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Nuclear irradiation-induced superconductivity in the binary semiconductor InAs

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A jump-like increase of the resistance as a function of magnetic field is observed in indium arsenide samples irradiated by α particles with an energy of 80 MeV. The effect is detected at $T < 5$ K. The observed effect is explained by the appearance in the crystal of superconducting areas created by nuclear irradiation. The magnetoresistance is caused by suppression of the superconductivity in the inclusions under magnetic field increase. The observed effect is considered in terms of a theory of the magnetoresistance of a medium with superconducting inclusions, proposed earlier. The proposed theory explains qualitatively the experimentally measured dependence of the resistance on magnetic field, namely: the jump of the resistance at a certain value of magnetic field; the shift of the curves towards higher magnetic fields with decrease of temperature; at lower values of the temperature the jump takes place in a wider range of magnetic fields (i.e., the curves became flatter).

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1. Introduction

In this paper we present experimental and theoretical results which show that areas of superconductivity can be created in a semiconductor crystal as a result of nuclear irradiation.

The appearance of metallic regions in such crystals may be caused by different technological processes, and in particular, as a result of solid-solution decomposition in multicomponent systems [1]. If one of the components exhibits superconducting properties at the corresponding temperatures, then its precipitation gives rise to superconducting regions in the crystal. Peculiarities of the conductivity and magnetic properties which could be interpreted as a phase transition to the superconducting state have been observed in the binary semiconductor PbTe [2–4]. The appearance of superconductivity in semiconductors with departures from the nominal stoichiometry has been observed in GaAs [5] and in other binar semiconductors [6] as well. Another way of creation of metal areas embedded in a material is the injection of molten metal into porous glass [7,8].

The aim of this work is to explain the peculiarities of the magnetoresistance observed in an InAs crystal irradiated by α particles at low temperature [9]. It is well known that irradiation of crystals by high-energy particles leads to generation of different types of radiation defects, for example, to the creation of macroscopic areas with properties differing significantly from those in bulk samples. In multicomponent systems the segregation effect and the creation of microscopic inclusions of the other phase, and in particular, precipitation of a metallic phase were reviewed in [10]. In some systems the metal regions created exist in the superconducting state. In this work it has been shown that the presence of such superconducting regions can explain the peculiarities of the magnetoresistance of irradiated InAs.

2. Experiment

The results of investigations of the radiation-induced abnormal conductivity of single crystals of indium arsenide with *n*- and *p*-type conductivity at temperatures in the range 2–6 K and in the magnetic fields up to 2 T are presented.

The samples, in the form of parallelepipeds (1×3×8 mm), before irradiation had *n*- and *p*-type conductivity, with concentrations of free carriers at a temperature of 78 K equal to $3.76 \cdot 10^{16}$ and $3 \cdot 10^{16}$ cm^{-3}, respectively. Before irradiation the curves of the temperature and magnetic field dependence of the conductivity of the samples in the given range of low temperatures had a form typical for InAs crystals, well described in the literature [11], and had no peculiarities.

These two samples were irradiated by 80 MeV α particles at room temperature in the U-240 cyclotron of the Institute for Nuclear Research, Kiev. The average beam current was 1 μA, and the summary fluence, $4.8 \cdot 10^{16}$cm^{-2}. As a result of irradiation of the samples, the electronic type of conductivity was formed, with the concentrations of free carriers of $1.0 \cdot 10^{18}$ and $7 \cdot 10^{17}$ cm^{-3} at the temperature 4.2 K.

The results of measurements of the irradiated samples after one-week storage at room temperature are adduced. Peculiarities in a form of a jumplike change of the resistance by 10–20% were revealed ($T < 5$ K) at certain values of the magnetic fields, temperatures, and currents through a sample. The dependence of the resistance on magnetic field at different values of the temperature is presented in Fig. 1 (dotted curves). An increase of the current through a sample leads to a decrease of the critical magnetic field H_c. An increase of the current from 10 to 1000 mA at a temperature of 4.22 K leads to a decrease of H_c from 0.6 to 0.3 T.

A jump in the temperature dependence of the resistance was observed as well [9].

The observed peculiarities can be explained as a phase transition from the superconducting state to the normal state on the assumption that irradiation of InAs by α particles leads to the formation of the superconducting phase in the volume of the sample.

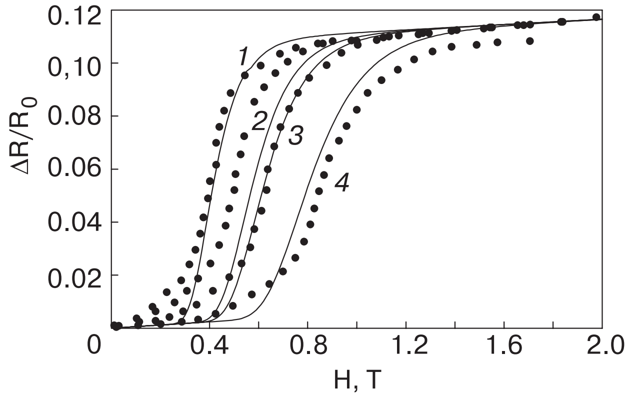

Fig. 1. Resistance of irradiated InAs sample as a function of magnetic field at different temperatures T, K: 4.22 (*1*); 3.49 (*2*); 3.23 (*3*); 2.02 (*4*). The solid lines correspond to the theoretical results, the dotted lines to the experimentally measured results. The fitting parameters are as follows: $r_0 = 0.52$; $s = 0.2$; $P = 0.07$; $\sigma_2 / \sigma_3 = 5$.

Other peculiarities in the properties of the samples were as follows:

– After the removal of surface layers up to 50 μm (1st sample), the sample was still in the superconducting state; that allows us to affirm that the superconducting areas are located in the volume of the crystal.

– The residual resistance ($3 \cdot 10^{-3}$ Ω) (in the *n*- and *p*-type materials (1st and 2nd samples, respectively) indicates that the volume of the superconducting areas is a small part of the whole volume of the crystal.

– The peculiarities in the conductivity of the irradiated sample disappeared upon room-temperature annealing. In the *p*-InAs sample the conductivity jumps disappeared irreversibly after 2 months storage at room temperature. In the *n*-type sample the peculiarities of the conductivity persisted over a longer period of time (about one year). As is well known, radiation defects in crystals can disappear as a result of room-temperature annealing. Therefore it is possible to consider the disappearance of peculiarities in the conductivity as another confirmation that the conductivity jump is caused by irradiation.

3. The model of the system. Comparison of the theory and experiment

We assume that the above-mentioned peculiarities of the magnetoresistance can be caused by the creation of superconducting areas in the crystals.

To explain the peculiarities of the conductivity of the irradiated crystal we apply the theory of the magnetic resistance of a crystal with superconducting inclusions, presented in [12,13]. According to this theory the crystal under consideration consists of a matrix and metallic inclusions, which can be either in the superconducting or in the normal state, depending on their radius. The critical magnetic field quenching the superconductivity of the inclusions increases with decreasing of the radius of the inclusion. Thus, if the magnetic field increases the number of the inclusions in the superconducting state is reduced.

To calculate the conductivity of a system containing superconducting inclusions we assume that the total volume occupied by the inclusions is less than the volume necessary for percolation to occur. Thus there is no superconducting current through the whole sample. So, in the calculation of the conductivity it was supposed that, depending on the temperature, magnetic field, and radius, a spherical inclusion can exist in two states: in a superconducting state with infinite conductivity, or in a normal state, with resistance corresponding to the material of the inclusion at the given temperature. Thus the irradiated crystal can be considered as a two-component system consisting of a nonsuperconducting matrix and the inclusions. According to the formula for the conductivity in multicomponent systems (see, for example, [14]) we have:

$$\frac{\sigma_1 - \sigma}{\sigma_1 + 2\sigma} P_s + \frac{\sigma_2 - \sigma}{\sigma_2 + 2\sigma} P_n + \frac{\sigma_3 - \sigma}{\sigma_3 + 2\sigma} P_3 = 0, \quad (1)$$

where σ_1 is the conductivity of an inclusion in the superconducting state ($\sigma_1 = \infty$), σ_2 is the conductivity of an inclusion in the nonsuperconducting state, σ_3 is the conductivity of the matrix ($\sigma_2 > \sigma_3$), and P_s and P_n are the relative volumes of the superconducting and normal inclusions, respectively,

$$P_s = P \frac{\int\limits_0^{r_c(T,H)} r^3 W(r) dr}{\int\limits_0^{\infty} r^3 W(r) dr}, \quad P_n = P - P_s, \quad P_3 = 1 - P, \quad (2)$$

where P is the relative volume of inclusions in the sample, and $W(r)$ is the distribution function of the spherical inclusion with respect to radius r. The numerical calculations were done for inclusions with a normalized Gaussian distribution over radius with a variance s^2 and center r_0:

$$W(R) = Zr^3 \exp\left[-\frac{(r - r_0)^2}{2s^2}\right]. \quad (3)$$

The critical radius at given T and H is determined by the formula $r_c(T,H) = \sqrt{5}\,(2\,\kappa/H)\,\sqrt{1 - T/T_{c0}}$ [15]. Thus the relative volume of inclusions in the superconducting state depends on the magnetic field. The criterion of applicability of this consideration and the results of calculations of the magnetoresistance at different parameters of the system $(r_0, s, \sigma_2, \sigma_3, \kappa)$ are presented in [12,13].

The theory describes the jumplike change of the resistance on changing temperature and magnetic field which is observed experimentally in irradiated InAs crystals. The values and location of these jumps depend on the radii of the inclusions, the radius variance, and other parameters. It should be noted that in the case considered, the dependence of the conductivity on magnetic field (magnetoresistance) is caused by suppression of the superconductivity by the magnetic field. As the magnetic field is increased, superconductivity is suppressed in the inclusions of the larger sizes and then in the inclusions of the smaller sizes.

From a comparison of the theoretical and experimental dependences of the resistance on the magnetic field, one can conclude that the curves have qualitatively similar behavior: 1) a jump of the resistance at a certain value of magnetic field is observed; 2) a shift of the curves towards a larger magnetic fields with the decrease of temperature is observed as well; 3) at the lower values of the temperature the jump takes place in a wider range of magnetic fields (i.e., the curves became flatter).

To find the parameters of the system the following experimental facts were used:

1. The critical temperature of the regions arising as result of the irradiation is equal to $T_{c0} \approx 5$ K.

2. From Eq. (2) one can determine the interrelation between the parameters being measured. Thus by the use of the solution of equation (1) for the two limiting cases a) $H = 0$ ($P_s = P$, $P_n = 0$) and b) $H >> H_0$ ($P_s = 0$, $P_n = P$) we obtain the formula for the conductivity jump η of the irradiated material: $\eta = (\sigma_0 - \sigma_\infty)/\sigma_3$. Here σ_0 is the value of the conductivity at zero magnetic field, and σ_∞ is the conductivity at a magnetic field value which exceeds the value of the critical field,

$$\frac{\sigma_2}{\sigma_3} = \frac{-9P + 2\eta + 9P^2 + 3\eta P - 18\eta^2 P^2 + 12\eta^2 P + 27\eta P^3 - 36\eta P^2 - 2\eta^2}{\eta\,(-27P^2 + 27P^3 + 9P - 1)}. \quad (4)$$

At the known η (according to the experimental data the value of the jump is approximately $\eta = 0.12$) formula (4) sets up a correspondence between the volume of the inclusions P and the ratio σ_2/σ_3.

3. The inflection point of the curve $\Delta R / R_0(H)$

$$\left(\partial^2 \frac{\Delta R}{R_0}(H,T) \,/\, \partial H^2 = 0 \Big|_{T=(T_1,H_1)} \right)$$

and the slope of the curve at the same point

$$\partial \frac{\Delta R}{R_0}(H,T) \,/\, \partial H = \gamma_1 \Big|_{T=(T_1,H_1)}$$

were taken from experiment. Here H_1 and γ_1 are the magnetic field and the slope at the inflection point for the curve observed at the temperature T_1.

To determine the parameters of a system we used the data (plateau, inflection, and slope) of only curve *1* from Fig. 1. The other curves *2–4* were obtained without introducing new fitting parameters. One can see that there is a satisfactory coincidence of the experimental and the theoretical curves (see Fig. 1; the solid lines correspond to the theoretical curves; the dotted lines denote the experimentally measured curves). From the calculations the value $\kappa H_{c0} = 0.2$ T was estimated. The other parameters are given in the figure caption.

It is seen that the curves coincide well enough except at low values of magnetic field. The disagreement of the theoretical and experimental results at low magnetic fields H may be explained by the fact that at the low fields the resistance is caused by inclusions of large sizes (the critical field of an inclusion is inversely proportional to r). Meanwhile, the proposed theory is correct for $r \leq 1$, and it cannot describe this magnetic-field range.

The proposed theoretical explanation of the observed effect is a phenomenological one. It confirms the appearance of the superconducting areas. To obtain experimental verification of the appearance of such areas, to estimate their sizes, and to determine their mutual arrangement, it will be necessary to carry out structural investigations.

The microscopic mechanisms responsible for creation of the metal areas may be the followings:

1) The appearance of the superconducting inclusions can be caused by the generation of metal-enriched regions due to instability of the binary crystals with respect to generation of the antisite defects during irradiation by high-energy particles [16,17]. These defects are formed by the abnormal substitution of the lattice sites by the atoms (i.e., the In atom is situated on the lattice site of the As and *vice versa*). Irradiation facilitates the accumulation of such types of defects. The metal-enriched region may have a high conductivity or be in the superconducting state. It should be noted that the appearance of superconducting properties in the binary semiconductor GaAs with departures from the nominal stoichiometry was explained in [17] by a large concentration of antisite defects.

2) The appearance of regions of high pressure near dislocations created by irradiation is possible as well. Such areas are centers of origination of strain-induced localized superconductivity [18].

Conclusion

Thus, the experimental magnetic-field dependence of the resistance of InAs irradiated by α particles can be explained by the presence of superconducting inclusions. The appearance of the superconducting regions may be caused by the generation of metal-enriched areas under irradiation. The presence of inclusions which are in the superconducting phase leads to an increase of the conductivity of a crystal at low temperatures. Also, at low temperatures a strong dependence of the conductivity on magnetic field takes place. The dependence is caused by phase transitions of the inclusions from the superconducting to the nonsuperconducting state upon increase of the magnetic field. All the effects listed depend strongly on the radius of the inclusions and the radius variance.

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