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Magnetoresistance of $GaP_{0.4}As_{0.6}$ Whiskers in Vicinity of MIT

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The magnetoresistance of $GaP_{0.4}As_{0.6}$ whiskers doped with silicon with a concentration of acceptor impurity in the range of Na = $1 \times 10^{17} \div 5 \times 10^{18}$ cm^{-3} was investigated. The study of the magnetoresistance of GaAs whiskers at cryogenic temperatures gives information on the nature of low-temperature conductivity in such crystals, and can also be used to create magnetic field sensors with a magnetoresistive principle of action. It is interesting to investigate the magnetotransport properties of GaP_xAs_{1-x} solid solution. The purpose of this work was to study the magnetic support of $GaP_{0.4}As_{0.6}$ whiskers doped with silicon with a concentration of acceptor impurity in the range of Na = $1 \times 10^{17} \div 5 \times 10^{18}$ cm^{-3} at low temperatures. The composition of the solid solution was chosen from the point of view of the change in the band structure of the varizonic semiconductor. The concentration of charge carriers in crystals was in the vicinity of the metal- insulator transition (MIT). In this work, the transverse and longitudinal magnetoresistances of the whiskers were studied in the range of 4.2-77 K in magnetic fields up to 12 T. For most samples, the exponential temperature dependence of the resistance is obtained, which corresponds to the dielectric side of the MIT. It is established that in the transverse and longitudinal magnetic fields the field dependence of the magnetoresistance of the crystals is quadratic and is determined mainly by the conductivity of localized A^+ states of the upper Hubbard zone. However, at low temperatures of 4.2-50 K, a negative magnetoresistance (up to 7 %) in weak magnetic fields (up to 4.5 T) was detected in $GaP_{0.4}As_{0.6}$ whiskers. A critical magnetic field was determined, in which a transition from negative to positive magnetoresistance occurs. It is shown that the magnitude of the critical magnetic field depends on the temperature and nature of the application of the magnetic field. The possible reasons for the appearance of a negative magnetic resistivity were analyzed: dimensional effect, distribution of impurities in the whiskers. The obtained results indicate that the mesoscopic dimensional effect does not appear in the studied samples due to sufficiently large crystal sizes. The results of mass spectroscopic studies have established a homogeneous distribution of impurities indicating the absence of clusters in the samples. The obtained negative magnetoresistance was probably connected with antiferromagnetic exchange interaction of the magnetic moments of charge carriers in the process of their hopping conductance on the delocalized states of the upper Hubbard zone.

Keywords: Whiskers, Negative magnetoresistance, Hopping conduction, Spin-dependent scattering.

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1. INTRODUCTION

Investigation of magnetoresistance (MR) and electrical conductivity of the $GaP_{0.4}As_{0.6}$ whiskers allows us to deepen knowledge about the nature of their conductivity in the region of cryogenic temperatures, as well as to determine the conditions for doping crystals to create sensors usable in strong magnetic fields.

Study of the MR of the GaAs as a well-known sensor material was shown in work [1]. Giant magnetoresistive effect was revealed in GaAs/AlGaAs heterostructure due to size effect of 2D electron gas [2]. Nevertheless, MR of GaAs/AlGaAs wires can become negative in a wide range of magnetic fields due to large boundary scattering of charge carriers [3]. On the other hand, a distinct microscopic structural disorder could result in negative MR like that in GaAs:Te monocrystals with large doping impurities [4]. Positive [5] and negative [6] MR and also crossover from negative to positive MR [7, 8] were revealed in the GaAs at different temperatures by the mentioned authors. The negative MR (NMR) is revealed at 80 K in the GaAs sample having Si doping density of 1.67×10^{12} cm^{-2} and the δ-doped layer with depth of 40 nm. The conduction channel in the δ-doped layer contains quantized states in the conduction and impurity bands. The origin of the NMR is connected with the presence of conduction in the inhomogeneous potential due to the impurity localization [9]. The NMR was also observed in the GaAs whiskers doped with magnetic Mn impurity [10, 11]. The NMR origin in the GaAs is explained by the MnAs clusters presence of about 1.5 % at a temperature of 30 K and magnetic field induction of 1 T due to spin scattering of the carriers by the magnetic nanoclusters [10]. In addition, the NMR origin is due to the spin-dependent scattering rather than to the weak localization for individual (Ga, Mn) As core-shell nanowires [11]. The NMR decreases according to the temperature elevation and, as result, the NMR vanishes at a temperature of about 100 K. The authors of [12] interpreted the NMR by the terms of spin-dependent hopping in the complex magnetic nanowire landscape of the magnetic polarons separated by the intermediate regions of the Mn impurity spins, due to the formation of the paramagnetic spin-glass phase. On the other hand, solid solution whiskers are widely used to create the magnetic field sensors. In particular, the behavior of the MR was studied depending on the germanium content in the SiGe solid solution whiskers with boron doping concentration in the vicinity of the metal-insulator transition (MIT) as well as the mechanical and temperature sensors were elaborated on their basis

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[13]. However, the magnetic resistivity of the $GaP_{0.4}As_{0.6}$ whiskers has not yet been studied.

The aim of the work is to study the electrical conductivity of the $GaP_{0.4}As_{0.6}$ whiskers with Si doping to concentration range of $10^{17}\div5\times10^{18}\ cm^{-3}$ at low temperatures 4.2÷77 K and strong magnetic fields up to 14 T for clarification the possibility of creating magnetic and temperature sensors, capable to the operation in the extreme condition.

2. EXPERIMENTAL

The $GaP_{0.4}As_{0.6}$ whiskers are grown by the method of chemical transport reactions in a closed bromide system using Si, gold and platinum impurities. The starting materials were the GaAs and GaP. The temperature of the source zone was 10÷70 K, the temperature of the crystallization zone was 970÷950 K. The composition of the solid solution was controlled by a microprobe analysis: the content of P in the whiskers was 40 at. %. The composition of the solid solution was chosen from the point of view of changing the band structure of the semiconductor (variation between X and L points of the Brillouin zone). The diameter of the whiskers was 40÷50 μm. Investigated crystals with a concentration of acceptor impurities covered the range from the deep dielectric side of MIT (~ $10^{17}\ cm^{-3}$) to the critical concentration of MIT ($N_c \sim 5\times10^{18}\ cm^{-3}$).

Temperature dependences (4.2÷300 K) of electrical conductivity of the $GaP_{0.4}As_{0.6}$ whiskers and their MR were measured in the range of magnetic fields with induction of 0÷14 T in the temperature range of 4.2÷77 K.

3. RESULTS AND DISCUSSION

Typical temperature dependences of resistance of the investigated $GaP_{0.4}As_{0.6}$ whiskers are shown in Fig. 1. As can be seen from Fig. 1, there is a typical exponential change in resistance with temperature indicating the proximity of samples to the transition of a metal insulator from the dielectric side.

Field and temperature dependences of MR in the $GaP_{0.4}As_{0.6}$ whiskers are shown in Fig. 2. It can be seen that the field dependence of the MR at low temperatures (near 4.2 K) can be approximated by the power function:

$$\frac{\Delta R}{R} \sim C \cdot B^n \quad (1)$$

(C = const, B is the magnitude of the magnetic field, n is the power index).

Studies have shown that the nature of the dependences of the MR $\Delta R_B/R$ on the magnetic field B significantly differs for samples with increasing temperature.

For the $GaP_{0.4}As_{0.6}$ whiskers, the MR at 4.2 K depends on the $\Delta R_B/R \sim B^2$ (Fig. 2, Fig. 3). At higher temperatures of 10÷60 K, there is the NMR, which is dependent on the value and direction of current and magnetic field induction. The maximum value of the NMR reaches 7 % at a magnetic field of 4.5 T and a temperature of 4.2 K. A similar effect was observed in [13] for p-type Si whiskers from the dielectric side of the MIT, however, in silicon whiskers, the effect is very weak in comparison with the $GaP_{0.4}As_{0.6}$ whiskers. Moreover, the NMR effect was observed in the InSb [14] and GaSb [15, 16] whiskers at low temperatures and high magnetic fields.

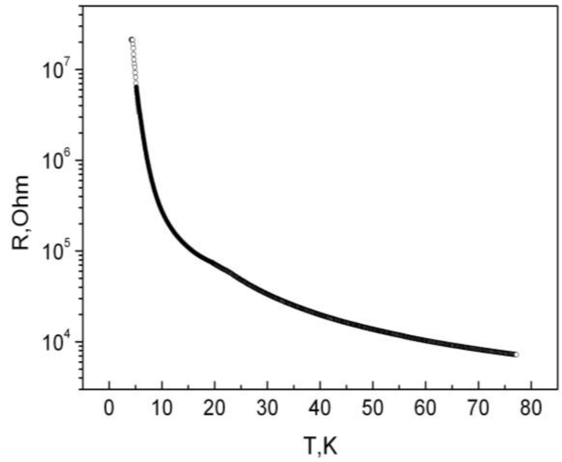

Fig. 1 – Temperature dependence of the resistance for the $GaP_{0.4}As_{0.6}$ whiskers

Analysis of the change in the NMR with increasing temperature is given in Table 1. Two characteristic parameters were taken into account:

1) the maximum value of the NMR;

2) the critical value of the magnetic field, in which the magnitude changes the sign from negative to positive.

Table 1 – The NMR parameters in the $GaP_{0.4}As_{0.6}$ whiskers

Current and field orientations	T, K	B_{cr}, T	Maximum NMR, %
$\boldsymbol{B \perp I}$	4.2	4	6
	10	7.5	2
	20	11	2
	40	10	0.8
	50	9.2	0.4
	60	6.5	0.05
$\boldsymbol{B \parallel I}$	4.2	4.5	7
	10	12	5
	20	> 12	1.5
	30	> 12	1.5

As can be seen from Table 1, the critical value of the transverse MR is maximum at a temperature of 20÷40 K, while there is a significant decrease of this parameter both during the rise and with the decrease of temperature. Regarding the absolute value of the NMR, a steady reduction of the effect was observed with increasing temperature. It is obvious that at the temperature of liquid nitrogen, the effect of the NMR is completely absent in the transverse geometry of the specimen – when the magnetic field is applied to the direction of flow of electric current.

Regarding the longitudinal MR (the magnetic field is applied along the direction of flow of electric current), despite the reduction of the NMR effect with increasing temperature, the value of the critical field far exceeds

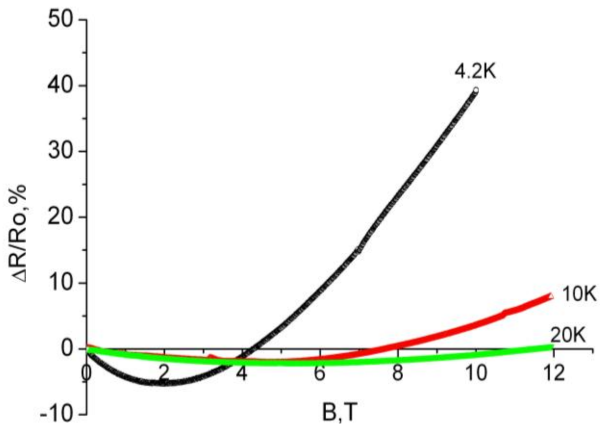

Fig. 2 – The behavior of the MR of the weakly doped $GaP_{0.4}As_{0.6}$ whiskers in the transverse magnetic field and a temperature range of 4.2÷30 K

the limits of experimental measurements: In $B_{cr} > 12$ T. That is, to establish critical fields for temperature increase, it is necessary to extend the interval of magnetic fields when measuring the parameters of crystals.

Since the objects of the study are whiskers, it is necessary to consider the possibility of influencing the measured parameters of such factors as:

1) size effect;

2) the nature of the distribution of impurities in the solid solution.

1) The possible manifestation of the size effects in the whiskers will be considered in the following three aspects:

a) microscopic (quantum) size effect;

b) mesoscopic size effect (associated with the influence of the surface on the properties of crystals);

c) macroscopic size effect (its occurrence is mainly due to the non-identity of samples of different sizes, therefore it is more appropriate to call this effect geometric).

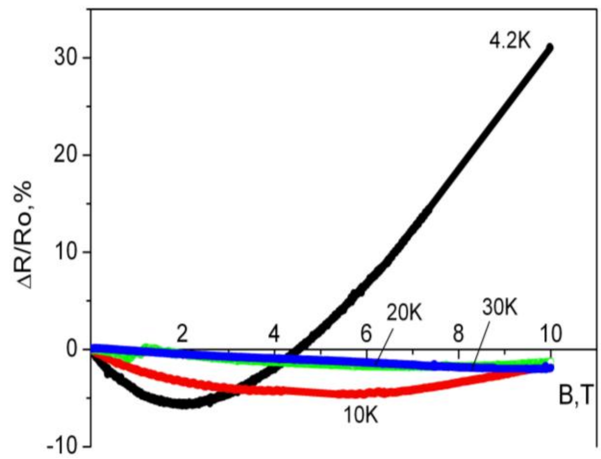

Fig. 3 – The behavior of the MR of the weakly doped $GaP_{0.4}As_{0.6}$ whiskers in the longitudinal magnetic field and a temperature range of 4.2÷30 K

In [17, 18], it was shown that the contribution of the quantum size effect to the electrophysical parameters of the whiskers should be taken into account in crystals with transverse dimensions.

$$a = \frac{\hbar \pi}{\sqrt{2 m_0 k T}} \quad (2)$$

where m_0 is the effective mass of holes; k is the Boltzmann's constant; T is the absolute temperature.

For the p-type conductivity GaAs whiskers $a \approx 150$ nm. Taking into account that the diameter of the investigated whiskers $d = 40 \div 50$ μm is much larger than the estimated parameter a, we can conclude that the influence of quantum size effects on the parameters of crystals can be neglected.

b) A number of mesoscopic effects were detected in the Si and SiGe whiskers in papers [19]. In particular, it has been shown that in the crystals with diameters $d < 1$ μm the lattice parameter change [19] takes place. These effects were due to the influence of the surface on subsurface layers of a small diameter crystal. Properties of whiskers with larger diameters $d > 1$ μm did not differ from the properties of bulk crystals. The latter conclusion was confirmed in the study of electrophysical parameters of Si whiskers with diameters of 20÷60 μm [19].

Since the whiskers which we are studying have diameters $d = 40 \div 50$ μm, it can be assumed that the superficial effect on their electrophysical parameters will be negligible.

c) We did not observe manifestations of the geometric effects of electrical conductivity and MR in the $GaP_{0.4}As_{0.6}$ whiskers of a certain alloy, since crystals of different diameters were grown in identical conditions.

2) It is known [20] that both electrical conductivity and MR depend to a large extent on the distribution of impurities in crystals. In particular, the formation of impurity clusters in the Si crystals can lead to a decrease in their MR. Therefore, to explain the experimental results, it is important to know the information about the distribution of Si in the whiskers. Preliminary investigations of the $GaP_{0.4}As_{0.6}$ whiskers by mass spectroscopy showed that doping impurities are distributed homogeneously in them, that is, the formation of clusters is not observed.

The above considerations show that the $GaP_{0.4}As_{0.6}$ whiskers can be considered as bulk materials with a homogeneous distribution of the impurity in the volume of the crystal by analogy with the SiGe whiskers.

3) It is known [13] that the quadratic law of the MR change with a field corresponds to bandwidth or conductivity in localized states of the upper Hubbard zone with activation energy ε_2. Previously, it has been shown that in the Si whiskers with concentrations of impurities in the immediate proximity to the MIT (~ 10^{18} cm^{-3}) at 4.2 K, indeed, there is a hopping conductivity with activation energy ε_2. Observation of the quadratic field dependence of the MR in the samples under study with a boron concentration $(1 \div 5) \times 10^{17}$ cm^{-3} and a specific resistance of 0.013÷0.025 Ohm × cm (Fig. 3) shows that, in this case, the conductivity is carried out into the localized states (A^+) of the upper Hubbard zone.

The NMR is usually observed in specimens with a concentration of impurity close to the critical concentration of MIT. We discovered the NMR in the InSb whiskers from the dielectric side of the MIT (Fig. 3). We assume that, as in [14], in such samples, the appearance of the NMR may be caused by the formation of hole pairs due to the antiferromagnetic exchange interaction of magnetic moments in the process of hopping conduction along the delocalized states of the upper Hubbard zone. The determined value of the activation energy of this conductivity is $\varepsilon_2 = 4.5$ meV. The high magnitude of the magnetic resonance impedance at 4.2 K is probably due to the fact that kT is small enough to provide conductivity in the upper Hubbard zone in such samples. Therefore, as expected, the maximum critical values of the NMR appear at higher temperatures of 20÷40 K.

4. CONCLUSIONS

At cryogenic temperatures, the MR and electrical conductivity of the GaP_xAs_{1-x} whiskers with acceptor concentration ($N_a = 1 \times 10^{17} \div 5 \times 10^{18}$ cm^{-3}) and P content ($x = 40$ at. %) doped with silicon impurity were studied.

The MR of the $GaP_{0.4}As_{0.6}$ whiskers with charge carrier concentration N_c at the liquid helium temperature is described by the quadratic dependence on the magnetic field and is mainly determined by the conductivity on the localized states A^+ of the upper Hubbard zone with activation energies $\varepsilon_2 = 4.5$ meV. In the whiskers with an dielectric side of MIT with a concentration of 1×10^{18} cm^{-3}, the NMR was detected, the magnitude of which reaches 7 % at a magnetic field induction of 4.5 T and a temperature of 4.2 K, which is probably due to the formation of hole pairs due to the antiferromagnetic exchange interaction of magnetic moments during the hopping conductivity on delocalized states of the upper Hubbard zone.

On the basis of the obtained results, it is still difficult to draw conclusions about the possible application of the $GaP_{0.4}As_{0.6}$ whiskers in sensors of magnetic field and temperature. MR of these crystals is quite high (about 40 %) and strongly depends on temperature. Therefore, the potential sensors of thermal quantities based on these crystals cannot be applied under the influence of high magnetic fields. On the other hand, the presence of NMR effect up to 7 % at a temperature of 4.2 K significantly limits the possibility of their using for the magnetic measuring.

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Магнітоопір ниткоподібних кристалів $GaP_{0.4}As_{0.6}$ в околі переходу метал-діелектрик

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Вивчення магнітоопору ниткоподібних кристалів GaAs при кріогенних температурах дає інформацію про природу низькотемпературної провідності в таких кристалах, а також може бути використано для створення сенсорів магнітного поля з магніторезистивним принципом дії. Цікаво дослідити магнітотранспортні властивості твердого розчину GaP_xAs_{1-x}. Метою роботи було дослідження магнітоопору ниткоподібних кристалів $GaP_{0.4}As_{0.6}$, легованих кремнієм з концентрацією акцепторної домішки в інтервалі Na = $1 \times 10^{17} \div 5 \times 10^{18}$ см$^{-3}$ за низьких температур. Склад твердого розчину обирався з точки зору зміни зонної структури варізонного напівпровідника. Концентрація носіїв заряду в кристалах була близька до переходу метал-діелектрик (ПМД). У роботі досліджувався поперечний та поздовжній магнітоопір зразків в інтервалі температур 4.2-77 К у магнітних полях до 12 Тл. Для більшості зразків отримана експоненційна температурна залежність опору, що відповідає діелектричному боку ПМД. Встановлено, що у поперечному та поздовжньому магнітному полі польова залежність магнітоопору кристалів є квадратичною і визначалася, головним чином, провідністю по локалізованих A^+ станах верхньої зони Хаббарда. Однак, за низьких температур 4.2-50 K в ниткоподібних кристалах $GaP_{0.4}As_{0.6}$ виявлено від'ємний магнітоопір (до 7 %) в слабких магнітних полях (до 4.5 Тл). Визначене критичне магнітне поле, за якого відбувається перехід з від'ємного до позитивного магнітоопору. Показано, що величина критичного магнітного поля залежить від температури та характеру прикладання магнітного поля. Аналізуються можливі причини виникнення від'ємного магнітоопору: розмірний ефект, розподіл домішок у ниткоподібному кристалі. Отримані результати вказують, що у досліджуваних зразках не проявляється мезоскопічний розмірний ефект через достатньо великі розміри кристалів. Результати мас-спектроскопічних досліджень встановили гомогенний розподіл домішок, що вказує про відсутність кластерів у зразках. Отриманий від'ємний магнітоопір, ймовірно, пов'язаний з антиферромагнітною обмінною взаємодією магнітних моментів носіїв заряду в процесі їх стрибкоподібної провідності по делокалізованих станах верхньої зони Хаббарда.

Ключові слова: Ниткоподібні кристали, Негативний магнітоопір, Стрибкова провідність, Спін-залежне розсіювання.