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Magnetoresistance of Bi_2Se_3 Whiskers at Low Temperatures

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Temperature dependencies of Bi_2Se_3 whiskers' resistance with Pd doping concentration of 1×10^{19} cm^{-3} where measured in temperature range 4.2 - 300 K. At temperature 5.3 K a sharp drop in the whisker resistance was found. The observed effect is likely connected with contribution of two processes such as the electron localization in the whiskers and transition in superconducting state at temperature 5.3 K, which is likely result from Pd complexes.

Transversemagnetoresistance in n-type Bi_2Se_3 whiskers with Pd doping concentration in the vicinity to themetal-insulator transition (MIT) from metal side of the transition were studied in magnetic field 0 -10 T. For the whiskers a resistance minimum was observed at temperature about 25 K that is connected with Kondo effect.

Keywords: Bi_2Se_3 whiskers; transversemagnetoresistance; effect Kondo; superconductivity

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Introduction

Nowadays, in sensor electronics silicon is a major material to create semiconductor piezoresistive mechanical sensors [1, 2]. On the basis of Si whiskers were developed various mechanical sensors [3]. However, mechanical sensors on the basis of silicon sometimes could not satisfy all of the appearing requirements due to the progress of new branches of science and technic. Therefore, it is interesting to search and study other semiconductor materials for sensors, particularly A^3B^5 compounds.

Magnetotransport properties of various semiconductor whiskers such as Si, Ge, InSb, GaSb at low temperatures have been widely studied in our previous works [4-7].

The aim of this paper is to study Bi_2Se_3 whisker's superconductivity and Kondo effect by measurement of their temperature dependence of resistance in the temperature range 4.2 - 300 K at magnetic field induction up to 10 T.

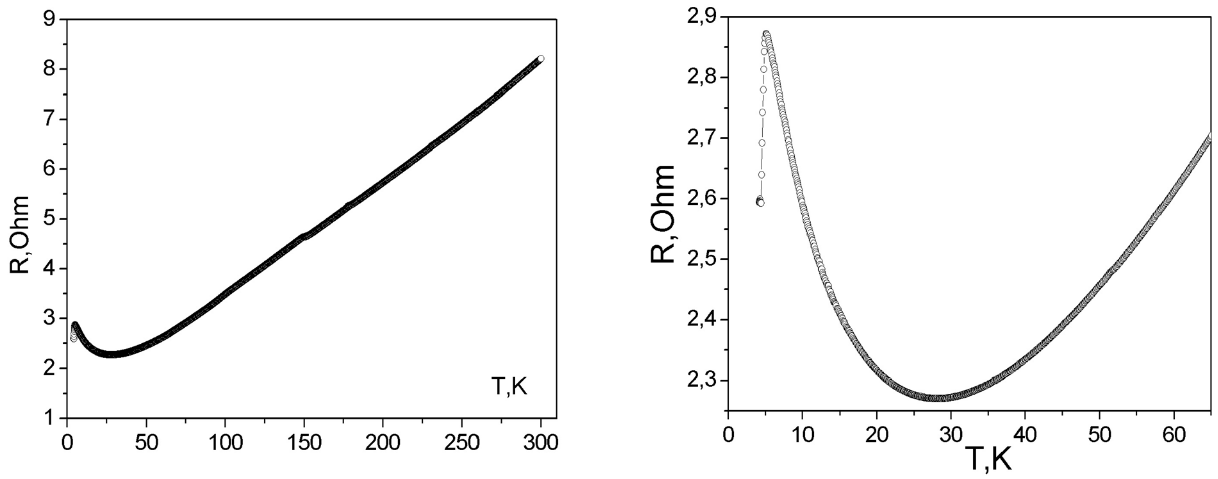
I. Experiment

N-type Bi_2Se_3 whiskers with doping Pd concentrations were selected for our studies. The microcrystals were grown by CVD method in the closed bromide system. The obtained whiskers have the diameter about 20 μm and length in the range 1-2 mm. According to the results of ion mass spectroscopy it was found Pd doping concentration in Bi_2Se_3 whiskers, which corresponds to metal side of the MIT and consists of 1×10^{19} cm^{-3}. The electrical contacts to the whiskers were created by the welding of Pt microwires with diameter 10 μmon the opposite ends of the crystals. The current contacts were ohmic according to measured I-V characteristics in the temperature range 4.2-300 K.

The temperature of liquid helium was reached with using of the helium cryostat. Bitter-magnet was applied for studying of the transversemagnetoresistance in n-type Bi_2Se_3 whiskers in the strong magnetic fields up to 10 T with deflection time of 1.75 T/min in the temperature range 4.2 - 77 K. Stabilized electrical current of 1–100 μA was generated by current source of type Keithley 224. Digital multimeters Keithley 2000 and Keithley 2010 were used for measuring of the potential contact voltage and thermocouple output signals. The accuracy reached to 1×10^{-6} V.

II. Results and discussion

Temperature dependence of resistance for Pd-doped Bi_2Se_3 whisker is shown in Fig. 1 over the temperature range 4.2 - 300 K. Reviled R(T) with monotonic decrease of the resistance from 8 to 2.5 Ohm in the temperature range 30 − 300 K corresponds to the metallic behaviour of the electric resistivity of the Bi_2Se_3 whiskers. For Bi_2Se_3whiskers a resistance minimum was observed at



a b

Fig.1. Temperature dependence of resistance for n-typeBi_2Se_3 whiskers with Pd doping concentration of 1×10^{19} cm^{-3} in temperature range: a) 4.2 - 300 K; b) 4.2 - 65 K.

temperature about 25 K, that may indicate in Kondo effect presence in the crystals. At temperatures below 5.3 K the behaviour of characteristics is significantly differs due to change of the carrier transport mechanism. Below let us consider the above effects in detail.

2.1. Superconductivity of Bi_2Se_3 whiskers.

Unexpectedly the sudden decrease of Bi_2Se_3 whiskerresistance from 2.9 to 2.6 Ohm is observed at temperature just below 5.3 K. This interesting behaviour of the resistance, namely, the sudden drop of R(T) at T ~ 5.3 K, could indicate the superconducting transition at this low temperature (Fig. 1). To be sure, firstly, it should be discussed to what extent the junction properties (welded Pt microwires) influence the measurement data at about 5K and may contribute to the observed drop in the resistance effect. To check the possible influence of Pt junctions, I-V characteristics of the whiskers were measured in the temperature range 4.2 K-300 K. The measurements have shown that I-V characteristics were linear at every fixed temperature and electrical contacts from Pt microwires remain ohmic. Thus, sudden drop in the whisker's resistance is hardly connected with influence of the Pt contacts at low temperatures.

On the other hand, the drop in resistance is very small, namely about 9.3 % and the resistance below 5.3 K is still very large in order to be interpreted as transition to the superconducting states, which expectedly is associated with a zero resistance. Nevertheless, one can suppose a presence of a small superconductive phase in the whisker. As can be seen from [8,9], Bi_2Se_3 doped with various impurities (Sr, Cu) being typical for II type superconducting state observed in the available temperature range from 2.7 K up to 3.8 K.

Thus, the partial superconducting transition of Bi_2Se_3 whisker is likely to occur at the critical temperature of about 5.3 K. Nevertheless, the reason of the superconductivity in the whiskers is not clear. The one possible reason of the transition may be Bi cluster presence at bicrystal interface, which are known to show a superconductivity up to 21 K [10]. Particularly in [11] was reported about a superconductivity in textured Bi clusters in Bi_2Te_3 films with Tc = 3.1 K. Authors of [12] observed Tc = 7.2 K and Tc = 8.3 K for Bi inclusions in polycarbonate porous materials. However, the above data does not correspond to our experimental value of Tc =5.3 K.

The most probable reason of the Bi_2Se_3 whisker superconductivity is connected with Pd doping. $PdBi_2$ complex is known to lead to superconductivity with Tc = 5.5 K in Bi_2Te_3 crystals [13]. One can suppose that inclusion of $PdBi_2$ complexes in Bi_2Se_3 whisker may call a superconductivity with Tc= 5.3 K. The microprobe analysis has shown a presence of Pd impurities with concentration of about 10^{19} cm^{-3}. The microprobe analysis gives information from the whisker surface and subsurface layers up to depth of about 1 μm. However, it is difficult to say about a configuration of Pd complexes in this region. Next XRD investigations are needed to establish a nature of Pd complex in the whiskers.

2.2. Kondo effect in Bi_2Se_3 whiskers.

Suppression of superconductivity by magnetic field is also informative for explanation its possible origin. In order to observe the influence of magnetic field on the resistivity drop below 5.3 K, one has to investigate the Bi_2Se_3 whiskers magnetoresistance $R_B(T)$. Transverse magnetoresistance of n-type Bi_2Se_3 whiskers was studied in the temperature range 4.2 – 77 K and magnetic fields 0 – 10 T. Results of these investigations for Bi_2Se_3 whiskers with Pd doping concentration 1×10^{19} cm^{-3}, which corresponds to metallic side of the metal-insulator transition, are presented in Fig. 2.

Peculiarities observed on the temperature dependences of resistance in Bi_2Se_3 whiskers with clearly minimum at low temperatures of about 25-30 K (Fig. 1, b) could be explained by Kondo effect.

Taking into account the typical finding on Kondo physics, the dominant role plays exchange interaction between magnetic moments of intrinsic 3d electron localized on magnetic impurities and free charge carriers. One can assume that the similar anomalies of the

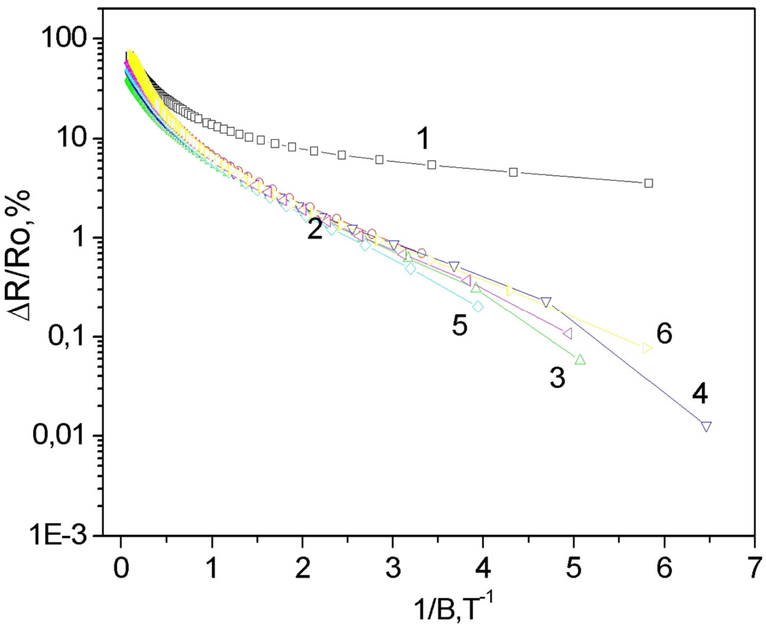


Fig. 2. Transverse magnetoresistance of n-typeBi_2Se_3 whisker at different temperatures: 1 - 4.2 K, 2 – 13 K, 3 – 29 K, 4 – 40 K, 5 – 50 K, 6 – 60 K.

temperature dependence of the resistance may occur in semiconductors doped with non-magnetic impurities to the concentration correspondent to MIT [14]. Then exchange interaction takes place between magnetic moments of twice occupied by charge carrier impurities and free charge carriers. Such Kondo effect was observed in heavily doped with boron Si-Ge whiskers that have no any magnetic impurities [15]. Now we observed the similar effect in n-type conductivity for Bi_2Se_3 whiskers with concentration near the MIT.

Studied properties of doped Bi_2Se_3 whiskers at low temperatures and high magnetic fields allow to design the sensitive sensor of temperature (Fig. 1) and magnetic field induction (Fig. 2) operated in the temperature range 30-300 K. The sensor sensitivity to measurement of temperature consists of 0.1 K, while the sensitivity to magnetic field induction measurement is about 0.05 T. The main advantages of the sensor are miniature dimensions as well as high radiation stability, which allow to use the sensor in harsh conditions.

III. Conclusions

Temperature dependences of the resistance in n-type Bi_2Se_3 whiskers with Pd impurity concentration in the vicinity to the MIT from metal side of the transition were studied in the temperature range 4.2 – 300 K.The peculiarities of whisker resistance such as sharp drop at low temperature range below 5.3 K were observed for BiSe whiskers with various doping concentrations, which could be explained by partial superconductivity of the whiskers. The most probable reason of the Bi_2Se_3 whisker superconductivity is connected with Pd doping. $PdBi_2$ complexes are likely existed in the whisker surface and lead to superconductivity with Tc = 5.3 K. XRD investigations are needed for further deepening a nature of the observed superconductivity in the whiskers.

For Bi_2Se_3whiskers a resistance minimum was observed at temperature about 25 K, that may indicate in Kondo effect presence in the crystals. The effect is connected with exchange interaction between magnetic moments of twice occupied by charge carrier impurities and free charge carriers and occurs only at certain impurity concentration at the vicinity to MIT.

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Магнетоопір ниткоподібних кристалів Bi_2Se_3 при низьких температурах

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Досліджено температурні залежності опору ниткоподібних кристалів Bi_2Se_3 легованих Pd до концентрації 10^{19} см$^{-3}$ в діапазоні температур 4,2 - 300 К. Виявлено різке падіння опору кристалів при температурі 5,3 К. Спостережуваний ефект, ймовірно, пов'язаний із внеском двох ефектів, таких як локалізація електронів у ниткоподібних кристалах та перехід в надпровідний стан при температурі 5,3 К, що, ймовірно, є результатом присутності комплексів домішки Pd.

Було вивчено поперечний магнетоопір ниткоподібних кристалів Bi_2Se_3 n-типу провідності з концентрацією домішки Pd, що відповідає близькості до переходу метал-діелектрик з металевого боку в магнітному полі 0 - 10 Тл. При температурі 25 К спостерігається мінімум на температурній залежності опору, що пов'язано із проявом ефекту Кондо.

Ключові слова: ниткоподібні кристали Bi_2Se_3; поперечний магнетоопір; ефект Кондо; надпровідність.