Semiclassical ballistic microcontact in strong magnetic field

A. A. Bykov, G. M. Gusev, Z. D. Kvon, V. G. Plyukhin, and S. I. Chikichev
Institute of Semiconductor Physics, Siberian Branch, Academy of Sciences of the USSR

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The resistance of a semiclassical ballistic point contact P based on a two-dimensional electron gas of an AlCaAs–CaAs heterojunction increases by three to four orders of magnitude when the Fermi level reaches the Landau level with $i = 2$. The $R(B)$ curve exhibits several plateaus near which $R = h/ie^2$ $(i \geqslant 4)$ if the Fermi level is situated near the diffuse Landau level.

The study of the transport phenomena in microstructures based on AlCaAs–CaAs heterojunctions has recently reached an extraordinary intensity, especially after the discovery that the resistance of a ballistic point contact could be quantized. Until now, however, almost all of the research has been concentrated on narrow point contacts, whose width W and length L are comparable to an electron wavelength λ, since quantization is observed under these conditions.

We have studied semiclassical ballistic point contacts with $\mathrm{l} > L \geqslant W \gg \lambda$, where l is the mean free path. We found that their behavior in a strong magnetic field differs from the behavior of quantum point contacts and from the behavior of macroscopic samples $(W, L \gg \mathrm{l})$. First, when the Fermi level is equal to the Landau levels with low values of the index ($i \leqslant 4$ with allowance for the spin degeneracy), the resistance of the point contact increases rapidly with decreasing temperature; at 1.5 K its value increases by three or four orders of magnitude in comparison with the value in zero magnetic field. The resistance of macroscopic samples in these magnetic fields is higher than that of a point contact by no more than an order of magnitude in the absence of a field, and is virtually independent of the temperature. Quantum point contacts, however, have no Shubnikov–de Haas oscillations. Secondly, when the Fermi level is situated near the diffuse Landau level with $i = 2$, the $R(B)$ curve exhibits several plateaus. One of these plateaus has a resistance of h/ie^2 $(i = 6)$ with an accuracy to the second digit.

The point contacts which we have studied were made on the basis of a 2D electron gas in a AlCaAs–CaAs heterojunction using optical lithography and reactive ion etching. The 2D electron gas had the following parameters: electron density $N_S = 3.5 \times 10^{11}\ \mathrm{cm}^{-2}$ and electron mobility $\mu = 4 \times 10^5\ \mathrm{cm}^2/(\mathrm{V \cdot s})$. The mean free path therefore was $l = 4\ \mu\mathrm{m}$. The cross section of a point contact is shown in Fig. 1a. As we can see in this figure, the etching of AlCaAs is terminated as soon as the etching surface reaches the spacer, since etching before CaAs causes, as we know, a drastic reduction of the mobility.[2] The topology of the point contact W, which is smaller than the geometrical width because of the presence of lateral depleted regions, was determined from the value of its resistance R in the absence of the magnetic field by using the relation $R = (h/2e^2)(\pi/K_F W)$, (Ref. 1) where $K_F = \sqrt{2\pi N_S}$, and N_S was determined from the period of the Shubnikov oscillations. The resistance of the point con-

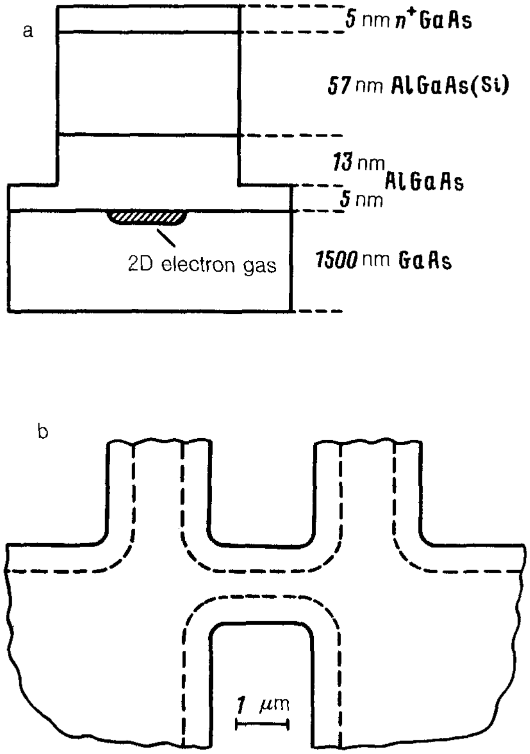

FIG. 1. a—Cross section of the point contact; b—topology of the point contact.

tact was measured by the two-probe and four-probe methods in fields up to 8 tesla at $T = 1.5\text{–}4.2$ K.

Figures 2a and 2b show the results of the measurements of R at 1.5 K using the four-probe method for a point contact with $W \sim 0.5\ \mu\text{m}$. We see that before the value of the field corresponding to the filling of more than two spin-degenerate Landau levels is reached, the amplitude of the Shubnikov–de Haas oscillations is comparable to the resistance in the absence of a magnetic field. When the filling factor approaches four, however, R increases by more than an order of magnitude. The effect is even greater upon passing the Landau level with $i = 2$: the resistance again increases by almost two orders of magnitude. We note that the amplitude of these two anomalous peaks in terms of height increases sharply with the decreasing temperature in the temperature range under investigation, in contrast with the macroscopic case in which the amplitude of the corresponding oscillations depends only slightly on the temperature.

Measurements carried out at a higher sensitivity level (Fig. 2b) reveal one more characteristic feature of the resistance of the point contact in a magnetic field: We see that there are two plateaus to the right of the second anomalous peak. This region of

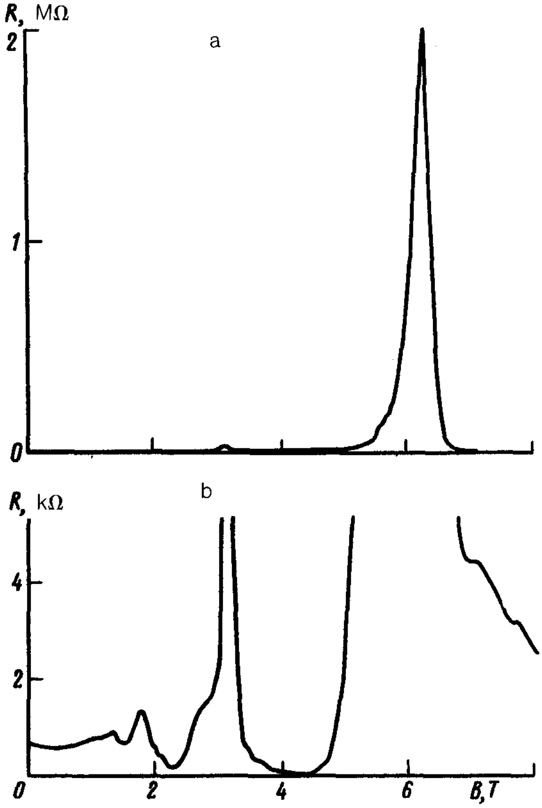

FIG. 2. a,b—Resistance of the point contact versus the magnetic field in two scales. $T = 1.5$ K.

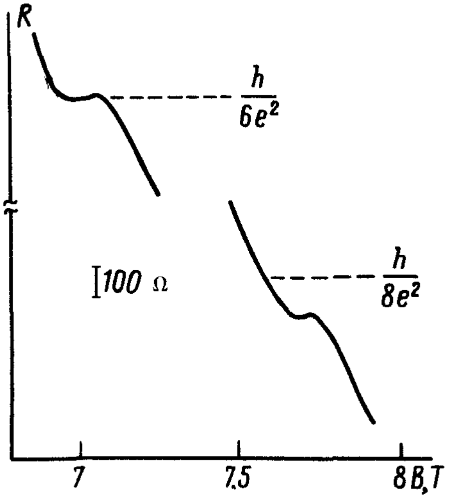

FIG. 3. R versus B in magnetic fields between 7 T and 8 T.

the magnetic fields is shown in greater detail in Fig. 3. An analysis of this figure shows that near the two plateaus the resistance retains its value within 2×10^{-3} in the range $\Delta B = 1$ kHz. The resistance at the first plateau corresponds to $R = 4.3 \pm 0.05$ kΩ, i.e., it is accurate within 10^{-2} $R = h/ie^2$, where $i = 6$, and at the second plateau $R = 3.1 \pm 0.05$ kΩ. Measurements based on the two-probe method also show the resistance increases sharply, although we saw no plateaus in this case.

An interband illumination makes it possible to regulate the resistance of the point contact by decreasing the width of the lateral depleted regions, thereby increasing W. An exposure to light reduced the resistance of the point contact to $R = 150$ Ω, which corresponds to $W = 1.7$ μm. Such a large increase in the resistance of the point contact nonetheless did not eliminate the anomalous oscillations: such a behavior was observed under the same conditions, i.e., at $i \ll 4$, just as that of a point contact with $W = 0.5$ μm. We thus conclude that the edge magnetic currents clearly play a key role in the explanation of the anomalies we have observed. Some plateaus were absent, but anomalous maxima were observed when the Fermi level was situated between the ground level and the first Landau level.

We have also analyzed a point contact with $W = 0.2$ μm. In this point contact we have also observed a plateau with $i = 6$, but we saw no plateau with $i = 8$. In addition, we saw a new plateau with $i = 12$ on the left-hand side of the peak. It should be noted, however, that the level of quantization accuracy in this sample was much lower (at the 5% level).

The fact that the condition $l > L, W$ must be satisfied can be seen from its comparison with that of Ref. 3. In Ref. 3 the geometry of the point contacts is similar to that of the structures studied by us, but the mobility of the samples is relatively low, so that $l < L$. On the basis of the behavior of those point contacts, we conclude that they did not exhibit the effects described above. On the other hand, the geometry of the samples is also important. The quasi-one-dimensional (in terms of the mean free path) and one-dimensional channels, which were studied in Refs. 4 and 5, are most similar, in terms of the geometry, to the point contacts studied by us. The quantum ballistic point contacts are also in this category. None of the systems mentioned above has the properties which were studied by us.

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