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BERRY PHASE APPEARANCE IN DEFORMED INDIUM ANTIMONIDE AND GALLIUM ANTIMONIDE WHISKERS

Anatoly Druzhinin, Igor Ostrovskii, Yuriy Khoverko, Natalia Liakh-Kaguy
Lviv Polytechnic National University, Lviv, Ukraine
druzh@polynet.lviv.ua , katerynaostrova@gmail.com, khoverko@lp.edu.ua, liakh76@gmail.com

Abstract: The influence of deformation on magnetoresistance features in indium antimonide and gallium antimonide whiskers of n-type conductivity with different doping concentration in the vicinity to the metal-insulator transition (MIT) **was** investigated in the temperature range 4.2–50 K and the magnetic field 0–14 T. The Shubnikov-de Haas oscillations in the whole range of magnetic field inductions were shown in deformed and undeformed whiskers. The amplitude of the magnetoresistance oscillations for both type of samples decreases in accordance with the increase in temperature. Berry phase existence under deformation influence was also revealed at low temperatures in the indium antimonide and galium antimonide whiskers, that indicates their transition into the state of topological insulators.

Keywords: indium antimonide and gallium antimonide whiskers; magnetoresistance; Shubnikov-de Haas oscillations; deformation; the Berry phase.

1. Introduction

The influence of deformation on the magnetoresistance of doped silicon was studied in works [1–3]. A number of interesting features of magnetoresistance behavior of silicon and silicon-germanium solid solution whiskers of p-type conductivity with different doping concentration in the vicinity to metal-insulator transition (MIT) have been identified in a wide temperature range 4.2–300 K [2, 3]. The investigation of deformation-induced effects in A3B5 compound semiconductors was also carried out, which made it possible to use them in some device applications [4]. Mobilities of the charge carriers in deformed samples were also investigated in papers [5, 6]. Deformation sensitivity was observed in indium antimonide InSb samples of p-type conductivity and gallium antimonide samples of n-type conductivity by the authors of [4].

Negative magnetoresistance effects were analyzed in undeformed semiconductors based on InSb at low temperatures due to the scattering mechanisms of different charge carriers [7–11]. Besides, negative magnetoresistance phenomena were considered in deformed indium antimonide whiskers of n-type conductivity with different doping concentration in the range 6×10^{16} – 6×10^{17}cm^{-3} [12].

The Shubnikov-de Haas oscillations were revealed on field dependencies of magnetoresistance in the undeformed InSb and GaSb whiskers in the temperature range 4.2–77 K [7, 13–16]. The analysis of their magnetoresistance oscillations allows one to determine a number of important parameters such as values of cyclotron effective mass of electrons, the Fermi energy and the Dingle temperature [13–15]. As a result of the magnetoresistance peak splitting revealed in the indium antimonide whiskers with the doping concentration in the vicinity to the MIT, a huge g*-factor equal to 36 was found [14]. The existence of the Berry phase that corresponds with the transition to topological insulator state was found in different materials due to the analysis of the Shubnikov-de Haas oscillations [17–19].

The aim of our paper is the study of the compressive deformation influence on the behavior of magnetoresistance for the indium antimonide and gallium antimonide whiskers of n-type conductivity with doping concentration corresponding with that in the vicinity to the MIT at low temperatures and magnetic fields up to 10 T.

2. Experimental procedure

The indium antimonide and gallium antimonide whiskers of n-type conductivity were the objects of our studies. The investigated whiskers were grown with the use of the method of a chemical transport reaction in a closed iodide system. Iodine was used as a transport agent. Temperatures of evaporation and crystallization zones were of about 800 ^{o}C and 600 ^{o}C, respectively. The indium antimonide and gallium antimonide whiskers were doped during their growth with tin and tellurium impurities, respectively. The doping concentration of tin was 2×10^{17} cm^{-3} in the indium antimonide whiskers and tellurium concentration was 2×10^{18} cm^{-3} in the gallium antimonide ones, both of them corresponding to those in the vicinity to MIT from the metal side of the transition.

For studying the magnetoresistance, the grown whiskers were selected according to the diametr of about 30–40 micrometers and the length of about 2–3 mm. Gold microwires of 10 micrometers in diameter were used for creating electrical contacts to indium antimonide and gallium antimonide whiskers by the pulsed welding technique with the formation of eutectic.

This method was tested in authors' previous works [2], and it allows the measurement of longitudinal resistance of the studied whiskers due to the use of a four contact scheme along the microcrystals. The additional contact was made for the studies of whiskers' galvanomagnetic properties.

Indium antimonide and gallium antimonide whiskers were deformed by mounting them on a copper substrate whose thermal expansion coefficient is different from that of the materials of studied crystals. Thermal compressive deformation of the whiskers in the crystallographic direction <111> was determined and it equals approximately -3×10^{-3} rel.un. at temperature 4.2 K. For cooling the studied samples to the temperature of liquid helium, helium cryostat was used. The magnetic field induction in the range 0–14 T was created due to the Bitter magnet used with the scanning time 1.75 T/min at temperatures 4.2–50 K. A current source Keithley 224 was used to create the stabilized electric current in the range of 1–10 mA depending on the resistance of the studied whiskers. A thermocouple Cu-CuFe was used to measure temperature in the range 4.2–300 K.

3. Experimental results and discussion

The field dependencies of magnetoresistance for the indium antimonide and gallium antimonide whiskers of n-type conductivity with doping concentration corresponding to the vicinity to MIT at temperatures 4.2–40 K and the magnetic fields up to 14 T were studied. Therefore, it would be interesting to consider the variation of the temperature dependences of the resistance of these samples in a zero magnetic field.

The behavior of the temperature dependences of resistance for the indium antimonide whiskers with doping concentration of tin 2×10^{17} cm^{-3} in the wide temperature range 4.2–300 K was analyzed. The results obtained show that for the deformed indium antimonide samples (see Fig. 1, curve 2) a stronger metal character was observed than for the case of the undeformed one (see Fig. 1, curve 1).

The low temperature dependences of the resistance in the range of 4.2–25 K were presented for the undeformed and deformed gallium antimonide whiskers in Fig. 2, *a* and Fig. 2, *b*, respectively. A small minimum for the deformed gallium antimonide whiskers (see Fig. 2, *b*) can be observed on the temperature dependences of resistance at 12 K, which corresponds to the transition to the dielectric side of the MIT induced by deformation. The doping concentration of tellurium 2×10^{18} cm^{-3} in the gallium antimonide whiskers corresponds to the vicinity to the transition from the metal side of the MIT. Therefore, the study of the deformation effect on the electrical transport characteristics of gallium antimonide whiskers allows detecting the deformation induced by the MIT in the dielectric phase at temperatures below 11 K, which can be used to create valve switches with MEM structures on their basis.

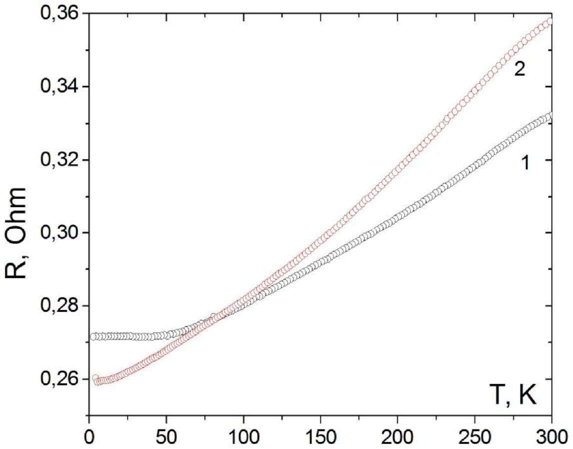
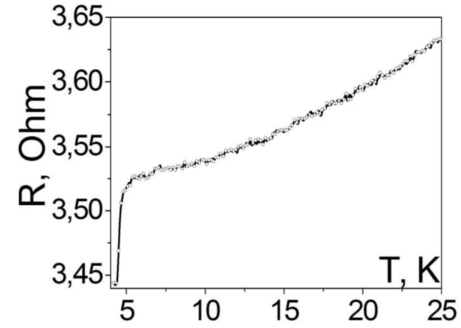
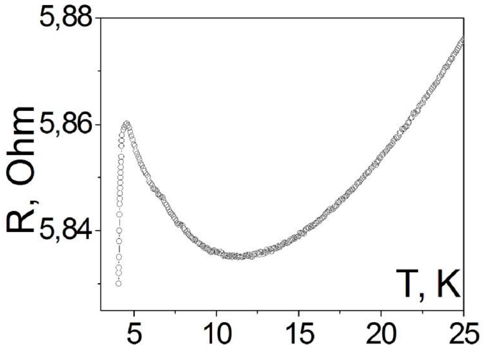


Fig. 1. The temperature dependences of the resistance for the indium antimonide whiskers of n-type conductivity: 1 – undeformed and 2 – deformed.



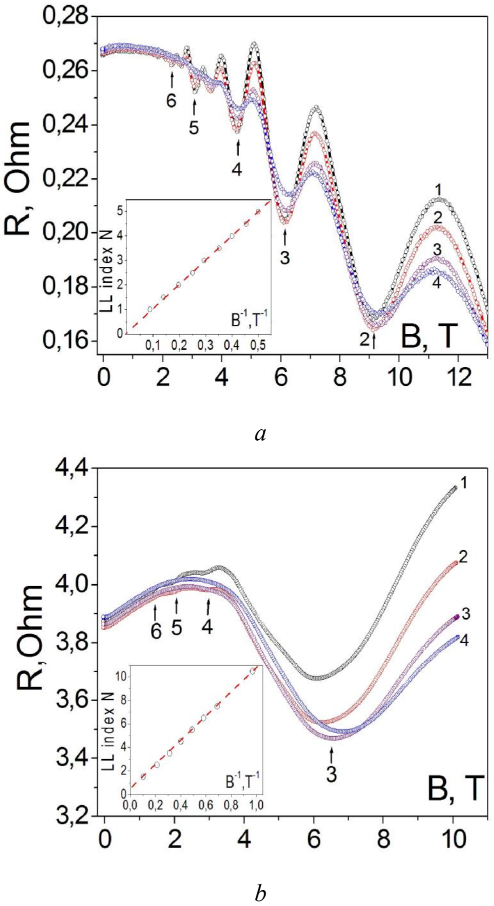
a



b

Fig. 2. The temperature dependences of the resistance for the gallium antimonide whiskers of n-type conductivity: a – undeformed; b – deformed.

In Fig. 3 and Fig. 4, respectively, the influence of deformation on the magnetoresistance for the indium antimonide and gallium antimonide whiskers of n-type conductivity in the range of magnetic fields 0–14 T was observed. The Shubnikov-de Haas oscillations are revealed on the field dependences of magnetoresistance for the undeformed and deformed indium antimonide and gallium antimonide whiskers at the fixed temperatures from 4.2 to 40 K in the whole range of magnetic fields. The peaks of the magnetoresistance correspond to the transitions between the Landau levels with the number N = 1, 2, 3, … Arrows in Fig. 3 and Fig. 4 show the number of magnetoresistance minimum values. The number of magnetoresistance minimum values for the indium antimonide and gallium antimonide whiskers doesn't change under the influence of deformation. The amplitude of the minimum values of magnetoresistance oscillations decreases with temperature increasing for the undeformed and deformed samples.

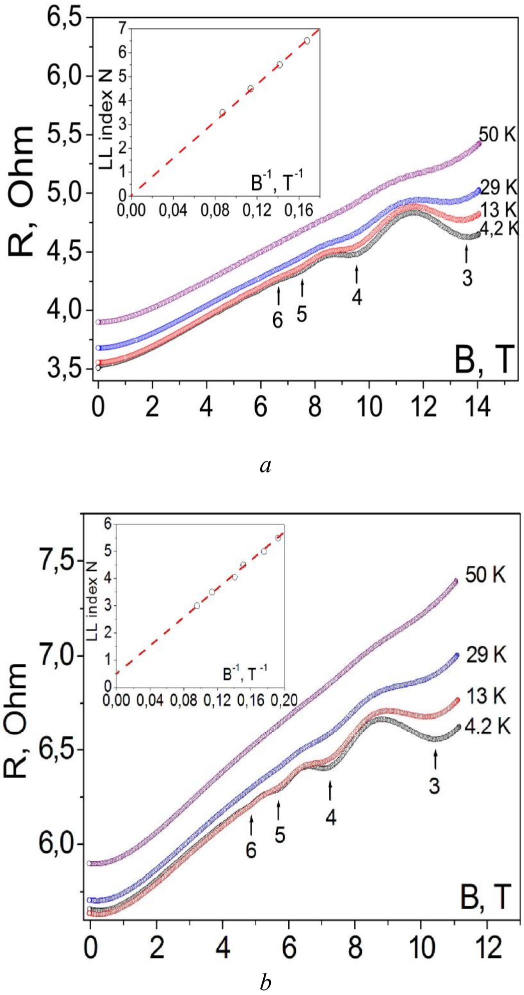


a

b

Fig. 3. Field dependences of magnetoresistance for a – undeformed and b – deformed indium antimonide whiskers of n-type conductivity at temperature, K: 4.2; 13; 29; 50. Insets: Landau level index number N of the Shubnikov-de Haas oscillation versus opposite magnetic field (1/B).

The index numbers of the Landau level for the Shubnikov-de Haas magnetoresistance oscillations as opposite to the reverse magnetic field were shown for undeformed and deformed indium antimonide whiskers in the insets in Fig. 3, *a* and Fig. 3, *b*, respectively. For gallium antimonide samples they were presented in the insets in Fig. 4. It can be seen that data points coincide with straight lines in the insets in Fig. 3 and Fig. 4. The linear fits are represented as the solid lines. The intercept of the linear fits with the axis of index number N yield zero phase β = 0 for the magnetoresistance of the undeformed indium antimonide and gallium antimonide whiskers (see Fig. 3, *a* and Fig. 4, *a*, respectively). These behaviour of the Landau fan diagrams indicate the classical transport of the charge carriers which are responsible for the Shubnikov-de Haas magnetoresistance oscillations. Therefore, the Berry phases of the magnetoresistance dependencies were absent in the undeformed indium antimonide and gallium antimonide whiskers. The Landau fan diagrams for the field dependences of magnetoresistance of the gallium antimonide whiskers with different doping concentration were also built according to the technique [24] in the authors' previous work [20]. The similar behaviour of the fan diagrams for the underformed samples are presented by the authors in [20].



a

b

Fig. 4. Field dependences of magnetoresistance for a – undeformed and b – deformed the n-type conductivity gallium antimonide whiskers at different fixed temperatures. Insets: Landau level index number N of the Shubnikov-de Haas oscillation versus opposite magnetic field (1/B).

However, for the magnetoresistance dependencies of the deformed indium antimonide and gallium antimonide whiskers the phases $\beta = ½$ are obtained and shown in Fig. 3, *b* and Fig. 4, *b*, respectively. Therefore, the appearence of the Berry phase of magnetoresistance was also found in the deformed samples with doping concentration in the vicinity to MIT, it being connected to the strong spin-orbit interaction [11].

The Berry phases were shown in the field dependencies of magnetoresistance in deformed indium antimonide and gallium antimonide whiskers with doping concentration removed into the metal side of the MIT (Fig. 3, *b* and Fig. 4, *b*). The appearance of the Berry phase can be explained as the influence of deformation shifts of the samples to the MIT.

The phase factor of the Shubnikov-de Haas oscillation can be described by the Lifshitz-Kosevich equation [28]:

$$\frac{\Delta\rho}{\rho} = R\left(B,T\right)\times\cos\left[2\pi\left(\frac{F}{B}+\gamma-\delta\right)\right] \tag{1}$$

where $R(B,T)$ has hyperbolic and exponential terms describing temperature and field damping of amplitude for the Shubnikov-de Haas oscillations, F is the frequency of the Shubnikov-de Haas oscillations in 1/B terms, $\gamma = \frac{1}{2} - \frac{\beta}{2\pi}$ is associated with the Berry phase divided by 2π. The Berry phase $\beta = 0$ is connected with a trivial case corresponding to undeformed samples of the magnetoresistance oscillations in the indium antimonide and gallium antimonide whiskers. The deviation from these values to $\beta = 1/2$ indicates the existence of the Dirac particle [29]. The shift of the phase δ is determined due to the Fermi surface dimensionality; value 0 corresponds to the 2D case and value 1/8 corresponds to 3D one [30]. The Landau fan diagrams for the deformed samples of indium antimonide and gallium antimonide (see Fig. 3, *b* and Fig. 4, *b*) show that $\beta = 1/2$. Therefore, the additional phase shift δ equals zero and is connected with the 2D electron transport in the deformed indium antimonide and gallium antimonide whiskers due to their core-shell structure [20], which also was described for nanowires based on indium and gallium in work [21].

Therefore, the appearance of the Berry phase in the studied deformed indium antimonide and gallium antimonide whiskers with doping concentration in the vicinity to the MIT corresponds to the transition into the state of a topological insulator.

4. Conclusions

The low temperature magnetoresistance effect of the indium antimonide and gallium antimonide whiskers with the doping concentration in the vicinity to the MIT from the metal side of transition was studied in the range of magnetic fields 0–10 T.

The deformation influence on the character of the temperature dependences of resistance and the field dependences of magnetoresistance for the studied samples was shown at temperatures 4.2–30 K. The Shubnikov-de Haas oscillations were found on the field dependences of magnetoresistance for undeformed and deformed samples in the whole range of magnetic fields. The amplitude of magnetoresistance oscillation minimum peaks decreases with the temperature increasing for indium antimonide and gallium antimonide whiskers under deformation and without it.

The deformation induced near to the MIT in the dielectric side of the transition was found on the temperature dependences of resistance of the gallium antimonide whiskers at temperature about 12 K, allowing their application to creating the valve switches.

The appearance of the Berry phase of the magnetoresistance dependences was found in the deformed indium antimonide and gallium antimonide whiskers with doping concentration corresponding to the vicinity to the MIT. The existence of the Berry phase was determined due to the strong spin-orbital interaction of charge carriers, which confirms the two-dimensional nature of electron transport in the deformed indium antimonide and gallium antimonide samples and their transition to a topological insulator state.

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ПОЯВА БЕРРІ ФАЗИ У ДЕФОРМОВАНИХ НИТКОВИДНИХ КРИСТАЛІВ АНТИМОНІДУ ГАЛІЮ

Анатолій Дружинін, Ігор Островський,
Юрій Ховерко, Наталія Лях-Кагуй

Вплив деформації на магніторезистивні властивості нитковидних кристалів (віскерсів) з антимоніду індію та антимоніду галію n-типу провідності та із різними домішками поруч із переходом «метал-діелектрик» досліджено у діапазоні температур 4,2–50 К та магнітному полі 0–14 Т. Осциляції Шубнікова – Де Гааза в усьому діапазоні індукції магнітного поля показано у деформованих та недеформованих віскерсах. Амплітуда магніторезистивних осциляцій для зразків обох типів зменшується із зростанням температури. Було визначено наявність фази Беррі за низьких температур у віскерсах з антимоніду індію та антимоніду галію, яка демонструє їхній перехід у стан топологічних діелектриків.

Anatoliy Druzhynin – D. Sc., professor, Head of the Department of Semiconductor Electronics at the Institute of Telecommunications, Radio-electronics and Electronic Engineering, Lviv Polytechnic National University, Ukraine.

He is also the winner of Ukrainian State Prize in Science and Technology (2011), Honored Worker of Science and Technology of Ukraine. The main scientific activities of prof. A. Druzhynin include: theoretical and experimental study of strain-induced effects in silicon, germanium and their solid solutions whiskers. Prof. Druzhynin has authored more than 140 scientific publications indexed in scientometric databases in Scopus and Web of Science and more than 50 inventor's certificates and patents. Under his supervision 6 doctors and 11 candidates in technical science were graduated.

Ihor Ostrovskyy – D. Sc., professor, professor of the Department of Semiconductor Electronics at the Institute of Telecommunications, Radio-electronics and Electronic Engineering, Lviv Polytechnic National University, Ukraine.

The main scientific activities of prof. I. Ostrovskyy include: theoretical and experimental study of strain-induced effects in silicon, germanium and their solid solution whiskers. Prof. Ostrovskyy has authored more than 400 scientific papers including more than 20 inventor's certificates and patents.

Yuriy Khoverko – D. Sc., professor, professor of the Department of Semiconductor Electronics of the Lviv Polytechnic National University. Research interests cover the physics and technology of semiconductor devices, micro-and nanoelectronic structures and sensor electronics.

Research findings are published in more than 200 scientific papers and and more than 10 patents by Ukraine.

Natalia Liakh-Kaguy – D. Sc., senjor researcher of the Department of Semiconductor Electronics at the Institute of Telecommunications, Radio-electronics and Electronic Engineering, Lviv Polytechnic National University, Ukraine. Researcher has authored more than 100 scientific papers including 10 patents by Ukraine.