Universal Behaviour of Metal-Insulator Transitions in the p-SiGe System

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Magnetoresistance measurements are presented for a strained p-SiGe quantum well sample where the density is varied through the B=0 metal-insulator transition. The close relationship between this transition, the high field Hall insulator transition and the filling factor $\nu=3/2$ insulating state is demonstrated.

The strained p-type SiGe system exhibits, in addition to the normal integer quantum Hall effect (IQHE) transitions, an insulating phase near filling factor $\nu = 3/2$ [1,2] and a B=0 metal-insulator transition of the kind observed in high mobility Si-MOSFETs [3]. Results are presented here that show the close relationship between these various transitions.

Samples were grown by a UHV chemical vapour deposition process. An intrinsic Si layer is followed by a 40nm Si$_{.88}$ Ge$_{.12}$ quantum well, a spacer layer of variable thickness and a boron doped silicon layer. The quantum well is sufficiently narrow that the lattice constant difference between the alloy and the pure Si is all taken up by strain which means the heavy hole band, characterised by a $|M_J| = 3/2$ symmetry, is well separated from other bands. The g-factor is large (of order 6) and depends only on the perpendicular component of magnetic field [4,5]. At high fields the spin splitting is further enhanced by exchange resulting in a fully polarised "ferromagnetic" spin system at $\nu = 2$. The ratio of the transport and quantum lifetimes, determined from the Shubnikov-de Haas oscillations, is about one [6] showing that the disorder is dominated by a short-ranged scattering potential.

Transitions between the N_L and N_{L+1} integer quantum Hall states are well described (in units of e^2/h) by [7]

$$\sigma_{xx} = s/(1 + s^2), \qquad \sigma_{xy} = N_L + 1/(1 + s^2). \qquad (1)$$

with a scattering parameter s, (which can be identified with the Chern-Simons boson conductivity $\sigma_{xx}^{(b)}$ [8]) given by

$$s = \exp[(\nu_c - \nu)(T_0/T)^\kappa]. \qquad (2)$$

Here ν_c is the critical filling factor and the exponent κ is close to 3/7 at low temperatures. For $N_L = 0$, ie at the termination of the Quantum Hall sequence, this gives

$$\rho_{xx} = s, \qquad \rho_{xy} = 1 \qquad (3)$$

corresponding to a quantised Hall insulator.

Near $\nu = 1.5$ another insulating phase is observed in many samples. The presence of this phase depends on density, disorder and on magnetic field tilt [1,2]. An activation analysis [2] correlates insulating behaviour with the existence of degenerate spin states at the Fermi level: that is it is suppressed when the ferromagnetic polarisation of the spins at $\nu = 2$

persists through $\nu = 1.5$ as the field is increased. This can be demonstrated to be a re-entrant transition, growing out of the $\nu = 1$ IQHE state although, but when it is very strongly developed it appears to grow directly out of the $\nu = 2$ or 3 states.

Figure 1a shows the $\nu=3/2$ and high field Hall insulating transitions measured using a two terminal technique in a sample with a density of $1.4 \times 10^{11} \text{cm}^{-2}$. A scaling plot of this data (fig.1b) shows ρ_{xx} plotted against $(\nu_c - \nu)/T^\kappa$ with $\kappa = 3/7$. There is good agreement with eqn.2 in both cases with slightly different values of T_0. The scaling deteriorates in the $\nu = 3/2$ insulating phase because of the close proximity of the two critical points.

For the B=0 metal-insulator transition the temperature dependence of ρ_{xx} in the insu-lating phase is well described over several orders of magnitude, by $\rho_c \exp[(T_0/T)^n]$ with $\rho_c \sim 0.5\text{h/e}^2$ and n ~ 0.4 [6]. In the metallic phase, at low T, it is of the general form

$$\rho_{xx}(T) = \rho_0 + \rho_1 \exp[-(T_1/T)^p]. \tag{4}$$

As is commonly observed in these systems [9,10], for densities near the critical value the resistance does not always increase monotonically and often has a maximum and a tilted separatrix between the metallic and insulating phases. This makes it difficult to indepen-dently determine the prefactor ρ_1 and the exponent p by fitting to eqn.4. Choices of p=1 (and ρ_1 small) or alternatively p ≈ 0.4 (with ρ_1 then of order 0.5 h/e^2) are equally successful. In each case, however, the parameter T_1 varies with density and there is a general similarity to eqn. 2.

Although the temperature dependence in the "metallic" phase is dominated by activated behaviour there is also evidence of weak localisation [11]. Within experimental error, a ln(T) term cannot be detected directly, but the negative magnetoresistance around B $= 0$ and positive behaviour at higher fields, can be consistently interpreted in terms of a sum of weak localisation and Zeeman contributions. The value of F* [12] extracted in this way is large (2.45). Combined with the cancellation between the two terms it leads to a coefficient for the ln(T) behaviour which is close to zero, consistent with the experimental data.

Figure 2 shows magnetoresistance data for a sample where the density was varied, by exploiting a persistent photoconductivity effect, through the B=0 critical value. The zero field resistivities (figure 3) show the critical density is $7.8 \times 10^{10} \text{cm}^{-2}$. For the highest density trace (figure 2a) there are three fixed points corresponding respectively to transitions into the $\nu = 3/2$ insulating phase, into the $\nu = 1$ QHE state and into the high field Hall insulating phase. As the density is reduced the first transition disappears (or moves to a much lower field); this is followed, in the next trace by the simultaneous disappearance of the two higher field fixed points so, at the lowest density, the temperature dependence over the whole field range is insulating. The low field Hall resistance is well defined through the whole range of densities. This indicates a Hall insulator with σ_{xx} and σ_{xy} both diverging but with the ratio $\rho_{xy} = \sigma_{xy}/\sigma_{xx}^2$ taking the classical value (B/pe, where p is the density). At higher fields it retains this classical behaviour until it becomes quantised near $\nu=1$ and approximate quantisation then continues well into the high field insulating state, consistent with eqn.3.

The critical resistivities for all three transitions: the B=0 transition, the $\nu = 3/2$ transi-tion, and the high field Hall insulator transition are approximately 0.5 h/e^2. In contrast to the situation in p-GaAs[[10]] the resistivity at the high field transition point (and also for

the $\nu = 1.5$ transition) is almost independent of density. Furthermore, the B = 0 transition is unchanged by magnetic field. Again, this is in contrast to the situation in p-GaAs where the B=0 transition transforms smoothing into the IQH effect transition. This difference in behaviour is probably a consequence of the strong spin-coupling in p-SiGe which quenches the independent degree of freedom of the spins.

The behaviour is summarised in a phase diagram (figure 4) which is to some extent schematic. At high densities a well defined Landau level structure is observed with the re-entrant $\nu = 3/2$ insulating phase. At lower densities this is washed out in a region where Γ (the Landau level broadening) is larger than $\hbar\omega_c$ (the Landau level spacing), but the high field and $\nu = 3/2$ insulating phases persist. At the lowest density the behaviour is insulating, over the whole field range, with no clear distinction between the three types of insulating behaviour. The well-known "floating-up" of the lowest Landau level is shown. In this case the condition $\Gamma = \hbar\omega_c$ is the same as the criterion for the appearance of the insulating behaviour $k_F l = 1$ (where l is the mean free path). For higher Landau levels, however, this is not the case and the disappearance of the Landau levels must be associated more with the dominance of the disorder than with "floating-up".

In all cases spin plays an important role. For the B = 0 transition, in the insulating phase, this is demonstrated by the insensitivity to magnetic field; in the metallic regime it is presumeably is the cause of the large value of F*. The high field quantised Hall insulating state is, by definition, spin polarised and spins also seem to play a role in the formation of the $\nu = 3/2$ insulating state.

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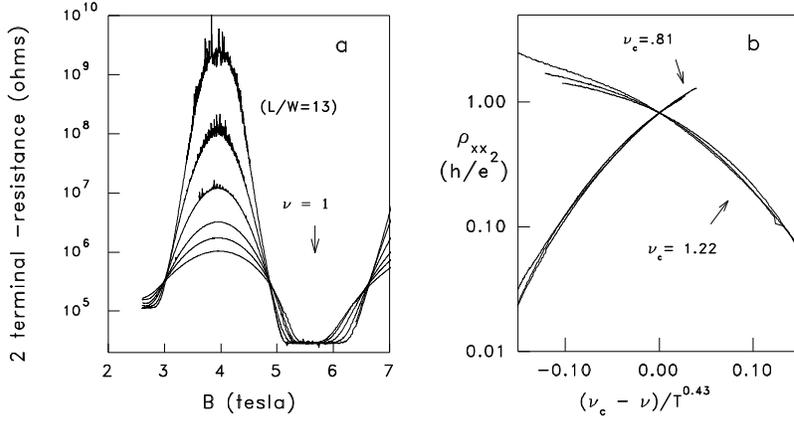
FIG. 1. (a) Two terminal resistance showing the $\nu = 3/2$ insulating phase with a critical point at ν_c=1.22 and the high field Hall insulating transition (with ν_c=.81) at T = 75, 120, 220, 400, 600 and 900mK. (b) Scaling plot for the 120,220 and 400mK data from (a).

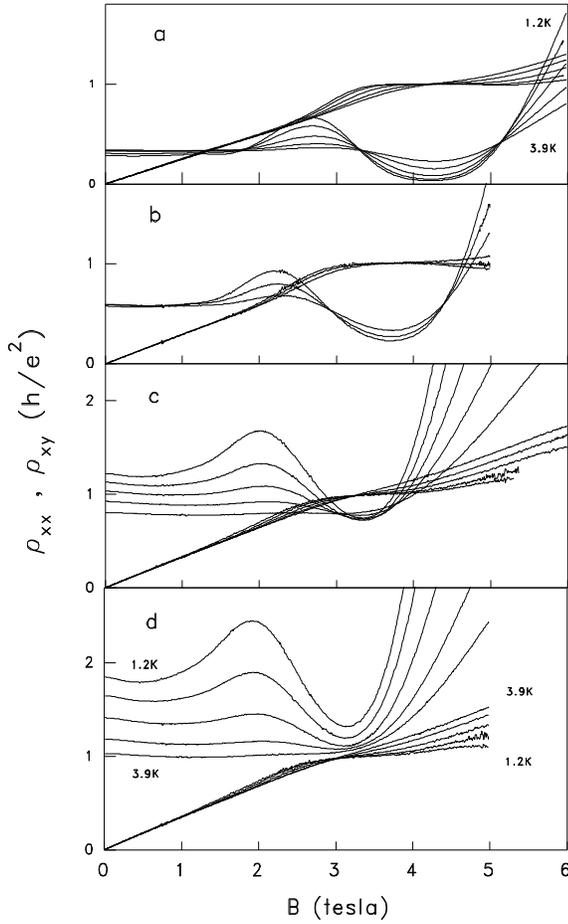FIG. 2. Magnetoresistance at temperatures of 1.2, 1.55, 2.15, 3.0 and 3.9K for densities (in units of 10^{10}cm^{-2}) of:(a) 9.7, (b) 8.1 (1.2 - 2.15K data only) , (c) 7.0, (d) 6.6.
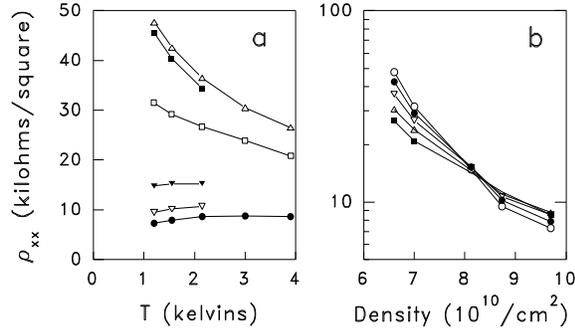
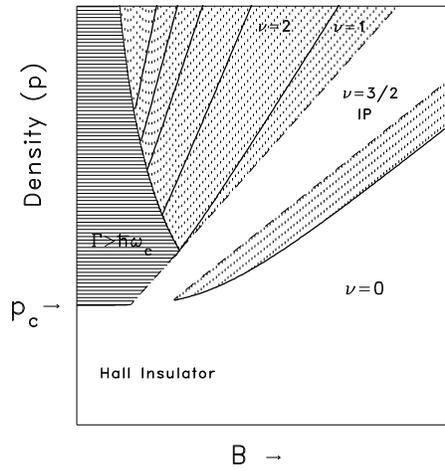FIG. 3. Zero field resistivity (a) as a function of T; (b) as a function of density.

FIG. 4. Schematic phase diagram showing Landau levels, the re-entrant insulating phase at $\nu=3/2$ and the high field insulating phase. p_c is the B=0 critical density. Note also the region where the Landau level broadening is larger than the spacing.

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