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Surface States in a HgTe Quantum Well and Scattering by Surface Roughness

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Scattering of two-dimensional electrons in wide ($d = 18–22$ nm) HgTe-based quantum wells has been thoroughly studied. The mobility has been found to reach a maximum and then to decrease at two-dimensional electron densities above $(2–6) \times 10^{11}$ cm^{-2} owing to scattering by roughness of the quantum well. The theory of scattering by roughness has been elaborated taking into account transformation of the wavefunction with an increase in the electron density. Good agreement of this theory with the experiment indicates the existence of surface states at the interfaces of the wide HgTe quantum well.

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HgTe quantum wells are currently among the most intensively studied objects of physics of two-dimensional electron systems (2DESs). This is primarily associated with a unique gapless energy spectrum of a 2DES in a HgTe quantum well, which is largely determined by relativistic effects and, consequently, by the spin–orbit interaction. Equally important is the fact that very high-quality HgTe quantum wells can be grown owing to recent progress in molecular-beam epitaxy of II–VI compounds. As a result, several new kinds of low-dimensional electron systems, namely, two-dimensional topological insulators, a two-dimensional semimetal, and two-dimensional gapless Dirac fermions, have been implemented in these quantum wells in the last years [1–6].

As is known [7], the scattering of electrons by surface roughness is the leading scattering mechanism in inversion surface layers at a high carrier density because the layer thickness decreases and the transverse quantized electron momentum increases with an increase in the field pressing the electrons. As will be seen below, the experimental dependence of the mobility in a HgTe layer also agrees with this picture. However, in the case of a HgTe quantum well, the localization of the wavefunction inside the quantum well varies depending on the magnitude of the electron wave vector k in the quantum well. At $k < \pi/d$ (where d is the well width), the maximum electron wavefunction square is situated in the center. However, at $k > \pi/d$, it splits into two. The formed maxima shift toward the well boundaries with an increase in k (each maximum shifts toward a certain boundary; the direction of the shift depends on the direction of electron motion along the boundary), ultimately forming surface states at the well boundaries. Such behavior of the electron wavefunction was predicted in [8] and confirmed by more accurate calculations in [9]. Experimental indication of the existence of such states is of undoubted interest.

In this work, we perform theoretical and experimental investigation of electron scattering by roughness at the interfaces of wide HgTe quantum wells, the width of which is a few times greater than the critical one ($d_c = 6.3$ nm) corresponding to the transition from the direct to inverted spectrum. We show that the scattering of two-dimensional electrons by well roughness starts to dominate at densities $N_s > 3 \times 10^{11}$ cm^{-2}. We elaborate the theory of 2D electron scattering by this roughness taking into account transformation of the wavefunction with an increase in the electron density predicted in [8, 9]. Comparative analysis of the theory and experiment indicates the emergence of surface states at the interfaces of wide HgTe quantum wells with an inverted spectrum.

We start with the description of the experiment and experimental results. The samples under investigation were 50-μm-wide field-effect Hall structures made of undoped 18–22-nm HgTe quantum wells with the (013) and (100) orientations and a distance of 100 and 250 μm between potentiometric contacts (see inset in Fig. 1). The fabrication technology was described in detail in [10]. The measurements were carried out at a temperature of 4.2 K in magnetic fields up to 1 T with the use of a standard lock-in detection at a frequency of 12 Hz and an excitation current through the sample of 100 nA, which excludes heating effects. The depen-