Viscous-liquid-like electron state in the dilute-metal-like *n*-type $Hg_{0.8}Cd_{0.2}Te$

J. Gebhardt, G. Nimtz, B. Schlicht, and J. P. Stadler
II. Physikalisches Institut, Universität zu Köln, 5000 Köln 41, Germany
(Received 2 August 1984; revised manuscript received 28 May 1985)

We have measured photoconductivity and hot-electron-carrier properties of pure *n*-type $Hg_{0.8}Cd_{0.2}Te$ in high magnetic fields. In this dilute-metal-like semiconductor the low-temperature magnetotransport is solely governed by an activated mobility of electrons. Obviously, the predicted magnetic-field-induced Wigner condensation of free electrons is established by a state similar to a viscous liquid.

In the narrow-gap semiconductor $Hg_{0.8}Cd_{0.2}Te$ a magnetotransport anomaly was discovered by Nimtz and coworkers.[1,2] Tentatively this effect was related to an electron-electron correlation, i.e., a magnetic-field-induced Wigner condensation.[1-4] A strong magnetic field favors the electron-electron interaction, since in the extreme magnetic quantum limit the kinetic energy of electrons decreases with the second power of the magnetic field. This is a consequence of the magnetic-field-modulated density-of-states function.[2] In *n*-type $Hg_{0.8}Cd_{0.2}Te$ with $n \approx 10^{14}$ electrons/cm^3 the magnetic quantum limit is passed in fields of about 0.5 T. The main characteristic of the anomaly is a thermally activated longitudinal conductivity, as shown in Fig. 1. The activated conductivity or reciprocal resistivity is observed at temperatures $\lesssim 10$ K for magnetic fields above the magnetic quantum limit. The energy of activation increases with magnetic field, as was recently observed by Stadler, Nimtz, Schlicht, and Remenyi.[5]

According to Hall-effect measurements the abovementioned narrow-gap semiconductor shows neither thermal nor magnetic freezeout of free carriers in pure undoped crystals.[6-8] Therefore, this crystal represents a dilute metal as required for the occurrence of electron condensation.[9] A dilute metal has a low carrier density and thus a low Fermi energy, i.e., a kinetic energy which is about the same as the electron interaction energy. The metallic behavior is based on the donorlike activity of Te vacancies in this compound, their energy levels being resonant with the conduction band, which is similar to the situation in $Pb_{1-x}Sn_xTe$.[6,7,10,11] Accordingly, the conduction band is always partially occupied as in a metal.

From Hall-effect experiments Nimtz and Schlicht concluded that the observed magnetic-field-induced activated conductivity is based on an activated mobility.[1,2] Because the interpretation of the Hall effect in high magnetic fields is still under discussion, we have carried out various experiments to measure both the carrier mobility and carrier density independent of Hall measurements.[8,12-14] The aim of these experiments was to determine whether mobility or carrier concentration is thermally activated. The results show that the electron concentration does not change with temperature or magnetic field. The activated conductivity is caused by an activated carrier mobility. The electrons behave like a viscous liquid of correlated atoms or molecules, which is characterized by an activated viscosity.

The current-field characteristic for *n*-type $Hg_{0.8}Cd_{0.2}Te$ in the activated region is shown in Fig. 2. With increasing

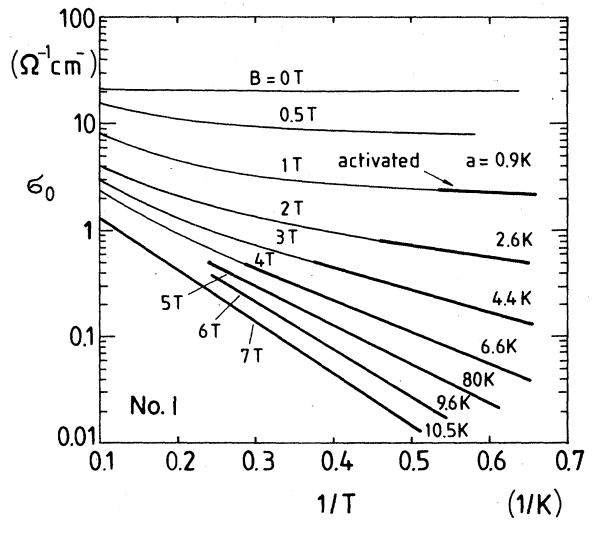

FIG. 1. Longitudinal magnetoconductivity vs reciprocal temperature for various magnetic fields. Thick lines emphasize the regions of activated behavior $\sigma_0 \sim \exp(-a/T)$ with activation energy a.

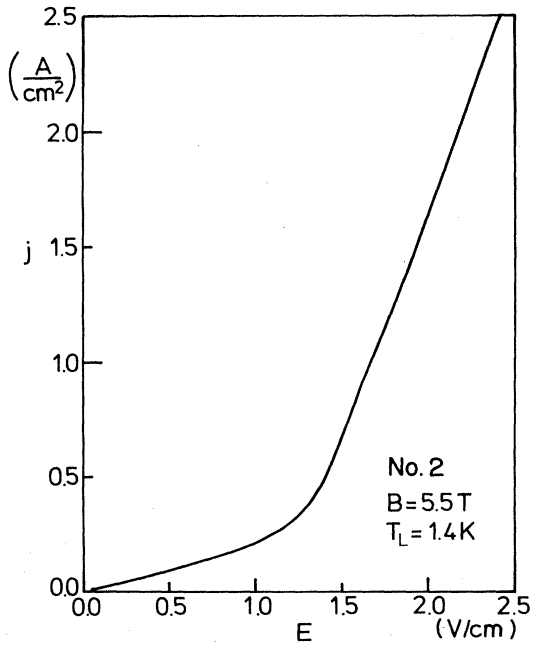

FIG. 2. Strongly nonlinear current-field characteristic of *n*-type $Hg_{0.8}Cd_{0.2}Te$ due to carrier heating.

electric field the temperature of the electron system is raised, while the lattice temperature is kept constant by immersing the samples into liquid helium. Any lattice heating could be ruled out by measuring the current-field characteristic with voltage pulses. There was no difference at all between the dc characteristic and the pulsed characteristic, measured with a duty cycle of 1/1000. The heating of the carriers in the electric field is accompanied by a strong increase of conductivity analogous to the thermal heating of the whole sample. This results in a strongly nonlinear current-field characteristic.

In order to determine whether carrier concentration or carrier mobility is activated, we have measured the Ohmic photoconductivity as a function of temperature by using electric fields as low as $E < 0.25$ V/cm, thus avoiding any carrier heating (see Fig. 2). With a constant number of photons applied to the sample, the number of photoionized excess carriers is also constant in the small temperature range of question. The ratio of photoconductivity to conductivity for n-type material is given by

$$\frac{\Delta\sigma_0}{\sigma_0(T)} = \frac{\Delta n[\mu_n(T)+\mu_p(T)]}{n(T)\mu_n(T)} , \tag{1}$$

where $\Delta\sigma_0(T)$ is the Ohmic conductivity due to photoionization, $\sigma_0(T)$ the Ohmic conductivity, $n(T)$ the carrier concentration at temperature T, Δn the number of photoionized electrons and holes, and μ_n and μ_p the electron and hole mobility, respectively. For n-type $Hg_{0.8}Cd_{0.2}Te$ the relation $\mu_n >> \mu_p$ holds and relation (1) yields approximately

$$\Delta\sigma_0(T) \approx [\Delta n/n(T)]\sigma_0(T) . \tag{2}$$

Experimental data of $\Delta\sigma_0$ and σ_0 are displayed in Fig. 3(a). Our measurements show that the change in conductivity due to photoionization increases with temperature like the conductivity. According to Eq. (2) this result proves that the carrier concentration does not change with temperature. The change in conductivity is only caused by the electron mobility.

In order to test whether the electric-field-induced increase of conductivity is also caused by the electron mobility, we measured the photoconductivity as a function of electric field, keeping the lattice temperature constant. The photoconductivity depending on electric field is analogous to Eq. (2), given by

$$\Delta\sigma(E) \approx [\Delta n/n(E)]\sigma(E) . \tag{3}$$

Experimental data are presented in Fig. 3(b). In agreement with the first experiment $n(E)$ does not increase with electric field or equivalently with electron temperature.

The photoconductivity experiments were carried out with two laser systems, namely, with 25-nsec-long photon pulses from a GaAs laser ($\lambda = 0.9$ μm) and with 2-μsec-long photon pulses of a CO_2 laser ($\lambda = 10.6$ μm). There was no significant difference in the photoconductivity signal if the photon intensity and the length of the laser pulses are taken into consideration. This observation is plausible since the energy relaxation of the photoionized excess carriers is very short compared with their recombination time.

In addition to photoconductivity experiments we have measured the time dependence of the hot-electron current following a small step variation ΔE superimposed onto a steady-state electric field E. The current response Δj consists of an instantaneous current jump according to the momentum relaxation time $\tau_m \approx 10^{-12}$ sec, and a slow increase according to the energy relaxation time τ_ϵ towards its new equilibrium value $j + \Delta j$ corresponding to $E + \Delta E$ (see inset of Fig. 4). We measured τ_ϵ by evaluating the time dependence of the current. In Fig. 4 the experimental data are presented together with the strongly nonlinear j/E

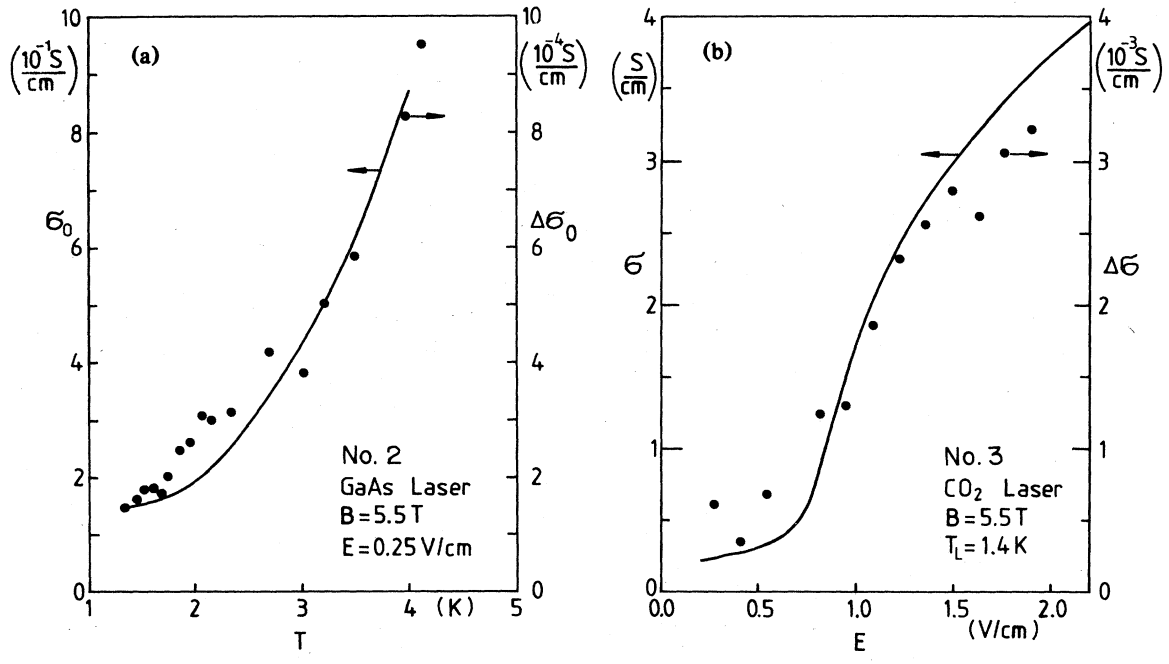

FIG. 3. (a) Ohmic conductivity and conductivity change $\Delta\sigma_0$ (dots) due to photoionization vs lattice temperature. (b) Hot-carrier conductivity and conductivity changes $\Delta\sigma$ (dots) due to photoionization vs electric field at constant lattice temperature T_L.

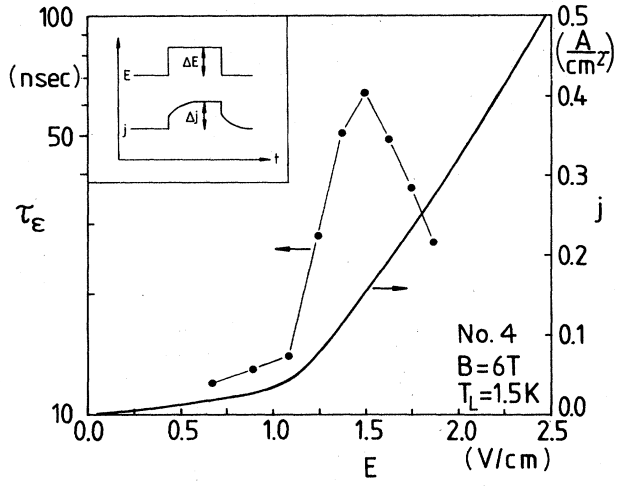

FIG. 4. Energy relaxation time (dots) and current density vs electric field. The inset schematically shows an applied electric field pulse and the corresponding time-dependent hot-electron current.

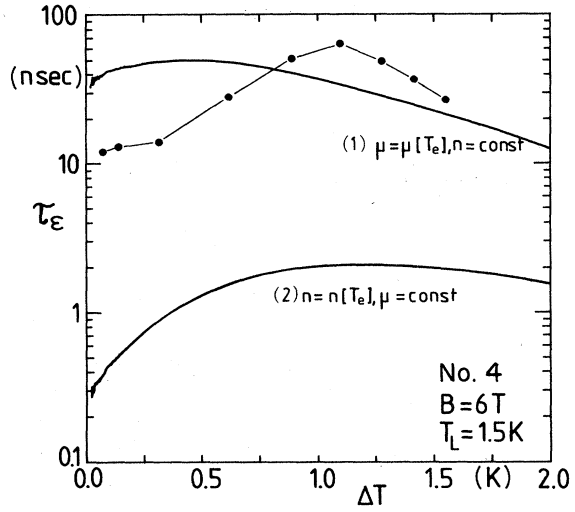

FIG. 5. Measured (dots) and calculated (lines) energy relaxation time vs temperature difference between lattice and electron systems. τ_ϵ was calculated assuming (1) an activated mobility or (2) an activated carrier concentration.

characteristic at fixed lattice temperature $T_L = 1.5$ K and $B = 6$ T.

The observed average energy relaxation times vary between 10 and 70 nsec with a maximum value near 1.4 V/cm. A similar behavior was observed for hot carriers in InSb without magnetic fields at 4.2 K (Ref. 15), and is interpreted by the competition of two inelastic scattering mechanisms: piezoelectric scattering, which decreases with electron temperature, and acoustic deformation-potential scattering, which increases with electron temperature.

To determine the temperature of the hot electrons T_e we compared the field dependence of the conductivity $\sigma(E)$ at fixed lattice temperature T_L with the temperature dependence of the Ohmic conductivity $\sigma_0(T)$, i.e., the thermally activated conductivity.[5]

Using this method we obtained the electron temperature T_e from the equation

$$\sigma(T_L,E) = \sigma_0(T_e) \sim \exp(-a/T_e) , \quad (4)$$

where a is the activation energy.

Assuming that all physical parameters depend only on the instantaneous average energy, the energy balance equation simplifies to

$$jE\tau_\epsilon = C\Delta T , \quad (5)$$

where C is the heat capacity of the electron system and $\Delta T = T_e - T_L$ the difference between electron and lattice temperature. For nondegenerate conditions the temperature-independent value of $\frac{3}{2}nk_B$ will be an estimation for C. Since the concentration of free carriers n is part of the heat capacity, we calculated τ_ϵ assuming two different mechanisms to be responsible for the activated mobility:

(1) an activated mobility [$\mu = \mu(T_e)$, n = const] due to a free-carrier correlation, which may be performed by a charge-density wave or an electron liquid,[4,8,16,17]

(2) an activated carrier concentration [$n = n(T_e)$, μ = const] which may be caused either by a freezeout into donors or by an excitation to a mobility edge, which separates localized and extended states due to random fields in the lattice.

The results of both hypotheses are presented in Fig. 5 and compared with the measured energy relaxation time. Again, the experimental results are in agreement with the assumption of an activated mobility.

At small temperature differences $\Delta T \lesssim 0.8$ K our calculation of the energy relaxation time yields significantly larger values than actually measured. We explain this according to Eq. (5) by a decrease of the electron liquid heat capacity at low temperatures. It follows from the analysis of our experimental data that the heat capacity drops by about 75%, cooling the electrons from 2.5 to 1.5 K. The heat capacity is an interesting physical property from both the theoretical and experimental points of view, and will be investigated more extensively in the near future by us.

In conclusion, photoconductivity experiments and the analysis of energy relaxation time have shown that in the dilute-metal-like n-type $Hg_{0.8}Cd_{0.2}Te$ a magnetic-field-induced activated mobility takes place at low temperatures. We interpret this behavior as caused by correlated electrons conducting by bodily movement. Disorder will act to deform and pin the correlated electron ensemble. As pointed out by Adkins[16,17] and Schlicht,[8] electron transport is therefore visualized as a viscous flow of an electron liquid past fixed pinning sites provided by the disorder. Thermal activation will promote continual microscopic rearrangement, so that there will be diffusion and the possibility of flow with an activated mobility, just as in classical theories of viscosity in normal fluids. Obviously, the theoretically expected magnetic-field-induced Wigner condensation of free carriers[3,4] is established by a state similar to a viscous liquid in reality.

Note added in proof. Due to the Landau quantization only one translational degree of freedom is left in high magnetic fields. Therefore, a reduced value of $\frac{1}{2}nk_B$ may be a better estimation for the heat capacity of free electrons. Using this

value in calculating the energy relaxation time according to Eq. (4) gives rise to a drop of both curve (1) and curve (2) in Fig. 5 by a factor of 3. Our conclusions, however, remain unchanged, as shown in a detailed analysis of the electron heat capacity.[18,19]

We gratefully acknowledge discussions with H. Lehmann, R. R. Gerhardts, and K. Heift. We thank H. Maier and J. Ziegler of Telefunken Electronic, Heilbronn, for supplying some $Hg_{0.8}Cd_{0.2}Te$ crystals. The investigation was sponsored by the Deutsche Forschungsgemeinschaft, Bonn.

[1]G. Nimtz, B. Schlicht, E. Tyssen, R. Dornhaus, and L. D. Haas, Solid State Commun. **32**, 669 (1979).

[2]G. Nimtz and B. Schlicht, in *Festkörperprobleme,* edited by J. Treusch, Advances in Solid State Physics, Vol. XX (Vieweg, Braunschweig, 1980), p. 369.

[3]W. G. Kleppmann and R. J. Elliot, J. Phys. C **8**, 2729 (1975).

[4]R. R. Gerhardts, Solid State Commun. **36**, 397 (1980).

[5]J. P. Stadler, G. Nimtz, B. Schlicht, and G. Remenyi, Solid State Commun. **52**, 67 (1984).

[6]G. Nimtz and B. Schlicht, in *Narrow-Gap Semiconductors,* edited by G. Höhler, Springer Tracts in Modern Physics, Vol. 98 (Springer, New York, 1983), p. 1.

[7]R. Dornhaus and G. Nimtz, in *Narrow-Gap Semiconductors,* edited by G. Höhler, Springer Tracts in Modern Physics, Vol. 98 (Springer, New York, 1983), p. 118.

[8]B Schlicht, Ph.D. dissertation, University of Cologne, 1983 (unpublished).

[9]E. P. Wigner, Phys. Rev. **46**, 1002 (1934).

[10]N. J. Parada and G. W. Pratt, Phys. Rev. **22**, 180 (1969).

[11]C. A. Swarts, M. S. Daw, and T. C. McGill, J. Vac. Sci. Technol. **21**, 198 (1982).

[12]A. Raymond, J. L. Robert, D. S. Kyriakos, and M. Royer, in *Proceedings of the Sixteenth International Conference on the Physics of Semiconductors, Montpellier, 1982,* edited by M. Averous [Physica **117-118B+C**, 428 (1983)].

[13]G. de Vos and F. Herlach, in *Application of High Magnetic Fields in Semiconductor Physics,* edited by G. Landwehr, Lecture Notes in Physics, Vol. 177 (Springer, New York, 1983), p. 878.

[14]A. B. Aleimikov, P. I. Barzuskii, and A. V. Zhidkov, Solid State Commun. **48**, 75 (1983).

[15]J. P. Maneval, A. Zylberstejn, and H. F. Budd, Phys. Rev. Lett. **23**, 848 (1969).

[16]C. J. Adkins, Philos. Mag. B **38**, 535 (1978).

[17]C. J. Adkins, J. Phys. C **11**, 851 (1978).

[18]G. Nimtz and J. P. Stadler, in *Proceedings of the Fourth International Conference on Hot Electrons in Semiconductors, July 8–12, 1985, Innsbruck,* edited by E. Gornik [Physica B (to be published)].

[19]J. P. Stadler and G. Nimtz (unpublished).