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# Weak Antilocalization in HgTe Quantum Wells near a Topological Transition

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The anomalous alternating magnetoresistivity in HgTe quantum wells with thicknesses of 5.8 and 8.3 nm, i.e., near the transition from the direct band spectrum to an inverted spectrum, has been revealed and analyzed. It has been shown that the revealed anomalous alternating magnetoresistivity in wells with an inverted spectrum is well described by the theory developed by S.V. Iordanskii et al. [JETP Lett. **60**, 206 (1994)] and W. Knap et al. [Phys. Rev. B **53**, 3912 (1996)]. A detailed comparison of the experimental data with the theory indicates the presence of only the cubic term in the spin splitting of the electronic spectrum. The applicability conditions of the mentioned theory are not satisfied in a well with a direct gap and, for this reason, such a certain conclusion is impossible. The results indicate the existence of a strong spin–orbit interaction in symmetric HgTe quantum wells near the topological transition.

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The idea of the appearance of a metallic state with a Dirac spectrum on the surface of an insulator with a strong spin–orbit interaction, which was first proposed more than 25 years ago [1, 2], was refreshed owing both to the further development of the theory [3, 4] and to the appearance of new experimental data indicating the existence of such states at the edges of HgTe quantum wells with an inverted band spectrum and a thickness slightly larger than the critical thickness of 6.3 nm [5, 6]. Spin–orbit effects are of critical importance for the appearance of these states. For these reasons, information on these effects is very important. However, they have already been studied only in wide quantum wells (about 20 nm) and at high electron densities, i.e., when a well has a thickness much larger than the critical value and is asymmetric. The effects in wells where a topological insulator can exist have not yet been studied except for in indirect experiments [5]. It is well known that weak antilocalization corrections to the conductivity of systems are characteristic transport phenomena that make it possible to obtain almost direct information on the effects of the spin–orbit interaction, because this interaction results in spin relaxation, which changes the sign of the interference localization correction to the conductivity. This interaction is responsible for the anomalous alternating magnetoresistivity of two-dimensional electron systems [7–10], which is currently the most direct source of information on the spin–orbit interaction in these systems. In this work, this anomalous alternating magnetoresistivity is studied for HgTe quantum wells whose thicknesses are slightly smaller and slightly larger than the critical value $d_c = 6.3$ nm at which the direct-band quantum well is transformed into the quantum well with the inverted spectrum [6].

The samples studied in this work are quantum wells with thicknesses $d_1 = 8.3$ nm and $d_2 = 5.8$ nm ($d_2 < d_c < d_1$) grown by molecular beam epitaxy at temperatures of 160 to 200 K on (013) GaAs substrates. It is worth noting that wells with both thicknesses were grown under almost the same conditions. The top panel in Fig. 1 shows the schematic section of the samples under investigation with the described quantum wells. The magnetic-field dependences $\rho_{xx}(B)$ and $\rho_{xy}(B)$ obtained after a short illumination are shown in Fig. 1a for a sample with a well thickness of 5.8 nm at $T = 1.5$ K and in Fig. 2a for a sample with a well thickness of 8.3 nm at $T = 3$ K. As is seen, both wells exhibit wide dips in the dissipative component of the resistivity tensor and a plateau in the Hall component. How-

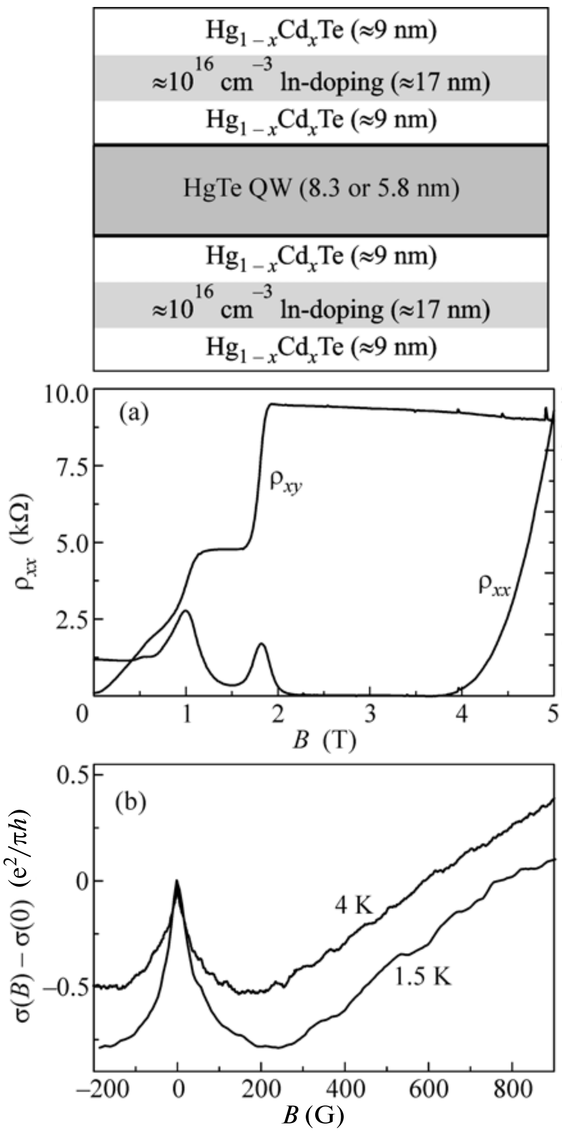


**Fig. 1.** (Top panel) The schematic section of the samples under investigation and the magnetic-field dependences (a) $\rho_{xx}(B)$ and $\rho_{xy}(B)$ of the sample with a well thickness of 5.8 nm at $T = 1.5$ K and (b) $\sigma(B) - \sigma(0)$ for the same sample at two temperatures.

ever, the transport parameters of the wells are strongly different. First, the resistivity of narrower wells is about 1 kΩ, whereas the resistivity of wider wells is about 20 kΩ, which is more than an order of magnitude larger. The relative difference between the charge carrier densities is much smaller: $N_s \approx 5 \times 10^{10}$ $cm^{-2}$ for wider wells and $N_s \approx 7.2 \times 10^{10}$ $cm^{-2}$ for narrower wells. This means that the mobility of electrons in a narrower well is an order of magnitude higher than that in a wider well, although the opposite relation should be expected at first glance. This fact indirectly indicates the fundamental difference between the spectra of the wells.

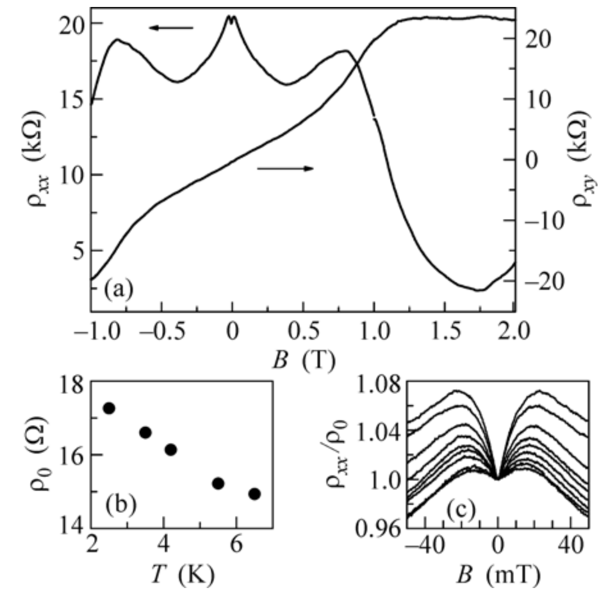


**Fig. 2.** (a) The magnetic-field dependences $\rho_{xx}(B)$ and $\rho_{xy}(B)$ at $T = 3$ K, (b) the temperature dependence of the resistivity $\rho_0$ at $B = 0$, and (c) the magnetic-field dependence $\rho_{xx}(B)/\rho_0$ near $B = 0$ at $T =$ (from top to bottom) 1.4, 1.55, 2, 2.5, 3, 3.5, 4.2, 5.5, and 6.5 K. The results are given for the sample with a well thickness of 8.3 nm.

First, let us discuss the behavior of the well with $d_1 = 8.3$ nm, i.e., the well that has the inverted spectrum and, thus, is assumingly a topological insulator [4]. As is seen in Fig. 2a, the resistivity of the sample at $B = 0$ is $\rho_0 \approx 20$ kΩ, indicating its closeness to the mobility threshold. The quantum Hall state with $\nu = 1$ and corresponding minima in $\rho_{xx}$ and a plateau in $\rho_x$ is observed at $B = 1.74$ T. Therefore, the carrier density in the quantum well is $N_s = 4.26 \times 10^{10}$ $cm^{-2}$ and, taking into account the above resistivity of the sample, the mobility is $\mu = 7000$ $cm^2/(V\ s)$. Figure 2b shows the temperature dependence of the resistivity in zero magnetic field. It is seen that the resistivity increases from 15 to 17 kΩ as the temperature decreases from 6.5 to 2 K. This means that in spite of the closeness to the mobility threshold, a weak logarithmic increase in the resistivity with a decrease in the temperature is observed, which is apparently caused by the electron–electron interaction in the diffusion channel [11]. The $\rho_{xx}$ curve in Fig. 2a is symmetric under the reversal of the sign of the magnetic field. The most pronounced feature of the $\rho_{xx}$ curve in Fig. 2a is a characteristic structure consisting of two peaks at $B \approx \pm 200$ G symmetric with respect to $B = 0$. Figure 2c shows more detailed measurements of this feature in $\rho_{xx}$ at temperatures from 1.4 to 6.5 K. As is seen, with an increase in the temperature, the height of the peaks decreases and they are shifted towards lower fields. Such features in the magnetoresistivity of the two-dimensional system are usually manifestations of weak antilocalization and

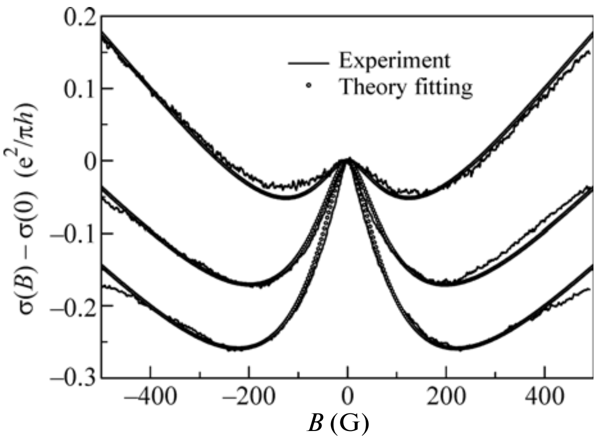


**Fig. 3.** Approximation of the experimental data for $\sigma(B) - \sigma(0)$ in the sample with a well thickness of 8.3 nm by the theory developed in [9, 10] for the temperatures $T$ = (from bottom to top) 1.4, 2, and 6.5 K.

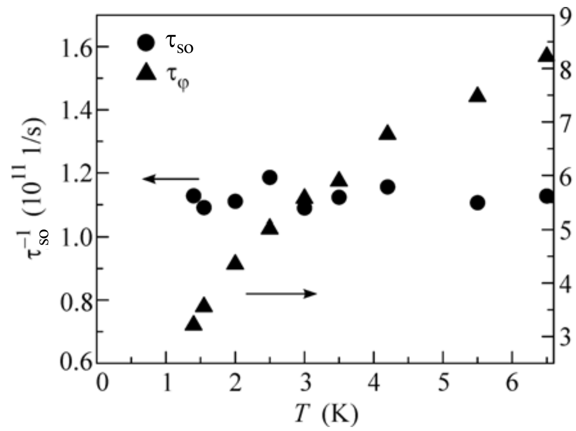


**Fig. 4.** Temperature dependences (circles) $\tau_{so}^{-1}(T)$ and (triangles) $\tau_\varphi^{-1}(T)$ obtained from the comparison of the theory developed in [9, 10] with the experimental data for the sample with a well thickness of 8.3 nm.

indicate the presence of strong spin–orbit scattering in the system. As far as we know, this is the first observation of weak antilocalization in HgTe quantum wells. Below, we present the results of the detailed comparison of weak antilocalization observed in HgTe quantum wells with the existing theory. First, we note that the antilocalization correction to the temperature dependence is usually smaller than the localization correction associated with the interaction in the diffusion channel; for this reason, the total correction leads to an increase in the resistivity with a decrease in the temperature (see Fig. 2b).

As is known, the main spin relaxation mechanism in two-dimensional systems is the D'yakonov–Perel mechanism attributed to the spin splitting in the spectrum owing to the absence of an inversion center in the system. The absence of the inversion center in the two-dimensional system can be associated with its absence both in the crystal itself and directly in the quantum well. Both cases can obviously be implemented in HgTe quantum wells. The splitting of the spectrum of the two-dimensional system that is associated with the absence of the inversion center in the initial crystal is described by two Dresselhaus terms cubic, $\Omega_3 = \gamma k^3/4$, and linear, $\Omega_1^{(1)} = \gamma k(\langle k_z^2\rangle - k^2/4)$, in the wavenumber of the electron $k$. The splitting associated with the absence of the inversion center in the quantum well is described by the single Rashba term $\Omega_1^{(2)} = \alpha k$ linear in the wavenumber of the electron $k$. In the general case, weak antilocalization in two-dimensional systems should be analyzed taking into account all of these three components of spin splitting in the spectrum, one cubic and two linear in $k$. The corresponding theory (ILGP theory) was developed in [9, 10]. Note that when both linear terms are zero and only the cubic term is present, the expression for the magnetoresistivity in the ILGP theory coincides with the result previously obtained in the first work [7] (AALKh theory) on weak antilocalization.

In the temperature range under investigation, taking into account the temperature dependence of the resistivity, the parameter $H_{tr} = \hbar/4eD\tau$ (where $D$ is the diffusion coefficient and $\tau$ is the pulse relaxation time) varies from 5.7 to 2.3 kG. Taking into account that the features of weak localization in our sample lie from 300 G to zero, the ILGP theory is applicable in our case. Comparing the features of weak localization observed in the magnetoresistivity dependences with the ILGP theory, we used three fitting parameters

$$H_\varphi = \hbar/4eD\tau_\varphi,$$

$$H_{so} = \frac{\hbar}{4eD}(2\Omega_1^2\tau_1 + 2\Omega_3^2\tau_3),$$

$$H_{so}^1 = \frac{\hbar}{4eD}2\Omega_1^2\tau_1,$$

$$\frac{1}{\tau_n} = \int(1-\cos(n\theta))W(\theta)d\theta,$$

where $\tau_\varphi$ is the phase relaxation time and $\Omega_1$ includes the Dresselhaus and Rashba contributions linear in $k$. The comparison of the theory with the experiment indicates that a satisfactory agreement is reached only with $H_{so}^1 = \Omega_1 = 0$ (see Fig. 3). In this case, the ILGP theory coincides with the AALKh theory and the spin relaxation of electrons in the system is determined only by the Dresselhaus term $\Omega_3$ cubic in $k$. Figure 4 shows the temperature dependences $\tau_{so}^{-1}(T)$ and $\tau_\varphi^{-1}(T)$ obtained from the comparison of the theory with the experimental data. The temperature dependence of $\tau_\varphi^{-1}$ is close to the linear dependence typical of the electron–electron scattering, whereas $\tau_{so}^{-1}$ is independent of the temperature within the errors in the range under investigation.

Let us now discuss the well with $d_1 = 5.8$ nm, i.e., the well with the direct band spectrum. As was mentioned above, the density of the electrons in this well is one and a half times higher and their mobility is much higher. Correspondingly, the plateaus not only with $\nu = 1$, but also with $\nu = 2$ and 3 are observed in this well. Figure 1b shows the anomalous alternating magnetoresistivity measured in this well at temperatures of 4 and 1.5 K. At first glance, the behavior of the anomalous alternating magnetoresistivity for the narrower well is similar to that described above. In particular, the maximum of the anomalous alternating magnetoresistivity is in the same magnetic field range of 200 to 250 G. However, since the mobility in the samples with the well thickness $d_1 = 5.8$ nm is about an order of magnitude higher, the $H_{tr}$ value in these samples is about 30 G, which is much lower than the fields in which the features of the anomalous alternating magnetoresistivity are observed. Since the theories developed in [7, 9, 10] are applicable only in the region $H < H_{tr}$, these theories cannot be, strictly speaking, compared with the experimental data for the samples with the well of the thickness $d_1 = 5.8$ nm. Indeed, the theory developed in [9, 10] does not provide a satisfactory approximation of the dependences shown in Fig. 1b. To correctly describe these dependences, the ballistic transport theory of the anomalous alternating magnetoresistivity [12] should be used; this will be the subject of future works.

To summarize, the results of this work indicate the existence of strong a spin–orbit interaction in HgTe quantum wells near the (insulator–topological insulator) transition.

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