SUPPRESSION OF THE METALLIC BEHAVIOR IN TWO DIMENSIONS BY SPIN FLIP SCATTERING

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We study the effect of the disorder on the metallic behavior of a two-dimensional electron system in silicon. The temperature dependence of conductivity $\sigma(T)$ was measured for different values of substrate bias, which changes both potential scattering and the concentration of disorder-induced local magnetic moments. We find that the latter has a much more profound effect on $d\sigma/dT$. In fact, the data suggest that in the limit of $T \to 0$ the metallic behavior, as characterized by $d\sigma/dT < 0$, is suppressed by an arbitrarily small amount of spin flip scattering by local magnetic moments.

1 Introduction

A metal-insulator transition (MIT) has been observed recently in a variety of two-dimensional (2D) electron and hole systems but there is still no generally accepted microscopic description of the 2D metallic phase. Some of the relevant properties of the 2D metal include: (a) an increase of conductivity $\sigma$ with decreasing temperature $T$ (i.e. $d\sigma/dT < 0$) for carrier densities $n_s > n_c$ ($n_c$ – critical density); and (b) a suppression of the $d\sigma/dT < 0$ behavior by magnetic field. The latter suggests the importance of the spin degrees of freedom, which can be probed further by studying the effect of local magnetic moments on the transport properties of the conduction electrons. In the experiment discussed below, the localized moments were induced by disorder and their number was varied in a controlled way.

The measurements were performed on a 2D electron system in Si metal-oxide-semiconductor field-effect transistors (MOSFETs). In such a device, the disorder is due to the oxide charge scattering (scattering by ionized impurities randomly distributed in the oxide within a few Å of the interface) and to the roughness of the Si-SiO$_2$ interface. For a fixed $n_s$, it is possible to change the disorder by applying the substrate (back gate) bias $V_{sub}$. In particular, the reverse (negative) $V_{sub}$ moves the electrons closer to the interface, which increases the disorder. It also increases the splitting between the subbands since the width of the triangular potential well at the interface is reduced by applying negative $V_{sub}$. Usually, only the lowest subband is occupied at low $T$, giving rise to the 2D behavior. In sufficiently disordered samples, however, the band tails associated with the upper subbands may be populated even at low $n_s$ and act as additional scattering centers for mobile electrons in the lowest subband. Clearly, the negative $V_{sub}$ reduces this type of scattering by depopulating the upper subband. The effect of scattering by electrons localized deep in the tails of the upper subband was first observed as an enhancement of the mobility $\mu$ at low $n_s$ with negative $V_{sub}$, and was subsequently studied in more detail by other groups using different measurements and techniques. Here we present a systematic study of $\sigma(T)$ as the disorder is varied using $V_{sub}$. We show that scattering by electrons localized in the tail of the upper subband has a much more profound effect on $d\sigma/dT$ than potential scattering due to oxide charges and surface roughness. This is attributed to spin flip scattering by electrons in localized states that are singly populated due to a strong on-site Coulomb repulsion, and act as local magnetic moments. For typical localization lengths of $\sim 100$ Å in Si MOSFETs, the on-site Coulomb repulsion is $\sim 10$ meV. Therefore, such states will be singly occupied at low $n_s$. [1]
2 Experimental Results

Our measurements were carried out on n-channel Si MOSFETs with the oxide charge density of $3 \times 10^{10}$ cm$^{-2}$. Other details of the sample structure have been given elsewhere$^2$. For a fixed $V_{sub}$, $n_s$ was controlled by the gate voltage $V_g$ and determined in a standard fashion$^8$. $\sigma(V_g)$ was measured at temperatures $0.3 < T < 4.5$ K for $n_s$ of up to $3 \times 10^{12}$ cm$^{-2}$ and for $-50 \leq V_{sub} \leq +1$ V. The effect of $V_{sub}$ on $\mu$ at 4.2 K was found$^2$ to be consistent with earlier work$^2$ and our interpretation. In particular, for $n_s < n_{max}$ ($n_{max} \sim 5 \times 10^{11}$ cm$^{-2}$ is the density where $\mu$ reaches its maximum), an increase of $\mu$ is observed$^2$ with the negative $V_{sub}$ as a result of the decreased scattering by local moments from the upper subband. For $n_s > n_{max}$, $\mu$ decreases with (negative) $V_{sub}$, consistent with the fact that surface roughness scattering is the dominant source of disorder in this range of $n_s$. For sufficiently high negative $V_{sub}$ ($-V_{sub} > 35$ V), the 4.2 K mobility decreases with $V_{sub}$ for all $n_s$, suggesting that the upper subband has been completely depopulated and that the further increase in $V_{sub}$ leads only to increasing disorder due to potential scattering from roughness at the Si-SiO$_2$ interface.

Fig. 1(a) shows some typical results for $\sigma(T)$ at low $n_s$ as a function of $V_{sub}$. The metallic behavior, such that $d\sigma/dT < 0$, spreads out towards lower $T$ with the increasing negative $V_{sub}$, i.e. as the scattering by local moments is reduced. In other words, $\sigma(T)$ displays a maximum at $T = T_m$, such that $T_m$ shifts to lower $T$ with the (negative) $V_{sub}$. As $-V_{sub}$ is increased beyond 35 V, i.e. when the upper subband is completely depopulated, the form of $\sigma(T)$ is no longer very sensitive to changes in $V_{sub}$ even though the disorder due to potential scattering
increases. In addition, we note that $d\sigma/dT < 0$ behavior is more pronounced in the case where scattering by local moments is reduced even though the total disorder (4.2 K mobility) is larger (lower). [See, for example, the data for $V_{\text{sub}} = -50$ and $-1$ V in Fig. (a).] This demonstrates clearly that scattering by electrons localized in the tail of the upper subband has a much more profound, and a \textit{qualitatively different} effect on $d\sigma/dT$ than potential scattering due to oxide charges and surface roughness. It is also qualitatively different from scattering among conduction electrons themselves, which gives rise to a negative contribution to $d\sigma/dT$. We find here that $d\sigma/dT > 0$ for $T < T_m$ and, in fact, $\sigma$ follows a $T^2$ form at the lowest $T$ [Fig. (b)]. Such $\sigma(T)$ is often considered to be a signature of localized magnetic moments, and results from the Kondo effect\cite{14}. Here it represents a direct evidence for the existence of local moments in our samples. A detailed study of this regime has been presented elsewhere\cite{15}. Fig. (b) also shows that the range of $T$ ($T < T_m$) where local moments dominate transport becomes smaller as their number is reduced by increasing negative $V_{\text{sub}}$.

For a fixed $V_{\text{sub}}$, $T_m$ shifts to lower $T$ with an increase in $n_s$ [Fig. (a)], and the low $T$ regime where the $T^2$ behavior holds is correspondingly reduced [Fig. (b)]. These data indicate that an increase in $n_s$ also reduces the number of local moments in the upper subband. We note, however, that the change in the number of local moments with $n_s$ becomes significant \textit{only} when $n_s > n_{\text{max}}$, as discussed in more detail below.

The maximum position $T_m$ is shown in Fig. (3). The data are plotted as a function of the inverse subband splitting for three values of $n_s$ in the metallic regime ($d\sigma/dT < 0$ for $T > T_m$). The subband splitting was controlled with $V_{\text{sub}}$ ($N_d$ is the depletion layer charge density, which increases with the reverse $V_{\text{sub}}$)\cite{8}. For each density, $T_m$ extrapolates to zero for a finite value of the subband splitting ($V_{\text{sub}} \sim -40$ V). This value is in agreement with the trend in the
4.2 K mobility discussed above. Fig. 3 also shows $T_m$ obtained for $V_{sub} = -1$ V by varying $n_s$ (*i. e. $V_g$*) (the values are marked by arrows in Fig. 2). Increasing $V_g$ both raises $E_F$ and increases the subband splitting. Larger $E_F$ tends to increase the number of localized moments, but larger subband splitting decreases their number by depopulating the upper subband. It is also possible that the number of localized moments might be reduced at high $n_s$ because of improved screening by the mobile electrons. Fig. 3 shows that, for fixed $V_{sub}$ and $n_s < n_{max}$, $T_m$ only depends very weakly on $n_s$: it appears to decrease for some $V_{sub}$ (*e. g. $-1$ V), but to increase slightly for other values of $V_{sub}$ (*e. g. $-2, -4, -8$ V). This suggests that the two effects (raising $E_F$ and increasing the subband splitting) are comparable in size and that the number of localized moments for $n_s < n_{max}$ is, therefore, roughly constant. On the other hand, there is a rapid decrease of $T_m$ with $n_s$ for $n_s > n_{max}$. Our data suggest (solid line in Fig. 3) that this drop results from an increase in the subband splitting and that other effects, such as screening, are not as significant. In fact, $T_m$ extrapolates to zero at about the same value of the subband splitting as that obtained from $T_m(V_{sub})$ for a fixed $n_s$ (dashed lines in Fig. 3): of the order of 30 meV, which is consistent with earlier measurements of band tails. Our results, therefore, show that the 2D metal with $d\sigma/dT < 0$ can exist at $T = 0$ only in the absence of scattering by disorder-induced localized moments. This is similar to the behavior observed in a magnetic field, and consistent with some theoretical models.

In the presence of scattering by localized moments, $d\sigma/dT < 0$ is observable at $T > T_m$. For a fixed $V_{sub}$, $\sigma(n_s, T)$ for $T > T_m$ exhibits all of the properties of a 2D MIT. We speculate that localized moments might exist in other materials as well but that the corresponding $T_m$ might be too low to be experimentally accessible in high-mobility devices.

Back gate bias was used recently in a 2D hole system in GaAs/AlGaAs to study the effect of the spin-splitting due to the spin-orbit interaction and the inversion asymmetry of the confining potential. It was found that the magnitude of the $d\sigma/dT < 0$ behavior was reduced as the spin-splitting decreased, *i. e. as the confining potential became more symmetric*. In our samples, we observe the opposite: the triangular confining potential becomes more symmetric with the application of the reverse $V_{sub}$, and that is exactly when the $d\sigma/dT < 0$ behavior appears. Therefore, even if the effect of the spin-orbit interaction exists in our samples, it does not drive the MIT. Our conclusion is consistent with the calculations that indicate that the
spin splitting in Si MOSFETs should be very close to zero, unlike that in some other materials.

3 Conclusion

Our study shows that the 2D metal with $d\sigma/dT < 0$ can exist in the $T \to 0$ limit only in the absence of scattering by local magnetic moments. Our results emphasize the key role of the spin degrees of freedom in the physics of the low density 2D electron system.

Acknowledgments

The authors are grateful to V. Dobrosavljević and A. B. Fowler for helpful discussions. This work was supported by NSF Grant No. DMR-9796339.

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