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

P.T. Coleridge, R.L. Williams, Y. Feng and P. Zawadzki
Institute for Microstructural Sciences, National Research Council, Ottawa, Ontario, K1A OR6, Canada
(31 July 1997)

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 characterised by a resistivity that decreases exponentially with decreasing temperature. This behaviour, 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-MOSFETs.

In high mobility Si-MOSFETs scaling measurements, as a function of both temperature and electric field, have shown that there is a well defined metal-insulator transition at B = 0 with a critical resistivity of order h/e². The transition is interesting not only because it contradicts the commonly accepted view that scaling theory predicts all states in a disordered noninteracting two-dimensional system to be localised 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 they have a common origin. The behaviour appears only in samples with a high mobility above about 1 m²/Vs. A recent experiment 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 shows that a 2D metal-insulator transition does not contradict general scaling principles but that the metal is likely not to be a Fermi liquid. Secondly, it has been argued that at low temperatures scattering in Si-MOSFETs is dominated by a “spin-gap” associated with strong spin-orbit coupling. In this case, where a sympletic ensemble is involved, rather than unitary or orthogonal, the scaling function β(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. 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 p-type modulation doped strained SiGe quantum wells. In symmetrically doped wells this has been observed both as a function of well width and, in a gated sample, as a function of density. 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-SiGe the energy associated with many-body interactions is large compared with the kinetic energy of the carriers: for example, in p-SiGe, at a density of 1×10¹⁵ m⁻² the hole-hole interaction energy is about 6.5 meV while the Fermi energy is only 0.5 meV. Also in p-SiGe the holes are in almost pure |M_f| = 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-CVD system, consisted of a n- substrate with a 300nm Si buffer layer and a 40nm Si₈₈Ge₄₂ quantum well. A spacer layer on top of the well was followed by a 30nm Si(B) layer with doping that varied between 0.5 and 3×10²⁴ 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 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 using a valence band offset of 120meV and an acceptor binding energy of 30meV (appropriate for B in Si). Also the mobilities are smaller than theoretically expected for scattering dominated by the remote ionised acceptors. The results are, however, consistent with additional negatively charged impurities, of unknown origin, at the interface as has been previously suggested.

Quantum mobilities, determined from the low field Shubnikov-de Haas (SdH) oscillations, 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 ionised acceptors. Effective mass values, deduced from the temperature dependence of the low field SdH oscillations, are in the range 0.2 – 0.3m₀ although there is a small uncertainty (~ 10%) in the interpretation of these measurements associated with the temperature dependence of the B = 0 resistivities.
TABLE I. Sample parameters. The conventional (transport) mobility $\mu_{tr}$ is the maximum value measured. The quantum mobility $\mu_q$ is derived from the low field SdH oscillations measured at approximately 50mK.

| Sample | Growth | Spacer (nm) | Hole Density $(10^{15}\text{m}^{-2})$ | $\mu_{tr}$ (max) $(\text{m}^2/\text{Vs})$ | $\mu_q$ $(\text{m}^2/\text{Vs})$ | $m^*/m_0$ |
|--------|--------|-------------|-----------------|-----------------|-----------------|----------|
| 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          | 1.3             | >1.18           | -               | -        |
| F      | CVD275 | 20          | 0.48            | 0.99            | -               | -        |

*Depleted in the dark, density after a small amount of illumination

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 caused by a spin-splitting that is larger than half the cyclotron spacing. Measurements in tilted fields show that at low fields the cyclotron splitting and the spin-splitting both depend only on the perpendicular component of magnetic field. This confirms that strain and confinement have raised the heavy-hole, light-hole degeneracy at the zone centre so that the holes lie in a split-off heavy-hole band ($J = 3/2, |M_J| = 3/2$) with very little admixture from other bands.

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 caused by a spin-splitting that is larger than half the cyclotron spacing. Measurements in tilted fields show that at low fields the cyclotron splitting and the spin-splitting both depend only on the perpendicular component of magnetic field. This confirms that strain and confinement have raised the heavy-hole, light-hole degeneracy at the zone centre so that the holes lie in a split-off heavy-hole band ($J = 3/2, |M_J| = 3/2$) with very little admixture from other bands.

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 caused by a spin-splitting that is larger than half the cyclotron spacing. Measurements in tilted fields show that at low fields the cyclotron splitting and the spin-splitting both depend only on the perpendicular component of magnetic field. This confirms that strain and confinement have raised the heavy-hole, light-hole degeneracy at the zone centre so that the holes lie in a split-off heavy-hole band ($J = 3/2, |M_J| = 3/2$) with very little admixture from other bands.

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 caused by a spin-splitting that is larger than half the cyclotron spacing. Measurements in tilted fields show that at low fields the cyclotron splitting and the spin-splitting both depend only on the perpendicular component of magnetic field. This confirms that strain and confinement have raised the heavy-hole, light-hole degeneracy at the zone centre so that the holes lie in a split-off heavy-hole band ($J = 3/2, |M_J| = 3/2$) with very little admixture from other bands.

\[ \text{FIG. 1. Temperature dependence of the zero field resistivity for samples A(▲); B(■); C(V); D(△) and F(●). Inset shows low temperature data for sample F with a logarithmic scale.} \]

\[ \text{FIG. 2. Zero field resistivities for densities (in units of } 10^{15}\text{m}^{-2} \text{) of } 0.48(▲); 0.59(●); 0.67(♦); 1.2(●); 1.5(●). Lines are only a guide to the eye.} \]

These results demonstrate a metal-insulator transition, of the same type seen in Si-MOSFETs. This can be seen more clearly in figure 2 where data over the range 1-4K, where the metallic behaviour was observed, has been replotted with extra results obtained using the PPC effect to change the density. The transition occurs at a critical density of about $1\times10^{14}\text{m}^{-2}$ with a critical resistivity, $\rho_c$, of order $0.5h/e^2$. 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, but here, as in the Si-MOSFETs, the resistivity drop in the metallic phase in fact eventu-
ally saturates at a constant value.

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, 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 behaviour for an interacting system. The predicted behaviour, around the critical density \( n_c \), is given by

\[
\rho_{xx}(\delta n, T) = \rho_c \exp(-A\delta n/T^{1/2})
\]

where \( A \) is an unknown constant, \( \delta n = (n - n_c)/n_c \) and \( z \) and \( \nu \) 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 agrees well with this expression using \( z \nu \approx 1.6 \).

The similarities between the metal-insulator transition in p-SiGe and Si-MOSFETs suggests 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/GaAlAs 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-SiGe samples showing the same effects also have high mobilities. Spin-orbit effects are probably important in both cases, in Si-MOSFETs because of the strongly asymmetric confining potential and in p-SiGe because the holes are in \( |M_J| = 3/2 \) states. With the holes in an asymmetric potential well, a spin-gap, at \( B=0 \) should also be a possibility in p-SiGe. 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 \( \nu = 3/2 \), although for SiGe this is complicated by a ferromagnetic-paramagnetic phase transition that occurs when the 0\( \uparrow \)+1\( \downarrow \) 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.

Experimental results are reported showing that low density p-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 behaviour 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 behaviour 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 behaviour.

We would like to thank S.V. Kravchenko, V.M. Pu-
dalov and A.S. Sachrajda for useful discussions.

1 S.V. Kravchenko, W.E. Mason, G.E. Bowker, J.E. Furneaux, V.M. Pudalov and M. D’Iorio, Phys. Rev. B 51, 7038 (1995)
2 S.V. Kravchenko, D. Simonian, M.P. Sarachik, W. Mason and J.E. Furneaux, Phys. Rev. Lett. 77, 4938 (1996); D. Simonian, S.V. Kravchenko, and M.P. Sarachik, Phys. Rev. B 55, R13421 (1997)
3 E. Abrahams, P.W. Anderson, D.C. Licciardello and T.V. Ramakrishnan, Phys. Rev. Lett. 42, 673 (1979)
4 V.M. Pudalov, Pis’ma ZhETF 66, 170 (1997); V.M. Pudalov, G. Brunthaler, A. Prinz and G. Bauer, Pis’ma ZhETF 65, 887 (1997); V.M. Pudalov, Proc. Int. Conf. on Electron Localisation and Quantum Transport in Solids, Jaszowiec, Poland (1996), Ed. T. Dietl, Inst. of Physics PAN, Warsaw (1996).
5 D. Popovic, A.B. Fowler and S. Washburn, preprint cond-mat/9704249
6 V. Dobrosavljevic, E. Abrahams, E. Miranda and S. Chakravarty, Phys. Rev. Lett. 79, 455 (1997)
7 S. Hikami, Prog. Theor. Phys., 64, 1425 (1980); see also S. Das Sarma in Perspectives in Quantum Hall Effects, Eds Das Sarma and Pinczuk, Wiley and Sons, New York.
8 M. D’Iorio, D. Stewart, S. Deblois, D. Brown and J.-P. Noël, Surface Science 361/362, 937 (1996)
9 M. D’Iorio, D. Brown, J. Lam, D. Stewart, S. Deblois and H. Lafontaine, Proc. 9th Int. Conf. on Superlattices, Microstructures and Microdevices, Liège, Belgium (1996); J. Lam, M.Sc. thesis, U. of Ottawa (1997)
10 F. Stern, Phys. Rev. B 5, 4891 (1972)
11 C.J. Emeleus, T.E. Whall, D.W. Smith, R.A. Kubiak, E.H.C. Parker and M.J. Kearney, J. Appl. Phys. 73, 3853 (1993)
12 E. Basaran, R.A. Kubiak, T.E. Whall and E.H.C. Parker, Appl. Phys. Lett. 64, 3471 (1994).
13 P.T. Coleridge, Phys. Rev. B 44, 3793 (1991)
14 F.F. Fang, P.J. Wang, B.S. Meyerson, J.J. Nocera and K.E. Ismail, Surface Science 263, 175 (1992)
15 P.T. Coleridge, A.S. Sachrajda, P. Zawadzki, R.L. Williams and H. Lafontaine, Solid. State Comm. 102, 755 (1997)
16 P.T. Coleridge, A.S. Sachrajda, H. Lafontaine and Y. Feng, Phys. Rev. B 54, 14518 (1996)
17 A. Gold and V.T. Dolgopolov, Phys. Rev B 33, 1076 (1986)
18 A. Yazdani and A. Kapitulnik, Phys. Rev. Lett. 74, 3037 (1995)
19 Measurements at the lowest temperatures were complicated, in some cases, by the Al bonding wires used to contact the Hall bar which provide the main thermal link to the carriers. When this is broken by the Al going superconducting very long time constants are introduced and it becomes difficult to establish the precise temperature of the holes.
20 W. Mason, S.V. Kravchenko, G.E. Bowker and J.E. Furneaux, Surface Science 361/362, 953 (1996); and ref-

21 Although it should be noted that subtraction of a constant impurity resistivity from the experimental data could significantly improve this.
22 A. M. Finkel’stein, Zh. Eksp. Teor. Fiz. 84, 168 (1983) [Sov. Phys. JETP 57, 97 (1982)]