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Quenching of the 2D Metallic State by Aligning the Electron Spins^{*}

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Abstract

We discuss the destabilisation of the electron 2D metallic state by an in-plane magnetic field. We demonstrate that such a field can destabilise the metallic state through spin polarisation which significantly enhances the exchange correlations between electrons. We find that the conducting phase of the fully spin polarised system is almost completely suppressed. We discuss this phenomenon within a memory function formalism which treats both disorder and exchange-correlation effects. We determine the shift in the position of the metal–insulator phase boundary as the system is polarised by an increasing parallel magnetic field.

1. Introduction

A number of recent experiments have shown that a parallel magnetic field destroys the conducting phase of 2D electron systems and makes the system insulating (Simonian *et al.* 1997; Pudalov *et al.* 1997*a*, 1997*b*; Hamilton *et al.* 1999). The critical magnetic field needed is of the order of 1 T in both Si and GaAs and varies with the carrier density. The physical mechanism is not related to the quantum Hall insulator induced by perpendicular magnetic fields (Pudalov 1996) since a magnetic field parallel to the 2D plane does not affect orbital motion within the plane.

We know from numerical simulations that spin polarised electrons are more strongly correlated than unpolarised electrons at the same density (Tanatar and Ceperley 1989), because of the additional exchange when all electrons have parallel spin. We are proposing as a mechanism for the destabilisation of the conducting phase that the polarised state is more likely to be in an insulating state than is the unpolarised state.

Here we focus on localisation of strongly correlated polarised and unpolarised systems when there is weak disorder. For very strong electron correlations, the pure electron system localises into the Wigner crystal (Tanatar and Ceperley 1989). This localisation is caused by the strong interactions between the electrons. Since it occurs even without impurities the mechanism for Wigner localisation is diametrically different from impurity driven Anderson independent-particle localisation. As we move away from the limit of very strong correlations where the density fluctuations $\rho(q, t) = \sum_{k < k_F} a_{k+q}^{\dagger}(t)a_k(t)$ cause Wigner localisation, to leading order the basis set remains the density fluctuations. In our formalism, defect scattering is incorporated in such a way that the Ward identities and particle conservation are satisfied within the density basis. By restricting the basis to

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density fluctuations we average over phase information of processes where the particles and holes propagate independently and so exclude the possibility of Anderson localisation. However, Anderson localisation is not expected to occur for very low densities.

2. Theory

We have previously proposed that strong correlations in the presence of weak disorder can localise the electrons into a glassy state (Thakur and Neilson 1996) and have obtained good agreement with the position of the metal–insulator transition in zero magnetic field for unpolarised electrons (Thakur and Neilson 1999). In our approach (for full details of the formalism see Neilson and Thakur 1999), we search for a metal–glass transition using the Kubo relaxation function

$$\Phi_{\nu}(q,t) \equiv \langle N_{\nu}(q,t) | N_{\nu}(q,0) \rangle.$$
(1)

Here $\Phi_{v}(q, t)$ is defined for the normalised dynamical density variable $N_{v}(q, t) = \rho(q, t)/\sqrt{\chi_{v}(q)}$, where $\chi_{v}(q)$ is the static susceptibility. The polarisation index v = p when the system is fully polarised with all the carrier spins aligned and v = u for the unpolarised system. We are interested in the dynamics of relaxation processes as time $t \to \infty$. The order parameters for the glassy states are given by the relaxation function in this limit, $f_{v}(q) = \lim_{t \to \infty} \Phi_{v}(q, t)$. When $f_{v}(q)$ is non-zero, spontaneous fluctuations do not decay even at infinite time.

For the calculation of $f_{v}(q)$ at a given carrier density, information about the electron correlations is needed as input. We take this from simulation data in Tanatar and Ceperley (1989}, expressing it through the static susceptibility $\chi_{v}(q) = \chi_{v}(q, \omega = 0)$, which we write as $\chi_{v}(q) = \chi_{v}^{(0)}(q)\{1 + V(q)[1 - G_{v}(q)]\chi_{v}^{(0)}(q)\}^{-1}$, where $\chi_{v}^{(0)}(q)$ is the static Lindhard function for polarisation v. The static local field factor $G_{v}(q)$ contains the correlations.

We find that the key property contained in $\chi_v(q)$ that determines the transition is the size of the area occupied by the density exclusion region in the exchange-correlation hole. We assume in the strongly correlated region that the overall shape of the exchange-correlation hole is not greatly affected by low levels of disorder, and so use data for the disorder-free system from Tanatar and Ceperley (1989) to determine $G_v(q)$ (Świerkowski *et al.* 1991). It is not an unreasonable approximation due to the fact that the Coulombic impurities which we considered are screened by the surrounding electron cloud thus weakening their scattering rate. For an impurity concentration around 0.05, which is typically used in our calculations, the system remains weakly coupled. This is because the electron-impurity interaction potential corresponding to these values of concentration is much smaller than the electron–electron interaction. For this reason we employed the local field factor G(q) of the pure and homogeneous electron gas in our calculations.

The level of disorder is expressed in terms of a scattering rate γ_v for carriers scattering from defects. We evaluate γ_v using the memory function formalism (Götze 1978; Gold and Götze 1983) which involves calculations of the force–force correlation function. The derivation of the force-fluctuation variable respects continuity and number conserving equations. After solving γ_v for an appropriate system's Hamiltonian, we expressed γ_v in terms of conductivity using $\sigma = (n_s e^2/m^*)(1/\gamma_v)$. In this paper we compare our calculated σ with experimental values.

The experimental systems we investigated in this paper are based on p-type GaAs semiconductors. These systems have only direct bands and no valleys. Among the direct bands in GaAs it is only the lowest energy band which is occupied.

In our formalism the spilling of the wave function normal to the 2D plane is characterised by a spatial decay parameter 2/b. Its value for GaAs systems at zero bias is around 0.12 nm. The spilling of this magnitude will only become important if the lowest cyclotron orbit $l = 26/\sqrt{H(T)}$ nm is much smaller than 2/b and this can lead to residual coupling of parallel magnetic field with orbital motion. This situation only arises at large values of H. The typical value of H used in GaAs experiments is less than 1 T, which makes l greater than 26 nm. At these high values of l the residual coupling can be totally neglected.

3. Results

Fig. 1 shows the order parameter $f_v(q = 2k_F)$ for the polarised and unpolarised states as a function of the in-plane impurity density n_i , expressed as an impurity concentration $c_i = n_i/n_s$, with n_s the carrier density. For c_i less than a critical density $f_v(q = 2k_F) = 0$, indicating a conducting phase. At the critical c_i the $f_v(q = 2k_F)$ discontinuously jumps to a finite value, signalling the transition to an insulator (Thakur and Neilson 1996).

We find that fully spin polarising the system destabilises the conducting phase except within a small range of carrier densities on the higher density side. The stable conducting phase is restricted to very small levels of disorder. This shrinkage of the conducting region is associated with the enhancement of exchange correlations for the fully polarised system, an effect which favours localisation. In the limit of a perfect system, which is of course an unrealistic limit, we do not predict an insulating state. Within this clean limit the system becomes translationally invariant and thus making the solid free to translate. Hence, there would not be a transition.

We propose that the disappearance of the conducting phase in the presence of an inplane magnetic field is associated with polarisation of the carrier spins. At low carrier densities the energy cost for spin aligned states is small and a weak magnetic field is



Fig. 1. Order parameters $f_v(q = 2k_F)$ for the unpolarised and fully polarised systems as functions of impurity concentration c_i at a carrier density corresponding to $r_s = 9$.







Fig. 3. Dependence of the critical magnetic field H_c on hole density p_s for the metal–insulator transition in GaAs (solid line). The impurity density is $n_i = 2.4 \times 10^9$ cm⁻². The experimental points are taken from Hamilton *et al.* (1999).

sufficient to fully polarise the electrons. While numerical simulations (Rapisada and Senatore 1996) indicate, at least for electron densities $r_s \leq 20$, that the ground state of the system remains an unpolarised electron liquid, for $r_s > 10$ the free energies of the fully spin polarised and unpolarised systems are very close and the Zeeman energy gain from a quite small parallel magnetic field will be sufficient to produce a polarised ground state. We estimate the critical magnetic field H_c by equating the difference in free energies $E_p - E_u$ of the polarised and unpolarised states with the Zeeman energy gain,

$$H_c = (E_p - E_u)\hbar/(g\mu_B).$$

In Fig. 2 we show H_c as a function of the carrier density parameter r_s . We have used $g\sigma_z = 1.1$ for holes in GaAs (Daneshvar *et al.* 1997).

Hamilton *et al.* (1999) have reported that, with a hole density corresponding to $r_s = 9$, a magnetic field $H \leq 0.7$ T drives the conducting state to an insulator for p-GaAs. We find at $r_s = 9$ that the critical magnetic field needed to fully polarise the system is $H_c = 0.6$ T, which is very close to this value. For electrons in Si MOSFETs the values of effective mass and $g\sigma_z$ are not very different from those for holes in GaAs and the measured value $H_c = 0.5$ T in Si by Simonian *et al.* (1997) at $r_s = 9$ is also in good agreement with our value. The critical disorder level needed to drive the fully polarised system to the insulating state corresponds to a conductivity of $\sigma \approx 4.5e^2/h$. This is consistent with the measured value at the transition of $\sigma \approx 5e^2/h$ for $r_s = 9$ (Hamilton *et al.* 1999).

Hamilton *et al.* (1999) gave a phase diagram showing the metal-insulator phase boundary as a function of hole density p_s and magnetic field. For a conductivity $\sigma \simeq 5e^2/h$ we obtain an in-plane impurity density of $n_i = 2.4 \times 10^9$ cm⁻². We find for this n_i that the value of r_s at the phase boundary drops from $r_s = 11.5$ for the unpolarised system (H = 0) to $r_s = 9.2$ for the fully polarised system (H = 0.6 T). To compare with the experimental points taken from Hamilton *et al.*, we use a linear interpolation between p_s and H to determine a critical magnetic field as a function of hole density. Fig. 3 compares the experimental points with our calculated H_c (solid line). There is reasonable agreement.

In conclusion, we have shown that enhancements in exchange correlations due to spin polarisation can drive the system into an insulating phase. Our estimate of the shift in the position of the metal-insulator transition boundary is in reasonable quantitative agreement with experiment. We predict a re-emergence of the conducting phase for the fully polarised system within a very narrow band of carrier densities.

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