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Probing the density of states in a metal-oxide-semiconductor field-effect transistor

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Tunneling spectroscopy was used to probe the density of states in a metal-oxide-semiconductor field-effect transistor that has tunneling contacts for the source/drain electrodes. For long channel transistors, the density of states of the two-dimensional gas exhibits a logarithmic dependence, consistent with weak electron interactions in the diffusive regime. For smaller devices deviations from this dependence were observed and attributed to screening from the nearby source/drain electrodes.

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Quantum-mechanical tunneling of electrons provides a powerful spectroscopic technique in probing the energetics of different materials.[1] A commonly observed effect in a diffusive metal or semimetal is the logarithmic singularity of the conductance around zero bias, known as the zero-bias anomaly (ZBA). It has been studied intensively for over 20 years because it is often a clear signature of electron-electron interactions[2] that are difficult to detect otherwise. In very clean high mobility two-dimensional (2D) semiconductors, such interactions are made stronger and thought to lead to a two-dimensional metal-insulator transition.[3,4] Although there are numerous theoretical treatments of the density of states (DOS) in a two-dimensional gas (2DG),[2–11] direct experimental verifications in semiconductors are mainly in high mobility GaAs/AlGaAs quantum well structures.[12–14] In this Brief Report we use electron-tunneling spectroscopy in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) with tunneling source and drain contacts[15] to directly explore the DOS of the 2DG. We find that for long channel devices the expected logarithmic dependence is observed but that for small devices screening from the source and drain electrodes can have a strong effect.

The transistor geometry is depicted schematically in the inset of Fig. 1. The device has metallic PtSi source and drain electrodes, which form a depletion width in the semiconductor near the metal/semiconductor contact, and at low temperatures results in tunneling from the metal to the semiconducting channel. The devices were fabricated at National Semiconductor[16] and are from the same wafer as in previous research.[17,18] Accumulation layers with a boron concentration of 5×10^{21} m^{-3}, a 34 Å gate oxide, and ~300 Å of PtSi for the source/drain contacts were used. The samples were mounted in a dilution refrigerator and measured at 50 mK using a standard lock-in technique. We investigated ~20 different MOSFETs with different channel lengths and widths and here discuss two representative devices.

We consider devices in three transport regimes,[19] which are defined based on the relative value of the channel length l and the depletion width $w_d=\sqrt{\frac{2\varepsilon_s}{qN}(\varphi_{ib}-V)}$ at the source and drain, ignoring the influence of the gate. Using standard semiconductor equations and appropriate boundary conditions, we calculate the potential between the source and drain for different size channel lengths, as shown in Fig. 1(b). In the *long channel regime* $l>2w_d$, the semiconducting channel is well defined and is typical of that in a conventional long channel MOSFET. For $\frac{w_d}{2}>L>2w_d$ the device is in the *reach-through regime* because the two depletion widths at the source and drain overlap. In the *flat-band regime*, $L<\frac{w_d}{2}$, at $V_g=0$ V an electric field extends throughout the entire channel length.

The current path through the device consists of three steps: (1) tunneling from the drain into the semiconductor, (2) transport through the semiconducting channel, and (3) tunneling from the semiconductor into the source. The temperature dependence at very small drain source bias V_{ds} bias reveals that transport is limited by tunneling through the depletion widths at the source and drain.[20] To describe this we write

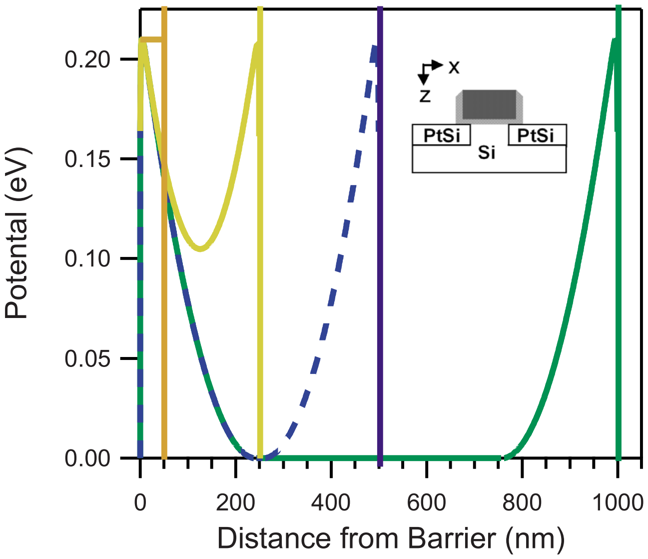


FIG. 1. (Color online) Electrostatic potential for transistor channel lengths of 1 (long channel regime), 0.5 (reach-through regime), and 0.25 μm (reach-through regime), and flat-band regime (0.05 μm) assuming that the bands are not modified by the gate. Inset: schematic of the SBMOSFET device structure.

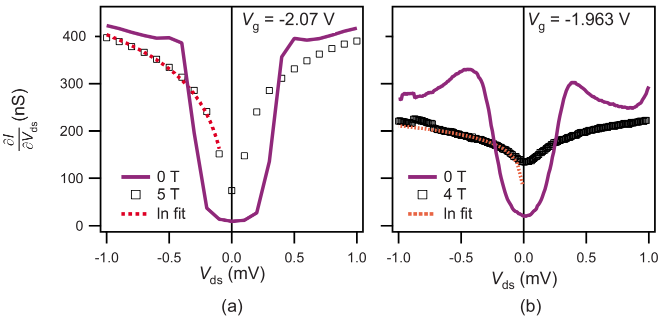
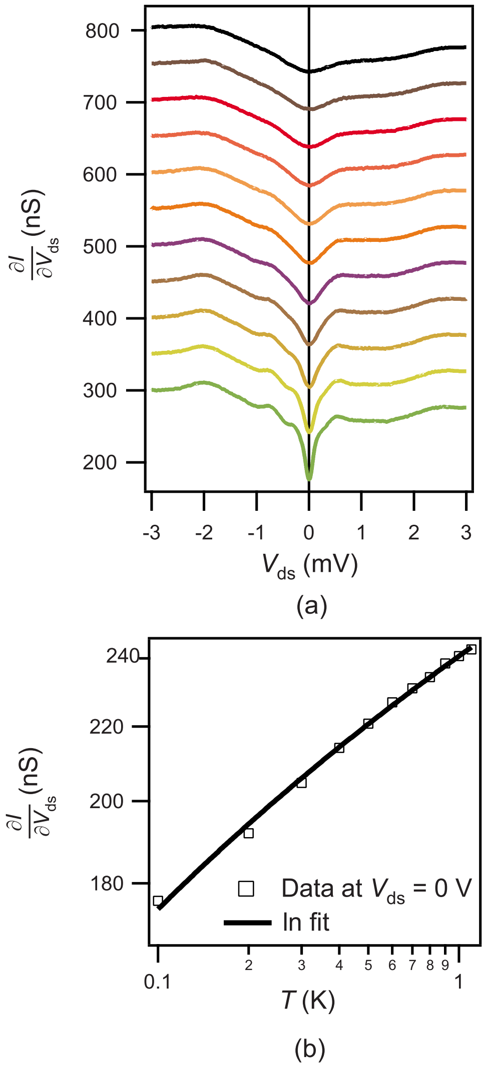


FIG. 2. (Color online) $\frac{\partial I}{\partial V_{ds}}$ versus V_{ds} characteristics for transistors with similar aspect ratios but in the (a) long channel (channel width/channel length=10 μm/2 μm) and (b) reach-through (channel width/length=5 μm/0.3 μm) regimes. Values of V_g were chosen so that the characteristics were not resonant with a single impurity located in the Schottky barrier (Ref. 19). The fitting parameters are: (a) $f(x)=a\ \ln(bx)$: $a=3.94\times10^{-7}\pm2.4\times10^{-9}$ S, $b=9.63\times10^{-8}\pm2.8\times10^{-9}$ mV^{-1}, and for (b) $f(x)=a\ \ln(bx)$: $a=3.624\times10^{-8}\pm5.6\times10^{-10}$ S, $b=470\pm42$ mV^{-1}.

$$J=\int_0^\infty dEn_1(E)n_2(E+eV)P(E)f(E)[1-f(E+eV)], \quad (1)$$

where $P(E)$ is the tunneling transmission probability and $n_{1,2}(E)$ is the density of states of the material on either side of the depletion width. Previous research[17,18] focused on transport dominated by $P(E)$ and especially on resonances that occur when the gate voltage V_g aligns the electrochemical potential in the metallic electrode and semiconducting channel with the resonant level of an impurity. Off resonance, $P(E)$ can be approximated by the WKB probability for a triangular barrier: $P(E)\propto\exp(\frac{(\Phi_b-V_{ds})^{3/2}}{F(E)})$, where $\Phi_b\approx0.2$ eV is the Schottky barrier height, and $F(E)$ is the electric field.[21] $P(E)$ is strongly dependent on gate voltage, which results in large changes in $F(E)$. At fixed V_g values, $P(E)$ is approximately constant for $V_{ds}\ll\Phi_b$. Thus for small V_{ds}, transport is strongly dependent on the density of states of the electrodes.

At low temperatures the PtSi becomes superconducting, and at low bias ($V_{ds}\leq2$ mV), a gap corresponding to the BCS density of states is observed. Figure 2 shows transport for devices in the long channel and reach-through regimes at 0 T and finite parallel field. The magnetic field suppresses the superconductivity but the current around zero bias is only partially restored. It now reflects the density of states of the semiconductor. We note that, for 0.4 T$<B<$5 T, $\partial I/\partial V_{ds}$ is weakly reduced but that its functional dependence on V_{ds} is not altered. In the diffusive transport regime in 2D, Altshuler *et al.*[5] showed that a logarithmic correction to the density of states $[n(E)\propto\ln(E\tau/\hbar)]$, where τ is the relaxation time, and conductivity $[\sigma(E)\propto\ln(T)]$ is possible for a weakly disordered and interacting 2D system. Further research showed that strongly interacting high mobility systems can lead to a metal-insulator transition,[3,4] a striking result because traditional localization says that such transitions are only possible in three dimensions. In closely related theoretical work, the density of states of the 2DG has been investigated in the quasiballistic regime at various degrees of disorder.[6,9–11] One research direction explored this limit nonperturbatively using path-integral techniques. They found that the DOS is suppressed but not singular, and that this suppression increases with decreasing electron density and is weakened by the screening from a gate electrode.[10] Another paper considered similar potentials using diagrammatic perturbation theory so as to obtain analytic expressions in the weak- and strong-interaction limits.[11] The devices considered here should be weakly interacting because of the relatively low mobility, and therefore the expected form of the zero-bias anomaly should be logarithmic as long as the channel remains diffusive.



(a)

(b)

FIG. 3. (Color online) (a) $\frac{\partial I}{\partial V_{ds}}$ versus V_{ds} characteristics at $V_g=-2$ V and 1.26 T for the device in Fig. 2(b), measured in a different cooldown. The temperatures range from 0.1 (lowest curve) to 1.1 K (upper curve) in 0.1 K steps. For clarity the curves are displaced along the y axis. (b) $\frac{\partial I}{\partial V_{ds}}$ at $V_{ds}=0$ V as a function of temperature. The solid lines are fits to: $f(x)=a\ \ln(bx)$: $a=2.888e-008\pm5.1e-010$ S and $b=4160\pm562$ mV^{-1}.

For long channel devices, we found that transport is indeed consistent with a logarithmic density of states, as shown by the solid fitted line in Fig. 2(a). Here V_g must be much greater than the threshold for conduction in the channel in order to have a sufficiently large tunneling current through the Schottky barrier; however its presence prevents the direct measurement of the channel resistance in this device. We observe a logarithmic density of states for $-2.5\ \text{V} < V_g < -1.5\ \text{V}$, indicating that conduction through the channel is most likely diffusive. This interpretation is consistent with previous work on MOSFETs in which the resistivity showed a logarithmic temperature dependence when the channel was ohmic.[22] The logarithmic density of states has been directly observed in AlGaAs/GaAs heterostructures[14] but this is the first time it has been directly observed in a MOSFET.

For devices in the reach-through regime, an example of which is shown in[Fig. 2(b), we found a weaker suppression around zero bias. Although the logarithmic dependence works well for $V_{ds} > 0.1\ \text{mV}$, around zero it strongly deviates. We found that a logarithmic fit captures the temperature dependence at $V_{ds}=0$, as shown in Fig. 3. We have measured several devices in the flat-band regime and typically found similar results.

This can be explained by considering the effect of screening of a nearby electrode.[7,23] For long channel SBMOSFETs, the ZBA, due to tunneling from the drain into the semiconductor and from the semiconductor into the source, should essentially be independent. Since the ZBA is symmetric in bias direction and because the bulk metal/semiconductor interfaces are nominally identical, for a long channel device these two processes are very similar and should approximately add together. As the device is made smaller, charges in the channel can feel the effect of their image charge on the opposite barrier. As a result, interactions are partially screened and the ZBA is reduced. While this effect is clearly observed in a bias-dependent measurement, screening remains constant as a function of temperature and thus a logarithmic dependence can be expected. We thus note that for small channel length devices in the quasiballistic regime, screening from the electrodes will be increasingly important and may need to be considered simultaneously with modifications of the interaction strength.

In summary we have directly observed the density of states in a Si MOSFET. We found that for long channel devices it has the expected logarithmic form and that for small channel devices it is strongly perturbed by screening from the nearby metallic electrodes. Such measurements provide a tool to investigate transport in silicon transistors. Further investigations of the semiconducting density of states using this geometry could help clarify the metallic nature of the two-dimensional gas.[3,4]

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