Conductance Oscillations Periodic in the Density of a One-Dimensional Electron Gas

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By use of x-ray lithography Si inversion layers have been fabricated with width ~25 nm and mobility ~15000 cm^2/V s. These display oscillations in their conductance that are periodic in the number of electrons per unit length, even in zero magnetic field. The oscillations reflect an oscillatory activation energy of the conductance and are accompanied by unusual nonlinearities suggestive of pinned charge-density waves.

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A variety of novel lithographic techniques have been used[1-4] to create quasi-one-dimensional inversion layers in Si metal-oxide-semiconductor field-effect transistors (MOSFET's), in order 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,[4,5] seen in quasi-one-dimensional metals as well,[6] and the former result from one-dimensional variable-range hopping.[1,7] Among the inversion layers studied to date, those with smaller width w generally[4] had lower mobility ($\mu \sim 3000$ cm^2/V s is typical for $w \sim 40$ nm). We report here studies of narrower inversion layers ($w \sim 25$ nm) with higher μ (15000 cm^2/V s) that reveal 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 with a dual gate device (Fig. 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, as discussed below. The gap in the lower gate was created with x-ray nanolithography and liftoff.[8] The lower gate was made of refractory metal in order that damage 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 s at 4.2 K for two-dimensional (2D) MOSFET's on the same wafer subjected to the same processing steps as the narrow devices. This corresponds to a mean free path of ~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 is reported elsewhere.[8]

Measurement were performed at temperatures of 100 mK to 3.2 K in a dilution refrigerator equipped with an 8-T superconducting magnet. The conductance of the inversion channel was measured with an ac lock-in method at a frequency of 28 Hz and a drain-source voltage smaller than kT/e to avoid electron heating. In most measurements the upper gate voltage was swept, with the lower gate held at a fixed voltage. A variety of sweep rates were used, and dc measurements were also made; the results were identical except for an increased level of noise at dc. The samples were always cooled down from ~20 K with the narrow channel inverted and the lower gate biased close to the value used during the experiment so that the depletion layer of the device was well established.

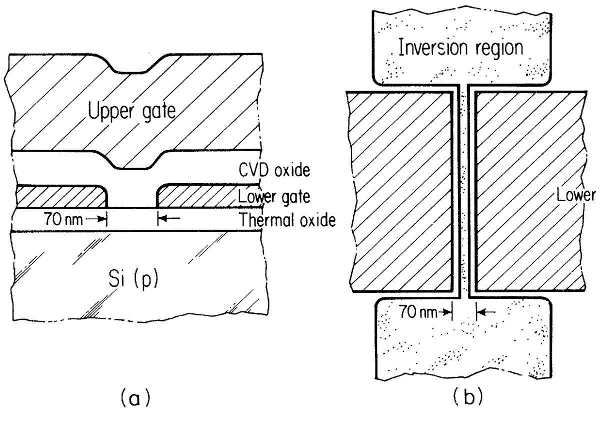

FIG. 1. (a) Schematic cross section and (b) top view of the slotted-gate device. The inversion layer, formed by the positively biased upper gate is confined by the lower gate. The thermal oxide and refractory metal lower gate are both 30 nm thick, and the chemical vapor deposition oxide is 45 nm thick. The width of the narrow inversion layer is exaggerated in (b).

The top panel of Fig. 2 shows G for a 10-μm-long MOSFET as a function of the voltage on the upper gate V_G, which is proportional to the number of electrons per unit length. The periodic oscillations can be clearly identified, although they are accompanied by random, noiselike fluctuations also seen in earlier quasi-one-dimensional 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, 2, and 1 μm lengths. Each device has a peak in its spectrum at a nonzero frequency, but the frequency of the peak varies in no systematic way with sample length. Indeed, we measured two different 2 μm devices that display frequencies differing by more than a factor of ~ 2. 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. Earlier devices with $w \sim 100$ nm and $\mu \sim 8000$ cm^2/V s have power spectra with only a zero-frequency peak, whose width is the correlation function of the random fluctuations.

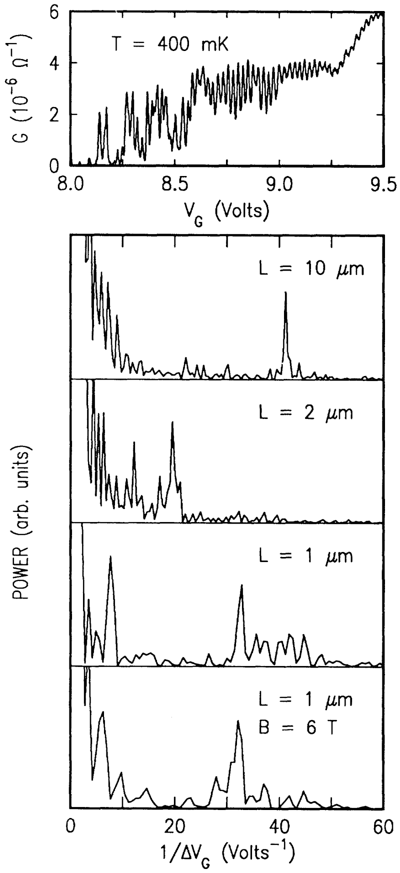

FIG. 2. Top panel: G vs V_G for a 10-μm-long inversion layer. Next three panels: Fourier power spectra of the data of the top panel and for 2- and 1-μm-long channels. Bottom panel: Fourier spectrum for the 1-μm-long channel in a magnetic field.

It should be stressed that the periodicity in Fig. 2 is observed in the absence of a magnetic field. In fact, for fields up to 8 T [applied normal to the (100) Si wafer] the frequency is independent of field, as can be seen in the bottom panel of Fig. 2. The peak in the transform actually sharpens with increasing magnetic field, apparently because the random fluctuations are reduced. It is significant, as discussed later, that the peaks in G vs V_G do not split as B is increased from 0 to 8 T.

The temperature dependence of the oscillations is most clearly examined by plotting the conductance at one pair of the periodic maxima and minima near threshold. This is done in Fig. 3. At the minimum the conductance is approximately thermally activated with activation energy ~ 50 μeV. At the maximum, the temperature dependence is much weaker, but the conductance does decrease by a factor ~ 4 between 1 and 0.1 K. Thus, the oscillations in G correspond to a periodic variation of the activation energy of the conductance.

So far we have discussed the dependence of G on V_G in the limit of very small V_{DS}. The dependence of G on V_{DS} is striking, as seen in Fig. 4. Shown there is the differential conductance, measured by applying a small modulation voltage (2 μV) in addition to the larger, continuous V_{DS}, while the latter is varied at fixed V_G. Data are shown at 3 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 ~ 0.2 V/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.

Before discussing possible explanations of the oscillatory behavior, it is important to estimate the capacitance and one-electron subband structure of our channel. Fortunately, our geometry is quite close to that examined in detail by Laux and Stern.[9] They found that a continu-

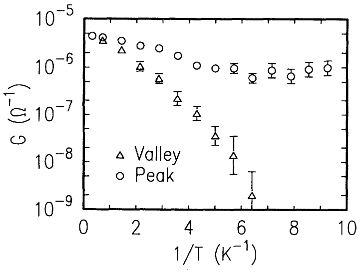

FIG. 3. Temperature dependence of a maximum and a minimum in the region in which the oscillations are exponentially large (i.e., near threshold) for the 10 μm channel (top panel, Fig. 2).

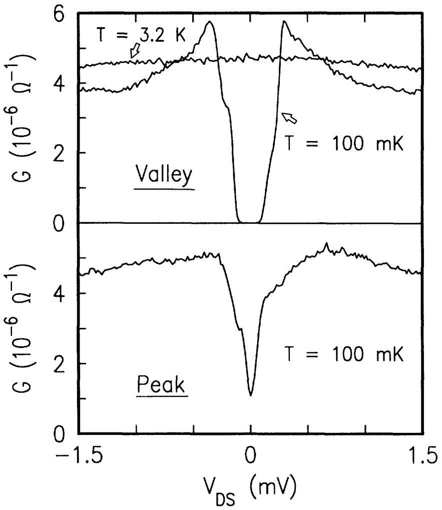

FIG. 4. Differential conductance as a function V_{DS} at a minimum (upper panel) and maximum (lower panel) in the region of large conductance oscillations for the 10-μm channel (top panel, Fig. 2).

um calculation gave results for the charge per unit length as a function of V_G almost identical to those of their self-consistent solution of the Schrödinger and Poisson equations. Using a similar continuum calculation we find the capacitance per unit length of our device is 7×10^5 electrons/cm per volt above threshold, and the width is 30 nm, almost independent of gate voltage. This width is in good agreement with the value 25 nm, obtained by scaling the conductance to that of a 2D device, at the same gate voltage above threshold, at 77 K. It is also close to the value of w estimated from sketches of the potential and wave functions in Ref. 9. Using our calculated capacitance per unit length, we can find the length associated with the period of the oscillations in Fig. 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 μm.

In the absence of a self-consistent calculation of the subband structure for our precise gate-electrode configuration, we assume that the subband level spacings will be approximately the same as those of the geometry in the calculation of Laux and Stern. They found that the Fermi energy lies in the lowest-subband for motion transverse to the narrow channel if the electron density is less than $\sim 10^6$/cm, which for our device corresponds to about 1.5 V above threshold. We conclude that the gate voltage range in which strong periodic oscillations are observed coincides with the dynamically one-dimensional regime.

One might propose that the periodic conductance arises from an interference phenomenon, like that for light in a Fabry-Perot interferometer. Suppose that charges that lie directly above the channel cause backscattering of the inversion-layer electrons with probability near unity. If these are δ-function scatterers, such backscattering would lead to a set of transmission resonances periodic in Fermi wave vector k_F or, equivalently, the number of electrons per unit length, n_L. The activation energy for conductivity would be large when E_F lies midway between two resonances and small when it coincides with a resonance. Such a model appears to make predictions, however, which are inconsistent with our observations. First, one would expect a series of steps in the current as a function of V_{DS}, one step whenever E_F passes a new resonance. Only one step is observed, as is evident from the single peak in the differential conductance of Fig. 4. Second, the energy separation of the levels is predicted to be proportional to n_L, whereas the activation energy is found to decrease with n_L. Third, the resonances are predicted to split in a magnetic field. The spin splitting is ~ 100 μeV at $B=1$ T for $g=2$, so by 8 T the spin splitting should be much larger than the energy spacing of the resonances, estimated to be ~ 100 μeV from the activation energy in the minima (Fig. 3) or directly from the model. Last, this resonance spacing is smaller than the average random potential, so the periodic activation energy is not expected to survive in this disordered system. For all these reasons, it is difficult to devise any one-electron explanation for the periodic oscillations we observe.

A model which explains more of 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 wave vector $2k_F$. The nearest-neighbor Coulomb interaction between electrons in the inversion layer is ~ 15 meV at $n_L = 10^6$/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 (Fig. 4) could result from depinning by the field, and the threshold field (~ 0.2 V/cm) is the same size as that found[10] for the well-studied CDW system, $NbSe_3$. It is because of this behavior that we argue for a charge rather than spin-density wave. 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.[10] 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 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. Since the system is one-dimensional, the CDW can slide only if it is free to slide everywhere along the channel. The most strongly pinned segment will, therefore, 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. Experiments are under way to search for the narrow-band noise and ac conductivity which are indicative of charge-density wave formation.

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