Z. D. Kvon, I. G. Neizvestnyĭ, and V. N. Ovsyuk. *Effect of a surface superlattice on a two-dimensional electron gas.* Quantum space-charge layers formed at the surface of a semiconductor by an external electric field in metal-insulator-semiconductor (MIS) structures are currently one of the most interesting objects in solid-state physics. Phenomena such as size quantization, charge localization, surface transfer of charge, and the quantum Hall effect appear to be sharpest and most multifaceted precisely in these systems.

One method for studying such layers involves quantum inversion channels on high-index surfaces (i.e., surfaces with high Miller indices), which are surfaces that are tilted at small angles θ away from the singular surfaces of the crystal. We studied in greatest detail silicon surfaces, tilted away from the (100) and (111) surfaces around the direction [011] by angles of $\theta = 1$–$10°$.

It was previously predicted that superlattices can in principle exist on such surfaces for two reasons: first, because of the appearance of new translational order[1] and, second, because of the possible presence of a periodic system of terraces and steps.[1,2] The existence of such a system was observed experimentally on the vicinal surfaces of silicon based on the splitting of the main reflections in the diffraction of slow electrons.[2] There now exist data indicating that the periodic system of steps and terraces is preserved also after thermal oxidation of the surface.[3,4] The anisotropy of charge-carrier transfer in inversion channels, formed on the vicinal surfaces of silicon in our work, was explained precisely by the partial disorder of this system.[5]

The anomalies caused by the superlattice were first observed in Ref. 6, but they were not entirely correctly interpreted because the electronic energy spectrum was not constructed correctly.

The expected mechanism by which the superlattice affects the properties of a two-dimensional gas is linked to the appearance of a minigap in the energy spectrum of the charge carriers in the first quantum subband. As soon as the Fermi energy E_F reaches the minigap under the action of a field applied perpendicular to the surface, a feature in the form of an inflection, instead of monotonic growth, appears in the curve of the conductivity of the channel G_c as a function of the surface excess of holes Γ_p in the channel. In a two-dimensional gas the quantity Γ_p^Δ, corresponding to the beginning of the feature, is related to the period of the superlattice L by the simple relation $\Gamma_p^\Delta = \pi/2L^2$. Thus, given the period L, it is easy to determine the required value of Γ_p^Δ.

We observed these features while studying the conductivity of the hole channel.[7] Figure 1 shows the derivative $dG_c/d\Gamma_p$ as a function of Γ_p for tilt angles $\theta = 2.2$ and 3° at 4.2 K; the indicated features are located at $\Gamma_p^\Delta = 2.2 \cdot 10^{12}$ and $4.2 \cdot 10^{12}\ \mathrm{cm}^{-2}$. The corresponding period of the superlattice $L_{\exp} = 80$–85 and 60–65 Å is indeed in good agreement with the value computed from the tilt angle $L_T = a/\sqrt{3}\sin\theta$, where a is the lattice constant in silicon. The experimentally determined periods for three angles θ, indicated in the inset in the figure, follow well the expected theoretical dependence.

The experiments described show that the existence of one-dimensional superlattices is a fundamental property of

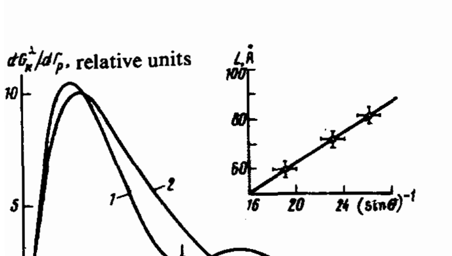

FIG. 1. The curves of $dG_c^\perp/d\Gamma_p$ versus Γ_p for two tilt angles θ (2.2° (1) and 3° (2)). The arrows mark the positions of the features. The dependence of the period of the superlattice on $(\sin\theta)^{-1}$ is shown in the inset (the circles are the experimental values, and the straight line represents the theoretical dependence $L_T = a/\sqrt{3}\sin\theta$).

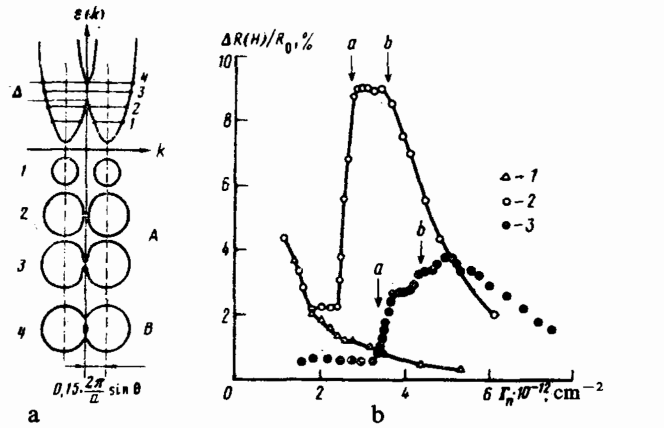

FIG. 2. a) Dispersion law for two-dimensional electrons on the vicinal surface (the vertical solid is the boundary of the Brillouin zone; the broken line is the position of the centers of the valleys; 1–4—isoenergetic contours in the plane of the MIS structure); b) dependence of the magnetoresistance $\Delta R(H)/R$ on Γ_n at $H = 3.3$ kG and $T = 4.2$ K for a current flowing parallel (1) and perpendicular (2, 3) to the axis of the superlattice (the arrows a and b mark the boundaries of the minigap, determined from the conductivity measurements).

vicinal surfaces, and it must be taken into account when analyzing not only hole, but also electron channels, where the appearance of minigaps is usually linked to intervalley splitting.[8]

It is well known that the magnetoresistance (MR) of a degenerate gas with a spherically symmetrical Fermi surface (FS) and an isotropic relaxation time τ is small and, in order of magnitude, is equal to $(\omega\tau)^2/(E_F/kT)$. The MR of real degenerate Fermi systems (in particular, metals) is usually much higher, which is most often explained by the complicated form of their FS.[9] The two-dimensional electron gas on the vicinal surface of silicon is a convenient object for observing the transition from the isotropic FS to the FS with a complicated configuration, since here this transition is quite simply realized by changing the surface excess of charge carriers.[10] Figure 2a shows the Fermi surfaces (more precisely, the contours) for different values of the surface excesses. It is evident that for low values of Γ_n the FS is virtually isotropic, and as Γ_n increases, i.e., as the boundaries of the Brillouin zone are approached, it begins to become distorted and acquires a complicated configuration, which is a function of the position of the Fermi level. In particular, when it is situated in the second miniband, the FS consists of two closed surfaces, having the form of a "dumbbell" and "lens" and in this case a transition should be observed from small values of MR, corresponding to an isotropic FS, to significantly higher values, corresponding to a Fermi surface which does not have spherical symmetry.[9]

Figure 2b shows the dependence of the MR of an MIS-transistor channel for directions along steps and perpendicular to them; in addition, curve 3 was measured for a sample with a large tilt angle away from the singular surface and with a lower mobility. It is evident that for small values of Γ_n (and, correspondingly, E_F) the MR behaves analogously to the channels on the singular surfaces and is the same for both directions of the current. In the direct vicinity of the minigap the MR increases rapidly and remains constant, while the Fermi level passes through the minigap. In the second zone the MR once again begins to decrease monotonically as Γ_n increases.

The results presented show that the observed phenomenon makes it possible to obtain information on the dispersion law and the behavior of the relaxation time in a two-dimensional Fermi system accompanying a change in the form of the Fermi surface. We note that in the course of the above-described change in Γ_n the FS undergoes two topological Lifshitz transitions.[9] These transitions were first observed from the anomalies in the phonon entrainment of two-dimensional electrons in Ref. 11.

Further studies of such systems include a study of the absorption and, especially, the emission of far-IR radiation, cyclotron resonance,[12] as well as transport phenomena in strong magnetic fields.[13]

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