Giant magnetoresistance and magnetothermopower in single-crystal $Bi_{1-x}Sb_x$ wires.

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***Abstract* — A signicative increase in the transverse magnetoresistance and magnetothermopower in single-crystal $Bi_{1-x}Sb_x$ wires obtained by liquid phase casting in the temperature range 80-100 K is found. A shift to the range of lower (T < 80 K) or higher (T > 100 K) temperatures leads to the suppression of the giant increase in the magnetoresistance. The effect is interpreted in terms of the substance transition to the "gapless state". According to the theoretical analysis of, the disappearance of the energy gap between the bands Eg is accompanied by a significant increase in mobility that leads to a sharp increase in the magnetoresistance; herein, the gapless state corresponds to the mobility maximum. While moving from the state with Eg = 0, the mobility decreases.**

***Index Terms* — magnetoresistance, thermopower, nanowire, gapless state, magnetic field.**

I. INTRODUCTION

Giant magnetoresistance is a subject of many researches in various nanostructures due to their unique physics and important applications [1-9]. In bismuth, the magnetoresistance value is determined by the relation $\omega\tau >> 1$, where the cyclotron frequency $\omega = eH^2 / m^* c$, τ is the scattering time of carriers, and m is their effective mass.

Therefore, an increase in the mobility is an important condition for an increase in magnetoresistance. Bismuth and alloys on its basis are of interest in the applied aspect because they are not magnetic and, hence, magnetoresistance has no hysteresis in strong magnetic fields.

It is known that narrow-gap semiconductors are widely applied in engineering; in some cases, due to specific features of their band structure, it appears almost impossible to replace them, in particular, for the design of operating components of thermoelectric, thermomagnetic, and anisotropic energy converters. Predicted significant increase in thermoelectric efficiency of nanostructures based on $Bi_{1-x}Sb_x$ contributes to the development of preparation procedures and to the study of $Bi_{1-x}Sb_x$-based nanowires[10,11].

The possibility to transform narrow-gap materials into the gapless state, which qualitatively differs from the semiconductor and metallic phases in many respects, is of considerable interest both for solid state physics and for practical applications.

It should be noted that the dependences for a gapless semiconductor differ in their form from analogous dependences for all known substances: semiconductors, metals, and superconductors. Therefore, according to its properties, a gapless semiconductor is a crucially new type of substance.

In bismuth and in bismuth-stibium alloys, by changing stibium concentration, pressure, or by strong magnetic field, it is possible to vary the energy gap over a wide range and to achieve the situation when the energy gap disappears completely and the conduction L-band is in contact with the valence T-band. At certain critical pressure p_k, which is often called the band inversion pressure, the energy gap E_g between them vanishes; that is, the gapless state appears. Further increase in pressure leads to the appearance of a saddle point in the spectrum of electrons and holes.

As one of the interesting specific features of the transition of a substance into the gapless state, we should mention the increase in current carrier mobility, which is a characteristic that shows to what extent the carrier velocity in the electric field of a specified intensity varies.

The theoretical analysis made by A.A. Abrikosov [12] shows that the disappearance of the energy gap between the bands, E_g, is accompanied by a significant increase in mobility; herein, the gapless state corresponds to the mobility maximum; while moving from the state with $E_g=0$ the current mobility decreases.

Study of gapless semiconductors and gapless state, in particular, in bismuth-stibium alloys, is not exclusively of scientific concern. Exhibiting a number of specific properties, gapless semiconductors are promising materials for various engineering applications. First of all, we should mention the design of high-efficiency solid-state refrigerators whose operation is based on thermomagnetic and thermoelectric effects.

However, it is rather difficult to obtain such a compound with definitely specified composition and degree of doping. Single-crystal wires of Bi and $Bi_{1-x}Sb_x$ in glass isolation obtained by the liquid phase casting by the

Ulitovsky method with diameters 0.5-5 μm are the most appropriate material for that sort of research.

The aim of the present work was to study specific features of the resistance and thermopower of $Bi_{1-x}Sb_x$ wires near the gapless state as a function of temperature, magnetic field, and wire diameter.

II. SAMPLES AND EXPERIMENT TECHNIQUE

Glass-coated single-crystal wires of bismuth 6at%Sb with various diameters (0.2-5 μm) were obtained by the liquid phase casting by the Ulitovsky method [13,14]. The orientation of wires were conferment by means of angular rotation diagrams of transverse magnetoresistance. All the measured wires had the same orientation. The long axis of the wires C_s made an angle ~ 19˚ with bisector axis C_1 in bisector trigonal plane. The magnetic field – dependent resistance R(H) and magnetothermopower α(H) in a magnetic field up to 14 T was meansered in the temperature range 9 – 300 K in a Bitter – type magnet in the International High Magnetic Field laboratory [10] (Poland, Wroclaw).

III. RESULT AND DISCUSSION

Figure 1 shows temperature dependences of the resistance (a) and the thermopower (b) of Bi-6at%Sb wires with different diameters.

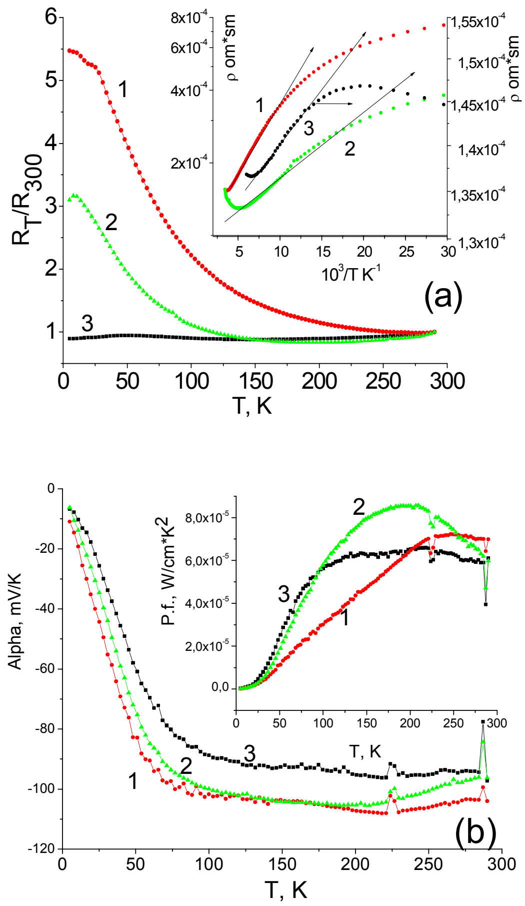


Fig. 1. Temperature dependences of the resistance (a) and thermopower (b). Inset dependences ρ(10^3/T) (a) and power factor (b) of nanowires $Bi_{0.94}Sb_{0.06}$ different diameter: 1 – 0.5 μm, ΔE_g=14 mev; 2 – 1.0 μm, ΔE_g=9mev; 3 – 4.5 μm, ΔE_g=6mev.

Dedpenence of kinetic coefficients on wire diameter is observed, particularly, in the low-temperature range, which is attributed to the manifestation of the classical size effect. In the dependences ρ(1/T) (the inset in Fig. 1a), exponential regions are observed. The thermal gap values which are calculated from temperature dependences of resistivity for wires with different diameters (the inset in Fig. 1a) show that an increase in the diameter leads to an increase in the gap. However, since the exponential regions take place in a narrow temperature range, the band gap determined by the dependence ρ(1/T) is estimative.

The thermopower is negative in the whole range of temperatures and diameters under study (Fig. 1b). The specific feature of the α(T) dependences is that in the range 300-90 K the thermopower hardly depends on temperature at all; it amounts to 100 μv/K ± 10 μv/K.. The decrease in the thermopower at diameters <1μm is attributed to the influence of surface scattering on path length of the most mobile charge carriers—electrons—that determine sign and value of thermopower. Temperature dependence of the power factor p.f.=$\alpha^2\sigma$, where α is the thermopower and σ is the resistivity, is depicted in Fig. 1b (the inset).

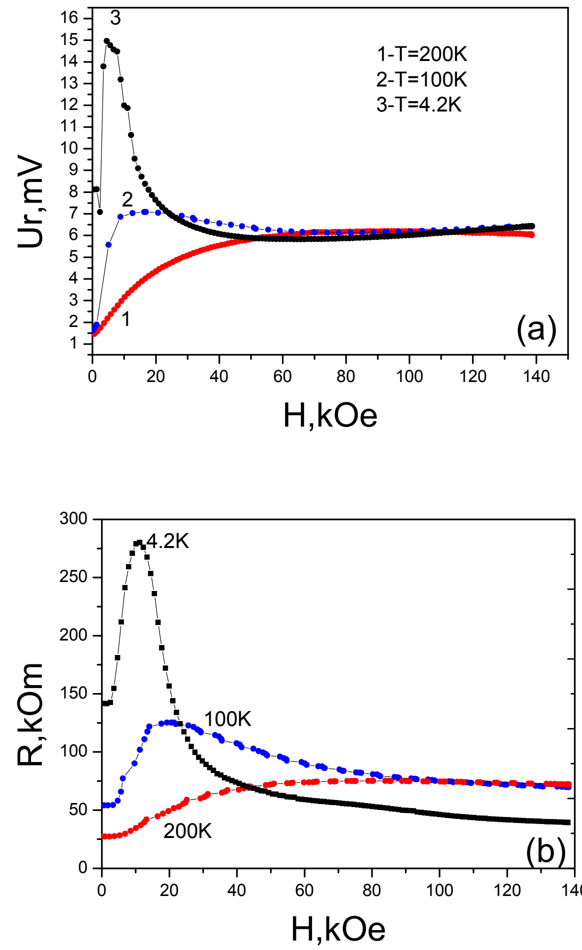
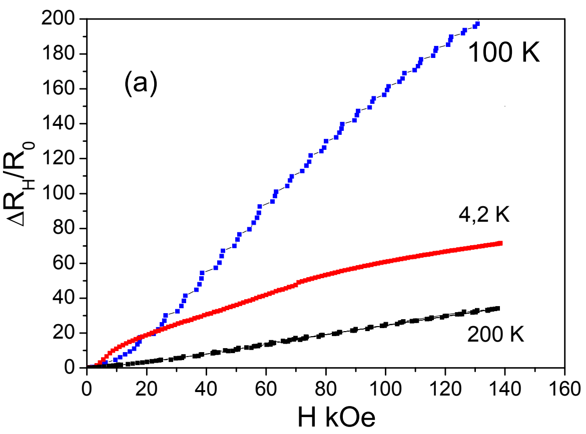


Fig. 2. Field dependences of longitudinal magnetoresistance of a $Bi_{0.94}Sb_{0.06}$ wire (d =4.5 μm (a), and d= 0.5 μm (b)) at different temperatures: 1 – 200 K; 2 – 100 K; 3 – 4.2 K

Figure 2 depicts field dependences of the longitudinal magnetoresistance of a Bi-6%Sb wire (d = 4.5 μm) at different temperatures. The fact comes under notice that, in the magnetic field range H > 50 kOe, the magnetoresistance hardly depends on temperature for wires with a diameter of 4.5 μm.

In a perpendicular magnetic field, (H ⊥ I) (fig 3a) a sharp square-law increase in the magnetoresistance is observed in weak magnetic fields; afterwards, at temperatures of 200 and 4.2 K, a weak increase in the magnetoresistance occurs. At a temperature of ~100 K a significant increase in the magnetoresistance R(H) (up to 20 000% at H = 14 T) is observed.



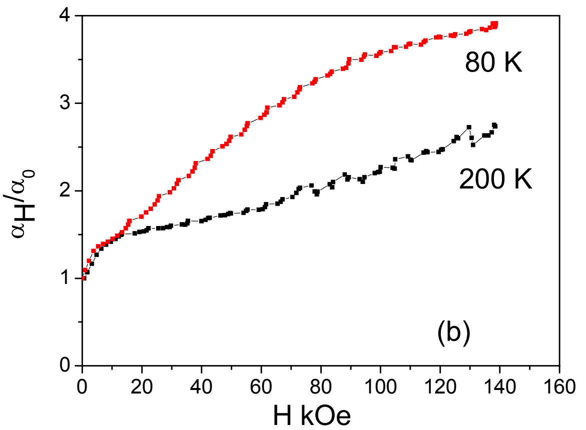


Fig. 3. Field dependences of transverse magnetoresistance (a) and thermopower (b) of a Bi-6%Sb wire (d = 4.5 μm) at temperatures (a): 1 – 200 K; 2 – 100 K; 3 – 4.2 K (b): 1 – 200 K; 2 – 80 K.

A shift toward lower (T < 80 K) and higher (T > 100 K) temperatures leads to the suppression of a giant increase in the magnetoresistance. In the range 90-100 K the thermopower increases by a factor of 4, achieving a value of 400-450 μv/K (Fig. 2b). The effect is interpreted in terms of the substance transition into the gapless state.

However, under studying TMR of wires and bulk samples of Bi, conformity of the magnetoresistance increase with decreasing temperature takes place. In addition, a conformity of linear increase in the magnetoresistance on wire diameter d [18] in the temperature range <70 K was found in pure bismuth wires.

Since the effective energy gap ΔEg in Bi-6at%Sb wires is approximately 6-10 meV, the “gapless” state will occur in the range 60-100 K, leading to an increase in the mobilities. As the temperature increases, due to smearing of kT, there occurs the “shift” from the gapless state into the “metallic range”; as the temperature decreases <60 K, the “shift” from the gapless state into the “semiconductor range” takes place.

Thus, studying the effect of transverse magnetoresistance on temperature and composition of Bi1-xSbx wire alloys, one can distinguish regions of maximum increase in the mobilities that leads to a significant increase in the magnetoresistance in certain temperature ranges, which is of interest for practical use of these wires for sensing magnetic fields.

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