Electrical And Thermoelectric Properties Of Semiconducting $Bi_{1-X}Sb_x$ Nanowires

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***Abstract* — In this paper we shall present the results obtained with measurements of transport effects in semiconducting $Bi_{1-x}Sb_x$ single crystal wires in glass cover, prepared by liquid phase casting, using the improved Ulitovsky method. The measurement included the electrical resistivity, Seebeck coefficient as functions of temperature, magnetic field and diameter wires. The wires diameters ranging from 100 nm to 1000 nm. The data were taken between 1.5- 300 K in magnetic field up to 15 T. The temperature dependences resistance R(T) and thermopower show the significant dependences on the wire diameters in low temperature region. We observed the quantum oscillations only in thin Bi-17at%Sb wires in longitudinal and transverse directions. In the thin (200 nm) Bi-17%Sb wires a sharp deviation from exponential temperature behavior resistance R(T) characteristic of bulk semiconductor is observed. The results are discussed in the context of the state the topological insulator and the influence of the surface state on the electronic properties of semiconducting $Bi_{1-x}Sb_x$ nanowires.**

***Index Terms* — nanowires, topological insulator, surface state, confinement effect.**

I. NTRODUCTION

Topological insulator represent another class of states that are topologically distinct from simple band insulators. They are symmetric under time reversal, and can therefore be realized experimentally without magnetic field.

It is known that $Bi_{1-x}Sb_x$ alloys demonstrated the topological nature of surface state. The surface states of pure Bi and Sb have been intensively studied experimentally and theoretically [1-5].

The semiconducting alloy of Bi and Sb is an example of 3D topological insulator [1, 3]. Authors [1, 3] developed a theory to analyze the topological nature of the surface state in $Bi_{1-x}Sb_x$ alloy. The first 3D topological insulator to be identified experimentally was the semiconducting alloy $Bi_{1-x}Sb_x$, whose unusual surface bands were mapped in an angle- resolved photo emission spectroscopy (ARPES). In work a systematic study of the surface state of $Bi_{1-x}Sb_x$ alloy on quantitative first – principles calculation. However, clear discrepancies exist between the theory and the experiment about the surface state [3].

At Sb concentration ($0< x< 0.2$), alloys $Bi_{1-x}Sb_x$ is a semiconductor with an inverted band spectrum [6]. In nanowires with an inverted spectrum, a topological insulator (TI) state occurs; it is a novel state of quantum matter.

The demonstrating the enhancement of the thermopower (Seebeck coefficient) in quantum wires is a subject of intense investigations both theoretical and experimental [4, 5, 7, 8]. Bi and $Bi_{1-x}Sb_x$ nanowires are particularly interesting because Bi are a good thermoelectric due to its low carrier effective mass and its high atomic mass.

Bismuth antimony alloys have long been studied for their thermoelectric properties [9]. Substituting bismuth with antimony changes the critical energies of the band structure. At an Sb concentration of $x\approx 0.04$, the gap Δ between L_c and L_u closes and gap less state is realized. As x is further increased this gap reopens with an inverted ordering. For $x> 0.07$ the top of the valence band at T moves below the bottom of the conduction. At $x\sim 0.09$ the material is a direct gap semiconductor.

Bulk $Bi_{1-x}Sb_x$ is semiconducting for $0.08< x<< 0.22$, with a maximum band gap at $x= 0.17$ and displays its best TE performance in this range [10].

Single crystal $Bi_{1-x}Sb_x$ nanowires in glass cover are the most suitable object for studied of the influence dimensional and surface state on electron transport and thermoelectric properties.

II. SAMPLES

Individual monocrystalline Bi-17at%Sb nanowires in glass capillary with diameter 100 nm – 1000 μm were prepared by liquid phase casting, using the improved Ulitovsky methods [11, 12]. The drop- temperature in glass (Pyrex) capillary was 1100° C and material $Bi_{1-x}Sb_x$ before with owning intensive stirring by high- frequency 880 kHz electromagnetic field the whole technological process in carrier out in the argon atmosphere. Multiple horizontal zone recrystallization of the nanowires was used for the homogenization and to improve their structural perfection.

According X-ray diffraction the Bi-17at%Sb wires are single crystal and have cleavage (111) forming in the angle 19.5° to the sample axes.

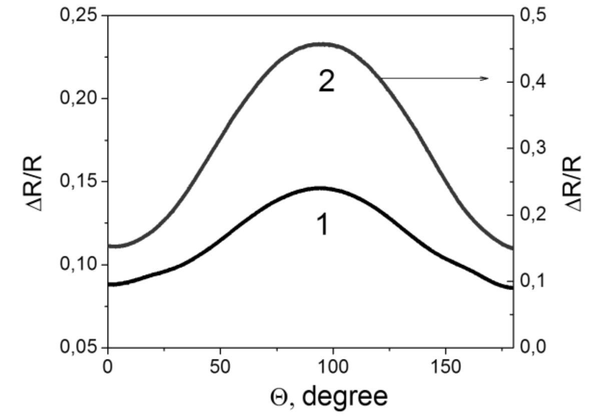

Fig.1 Rotation angular diagrams of the transverse residual magnetoresistance ΔR/R(θ) of Bi-17at%Sb wires at T= 77 K, $H_{\perp}$=0.4 T: 1. d= 200 nm, 2. d= 900 nm.

The fact that the Bi-17at%Sb wires with different diameters have the same orientation was verified by the rotation angular diagrams of transverse magnetoresistance (Fig. 1). We observed decrease in the anisotropy of the magnetoresistance with decreasing of the wire diameter d.

III. RESULTS AND DISCUSSION

The temperature dependences of electrical resistivities between 1.5-300 K of a series Bi-17at%Sb wires are shown in Figure 2. It is seen that at region at the room temperature the difference in the resistivities various diameters wires is small. At 77 – 100 K the difference is very pronounced. The change in R(T) with diameter is more clearly reflected in the low temperature (4.2 K). For the wires with different diameters, the resistivity tend to increase with decreasing temperature indicating that these wires are semiconductors hawing narrow band gaps. But the behavior of the R(T) in the range 300 – 120 K and 120 – 4.2 K is different for wires with different diameters.

We have calculated the thermal energy gaps from the temperature dependence of resistivity with an assumption that the resistivity fallows an exponential low:

$$\rho = \rho_0 exp\left(\frac{E_g}{2\kappa T}\right), \quad (1)$$

were ρ_0 is a const= 170 Ohm*cm, and E_g is the band gap. The results are shown on Figure 2 (inset). The present data indicates that ΔE_g weakly increases with decreasing diameter, and ΔE_g = 19±1 meV, as compared with values at bulk composition between 12-18at%Sb reported in papers [15, 16]. At T< 100 K character of the dependences R(T) significantly dependences from diameter wires d.

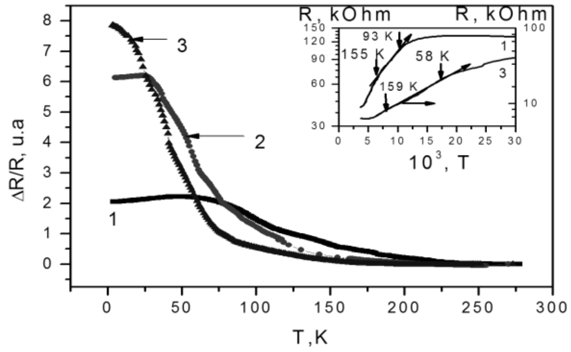

Fig.2 Temperature dependence residual resistances ΔR/R(T) of Bi-17at%Sb wires with different diameters: 1. d=200 nm, 2. d=600 nm, 3. d= 900 nm. Inset: the dependence R from 10^3/T.

At low temperatures in the thin wires d= 200 nm (Fig. 2, curve 1) a sharp deviation from exponential temperature behavior resistance R(T) is observed. With decreasing diameter of the wires deviation from the exponential dependence of R(T) occurs at higher temperatures and the dependence R(T) for the wire Bi-17at% Sb with d= 200 nm similar to dependence R (T) semimetallic wires of pure Bi with d< 100 nm and semimetallic $Bi_{1-x}Sb_x$ wires with d< 300 nm [12,13,14].

In order to explain the experimental results of R(T) shown in Figure 1, we need to take the surface state into account. According to the this deviation correspond to a considerable influence of a metalized well conducting near surface layer formed from the surface states arising through a spin- orbital Rashba interaction in nanowires. We measure the field dependences resistance R(H) at 1.5-4.2 K and observed quantum oscillations only in thin Bi-15at%Sb wires in longitudinal and transverse directions. This fact indicates a essential contribution of surface states in electron transport a semiconducting $Bi_{1-x}Sb_x$ nanowires.

The Seebeck coefficients (thermopower) of Bi-17at%Sb wires along the wire axis are shown as a function of temperature in Figure 3.

For all wires the thermopower are negative in all temperature region. It may be seen that the thermopower α the absolute value of which increases with decreasing temperature from 100 μV/K to about ~ 160 μV/K in area 40-120 K and then decreases again with decreasing temperature up to 4.2 K. By contraыt, the thin Bi and semimetal $Bi_{1-x}Sb_x$ wires changes its sign from negative to positive formed the positive polarity peak at low temperatures(20-50 K) [13, 14].

We calculated the Power factor P.f.= $\alpha^2\sigma$, and its temperature dependence for all the wires used diameters, using date Fig. 2 and Fig. 3. The P.f. is shown as a function of temperature in Figure 3 (inset).

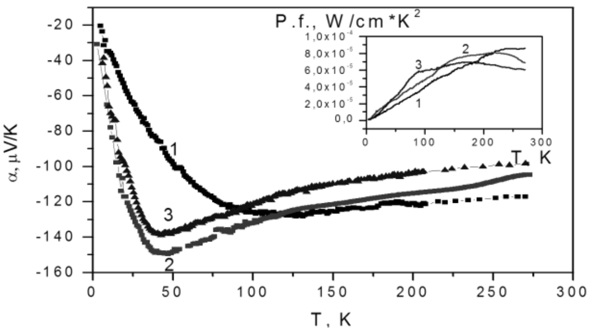

Fig. 3 Temperature dependence thermopower $\alpha(T)$ of Bi-17at%Sb wires with different diameters: 1. d= 200 nm, 2. d= 600 nm, 3. d= 900 nm. Inset: temperature dependences P.f.= $\alpha^2\sigma(T)$.

It should be mentioned that using combination semimetallic $Bi_{1-x}Sb_x$ wires and semiconducting Bi-17at%Sb nanowires it has been possible to obtain n- type and p- type legs in thermoelectric device at low (30- 50 K) temperatures and a maximum TE cooling at 40- 50 K.

IV. CONCLUSION

The electrical resistivity, thermopower and magneto-resistivity has been measured with different diameter semiconducting Bi-17at%Sb nanowires in glass cover in the temperature range 1.5- 300 K in magnetic fields up to 14 T, along the wire axis.

From these date, the thermoelectric Power factor have been calculated.

The interval temperatures in which investigated wires can be used as n-type legs in thermoelectric energy converters has been defined.

It is established that temperature dependence of the resistance R(T) of thin wires $Bi_{1-x}Sb_x$ exhibit the properties of topological insulators.

A considerable influence in electron transport a semiconducting Bi-17at%Sb wires of a metalized well conducting near surface layers was established.

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