COULOMB EFFECTS ON THE MAGNETOCONDUCTANCE OF A TWO-DIMENSIONAL ELECTRON GAS IN A LATERAL SUPERLATTICE: A SCREENED HARTREE-FOCK CALCULATION

A. MANOLESCU
Institutul de Fizica și Tehnologia Materialelor, C.P. MG-7 București-Măgurele, România

R. R. GERHARDTS
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-70569 Stuttgart, Federal Republic of Germany

We calculate the magnetoconductivity tensor of a 2D electron gas in a 1D periodic potential and quantising magnetic fields. We study the internal structure of the Shubnikov-de Haas peaks and analyse recent experimental results. The electron-electron interaction is accounted for within a screened Hartree-Fock approximation (HF A), which describes both compressible strips and an exchange-enhanced spin splitting, unlike the Hartree and the standard HFA.

1 Introduction

Recent magnetotransport experiments on GaAs-AlGaAs heterostructures with a built-in 1D lateral electric modulation, in the $x$ direction, have focused on the internal structure of the Shubnikov-de Haas peaks of the resistivity $\rho_{xx}$. This structure is determined by the density of states (DOS) of the 1D Landau bands and by their exchange-enhanced spin splitting. The interpretation of the experimental results is however difficult and still unclear.

The electron-electron interaction has important effects. The electrostatic and the exchange components act oppositely: The Hartree screening reduces the energy dispersion of the Landau bands, increasing the DOS, while the negative exchange energy of the occupied states broadens the bands, decreasing the DOS. Our previous attempt to take into account such effects in a magnetotransport calculation suggested that the standard Hartree-Fock approximation (HFA) overestimates the exchange. The resulting van Hove singularities (VHS) of the DOS become very sharp, and for modulation periods much larger than the magnetic length $l$ the competition between the long-range electrostatic screening and the exchange broadening may result in unrealistic short-range oscillations of the charge density.

In the present paper we overcome such artefacts by using a screened HFA (SHFA), i.e. we include the screening influence on the exchange interaction.
We show that the enhanced spin splitting can coexist with the picture of compressible/incompressible strips. Our modulation model is a simple potential $V \cos K x$, uniform on the $y$ axis. The material parameters are those for GaAs.

## 2 Screened Hartree-Fock Approximation

Our one-particle Hamiltonian has the form $H = H^0 + \Sigma^{ee} + \Sigma^{ei}$, in which $H^0$ describes an electron in the plane $\{r = (x, y)\}$, in a perpendicular magnetic field $B$ and in the periodic potential, while $\Sigma^{ee}$ and $\Sigma^{ei}$ are the electron-electron and electron-impurity self-energies. We use the Hartree-Fock expression for $\Sigma^{ee}$, at a finite temperature $T$, and we include the polarisation loop in the interaction line of the exchange diagram by replacing the Coulomb potential $u(q) = 2\pi/q$ by $u(q)/\varepsilon(q)$. Here $\varepsilon(q)$ is the static dielectric function of the 2D electron gas, which we consider quasi-homogeneous, characterised by $lV/a \ll \hbar \omega_c$, $a = 2\pi/K$. We calculate $\varepsilon(q)$, for an arbitrary $q$, in the spirit of the random-phase approximation, using the Lindhard formula self-consistently with the eigenstates of the Hamiltonian $H$, within a numerical iterative scheme. The dominant screening corresponds to $q l \ll 1$ and is due to the intra-band transitions, which are determined by the DOS at the Fermi level, $D_F$. In our SHFA, charge-density instabilities of the homogeneous system ($V = 0$) are no longer possible, in contrast to the standard HFA.

In Fig.1 we show typical results in the limit of isolated wires, created by a long-period modulation. This picture combines the specific aspects of both Hartree and Hartree-Fock approximations. The former leads to strong screening, but only bare spin splitting (very small for GaAs), the latter to strong exchange enhancement, but poor screening. In the SHFA the spin splitting of the compressible edge states is accomplished by local fluctuations of the Landau bands with opposite spins, and of the spin density, but each band is individually pinned at the Fermi level. This result disagrees with the prediction of Dempsey et al. that when the lateral confinement decreases, a sharp transition from spin unpolarised to spin polarised edge states, with a steep energy dispersion at the Fermi level, should occur. We believe this prediction is related to the artefacts of the HFA. Note that, due to the exchange effects we can obtain stable incompressible strips in the bulk of the wires, even without impurity broadening.

## 3 Conductivities

We consider the electron-impurity interaction in a phenomenological self-consistent Born approximation, taking $\Sigma^{ei}$ as a c-number determined by a charac-
teristic energy parameter $\Gamma = \gamma \sqrt{B [\text{Tesla}] [\text{meV}]}$. We calculate the conductivities using the Kubo formalism adapted to our system, in which we define the velocity operators as $v = i[H, \mathbf{r}] / \hbar$. The only contribution of the self-energy to the commutator is that of the (nonlocal) exchange interaction, which is in fact the current vertex correction required by the Ward identity.

The relation between the conductivities and the DOS is complicated. Both the diagonal conductivities $\sigma_{xx}$ and $\sigma_{yy}$ have inter-band-scattering components, proportional to $(\Gamma D_F)^2$ and sensitive to the VHS of the 1D Landau bands, when the impurity broadening $\Gamma$ is small. Due to the anisotropy of the system, only $\sigma_{yy}$ has an intra-band term, related to the dispersion of the Landau band, or, classically, related to the drift of the electronic orbits perpendicular to the modulated electric field. This band conductivity is, contrary to the one due to scattering, approximately proportional to $(\Gamma D_F)^{-2}$, thus vanishing near the VHS, but dominating in $\sigma_{yy}$ for $\Gamma \to 0$.

For a comparison with the experiment we need to invert the conductivities into resistivities, $\rho_{xx,yy} = \sigma_{yy,xx} / (\sigma_{xx} \sigma_{yy} + \sigma_{xy}^2)$, and usually $\sigma_{xx} \sigma_{yy} \ll \sigma_{xy}^2$. For the results presented in Fig.2a we have chosen a sufficiently large impurity broadening, so that we have a small band conductivity and consequently $\sigma_{xx} \approx \sigma_{yy}$. In this case the spin splitting is not resolvable even without modulation. For a finite modulation amplitude the Shubnikov-de Haas oscillations of both longitudinal resistivities may have the double-peak structure of the DOS. Such a situation has been observed by Weiss et al. for $\rho_{xx}$, in the second Landau band, $n = 1$, while here we get it more clearly in the third band, $n = 2$. At higher magnetic fields the stronger screening reduces the band width and the resolution of the VHS is rather poor. The spin-splitting is resolved in Fig.2b where both modulation amplitude and impurity broadening are small. For $n = 2$ the spin splitted Landau bands still partly overlap. The VHS are now observable only in $\rho_{yy}$, and are covered by the band conductivity in $\rho_{xx}$.

Recent measurements have shown a more complicated, double- and triple-peak profile in $\rho_{xx}$, which may be attributed to a combined effect of VHS and band conductivity. But as we have shown, screening effects might be very strong. The screening can be reduced for a modulation with a shorter period, comparable to $l$. The steeper energy dispersion may allow the resolution of the VHS when the band conductivity is suppressed by disorder, as suggested in the experiments by Sfaxi et al. However, a comparative measurement of both $\rho_{xx}$ and $\rho_{yy}$, in high magnetic fields, indicating the scattering and the band conductivity contributions is, to our knowledge, not available.

In conclusion, our SHFA describes both screening and exchange-enhanced spin splitting of the Landau bands, interpolating in the expected manner between the contradictory results of the Hartree and the standard Hartree-Fock
approximations. The theoretical resistivities are in qualitative agreement with the available experimental data. Calculational details will be published elsewhere.

Acknowledgments

We are grateful to Gabriele Ernst, Behnam Farid, Marc Tornow and Dieter Weiss for stimulating discussions.

References

1. D. Weiss, K. v. Klitzing, K. Ploog and G. Weimann, Surf. Sci. 229, 88 (1990).
2. A. Manolescu, R. R. Gerhardts, M. Tornow, D. Weiss, K. v. Klitzing and G. Weimann, Surf. Sci. 361/362, 513 (1996).
3. A. Manolescu and R. R. Gerhardts, Phys. Rev. B 51, 1703 (1995).
4. D. B. Chklovskii, B. I. Shklovskii and L. I. Glazman, Phys. Rev. B 46, 4026 (1992).
5. K. Lier and R. R. Gerhardts, Phys. Rev. B 50, 7757 (1994).
6. J. Dempsey, B. Y. Gelfand and B. I. Halperin, Phys. Rev. Lett. 70, 3639 (1993).
7. C. Zhang and R. R. Gerhardts, Phys. Rev. B 41, 12850 (1990).
8. R. R. Gerhardts, Z. Phys. B 22, 327 (1975).
9. L. Sfaxi, F. Petit, F. Lelarge, A. Cavanna and B. Etienne, Surf. Sci. 361/362, 860 (1996).
Figure 1: (a) Landau bands for isolated wires produced by a modulation with $V = 300 \text{ meV}$ and $a = 1000 \text{ nm}$; the dashed line shows the Fermi level and $X_0$ is the center coordinate. (b) Particle and spin densities, $\rho_{\uparrow,\downarrow}$, full and dashed lines. $B = 6 \text{ T}$ and $T = 0.5 \text{ K}$.

Figure 2: The resistivities $\rho_{xx}$, dashed lines, and $\rho_{yy}$, full lines, for a modulation period $a = 300 \text{ nm}$. (a) $V = 12 \text{ meV}, \gamma = 0.3, T = 4.2 \text{ K}$. Inset: Landau bands with $n = 1$ for $B = 2.9 \text{ T}$. (b) $V = 6 \text{ meV}, \gamma = 0.05, T = 1 \text{ K}$. 