Microwave photoconductivity in a two-dimensional system with a periodic potential of antipoint contacts

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(Submitted 12 March 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 8, 407–410 (25 April 1991)

The microwave photoconductivity of a two-dimensional electron gas in a lateral superlattice consisting of quantum point contacts with a repulsive potential (antipoint contacts) was studied. New resonances of the photoconductivity were found at the frequencies $\omega \approx (1.4 V_f n)/d$, where $n = 1$ and 2, V_F is the Fermi velocity of the electrons, and d is the period of the superlattice. The resonances were manifested as an increase in the amplitudes of the Shubnikov oscillations and of the cyclotron resonance in weak magnetic fields. It was found that as the frequency decreases, the position of the cyclotron resonance as a function of the magnetic field deviates from the linear law.

New interesting objects—quantum point contacts—in which the motion of the electrons is quantized in all dimensions, recently appeared in the physics of few-dimension systems.[1–4] They were immediately followed by two-dimensional electronic systems containing a lateral superlattice of quantum point contacts with a repulsive potential—antipoint contacts.[5,6] This development gave rise to new ways in which the transport properties in a system with a periodic potential could be studied.

In this paper we report the development of such a system by means of electron-beam lithography and reactive ion etching based on a two-dimensional gas with high mobility. We also report the results of an experimental study of its high-frequency properties, in particular, the microwave photoconductivity in a magnetic field.

The starting AlGaAs/GaAs heterostructures, which were prepared by means of molecular-beam epitaxy, had the following parameters: the electron density $n_s = (3.5\text{–}5)\times 10^{11}\ \text{cm}^{-2}$ and mobility $\mu = (1\text{–}5)\times 10^5\ \text{cm}^2/\text{V}\cdot\text{s}$. We exposed $\sim 2\times 10^7$ holes with a diameter of 0.3 μm and a period of 1 μm, using an electron-beam lithography device based on ELP-20 positive resistance; the holes were then etched down to the size of the "spacer" by means of reactive ion etching.[7] The resistance of the structures prepared in this manner was measured in the Van-der-Pauw geometry using a 20-Hz alternating current in magnetic fields of up to 8 T at temperatures of 1.3–4.2 K. The microwave photoconductivity was measured by the double-modulation method, described previously in Ref. 8, in the microwave frequency range 35–150 GHz. Interband pumping made it possible to vary the carrier density and the width of the depletion regions created around the antipoint contacts. This procedure also changed the diameter of the antipoint contacts.

Negative magnetoresistance, a feature in the magnetic field $B \approx 2V_F mc/ed$, and a shift of the period of the oscillations at low densities under conditions of the quantum

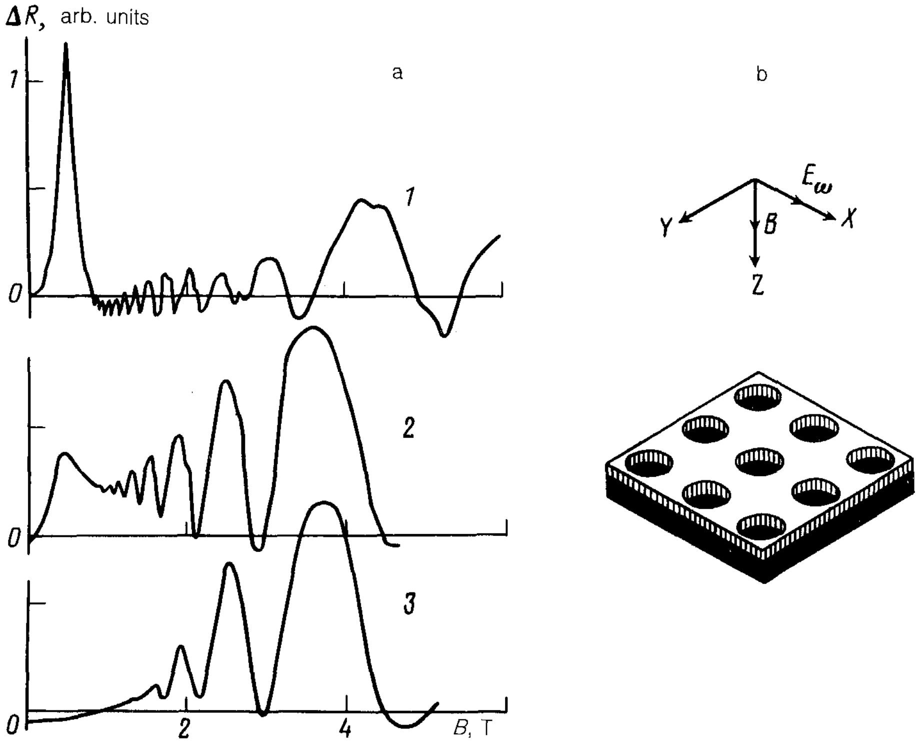

FIG. 1. Photoresistance versus the magnetic field for different samples. 1—Structure without antipoint contacts; $f = 126$ GHz; 2—structure with antipoint contacts; $f = 145.5$ GHz; 3—$f = 126.5$ GHz, $T = 4.2$ K.

Hall effect, which were reported in Refs. 5 and 6, were observed on the curve of the resistance of the structure versus the magnetic field B. These and other features of the transport phenomena will be reported in a separate paper. Assuming that the carrier density is uniform, the effective mobility was found to be $\sim 8 \times 10^4$ cm^2/V·s with a mobility $\sim 4 \times 10^5$ cm^2/V·s in the starting material. This result shows the advantage of this method of preparing microstructures over that of Ref. 6, where the lattice of antipoint contacts was obtained by implanting Ga^+ ions and led to a sharp (by more than an order of magnitude) decrease of the electron mobility.

Figure 1 shows the dependence of the microwave photoresistance ΔR on the magnetic field in the presence and absence of antipoint contacts for different frequencies of the microwave radiation. We see that a sample which has no periodic potential antipoint contacts in fields of ~ 0.4 T exhibits a cyclotron resonance peak, which is several times larger in amplitude than the Shubnikov photoconductivity oscillations that arise in stronger magnetic fields. A sample containing antipoint contacts has a cyclotron resonance weaker by an order of magnitude. It is evident from this figure that when the frequency ω of the microwave field is changed by a small amount, the amplitudes of the cyclotron resonance (CR) and Shubnikov oscillations in fields $B < 2$ T decrease sharply, while the amplitude of the photoresistance remains the same in

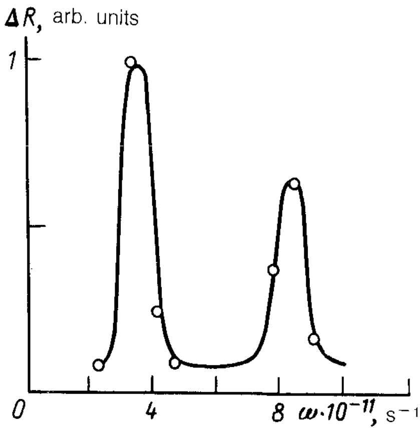

FIG. 2. The amplitude of the Shubnikov–de Haas oscillations of the photoconductive cell at $B = 0.9$ T as a function of the microwave frequency; $n_s = 3.6 \times 10^{11}$ cm^{-2}.

strong magnetic fields. This behavior is not observed in the sample without antipoint contacts. In these structures the amplitude of the cyclotron resonance decreases monotonically with decreasing ω and vanishes completely at $\omega \leqslant 4 \times 10^{11}$ s^{-1}. We note, however, that when the absorption is measured under cyclotron-resonance conditions, the cyclotron-resonance peak is observed up to $\omega \approx 2 \times 10^{11}$ s^{-1}.

For detailed analysis Fig. 2 shows the amplitude of the Shubnikov–de Haas oscillations of the photoresistance at $B = 0.9$ T as a function of the microwave frequency for a sample with a periodic lattice of antipoint contacts. It is obvious that the photoresistance exhibits resonant behavior as a function of the frequency. We see two resonance frequencies, which can be described by the relation

$$\omega_{1,2} = \frac{\alpha V_F}{d} n, \quad n = 1, 2,$$

where V_F is the Fermi velocity of the electrons, d is the period of the superlattice, and the coefficient α is equal to 1.3 for $n = 1$ and 1.6 for $n = 2$; i.e., the frequencies are multiples of each other with the coefficient of proportionality of 2.5. This dependence is also observed for the amplitudes of the cyclotron resonance and for other Shubnikov–de Haas oscillations up to magnetic fields of 2 T.

The system of electrons with antipoint contacts has a periodic potential of two types. The antipoint contacts are surrounded by the potential of the depletion region. As a result, electrons are repelled from the antipoint contacts, causing the barrier to increase in the narrow region between the antipoint contacts. Measurements in ballistic microbridges[7] have shown that in the region of the neck of a bridge whose width is $W \sim 1$ μm the carrier density can differ from n_s in the wide part of the sample by more than a factor of 2. Thus, in this system the electron is situated in a lattice of scatterers with an infinitely high potential (antipoint contacts) and a strongly modulated periodic potential with barrier height $V \sim E_F/2$ at the neck. In a one-dimensional superlattice the Landau level is broadened into a magnetic band; oscillations of this band result in oscillations of the conductivity in weak magnetic fields,[9] and the divergence of the density of states at the edges of the miniband results in splitting of the cyclotron-

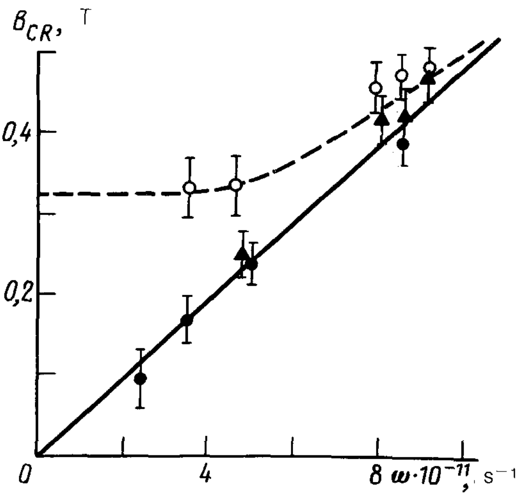

FIG. 3. The position of the cyclotron resonance peak as a function of the microwave frequency: ○—Structure with antipoint contacts; $n_s = 3.6 \times 10^{11}$ cm^{-2}; ●—structure without antipoint contacts; data taken from absorption measurements; ▲—structure without antipoint contacts; data taken from photoconductivity measurements.

resonance and Shubnikov oscillation peaks.[10] For these effects the superlattice potential must be relatively weak, $V \ll E_F$. This is not what we have observed experimentally. A theory of the behavior of electrons in a strongly modulated potential must be developed. Another effect that can be observed in a lateral superlattice is the excitation of plasma oscillations.[11] However, the frequency of these oscillations is much higher than the frequencies at which the indicated resonances are observed. An exception is the "acoustic" plasmon branch, for which $\omega \sim qV_F$. But, to excite plasmons of this type, two species of particles must be present.[11] It is possible that another condition for excitation of "acoustic" plasmons is that the system must be strongly nonuniform, which is true in our case.

Another characteristic feature of this system has to do with the position of the cyclotron-resonance peak. Figure 3 is a plot of B_{CR} as a function of frequency for electron density $n_s = 3.5 \times 10^4$ cm^{-2} in a sample with antipoint contacts and in a normal heterojunction. It is clear that if in the two-dimensional electron gas B_{CR} decreases linearly with decreasing frequency, then in a system with antipoint contacts the value of B_{CR} is slightly higher and as the frequency decreases, B_{CR} increases above the usual values of the field for the cyclotron resonance. We note that this value, $B_{CR} = 0.35$ T, is the limiting magnetic field, for which the motion of an electron at the cyclotron radius still falls between the antipoint contacts. A resonance is not observed when ω is reduced to 2.5×10^{11} s^{-1}. The above-described potential can lead to the appearance of a bound state in the region between antipoint contacts. In this case, however, the $\omega(B)$ curve should have two branches, one of which lies below B_{CR} for the ordinary two-dimensional gas.[2,4,6] This behavior has not been observed experimentally. The observed result requires a theoretical explanation. Absorption experiments must also be carried out.

We wish to thank A. L. Aseev, M. R. Baklanov, and V. N. Ovsyuk for support. We also thank S. I. Chikichev for providing the GaAs–AlGaAs heterostructures.

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Translated by M. E. Alferieff