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Metal-insulator transition at $B=0$ in p-type SiGe

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Observations are reported of a metal-insulator transition in a two-dimensional hole gas in asymmetrically doped strained SiGe quantum wells. The metallic phase, which appears at low temperatures in these high-mobility samples, is characterized by a resistivity that decreases exponentially with decreasing temperature. This behavior, and the duality between resistivity and conductivity on the two sides of the transition are very similar to that recently reported for high-mobility Si metal-oxide-semiconductor field-effect transistors. [S0163-1829(97)53044-X]

In high-mobility Si metal-oxide-semiconductor field-effect transistors (MOSFETs), scaling measurements, as a function of both temperature and electric field,[1,2] have shown that there is a well-defined metal-insulator transition at $B=0$ with a critical resistivity of order h/e^2. The transition is interesting not only because it contradicts the commonly accepted view that scaling theory[3] predicts all states in a disordered noninteracting two-dimensional system to be localized at $B=0$, but also because on the metallic side of the transition the resistance is unconventional in the sense that it decreases exponentially with decreasing temperature. This strong enhancement of the conductivity closely parallels the exponential increase in resistivity on the insulating side of the transition and strongly suggests that they have a common origin.[2] The behavior appears only in samples with a high mobility[4] above about 1 m^2/Vs. A recent experiment[5] has shown this explicitly by independently varying the sample mobility using a substrate bias.

Two recent developments have pointed to a resolution of the apparent conflict between these results and one-parameter scaling theory. For interacting electrons a recent paper[6] shows that a 2D metal-insulator transition does not contradict general scaling principles but that the metal is not likely to be a Fermi liquid. Second, it has been argued that at low temperatures, scattering in Si MOSFETs is dominated by a ''spin gap'' associated with strong spin-orbit coupling.[4] In this case, where a sympletic ensemble is involved, rather than unitary or orthogonal, the scaling function $\beta(g)$ (given by $d[\ln(g)]/d[\ln(L)]$ where g is a conductance and L the size of the system) remains positive in the large g (low disorder) limit.[7] As the disorder increases and β eventually becomes negative, a metal-insulator transition can occur. The ''spin-gap'' is well developed when large angle scattering dominates and a significant fraction of the scattering events involve a reversal of the k vector and an effective spin flip.

Evidence for a metal-insulator transition at $B=0$ has also been seen in symmetrically doped p-type strained SiGe quantum wells. This has been observed as a function of well width[8] and, in a gated sample, scaling behavior has been seen on the insulating side of the transition.[9] Results are reported here of transport measurements in asymmetrically doped wells that show the same kind of transition with a resistivity in the metallic phase that decreases exponentially with temperature. In both Si MOSFETs and p-type SiGe, the energy associated with many-body interactions is large compared with the kinetic energy of the carriers: for example, in p-type SiGe, at a density of 1×10^{15} m^{-2} the hole-hole interaction energy is about 6.5 meV while the Fermi energy is only 0.5 meV. Also, in p-type SiGe the holes are in almost pure $|M_J|=\frac{3}{2}$ states, so as in the Si MOSFETs spin-orbit effects are likely to play a significant role.

The samples, grown in a UHV–chemical vapor deposition (CVD) system, consisted of a n substrate with a 300 nm Si buffer layer and a 40 nm $Si_{.88}Ge_{.12}$ quantum well. A spacer layer on top of the well was followed by a 30 nm Si(B) layer with doping that varied between 0.5 and 3×10^{24} m^{-3}. The SiGe well is compressively strained and the asymmetric doping means the holes reside in an approximately triangular potential well. Measurements were made on Hall Bar samples (width 200 μm) with Al contacts alloyed in at a temperature of approximately 540 °C. Sample parameters are listed in Table I. Low-temperature illumination using a red light-emitting diode (LED) usually produced a small persistent photoconductivity (PPC) effect which could be exploited to produce small increases in the density. The measured hole densities are all larger than can be explained in terms of the standard electrostatic model[10] using a valence-band offset of 120 meV and an acceptor binding energy of 30 meV (appropriate for B in Si). Also, the mobilities are smaller than theoretically expected for scattering dominated by the remote ionized acceptors.[11] The results are, however, consistent with additional negatively charged impurities, of unknown origin, at the interface as has been previously suggested.[11,12] Quantum mobilities, determined from the low-field Shubnikov–de Haas (SdH) oscillations,[13] are all within about 20% of the peak transport mobilities which is consistent with large angle scattering produced predominantly by these impurities rather than by the remote ionized acceptors. Effective mass values, deduced from the temperature dependence of the low-field SdH oscillations, are in the range 0.2–0.3 m_0 although there is a small uncertainty ($\sim$10%) in the interpretation of these measurements associated with the temperature dependence of the $B=0$ resistivities.

In all samples, the low-field SdH oscillations are dominated by minima that occur at odd filling factors. This is a well-known phenomenon in this system[14] caused by a spin splitting that is larger than half the cyclotron spacing. Measurements in tilted fields[15,16] show that at low fields the cy-

TABLE I. Sample parameters. The conventional (transport) mobility μ_{tr} is the maximum value measured. The quantum mobility μ_q is derived from the low-field SdH oscillations measured at approximately 50 mK.

Sample	Growth	Spacer (nm)	Hole Density (10^{15} m^{-2})	μ_{tr}(max) (m^2/Vs)	μ_q (m^2/Vs)	m*/m$_0$
A	CVD121	20	3.05	1.13	1.42	0.28–0.32
B	CVD191	12	2.8	1.51	1.4	0.29
C	CVD193	20	1.5	1.87	1.41	0.24
D	CVD192	36	1.2	1.18	1.30	0.22
E	CVD276	20	1.15	1.50	1.14	
F	CVD275	20	0.48[a]	0.99		

[a]Depleted in the dark; density after a small amount of illumination.

clotron splitting and the spin splitting both depend only on the perpendicular component of the magnetic field. This confirms that strain and confinement have raised the heavy-hole, light-hole degeneracy at the zone center so that the holes lie in a split-off heavy-hole band ($J=\frac{3}{2}$, $|M_J|=\frac{3}{2}$) with very little admixture from other bands.

Figure 1 shows the temperature dependence of the zero-field resistivity. At high densities the behavior is dominated by a monotonic decrease with temperature conventionally associated with a reduction in the impurity scattering rate.[17] There is also a peak around 5–10 K which systematically develops as the density is reduced. A similar peak is seen in Refs. 9 and 12 although in the latter case it was attributed to changes in screening. The peak results from competition between insulating behavior ($d\rho/dT<0$), which develops as the density is reduced, and a new type of strongly enhanced conductivity that dominates at lower temperatures (below about 4 K). The enhanced conductivity produces a drop in resistance, typically by a factor of about 3, and metallic behavior ($d\rho/dT>0$). In the lowest density sample, however, the insulating behavior dominates and $d\rho/dT$ remains negative at least down to 0.1 K.

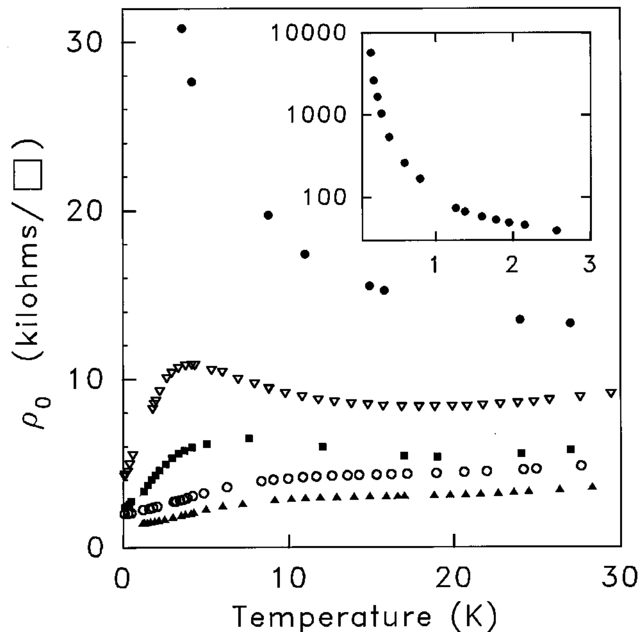

FIG. 1. Temperature dependence of the zero-field resistivity for samples *A* (○), *B* (▲), *C* (■), *D* (▽), and *F* (●). Inset shows low-temperature data for sample *F* with a logarithmic scale.

These results demonstrate a metal-insulator transition, of the same type seen in Si-MOSFETs. This can be seen more clearly in Fig. 2 where data over the range 1–4 K, where the metallic behavior was observed, has been replotted with extra results obtained in sample *F* by using the PPC effect to change the density. The transition occurs at a critical density of about 1×10^{15} m^{-2} with a critical resistivity ρ_c, of order 0.5 h/e^2. On the two sides of the transition the resistivity varies approximately as $\rho_c\ \exp[\pm(T_0/T)^{1/2}]$. At the lowest temperatures this implies a resistance going to zero, as is observed, for example, in superconducting-insulating transitions,[18] but here, as in the Si MOSFETs, the resistivity drop in the metallic phase in fact eventually saturates at a constant value.[19]

Although the $\exp(a/T^{1/2})$ dependence on the insulating side of the transition suggests that variable range hopping, with a Coulomb gap, may play an important role,[20] this is not necessarily the case. A Coulomb gap provides no obvious explanation for the enhanced conductivity on the metallic side of the transition but the temperature dependence on both sides of the transition can be naturally explained in terms of scaling behavior for an interacting system.[6] The predicted behavior, around the critical density n_c, is given by

$$\rho_{xx}(\delta n,T)=\rho_c\ \exp(-A\,\delta n/T^{1/z\nu}),$$

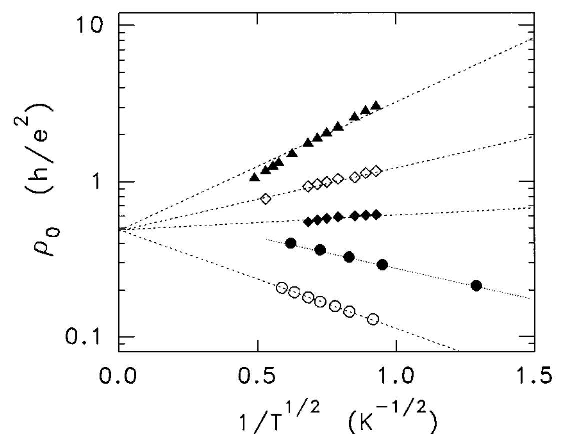

FIG. 2. Zero-field resistivities for densities (in units of 10^{15} m^{-2}) of 0.48 (▲), 0.59 (◇), 0.67 (◆), 1.2 (●), 1.5 (○). Lines are only a guide to the eye.

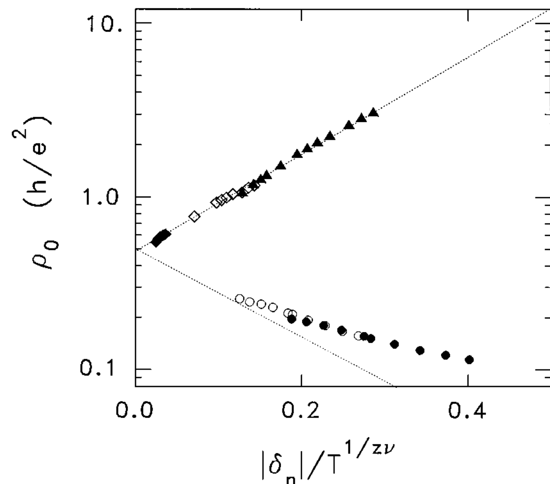

FIG. 3. Scaling plot (with $z\nu=1.6$) for data from two samples with critical densities (n_c) of 1.0×10^{15} m^{-2} (sample *E*) and 0.7 $\times10^{15}$ m^{-2} (sample *F*). The density was varied using the PPC effect and temperatures measured in kelvins. Dotted lines have slopes of equal magnitude but opposite sign.

where *A* is an unknown constant, $\delta n=(n-n_c)/n_c$, and z and ν are, respectively, the dynamical and correlation length exponents. The value of $z\nu$ then determines the temperature dependence in both the insulating and metallic phases. Data from Si MOSFETs agree well with this expression[1,2,5] using $z\nu\approx1.6$.

Figure 3 shows the p-type SiGe results plotted in this way for two samples (*E* and *F*) where the density was varied using the PPC effect. Both samples had a spacer layer of 20 nm but different doping levels. The general behavior is explained well although slightly different values of n_c (0.7 and 1.0×10^{15} m^{-2}) are required in each case to collapse the data to a single curve. Also, slightly different values of the coefficient *A* appear to be required in each case so full duality is not observed.[21] This is not surprising as there is no reason to expect changes in density produced by changing the doping level or by exploiting the PPC effect to be equivalent. Because of the relatively small range of densities the exponent $z\nu$ cannot be determined with any precision from these measurements but values of $z\nu=1.6$, used in Fig. 3 for comparison with the Si MOSFETs, or $z\nu=2$ (suggested by Fig. 2) are both at least approximately correct.

The scaling theory accounts naturally for the existence of a metal-insulator transition and the duality between the temperature dependence in the metallic and insulating phases. It does not identify any specific mechanism driving the transition. Strong many-body interactions, as suggested previously,[22] are an obvious possibility; another could be the spin gap, suggested by Pudalov,[4] which occurs because the spin-orbit splitting is nonzero even at $B=0$.

For the results shown in Fig. 3, different values of n_c are required to produce scaling in the two different samples. It can also be seen from Fig. 1 and Table I that the relationship between the density and insulating behavior, in different samples, is not monotonic. For example, sample *A* has a higher density than sample *B* but appears to show a more insulating behavior. The two samples differ principally by having a different dopant set back and therefore a different amount of band bending. This implies that the critical density depends not only on the material system but also on the shape of the confining potential and (maybe) the exact nature of the impurities.

The similarities between the metal-insulator transition in p-type SiGe and Si MOSFETs suggests that the same mechanism is driving the transition in the two cases. In both systems, many-body effects (electron-electron or hole-hole interactions) are an order of magnitude larger than the Fermi energy, in contrast to the situation in more conventional 2D systems such as $GaAs/Ga_xAl_{1-x}As$ heterojunctions, where the two energies are of a very similar magnitude. In Si MOSFETs the characteristic and unconventional temperature dependence in the metallic phase is seen only in high-mobility samples: p-type SiGe samples showing the same effects also have high mobilities. In Si MOSFETs it is argued by Pudalov[4] that in the strongly asymmetric confining potential the spin-orbit splitting is sufficiently large that even at $B=0$ a spin gap can develop. In p-type SiGe, with the holes in $|M_J|=\frac{3}{2}$ states, the spin-orbit coupling is strong and in an asymmetric potential well a spin gap at $B=0$ should also be a possibility. For the spin gap to not be washed out, large angle scattering processes must dominate in producing the resistance. This is the case here, in both systems, with the quantum and transport mobilities essentially the same. Finally, it is also perhaps noteworthy that in both systems an insulating phase is also observed around $\nu=\frac{3}{2}$,[1,15,16] although for SiGe this is complicated by a ferromagnetic-paramagnetic phase transition that occurs when the $0\uparrow$ and $0\downarrow$ Landau levels cross. It is not clear at this stage which of these several factors are required for the occurrence of the $B=0$ metal-insulator transition.

In summary, experimental results are reported showing that low-density p-type SiGe samples exhibit the same kind of metal-insulator transition at $B=0$ seen in Si MOSFETs. In particular the resistivity in the metallic phase is unconventional, decreasing exponentially with temperature. This behavior confirms other experimental observations that a metal-insulator transition is allowed in 2D systems, at $B=0$. It is also consistent with predictions that the metallic behavior is not Fermi-liquid-like. Interaction effects are large in both systems and spin-orbit effects are also possibly important. Either, or both, of these properties can reconcile the apparent conflict between the experimental observation of a metal-insulator transition and the predictions of one-parameter scaling theory and can account for the anomalous metallic behavior.

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