Conductance in Restricted-Dimensionality Accumulation Layers

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Conductance has been studied in metal-oxide-silicon field-effect transistor accumulation-layer samples in which it is possible to constrict the channel to small dimensions both perpendicular to the surface and perpendicular to the channel. A temperature-dependent conductance $\sigma = \sigma_0 \exp[-(T_0/T)^n]$ is observed, where $n = \frac{1}{2}$ for small channel widths and $n = \frac{1}{3}$ for larger channel widths. It is believed that this behavior arises from a transition from one-dimensional to two-dimensional variable-range hopping in the sample.

For the past 16 years inversion layers in metal-oxide-silicon field-effect-transistor (MOSFET) structures[1] have been used to study the properties of two-dimensional systems. These structures are particularly useful because it is possible to vary the Fermi energy in one sample by simply changing the externally applied gate voltage. A change in gate voltage changes the carrier concentration, N_S, which fills the available states in the sample. In this Letter we report the results of an experiment in which an attempt has been made to change the dimensionality of the electrons in an accumulation layer from two dimensions to one dimension by using a novel electrode configuration in a single sample. This was done by confining the accumulation-layer channel to a lateral dimension small compared to a relevant length in the problem. This relevant length would be expected to be a mean free path for electrons if the electrons are free, a Thouless length[2] for weakly localized electrons, or the most probable hopping or tunneling length if the electrons are strongly localized.

The most obvious way to effect such a confinement is to use a gate that is narrow and is very close to the semiconductor. This requires the use of techniques that are difficult but possible with use of silicon technology. We have studied another type of device modeled on an experiment in which Pepper[3] reduced the dimensionality for impurity-band conduction in GaAs from three dimensional to two dimensional by pinching down the conduction channel in a metal-semiconductor field-effect-transistor structure. There the reverse bias on a Schottky junction increased the depletion charge and reduced the thickness of the channel. In our samples, which are similar to samples proposed by Pepper,[4] the same principle is used.

Both a plan and a section of our samples are shown in Fig. 1. The device consists of a lightly doped n-type silicon substrate, n^+ source and drain contacts, p^+ "control" electrodes, and an Al gate over a 300-Å oxide. An n-channel MOSFET is operated in accumulation rather than in inversion, which limits the available temperature to ≤ 10 K where the 10-Ω-cm substrate is
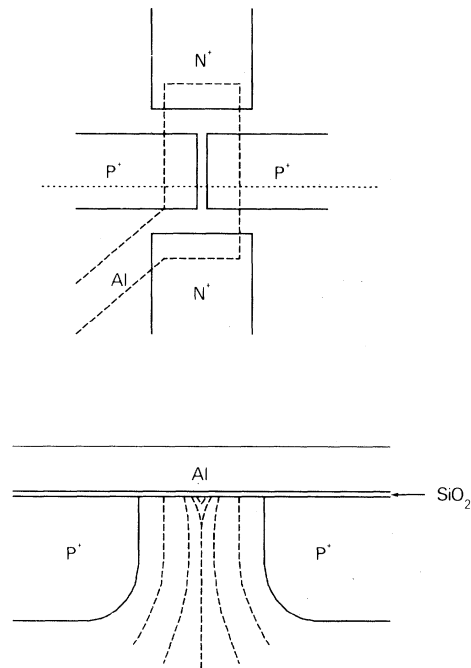

FIG. 1. The upper part shows an idealized plan of a sample. The two n^+ regions are the source and drain. The p^+ regions are the control electrodes. In this case the n-type substrate was 10-Ω-cm Si. The width between the controls was 1–2 μm. The length of the controls is 14 μm. The lower part shows a section through the device along the dotted lines. The diffusions were about 1 μm deep and the oxide was 300 Å thick. Potential lines are sketched for a positive gate voltage.

frozen out (the donors are not ionized). The control electrodes were made by using p^+ diffusions on the sides of the channel. The depletion charge arising from the junction between the control electrodes and the substrate can then be used to pinch off or constrict the channel. In the samples used the width between the control electrodes was about 1 μm so that even without a negative bias the channel was pinched off.

When a sufficiently high gate voltage is applied, the first electrons induced will occupy a narrow channel near the center of the structure as shown schematically in the cross section in Fig. 1. As the gate voltage is increased above the threshold for conductance the channel will broaden. If the channel is narrow enough at low gate voltages to be considered as one dimensional, it may broaden enough at high gate voltages to be considered two dimensional. At such high gate voltages, application of a negative control bias should be expected to narrow the channel and again reduce the dimensionality. Thus one might hope to observe a transition in dimensionality in two ways.

These samples were studied from 0.05 to 8 K, although most measurements were made below 4 K. The conductance was found to increase as a function of gate voltage (V_g) approximately as $\exp(-A/V_g)$, with A, a constant, increasing as the temperature was lowered. Typical data are shown in Fig. 2. Even at the highest gate voltages a strong temperature dependence was seen so that surprisingly no metal-insulator transition was observed. The highest gate voltages correspond to $N_S \approx 5 \times 10^{12}$ cm^{-2}. Activated behavior has never been observed above $N_S \approx 1 \times 10^{12}$ cm^{-2} in any other two-dimensional inversion layer. Even if we use the full channel width of 1 μm to calculate the surface conductivity, it is larger than the minimum metallic conductivity (or transition to weak localization) seen in any two-dimensional samples.

Another striking characteristic of the data is that there is strong, reproducible structure in the conductance with gate voltage. This structure is dense in the gate voltage and shows no discernible pattern so that we do not believe that it corresponds to the variations in the density of states arising from a ladder of subbands in a one-dimensional free-electron model. The structure increases as the gate voltage is decreased and varies from sample to sample. It shifts as the control voltage is changed so that it is associated with the narrow channel and not with the source or drain contacts. As the temperature is
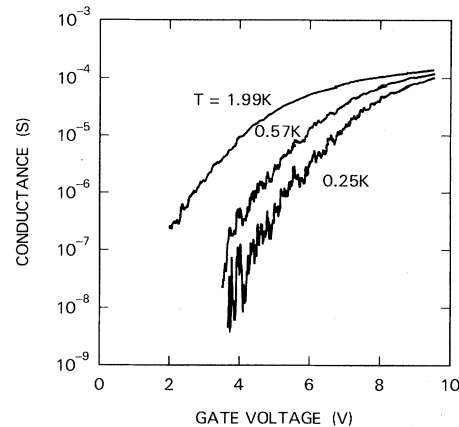

FIG. 2. Conductance as a function of gate voltage for three temperatures.

lowered, the gross structure remains at the same values of V_g and increases in relative amplitude, while even finer structure becomes resolved. As an example one splitting of a single peak into two peaks is observed to occur at about $V_g = 4.6$ V and 1 K. The gate voltage difference between the peak and the valley is 0.05 V. For a two-dimensional density of states this change in N_S corresponds to a change of the Fermi energy of about $k_B T$. Thus it might be reasonably inferred that the conductance structure corresponds to structure in the density of states. It will be argued below that the channels are 100–1000 Å wide. The length of the sample is about 10 μm. Therefore one might expect 10^3 to 5×10^4 electrons or bound states in the channel, so that the statistics would give large structure in the density of states. This structure might be expected to be relatively larger for low gate voltages which correspond to energies low in the band tail.

A narrow channel less than 1000 Å wide is consistent with the absence of magnetoconductance oscillations. In fact no qualitative change was observed in the structure up to 5 T at 2 K. If the structure had been due to a one-dimensional quantization of the electron gas, then the structure should have changed with magnetic field.

Extensive studies were made of the temperature dependence of the conductance for different gate and control voltages. Typical data measured at conductance minima are shown in Fig. 3 for the control electrodes and the substrate grounded to the source. These data were obtained with use of a source-drain signal of 3 μV. The current was Ohmic to more than 10 μV at all temperatures. It was found to be extremely important to elimi-
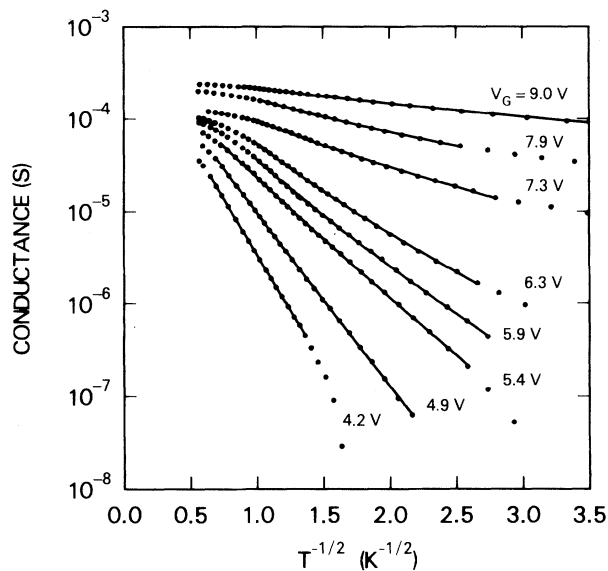
FIG. 3. The log of conductance plotted as a function of $T^{-1/2}$ for various gate voltages (V_g) with the substrate and controls grounded to the source. The solid lines are the best least-squares fits to the data.
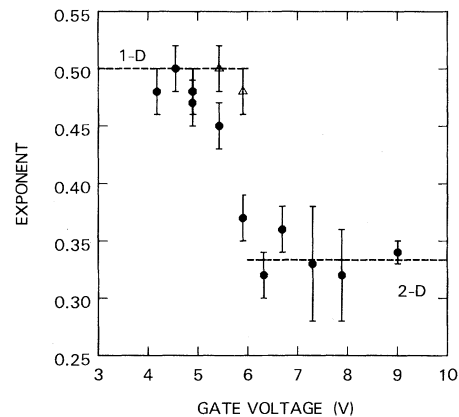

FIG. 4. The power laws that best fit the data in Fig. 3 as a function of gate voltage. The error bars are estimated by deleting points from the ends of the fits. The error from the least-squares fit parameters is better. The open triangles are fits to a restricted low-temperature range only.

nate all sources of noise that could heat the electrons. Measurements were made to currents as low as 10^{-13} A.

These data are shown plotted as $\ln\sigma$ vs $T^{-1/2}$ in Fig. 3. Such a plot gives a straight line for the low–gate-voltage range except at the highest temperatures, where the conductance appears to be simply activated. At higher gate voltages the curves are not as well rectified on this plot as on a plot against $T^{-1/3}$.

To determine the best exponent for a particular gate-voltage curve, least-squares fits were made to the curves eliminating the highest-temperature data and also the lowest-temperature points when the measurement error was large. The exponent, n, in the relationship $\sigma = \sigma_0 \exp[-(T_0/T)^n]$ was varied to find the fit with the smallest square deviation. These fits were quite sharp at the best value of n. The sums of the squares of the deviations always differed by factors of more than 3 between the "best" value, n, and $n \pm 0.15$.

The values of the exponent, n, are shown plotted as a function of gate voltage in Fig. 4. It may be seen that there is a surprisingly sharp transition from $n = 0.5$ to $n = 0.33$ at $V_g \approx 5.9$ V. Near this gate voltage the higher-temperature data fit $n = 0.33$ better and the lower-temperature data fit $n = 0.5$ better. The points shown in the figure as the open triangles are these low-temperature fits.

The control voltage was varied to shift the position of this transition. A negative bias extended the range of $n = 0.5$ behavior to higher gate voltages. This was expected because the effect of such a bias is to constrict the channel as well as to shift the threshold. The transition is shifted much more than the threshold. We have also observed a transition from $n = 0.5$ to $n = 0.33$ with varying control voltage but constant gate voltage. The curve looks similar to Fig. 4.

Two different models must be considered as potentially explaining these results. The first is a transition from one-dimensional to two-dimensional variable-range hopping as the channel broadens. The other is that the hopping is controlled by Coulomb repulsion at low gate voltage and that the Coulomb gap is reduced at higher gate voltages, where the electron density is increased; then two-dimensional variable-range hopping obtains.

A simple model of one-dimensional variable-range hopping is that the channel has a width, w, so that the one-dimensional density of states, N_1, is about wN_2, where N_2 is the two-dimensional density of states. To be one dimensional w must be small compared to the most probable hopping distance, R, as defined by Mott.[5] Then T_0, occurring in $\sigma = \sigma_0 \exp[-(T_0/T)^{1/2}]$ is given by $4\alpha/N_1 k_B$, where α^{-1} is the decay length of the localized wave functions and $R = (4\alpha N_1 k_B T)^{-1/2}$. It should be noted that this assumes N_1 to be constant over $k_B T$ around the Fermi energy. We ob-

serve that T_0 varies between 8 and 40 K. When reasonable values[6] of $\alpha^{-1} \approx 100$–500 Å and N_2 $\leq 1.6 \times 10^{14}$ eV^{-1} cm^{-2} are inserted in these expressions, it is found that w is typically 200–500 Å and w/R is typically 0.1–0.5. Thus this explanation is at least plausible, given the approximations.

In the Coulomb-gap model[7] $T_0 = 8\alpha e^2/\kappa k_B$, where κ is the dielectric permittivity of the Si. When the full Coulomb potential is used to determine T_0, it is found that $T_0 = 280$ K. Thus for the Coulomb-gap argument to obtain the Coulomb potential would have to be reduced by a factor of about 10. The Coulomb-gap theory therefore would seem to be inconsistent with our data.

It has been theoretically shown[8] that simply activated behavior ($n = 1$) should be observed in a one-dimensional chain because there are no percolation paths and one large barrier will control the current. It has been argued[9,10] that in short enough samples no such blockades exist and that the $\ln\sigma \approx (T_0/T)^{1/2}$ law obtains. We are not convinced that the last theoretical word has been heard on this subject. Other experimental results[11] also seem to give $n = \frac{1}{2}$ for chains or narrow samples.

We do not have a plausible explanation as to why strong localization persists to such high values of N_S or gate voltage in these dimensionally restricted samples, even when they follow a two-dimensional variable-range hopping law. These samples do not lend themselves easily to a solution of Poisson's and Schrodinger's equation, so

that no simple model is at hand for the induced electron distribution in the accumulation layer. While we cannot argue conclusively that a transition from one-dimensional variable-range hopping to two-dimensional variable-range hopping explains these results, we favor this explanation as the simplest and most plausible.

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Observation of Rotational Excitations of H₂ Adsorbed on Ag Surfaces

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High-resolution electron-energy-loss studies of H₂ on Ag at ~ 10 K reveal both rotational and rotational-vibrational excitations of molecularly adsorbed and condensed H₂. The rotational losses for submonolayers of adsorbed H₂ indicate unhindered rotational motion as well as a H-H internuclear separation which is within ~ 2% of that of condensed H₂. Adsorbed H₂ is also converted from predominantly orthohydrogen to parahydrogen.

Several recent theoretical studies[1-5] have considered the interaction of molecular hydrogen with a metal surface. These studies have investigated the nature of bonding for a variety of metal-molecule bonding distances and molecular orientations, as well as the mechanisms of dissociation to form atomic hydrogen. Despite hydrogen's

apparent role as a simple theoretical prototype adsorbate, relatively little direct experimental information exists for comparison or for insight to such questions. Here, we report high-resolution electron-energy-loss studies of molecularly adsorbed and condensed H₂ on Ag films and a Ag(111) surface which provide new information as