single electron blockade model was developed for the operation of the SET and agrees well with experimental observation.

IIB-2 Effects of Single Impurity Scattering on One-Dimensional Quantum-Effect Devices—C. C. Eugster, J. A. del Alamo, M. R. Melloch*, and M. J. Rooks,** Massachusetts Institute of Technology, Rm. 13-3018, Cambridge, MA 02139 (617) 253-4699.

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 oscil-

lations 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.

*M. R. Melloch is with the School of Electrical Engineering, Purdue University, West Lafayette, IN 47907.

**M. J. Rooks is with NNF, Cornell University, Ithaca, NY.

[1] C. C. Eugster *et al.*, *Appl. Phys. Lett.*, vol. 60, p. 642, 1992.

[2] C. C. Eugster *et al.*, *Phys. Rev. Lett.*, vol. 67, p. 3586, 1991.

IIB-3 Current Switching and Modulation Based on Electron Interference in Electron Waveguides: A Zero Gap Electron Wave Coupler—Mason Thomas, Nadir Dagli (805 893 4847), Jonathan Waldman, and Arthur Gossard, Electrical and Computer Engineering Department; Esther Yuh and Elizabeth Gwinn, Physics Department, University of California, Santa Barbara, CA 93106; Richard Muller and Paul Maker Jet Propulsion Laboratory, Pasadena, CA 91109.

For the first time we fabricated electron waveguide devices analogous to optical guided wave devices. Specifically, we made a zero gap electron wave coupler which demonstrated current switching and modulation based on electron interference in electron waveguides. Fabrication involves forming Schottky gate electrodes on the surface of a high-mobility two-dimensional electron gas sample. Under appropriate reverse bias, areas under gate electrodes are depleted of electrons and conduction from one side to the other can only occur through the narrow and short channels. These channels behave as electron waveguides if their dimensions and temperature of operation are appropriate. The gate geometry is such that two individual single-mode waveguides at the input and output open up smoothly with the help of tapers to a double-moded waveguide section in the center. The lithographic length and width of the wide waveguide section in the center are 3000 and 9000 Å, respectively. The lithographic width of the input and output waveguides are about 4500 Å. In the rest of the discussion we will assume that electrons propagate as coherent waves and their phases are preserved along the length of the device. Therefore, we can utilize the phase of the electrons to create electron interference resulting in spatial modulation of current. It is precisely this point that needs experimental verification to open up the possibility of new and novel electron devices based on electron waveguiding in analogy with optical waveguiding. We call this device zero gap electron wave coupler, because its principle of operation is identical to zero gap coupler in integrated optics. An electron wave incident from one of the single-mode waveguides can emerge from either one of the output waveguides depending on the phase shift between the modes of the double-moded waveguide. Therefore, it could be possible to achieve current switching with this device. The shape of the potential and the number of modes that exist in the wide center waveguide are controlled by the side gate voltages V_g. The coupler is driven by a constant current source of value 5.5 nA from the upper right port. The lower right port is left floating so the current in or out of this port is zero. We monitor the current coming out of the upper (direct current) and lower ports (coupled current) on the left. These so-called direct and coupled currents versus V_g show an oscillatory behavior. One observes strong modulation of both currents at 0.1 K. This type of behavior is indicative of modal interference. The currents, however, do not modulate very strongly and the maximum modulation is about 40%. This is because the wide central waveguide always has more than two modes. As a result, the number of modes that interfere in the central region is large. It is well known that interference of many waveguide modes creates a complicated interference pattern which never goes to zero. The situation gets worse as the number of modes interfering increases and in the limit of many modes interference effects become very vague. In this geometry, as V_g decreases, the number of modes of the wide waveguide at the center decrease and modal interference becomes stronger. But before the center guide gets sufficiently narrow, the input and output waveguides are pinched off because of geometrical considerations. It is observed that