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A low-temperature insulating phase at $\nu = 1.5$ for 2D holes in high-mobility Si–$Si_{1-x}Ge_x$ heterostructures with Landau level degeneracy

R B Dunford†§, E E Mitchell†, R G Clark†, V A Stadnik†, F F Fang‡, R Newbury†, R H McKenzie†, R P Starrett†, P J Wang‡ and B S Meyerson‡

† National Pulsed Magnet Laboratory, School of Physics, University of New South Wales, Sydney 2052, Australia

‡ IBM T J Watson Research Center, PO Box 218, Yorktown Heights, NY 10598, USA

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Abstract. Magneto-transport measurements of the 2D hole system (2DHS) in p-type Si–$Si_{1-x}Ge_x$ heterostructures identify the integer quantum Hall effect (IQHE) at dominantly odd-integer filling factors ν and two low-temperature insulating phases (IPs) at $\nu = 1.5$ and $\nu \lesssim 0.5$, with re-entrance to the quantum Hall effect at $\nu = 1$. The temperature dependence, current–voltage characteristics, and tilted field and illumination responses of the IP at $\nu = 1.5$ indicate that the important physics is associated with an energy degeneracy of adjacent Landau levels of opposite spin, which provides a basis for consideration of an intrinsic, many-body origin.

Recently there has been much interest in the growth of lattice-mismatched Si–$Si_{1-x}Ge_x$ heterostructures following significant advances in achieving strain relaxation of the alloy layers with minimal threading dislocations [1–3]. In modulation-doped n-type structures this has opened up new possibilities for preparing strained Si layers on strain-relieved SiGe alloy buffers in such a way that the band structure is suitably modified, together with smoothness of the heterointerface, to form a two-dimensional (2D) electron system of high mobility (1–5×10^5 cm^2 V^{-1} s^{-1}) not realized in conventional Si MOSFETs. The fractional quantum Hall effect (FQHE) has been observed in such high-quality Si–SiGe samples [4, 5]. In particular, the role of valley index in the FQHE ground states [6] provides additional physics that cannot be obtained from studies in GaAs.

In GaAs–AlGaAs heterostructures, comparison of low-temperature measurements for 2D electron [7] and hole systems [8–10] (2DESs and 2DHSs) has been important in probing the details of such fundamental phenomena as the FQHE and Wigner crystallization, despite differences of up to an order of magnitude in mobility. The investigation of devices fabricated on new semiconductor materials with a different scale of interactions is important. There have been a number of studies of low-temperature insulating phase (IP) transitions for electron systems in Si MOSFETs [11, 12], but the analogous study of holes in a silicon-based device has until recently not been possible due to the low hole mobility. Although the first 2D systems investigated at an Si–SiGe interface were hole systems [13] confined in biaxially compressed SiGe grown on a silicon substrate, detailed studies of the 2DHS in Si–SiGe are at an early stage [14–20].

§ Currently at NHMFL, FSU, 1800 E Paul Dirac Drive, Tallahassee, FL 32306-4005, USA.

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In earlier work we reported low-temperature transport measurements of high-quality p-type Si–SiGe heterostructures in steady and pulsed magnetic fields, which identified, in addition to anomalies in the integer quantum Hall effect (IQHE), two low-temperature IPs at Landau level filling factor $\nu = 1.5$ and $\nu \lesssim 0.5$ [17]. In this paper we show that the IP centred at $\nu = 1.5$ exhibits similarities with IPs in both higher-quality p-type GaAs–AlGaAs heterostructures [8–10] (observed between the $\nu = 2/5$, 1/3 and 2/7 FQHE states) and n-type Si MOSFETs [11, 12] (observed between integer filling factors). We use tilted field and illumination experiments to manipulate the energy level scheme and argue that this IP is associated with an unusual energy degeneracy of adjacent Landau levels of opposite spin.

The p-type samples are grown in a multi-wafer UHV/CVD system at 550 °C [1]. In these structures a 400 Å $Si_{1-x}Ge_x$ layer is clad between the (100) n^- Si substrate and a modulation-doped Si cap layer comprised of a 60 Å undoped spacer at the heterointerface and a 200 Å boron-doped (2×10^{18} cm^{-3}) region [14]. The Ge mole fraction x is ~0.12 [15]. The lattice constant of SiGe is ~0.5% larger than that of Si so this layer is under compressive biaxial stress. The 2DHS forms in the SiGe layer at the top Si–SiGe heterointerface [14]. Ohmic contacts were made to the 2DHS by alloying Al at the corners of the 2×2 mm^2 samples.

Transport measurements using AC lock-in techniques at sample temperatures down to 30 mK were performed using a dilution refrigerator equipped with a superconducting magnet. Illuminated data were taken using a refrigerator with optical fibre access. DC measurements in 20 ms duration pulsed magnetic fields to 50 T at temperatures down to 0.3 K were carried out using a ^{3}He system in a liquid nitrogen-cooled, reinforced Cu coil [21].

Figures 1 and 2 show magneto-resistance data for an Si–SiGe sample with hole density $n_d = 3.8 \times 10^{11}$ cm^{-2} and mobility $\mu \cong 8000$ cm^2 V^{-1} s^{-1} at 1.4 K, amongst the highest reported for 2D holes in a silicon-based system [15, 20]. The longitudinal resistivity ρ_{xx} data and its temperature dependence are shown in figure 1. In the region $2 > \nu > 1$ the data are dominated by an anomalously large ρ_{xx} peak centred at $\nu = 1.5$ which increases from $\rho_{xx} \sim 5$ kΩ at $T = 1.75$ K to ~40 kΩ below 100 mK, as shown in figure 1(a). This IP was reproduced in two samples (see figure 4, trace a) and on numerous cool-downs.

The detailed temperature dependence of ρ_{xx} at $\nu = 1.5$ is shown in figure 1(b) and its behaviour is contrasted with the temperature dependence at $\nu = 2.1$ (the next largest ρ_{xx} peak to lower field) and $\nu = 2^-$ (the ρ_{xx} minimum at a field value slightly higher than the $\nu = 2$ position as determined from the lower-field Shubnikov–de Haas oscillations). The temperature dependence at the filling factors $\nu = 1.5$, 2.1 and 2^- are characteristic of insulating, metallic and activated IQHE behaviour respectively. The saturation of the IP below 100 mK shown in figure 1(b) is not due to self-heating effects (as it does not vary with currents of 1–10 nA) and is more pronounced than the saturation shown by higher-mobility p-type GaAs samples [8–10]. The origin of this saturation is not clear.

We also note a second IP, characterized by a rise in resistance to >10 MΩ in the region $\nu < 1$ in figure 2(a), where data beyond 16 T were taken in pulsed fields. Whilst ρ_{xx} increases below $\nu = 1$, a prominent divergence sets in around 30 T ($\nu \lesssim 0.5$) at 340 mK, which is quenched with increasing temperature (see the 1.3 K data shown for comparison in figure 1(a)). Further measurements of the IP at $\nu \lesssim 0.5$ will be presented elsewhere; in this paper we will concentrate on the IP at $\nu = 1.5$.

Figure 2(a) and (b) shows in more detail the ρ_{xx} and Hall resistivity ρ_{xy} traces respectively for $\nu > 1$ at 30 mK. Note that the IQHE (ρ_{xx} minima accompanied by quantized ρ_{xy} plateaux) are only observed at odd-integer filling [15]. However anomalous

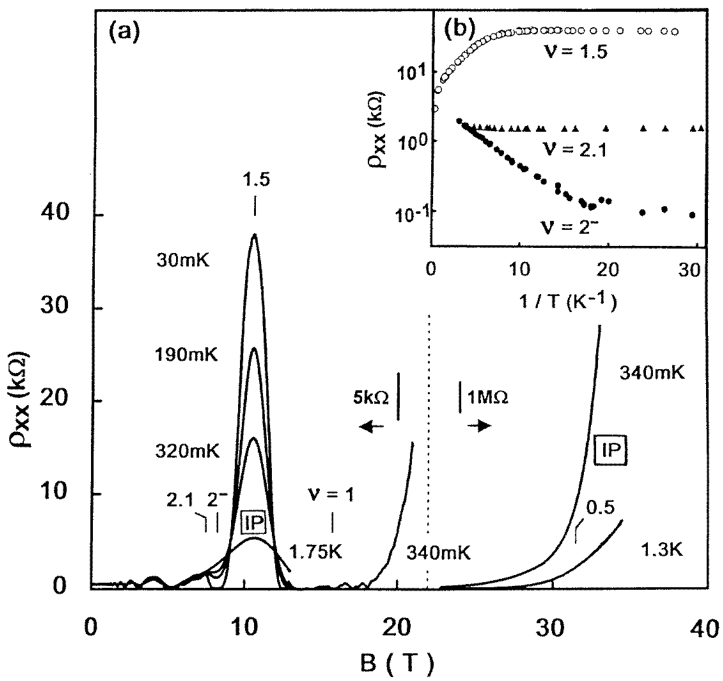

Figure 1. (a) The temperature-dependence of ρ_{xx} in the IP region $2 > \nu > 1$ (30 mK–1.75 K, steady fields) and for a second, dominant IP in the region $\nu < 1$ (340 mK and 1.3 K, pulsed fields) which sets in around 30 T ($\nu \sim 0.5$) (note the ρ_{xx} scale change). The re-entrant $\nu = 1$ IQHE state is shown at 340 mK. (b) The detailed temperature dependence of ρ_{xx} at $\nu = 1.5$, 2.1 and 2^-, illustrating insulating, metallic and activated IQHE behaviour, respectively.

local maxima ('overshoots') in ρ_{xy} are observed between the odd-integer plateaux. No even-integer ρ_{xx} minima are observed except near $\nu = 2$ where the situation is complex. Firstly, the position of the ρ_{xx} minimum at 8.2 T in figure 2(a) is 0.6 T higher in field than the true $\nu = 2$ position determined from the odd-integer sequence to lower field (in figure 1 the filling factor at this ρ_{xx} minimum was denoted $\nu = 2^-$). Secondly, in figure 2(b) the corresponding ρ_{xy} plateaux at $h/2e^2$ is clearly absent and at $\nu = 2$ filling ρ_{xy} rises sharply to h/e^2, which is most unusual. In the IP region ρ_{xy} has a minimum, the depth of which depends on the polarity of the magnetic field $(+B, -B)$. The average value B_{AV} (which removes ρ_{xx} admixture effects associated with the contact configuration) is reasonably close to the classical value, B/ne (indicated by the straight line in figure 2(b)). At higher field, outside the IP region, ρ_{xy} recovers its $\nu = 1$ h/e^2 plateaux. The tilted field data of figure 2(c) will be discussed later.

There are also other anomalies in the magneto-transport. Weak ρ_{xx} minima develop close to $\nu = 7/3$ and 8/3 (arrowed in figure 2(a)); however the ρ_{xy} plateau-like structure which forms close to $(3/7)h/e^2$ does not line up in field with the $\nu = 7/3$ ρ_{xx} minimum. The $\nu = 7/3$ structure was not observed in a second sample (see figure 4, trace a). Instead of assigning this structure to the FQHE, we associate both these local minima and the IP with the unusual Landau level (LL) degeneracy in these samples, which we discuss next.

The energy level scheme for these samples in a magnetic field is unusual and can explain many of the unusual transport features in figures 1 and 2. The degeneracy of the valence

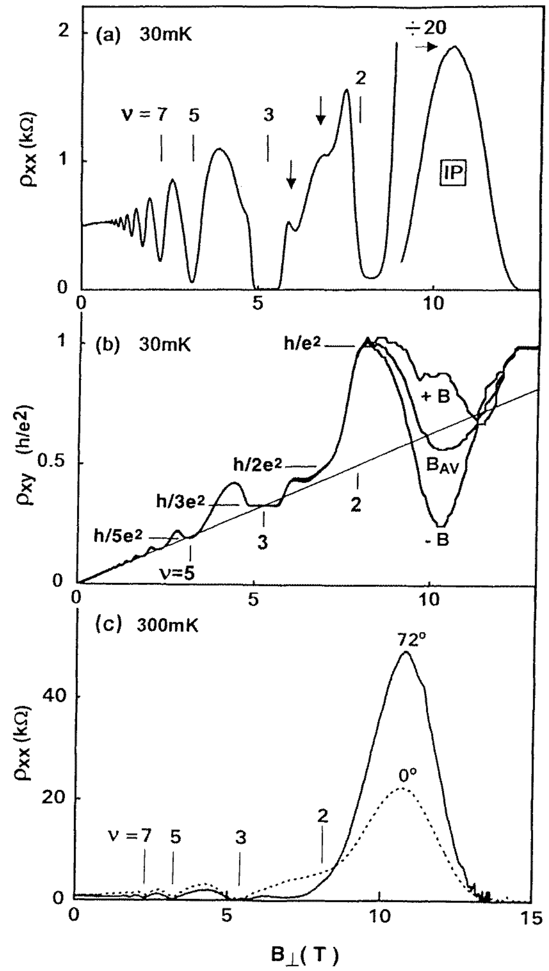

Figure 2. (a) Longitudinal ρ_{xx} and (b) Hall ρ_{xy} resistivities in the region $\nu > 1$ at $T = 30$ mK for the 2DHS in p-type Si–SiGe ($n_d = 3.8 \times 10^{11}$ cm^{-2}). An IP is identified between the $\nu = 1$ and $\nu = 2$ IQHE. The straight line in (b) is the classical Hall slope. (c) Pulsed field ρ_{xx} data as a function of the normal field ($B_\perp = B_T \cos\theta$) at tilt angles $\theta = 0$ and 72° at $T = 300$ mK ($n_d = 3.9 \times 10^{11}$ cm^{-2}). At $\nu = 1.5$, $B_T(72°) = 35$ T.

bands is lifted by more than the Fermi energy due to both strain and confinement [15]; the $m_j = \pm 3/2$ heavy-hole band has the lowest energy for holes. In p-type SiGe samples $g^*_\perp \sim 6$–8 [15], much greater than for other materials. Consequently LL degeneracy is realized in these samples because the spin splitting $g^*_\perp \mu_B B$ is comparable to the cyclotron energy $\hbar\omega_c = \hbar e B_\perp / m^*$, where $m^* = 0.24 m_e$ is determined from the temperature dependence of the low-field Shubnikov–de Haas oscillations [22] (not shown); see also [23] for cyclotron resonance measurements of m^*. The ratio R of LL width due to disorder [22] to the cyclotron energy is given by $R = 3/(2\pi\omega_c\tau)^{1/2}$ (where the lifetime $\tau = m^*\mu/e$); this indicates that LL broadening is ~25% of the cyclotron splitting at 10 T. In this system spin-up and spin-down energies associated with extended states of adjacent LLs overlap (except for the lowest-spin state of the lowest LL), and the IQHE is only observed at odd-integer filling,

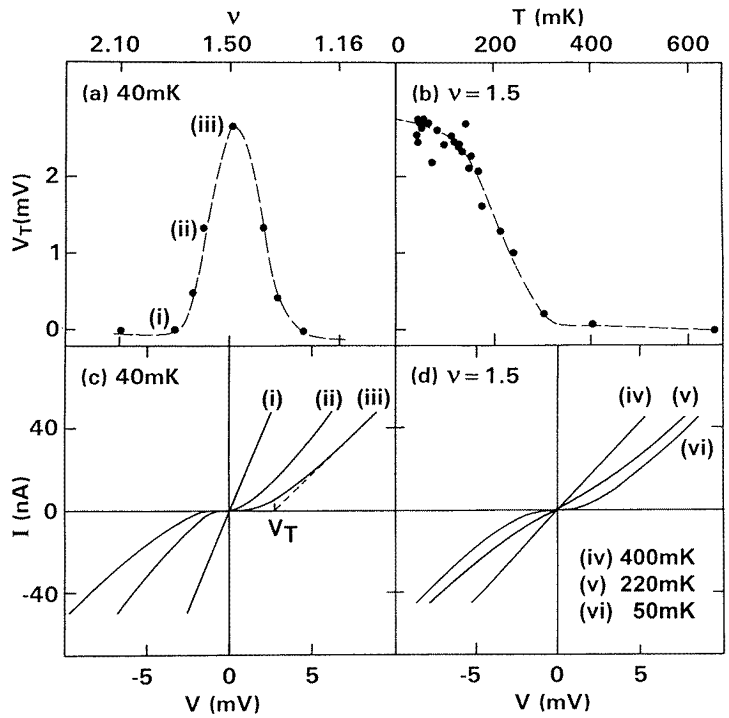

Figure 3. Threshold voltages V_T for the IP centred at $\nu = 1.5$, shown (a) as a function of ν at $T = 40$ mK and (b) as a function of temperature at $\nu = 1.5$, derived from selected non-linear I–V data shown in (c) and (d). (c) I–V data at 40 mK for (i) $\nu = 1.8$, (ii) $\nu = 1.6$ and (iii) $\nu = 1.5$. V_T is estimated by linear extrapolation as shown by the short-dashed line from trace (iii). (d) I–V data at $\nu = 1.5$ for (iv) 400 mK, (v) 220 mK and (vi) 50 mK.

as shown for $\nu \geqslant 3$ in figure 2(a). Similar behaviour has been observed for the 2DHS in strained GaInSb–GaSb quantum wells [24] and induced in the 2DES of Si–SiGe [25] and GaInAs–InP [26] heterostructures by tilted magnetic field studies.

The ρ_{xy} 'jump' to h/e^2 at $\nu = 2^-$ and the ρ_{xx} minimum at a field value slightly higher than the expected $\nu = 2$ position can be understood from the unusual energy level degeneracy. At exactly $\nu = 2$ filling with unresolved spin states of adjacent LLs, the Fermi energy E_F will be in overlapping extended states of the $0\downarrow$, $1\uparrow$ levels and ρ_{xx} will be finite. If the band of extended states is sufficiently narrow, a small increase in magnetic field will move E_F into localized states with only the lowest LL ($0\uparrow$) extended states below E_F resulting in $\rho_{xx} \to 0$ and $\rho_{xy} \to h/e^2$, as observed. If the LL degeneracy persists to higher fields, a very broad $\nu = 1$ ρ_{xy} plateau would be expected, which is not the case in our data due to the observed onset of an IP centred at $\nu = 1.5$, for which the single-particle density of states picture above is unlikely to be appropriate, as will be discussed below. Any magnetic field dependence of the g^* factor in this system adds to the complexity and the weak ρ_{xx}, ρ_{xy} structure close to $\nu = 7/3$ and 8/3 and the overshoots in ρ_{xy} observed between odd-integer plateaux in figure 1 are likely to arise from similar mechanisms.

I–V measurements carried out in the IP region between $\nu = 1$ and 2 are shown in figure 3. Non-linear effects are observed which are characterized by a threshold voltage V_T, defined as shown in trace (iii) of figure 3(c). Figure 3(a) shows the V_T variation as a function of ν at 40 mK derived from the selected measurements shown in figure 3(c); V_T has a peak value of 2.7 mV at $\nu = 1.5$. The temperature dependence of the I–V measurements and at $\nu = 1.5$ (figure 3(b) and (d)) indicates that this peak threshold value falls to zero around 300 mK. The non-linear I–V measurements in figure 3 are reminiscent of those reported in GaAs–AlGaAs heterostructures [7] and Si MOSFETs [12] that have been associated with many-body effects (Wigner crystallization).

The unusual energy level degeneracy in p-type Si–SiGe described above appears to be central to the formation of the IP at $\nu = 1.5$. Experimentally, the overlap of the adjacent LLs is usually manipulated by tilting the sample in a magnetic field which (at fixed ν) changes the spin splitting (proportional to the total magnetic field) but not the cyclotron splitting (proportional to the normal component of the magnetic field). In SiGe this is difficult because a very large tilt angle, θ, (and therefore pulsed magnetic fields to >45 T) is required to achieve only a very small change in the spin splitting because of the highly anisotropic nature of the g^* factor [15]. A further complication in p-type SiGe is that it is not clear whether tilt increases or decreases the g^* factor [18]. There are two possibilities for the ordering of the LLs (from lowest to higher energies): (i) $0\uparrow$, $0\downarrow$, $1\uparrow$, $1\downarrow$, where the $0\downarrow$ and $1\uparrow$ LLs are nearly overlapping and their overlap will be increased if the spin splitting increases relative to the cyclotron splitting $\hbar\omega_c$, and (ii) $0\uparrow$, $1\uparrow$, $0\downarrow$, $2\uparrow$ where the $1\uparrow$ and $0\downarrow$ LLs are nearly overlapping and their overlap will be increased if the spin splitting decreases relative to $\hbar\omega_c$. Both scenarios would result in increased LL degeneracy as the magnetic field is tilted. The work of [27] may also be relevant to understanding the angular dependence of the g^* factor.

Figure 2(c) compares 300 mK ρ_{xx} data at $\theta = 0$ and 72° tilt angles where θ is the angle between the sample normal and the applied magnetic field. The dramatic increase in the IP resistance by more than a factor of two to ∼50 kΩ (at 300 mK) with $\theta = 72^\circ$ can be attributed to the increased degeneracy. Lower-temperature ρ_{xx} data (30 mK, not shown) taken at a smaller tilt angle (30°) show a smaller increase in the IP resistance by a factor of 1.3 to ∼47 kΩ; the detailed temperature dependence of the IP at $\theta = 30^\circ$ is similar to the $\theta = 0^\circ$ data of figure 1(b). At $\theta = 30^\circ$ the $\nu = 2$ state is still anomalous as would be expected with increased LL degeneracy.

The anisotropic g factor in these samples precludes further tilting of the sample to resolve the LL degeneracy. An alternative technique is to illuminate the sample. This is demonstrated in figure 4, where the sample is systematically illuminated using a Ti:sapphire laser operating at $\lambda = 785$ nm and extremely low power levels (<1 μW). Illumination lifts the energy level degeneracy by changing both g^* and m^* in our p-type Si–SiGe samples and there is also an effect due to the narrowing of the LL width. Photoconductivity (PC) measurements at low field ($\nu > 3$) indicate that after illumination the degree of degeneracy (given by the ratio $\hbar\omega_c/g^*_\perp\mu_B B$) decreases from unity to 0.7; further details and PC data are given in [28].

The lifting of LL degeneracy by sample illumination is clearly evidenced by comparison of ρ_{xx} and ρ_{xy} data at $\nu = 2$ for fully illuminated density n_2 (figure 4, traces c and d) with the situation at dark density n_d (figure 4, trace a and figure 1(b)). At density n_2 the $\nu = 2$ ρ_{xx} minimum becomes broad, is accurately zero and is at its correct position in magnetic field and, most importantly, is now accompanied by a corresponding ρ_{xy} plateau quantized at $h/2e^2$, in striking contrast to the ρ_{xx} and ρ_{xy} anomalies at dark density. The activation energy Δ at $\nu = 2$ (derived from $\rho_{xx} = C\exp(-\Delta/2kT)$) increases from a dark value of 0.4 to 9 K after illumination. There is also evidence in figure 4, traces c and d, for resolution of the $\nu = 4$ IQHE in both ρ_{xx} and ρ_{xy} structure at illuminated density n_2. Data taken using a highly sensitive PC technique [28] resolve emergent structure at even-integer filling up to

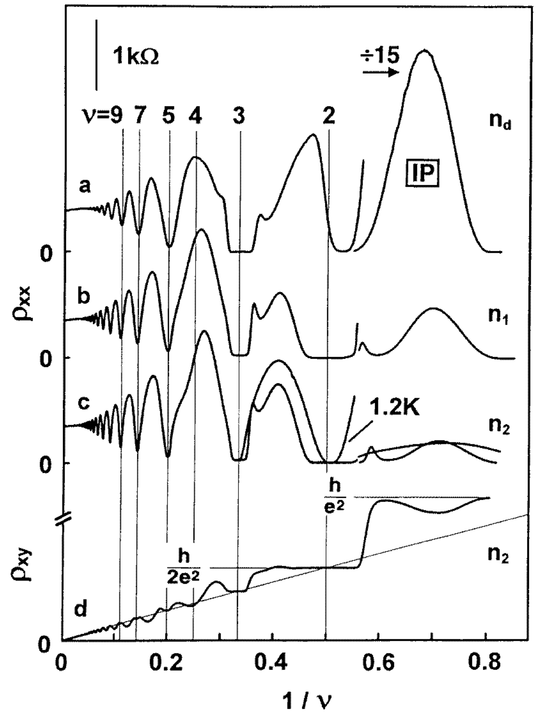

Figure 4. Longitudinal resistivity ρ_{xx} for the region $\nu > 1$ with increasing sample illumination: trace a, dark concentration $n_d = 3.8 \times 10^{11}$ cm^{-2} (at $T = 30$ mK); traces b and c, illuminated densities n_1 and $n_2 = 4.26$ and 4.43×10^{11} cm^{-2} (at $T = 130$ mK). The corresponding Hall resistivity ρ_{xy} for illuminated density n_2 is shown in trace d.

$\nu = 12$ at this illuminated density. The important observation is that, in lifting the energy level degeneracy in this way, the IP resistance at $\nu = 1.5$ collapses to $\sim$10% of its dark value and does not vary with temperature (see figure 4, trace c, 1.2 K data). Whilst higher LLs can be resolved with illumination, it is unlikely that such a significant collapse can be induced by the small change in the disorder potential associated with the marginal increase in zero-field mobility observed. With a finely tuned degeneracy of LLs, the rapid rise of ρ_{xy} between the $h/2e^2$ and h/e^2 plateaux (figure 4, trace d) and the anomalous ρ_{xx} structure in the region $1.2 < \nu < 1.6$ (like the ρ_{xx} minima at $\nu = 7/3$ and 8/3) can all be conceivably caused by the magnetic-field-dependent variation of the LL degeneracy in this region, which makes the transport structure very complex. Notwithstanding these complications however, the observation of a substantially reduced IP at illuminated densities (figure 4, traces b and c) firmly links the existence of the IP to the unusual LL degeneracy.

Finally we present ρ_{xx} data for a symmetric double-side-doped sample in which a second identical interface is placed 400 Å below the first [14]. The separation between the two wells is such that they can be considered to be non-interacting [15]. The sample density measured from the Shubnikov–de Haas oscillations ($n_d = 4.4 \times 10^{11}$ cm^{-2}) is half that measured from the Hall resistance; as the latter measures both wells this confirms that the wells are nearly identical [15, 23]. Figure 5 compares dark ρ_{xx} data for this double-side-doped sample ($n_d = 4.4 \times 10^{11}$ cm^{-2}) to the single-side-doped sample ($n_d = 3.8 \times 10^{11}$ cm^{-2}) discussed previously. For the double-side-doped sample ρ_{xx} at $\nu = 1.5$ is quenched to 15%

of the value for the single-side-doped sample and its temperature dependence is weak. Whilst the odd-integer ρ_{xx} minima still dominate, additional structure is resolved at even integers $\nu = 4, 6, 8$ for the double-side-doped sample. Although the $\nu = 2$ ρ_{xx} minimum is still positioned to higher field, ρ_{xy} shows a plateaux close to $h/2e^2$ (not shown) in marked contrast to the single-side-doped sample. Plateaux-like structure in ρ_{xy} is also observed at the other even integers. It is probable that the higher density of the double-side-doped sample has caused the LL degeneracy to be lifted and again this has resulted in a substantially reduced IP. A transition from an insulating phase to metallic behaviour occurred for $3.8 < n_d < 4.4$ ($\times 10^{11}$ cm^{-2}); other workers found a similar transition for $2.5 < n_d < 5.3$ ($\times 10^{11}$ cm^{-2}) [18]. The reverse transition was also found for $1.8 < n_d < 3.1$ ($\times 10^{11}$ cm^{-2}) in a lower mobility sample at zero field [19].

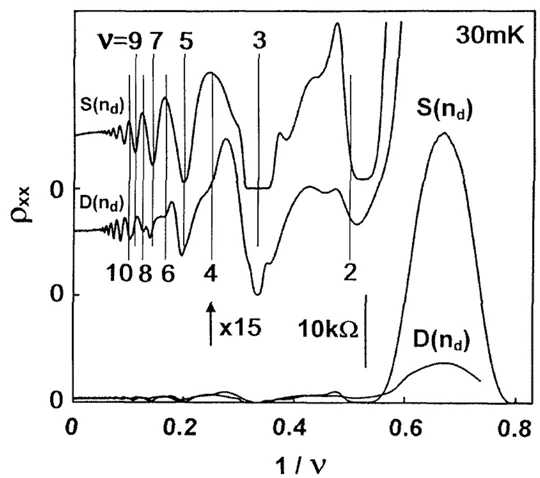

Figure 5. Longitudinal resistivity ρ_{xx} for the region $\nu > 1$ for a double-side-doped sample (D, $n_d = 4.4 \times 10^{11}$ cm^{-2}) compared to a single-side-doped sample (S, $n_d = 3.8 \times 10^{11}$ cm^{-2}) at 30 mK.

The IP at $\nu = 1.5$ in figures 1(b) and 2(a) is characterized by finite ρ_{xy} and an order of magnitude increase in ρ_{xx} as the temperature is lowered, characteristic of a Hall insulator [29–31]. The global phase diagram that situates the onset of an insulating phase on a plot of sample disorder versus inverse filling factor excludes such a phase being observed in a transition between $\nu = 1$ and 2 IQHE states. A disorder-related IP cannot be completely ruled out on this basis alone as there have been numerous experimental reports of similar violations [32, 33] and indeed the theory was never intended to address the unusual energy level scheme in p-type SiGe. However the reduction of the IP on illumination (accompanied by only small improvement in mobility) (figure 4) and the tilted field data (figure 2(c)), when taken together with the unusual LL level degeneracy, make disorder-related effects appear unlikely.

The observation of an IP at $\upsilon = 1.5$ characterized by a 'melting' temperature $\sim$300 mK and a low threshold voltage for non-linear I–V characteristics ($\sim$3 meV) raises the possibility of many-body effects. Wigner crystallization is clearly not expected at this filling factor in a conventional spin-polarized model; using $m^* = 0.24m_e$ and $\epsilon = 12.6$ (for the SiGe layer) the Wigner–Seitz radius r_s is only $\sim$3 (too small) and additionally the cyclotron radius at $\sim$11 T ($\nu = 1.5$) is $\sim$70 Å, which is too large compared to the inter-particle separation ~90 Å for $n = 3.8 \times 10^{11}$ cm^{-2}. The relatively low mobility for holes (compared to the situation in p-type GaAs) and the absence of transport structure at fractional filling factor that can be clearly attributed to the FQHE should also be noted.

A recently proposed model [18] explains this IP in terms of percolation phenomena. Although the experimental data of [18] also shows the IP resistance increasing as the sample is tilted, their model requires the LL degeneracy to *decrease* for this to occur. Our experimental data, which include both tilted field and illuminated measurements (in which we can see even-integer IQHE), leads us to an opposite conclusion, that the IP resistance increases when the sample is tilted because the LL degeneracy *increases*. There is no evidence for decreased LL degeneracy in the tilted field data of figure 2(c). The illuminated data in which the degeneracy was decreased show that we would expect to see a deep ρ_{xx} minimum at $\nu = 2$ and corresponding ρ_{xy} plateau in figure 2(c) if the LL degeneracy were in fact being decreased.

Although more complicated mechanisms could be proposed, we believe that an explanation in which the insulating phase is driven by LL degeneracy is compelling. We have demonstrated this using two contrasting methods: by tilting the sample to increase the LL degeneracy the insulating phase increases in resistance and conversely by using illumination to decrease the LL degeneracy a corresponding decrease in the insulating phase resistance was observed. The important link between the IP and the degeneracy of energy levels of adjacent LL indices n and $n+1$ and opposite spin (for which holes have a different orbit radius) provides a basis for consideration of an intrinsic, many-body origin. For the energy level scheme realized in our samples an intrinsic phase transition (at $\nu = 2$) to a fully polarized state in which two LLs of equal spin are filled has been proposed [34] and examined experimentally by tilted field studies in n-type GaInAs–InP heterostructures [26]. With reference to this work, the (unilluminated) situation in our p-type Si–SiGe samples, where the IP at $\nu = 1.5$ is observed, is analogous to the 'low-mobility' samples in [26] where LL degeneracy (vanishing of the $\nu = 2$ ρ_{xy} plateau) can be smoothly achieved with tilt angle. This would imply that a spin phase transition similar to that predicted at $\nu = 2$ under certain conditions is not likely to be directly relevant to the IP at $\nu = 1.5$ in our samples. Whilst it is clear that in a conventional, fully polarized model Wigner crystallization is unlikely, it is interesting to speculate whether Wigner crystallization could occur for degenerate holes of opposite spin, particularly in the filling factor region of the observed IP. This has been the subject of theoretical calculation in three dimensions and zero field [35].

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