# Nonmonotonic Variations of the Conductance with Electron Density in ~70-nm-Wide Inversion Layers

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The conductance of metal-oxide-silicon field-effect transistors with ~70-nm-wide inversion layers exhibits nonmonotonic variations with electron density below 15 K. The variations are largest at low electron concentrations and are the result of variations of the activation energy $E_A$. When $E_A$ is largest the current is found to be limited by spatial barriers which contain tunneling channels at discrete energies, as in the model of Azbel.

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Several groups[1-4] have observed nonmonotonic conductance variations with electron concentration in ultranarrow Si inversion and accumulation layers. These variations, seen at cryogenic temperatures, are the result of the quasi one-dimensional (Q-1D) structure of the devices, and are not, therefore, found in wide inversion layers. For devices which are narrow but are more than 100 nm wide, the variations are small and have been interpreted[2,3] in terms of the theories of weak localization and interaction. On the other hand, for devices less than 100 nm wide the variations can be very large, and it has been suggested[1,2] that they may result from statistical variations of resistance associated with strong localization. To investigate these large variations we have studied an inversion layer whose mean width is ~ 70 nm. By measuring the current as a function of both the temperature $T$ and voltage drop along the inversion layer $V_D$, we find that the current at low electron density is limited by tunneling through spatial barriers.

Our device is a metal-oxide-silicon field-effect transistor (MOSFET) on a (100) Si surface with a gate that is a narrow aluminum wire. When a gate voltage $V_G$ is applied, the electric field confines the electrons to a narrow potential well directly under the gate (see Fig. 1). The narrow gate is created by first reactive-ion etching a 50-nm step down into the 100-nm-thick gate oxide using photoresist as the mask, and then evaporating Al into the step at a glancing angle to the surface. Residual Al is removed by a liquid etch. The resulting gate is 70 nm wide and 55 nm high with a ~ 20% variation in width. Computer simulations suggest that the inversion layer has about the same width as the gate. As sketched in Fig. 1, wide gates overlap the $n^+$ regions so that electrical contact to the narrow inversion layer is made through ~1-mm-wide inversion layers. Electrical continuity of the gate is confirmed by measuring the resistance between the two wide parts of the gate that overlap the narrow one and are separated by 7 $\mu$m. Conventional (wide) devices were prepared simultaneously on the same wafer over an oxide which was also reactive-ion etched. These wide devices are found to have a fairly high mobility (8000 cm$^2$/V-s at 4.2 K).

For our narrow devices, increasing $V_G$, which is proportional to the electron concentration, causes the conductance to increase almost linearly at $T \gtrsim 15$ K. This is the same behavior seen at all temperatures in wide MOSFETs. However, as the temperature is reduced below ~15 K the conductance near threshold decreases, with precipitous drops at particular values of $V_G$ revealing the large variations in the conductance mentioned above (see Fig. 2). In Fig. 2 we show an expanded version of the structure near threshold. When $V_G$ is increased beyond the first few maxima the conductance decreases by as much as three orders of magnitude at 2 K with a gate-voltage change of 0.05 V. Note that the inversion layer contains only $10^3$–$10^4$ electrons because it is so narrow, and the large decrease in the conductance is achieved with an increase of $V_G$ cor-

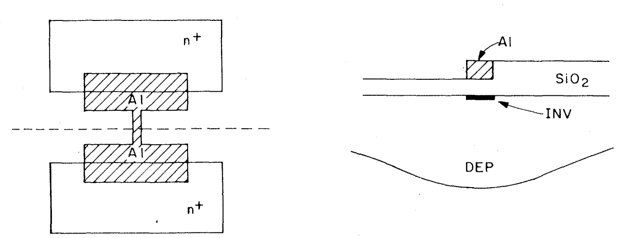


FIG. 1. Left: Schematic top view of the narrow-gate MOSFET. The resistivity of the $p$-type Si substrate is 3 Ω-cm. Right: Cross section through the device along the dotted line in the left figure. Shown are the narrow inversion layer situated under the narrow gate and the boundary of the depletion region.

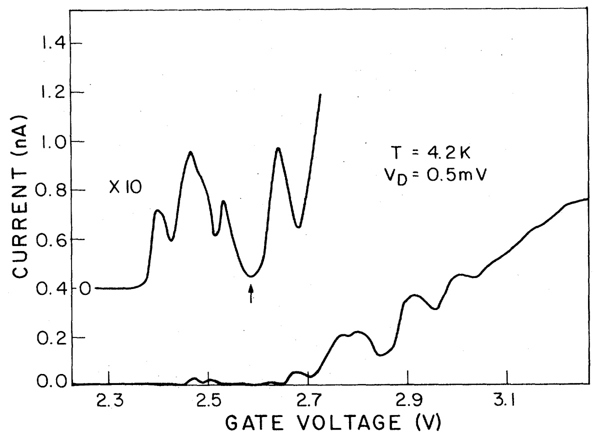


FIG. 2. Current vs gate voltage. The arrow indicates the gate voltage (2.585 V) of the deep minimum explored in this Letter.

responding to the addition of only ~200 electrons to the inversion layer.

We find that the pattern of conductance variations changes when the temperature is temporarily raised to $T \gtrsim 200$ K or when $V_G$ is temporarily raised by several volts above threshold. High, positive $V_G$ reduces the magnitude of the conductance variations, but application of high, negative gate voltage $V_G$ restores the original size, although not the original pattern. These observations suggest that the changes in the pattern are the result of diffusion of ions or electrons on or in the oxide at high $T$ and field-assisted tunneling of these charged species at low $T$. We infer that the random potential resulting from these charges strongly affects the pattern.

To study the variations despite their sensitivity to changes of $V_G$, we keep $V_G$ constant and vary only $T$ and $V_D$. We first focus on the $T$ dependence. At the conductance maxima the current decreases slowly as $T$ is lowered. If this $T$ dependence is fitted by an activated form the activation energy is always found to be less than ~1 meV. However, at the minima the current decreases rapidly. For example, for the valley at $V_G = 2.585$ V (indicated by the arrow in Fig. 2) we find that the current follows $\exp(-E_A/kT)$ with $E_A = 2.5$ meV in the limit that $V_D$ is less than ~1 mV (see Fig. 3). This large activation energy makes the conductance too small to measure below 2.5 K, and this limitation makes it impossible to distinguish between a simple activated form and that for variable-range hopping, $\exp[-(T_0/T)^{1/2}]$. We conclude that the large variations in current with $V_G$ seen at low $T$ are the result of

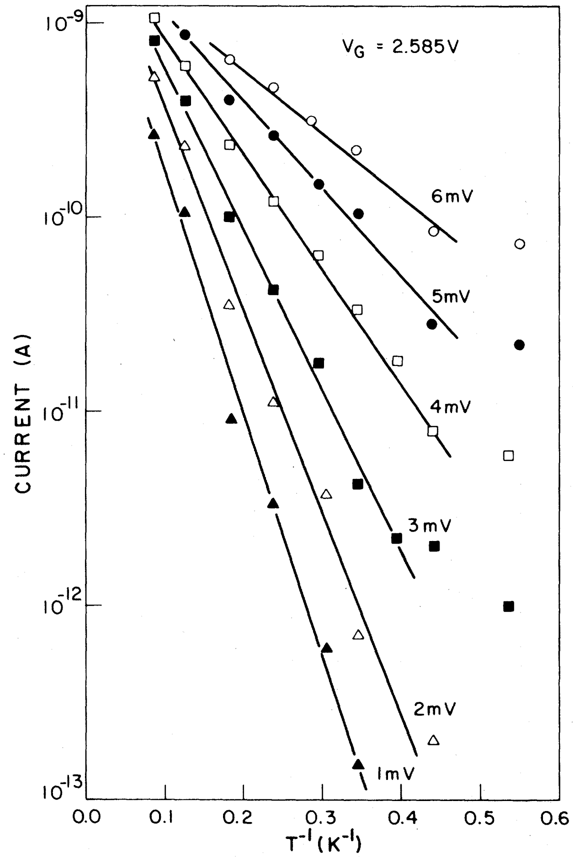


FIG. 3. Logarithm of current vs inverse temperature at six values of $V_D$. The precision is ±0.2 pA.

variations in the activation energy, even if that energy depends on $T$ as in variable-range hopping.

As can also be seen from Fig. 3 the activation energy decreases with $V_D$. We find that, albeit with some deviation[5] at the lowest $T$, we measure

$$E_A = E_0 - fe\,V_D, \tag{1}$$

where $E_0$ is the energy in the limit $V_D = 0$, and $f$ is the fraction of the voltage which lowers $E_A$. Equation (1) implies that the current increases exponentially with $V_D$, and this is clearly seen in Fig. 4. Of course, the current cannot depend exponentially on $V_D$ to arbitrarily small $V_D$ but is found to be proportional to $V_D$ for $V_D \lesssim kT/ef$. The exponential dependence cannot extend to arbitrarily high $V_D$ either. For the data of Fig. 4, $I$ increases less rapidly when $V_D \gtrsim 6$ mV or, equivalently, when $E_A$ is reduced to ~1 meV. The lower inset of Fig. 4 shows that at the highest $V_D$ the current increases with a constant

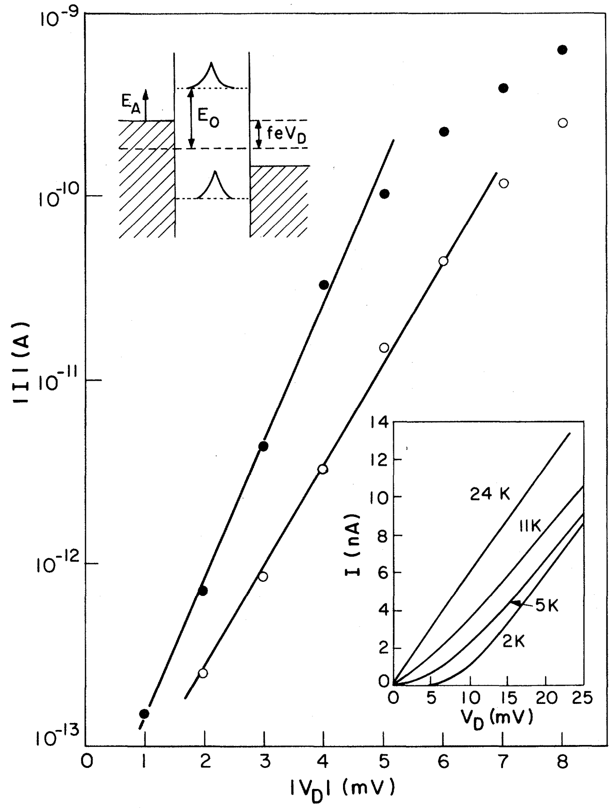


FIG. 4. Logarithm of current vs $V_D$ at 2.9 K and $V_G = 2.585$ V for both polarities of $V_D$. Lower inset: Linear plot of the current as a function of $V_D$ at four temperatures. Upper inset: Schematic view of the spatial barrier described in the text, here depicted with metallic conductors on both sides. Localized wave functions are sketched at the energy levels (dotted lines) of the tunneling channels. $V_D$ separates $E_F$ on the two sides and reduces $E_A$.

differential conductance. In these linear plots of $I$ vs $V_D$ the exponential part of the curve results in an apparent threshold voltage above which $I$ increases linearly with $V_D$.

The exponential increase of $I$ with $V_D$, the most surprising new result of this study, cannot be the result of electron heating. Since the conductance is thermally activated, thermal switching[6] would be observed at low $T$ if the heating were sufficient to increase the conductance by more than a factor of $\sim 3$. Figure 4 shows that the current increases by more than $10^3$, and no such instability is observed. Furthermore, electron heating would not give the activated behavior seen at high $V_D$ in Fig. 3. Electron heating is negligible because the conductance at the deep minimum is $\sim 10^3$ smaller than at the adjacent maxima and since the electron density is almost the same, the heating at the minimum is orders of magnitude smaller than the few degrees expected[7] at the maxima.

Azbel's model[8] of resonant tunneling through a disordered 1D system explains many of our observations. In that model the current is carried by tunneling through the entire sample via localized electronic states. States near the middle of the sample dominate the current since the transmission through them is exponentially larger than for states elsewhere. When the Fermi energy $E_F$ coincides with the energy of such a state, the current will be high. However, if $E_F$ is moved below (above) such a level, the current will be proportional to the thermally activated number of electrons (holes) that are still resonant with the localized state. Since the fraction of states with such high transmission is small the energy separation between them, and consequently the activation energy for off-resonance conduction, is large.

The strong dependence of $I$ on $V_D$ can be explained with a simple extension of Azbel's model. As sketched in the upper inset of Fig. 4, the application of a voltage will reduce the activation energy determining the number of electrons (holes) which are resonant with states above (below) $E_F$. This is described by Eq. (1) and causes the exponential dependence seen in Fig. 4.

In Azbel's model the tunneling barrier is the entire disordered sample. Our observations suggest, however, that our barriers are shorter than the overall length of the device (7 $\mu$m). As can be seen in the lower inset of Fig. 4, the current at high $V_D$ is characteristic of that limited by a conventional resistor in series with a spatial barrier (e.g., a $p$-$n$ junction). This limiting resistance is approximately that at the peaks adjacent to the deep conductance minimum, suggesting that most of the channel has this larger conductance, and that at the deep minimum one subsection of the channel has a particularly high resistance at low $V_D$. This, in turn, suggests that the sample is not a single barrier but rather a chain of barriers of various level spacings and resistances at each fixed $E_F$. Furthermore, since the current appears activated even at the peaks, they cannot be attributed to resonances for tunneling through the entire sample. Rather, at these values of $E_F$ all the activation energies of the barriers along the channel happen to be small. Under such circumstances the voltage probably falls across several current-limiting barriers, whereas the accurately exponential dependence in Fig. 4 indicates that for the largest $E_0$ only one barrier is involved.

As already mentioned, we cannot distinguish between the forms $\exp(-E_0/kT)$ and $\exp[-(T_0/T)^{1/2}]$ at the deepest minimum because of the large value of $E_0$. Both the variable-range hopping model[1] and the Azbel model[8] predict the latter form. However, the strong dependence on $V_D$ appears to be in conflict with variable-range hopping. For that case the effective activation energy (which depends on $T$) is predicted to decrease by $feV_D$, as is found experimentally, but with $f$ somewhat smaller than the ratio of the hopping distance to the sample length.[9] Our value of $f \gtrsim 0.3$ is much larger than this for any reasonable estimate of the hopping distance.

At most of the conductance minima as well as the maxima, the activation energy is $\sim 1$ meV. The reason for the extraordinarily large $E_0$ at the deep minimum near threshold is not clear. The energy spacing of levels within a localization length of midsample (the high-transmission resonance in Azbel's model) is $\sim(g\lambda)^{-1}$ where $g$ is the density of states at $E_F$. The random potential, to which the conductance variations appear so sensitive, may be inhomogeneous, causing variations of $g$ or $\lambda$ from point to point along the ininversion layer and thus leading to the anomalously large $E_0$.

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[1]A. B. Fowler, A. Hartstein, and R. A. Webb, Phys. Rev. Lett. 48, 196 (1982).

[2]W. J. Skocpol *et al.*, to be published.

[3]R. G. Wheeler, K. K. Choi, A. Goel, R. Wisnieff, and D. E. Prober, Phys. Rev. Lett. 49, 1674 (1982).

[4]M. Pepper and M. J. Uren, J. Phys. C 15, L617 (1982).

[5]Temperature-independent tunneling might account for the excess current at low $T$.

[6]J. J. O'Dwyer, *The Theory of Dielectric Breakdown of Solids* (Oxford Univ. Press, London, 1964), p. 47.

[7]R. A. Höpfel and E. Gornick, to be published.

[8]M. Ya. Azbel, Solid State Commun. 45, 527 (1983).

[9]M. Pollak and I. Riess, J. Phys. C 9, 2339 (1976).