ISSN 1063-7826, Semiconductors, 2018, Vol. 52, No. 11, pp. 1469–1473. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © A.A. Dobretsova, Z.D. Kvon, L.S. Braginskii, M.V. Entin, N.N. Mikhailov, 2018, published in Fizika i Tekhnika Poluprovodnikov, 2018, Vol. 52, No. 11, pp. 1357–1361.

XXII INTERNATIONAL SYMPOSIUM "NANOPHYSICS AND NANOELECTRONICS", NIZHNY NOVGOROD, MARCH 12–15, 2018

Gapless Dirac Electron Mobility and Quantum Time in HgTe Quantum Wells

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Submitted April 25, 2018; accepted for publication May 7, 2018

Abstract—The mobility and quantum time of Dirac electrons in HgTe quantum wells with near-critical thickness corresponding to the transition from the direct to inverted spectrum are experimentally and theoretically investigated. The nonmonotonic dependence of the mobility on the electron concentration is experimentally established. The theory of the scattering of Dirac electrons by impurities and irregularities of the well boundaries leading to well thickness fluctuations is constructed. The comparison of this theory with an experiment shows their good agreement and explains the observed nonmonotonic behavior by a decrease in the ratio between the de Broglie wavelength of Dirac electrons and the characteristic size of irregularities with increasing electron concentration. It is established that the transport time is larger than the quantum time by almost an order of magnitude in the case of the dominance of roughness scattering. The transition from macroscopic to mesoscopic samples is studied and an abrupt decrease in both the mobility and quantum time is observed. This behavior is attributed to the size effect on the free path length.

DOI: 10.1134/S1063782618110076

As was shown in recent studies [1–4], in mercury-telluride quantum wells with a width similar to the critical width d_c, which corresponds to the transition from the direct to the inverted spectrum, a system of single-valley two-dimensional Dirac fermions with a gapless nature and, consequently, a linear energy spectrum (a two-dimensional Weyl semimetal) is implemented, which gives rise to a number of features in its transport [2, 3] and optical [1, 4] responses. However, to date, there has been a lack of detailed and systematic studies on the mobility and quantum time in this system and the available data are limited to little information from [2, 5]. The present work fills this gap. Here, we investigate the behavior of the mobility and quantum time to the right of the Dirac point. We find a nonmonotonic dependence of the mobility on the two-dimensional electron concentration caused by a peculiarity of their scattering at fluctuations in the quantum-well width. In addition, we establish that the transport time is significantly longer than the quantum time.

The investigated samples were macroscopic and mesoscopic field Hall structures based on HgTe quantum wells with thicknesses of 6.3, 6.4, 6.6, and 7 nm and the (013) orientation. It should be noted that, in contrast to the other wells, the 7-nm-thick well already corresponds to the two-dimensional topological insulator state. The macroscopic samples had a width of 50 μm and distances of 100 and 250 μm between potentiometric contacts; in the mesoscopic samples, these quantities were 3.2 and 35 μm, respectively.

The measurements were performed at a temperature of 4.2 K in magnetic fields of up to 2 T using a standard phase-sensitive detector circuit at frequencies of 12 Hz and a measuring current of 100 nA through the sample, which excluded heating effects.

Figure 1 shows the typical dependences of the sample conductivity on the effective gate voltage $\sigma(V_g^{\text{eff}})$, where $V_g^{\text{eff}} = V_g - V_g^{\min}$ is the applied gate voltage and $V_g^{\min}$ is the gate voltage corresponding to the minimum conductivity, at all four quantum-well thicknesses. It can be clearly seen that all the dependences pass through the minimum and the minimum conductivity for all of the curves is higher than e^2/h, which confirms the conclusion about the quasimetallic behavior of wells with thicknesses similar to the critical value at the Dirac point [2]. It is noteworthy that in the vicinity of the Dirac point, they are almost symmetric relative to $V_g^{\text{eff}} = 0$. With further growth in the gate-voltage amplitude, this symmetry is lost because of the proximity of the heavy-hole valleys [2]. Below, we only discuss the behavior of the conductivity to the right of the Dirac point, where the transfer is implemented by