Double Dimensional Crossovers of Nonclassical Conductivity

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Dimensional crossovers of nonclassical conductivity have been observed going from 1D to 2D and from 2D to 3D in bulk n-$Hg_{0.8}Cd_{0.2}Te$ for the first time. Various samples of micron dimensions were studied at relative high temperatures between 1.4 and 30 K. Dimensional crossovers were provoked by changing the sample temperature. In this narrow-gap semiconductor, with an extremely small effective mass, the nonclassical conductivity is related to electron-electron interaction.

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Recently, 3D nonclassical contributions to conductivity due to electron wave interference in bulk n-$Hg_{0.8}Cd_{0.2}Te$ were reported [1]. Since energy relaxation times τ_{in} were measured up to 0.1 μs at liquid-helium temperature in this material [2,3], the characteristic phase breaking length L_{in} of electrons according to the random diffusion model has been estimated up to 10 μm at that temperature. Such a length is very large compared with those known from other semiconductors and metals and thus becomes comparable to or even larger than the narrow dimensions of standard infrared detector elements of this semiconductor. Thus, lower-dimensional behavior and dimensional crossovers of nonclassical conductivity are expected at unusual high temperatures and sizes in this material.

Both small effective electron mass ($0.005m_0$) and low carrier density ($n \sim 10^{15}$ cm^{-3}) lead to a long screening length and thus favor the electron-electron interaction in $Hg_{0.8}Cd_{0.2}Te$. In addition, the ratio between Coulomb potential energy and kinetic energy is large compared to other materials. Thus $Hg_{0.8}Cd_{0.2}Te$ presents excellent material for the investigation of nonclassical contributions to conductivity due to electron-electron interaction (EEI).

For example, a 2D-to-1D transition of magnetoresistance due to EEI was observed in the two-dimensional electron gas of GaAs-$Al_xGa_{1-x}As$ heterostructures by Choi, Tsui, and Palmateer [4]. In this Letter, we shall introduce results of double dimensionality crossovers of nonclassical conductivity observed in several n-$Hg_{0.8}Cd_{0.2}Te$ samples. The nonclassical part of the conductivity has also been caused by EEI. With decreasing temperature we observed in sample A2 of dimension $2.1\times3.6\times35$ μm^3, first a crossover from 3D to 2D behavior at 11 K, and finally a crossover to 1D behavior at 3 K. Several crossovers between different dimensions were observed at 18, 12, 10, and 5 K in samples A7, B9, B6, and MC2 with dimensions $1.7\times1.7\times35$, $2.0\times4.5\times35$, $2.3\times5.9\times35$, and $1.0\times3.2\times35$ μm^3, respectively.

The sample preparation is based on the standard technique for preparing n-$Hg_{0.8}Cd_{0.2}Te$ photoconductive detector arrays. The n-$Hg_{0.8}Cd_{0.2}Te$ wafers were first lapped and polished on one side to obtain a flat surface and then etched and bonded with an epoxy to a sapphire substrate. The back side was further lapped, polished, and etched to a thickness of 10 μm. The next step was to delineate the thin material with wet etching of bromine methanol to strips of about 15 μm in width, and to metalize extended contacts on both terminals of each element. The final step was to etch the strips once more with diluted bromine methanol down to small elements with various widths ranging from 1 to 6 μm. The actual sizes depend on the etching speed which is influenced by the initial appearance of the surface and edges of each element. A photograph of the samples is shown in Fig. 1. The surfaces of the sample were free of passivation in order to reduce the surface accumulation layers, which always exist on n-$Hg_{0.8}Cd_{0.2}Te$ surfaces [5].

It should be noted that the technique described above has only been successful for the preparation of sample widths larger than 1 μm. Samples of smaller width broke during preparation. Samples with a width of less than 2 μm are likely to be damaged during the experiment as the temperature decreases. Both difficulties have prohibited the investigation of samples of smaller sizes than given above.

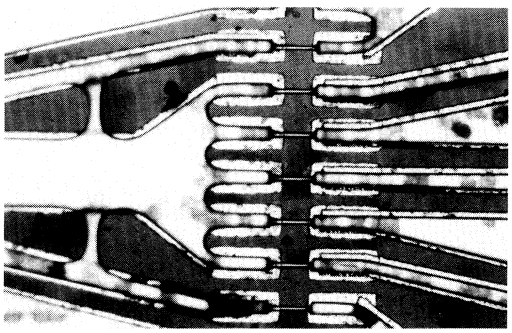

FIG. 1. A photograph of the investigated n-$Hg_{0.8}Cd_{0.2}Te$ samples.

We have measured the differential resistance dU/dI of the samples as a function of electric field with the temperature as a parameter. This method allows us to detect very small deviations from the Ohmic behavior. Figure 2 presents a typical result of resistance R as a function of the second power of electric field E. The nonclassical component of resistance disappears with increasing electric field and only the classical component proportional to E^2 remains, which is typical for warm carriers [6]. This procedure allows the separation of the nonclassical from the classical component of conductivity. A separation of the two components by magnetoresistance measurements is not possible in the case of n-$Hg_{0.8}Cd_{0.2}Te$ because of the large classical contribution of the magnetoresistance as resulting from the small effective mass. The experimental analysis was described elsewhere by Schilz *et al.* [1]. The temperature dependence of the nonclassical conductivity was found to vary with the range of temperature. Results are presented in Figs. 3(a) to 3(c). In the high-temperature range (11 to 30 K), the nonclassical conductivity $\Delta\sigma$ of sample A2 varies in proportion to $\sqrt{T}$ [Fig. 3(c)], between 11 and 3 K the proportionality $\ln T$ fits the data [Fig. 3(b)], and at lower temperatures we observed a $\sqrt{1/T}$ behavior [Fig. 3(a)]. Sample MC2 showed a logarithmic dependence of $\Delta\sigma$ in the temperature range between 5 and 24 K, while at lower temperature, the data fitted a $\sqrt{1/T}$ dependence. For comparison, the data from a large sample U6 ($10\times28\times25$ μm^3) are included in Figs. 3(a) to 3(c), which displays obviously a square-root dependence on temperature.

The nonclassical conduction can arise from weak localization (WL) or from electron-electron interaction. Both show the same temperature dependence; however, their magnetic-field behavior is different [7–9]. The WL can be destroyed by very small fields. We could only investigate the magnetic-field dependence in a longitudinal field. A transversal field hampers the heating by the electric field and a separation of the weak nonclassical effect is not possible. Longitudinal magnetic fields up to 0.1 T had no effect on the nonclassical conduction in the whole temperature regime. Thus we conclude that the effect is

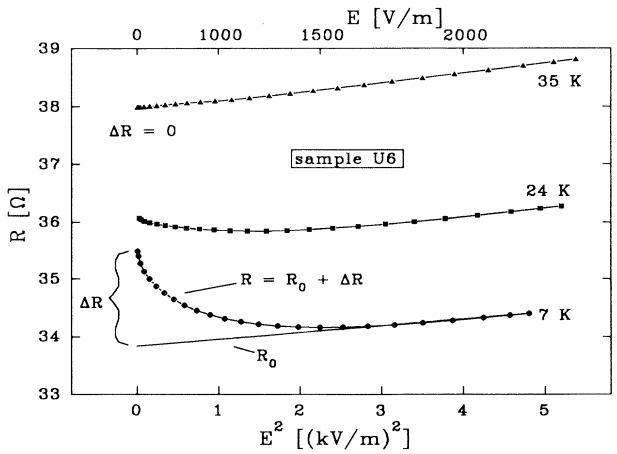

FIG. 2. Resistance R vs the second power of electric field for sample U6.

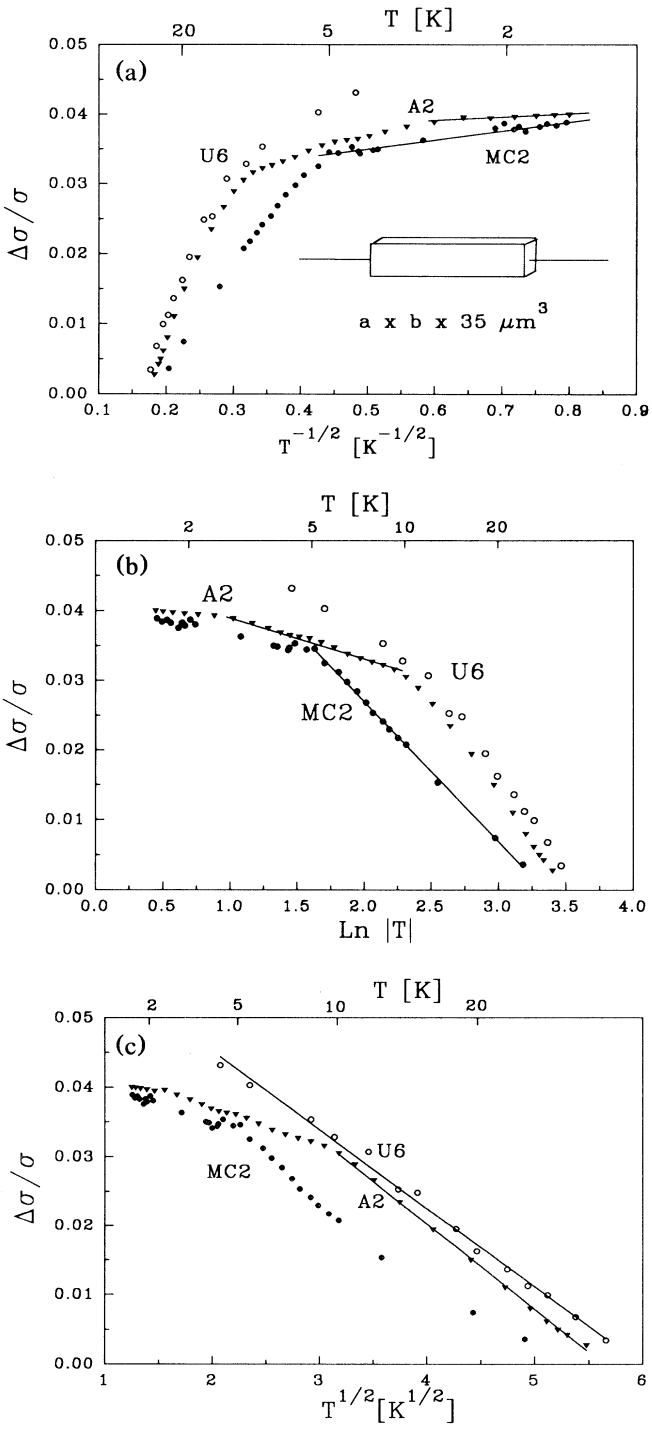

FIG. 3. The $\Delta\sigma/\sigma_0$ of samples MC2, A2, and U6 as a function of (a) $T^{-1/2}$, (b) $\ln T$, and (c) $T^{1/2}$.

based on EEI, since the WL should be destroyed in fields of less than 0.003 T.

The EEI theory predicts the following relations for the three electron-gas dimensionalities [8]:

$$\Delta\sigma_{\mathrm{I}} = -\frac{1}{A}\frac{e^2}{\hbar}\frac{1}{2\pi}\left(4-\frac{3}{2}\tilde{F}_\alpha\right)\left(\frac{\hbar D}{2k_BT}\right)^{1/2} \quad (1)$$

for 1D,

$$\Delta\sigma_{\mathrm{II}} = \frac{e^2}{\hbar}\frac{1}{4\pi^2}\left(2-\frac{3}{2}\tilde{F}_\alpha\right)\ln\left(\frac{k_BT\tau_0}{\hbar}\right) \quad (2)$$

for 2D,

$$\Delta\sigma_{\mathrm{III}} = \frac{e^2}{\hbar}\frac{1}{4\pi^2}\frac{1.3}{\sqrt{2}}\left(\frac{4}{3}-\frac{3}{2}\tilde{F}_\alpha\right)\left(\frac{k_BT}{\hbar D}\right)^{1/2} \quad (3)$$

for 3D, where

$$\tilde{F}_\alpha = 8(1+F/2)\ln(1+F/2)/F - 4$$

in 2D, and

$$\tilde{F}_\alpha = -[32/d(d-2)][1+dF/4-(1+F/2)^{d/2}]F$$

in $d\neq 2$. A is the wire cross-section area, D is the diffusion coefficient, τ_0 is the elastic scattering time, and F is a screening parameter depending on the ratio between k_F (the Fermi wave vector) and the inverse screening length χ. F can be approximated by [9]

$$F = \ln[(1+x)/x],$$

with

$$x = (2k_F/\chi)^2.$$

The observed temperature-dependent conductance fit well with the corresponding theoretical predictions (Fig. 3). This result evidences that dimensional crossovers take place. In the temperature range 10 to 3 K, sample A2 shows not a perfect $\ln T$ behavior [Fig. 3(b)]. The slope in this range is comparable to the slope in the 1D case [Fig. 3(a)]. This is assumed to be due to the small ratio between width and thickness (<2). Such close values which correspond to very close dimensional crossover temperatures (10 and 3 K) hamper the observation of a strict 2D behavior. Actually, the behavior of sample A2 in the temperature range between 10 and 3 K is a 2D behavior mixed with 1D property. In addition, one has to realize that the etching procedure does not deliver samples with an ideal constant cross section along its length. The same temperature range is the transition regime for sample A2 to cross from 3D to 1D behavior with decreasing temperature.

In the case of EEI one expects 3D-to-2D and 2D-to-1D crossovers when the sample thickness or width becomes less than the critical thermal length $L_{\mathrm{th}} = \pi(\hbar D/k_BT)^{1/2}$ [4,8]. Thus the relation between the critical sample dimension L_{crit} and the crossover temperature T_{co},

$$L_{\mathrm{crit}} \propto (1/T_{\mathrm{co}})^{1/2}, \quad (4)$$

should hold. The experimental data in Fig. 4 demonstrate that we have observed such a $(1/T_{\mathrm{co}})^{1/2}$ behavior. This provides further evidence that the nonclassical conductivity is due to EEI. From the slope of the linear fit we calculated $D = 0.4\ \mathrm{m^2 s^{-1}}$, which is compatible with the bulk value of this high mobility semiconductor.

In order to destroy the nonclassical conductance we have carried out hot-electron experiments. While the lattice was kept at low temperature, the electron gas was heated up to much higher temperatures. The balance of thermal energy and electric energy of the electron gas is given by

$$C_{\mathrm{el}}\Delta T_{\mathrm{el}}(E) = \sigma E^2 \tau_E, \quad (5)$$

where C_{el} is the electron heat capacity, σ the conductivity, T_L the lattice temperature, and ΔT_{el} the electron temperature increase. τ_E is the energy relaxation time determined by inelastic electron-phonon scattering, and therefore a function of T_{el}. According to the experimental results presented in Fig. 2 the nonclassical resistance disappears at $E\sim 1500$ V/m at a lattice temperature of 7 K. This means that the electron gas has been heated up to at least 30 K at this field strength.

In the investigated samples having lengths as short as 35 μm, the time required by an electron to cross the sample is in the nanosecond range even at low electric fields. The maximum scanning voltage applied across the sample was 180 mV, which heats the electrons up to energies as large as the polar LO-phonon energy V_{OP} in $Hg_{0.8}Cd_{0.2}Te$ (~ 17 meV). Thus electric-field-induced emission of LO phonons is expected to take place and τ_E becomes governed by the time an electron needs to acquire the LO-phonon energy. In this case we assume in first-order approximation

$$\tau_E = V_{\mathrm{OP}}/e\mu E^2. \quad (6)$$

τ_E can be as small as 5×10^{-11} s, which is more than 2

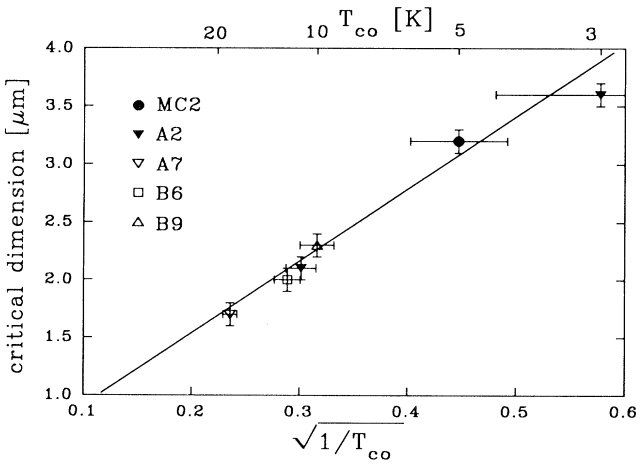

FIG. 4. The critical sample dimensions L_{crit} corresponding to a dimensionality crossover vs $(1/T_{\mathrm{co}})^{1/2}$.

orders of magnitude smaller than the energy relaxation time at zero field [2,3], but still much larger than the elastic scattering time ($\tau_0 \approx 10^{-13}$ s). At these high fields $\Delta T_{el} \gg T_L$ is valid and from Eqs. (4) and (5) follows

$$\Delta T_{el} = \frac{1}{\pi k_B} \left(\frac{3eDV_{OP}}{\mu} \right)^{1/2} . \quad (7)$$

This yields a temperature saturation of the electron heating if the mobility μ is assumed to be constant. With $\mu = 14\ m^2 V^{-1} s^{-1}$ we obtain an electron-gas temperature of about 140 K.

In conclusion, we have observed a nonclassical conductance contribution due to EEI up to 30 K in the narrow-gap semiconductor $Hg_{0.8}Cd_{0.2}Te$. The samples show dimensionality crossovers from 1D to 2D and from 2D to 3D. Obviously this very material is destined to investigate electron interference effects due to the unusually long electron coherence length and extremely small effective mass. This has allowed the study of thermally induced dimensional crossovers in rather large samples and at elevated temperatures. The high mobility and diffusion constant favor both the study of hot carrier effects in the region of nonclassical conduction and the size quantization in all three dimensions.

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[1] J. Schilz, J. Lange, L. Mester, and G. Nimtz, Z. Phys. B **81**, 381 (1990).

[2] J. P. Stadler and G. Nimtz, Phys. Rev. Lett. **56**, 382 (1986).

[3] G. Nimtz and J. P. Stadler, Physica (Amsterdam) **134B**, 359 (1985).

[4] K. K. Choi, D. C. Tsui, and S. C. Palmateer, Phys. Rev. B **32**, 5540 (1985).

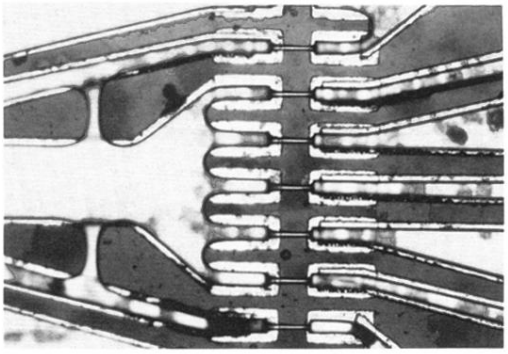
[5] J. P. Stadler, G. Nimtz, H. Maier, and J. Ziegler, J. Phys. D **18**, 2277 (1985).

[6] K. Seeger, *Semiconductor Physics,* Springer Series in Solid-State Sciences Vol. 40 (Springer-Verlag, Berlin, 1989), 4th ed., p. 102.

[7] B. L. Altshuler and A. G. Aronov, Solid State Commun. **30**, 115 (1979).

[8] P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).

[9] T. R. Rosenbaum, R. F. Milligan, M. A. Paalanen, G. A. Thomas, and R. N. Bhatt, Phys. Rev. B **27**, 7509 (1983).



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