Negative magnetoresistance in a two-dimensional electronic system in the region of hopping conductivity

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Negative magnetoresistance which is quadratic in the magnetic field was detected in a Si MIS structure in the hopping-conductivity regime. As the field increases, the magnetoresistance passes through a minimum and then rapidly increases exponentially. It was found that the position of the minimum H_t is virtually temperature-independent in the range 1.4 K $<T<$4.2 K. The observed field dependence $\rho_{xx}(H)$ agrees with the theoretically predicted behavior of the magnetoresistance under conditions of electron tunneling in a continous potential.

The conduction mechanism in two-dimensional disordered systems in the regime of strong or weak localization continues to be of interest from both the theoretical and experimental points of view.

A logarithmically weak, negative magnetoresistance (NMR) has been observed in the weak-localization regime in many studies.[1] It is explained well by suppression of the coherent "backscattering" by a magnetic field (Ref. 2). Such effects appear in fields $H<\phi_0/l^2 \leqslant 100$ G, where ϕ_0 is a flux quantum, and l is the phase-breaking length.

In the strong-localization regime, where the hopping mechanism of conduction predominates, exponential growth of the magnetoresistance $\rho_{xx}(H)$ in fields $H>H_q \geqslant n\phi_0 \sim (1-5)\times 10^4$ G (n is the electron concentration) is usually observed.[3] This growth is associated with the increase in localization as a result of a decrease in the overlapping of the wave functions of the electrons in a magnetic field. For $H<H_q$ the magnetic field can weaken the localization, causing the sign of the magnetoresistance to change. One delocalization mechanism, which is associated with the coherent interference,[4,5] leads to the magnetic-field dependence $\ln(\rho_{xx}(H)/\rho_{xx}(0)) \propto -H^{1/2}$. Such a dependence has been observed in strongly disordered, quasi-two-dimensional structures: In_2O_{3-x} films[6] and $GaAs/Al_xGa_{1-x}As$ heterostructures with low mobility (Ref. 7). For the two other localization mechanisms which are not associated with quantum interference — tunneling in a random long-period potential[8] and hops in the presence of a third impurity[9] — it has been predicted theoretically that the negative magnetoresistance is a quadratic function of the field.

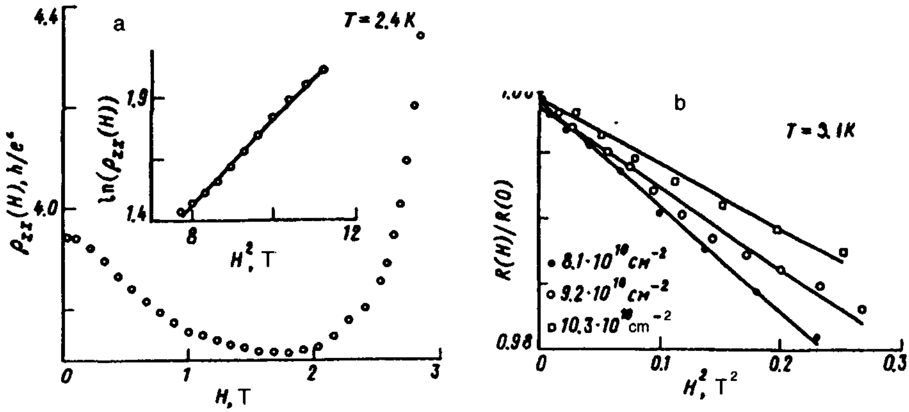

FIG. 1. a — Resistance in units of h/e^2 as a function of the field at a temperature of $T = 2.4$ K and electron concentration $n = 8.4 \times 10^{10}$ cm^{-2}. Inset: Logarithmic dependence of the resistance as a function of H^2. b — Normalized magnetoresistance as a function of H^2 for three different concentrations.

In the present paper we report the observation of negative magnetoresistance which is quadratic in the field in a two-dimensional electron system in a silicon MIS structure in the hopping-conduction regime. The measurements were performed on a (100)-Si MIS transistor in the Hall geometry with a 0.8×5-mm channel and maximum mobility 5×10^4 cm/(V·s) in the temperature range 1.4 K$<T<$4.2 K. The electron concentration n of the two-dimensional system was varied by varying the blocking voltage. The measurements were performed by the four-contact scheme, using an electrometric amplifier with high input resistance and a current source which is galvanically decoupled from the other devices. Figure 1a shows the resistance as a function of the field at a temperature of 2.4 K. We see from the figure that for a low electron concentration in the dielectric state ($\rho_{xx} > 3h/e^2$) the magnetoresistance is negative in fields $H < 1.7$ T. As the field increases, the magnetoresistance becomes positive and rapidly increases exponentially (inset in Fig. 1a).

The temperature dependence of the resistance at $H=0$ for the given sample in the dielectric state was investigated in detail in Refs. 10 and 11 in a wide temperature range from 30 mK to 3 K. It was found that the temperature dependence of the resistance corresponds to variable-length hopping conduction in the presence of a Coulomb gap. The exponential growth of the resistance as a function of the field (inset in Fig. 1a) is further confirmation of the fact that in the present experimental system the conductivity is of a hopping character.[3] These circumstances make it possible to choose appropriate theoretical models for making comparisons. As one can see from Fig. 1b, in weak fields the resistivity $\rho_{xx}(H)$ decreases quadratically with the field. This dependence of the resistance does not agree with the model of coherent interference,[5] in which the field dependence of the resistance is expected to be of the form $\ln(\rho_{xx}(H)/\rho_{xx}(0)) \propto - H^{1/2}$.

Raikh proposed a different mechanism for the appearance of negative magnetoresistance[9] In this mechanism hopping of an electron from impurity 1 to impurity 2 in the presence of a third impurity is studied. The magnetic field decreases the over-

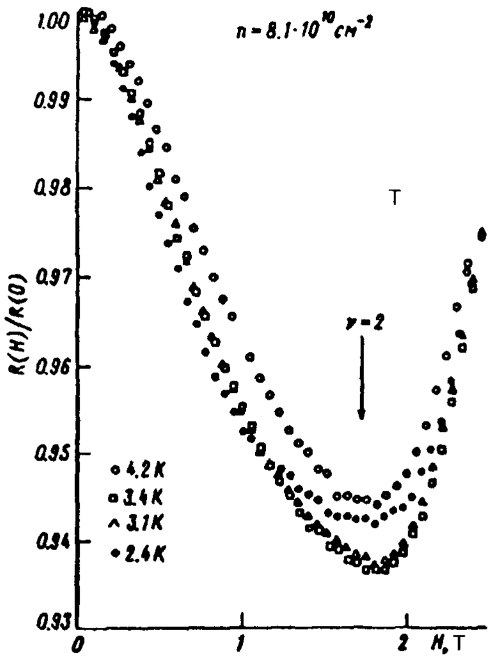

FIG. 2. Normalized magnetoresistance at a fixed concentration for four values of the temperature.

lapping between the wave functions of the neighboring impurities 1 and 3, thereby decreasing the activation energy for a hop, which leads to the appearance of negative magnetoresistance. In this case the magnetoresistance depends on the field as[9]

$$\ln(R(H)/R(0)) = (T_0/T)^{1/4}(\exp(-Z^2) + kZ^2\exp(-3Z^2)). \qquad (1)$$

Here $Z \propto H$ and $k \propto (T_0/T)^{1/2}$. We see that in sufficiently weak fields the resistance is a quadratic function of the field: $\ln(R(H)/R(0)) \propto (k-1)H^2$. The experimentally observed quadratic dependence of the resistance (Fig. 1b) evidently agrees with this model. It was pointed out above that in fields $H > 1.5-2$ T the magnetoresistance becomes positive and rapidly increases exponentially. As one can see from Fig. 2, the point H_t of the transition from negative to positive magnetoresistance is nearly independent of the temperature (in the temperature range 2.3–4.2 K) and corresponds to a filling factor $\nu \approx 2$ of the Landau levels. A similar absence of a dependence of H_t on T was also observed in Ref. 7 in a $GaAs/Al_xGa_{1-x}As$ heterostructure. However, the field dependence of the negative magnetoresistance was weaker ($\propto H^{1/2}$) than in our case, and the experimental system was much more strongly disordered. This result does not agree with the model of Ref. 9 which we are discussing. In this model the value of H_t should depend strongly on the temperature, $H_t \propto (T_0/T)^{3/4}$.

In the Raikh–Glazman model[8] of tunneling in a random continuous potential the electron gas is divided into macroscopic electron "lakes" which are spatially separated by potential barriers. The conductivity of the system is determined by tunneling between

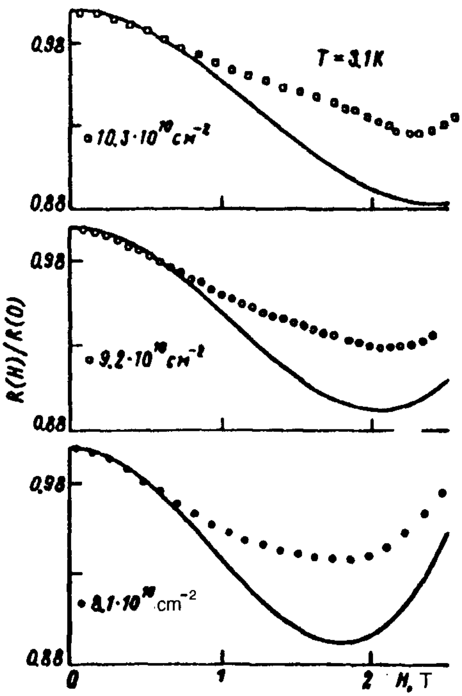

FIG. 3. Approximation of the experimental data by a theoretical curve for three different concentrations at a fixed temperature. The symbols represent the experimental data; the solid lines represent the approximation by the theoretical relation (2).

neighboring lakes. The magnetic field increases the overlapping between the wave functions of the electrons on both sides of the barrier, thereby increasing the conductivity of the system. In this case the resistance depends on the field as

$$R(H)/R(0)=\exp(H^2/H_0^2)/\cosh^2(H/H_1), \qquad (2)$$

where H_0 and H_1 are parameters characterizing the width of the barrier and the size of a lake, respectively. Here $H_1 \approx \phi_0/S$, where S is the characterisitic area of the electron lake, and $H_0/H_1 \approx L/\lambda$, where L is the characteristic size of a lake, and λ is the characteristic width of a barrier. We see from Eq. (2) that in sufficiently weak fields the resistance is a quadratic function of the field: $R(H)/R(0) \propto (1/H_0^2 - 1/H_1^2)H^2$. The experimentally observed quadratic field dependence of the resistance (Fig. 1b) and the weak temperature dependence (Fig. 2) agree with the model being discussed.

Since the model of tunneling in a random continuous potential agrees qualitatively with the experimental data, we approximated the measured curves $R(H)$ by a theoretical dependence (Fig. 3). As the input parameters for the approximation, we employed the slope of the straight lines in weak fields (Fig. 1b) and the position H_t of the minimum (Fig. 2). By means of the approximation we determined the parameters in the model: The characteristic lake size is $L \approx 500$ Å and the ratio $H_0/H_1 \approx L/\lambda \approx 1.1$. The value found for L agrees with the estimates made previously in Refs. 12 and 13 from measurements of the width of the QHE plateau and the relief of the Si/SiO_2 interface, respectively. Since the magnetic length is $l_H \approx 250$ Å, each lake contains approximately $(L/l_H)^2 \approx 4$ electrons. The theoretical field dependence (2) of the magnetoresistance was calculated under the assumptions that $L \gg \lambda$ and that each lake contains many electrons. The partial discrepancy between the theoretical curve and the experimental data, noted in Fig. 3, can be attributed to the fact that these two conditions are not satisfied in our system.

In summary, we showed that in a two-dimensional electronic system in the hopping conduction regime a magnetic field $H \leq 1.5$ T weakens localization, which leads to the appearance of negative magnetoresistance that depends quadratically on the field. As the field increases, electron localization intensifies, as is indicated by the exponential growth of the magnetoresistance.

On the basis of the analysis made above it can be stated that the behavior of the negative magnetoresistance in weak fields agrees with the model for tunneling in a "smooth" random potential. The exponential increase of the resistance in strong fields corresponds to the well-known picture of "magnetic freeze-out" or compression of the electron wave functions in a magnetic field.

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