QUANTUM PHASE TRANSITIONS IN THE P-SIGE SYSTEM

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The rich variety of phase transitions observed in the strained p-SiGe system are considered and compared. It is shown that the integer quantum Hall effect transitions, the Hall insulating transition and the re-entrant transition into an insulating phase near filling factor 3/2 are all very similar and good examples of quantum critical phase transitions. The B=0 metal insulator transition also shows many similarities to these transitions but requires the inclusion of an extra impurity scattering term to fully explain the data.

Introduction

The strained p-type SiGe system exhibits a variety of interesting phenomena. They include: a large and anisotropic g-factor [1], the appearance of an insulating phase [2] near filling factor ν = 3/2 and a paramagnetic/ferromagnetic spin transition [3] between $\nu = 3$ and 2 . In addition there is the usual quantum Hall insulator transition (from filling factor $\nu = 1$ into the ν=0 insulating phase) and it has also recently been established [4] that there is a B=0 metal-insulator transition of the kind observed in high mobility Si-MOSFETs [5]. It is argued here that many of these features are closely related and that the B=0 transition, the $\nu = 3/2$ transition and the Hall insulating transitions have the same general character as the standard integer quantum Hall effect transitions.

Samples

The samples used to obtain the results discussed here are grown by an ultra-high vacuum chemical vapour deposition process (UHV-CVD). An intrinsic Si layer is followed by a 40nm $Si_{.88}Ge_{.12}$ quantum well, a spacer layer and a boron doped silicon layer. The modulation doping ensures the holes from the ionised acceptors transfer to the quantum well which, because the doping is asymmetric, is triangular. The SiGe layer is sufficiently narrow that the lattice constant difference between the alloy and the pure Si is all taken up by strain. Then the heavy hole band, characterised by a $|M_J| = 3/2$ symmetry, is well removed from other bands. This means the g-factor is large (of order 6) and depends only on the perpendicular component of magnetic field so, unlike the more usual situation, the spins cannot be decoupled from the orbital motion by tilting the magnetic field. The large g-factor also means that exchange enhancement of the spin-splitting induces a fully spin polarised state [3] at $\nu = 2$. Typically mobilities are 1-2 m^2/Vs with quantum mobilities that are very similar [4] implying the dominant scattering potential is short-ranged.

Integer Quantum Hall transition

This system provides one of the few cases where there is a good theoretical description for the integer quantum Hall transitions [6]. For transitions between the n_L and $n_L - 1$ states the conductivities (expressed in units of e^2/h) are given, following the Chern-Simons boson formulation [7], in terms of a parameter s with

$$\sigma_{xx} = 2\sigma^{pk} s/(1+s^2), \quad \sigma_{xy} = n_L - s^2/(1+s^2). \tag{1}$$

For $n_L = 2$ the peak value of σ_{xx} is 0.46 and the two components of the conductivity are connected by an essentially semi-circular relation (see figure 1). The fact that σ^{pk} deviates from

the theoretically expected universal value [6] of 1/2 by only 10 % (the deviation is more usually a factor of order two) is attributed to the short-ranged scattering potential. This means the transport coefficients are not affected by a multiple scattering momentum weighting term and reflect accurately the underlying quantum critical phase transition.

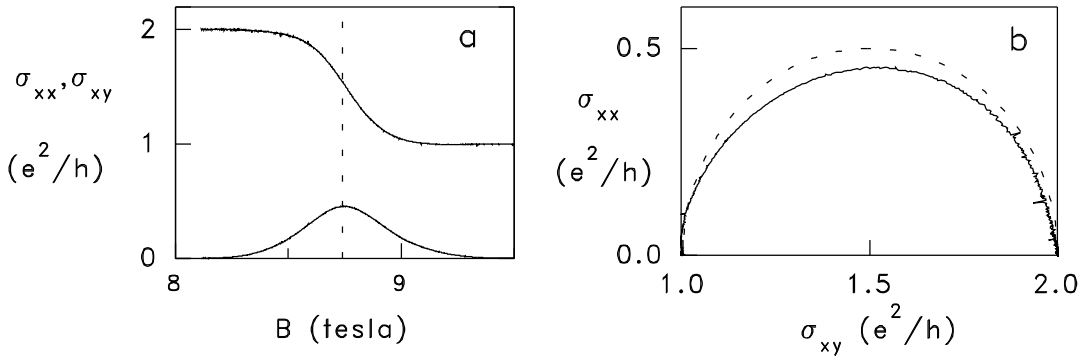

Figure 1: Integer quantum Hall transition, $\nu = 2$ to 1 . (a) σ_{xx} and σ_{xy} at T $\approx$ .05K; (b) σ_{xx} versus σ_{xy} with semicircle (dashed) shown for comparison.

At low temperatures, and not too far from the critical value ν_c, it is found empirically that $s = \exp[(\nu_c - \nu)(T_0/T)^\kappa]$, with κ close to the theoretically expected value [8] of 3/7. This dependence has also recently been obtained theoretically [9]. The same expressions, with $n_L = 1$ and σ^{pk} also very close to 1/2, explain the transition into the Hall insulator state (see figure 2).

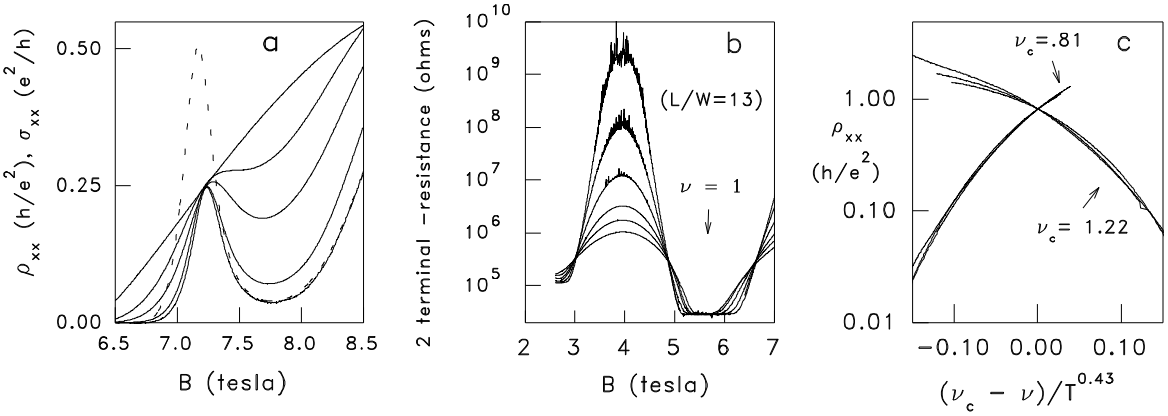

Figure 2: (a) Quantum Hall transition, $\nu = 2$ to 1, for a sample (density of $2.6\times10^{15}\mathrm{m}^{-2}$) where the $\nu = 3/2$ insulating phase appears at about 9T. The dashed line is σ_{xx} at 30mK; solid lines ρ_{xx} for T = 30 to 1000mK. (b) Two terminal resistance of a sample with a density of $1.4\times10^{15}\mathrm{m}^{-2}$, T = 75 - 900mK, showing the $\nu = 3/2$ insulating phase with a critical point at ν_c=1.22 and the Hall insulating transition (with ν_c = .81). (c) Scaling plot for the 120,270 and 400mK data from (b).

Insulating phase at $\nu \approx 3/2$

An insulating phase near $\nu = 3/2$ has been reported [2,3] in many high mobility p-SiGe samples. While this often appears to pre-empt and replace the $\nu = 2$ to 1 quantum Hall transition a careful examination of the data on the low field side of the transition (see figure 2a) shows it develops from the $\nu = 1$ quantum Hall phase and is re-entrant, returning to the same $\nu = 1$ phase at higher fields. As shown in figure 2c it is clearly similar to the Hall insulator transition with the same critical resistivity and temperature scaling. Scaling is poor, however, actually in the insulating phase because of the re-entrant character and close proximity of the two critical points.

Ferromagnetically polarised spin state

It has been demonstrated [3], that a paramagnetic/ferromagnetic phase transition, of the type first predicted by Guiliani and Quinn [10], occurs in p-SiGe. This results from exchange enhancement of the spin splitting, which increases as the system becomes progressively polarised, leading eventually to a fully polarised spin system at ν =2. The question arises of whether there is a reverse transition (back into a paramagnetic state) as the field is further increased to ν=1. Analysis of activation measurements [3] show that this reverse transition occurs for smaller values of the (bare) g-factor and that it is associated with the emergence of the insulating phase. This interesting correlation, whereby the insulating phase seems to appear only out of the paramagnetic state, and is suppressed by a ferromagnetic spin polarisation, is not yet understood.

B = 0 metal insulator transition

Results obtained in a series of p-SiGe samples [4], where the density was varied by changing the spacer thickness, show the temperature coefficient of the resistivity (at low T) changes from negative (ie insulating behaviour) to positive (metallic) as the density increases. The system exhibits the same B=0 metal-insulator transition first observed in high mobility Si- MOSFETs [5] and also found in p-GaAs [12,13] and n-AlAs [14]. As in the other systems the ratio of the coulomb energy to the Fermi energy is large, typically 5-10 here.

In the insulating phase the resistivity varies as $\rho_c \exp[(T_0/T)^m]$ with m of order 0.5, the prefactor ρ_c approximately 0.5 h/e^2 and T_0 varying with density. Good scaling behaviour is observed [4] with T_0^m proportional to (p_c - p) with p the density and p_c the critical density.

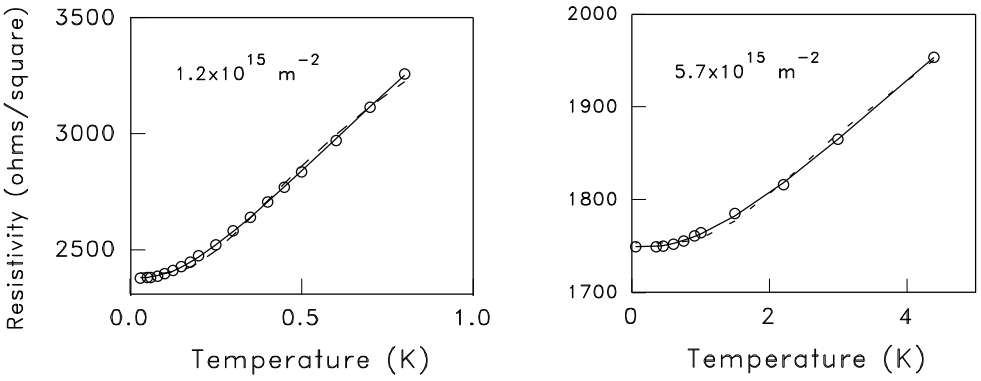

Figure 3: Temperature dependence of ρ_{xx} at B = 0 for two samples with fits to eqn. 2 for n = 0.4 (solid line) and n = 1 (dashed line). In the first case ρ_1 is of order 0.5 h/e^2; in the second .08 and .02 h/e^2 for samples A and B respectively.

On the metallic side of the transition the behaviour is a little more complex. Data is shown in fig.3 for two samples: A, relatively close to the critical density (approximately 1×10^{15}m^{-2}) and B, deep in the metallic phase. In both cases there is a constant background term and an exponential increase with temperature of the general form

$$\rho(T) = \rho_0 + \rho_1 \exp[-(T_0/T)^n], \tag{2}$$

The same behaviour is also observed in Si-MOSFETs [11] and p-GaAs [12]. In p-SiGe, fitting to eqn.2 with n=1, gives a prefactor ρ_1 that is small: this is also the case in p-GaAs. In the spirit of the argument given by Pudalov [11], this expression can be understood in terms of two scattering processes, one leading to a normal impurity resistivity, and the other involving another mechanism such as activation across a gap.

A somewhat better fit to the data in fig. 3 is obtained for n $\approx$ 0.4. The prefactor ρ_1 is then of order 0.5h/e^2 and there is a strong similarity with the expression describing the insulating behaviour (but with an exponent of the opposite sign). Indeed, because ρ_0 is small, the variation over a range of densities, including the critical value, can be described by

$$\rho(T) = \rho_0 + \rho_c \exp[-A\delta_p/T)^\kappa] \tag{3}$$

with A a constant, $\delta_p = (p - p_c)/p_c$, ρ_c of order h/e^2 and κ about 0.5. Eqn. 3 is essentially that proposed by Dobrosavljević*et al* [15], to explain the B=0 transition as a quantum critical phase transition, but with the addition of the extra impurity scattering term.

Weak localisation

Some support for this dual scattering model comes from the magnetic field dependence. There is no obvious evidence of a ln(T) term in figure 3 but the low field magnetoresistance (figure 4a) has the characteristic shape associated with phase breaking of weak localisation by the magnetic field. At higher fields a positive magnetoresistance develops typical of the Zeeman interaction term.

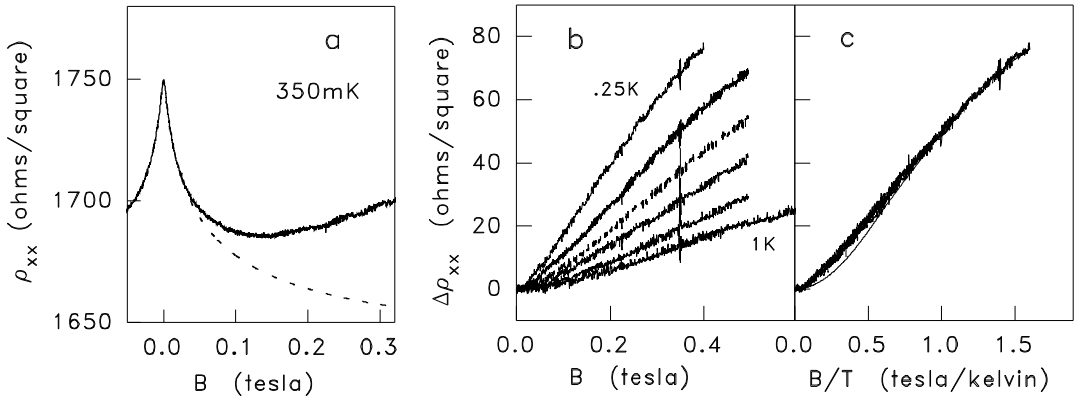

Figure 4: (a) Magnetoresistance, at T = 350mK, for sample B in fig. 3. The fit to the standard expression (dashed line) gives τ_ϕ = 46ps and α = .71. (b) Residues from the weak localisation fits for temperatures of .25, .35, .45, .6, .75 and 1.0K. (c) Data from (b) plotted against B/T. The solid line is G(b) (see text) fitted at large B/T.

Fitting to the very low B behaviour, using the standard expression for the destruction of weak localisation by magnetic field [16], gives good fits with τ_ϕ between 100 and 3 ps (for temperatures between 0.1 and 1K) and an amplitude α of approximately 0.7. The residues from these fits, shown in figure 4b, are then attributed to the Zeeman interaction term, $\Delta\sigma_2(B) = -(e^2/\pi h)(F^*/2)G(b)$ (where the function G(b), with b = $g\mu_B B/k_B T$ is known [17]). Some confidence in this procedure is obtained from the collapse of this data onto a single curve, when plotted as a function of B/T (see fig. 4c). This should be G(b) but there are small discrepancies. A fit at high B/T gives a g-factor of 6.4, consistent with the expected value, and an amplitude F* of 2.45.

The value of F* is unphysical (it should be less than 1) but discrepancies of a similar magnitude are also seen in Si-MOSFETs both for F* and for G(b) [17]. It is interesting to note though, that if the derived value of F* is used to determine the coefficient of the ln(T) dependence, $\alpha p + 1 - 3F^*/4$, it is close to zero (taking the usual value of p=1 for the exponent characterising the temperature dependence of τ_ϕ). That is, the results appear empirically to be consistent with weak localisation although there are some problems with the magnitude of the parameters.

The background, impurity, term therefore appears to behave as expected for a standard 2-D system. In particular, it appears to be weakly localised as T $\rightarrow$ 0 but with a fortuitious cancellation between the dephasing and Zeeman interaction terms.

Summary

In the p-SiGe system the Quantum Hall, Hall insulator and ν=3/2 transitions all appear to be good quantum critical phase transitions with a resistivity that depends exponentially on $(\nu - \nu_c)$ and, at least at low T, scales with a temperature exponent close to 3/7. The B=0 metal-insulator transition exhibits many of the same quantum critical characteristics but appears to involve dual scattering mechanisms with an additional impurity resistivity, at least in the metallic phase, that behaves as a normal 2-dimensional system including being weakly localised at low temperatures.

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