THERMODYNAMICS OF QUANTUM WIRES WITH A PARABOLIC POTENTIAL IN TILTED MAGNETIC FIELDS

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The magnetic susceptibility, specific heat and entropy of parabolic quantum wires in tilted magnetic fields is studied. The dependence of the magnetic susceptibility, specific heat and entropy on the magnitude of the magnetic field and the direction of the magnetic field, and parameters of a parabolic wells is shown explicitly.

During the past three decades, the physics of low-dimensional semiconductors has become a vital part of present –day research. Low - dimensional structures allow the study of a variety of new mechanical, optical,, and transport phenomena. In this context, one dimensional systems have been of particular interest for past decade [1-8].

The improvements of the semiconductor growth techniques have offered the possibility to obtain low-dimensional semiconductor structures with any desired well shapes. One of those structures is the so-called parabolic quantum well. Theoretically, parabolic confining potentials are very attractive, since the spectrum and wave functions of one-electron states have a simple analytical form, it is possible to derive explicit analytical expressions for the different physical parameters.

The magnetic field is an interesting additional parameter, since it can be applied experimentally in a well-controlled way and modifies fundamentally the electronic structure. The application of a magnetic field to a crystal changes the dimensionality of electronic levels and leads to a redistribution of a density of states. The magnetic field is assumed to be tilted with respect to the normal, it serves to add an extra confining potential to the initial confinement, gives rise to two different kinds of Landau level indices, and causes a dramatic change in the energy spectrum, leading to so-called hybrid magnetoelectric quantization.

As is known, thermodynamic properties is very important aspect for a low – dimensional electron gas [9-12]. This paper reports the thermodynamic properties of electrons in parabolic quantum wires in tilted magnetic fields. We consider the transport of an electron gas in a Q1D electron quantum wire structure as treated in [5, 6], in which a Q1D electron gas is confined by two confinement frequencies ω_1 and ω_2 in the x and z directions, respectively, and the conduction electrons are free along only one direction (y direction) of the wire. Considering the magnetic field transverse tilt direction, $H=(H_\chi, 0, H_z)$ with the Landau gauge $A=(0, xH_z-zH_\chi,0)$, the eigenvalues $E_{nl}(ky)$ are written as [5,6]

$$E_{nl}(k_y)=(n+1/2)\hbar\Omega_1+(l+1/2)\hbar\Omega_2+\frac{\hbar^2k_y^2}{2\tilde{m}} \quad (1)$$

where $\Omega_1^2=\omega_1^2+\omega_z^2$, $\Omega_2^2=\omega_2^2+\omega_x^2$, $\omega_x=eH_x/m^*c=\omega_c\cos\vartheta$, $\omega_z=eH_z/m^*c=\omega_c\sin\vartheta$, $x_0=-b_1l_{B1}^2k_y$, $z_0=b_2l_{B2}^2k_y$, $\tilde{m}=m^*(\Omega_1^2\Omega_2^2)(\omega_1^2\omega_2^2-\omega_x^2\omega_z^2)^{-1}$. Here $l_{B1}=(\hbar/m^*\Omega_1)^{1/2}$, $l_{B2}=(\hbar/m^*\Omega_2)^{1/2}$, $b_1=\omega_z/\Omega_1$ and $b_2=\omega_x/\Omega_2$.

It is known that all of the thermodynamic properties of a system can be obtained as derivatives of the free energy of system. The free energy of the nondegenerate electron gas is [13]

$$F=K_BTN\ \ln\frac{e}{N}\sum_{n,l,k_y}\exp\left[-E_{nl}(k_y)/K_BT\right] \quad (2)$$

Summing geometric series in (2) we have

$$F=K_BTN\ln\left[\frac{eL_y\sqrt{m^*K_BT}}{4\sqrt{2\pi}N\hbar sh(\hbar\Omega_1/2K_BT)sh(\hbar\Omega_2/2K_BT)}\right] \quad (3)$$

Magnetic susceptibility is determined by the formula [9]

$$\chi_{ij}=-\frac{1}{V}\left(\frac{\partial^2F}{\partial H_i\partial H_j}\right) \quad (4)$$

where i,j=1,2; H_1=H_x; H_2 =H_y; V is the volume of the crystal.

The components of the magnetic susceptibility are

$$\frac{\chi_{11}}{\chi_0}=sh^{-1}\left(\frac{\hbar\Omega_1}{2K_BT}\right)\left\{\frac{K_BT}{\hbar\Omega_1}\left(1-\frac{\omega_c^2}{\Omega_1^2}\right)-cth\left(\frac{\hbar\Omega_1}{2K_BT}\right)\frac{\omega_c^2}{2\Omega_1^2}\right\}$$

$$\frac{\chi_{22}}{\chi_0} = sh^{-1}\left(\frac{\hbar\Omega_2}{2K_BT}\right)\left\{\frac{K_BT}{\hbar\Omega_2}\left(1-\frac{\omega_c^2}{\Omega_2^2}\right) - cth\left(\frac{\hbar\Omega_1}{2K_BT}\right)\frac{\omega_c^2}{2\Omega_1^2}\right\} \quad (5)$$

where

$$\chi_0 = \frac{N}{2K_BT}\left(\frac{e\hbar}{m^*}\right)$$

The specific heat is given as [10]

$$C = -T\frac{\partial^2 F}{\partial^2 T} \quad (6)$$

After some manipulation one obtains

$$C = K_BN\left(sh^{-2}\left(\frac{\hbar\Omega_1}{2K_BT}\right)\left(\frac{\hbar\Omega_1}{2K_BT}\right)^2 + sh^{-2}\left(\frac{\hbar\Omega_2}{2K_BT}\right)\left(\frac{\hbar\Omega_2}{2K_BT}\right)\right) \quad (7)$$

The entropy $S = -(\partial F/\partial T)_V$ [13], can be calculated from (3) to give

$$S = K_BN\left\{\ln\left[\frac{L_y e\sqrt{m^*K_BT}}{4\sqrt{2\pi}\hbar N} sh^{-1}\left(\frac{\hbar\Omega_1}{2K_BT}\right) sh^{-1}\left(\frac{\hbar\Omega_2}{2K_BT}\right)\right] - cth\left(\frac{\hbar\Omega_1}{2K_BT}\right)\left(\frac{\hbar\Omega_1}{2K_BT}\right) - \frac{1}{2}\right\} - K_BNcth\left(\frac{\hbar\Omega_2}{2K_BT}\right)\left(\frac{\hbar\Omega_2}{2K_BT}\right) \quad (9)$$

Thus, expressions for the magnetic susceptibility, specific heat and entropy of parabolic quantum wires in tilted magnetic fields have been obtained. As seen from expressions (5), (7) and (9), the components magnetic susceptibility, specific heat and entropy depend on the magnitude of the magnetic field and the direction of the magnetic field, and parameters of a parabolic wells $\omega_{1,2}$. The typical diagrams of this dependence are given in a fig. 1-2.

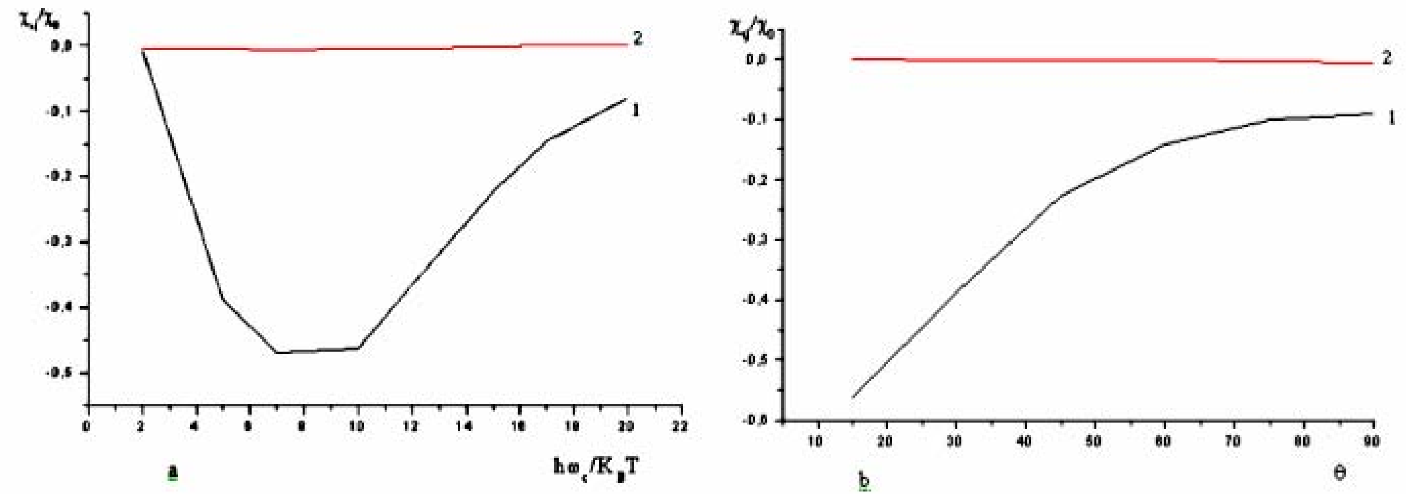

Fig. 1. a. Magnetic-field dependence of the components of the magnetic susceptibility ($\vartheta=30^\circ$, $\frac{\hbar\omega_1}{K_BT}=5$, $\frac{\hbar\omega_2}{K_BT}$). 1-χ_{11}, 2-χ_{22};

b. Dependence of the components of the magnetic susceptibility on the angle ϑ, $\left(\frac{\hbar\omega_c}{K_BT}=\frac{\hbar\omega_1}{K_BT}=5,\ \frac{\hbar\omega_2}{K_BT}=10\right)$. 1-$\chi_{11}$, 2-$\chi_{22}$.

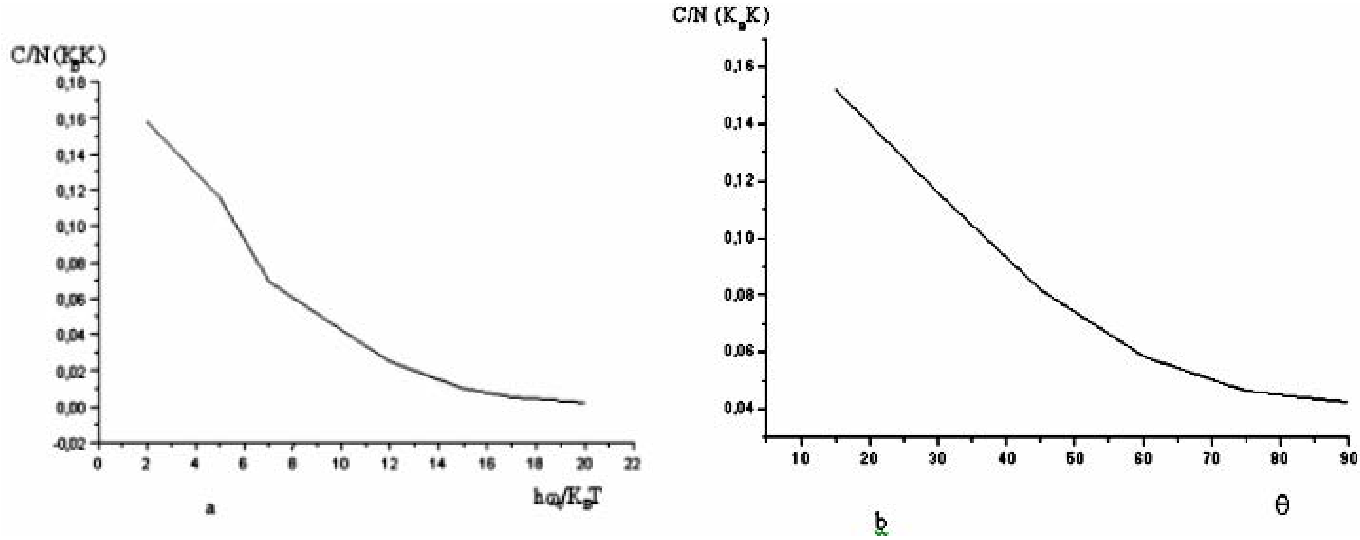

*Fig.2.*a. Magnetic-field dependence of the specific heat ($\vartheta=30^\circ$, $\frac{\hbar\omega_1}{K_BT}=5$, $\frac{\hbar\omega_2}{K_BT}$).

b. Dependence of the specific heat on the angle $\vartheta\left(\frac{\hbar\omega_C}{K_BT}=\frac{\hbar\omega_1}{K_BT}=5,\ \frac{\hbar\omega_2}{K_BT}=10\right)$.

The magnetic-field and angle (ϑ) dependence of the components on the magnetic susceptibility are shown in Fig.1a and Fig.1b, respectively. Figures 2a and 2b show the specific heat per electron in units of K_B.

[1] *L. Brey, N.E. Johnson and. B. J. Halperin.* Phys. Rev. B, 1989, 40, 10647.
[2] *P. Vasilopoulos, F.M. Peeters.* Phys.Rev.B, 1989, 40, p. 10079.
[3] *D. Jovanovic, S. Briggs and J.P. Leburton.* Phys. Rev. B, 1990, 42, p. 11108.
[4] *V.D. Shadrin and F.E. Kistenev.* J. Appl. Phys., 1994, 75, p. 985.
[5] *G. Ihm, M.L Falk, S.K. Noh and J.I. Lee.* Phys.Rev.B, 1992, 46, p. 15530.
[6] *Jai Yon Ryu, G.Y. Hu and R.F. O'Connell.* Phys.Rev. B, 49, p. 10437(1994).
[7] *C.C. Wu and C.J. Lin.* J. Appl. Phys., 1998, 83, p. 1390.
[8] *G.B. Ibragimov.* J.Phys:Condens.Matter., 2002, 14, p. 8145; 2003, 15, p.1427; 2003, 15, p. 8949.
[9] *V.A. Geyler, V.A. Margulis, A.G. Nesmelov, I.I.Chuchaev.* FTT, 1994, 36, c. 1994.
[10] *Tong-zong Li, Ke-lin Wang and Jin-long Yang.* J.Phys.: Condens. Matter., 1997, 9, p.9299.
[11] *W. Zawadzki.* In Two-Dimensional Systems, Heterostructures, and Superlattices. Editors: *G.Bauer, F.Kuchar, and H. Heinrich.* p.79. Springer – Verlag Berlin, 1984.
[12] *F.M. Gashimzade, A.M. Babaev, KH.A. Gasanov.* Fizika, 2002, 8, p.28.
[13] *L.D. Landau and E.M. Lifshich.* Statistical Fizika (in Russian) M.Nauka 1964.p.567.

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MEYLLİ MAQNİT SAHƏSİNDƏ PARABOLİK POTENSİALLI KVANT NAQİLLƏRİN TERMODİNAMİKASI

Meylli maqnit sahəsində yerləşmiş parabolik potensial çuxurlu kvant naqillərdə maqnit qavrayıcılığı, entropiya və xüsusi istilik tutumu öyrənilmişdir. Maqnit qavrayıcılığının, entropiyanın və xüsusi istilik tutumunun maqnit sahəsindən, onun meyl bucağından və kvant çuxurun parametrindən asılı analitik ifadə alınmışdır.

Г.Б.Ибрагимов

ТЕРМОДИНАМИКА КВАНТОВОЙ ПРОВОЛОКИ С ПАРАБОЛИЧЕСКИМ ПОТЕНЦИАЛОМ В НАКЛОННОМ МАГНИТНОМ ПОЛЕ

Изучена магнитная восприимчивость, энтропия и теплоемкость электронного газа в квантовой проволоке, образованной потенциалом параболической ямы, помещенной в наклонное магнитное поле. Найдены аналитические зависимости теплоемкости, энтропии и компонент тензора магнитной восприимчивости от величины и направления магнитного поля и параметров ям.

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