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Two-dimensional topological Anderson insulator in quasi-ballistic transport mode

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An experimental study of a two-dimensional topological Anderson insulator based on HgTe quantum wells in submicron-sized samples has been carried out, in which both diffusion and quasi-ballistic transport modes along edge current states are implemented. A comparative analysis of these modes allowed us to obtain information about the scattering behavior along the edge state. It is established that the inclusion of a magnetic field does not lead to localization effects in the onedimensional transport of edge states.

Keywords: two-dimensional systems, semimetal, topological insulator, HgTe quantum well.

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1. Introduction

More than 15 years after its discovery, the two-dimensional topological insulator (TI) in HgTe quantum wells with an inverse band spectrum is still one of the brightest and most reliable experimental implementations of topological insulators [1–5]. Anyway, all the main experiments with this two-dimensional TI were carried out with samples based on wells having thicknesses of $7-11$ nm, when there was a gap in its volume ranging from several tens meV [6–11] to several meV [12,13].

Recently, a new type of two-dimensional topological insulators was experimentally implemented in Ref. [14] — a two-dimensional topological Anderson insulator (TAI) in which the transfer of charge carriers in the volume of a quantum well is negligible not due to the presence of a gap, but as a result of Anderson localization. It was shown in Ref. [14] that in a two-dimensional system having the energy spectrum of a semimetal and characterized by the presence of an Anderson localization in the vicinity of the point of charge neutrality, at temperatures below 0.5 K, a situation is realized when transport along the edge states is dominant. Thus, a fundamentally important fact was established, which suggests that while two-dimensional transport in the volume of a quantum well is characterized by strong localization, one-dimensional transport along edge states is topologically protected from localization. Samples of macroscopic sizes (characteristic size $> 100\,\mu$m) were studied in Ref. [14]. Accordingly, only diffusion transport was observed in them, characterized by a free path length of several microns. This paper reports for the first time on the observation of quasi-ballistic transport in two-dimensional TAI.

2. Experiment

The experimental samples were submicron-sized structures of special Hall geometry provided with a gate consisting of a layer of low-temperature SiO_2 and a metal TiAu gate sputtered onto it (Figure 1, *a*), made on the basis of HgTe quantum wells with a thickness of 13 and 14 nm and with orientation (013), in which the energy spectrum of a two-dimensional half metal is realized with an overlap of conduction band and valence band ~ 5 meV [15] (Figure 1, *b*). The measurements were carried out in the temperature range of $0.18-10$ K in magnetic fields up to 2 T using a standard phase-sensitive detection scheme at frequencies of $3-6$ Hz at pulling current values of $1-10$ nA, excluding the effects of heating. Figure 1, *c* and *d* show the results of measurements of the dependence of resistances on the gate voltage in local R_{loc} (V_g) and non-local $R_{\text{nonloc}}(V_g)$ configurations for two samples at a temperature of ~ 180 mK. As can be seen, all of them are characterized by a noticeable amount of nonlocal resistance at the maximum of these dependencies, which indicates the key role of edge transport at the specified temperature and thereby confirms the conclusion about the existence of a two-dimensional topological Anderson insulator made in Ref. [14]. In this case, the region in the vicinity of the resistance maxima corresponds to the passage of a zone of localized states by the Fermi level (Figure 1, *b*). The temperature dependence of the studied resistances at the maximum ($R_{\text{loc}}^{\max}$ and $R_{\text{nonloc}}^{\max}$) is shown in Figure 2.

3. Discussion of the results

Let's discuss the data shown in these figures. Figure 1, *c* shows that the local resistance value in the sample 240607-4

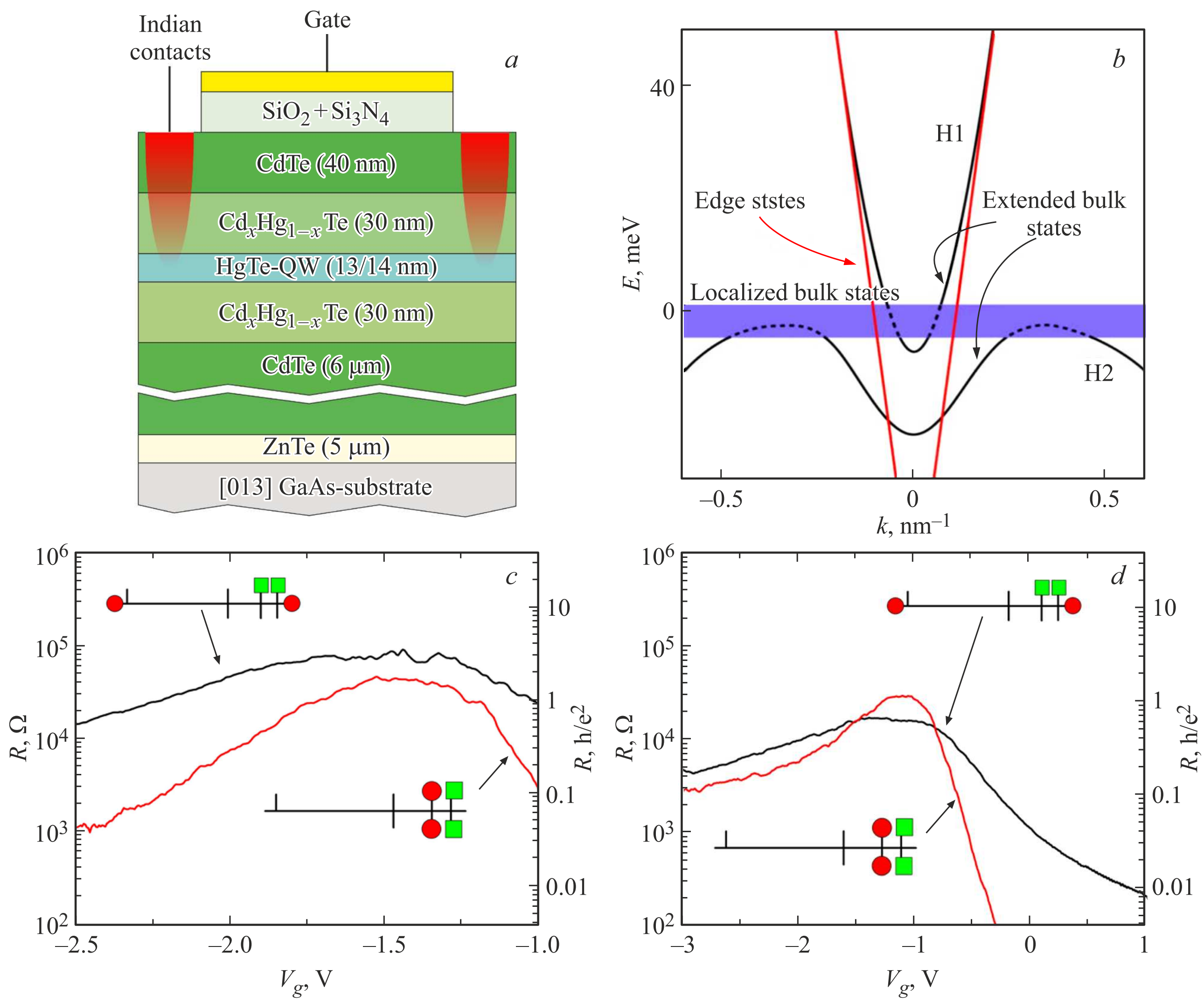

Figure 1. Schematic section of the sample (a). A qualitative pattern of the energy spectrum of the studied system (b). Dependences of the local $R_{\mathrm{loc}}(V_g)$ and non-local resistances $R_{\mathrm{nonloc}}(V_g)$ on the gate voltage: c — sample with diffusion transport, d — sample with quasi-ballistic transport.

is 16 kOhm in the mode of edge transport dominance, i. e., this sample has a value of $R_{\mathrm{loc}}^{\mathrm{max}}$ slightly exceeding $h/2e^2$. This fact means that a transport close to ballistic is realized in this sample at the shortest ($\sim 10\,\mu$m) section of the studied Hall structure. The sample 240607-3 shows in the same area a value of $R_{\mathrm{loc}}^{\mathrm{max}}$ exceeding $h/2e^2$ by almost an order of magnitude, i. e., it implements transport close to diffusion. Let us now analyze the temperature dependences of local $R_{\mathrm{loc}}^{\mathrm{max}}(1/T)$ and nonlocal $R_{\mathrm{nonloc}}^{\mathrm{max}}(1/T)$resistances for samples with quasi-ballistic (240607-4) and diffusive (240607-3) transport. It is clearly seen that both dependences are characterized by qualitatively identical behavior, i. e., at the highest temperature (6 K), the values of local resistance are slightly less than at the lowest (0.17 K) temperature, while the values of nonlocal resistance at 6 K are almost an order of magnitude less than at 0.17 K. Accordingly, as the temperature decreases, there is a slight increase in local and a strong — non-local growth, which at $T < 1$ K practically stops and the dependencies $R_{\mathrm{loc}}^{\mathrm{max}}(1/T)$ and $R_{\mathrm{nonloc}}^{\mathrm{max}}(1/T)$ reach saturation. The described behavior of temperature dependences in Figure 2 confirms the main result of the study in Ref. [14]: while two-dimensional transport in the volume of a quantum well with an inverse and semi-metallic spectrum is characterized by strong localization, leading to an exponentially strong increase in its resistance with decreasing temperature, one-dimensional transport along edge states is topologically protected from localization. The activation energy of the bulk states Δ, determined from the temperature dependences in Figure 2, is equal to $\Delta \approx 0.5$ meV for a sample with diffusive transport and $\Delta \approx 0.2$ meV for a sample with quasi-ballistic transport. This result means that the degree of disorder in the diffusion case is noticeably higher than in the case of quasi-ballistics, while the edge transport also reflects this fact, since quasi-ballistics transport is realized in a sample with a lower volume disorder.

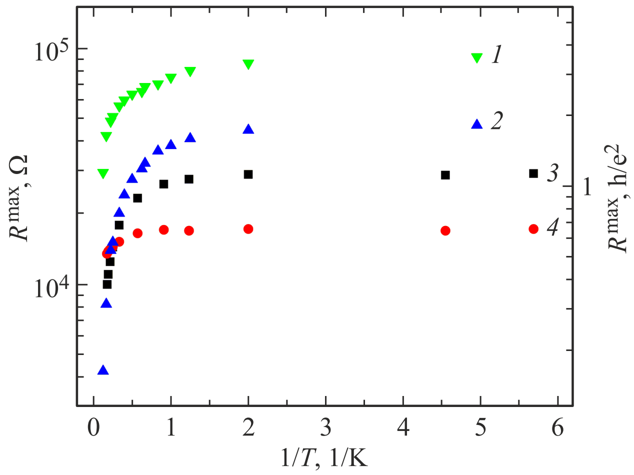

Figure 2. Temperature dependences of local and nonlocal resistances: *1* — $R_{loc}^{max}(1/T)$ for a sample with diffusion transport, *2* — $R_{nonloc}^{max}(1/T)$ for a sample with diffusion transport, *3* — $R_{nonloc}^{max}(1/T)$ for a sample with quasi-ballistic transport, *4* — $R_{loc}^{max}(1/T)$ for a sample with quasi-ballistic transport.

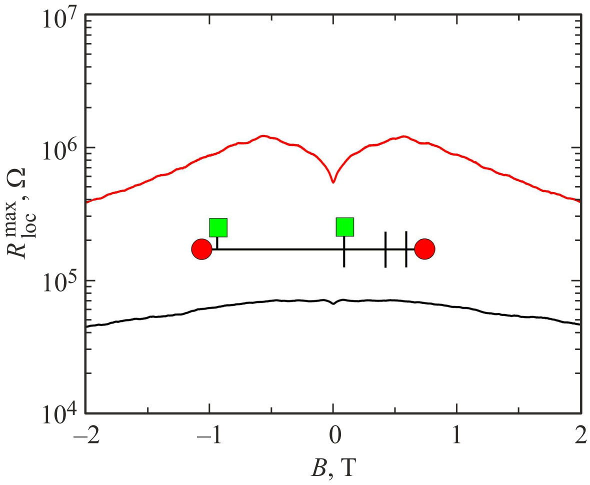

Figure 3. Dependences of local resistances on the magnetic field $R_{loc}^{max}(B)$ on a long ($35\,\mu$m) section of the Hall structure for samples with quasi-ballistic (black curve) and diffusion (red curve) transport.

Let us now discuss the behavior of local and nonlocal transport in the saturation mode of temperature dependence. The value of R_{nonloc}^{max} exceeds R_{loc}^{max} by 1.7 times in this mode in the case of a quasi-ballistic sample, and it is 2 times less in the case of a diffusive sample. However, this ratio in the studied samples should be $R_{nonloc}^{max}/R_{loc}^{max} \approx 4$ at the lowest temperatures, when edge transport completely dominates. This contradiction suggests that the mode of ideal edge transport is not realized in both types of structures under study, and indicates a noticeable contribution of volumetric conductivity, most likely due to the small (submicron) dimensions of the measured Hall structures, which leads to a situation where the characteristic size of the conductor becomes smaller than the length of the temperature coherence and its conductivity ceases it depends on the temperature, or rather, it decreases as it decreases. The procedure for the phenomenological calculation of resistances in local and nonlocal configurations, taking into account the flow of current through volume and edge states, as well as the interaction between them, was developed in Ref. [14]. Obviously, the contribution of volumetric resistance to the measured local resistance is trivial:

$$1/R_{mes} = 1/R_{edge} + 1/R_{bulk}.$$

The calculation of the nonlocal response is much more complicated and requires a numerical calculation of the distribution of currents. It was made with the assumption that the resistivity of the quantum well (ρ) does not depend on the size of the conductor. A comparison of the calculation and experiment results in $\rho \approx 2.8$ MOhm for a sample with quasi-ballistic transport and $\rho \approx 17.5$ MOhm for a sample with diffusion transport. From this it can be concluded that volumetric leakage significantly affects the magnitude of the measured nonlocal resistance, but its contribution to the measurement of local resistance is relatively small ($< 10\,\%$). Thus, we obtain almost accurate information about the nature of edge transport by measuring the resistance in the local configuration. Figure 3 shows the dependences of the local resistance of the longest section of the studied Hall structures on the magnetic field for both varieties at $T = 0.2$ K. It can be seen that both dependencies have qualitatively the same behavior. Positive magnetoresistance (MR) is observed in weak magnetic fields, then it passes through a peak, and the resistance begins to fall with a further increase of the magnetic field. However, the MR value for the diffusion case is noticeably higher, i. e., at the maximum of the curve $R_{loc}^{max}(B)$, the resistance is 2 times greater than its value in the zero field, whereas in the quasi-ballistic case it increases by only a few percent. In any case, the described behavior of the MR shows that the behavior of a two-dimensional Anderson insulator at submicron scales changes slightly when a magnetic field is applied in both the diffusion transport and quasi-ballistic modes, and unlike conventional two-dimensional TI, it does not undergo an Anderson localization induced by a magnetic field [14]. Finding out the reason for this difference requires further research.

4. Conclusion

Thus, the quasi-ballistic transport regime in a two-dimensional Anderson topological insulator was implemented and studied for the first time in this paper, and a comparative analysis with the diffusion transport regime was carried out owing to this, showing that disorder in the volume of a quantum well significantly affects the nature of edge transport.

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Conflict of interest

The authors declare that they have no conflict of interest.

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