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Influence of Quantum Effects on Photoconductor Properties

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Abstract

We observed for the first time non-classical contributions to the resistivity in standard photoconductor elements made from n-$Hg_{0.8}Cd_{0.2}Te$. These effects appear below the rather elevated temperature of 35 K and are due to electron interference.
A novel photoconductor device, based on a lateral confinement effect only, is introduced.

1 Introduction

Progress in fabricating smaller and smaller electronic structures initiates the research on devices which are influenced by lateral quantization and other interference effects of electrons, e. g. weak localization of electrons (coherent backscattering) and electron correlation (electron-electron interaction). Both interference mechanisms take place in a weakly disordered system.

We show that there are already standard photoconductor devices fulfilling the prerequisites for electron interference effects. Measurements on the narrow gap semiconductor compound n-$Hg_{0.8}Cd_{0.2}Te$ are presented, indicating a non-classical contribution to the resistivity.
It will be discussed how such interference effects can influence the performance of a photoconductor.

Finally, a minute photoconductor device made from n-$Hg_{0.8}Cd_{0.2}Te$ is proposed. This is working on a lateral confinement effect — the electronwave cut-off condition. We call such a device a 'Quantum Valve'.

2 Weak localization and electron correlation effect

Miniaturizing a crystal eventually leads to the need of introducing additional correction terms to the resistivity [1,2,3]. In this case the resistivity can be written as

$$\rho = \rho_0 + \Delta\rho,$$

with ρ_0 the classical Drude contribution and $\Delta\rho$ representing the additive non-classical correction. The geometrical size, where such a correction has to be taken into account, are dependent on the elastic and inelastic scattering times, τ_0 and τ_{in}. As soon as one sample dimension approaches the electron coherence length

$$\ell = \sqrt{D \cdot \tau_{in}} = v_F \cdot \sqrt{\tau_0 \cdot \tau_{in}/d},$$

— where D is the diffusion coefficient for electron motion, v_F the Fermi velocity, and $d = 1, 2, 3$ the effective dimensionality of the sample — the correction terms become important. In this definition, a two-dimensional sample is a solid having one dimension smaller than the coherence length ℓ.

For a three-dimensional sample the correction terms both for weak localization and for electron-electron interaction have a $\sqrt{T}$-dependence. In two dimensions, the correction $\Delta\rho$ for weak localization depends logarithmic on T [1,2,3].

2.1 Experiments and results

Our investigations revealed quantum effects in the well known ternary $Hg_{0.8}Cd_{0.2}Te$ infrared semiconductor. The experiments were carried out on standard detector elements, with thicknesses around 10 μm and lateral dimensions of a few tens of microns. We found that such quasi-bulk samples show non-metallic behaviour even up to 35 K. Below this temperature, electron interference provides an additive contribution $\Delta\rho$ to the normal metallic resistivity ρ_0, so that $\rho = \rho_0 + \Delta\rho$.

The two resistivity contributions were separated heating the electron ensemble by means of an electric field. The experimental method is described elsewhere[4]. Fig. 1 shows $\Delta\rho/\rho_0$ *vs* temperature T. The temperature dependence of the observed resistivity correction $\Delta\rho/\rho_0(T)$ is proportional to $\sqrt{T}$. As explained above, such a dependence is either due to weak localization or to electron-electron interaction.

Additional experiments on the transverse and longitudinal magnetoresistivity revealed that the major contribution to the non-metallic resistivity is given by the electron correlation effect. A detailed discussion will be published elsewhere[5]. However, heating the electron system — in this case by an electric field — forces the non-classical $\Delta\rho$ to vanish. This heating can also be done by absorbing photons having energies slightly higher than the band gap. Since the dark resistivity is increased by $\Delta\rho$, the photoresponse is correspondingly enlarged.

The experiments show, that not only future minute devices but also photoconductors with present state-of-the-art sizes are affected by quantum effects. This leads to the idea that not much further miniaturization is needed to fabricate a photoconductor completely working on the base of non-classical conductivity. Such a device will be introduced in the next section.

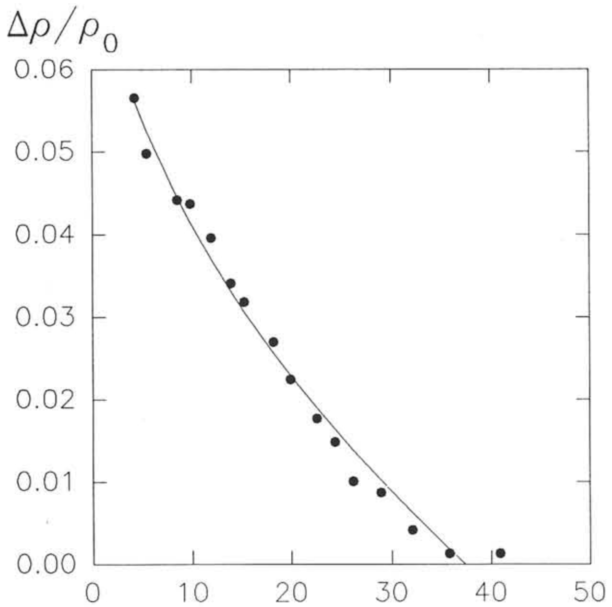

Figure 1: Relative correction to the classical resistivity $\Delta\rho/\rho_0$ as a function of temperature T. The data fit to the formula $\Delta\rho/\rho_0(T) = \Delta\rho/\rho_0(0) - 0.0139 \cdot \sqrt{T}$.

3 Waveguides for electrons

Similar to the quantization of electromagnetic waves in resonators and waveguides, electron energies are quantized due to a geometrical confinement, if the sample size (at least one dimension) is smaller than the coherence length and approaches the de-Broglie wavelength[6]. Only electrons with wavelengths $\lambda \leq 2w$ can propagate through a one-dimensional structure (or waveguide) having width w. The condition $\lambda > 2w$ acts as a cut-off condition for the conductivity[7].

Numerical estimates of such a "cut-off wavelength" (COW) device made from n-$Hg_{0.8}Cd_{0.2}Te$ having dimensions $l = 10$ μm, $L = 10$ μm, $w = 0.5$ μm, $d = 1$ μm (see Fig. 2), gives a vanishingly small conductivity at $T = 4.2$ K, because all occupied subbands have wavelengths λ, which exceed the cut-off wavelength[8]. Because of the exceptionally small effective mass ($m^* = 5 \cdot 10^{-3} m_0$) even this mesoscopic structure leads to extremely large subband splittings. Giving the electron ensemble additional energy, i. e. by heating in an applied electric field (see previous section), by absorbing photons or phonons, will increase the average momentum $\hbar k_F$ (k_F = Fermi-wavevector) and correspondingly decrease the wavelength. This leads to a finite conductivity of the sample. Estimates of the responsivity of such a quantum size device ('quantum valve') is described elsewhere[8].

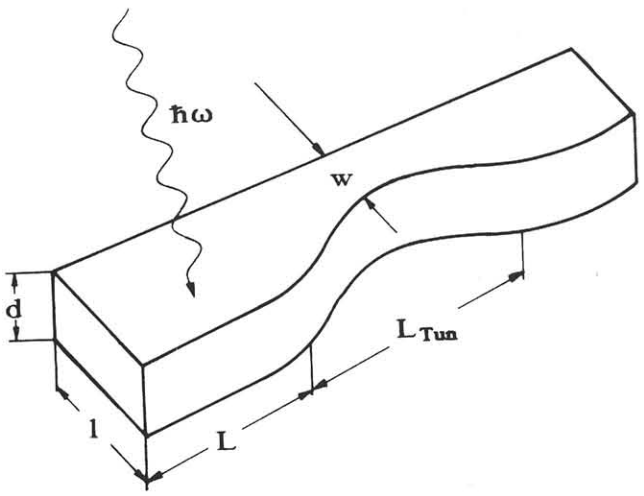

Figure 2: A sketch of a quantum valve device.

4 Conclusions

The IR-n-$Hg_{0.8}Cd_{0.2}Te$ system is characterized by some outstanding properties, such as extremely long inelastic relaxation times and small effective electron mass. This makes it a promising material to exploit quantum effects for the performance of photoconducting devices or the developement of a quantum valve sensor.

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