PHYSICS AND CHEMISTRY OF SOLID STATE
V. 23, No. 3 (2022) pp. 468-472

Section: Physics

DOI: 10.15330/pcss.23.3.468-472

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ФІЗИКА І ХІМІЯ ТВЕРДОГО ТІЛА
Т. 23, № 3 (2022) С. 468-472

Фізико-математичні науки

УДК 61.72.uj, 73.43.Qt

ISSN 1729-4428

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Quantum Magnetoresistance of GaPAs Whiskers

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The magnetoresistance of GaP_xAs_{1-x} (x = 0…0.45) whiskers with doping concentration of silicon in the range from the deep dielectric side of metal-insulated transition (~10^{17} cm^{-3}) to its critical concentration (N_c ~ 5×10^{18} cm^{-3}) at cryogenic temperatures of 4.2÷77 K and magnetic field induction of 0÷14 T was studied. A negative magnetic resistance (NMR) with maximum value of 7 % was found at temperature 4.2 K and magnetic field 4.5 T, which is dependent on magnetic field induction and current direction. The NMR absolute value reduces with increasing temperature was observed in the transverse and longitudinal magnetoresistance. The nature of the revealed NMR effect was discussed in the studied samples. There are four possible reasons of the NMR effect in the GaP_xAs_{1-x} whiskers such as the dimensional quantization, the magnetic ordering of electron spins or magnetic ordering due to uncontrolled magnetic dopant introduction and quantum interference of the electron wave function. The GaP_xAs_{1-x} whisker application as the temperature sensor was proposed due to the studied results of the temperature dependence of their conductivity.

Keywords: GaPAs whiskers, magnetoresistance, metal-insulated transition, sensor, cryogenic temperatures.

Received 14.01.2022; Accepted 26.07.2022.

Introduction

In the last decade, III-V compound nanostructures have been studied by modern researchers in view of their wide practical application [1]. The compounds based on GaAs are widely used as high bandwidth photodiode [2]. The use of a solid solution allows to control the wavelength and spectral composition of the photodiode radiation by changing the composition. Recent developments in the band-gap engineering technologies have lead an impact to development of low-dimensional multi-junction solar cell. Thus, *GaPAs/GaInAs* multiple quantum wells due to a theoretical prediction could yield the efficiency limit to 59 % in series that constrained AM1.5 of the global radiations [3]. In addition, GaPAs/GaP nanowires were used for design of emitting diode in red spectral region [4]. GaPAs/GaP nanowire array LED devices were processed on Si grown substrate revealing good electroluminescence properties in the range of 670 nm [4]. On the other hand, GaPAs whiskers were successfully used as humidity sensors at the range of near room temperatures [5]. Electronic properties of GaPAs crystals were studied in [6]. The results of the work determine that the crossover point (Γ-Γ) for direct and (Γ-x) for indirect gap of energies, which occurs with composition about x = 0.46 is with excellent agreement to the experiment. It is worthy to note that electron and hole mobility linearly changes with a crystal composition, decreasing in order of magnitude at transition from direct band GaAs to indirect band GaP crystals [7]. The authors of [8] investigated the surface properties of GaPAs compound, which was situated in electrolyte. Due to existence of thin oxide on the crystal surface capacitance-voltage characteristics were obtained [8] that could be used for capacity sensors of various physical values. However, an appearance of hysteresis of current-voltage characteristics due to depletion region arising on the crystal surface [8] to a large extent restricts the application. Therefore, an investigation of transport properties of GaPAs nanostructures is of great interest, i.e. for their practical application. In our previous work we have investigated the magnetoresistance of GaPAs whiskers [9]. Negative magnetoresistance (NMR) was shown in a wide range of magnetic fields. The effect was explained in the framework of existence of size effects in the whiskers. Our next investigations have shown and existence of NMR in a wide range of the whisker composition. An potential explanation of the effect observed is a goal of the studies. Besides, we have underlined the potential application of the whiskers.

The aim of present work consists in studies of magnetoresistance of GaPxAs1-x (x=0 …0.45) whiskers at cryogenic temperatures up to 4.2 K in the range of high magnetic field up to 14 T. This is a continuing of cycle of works directed in studies of the whiskers.

I. Methods

The GaPAs whiskers were grown by the method of chemical transport reactions (CTR) in a closed bromide system with use of Si, Au and Pt impurities. Si was used as doping impurity, while Au or Pt were used as initiator of the whisker growth due to VLS mechanism. The starting materials were GaAs and GaP crystals. The temperature of the source zone was 10÷70 K, the temperature of the crystallization zone was 970÷950 K. A composition of GaPAs alloys was studied in [10], where the problems of alloy stoichiometry was under investigation. The way to improve a stoichiometry of GaPAs alloys is a use of MBE technology [11]. Prediction of solid solution composition demands an information about the interaction V molecule group with surface of growth, which is required to create a growth model [11]. A cheap method to create the compound is CVD transport in closed system, which was used in our experiment.

The solid solution composition has been controlled due to microprobe analysis: content of P changes in the range 0-40 at. % in the GaPAs whiskers. The diameter of the whiskers was 10÷50 μm. Studied whiskers with doping concentration corresponding to range from deep insulator side of the MIT (~ 10^{17} cm^{-3}) to the critical concentration of MIT (N_c ~ 5×10^{18} cm^{-3}). The electrical contacts to the whiskers were created according to pulse welding method [12, 13] by Au microwires, which provides the ohmic contacts.

The temperature dependencies (4.2÷300 K) of electrical conductivity of the GaPAs whiskers and their magnetoresistance were determined at magnetic field induction range of 0-14 T ant temperature range of 4.2÷77 K.

II. Experimental results

Typical temperature dependencies of conductivity for investigated GaP_xAs_{1-x} (x=0.4) whiskers were shown in the Fig 1. As could be seen in Fig. 1, the typical exponential change in conductivity with reverse temperature was found. The data of Fig.1 presented in logarithmic scale gives a straight line in the temperature range 4.2 K – 20 K, which allows to determine the value of the charge carrier activation energy. The obtained value of ε_2 is about 6 meV.

Field and temperature dependences of magnetoresistance in the GaP_xAs_{1-x} (x=0.4) whiskers are shown in Fig. 2. Investigations were shown that nature of the magnetoresistance dependencies $\Delta R_B/R$ on the magnetic field B significantly differs for samples with increasing temperature.

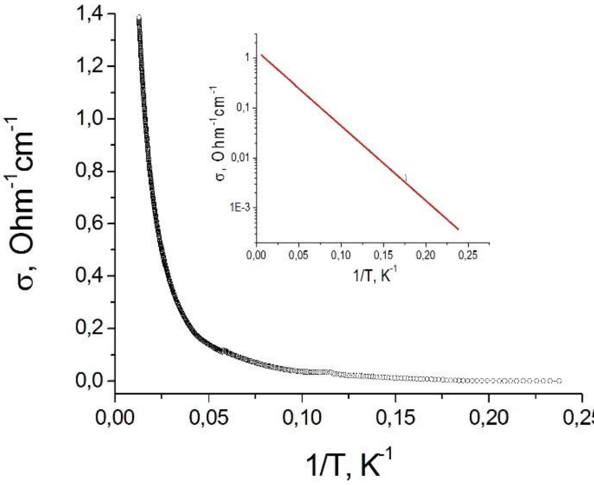

Fig. 1. Temperature dependence of GaP_xAs_{1-x} whisker conductivity. Inset: Calibration characteristic of the temperature sensor based on the GaP_xAs_{1-x} whiskers.

For GaP_xAs_{1-x} (x = 0.4) whiskers, the magnetoresistance depends on $\Delta R_B/R$~B^2 at temperature 4.2 K (Fig. 2). At higher temperatures of 10-60 K there is a negative magnetic resistance (NMR), which is dependent on magnetic field induction and also direction and value of current. The NMR maximum value achieves 7 % at magnetic field induction 4.5 T and temperature 4.2 K. Similar effect was revealed in [14] for Ge whiskers from the insulating side of the MIT, however, NMR effect was sufficiently weak in comparison to GaP_xAs_{1-x} (x=0.4) whiskers. Besides the NMR effect was observed in the InSb [15, 16] and GaSb [17] whiskers at high magnetic fields and low temperatures.

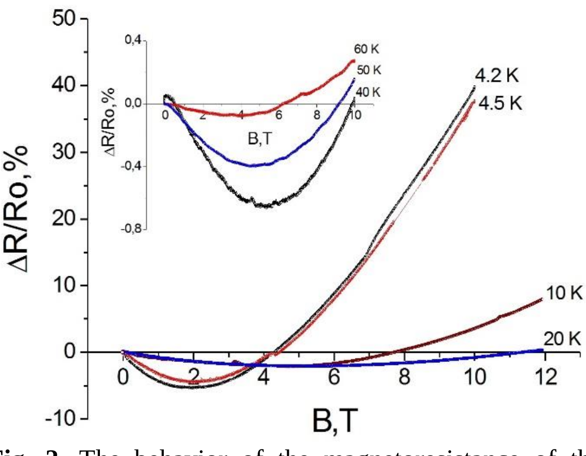

Fig. 2. The behavior of the magnetoresistance of the weakly doped the GaP_xAs_{1-x} (x=0.4) whiskers in the transverse magnetic field and temperature range of 4.2÷60 K.

The analysis of NMR changes with temperature rise has shown that should take into account two characteristic parameters:

1) NMR maximum values;

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

The critical value of the transverse magnetoresistance was maximum in the temperature range of 20-40 K, with a significant decrease in this parameter both during increase and decrease in temperature. Regarding the NMR absolute value, with increasing temperature there was a steady decrease in the effect. It was shown that at liquid nitrogen temperature the NMR effect was completely absent in transverse geometry of the sample, when magnetic field induction was applied into the electric current direction.

Regarding a longitudinal magnetoresistance, when magnetic field induction was applied along the electric current direction, despite a decrease in NMR effect with the temperature increasing, the critical field value significantly exceeds limits of the experimental measurements (B_{cr} > 12 T). That is, set the temperature critical fields increase, it is necessary to extend the interval of magnetic fields when measuring the parameters of crystals.

III. Discussion

A remarkable explanation of revealed the negative magnetoresistance (NMR) on the transverse magnetic field dependences in this work.

Possible causes of the presented effects can include:

1) presence of the dimensional quantization in the whiskers [18];

2) presence of the magnetic ordering in the electronic spins for the GaPAs whiskers with doping concentration near the metal-insulator transition [19];

3) presence of the magnetic ordering for the GaPAs whiskers due to the introduction of uncontrolled magnetic dopants [20];

4) the effect of quantum interference in the wave function of electrons [21, 22];

Presence of the dimensional quantization in the GaPAs whiskers can be excepted, that associated with their large diameters of 40-50 μm (the transverse dimension is much larger than the de Broglie wavelength).

The probable reason for the revealed features of the magnetic resistance in the GaPAs whiskers can be presence of the magnetic ordering in the electronic spins on Si-impurities in the strongly doped semiconductors. The appearance of the negative magnetoresistance according to the Toyozawa model is connected with the spin reorientation, which localized on the dopant atoms [19]. As a result, the possible scattering channels of the charge carriers is excepted, which leads to a decrease in the magnetoresistance that was detected in Ge whiskers as the negative magnetoresistance effect [14]. Nevertheless, the studied effect should quickly disappear with increasing temperature above 40 K, where there should be a transition from the hopping conductivity to the classical conductivity mechanism. However, in the experiments conducted in this work, the NMR effect is shown at temperatures up to 60 K (Insert in Fig. 2). The NMR presence at high temperatures is still unclear. In addition, the Toyozawa model at low temperatures is undoubtedly explained by such large NMR values.

Presence of the magnetic ordering for the GaPAs whiskers due to the introduction of uncontrolled magnetic dopants, for example Mn that leads to appearance of the negative resistance in field magnetic dependences [20]. According to the work [20] presence of the NMR depends on the orientation of the electron scattering spin on ions of Mn^{2+}. Therefore, presence of the uncontrolled magnetic dopants was not revealed in the GaPAs whiskers according to the results of this studies of the dopant elemental content in our samples due to microprobe analysis. However, studies of surface in the GaPAs whiskers would be the task of our further investigations.

The NMR presented in works [21, 22] can be explained due to the quantum interference in the wave function of electrons. The negative magnetoresistance disappearance is connected to destruction of the interference of electron wave functions by the magnetic field. This leads to weak localization effect and also the interaction of electron-electron. The observed effects at the low spin-orbit interaction result in increase of the resistance. The determination of the quantum interference effect in GaPAs whiskers, it would be necessary to study the resistance behavior in the weak magnetic fields down to 1-2 T at low temperatures 1.7 - 4.2 K. However, the effect of quantum interference (on small correction to conductivity) cannot name such a large value of the negative magnetoresistance about 10 %, which was shown in the experiment (Fig. 2).

Another explanation for the observed phenomenon was proposed. First, the advantage of surface conductivity in the samples compared to the bulk one should be noted. Conclusion is the result of a study of the longitudinal and transverse resistance for GaPAs whiskers (Fig. 2). Comparing these two figures, it is clear that the longitudinal resistance is less than the transverse one that explains prevalence of the surface conductivity in the transverse geometry of the sample due to the whisker core-shell structure. A similar phenomenon was found for InSb samples, where an increase in the doping concentration of the alloying substance was found, approaching the surface of whiskers [16].

It can be assumed the same whisker growth mechanism due to the chemical vapor deposition in a closed halogen system causes to a similar impurity doping during process of the growth. Another cause for the increasing in the doping concentration near surface of the crystals could be the impurity diffusion to surface during annealing process of the sample after GaPAs whisker growth.

Taking into account the above consideration, one can conclude that magnetoresistance characteristics does not allow to measure the magnetic field induction due to existence NMR. Nevertheless, the GaPAs whiskers can be used as temperature sensors in the wide range of temperature. The calibration characteristic of the temperature sensor based on the GaP_xAs_{1-x} whiskers was shown in the inset of Fig. 1. As shown from the Figure 1, linear logariphmic change of conductivity occurs, that allows to measure the temperature with high accuracy.

Conclusions

The electrical conductivity and magnetoresistance of the GaP_xAs_{1-x} whiskers with P content (x = 40 atom %) and silicon concentration ($N_a = 1\times10^{17}\ldots\ 5\times10^{18}$ cm^{-3})

were studied in the wide temperature range. The whisker magnetoresistance with critical concentration of MIT N_c was described as quadratic dependence on magnetic field at temperature 4.2 K. The value of charge carrier activation energy ε_2 of 6 meV was found in the temperature range 4.2-20 K as the result of investigated the temperature dependence of the GaP_xAs_{1-x} whisker conductivity. The NMR effect of the studied whiskers with doping concentration of 10^{18} cm^{-3} that corresponds to insulator side of the MIT was observed in the wide temperature range from 4.2 K to 60 K with its maximum magnitude up to 7 % at the liquid helium temperature. The behavior of the magnetoresistance of the weakly doped the GaP_xAs_{1-x} (x=0.4) whiskers changes the sign with magnetic field increasing that becomes positive at high magnetic field, that allows us to determine the critical magnetic field of the transition.

The revealed negative magnetoresistance was discussed due to some mechanisms: presence of the charge carrier quantization in GaPAs whiskers, the magnetic ordering presence as result of the electron spin superposition, the magnetic ordering presence due to the uncontrolled magnetic dopants introduction in the samples and the quantum interference of wave function of electrons. The potential reason of the studied NMR effect was analysed in the GaP_xAs_{1-x} (x=0.4) whiskers and connected with prevalence of the surface conductivity taking into account their core-shell structure.

The application of the researched GaP_xAs_{1-x} whiskers was shown as temperature sensor that was based on the obtained results of the temperature dependence of conductivity. Therefore, the sensor of thermal quantities on the whisker basis couldn't be applied in the high magnetic fields due to the NMR effect presence about 7 % at temperature of 4.2 K pointedly limits their using for magnetic field measuring.

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Квантовий магнетоопір віскерів GaPAs

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Досліджено магнетоопір віскерів GaP_xAs_{1-x} (x = 0…0,45) з концентрацією легувальної домішки в околі від глибокого діелектричного боку переходу метал–діелектрик (~10^{17} см$^{-3}$) до критичної концентрації (N_c ~ 5×10^{18} см$^{-3}$) за кріогенних температур від 4,2 до 77 K і в магнітному полі 0÷14 Тл. Виявлено негативний магнетоопір (НМО) з максимальним значенням 7 % за температури 4,2 K і в магнітному полі з індукцією 4,5 Тл. Встановлено, що з підвищенням температури абсолютне значення НМО зменшувалось як для поздовжнього так і поперечного магнетоопору. Обговорюються можливі причини прояву НМО у віскерах GaP_xAs_{1-x}, зокрема, розмірне квантування, магнітне впорядкування спіна електронів або магнітне впорядкування внаслідок неконтрольованого входження магнітної домішки, а також квантова інтерференція хвильової функції електрона. Запропоновано використовувати віскери GaP_xAs_{1-x} як чутливі елементи сенсорів температури.

Ключові слова: віскери GaPAs, магнетоопір, перехід метал–діелектрик, сенсор, кріогенні температури.