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Magnetotransport in quantum wires.

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The temperature-dependent magnetoconductivity of quantum wires has been obtained by solving a Boltzmann equation, which includes the effect of impurity scattering as well as scattering against acoustical and optical phonons.

1. INTRODUCTION

In the present work we consider the transport properties of quantum wires formed by additional confinement of the two-dimensional electron gas of a GaAs-GaAlAs heterojunction[1]. The presence of a confining potential in addition to the magnetic field removes the degeneracy of the Landau levels and allows one to associate a group velocity with each single-particle state. The distribution function describing the occupation of these single-particle states satisfies a Boltzmann equation, which we solve exactly in the case of impurity scattering. In the case of electron-phonon scattering we solve numerically - and in certain limits analytically - the integral equation for the distribution function. The conductivity is determined as a function of temperature and magnetic field in the case when both impurities and phonons contribute to the scattering of the electrons.

2. THE BOLTZMANN EQUATION

We consider an electron moving in the xy-plane under the influence of a constant magnetic field in the z-direction. In addition a parabolic confinement potential limits its motion in the y-direction whereby a wire is formed in the x-direction. The Hamiltonian for such an electron is

$$H = \frac{1}{2m^*}(\boldsymbol{p} + e\mathbf{A})^2 + \frac{1}{2}Ky^2, \qquad (1)$$

where m^* is the effective (band) mass of the electron. The vector potential is taken to be $\mathbf{A} = (-By, 0, 0)$. For simplicity we neglect the Zeeman splitting due to the electron spin. The one-electron energy eigenvalues are then

$$\varepsilon_{nk} = \hbar\omega_h\left(n + \frac{1}{2}\right) + \frac{\hbar^2 k^2}{2m}, \quad n = 0, 1, 2, \cdots. \qquad (2)$$

Here $\omega_h = \omega_c(1+\gamma)^{\frac{1}{2}}$, with $\omega_c = eB/m^*$ being the cyclotron frequency and $\gamma \equiv K/m^*\omega_c^2$, while $m = m^*(1+\gamma)/\gamma$.

We consider the distribution function f_{nk} for the excitations specified by the energy ϵ_{nk}, with group velocity $v_{nk} = \hbar k/m$. The effect of the electric field E in the x-direction is included through the acceleration equation $\hbar\dot{k} = -eE$. The linearized Boltzmann equation is

$$\frac{eE}{k_{\rm B}T} v_{nk} f^0_{nk}(1 - f^0_{nk}) = \left(\frac{\partial f_{nk}}{\partial t}\right)_{\rm coll}, \qquad (3)$$

where f^0 is the equilibrium distribution function, and the collision term on the right hand side involves the scattering against impurities and phonons. In the case of scattering from acoustical phonons we include both deformation-potential and piezoelectric coupling, using realistic parameters appropriate to GaAs. Once the distribution function has been obtained by solving the Boltzmann equation, the current density j and hence the conductivity σ may be calculated from

$$j = \sigma E = -2e \sum_n \int_{-\infty}^{\infty} \frac{dk}{2\pi} v_{nk} f_{nk}. \qquad (4)$$

The chemical potential is assumed to be independent of temperature, equal to $\epsilon_{\rm F}$, since the quantum wire under typical experimental conditions is in contact with a large reservoir of electrons.

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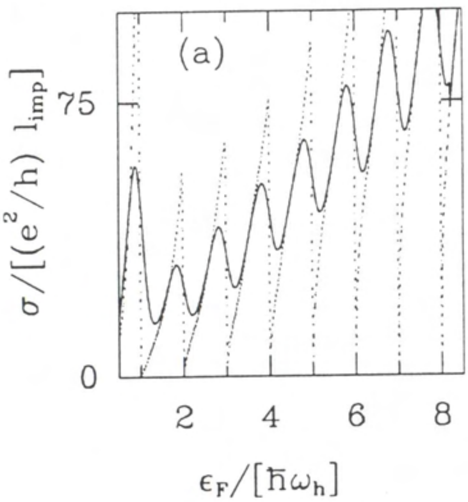
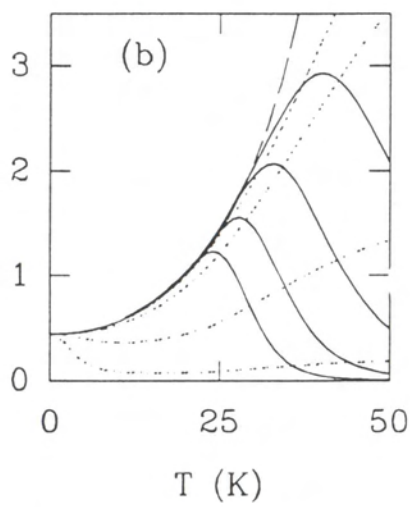
3. RESULTS

It is convenient to write our results in terms of the zero-temperature mobility of the two-dimensional gas $\mu_{\text{imp}} = e\tau_{\text{imp}}/m^*$, in the absence of the magnetic field and the confinement potential. We express the calculated conductivity in units of $(e^2/h)l_{\text{imp}}$, where $l_{\text{imp}} = 2\tau_{\text{imp}}\omega_c l_c$ and $l_c = \sqrt{\hbar/eB}$.





In the first figure (a) the calculated conductivity for a quantum wire with impurity scattering is plotted versus the Fermi level for a choice of confinement potential corresponding to $\gamma = 1$. The dashed lines are the $T = 0$ result and the solid lines correspond to $k_B T = 0.05\ \hbar\omega_h$. The magnetic field is 9 T. The pronounced structure is due to the opening of new "channels" for scattering each time the Fermi energy exceeds $(n+1/2)\hbar\omega_h$.

The second figure (b) shows the conductivity with combined impurity and phonon scattering for a GaAs quantum wire. The normalized conductivity is plotted versus temperature. The magnetic field is $B = 9$ T and the confinement parameter is $\gamma = 1$. The Fermi level is $\varepsilon_F = 0.6\ \hbar\omega_h$, *i.e.*, close to the bottom of the first band. The curve given by long dashes is the result of taking only impurity scattering into account, while the other eight curves involve both impurity and phonon scattering. The conductivity is shown for each of the following values of the zero-field, zero-temperature mobility, $\mu_{\text{imp}} = 0.9, 9, 90$, and $900\ \text{m}^2/(\text{Vs})$. The full curves are for scattering against optical phonons. Note the presence of a maximum which shifts to lower temperatures with increasing purity. The dashed curves are for the case where the scattering is due to acoustical phonons.

4. CONCLUSION

We have found that the magnetoconductivity exhibits a maximum as a function of temperature, depending on the relative strength of the impurity and electron-phonon scattering. The calculated magnetoconductivity oscillates when the Fermi energy or the magnetic field is varied. Our detailed calculations show that the scattering against optical phonons in quantum wires is significant at temperatures somewhat smaller than the corresponding temperatures for the two-dimensional case. The effects predicted in this paper should be observable in quantum wires of sufficient purity, since otherwise the electron density may vary considerably due to fluctuations in the electrostatic potential from the donors.

REFERENCES

1. For a recent review, see C. W. J. Beenakker and H. van Houten, Solid State Physics **44**, 1 (1991).