Heat Capacity of a Condensed Electron System in the Dilute Metal n-$Hg_{0.8}Cd_{0.2}Te$

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The magnetic-field–induced Wigner condensation was studied as a function of the electron temperature. Evaluating energy relaxation time and transport measurements we have determined the heat capacity of electrons in n-$Hg_{0.8}Cd_{0.2}Te$. As far as we know, this procedure yields the first experimental data of the heat capacity of a condensed, low-density electron system ($n \approx 10^{14}$ electrons/cm^3). The data revealed a transition of the electron gas to a liquidlike state and eventually to a solidlike state with decreasing temperature.

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In a series of experimental studies[1–11] it was shown that strong magnetic fields induce electron correlation effects in the dilute metal n-$Hg_{0.8}Cd_{0.2}Te$. Strong magnetic fields favor the importance of electron-electron interaction by reducing the Fermi energy. This so-called magnetic-field–induced Wigner condensation was discovered as a significant change of the magnetotransport properties from the one-electron behavior below a critical temperature.[1–5] Eventually it was observed that the electron mobility becomes activated in the correlated state like the transport of a viscous liquid.[2,5,6,10] In this Letter we report the first experimental data of the specific heat of the correlated electrons. In determination of this thermodynamical equilibrium property as a function of temperature, a behavior was observed which supports the conclusions drawn recently from the anomalous magnetotransport.

Using hot-carrier energy relaxation measurements,[12–15] we have determined the specific heat of a low-density electron system ($n \simeq 3\times 10^{14}/cm^3$) in the dilute metal n-$Hg_{0.8}Cd_{0.2}Te$ at low temperatures in the magnetic quantum limit (MQL). Because of the small effective mass ($m^* \approx 0.005 m_e$) of electrons in n-$Hg_{0.8}Cd_{0.2}Te$, the MQL (i.e., all carriers are occupying the lowest Landau level) is reached at magnetic fields of only 0.5 T.[16] Above the MQL the Fermi energy decreases as $\sim 1/B^2$ and electron-electron correlation becomes dominant. Under these conditions a magnetic-field–induced correlation takes place and the conductivity is activated below a critical temperature.[2,5] Independent measurements of the Hall effect, photoconductivity, and energy relaxation time have shown that the observed activation is caused by an activated electron mobility while the carrier concentration remains constant.[6–8] The activated mobility is shown in Fig. 1(a). The condensed electrons with activated mobility behave like a viscous liquid.[5,6,8] Below a certain conductivity this activated behavior is partly obscured by a temperature-independent surface conductance which shunts the activated bulk conductivity with decreasing temperature.[5,11] The current-voltage characteristic is strongly nonlinear in the temperature range of activated mobility as shown in Fig. 1(b). An electric field raises the electron temperature T_e above the lattice temperature T_l and because of the thermally activated mobility the conductivity increases strongly. The shape of the nonlinear current-voltage characteristic is determined by the energy balance in

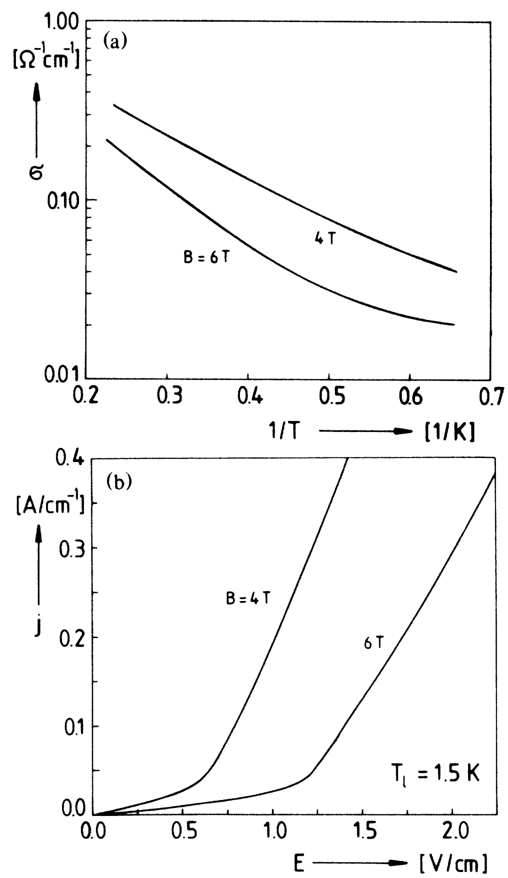

FIG. 1. (a) The activated longitudinal magnetoconductivity as a function of reciprocal temperature. Below a certain conductivity the activation is partly obscured by a temperature-independent surface conductance (see Refs. 5 and 10). (b) Because of carrier heating in an electric field the current-voltage characteristics are strongly nonlinear.

the steady state which can be described by the simplified energy-balance equation

$$jE\tau_\epsilon = C_V \Delta T, \tag{1}$$

where $\Delta T = T_e - T_l$ is the temperature increase due to the electric field E and the current density j. C_V is the heat capacity of the electron system and τ_ϵ the electron energy relaxation time.

The specific heat of a nondegenerate electron gas of density n is expected to be $\frac{3}{2}nk_B$ (k_B is the Boltzmann constant) as long as collective excitations such as plasmons are negligible. This value was found in the semiconductor InSb ($n \approx 10^{14}$ cm^3) by Nimtz and Stadler[12] quite recently. In the magnetic quantum limit, however, the electrons are expected to have a specific heat of $\frac{1}{2}nk_B$ only. As a consequence of the Landau quantization in strong magnetic fields there is only one translational degree of freedom left. In fact this value was observed by Aronzon and Meilikov[17] studying the propagation of helicons in InSb.

Our experiments were carried out with high-purity n-$Hg_{0.8}Cd_{0.2}Te$ with $n = 3.4\times10^{14}/\mathrm{cm}^3$ and $\mu_e = 5\times10^5$ cm^2/V·s as determined from Hall measurements at 4.2 K. Ohmic contacts were fabricated by evaporation of indium onto samples of typical dimensions $3\times2\times0.5$ mm^3. The samples were mounted in a longitudinal configuration within a ^{4}He-bath cryostat. A lock-in technique was used to measure the Ohmic conductivity while the nonlinear current-voltage characteristics were measured with both dc and pulsed electric fields (duty cycle $\leq 1/1000$). Since up to the highest electric fields there was no difference between the dc and the pulsed characteristics we can rule out any lattice heating.

The temperature of the electron system T_e was determined by comparison of the electric field dependence of the conductivity $\sigma(E)$ at fixed lattice temperature T_l with the temperature dependence of the Ohmic conductivity $\sigma_0(T)$ at low measuring current, $I \leq 1\ \mu$A. Using the conductivity as a thermometer of the electron temperature we obtained a relation between E and T_e.[12–15]

The energy relaxation time was measured by evaluation of the time dependence of the hot-electron current Δj following a *small* step variation ΔE superimposed onto a steady-state electric field E as shown in Fig. 2.[12–15] With the assumption that, for the time scale of interest, the physical parameters depend only on the instantaneous average energy, the time dependence of the current and energy are given by the same exponential.[13,14]

The current response Δj consists of two contributions. These are, first, an instantaneous current jump according to the momentum relaxation time $\tau_m \approx 10^{-12}$ s, followed by a slow increase according to the energy relaxation time toward the new equilibrium value $j+\Delta j$ corresponding to $E+\Delta E$. The energy relaxation time τ_ϵ was determined by fitting of an exponential increase to the second part of the current change Δj. These fit calculations showed clean exponential behavior and yielded results of the energy relaxation time which are plotted in Fig. 3. The energy relaxation time varies in the investigated temperature range between 8 and 45 ns with a maximum near 1.9 K. Similar values of the energy relaxation time were measured in an independent experiment by hot-carrier millimeter-wave mixing with $Hg_{0.8}Cd_{0.2}Te$.[18] The dependence of the energy relaxation time on electron temperature is determined by the competition of two inelastic electron-phonon scattering mechanisms: piezoelectric scattering, which decreases with electron temperature, and acoustic deformation potential

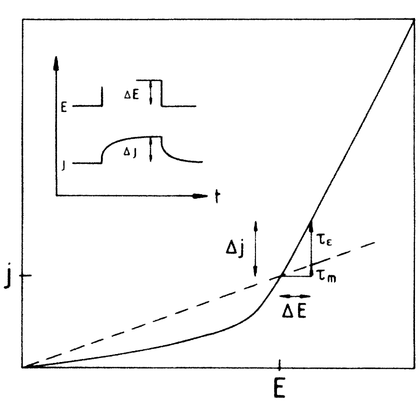

FIG. 2. j-E characteristic and schematic pulse configuration to illustrate the determination of the energy-relaxation time τ_ϵ. A small step variation ΔE results in an essentially instantaneous Ohmic current jump within the momentum relaxation time and a slow increase toward the new equilibrium value $j+\Delta j$ within the energy relaxation time τ_ϵ.

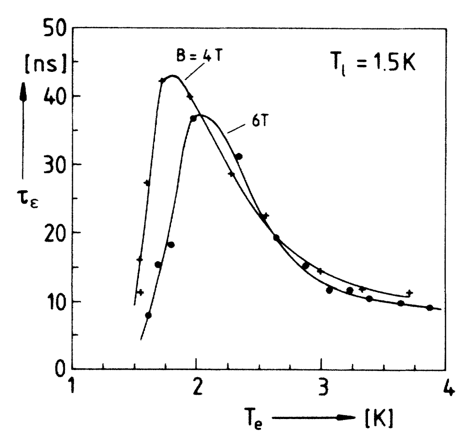

FIG. 3. The measured energy-relaxation time τ_ϵ as a function of the electron temperature T_e for two magnetic fields.

scattering, which increases with electron temperature.[15,16,19]

Knowing the energy relaxation time τ_ϵ we used the energy balance equation (1) to determine the heat capacity of the electron system:

$$C_V = jE\tau_\epsilon/\Delta T. \tag{2}$$

Using Eq. (2) we calculated the specific heat of the condensed electron system. An error analysis was made to estimate the overall error within the calculation of C_V. The main part of the error stems from uncertainty in the determination of the electric power jE delivered to the electron system. This error is due to the observed surface conductance.[5,11] Therefore we determined the surface influence by using a fit calculation which assumes a temperature-independent surface conductance to shunt the bulk. Knowing the surface conductance we could calculate the current flowing through the surface and estimate the corresponding error.

The electron specific heat is shown in Fig. 4. The estimated error according to the above-mentioned procedure is displayed by error bars in the same figure. The heat per electron approaches the value $\frac{1}{2}k_B$ at temperatures between 2.5 and 3.5 K. This value corresponds to the theoretical value of the specific heat for a nondegenerate electron gas in the magnetic quantum limit as mentioned above.

An increase at temperatures above 3.5 K is expected from the excitation of plasmons, the plasma frequency of the sample being ≈ 10 K. At lower temperatures there appears a maximum of about $0.7k_B$, which is followed by a strong decrease down to $0.1k_B$ at the lowest temperature measured.

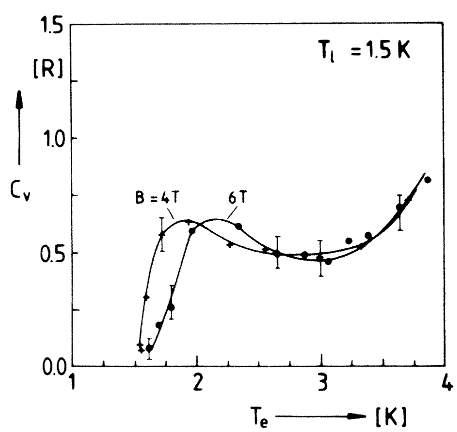

FIG. 4. Heat capacity of the electron system with $n = 3.4\times10^{14}/\mathrm{cm}^3$ vs electron temperature. R is the gas constant. The sharp increase of C_V with T_e in the temperature range 1.5–1.9 K corresponds to the "melting" of the Wigner lattice. In agreement with theoretical predictions the "melting point" shifts to higher temperatures as the magnetic field is increased. The value of 0.5 R near 3 K corresponds to the specific heat of an electron gas in the MQL. The increase of the specific heat at higher temperatures is expected as caused by the excitation of plasmons.

We interpret the temperature dependence of the specific heat as follows. At elevated temperatures the correlation of the electrons is negligible (the activation of mobility vanishes for $T > 5$ K at magnetic fields of $B < 6$ T).[5] Thus this gaslike state is characterized by $C_V \simeq \frac{1}{2}k_B$ in agreement with the theoretical value as long as plasmon excitation is negligible.

At lower temperatures correlation effects become apparent as a result of the formation of a charge-density wave. According to Hartree-Fock calculations by Gerhardts,[20] with decreasing temperature higher harmonics evolve and the charge-density wave gradually changes into a Wigner lattice in between going through a liquidlike phase. This evolution is seen first as an increase of the specific heat with decreasing temperature below 2.5 K. After eventually passing through a maximum C_V becomes extremely small indicating the formation of a Wigner crystal.

The Wigner crystal is expected to have an extremely small specific heat at low temperatures ($C_V \lesssim 10^{-4}k_B$) as shown by Nagai and Fukuyama recently.[21] Their model calculation yields, for $Hg_{0.8}Cd_{0.2}Te$, a Debye temperature of about 300 K which is two orders of magnitude higher than the "melting point" between 1.5 and 2 K (depending on magnetic field) as observed by us.

The observed continuously changing phases agree with the theoretical predictions.[20] As proposed by Kuramoto,[22] the electron system might even be above its critical temperature at the temperatures studied here.

In conclusion we have presented first experimental data of the specific heat of nondegenerate electrons within a magnetic-field–induced condensed phase. With decreasing temperature the condensed electrons go from the gas state to a Wigner solid, in between showing a maximum of the specific heat characteristic of a liquidlike state. The observed values in the gaslike state are in agreement with expectation. At the lowest temperatures measured for the specific heat decreases drastically again as predicted for an electron crystallization.

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