2D electron channels at block boundaries: physical properties of $Cd_xHg_{1-x}Te$ single crystals

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Experiments reveal 2D electron channel at block boundaries in $Cd_xHg_{1-x}Te$ (CMT) single crystals. The surface electron density in the channels has been determined: $n_s = 2.7\times 10^{12}$ cm^{-2}. The anomalous kinetic effects in CMT are explained on the basis of the existence of an additional 2D conductivity of the sample along small-angle block boundaries.

Research has been carried out on the physical properties of $Cd_xHg_{1-x}Te$ (CMT) compounds for more than twenty years now,[1] but the nature of the anomalous behavior caused in many effects by charge carriers has yet to be explained. The distinctive features of the CMT band structure, the low effective masses of the electrons, and the substantial inhomogeneity of the samples have made it possible to observe several new effects in CMT: a transition from a metallic conductivity to an activation conductivity in a strong magnetic field (an MA transition),[2] effects which are interpreted as a Wigner crystallization,[3] a cluster conductivity mechanism,[4] etc.

As they were discovering the new properties of the CMT compounds, the investigators occasionally assumed that these properties were responsible for the anomalies, but it later turned out that the new effects themselves were not completely clear. We do not have room here to discuss many other properties of CMT (photoelectric properties, optical properties, plastic deformation, etc.) whose interpretation runs into difficulties, but we might point out that in most of these studies the investigators have been forced to assume the existence of an additional electron subsystem with properties different from the bulk properties.

In this letter we discuss the results of an experimental study of the conductivity of 2D electron channels at small-angle block boundaries in CMT single-crystals.

The mosaic structure of $Cd_xHg_{1-x}Te$ single crystals results from a particular aspect of the procedure by which these materials are synthesized. Ordinarily, CMT samples have a mosaic structure with a small-angle or intermediate-angle (depending on the growth method) disorientation of blocks.[5] The accumulation of charged dislocations at small-angle boundaries results in the formation of 2D spatial layers of charge, in a curvature of the bottom of the conduction band, and in the appearance of conducting layers in a process similar to that which occurs at the intergrowth boundary of a germanium bicrystal.[1)] A CMT sample thus has a bulk conductivity and a two-dimensional conductivity along small-angle boundaries. The concentrations of the two groups of electrons in an n-type sample can be determined, and the 2D nature of the conductivity along small-angle boundaries can be established by studying Shubnikov–de Haas oscillations.

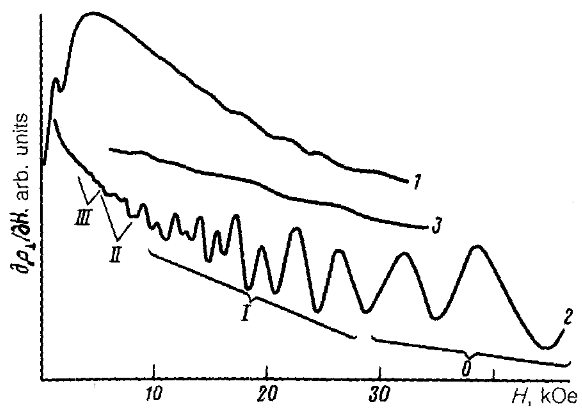

FIG. 1. Derivative of the transverse magnetoresistance, $\partial\rho_\perp/\partial H$, versus the magnetic field. 1—Bulk sample; 2, 3—thin layers.

Curve 1 in Fig. 1 shows the field dependence of the derivative of the transverse magnetoresistance, $\partial\rho_\perp/\partial H$, for a $Cd_{0.185}Hg_{0.815}Te$ sample with dimensions of $6\times1.5\times0.5$ mm. The concentration and mobility of the electrons at $T=4.2$ K which were found from galvanomagnetic measurements are $n=1.4\times10^{14}$ cm^{-3} and $\mu=1.05\times10^{5}$ cm^2/(V·s). The Shubnikov–de Haas oscillation at $H\approx1.5$ kOe correspond to the value found for n from Hall-effect measurements. In fields $H>10$ kOe we can see (curve 1) some oscillations in $\partial\rho_\perp/\partial H$—just barely distinguishable at the highest sensitivity of the apparatus—which are caused by the quantization of the electron gas in the 2D channels along small-angle boundaries. The very low amplitude of these oscillations is explained on the basis that only a small fraction of all boundaries are oriented perpendicular to the given direction of the magnetic field, and it is at these boundaries that the quantization occurs; there are twice as many boundaries oriented parallel to **H**; these boundaries have a lower resistance and they shunt the channels responsible for the oscillations in $\rho(H)$. The shunting effect of this fraction of the channels can be eliminated by reducing the thickness of the sample to values less than the average block size: 100–400 μm.

Curve 2 shows a recording of $\partial\rho_\perp/\partial H$ for a layer 65 μm thick obtained from a bulk sample by mechanical polishing and chemical etching. Curve 2 corresponds to the case in which **H** is parallel to the surface of the thin layer, while curve 3 corresponds to the perpendicular orientation. The oscillations in $\partial\rho_\perp/\partial H$ on curve 2 have the characteristic shape for the behavior of the magnetoresistance of 2D channels in which the electrons fill several 2D subbands. The anisotropy of the oscillation pattern with respect to the orientation of **H** and the appearance of the oscillations themselves can be explained in the following way. If the thickness of the sample is reduced to a monolayer with respect to a block, nearly all of the small-angle boundaries will be oriented perpendicular to the surface of the film. If the magnetic field is directed perpendicular to the surface of the film, it will not cause a quantization in the channel, since in this case the channels run parallel to **H** (curve 3). If the magnetic field is instead directed parallel to the surface of the film (but if the orientation $\mathbf{H}\perp\mathbf{j}$ is retained), some of the boundaries will be oriented perpendicular to **H**. An important point is that the current absolutely must flow through these channels (which are perpendicular to **H**), since any other current flow mechanism would be ruled out in the 2D network of boundaries which forms in the film. Consequently, no shunting effect occurs in the film: The unquantized channels are connected in series with the quantized channels. When the direction of **H** is changed in the plane of the film, the oscillation pattern does not change substantially; this result verifies the random nature of the current flow along the two-dimensional channels. Analysis of the set of Shubnikov–de Haas oscillations (curve 2) shows that electrons fill four 2D subbands of a channel with the following concentrations: $n_0 = 0.7n_s$, $n_1 = 0.19n_s$, $n_2 = 0.07n_s$, $n_3 = 0.04n_s$. The total surface density in a channel is $n_s = 2.7\times 10^{12}$ cm^{-2}. In Fig. 1, the numerals 0–III label groups of extreme values corresponding to the ground subband (0) and the excited 2D subband (I, II, III).

The existence of a 2D conductivity along the framework of small-angle boundaries in CMT crystals explains many physical effects for which no clear explanation has previously been available. We will discuss two of these effects here: the residual conductivity after the metal-activation transition in a magnetic field[7] and the Hall effect.[8]

We know[2,7] that the localization of electrons in the wells of the potential relief in CMT samples with a concentration $n \cong 10^{14}$ cm^{-3} at $T = 4.2$ K begins at magnetic fields $H > 5$ kOe. As H is increased, the bulk conductivity disappears, and we are left with only the conducting framework of small-angle boundaries; it is this framework that determines the residual conductivity. It seems highly probable that this model can also explain the experiment of Ref. 3, where the anomalous behavior of $\rho(H)$ in the quantum limit in terms of H was interpreted as the Wigner crystallization of an electron gas.

The negative value of the Hall constant R in p-type CMT samples at lower temperatures and in strong magnetic fields (the low-temperature inversion[2] of the sign of R; Ref. 8) can also be explained in terms of a conductivity along 2D electron channels. In this case, questions pertaining to the metallic conductivity along an acceptor band ("heavy electrons"),[8] etc., are eliminated.

It was not possible to observe Shubnikov–de Haas oscillations involving 2D channels in all of the samples cut from a single disk. This circumstance suggests that the conducting framework of small-angle boundaries is a structure consisting of conducting plane channels with random breaks in the planes and joints. We see the emergence here of a problem of percolation theory which is similar to the problem of nodes and links.

Anomalous oscillations have been observed previously,[9] but they were not explained at the time.

[1)]A germanium bicrystal has a p-type inversion layer.[6]
[2)]A transition from a positive value of R to a negative value when holes freeze out at acceptors.

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