Classical magnetoresistance of a two-dimensional electron gas in a one-dimensional superlattice

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The magnetoresistance due to restructuring of the Fermi surface of electrons under the action of a one-dimensional superlattice has been predicted and observed in a degenerate two-dimensional electron gas on a high-index surface of silicon. The effect is sharply anisotropic and can be used as a new method for investigating the indicated system.

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It is known that the magnetoresistance (MR) of a degenerate gas with a spherically symmetrical Fermi surface (FS) and an isotropic relaxation time τ is small [of the order of $(\omega_c \tau)^2 (kT/E_F)$][1] The observed MR of real degenerate Fermi systems, in particular, metals, is usually much higher. This is most often explained by the complex shape of their FS (see, for example, Refs. 1 and 2).

From the point of view of this problem, it would be interesting to observe the change in the MR with the transition from an isotropic FS to a FS with a complex configuration. Since control of the shape of the Fermi surface is essentially eliminated in metals, it is impossible to realize such a transition in them. A convenient object for observing this transition is a degenerate two-dimensional gas on a high-index surface of silicon (one of the varieties of a Fermi system), since here this transition is realized quite simply by changing the excess of charge carriers $\Gamma_{n,p}$ near the surface. The essence of what has been said lies in the following. Until now, it has been established[3,4] that a two-dimensional gas of electrons and holes on the vicinal surface of silicon is located in a one-dimensional superlattice (SL), whose period is determined by the translational symmetry of this surface. In such a one-dimensional SL, for small excesses of charge carriers, the FS is nearly isotropic, while with an increase in $\Gamma_{n,p}$, i.e., as the boundaries of the Brillouin zone of the SL are approached, it begins to distort and acquires a complex configuration, which changes as a function of the position of the Fermi level. In particular, when it is situated in the second minizone, for electronic channels, the FS consists of two closed surfaces shaped like a "dog bone" and a "lens" (for more detail see Ref. 5).

Thus, as $\Gamma_{n,p}$ increases, a transition should be observed from small MR, corresponding to an isotropic FS, to significantly higher values, corresponding to a Fermi surface that does not have spherical symmetry. The observation of the effect described would also give a new method for investigating the two-dimensional gas on the vicinal surface of silicon.

In the present work, the indicated transition is observed experimentally at 2–4.2

K in a two-dimensional electron gas on the surface of silicon tilted at an angle θ of the order of 10° away from the (100) surface. The specimens consisted of MOS transistors with channel length $L = 1200$ and width of $W = 400$ μm, prepared on the surfaces indicated with an angle $\theta = 9° 30'$ and with maximum mobility $\mu_{nS}^{m} = 1.9 \times 10^4$ cm^2/V s (specimen 1) and an angle $\theta = 10° 40'$ with $\mu_{nS}^{m} = 7 \times 10^3$ cm^2/V s (specimen 2).

It should be noted that in the spectrum studied even at fields of several kG the contribution of the anomalous negative MR, related to Anderson localization,[6] is significant and it had to be included in order to determine correctly the positive MR. The measurements in fields up to 200 G, when the positive MR is negligibly small, showed that the magnetic field dependence of the negative MR is well described by Eq. (1) in Ref. 6. Using this fact, it was possible to determine the magnitude of the negative MR for large values of H. The true value of the positive MR was found by subtracting the negative MR determined in this manner from the directly measured value; the error in determining the positive MR did not exceed 10%.

Figure 1 shows the experimental dependence of the positive MR for the current oriented along the SL axis ($\Delta R_{\parallel}/R_{\parallel}$) and perpendicular to it ($\Delta R_{\perp}/R_{\perp}$). We shall examine the data for specimen 1. For small values of Γ_n, the MR behaves analogously to channels on singular (100) surfaces and identically for both orientations of the current. The existence of this MR is due to the finiteness of the ratio $L/W = 3$, while the MR itself is proportional to the square of the mobility. As the bottom of the minigap is approached (and, therefore, the boundary of the Brillouin zone), $\Delta R_{\parallel}/R_{\parallel}$ stops decreasing, and in the direct proximity to the minigap, it increases sharply to some value which remains constant as the Fermi level passes through the minigap. As the second minizone is reached, $\Delta R_{\parallel}/R_{\parallel}$ begins to decrease monotonically with in-

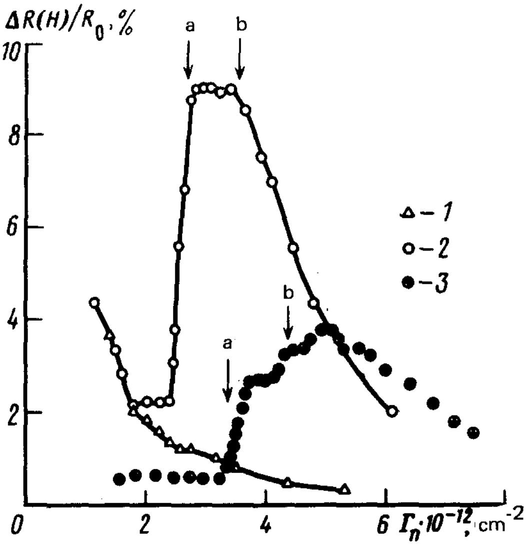

FIG. 1. $\Delta R(H)/R$ as a function of Γ_n for $H = 3.3$ kG and $T = 4.2$ K with the current oriented along the SL axis (1) and perpendicular to it (2, 3) (1 and 2 are for specimen 1; 3 is for specimen 2; the arrows a and b indicate the boundaries of the minigap, determined from conductivity measurements).

creasing Γ_n. The dependence of $\Delta R_\perp/R_\perp$ on Γ_n shows a different behavior. The quantity $\Delta R_\perp/R_\perp$, as before, decreases monotonically with increasing Γ_n in proportion to the square of the mobility and is an order of magnitude smaller than $\Delta R_\parallel/R_\parallel$, (when $\Gamma_n > \Gamma_n^\Delta$, where Γ_n^Δ corresponds to the beginning of the minigap). Thus the predicted effect is observed only along the SL axis. This means that the one-dimensional SL on the vicinal surface of silicon changes the form of the FS in such a way that the change in τ and the effective mass of electrons m_n with motion along it has a sharply anisotropic nature: the ratio τ/m_n, corresponding to drift along the SL axis, changes strongly, while the ratio corresponding to drift in a perpendicular direction remains constant, at least within the limits of error of MR measurements.

It is also interesting to note that while the Fermi level remains in the minigap, the magnitude of $\Delta R_\parallel/R_\parallel$ does not change, which apparently indicates that the shape of the FS is constant for electrons in this energy range.

The dependence of $\Delta R_\parallel/R_\parallel$ on Γ_n for specimen 2 has two differences. First, the onset of the sharp increase in MR is shifted toward large Γ_n; this effect is related to the large tilting angle of the surface, which is confirmed by the magnitude of the shift equal to $\Gamma_n = \Gamma_n^\Delta(\theta = 10^\circ 40') - \Gamma_n^\Delta(\theta = 9^\circ 30')$. Second, the quantity $\Delta R_\parallel/R_\parallel$ decreased strongly, while the region in which it is constant narrowed sharply. This behavior is a result of the fact that in the region of the minigap the relaxation time for specimen 1 is twice as large as for specimen 2, i.e., the observed effect is sensitive to smearing of the Fermi surface caused by electron scattering.

These results show that the observed phenomenon makes it possible to obtain new information on the dispersion law and behavior of the relaxation time in the two-dimensional systems described; prior to the present experiment, there were no data on the behavior of FS as the Fermi level passes through the minigap.

In this connection, it should be noted that a quantitative theory of MR in a two-dimensional electron gas with one-dimensional SL would permit obtaining more complete information on the properties of this two-dimensional system.

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