Giant Quantum Oscillations of the Seebeck Coefficient in Magnetic Field at the Electron Topological Transition of Quantum Wires Bi- Te induced by Stretch

A.A. Nikolaeva, * [1,3], D.V. Gitsu [1], T.E. Huber [3] , Bodiul.P.P.1 [1]
O.Botnary [1]
[1] Institute of Applied Physics, Academy of Sciences, str. Academiei 5, Kishinau, MD-2028, Moldova,
[2]Department of Chemistry, Howard University, 525 College St., N.W., Washington, DC 20059
[3] International Laboratory of High Magnetic Fields and Low Temperatures, Wroclaw, Poland

Abstract

The temperature dependences of thermopower and resistance Te-doping Bi-wire were investigated at electron topological transitions (ETT) induced by stretch in the temperature interval 4.2-300 K and magnetic fields up to 14T. Single Bi, Bi<Te> wires were obtained by the liquid phase casting by the Ulitovsky method. They were mono crystals of strictly cylindrical form in a glass cover with orientation <1011> along the wire axis. In thin wires of Bi doped with Te a number of anomalies were found out at ETT, of the type of formation of new Fermi surface cavity (T-hole) induced by extension. The "giant" oscillations of the thermopower in magnetic field and singularities in deformation curves of thermopower and resistance may be referred to these anomalies. In general they give evidence that the interband scattering of carriers plays the decisive role in wires of Bi and Te-doped Bi-wires in the low temperature .

Introduction

In nanowires on the basis of Bi and its alloys a number of specific, unique effects were displaced, Aharonov – Bohm [1] and confinement effects [2], appearance of spherical Fermi surface [3], effects of localization and diffusion electron interaction [4], etc., whose investigation at electronic-topological transitions (ETT) seems to be very topical. Recently great attention is paid to Bi-based nanowires. A significant figure of merit $Z=\alpha^2\sigma/\kappa$ (α is the thermopower, σ is the conductivity, κ is the thermal conductivity) increasing was predicted due to size-quantization of the energy spectrum of carriers and semimetal – semiconductor transition which is a particular case of ETT [5,6].

Research of abnormal kinetic properties on Bi and its alloys single crystals at Lifshits electronic-topological transitions [7] attracts great attention, as result of low characteristic energies in Bi (electron Fermi energy ε_F^L = 30 meV, hole Fermi energy at T point of Brillouin zone ε_F^T = 12 meV, the gap at the point L ε_g = 15 meV). ETT may be easily obtained by weak doping with donor impurity (Te) or acceptor one (Sn), as well as by deformation. According to [7] kinetic coefficients in the vicinity of ETT should have singularities of type $|Z|^{\pm 1/2}$, where $Z=\mu-\varepsilon_c$, (μ is the chemical potential, ε_c is its critical value). In paper [8] it was shown that singularities behavior of kinetic coefficients are determined by singularities of the carriers relaxation time τ. The most pronounced peculiarities $\alpha\sim |Z|^{-1/2}$ appear for thermopower. Singularities for conductivity are of the type $\sigma\sim|Z|^{1/2}$.

In paper [9] it was shown that the interband scattering of carries plays the decisive role in the dependence of σ and α on ETT. Intervalley and interband transitions of carriers in Bi are realized by acoustic phonons with energy 40 K, their contribution in scattering processes exponentially falls with temperature decreasing. At 4.2 K the relaxation time of intervalley transitions is almost 100 times greater than the pulse relaxation time due to intravalley scattering.

However, in low-dimensional objects it may be expected that due to surface scattering relaxation times will be of the same order, similar to impurity scattering in Bi-Sb alloys [10]. In particular, the positive values of thermopower in Bi nanowires was explained assuming an interband scattering in the low temperature range [11].

Avialability of the magnetothermopower "gigant" quantum oscillations also point out the essential role of the interband carriers scattering. [11]

Bismuth and its alloys are extremely convenient object to observe singularities of kinetic coefficients at ETT, as far as at deformation a continuous transition over critical values of Fermi energy may be obtained on the same sample. From this point of view the most attractive are Bi-based thin monocrystalline wires in glass coating . In such objects it is methodically easy to obtain uniaxial elastic extension, and at the same time such wires resist elastic deformations up to 3% of relative extension , that by an order of magnitude exceeds possibilities of bulk samples [15].

This paper deals with investigation of characteristic properties of thermopower, magnetothermopower and of resistance at ETT induced by extension of Bi wires doped with Te.

Samples.Experiment

Thin wires of Bi and its alloys with Te were prepared by liquid-phase casting, in a glass coating, with diameter from 100 nm to 1 μ. [1]

All samples were monocrystalline of cylindrical shape. They have the same orientation, the wire axis coincides with ΓL direction of the reduced Brillouin zone, that is in [1011] crystal direction.

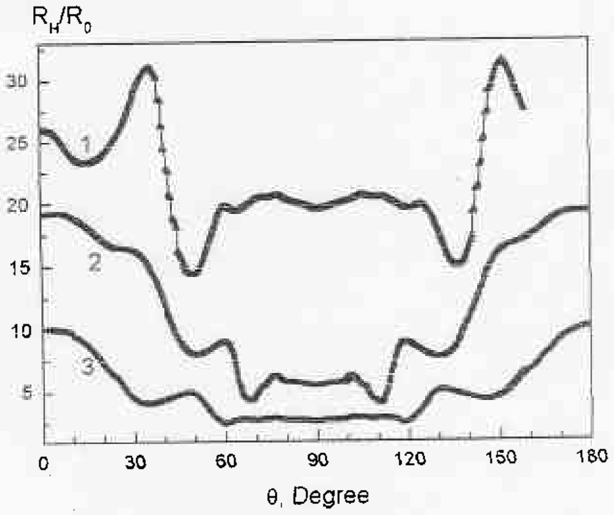


Fig. 1 Angle diagrams transverse magnetoresistance (H⊥ I) Bi nanowires T=4.2 K. 1- Bi, d=350 nm, H=5T; 2- Bi-0.0025 at.% Te, d=330nm; 3- Bi-0.001 at.% Te, d=100 nm, H=14T

Rotation angle diagrams of transverse magnetoresistance of pure Bi and Bi-Te wires are shown in Fig. 1. The structure of such diagrams allows to conclude that the samples have the same orientation. At the position $\theta=90^0$ the magnetic field H is along to the binary C_2 axis transversal to wire. The extension device represent a displacement transformer, it is a thin-ring made of beryllium bronze in which a sample is fixed. The device allows to measure automatically resistance and thermopower versus extension $\xi=\Delta l/l_0$, where l_0 is the initial sample length of about 2-3mm . During α measurements the temperature gradient was at the level of 2-3° .

Changes in Fermi surface cross section was reliably registered using Shubnikov – de Haas oscillations (ShdH) in magnetic field up to 14 T. Magnetic measurements were performed in the International Laboratory of Strong Magnetic Fields and Low Temperatures, Poland, Wroclaw.

The excellent data reproduction of dependences of resistance R and α, as well as Shubnikov – de Haas oscillations as a function of deformation allows to conclude that all research was made in the range of elastic deformations.

Result and Discussion

We have studied the wires with composition Bi - 0.001at%Te, Bi - 0.0025at%Te, Bi - 0.005at%Te and diameter of 100 nm - 1μ. Dependences of longitudinal magnetorestance (H II I) at 4.2 K are shown in Fig. 3,4. The pronounced pattern of ShdH oscillations from two electronic ellipsoids symmetrical with respect to the wire axis has allowed to determine their quasi-classical frequencies according to $\Delta_b^{-1}=c*S_a/eh$ and evaluate ε_F position for all three compositions: 37, 43, 47 meV, respectively,according [14]. That is, for composition Bi - 0.0025at%Te ε_F is located near the top of the T- valence band energetic extremum on the distance about 1~ meV. For wires with 0.005at%Te ε_F is located at the distance ~5-6 meV above the T- valence band. Thus, in those wires the Fermi surface consists of three electronic ellipsoids in L point of Brillouin zone. In wires with Bi - 0.001at%Te ε_F is found lower the top of T – valence band. Concentrations of carriers estimated according to expression

$$n=\left(\frac{2e}{\hbar c}\right)^{\frac{3}{2}}\times\frac{N_c}{3\pi^2}\times\left(\frac{1}{\Delta_1\Delta_2\Delta_3}\right)^{\frac{1}{2}}$$

was $4.5*10^{-17}$ cm^{-3}, $7*10^{-17}$ cm^{-3}, $1*10^{-18}$ cm^{-3} this coincides well with values obtained in bulk samples of the same composions [14]. Contrary to results obtained for Bi-Te nanowire arrays the Te efficiency coefficient is close to unity.

In order to clear up the changing of extremal sections of Fermi surface (FS) at deformations the dependences of resistance R(H) and magnetothermopower α(H) versus magnetic field (to 14 T, H II I) were measured at constant extension ξ values.The subsequent increasing of $\xi = \Delta l/l_0$ allows sure to follow the period of ShdH quantum oscillations alteration and register corresponding the Fermi surface topology changing. The dependences of resistance R and thermopower α were measured without magnetic field at various temperatures with the aim to study ETT manifestations on $\alpha(\xi)$ and $R(\xi)$.

First the dependences of R and α as function of temperature purpose to find out the size effect influences on these characteristics were measured in the temperature range 4.2 – 300 K for wires oand various diameters with the purpose to find out the size effect influences on these characteristics (Fig.2,a,b).

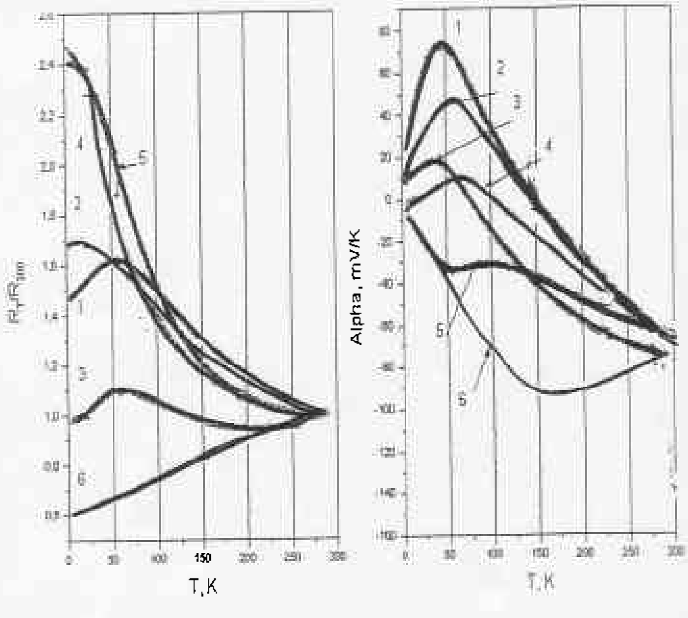


Fig. 2. The temperature dependences of the rceidual resistance Rt/R300 (**a**) and thermopower α (**b**) nanowires Bi with donor impurity Te as parameter: 1.Bi-0.0005at%Te, d=200nm; 2.Bi-0.001at%Te, d=100nm; 3-Bi-0.0015at%Te, d=200nm; 4-Bi-0.0025at%Te, d=200nm; 5.Bi-0.005at%te; d=300nm; 6.Bi-0.02at%Te, d=350nm

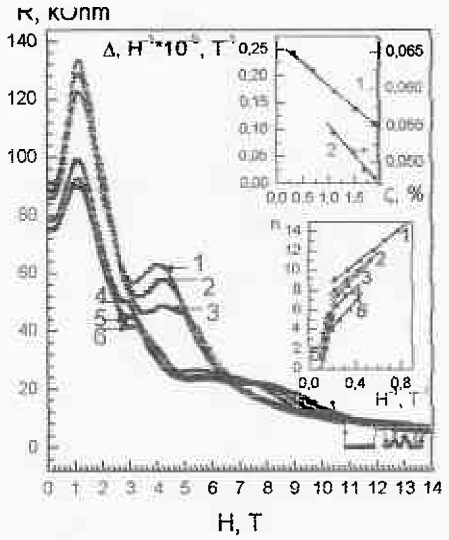


Fig. 3a The resistance of Bi-0.0025at%Te – wire,d=200nm as a function of the magnetic field with relative elongation ξ as a parameter:1.ξ=0, 2.ξ=0.7%, 3.ξ=1.1%, 4.ξ=1.5%, 5.ξ=1.7%, 6.ξ=1.9%. Insert(on the bottom) the dependences of guantum number SdH oscillations vs 1/H, (on the top)-the the period SdH oscillations from L-electrons and T-hols vs ξ.

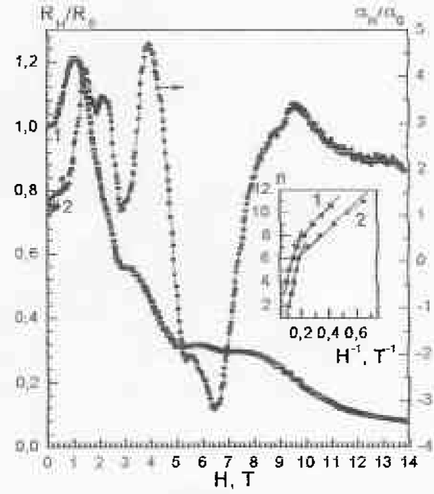


Fig. 3b The dependences of the resistance and thermopower in magnetic field for Bi - 0.0025 at % Te-wire, ξ=1.8%. Insert - the dependences of guantum number SdH oscillations vs 1/H.

On Figs. 3 a,b and 4 a,b the dependences of the resistance and thermopower in magnetic field for wires with compositions Bi - 0.0025 at % Te and Bi - 0.005 at % Te,respectively at various extensions are shown.

Redistribution of carriers between L_i valleys at extension leads to Fermi level displacement down along the energy scale relative to the term in T. At some ξ value the Fermi level comes in contact with the valence band top, and a hole surface appears in T-point of Brillouin zone. As well as in paper [15], for bulk sample of the same composition the contact moment (on the base of ShdH oscillations due to holes appearance in T) was not observed in experiment while measuring R(H) and α(H). This is due to low hole concentration and their high effective mass. However possibility to perform an elastic extension of thin wires up to 1.5-1.8% enabled us to reveal the T-hole ShdH oscillations at ξ>1%, when their concentration in the extension process has become of the order of 3×10^{17} cm^{-3}. This concentration is near to one in pure Bi without extension.

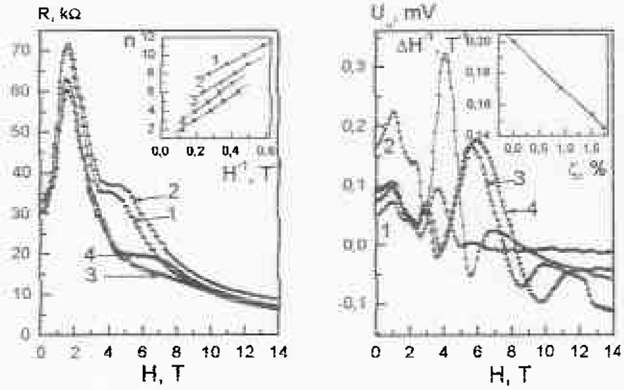
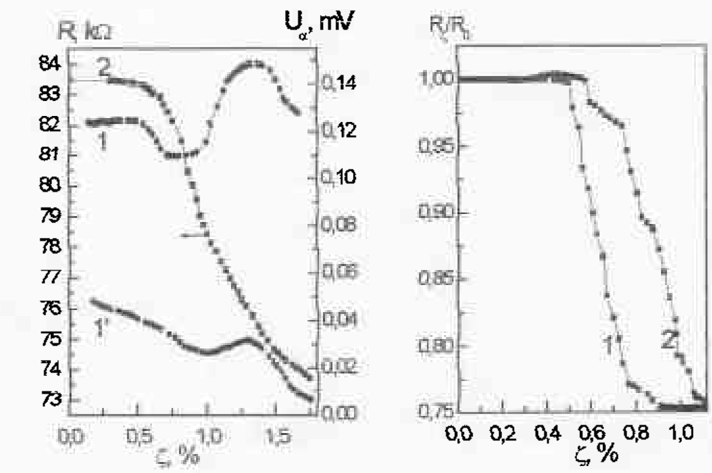


Fig.4 The dependences of resistance **(a)** and thernopower **(b)** as a function of the magnetic field with relative extensions ξ as a parameter Bi-0.005at%Te –wire, d=300 nm. 1- ξ=0%, 2- ξ=0.9%, 3- ξ=1.5%, 4- ξ=1.7%. Insert (a) the dependences of guantum number SdH oscillations vs 1/H. Insert(b) - the dependece of the period of ShdH oscillations vs ξ.

The most pronounced oscillations of that kind due T-holes may be seen on the α(H) curve at ξ>1.8% of the relative extension (Fig.3,4, b). Changes in the Fermi surface topology are determined by the flow phenomenon of carriers between L_i extremums.



a b

Fig. 5. Deformation dependences resistivity R(ξ) , the scale on the left and thermopower α(ξ)(absolut signal value), the scale on the right Bi-0.0025at%Te wire with d=200nm.

1,2 - T=20K; 1'- T=60K; **(b)** Deformation dependences of the resistivity Bi-0.0025at%Te wire, d=220nm, 1- T=1.6 K, 2-T=4.2 K.

The moment of overlapping with T-term appears may be determined from dependences of resistance R(ξ) and thermopower α(ξ) versus deformation (Fig.5).

This dependences resestivity R(ξ) are tipical for phase transition: the sharply decreasing (~25%) at low temperature (1.6K) in the the interval elastic tension ξ - 0.6-0.8% and slawly montonically decreasing (~10 %) at the heights temperature (20K) in the interval ξ - 0.6 – 1.75 %.

Thermopower in the ETT point has a pronounced peak of negative polarity (Fig.5) , and resistance begins to fall, when hole cavity of the Fermi surface appears. Increasing of the total number of carriers leads to decreasing of resistance.

At further extension a maximum of positive polarity appears on the deformation curve α(ξ) (Fig.5), it gives evidence that one of L-electronic ellipsoids disappear. Qualitatively the results obtained are in good agreement with conclusions of paper [8]. The thermopower does not change its sign in the vicinity of ETT, as result of fact that at approaching to the ETT transition interband scattering first becomes significant for electrons located under the Fermi level. By this reason it compensate the contribution of electrons located above the Fermi level in less degree, so that thermopower peak appears of the same sign as the thermopower has far from the transition.

As it is seen from Figs. 3, 4 the "giant" thermopower oscillations in magnetic field also appear as result of the involving in transport of T-holes. Here the amplitude of ShdH oscillations on the resistance curves R(H) decreases at extension. According to [11] this anomaly is also related with interband scattering, that is most pronounced in thermopower, which at strong degeneration present the difference of two great quantities: thermopower of electrons located above the Fermi level and those located under the Fermi level.

Summary

In thin wires of Bi doped with Te a number of anomalies were found out at ETT: the "giant" oscillations of the thermopower in magnetic field and peculiarities in deformation curves of thermopower and resistance . In general they testify that the interband scattering of carriers plays the decisive role in wires of Bi and Te-doped Bi at low temperature area.

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