Chapter 4. Ultralow Temperature Studies of Nanometer Size Semiconductor Devices

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A variety of novel lithographic techniques have been used[1] to create quasi-one-dimensional (Q1D) inversion layers in Si MOSFETs to study how their conductance depends on carrier density. It is remarkable that, despite the differences in the structure of the devices, the results are qualitatively similar: one observes random, but time-independent, fluctuations in the conductance G as a function of electron density, which are exponentially large at small G and of order e^2/h at large G. The latter are the universal conductance fluctuations[2] seen in Q1D metals as well,[3] and the former result from one dimensional variable-range hopping.[4] Among the inversion layers studied to date, those with smaller width w generally[5] had lower mobility ($\mu \sim 3000 \, \text{cm}^2/\text{V} \cdot \text{s}$ is typical for w $\sim$ 40 nm). In *Phys. Rev. Letters* 62:583 (1989), we reported studies of narrower inversion layers (w $\sim$ 25 nm) with higher μ (15000 $\text{cm}^2/\text{V} \cdot \text{s}$) than previously reported that revealed qualitatively new behavior. The variations in G are still exponentially large at small electron density and very small at high density, but the variations are *periodic* in the density of electrons in the inversion layer, even in the absence of a magnetic field.

The narrow inversion layers were created using a dual gate device (figure 1) with a 70 nm gap in the lower gate. The lower gate shields the Si/SiO_2 interface from the upper gate, so that when the lower gate is biased below threshold relative to the Si, the inversion layer is confined to the region beneath the gap. In fact, the fringing fields of the lower gate confine the electrons to a region substantially narrower than the gap. The gap in the lower gate was created using X-ray nanolithography and liftoff.[6] The lower gate was made of refractory metal so that damage

1 A.B. Fowler, A. Hartstein, and R.A. Webb, *Phys. Rev. Lett.* 48:196 (1982); M. Pepper and M.J. Uren, *J. Phys. C* 15: L617 (1982); R.G. Wheeler, K.K. Choi, A. Goel, R. Wisnieff, and D.E. Prober, *Phys. Rev. Lett.* 49:1674 (1982); W.J. Skocpol, P.M. Mankiewich, R.E. Howard, L.D. Jackel, D.M. Tennant, and A.D. Stone, *Phys. Rev. Lett.* 56: 2865 (1986).

2 W.J. Skocpol, P.M. Mankiewich, R.E. Howard, L.D. Jackel, D.M. Tennant, and A.D. Stone, *Phys. Rev. Lett.* 56: 2865 (1986); P.A. Lee and A. D. Stone, Phys. Rev. Lett. 55:1622 (1985); B. L. Altshuler, *Pis'ma Zh. Eksp. Teor. Fiz.* 53 (1985); *Phys.-JETP Lett.* 41:648 (1985).

3 C.P. Umbach, S. Washburn, R.B. Laibowitz, and R.A. Webb, *Phys. Rev. B* 30:4048 (1984).

4 A.B. Fowler, A. Hartstein, and R.A. Webb, *Phys. Rev. Lett.* 48:196 (1982); R.F. Kwasnick, M.A. Kastner, J. Melngailis, and P.A. Lee, *Phys. Rev. Lett.* 52:224 (1984); P.A. Lee, *Phys. Rev. Lett.* 53 :2024 (1984).

5 W.J. Skocpol, P.M. Mankiewich, R.E. Howard, L.D. Jackel, D.M. Tennant, and A.D. Stone, *Phys. Rev. Lett.* 56: 2865 (1986)

6 J. H.F. Scott-Thomas, M.A. Kastner, D.A. Antoniadis, H.I. Smith, and S.B. Field, *J. Vac. Sci Technol.* Nov./Dec.
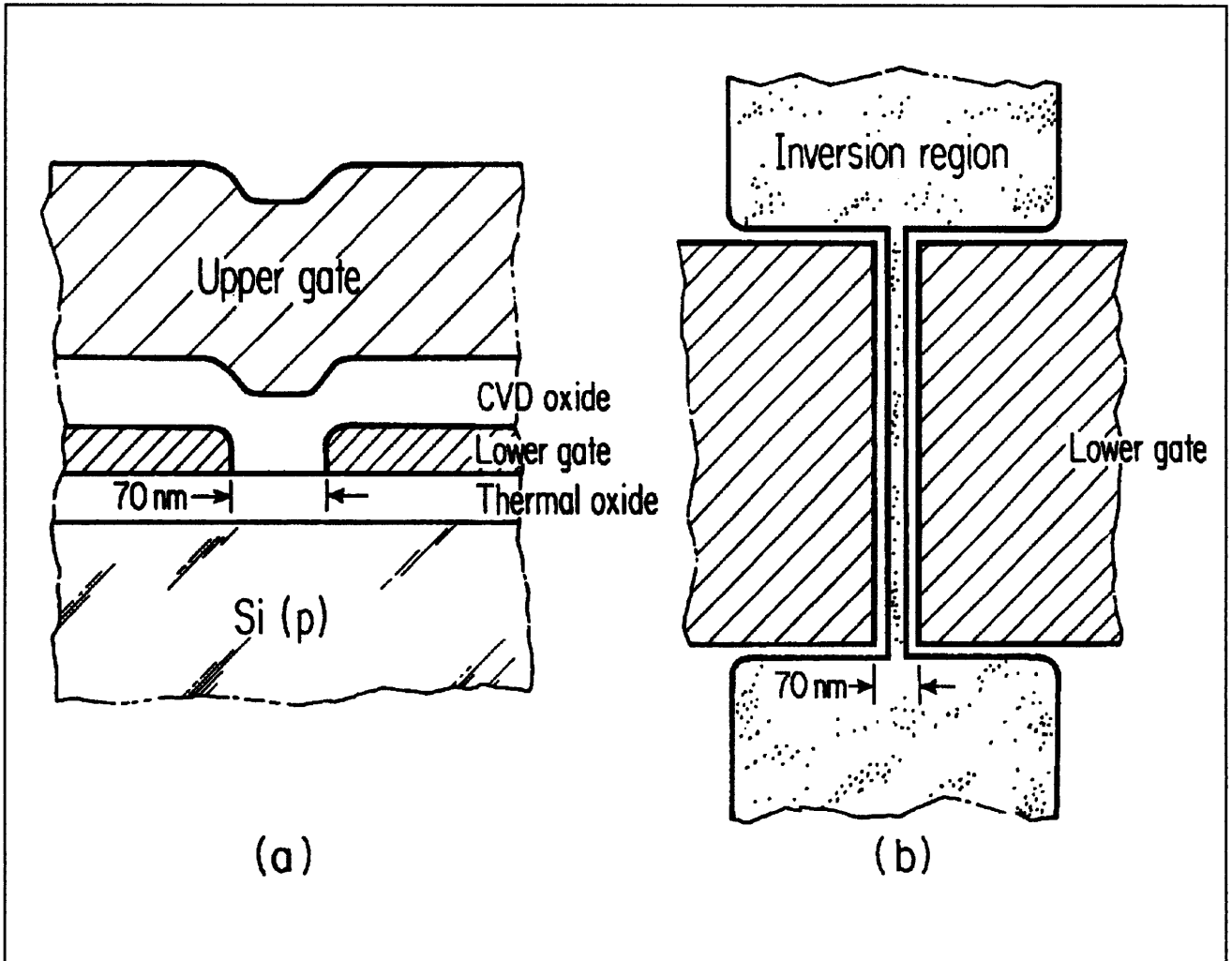
Figure 1. Schematic cross-section (a) and top view (b) of the slotted-gate device. The inversion layer, formed by the positively biased upper gate is confined by the lower gate. The thermal oxide and refractory metal lower gate are both 30 nm thick, and the CVD oxide is 45 nm thick. The width of the narrow inversion layer is exaggerated in (b).

to the Si/SiO_2 interface caused by processing could be repaired by a high-temperature vacuum anneal. The mobility was 15000 $cm^2/V\cdot s$ at 4.2 K for two-dimensional (2D) MOSFETs on the same wafer subjected to the same processing steps as the narrow devices. This corresponds to a mean free path of $\sim$ 100 nm. The lower gate extends over only part of the length of the upper gate, which overlaps source and drain n^+ pads; this means that contact to the narrow inversion channel is made by wide, 2D-electron-gas regions. Although two leads are connected to each of these 2D regions, this is fundamentally a two-probe measurement of the narrow MOSFET. The detailed fabrication procedure was reported in a separate paper.[7] Measurements were performed at temperatures of 100 mK to 3.2 K in a dilution refrigerator equipped with an 8 T superconducting magnet.

The top panel of figure 2 shows G for a $10\mu m$ long MOSFET as a function of the voltage on the upper gate V_G, which is proportional to the number of electrons per unit

(1988); the technique is based on the method of A.C. Warrren, D.A. Antoniadis, and H.I. Smith, *Phys. Rev. Lett.* 56:1858 (1986) and references therein.

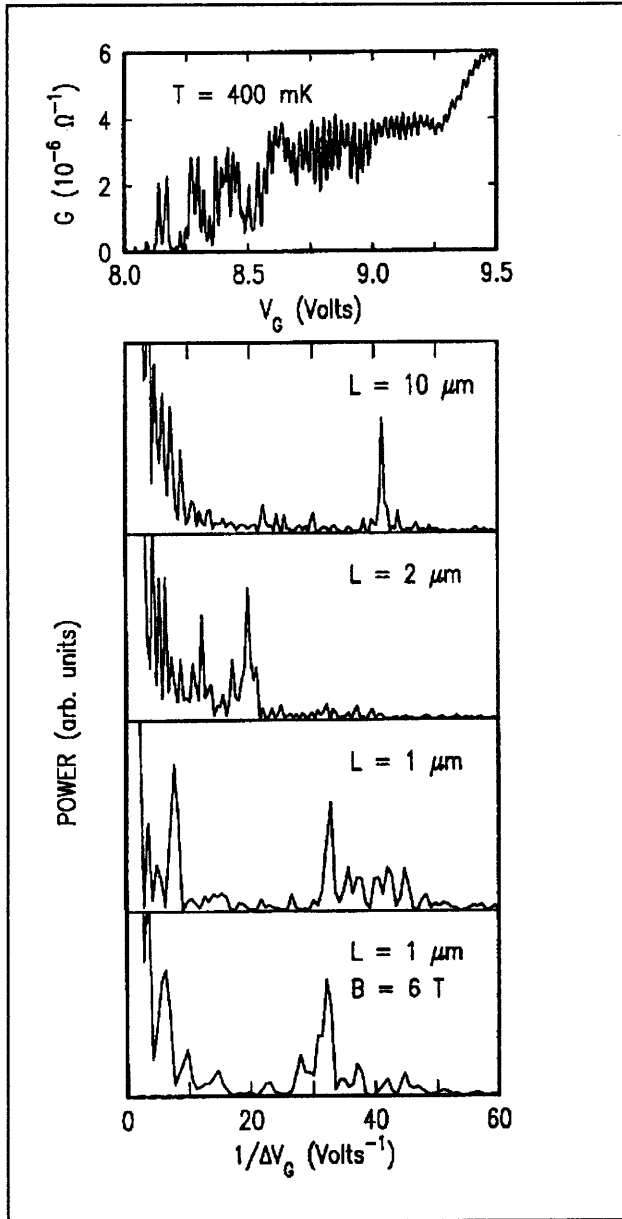7 P.A. Lee and T.M. Rice, *Phys. Rev. B*19:3970 (1979) and references therein.

Figure 2. Top panel: G vs V_G for a 10 μm-long inversion layer. Next three panels: Fourier power spectra of the data of the top panel and for 2 μm and 1 μm-long channels. Bottom panel: Fourier spectrum for the 1 μm-long channel in a magnetic field.

length. The periodic oscillations can be clearly identified, although they are accompanied by random, noise-like fluctuations also seen in earlier Q1D inversion layers. That the oscillations are truly periodic is demonstrated in the next three panels which show the power spectral density, that is, the

square of the modulus of the Fourier transform, for devices of 10 μm, 2 μm, and 1 μm lengths. Each device has a peak in its spectrum at a non-zero frequency, but the frequency of the peak varies in no systematic way with sample length. In addition to the dominant periodicity, smaller peaks are often seen in the power spectrum corresponding to frequencies which are not harmonics of the dominant one. It should be stressed that the periodicity in figure 2 is observed in the absence of a magnetic field. In fact, for fields up to 8 T (applied normally to the (100) Si wafer) the frequency is independent of field, as can be seen in the lowest panel of figure 2.

By calculating the capacitance per unit length, we can find the length associated with the period of the oscillations in figure 2, that is, the length L_0 to which one electron must be added to complete one period. For all samples studied $L_0 \sim 0.25 - 0.5\mu$.

The oscillations in G correspond to a periodic variation of the activation energy of the conductance, as we found by measuring its temperature dependence. The dependence of G on V_{DS} is also striking, as seen in figure 3. This figure shows the differential conductance, measured by applying a small modulation voltage (2μV) in addition to the larger, continuous V_{DS}, while the latter is varied at fixed V_G. Data is shown at 3 K and 0.1 K for a minimum in G vs V_G and at 0.1 K for a maximum. At the minimum, the differential conductance increases by orders of magnitude as V_{DS} approaches ~ 0.2 meV, corresponding to a critical field of ~ 0.2V/cm. Above the critical field, the conductance overshoots and then decreases, eventually approaching its high-temperature value. Qualitatively similar behavior is observed at the maximum in G vs V_G, but with a lower critical field.

From calculations by Laux and Stern[8] for a geometry similar to that for our device, we conclude that the gate voltage range in which strong periodic oscillations are observed coincides with the dynamically one-dimensional regime. We have thus fab-

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8 S.E. Laux and F. Stern, *Appl. Phys. Lett.* 49:91 (1986).

ricated the first truly one-dimensional field effect transistor.

A model which explains the observations is one in which the electrons in the channel form a charge-density wave (CDW) or Wigner crystal. A one-dimensional electron gas is unstable to a charge or spin density wave of wavevector $2k_F$, where k_F is the Fermi wavevector. The nearest-neighbor Coulomb interaction between electrons in the inversion layer is ~ 15 meV at a linear density of $n_L = 10^6/cm$ assuming a dielectric constant of 10. This is larger than the average random potential (~ 1 meV) arising from the Coulomb interaction between the inversion-layer electrons and fixed interface charges. It is also larger than the Fermi energy, which is less than ~ 10 meV if E_F is in the lowest subband, according to Laux and Stern. Since the Coulomb interaction between electrons is about the same size as the zero-point kinetic energy of confinement in length $1/n_L$ at $n_L = 10^6/cm$, the amplitude of the charge-density modulation is expected to be large, large enough perhaps, for the system to be considered a Wigner crystal.

Of course, such a CDW would be pinned by impurities. The behavior of the differential conductance (figure 3) could result from depinning by the field. The pinning may be caused by interface charges that lie directly over the narrow inversion layer. Given that their density is $\sim 10^{10}/cm^2$, for a channel of 30 nm width, such charges will be found every ~ 300 nm, comparable to L_0, suggesting that it is these charges that determine L_0. This would also explain why L_0 varies at random from sample to sample.

The pinning energy has two components.[9] One comes from the coupling of the CDW to the pinning centers, and the other from the elastic energy caused by the adjustment of the density of the CDW to satisfy the phase requirements of the pinning centers. The latter will be minimized for any pair of
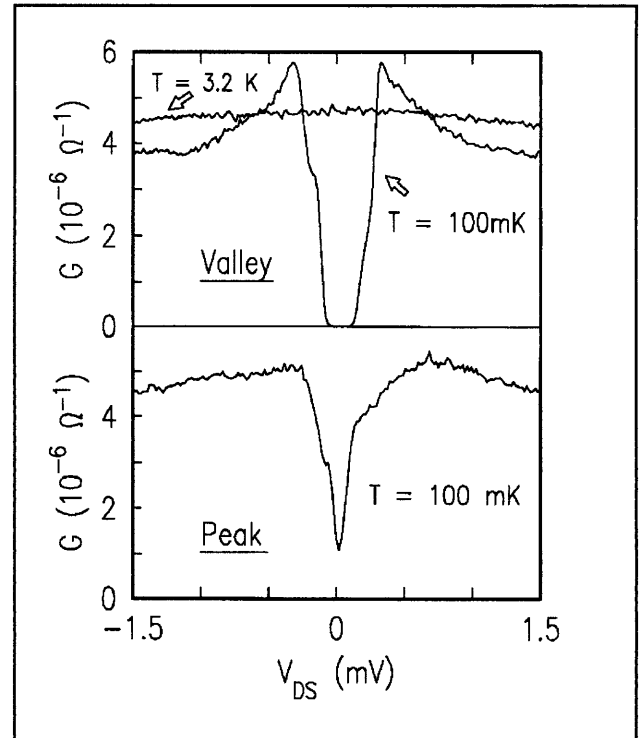

Figure 3. Differential conductance as a function of VDS at a minimum (upper panel) and maximum (lower panel) in the region of large conductance oscillations for the 10 mm channel (top panel, figure 2).

centers whenever the mean density is consistent with an integer number of electrons between the two centers; this will result in a periodic oscillation of the pinning energy and pinning field for any pair of pinning centers. The most strongly pinned segment will limit the current, and it is the periodic activation energy and pinning field of that segment that will be observed. Of course, several segments may have comparable pinning energies, and this may explain the multiple periods sometimes observed. If, as we have argued, the charge density modulation is near that of the Wigner crystal, the period of the CDW will be independent of magnetic field, as observed. This would then be the first clear observation of Wigner crystalization in a degenerate electron gas.

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9 P.A. Lee and T.M. Rice, *Phys. Rev. B*19:3970 (1979) and references therein.