Conductance of the surface inversion layer of *p*-type InAs in In–InAs and Cu–InAs structures at low temperatures

O. V. Zharikov and Yu. K. Krutenyuk
Institute of Solid State Physics, Academy of Sciences of the USSR

(Submitted 4 May 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **38**, No. 2, 45–47 (25 July 1983)

Quantum corrections to the conductance of the surface inversion layer of *p*-type InAs are observed experimentally. Penetration of Cooper pairs into the two-dimensional conducting layer of InAs, when this layer is in contact with a superconductor, is observed.

PACS numbers: 73.25. + i, 73.40.Ns

In recent years, the unusal electrical and magnetic properties of two-dimensional conducting systems at low temperatures have been analyzed in many theoretical papers.[1–4] The predicted effects have now been observed experimentally in Si MIS structures,[5] in the cleavage face of Ge in helium,[6] and in thin metallic films.[7]

In this work, we investigated the conductivity and magnetoresistance of *p*-type InAs in order to observe the possible quantum corrections to the resistance of the surface inversion layer of this compound at low temperatures.[1)] In addition, we were interested in a question that apparently has not yet been studied: What phenomena arise in the case of contact between a two-dimensional conducting system and a superconductor and do these phenomena arise in general?

Specimens with dimensions $4 \times 4 \times 0.3$ mm were cut out of plates of single-crystalline *p*-type InAs with a (111) type surface, doped with Zn up to a concentration 2×10^{16}. The specimens were then etched for several seconds in dilute HF, washed with alcohol, and subjected to ionic etching for 5 minutes at $U = 800$ V and $I = 0.1$ mA under an argon pressure of $\cong 1.5 \times 10^{-4}$ Torr. This was done in order to clean the surface, additionally to increase the conductance of the inversion layer,[9] and to stabilize the conductance at a single level for all specimens. Very pure In or Cu were then deposited through a mask (see insert in Fig. 1) without intermediate depressurization at $\cong 10^{-5}$ Torr. Narrow sections in the mask were 160 μm wide and 500 μm long. A slit of size d, which was varied in the experiments in the range 5–100 μm, was cut out with a special micromanipulator. The conductance of the inversion layer remained nearly constant after this procedure. The magnitude of d was determined in a JSM-25 scanning electron microscope. The resistance R was measured in a He^3/He^4 dilution refrigerator at temperatures (T) down to 0.045 K. The measuring current was in the range 1–10 μA. The temperature was recorded with a carbon resistance thermometer, whose calibration was monitored by measuring the susceptibility of the paramagnetic salt CMN. The magnetoresistance was studied at 1.2–4.2 K in a transverse magnetic field H.

We shall now describe the results of the measurements for the structure Cu–InAs–Cu. Figure 1 shows the temperature dependence $R(T)$ of a specimen with $d = 93$

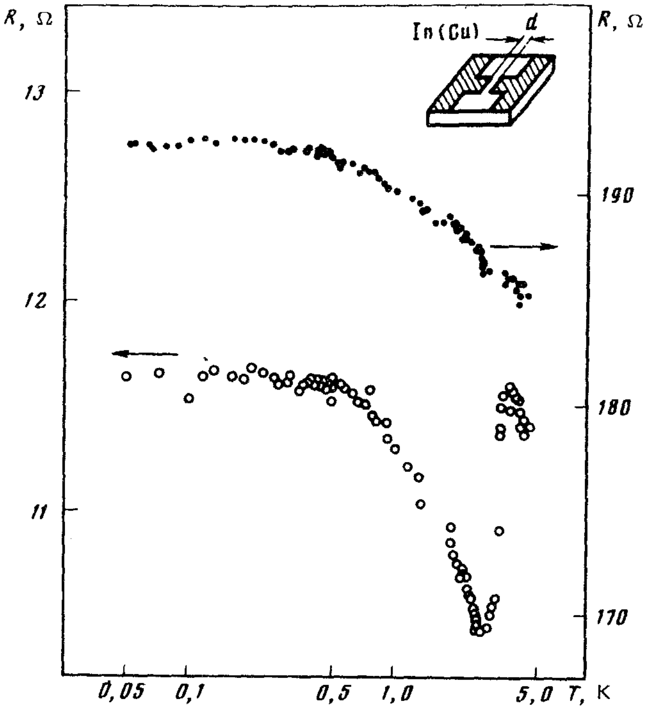

FIG. 1. Resistance as a function of temperature for the following specimens: ● with Cu–InAs–Cu structure; ○ with In–InAs–In structure.

μm and a resistance $R^{\square}_{4.2} = 320\ \Omega$. The temperature scale is logarithmic. It is evident that R increases with decreasing T at least down to 0.3 K, after which saturation sets in. It is evident that the experimental points are satisfactorily described by the dependence $R \sim \ln(1/T)$. A small initial nonlinear section was observed on the I-V curve of the specimens investigated for small I, such that $dU/dI > R_{4.2}$ with a gradual appearance of a linear dependence with slope corresponding to $R_{4.2}$. For measuring currents of 1–10 μA, i.e., on the linear part of the I-V curve, $R(T)$ was essentially independent of I. For $T \gtrsim 4$ K, the I-V curves were linear. $R(H)$ (see Fig. 2) exhibits a positive magnetoresistance.

The dependence $R(T)$ for the specimen with the structure In–InAs–In ($d = 5\ \mu$m, $R^{\square}_{4.2} = 340\ \Omega$) is more complicated. As T is reduced from $\simeq$3.5 K (for In, $T_c = 3.4$ K) to $\approxeq$2.6 K, there is an appreciable decrease in R and the corresponding I-V curves have an initial section with $dU/dT < R_{4.2}$, after which the curves become linear. Further cooling increases the resistance, while the I-V curves are analogous to the curves described above for Cu–InAs–Cu. We note that the relative increase in resistance in this case is several times greater than for the structure Cu–InAs–Cu. The results of measurements of $R(H)$ for a specimen with the In–InAs–In structure are shown in Fig. 2. A positive magnetoresistance is observed in low fields; then, R increases sharply as H increases to the critical field H_c of the In film. (The characteristic

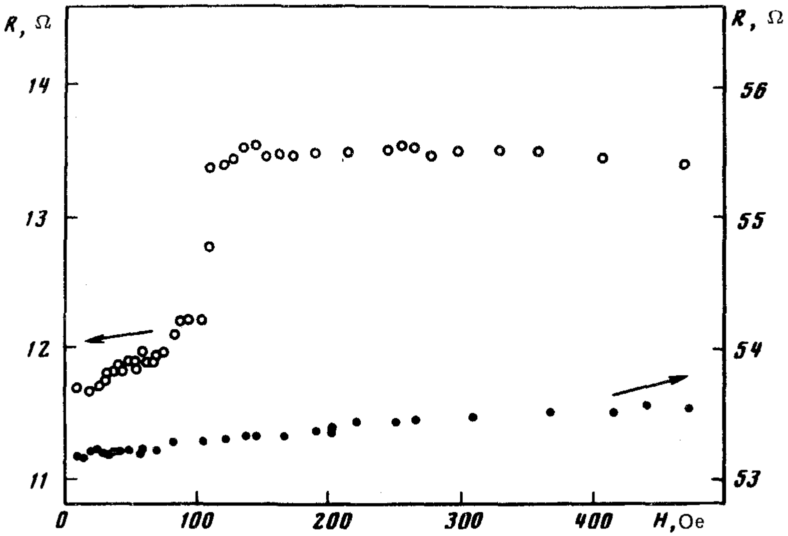

FIG. 2. Resistance as a function of the magnetic field for the following specimens: ● with Cu–InAs–Cu structure; ○ with the In–InAs–In structure.

resistance of an In film, which is three orders of magnitude smaller than the observed effects, is $\sim 10^{-4}\ \Omega$.)

It is not clear why the dependences $R(T)$ saturate, but this could be due to overheating of the electronic subsystem.[10] Such an effect was observed at low temperatures in Refs. 5 and 7.

A trivial reason for the change in R near T_c and H_c could be incomplete (with respect to thickness) section of the indium film or the presence of "islands" of In and a superconducting transition in these higher-resistance sections. However, they are estimated to be less than 10 Å thick. In addition, it is possible to prepare specimens with soldered indium contacts, avoiding the stages of deposition and cutting, in which the observed effects remain.

The results obtained lead to the following preliminary conclusions. The temperature dependence $R(T)$ and the positive mangetoresistance in fields ~ 100 Oe, i.e., for classically weak fields, could apparently indicate the contribution of quantum corrections[4] to the conductance of the surface inversion layer of p-type InAs. Further investigation of $R(H,T)$ over a wider range of fields will clarify the nature of these effects.

In the case of an inversion layer in contact with a superconductor, it appears that Cooper pairs penetrate into the conducting layer as a result of the proximity of the superconductor. As the temperature is reduced, the increase in the resistance, which is attributable, as in the first case, to the two-dimensional nature of the inversion layer, becomes dominant.

We thank E. P. Vol'skiĭ, A. I. Larkin, A. V. Shmidt, and D. E. Khmel'nitskiĭ for useful discussions and S. T. Boldyrev and V. M. Mishachev for valuable discussions involving the operation of the refrigeration or discussions and questions involving thermometry.

[1)] It is known that a surface inversion layer with electronic conductivity exists in *p*-type InAs. See, for example, Ref. 8.

---

[1] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979).

[2] B. L. Al'tshuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980).

[3] B. L. Al'tshuler, D. E. Khmel'nitskiĭ, A. I. Larkin, and P. A. Lee, Phys. Rev. B **22**, 5142 (1980).

[4] B. L. Al'tshuler, A. G. Aronov, A. I. Larkin, and D. E. Khmel'nitskiĭ, Zh. Eksp. Teor. Fiz. **81**, 768 (1981) [Sov. Phys. JETP **54**, 411 (1981)].

[5] D. J. Bishop, D. C. Tsui, and R. C. Dynes, Phys. Rev. Lett. **44**, 1153 (1980).

[6] B. M. Vul, E. I. Zavaristkaya, and V. N. Zavaritskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **37**, 87 (1983) [JETP Lett. **37**, 105 (1983)].

[7] G. J. Dolan and D. D. Osheroff, Phys. Rev. Lett. **43**, 721 (1979).

[8] S. Kawaji and Y. Kawaguchi, Phys. Soc. Jpn., Suppl. **21**, 336 (1966).

[9] M. F. Millea, A. H. Silver, and L. D. Flesnier, Thin Solid Films **56**, 253 (1979).

[10] P. W. Anderson, E. Abrahams, and T. V. Ramakrishnan, Phys. Rev. **43**, 718 (1979).

Translated by M. E. Alferieff
Edited by S. J. Amoretty