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Mobility of Dirac Electrons in HgTe Quantum Wells

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The mobility of Dirac electrons (DEs) in HgTe quantum wells with the thickness close to the critical value corresponding to the transition from the direct to inverted spectrum has been studied experimentally and theoretically. The nonmonotonic dependence of this mobility on the electron density is found experimentally. The theory of DE scattering on impurities and fluctuations of the thickness of a well caused by its roughnesses is elaborated. This theory is in good agreement with experiment and explains the observed nonmonotonicity by the decrease in the ratio of the de Broglie wavelength of DEs to the characteristic size of the roughness with the increase in their concentration.

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It was shown in recent works [1–4] that mercury telluride quantum wells with the thickness close to the critical value (d_c) corresponding to the transition from the direct to inverted spectrum allow a system of single-valley two-dimensional Dirac fermions having a gapless nature and, respectively, a linear energy spectrum (two-dimensional Weil semimetal), which leads to a series of features in its transport [2, 3] and optical [1, 4] responses. However, detailed and systematic studies of the mobility in this system are absent to date and information is limited to only fragmentary data in [2, 5]. This work completes the specified omission. It presents a detailed study of the behavior of the mobility to the right of the Dirac point and reveals the nonmonotonic dependence of the mobility on the density of two-dimensional electrons caused by a feature of their scattering on fluctuations of the thickness of the quantum wells.

The studied samples were field Hall structures manufactured on the basis of HgTe quantum wells with the thicknesses of 6.3, 6.4, 6.6, and 7 nm and the (013) orientation. It should be noted that unlike other wells, the well with a thickness of 7 nm already corresponds to a two-dimensional topological insulator. Samples had a width of 50 μm and the distance between potentiometric contacts of 100 and 250 μm (their detailed description is given in [2, 3]). The measurements were carried out at a temperature of 4.2 K and in magnetic fields to 1 T using a standard scheme of phase-sensitive detection at a frequency of 12 Hz and at a measuring current through the sample of 100 nA excluding the heating effects.

Typical dependences of the conductivity of samples on the effective gate voltage $\sigma(V_g^{\mathrm{eff}})$ (where $V_g^{\mathrm{eff}} = V_g - V_g^{\min}$, V_g is the applied gate voltage, and $V_g^{\min}$ is the gate voltage corresponding to the minimum conductivity) for all four thicknesses of quantum wells are shown in Fig. 1. It is clearly seen that all dependences pass through a minimum, and the minimum conductivity for all curves exceeds e^2/h, which confirms the conclusion made in [2] about the quasi-metallic behavior of wells with the thickness close to the critical value at the Dirac point. We also note that, near the Dirac point, they are almost symmetric with respect to $V_g^{\mathrm{eff}} = 0$. At the further increase in the gate voltage amplitude, this symmetry is lost owing to the closeness of valleys of heavy holes [2]. Below, we will consider only the behavior of the conductivity to the right of the Dirac point, where transfer is ensured by Dirac electrons (DEs). The analysis of the behavior of Dirac holes is complicated because of the effect of already mentioned side valleys of heavy holes [2, 6] and is outside the scope of this work.

Figure 2 shows the density dependences of the mobility of electrons determined from conductivity measurements. It is seen that the mobility of wells with thicknesses of 6.3 and 6.4 nm increases in the total density range, and this increase changes at $N_s = (0.9–1.3)\ \ 10^{11}\ \mathrm{cm}^{-2}$ from sharp at low densities to smooth at high densities. A kink in the mobility at the density $N_s \approx 2.8\ \ 10^{11}\ \mathrm{cm}^{-2}$ is also observed for