Topological Transitions in the Strain Dependences of Thermopower and Resistance in Nanowires Based on Bi –Sn

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***Abstract* — We studied the strain dependences of the resistance and thermopower of nanowires of Bi and its alloys with Sn in conditions of an anisotropic elastic strain with values of 2% elongation, which is one order of magnitude higher than the value achieved in the bulk samples.**

Glass-coated wires with diameters ranging from 150 nm to a few microns were prepared by liquid phase casting; they were single crystals with a strictly cylindrical shape. The change in the Fermi surface was calculated using Shubnikov de Haas oscillations. In thin wires of Bi doped with Sn the anomalies in thermopower were found out: the peculiarities on the deformation dependences of the thermopower $\alpha(\xi)$ in Bi-0.025at%Sn of the thermopower. The peculiarities in deformation curves of thermopower connected with electron topological transitions (ETT).

The interband scattering plays key role in manifestations of above mentioned anomalies in thermopower at ETT which takes place only in doped Bi-wires at low temperatures. It is shown that the high concentrations and higher temperatures leads to a reduction in the thermopower anomalies which corresponds to the exit from the ETT.

***Index Terms* — electron topological transitions, elastic strain, Bi-Sn - nanowires.**

I. INTRODUCTION

The essence of the electronic topological transition (ETT) is a qualitative change in the topology of the Fermi surface for a smooth change of lattice parameters under pressure, uniaxial strain, doping. Topological changes of the Fermi surface, in turn, lead to a drastic change in the dynamic properties of electrons with energies close to the Fermi energy [1].

According to [1] 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 [2] it was shown that singularities behaviour of kinetic coefficients are determined by singularities of the carriers relaxation time τ. The most pronounced peculiarities appear for thermopower $\alpha \sim |Z|^{-1/2}$. Singularities for conductivity are of the type $\sigma \sim |Z|^{1/2}$.

In Bi owing to the low characteristic energies (electron Fermi energy $\varepsilon_F^L = 30$ meV, hole Fermi energy at T point of Brillouin zone $\varepsilon_F^T = 10$ meV, the gap at the point L $\varepsilon_g = 10$ meV), the ETT may be easily obtained by weak doping with acceptor one (Sn), as well as by deformation. In paper [3] 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, the impurity scattering in Bi-Sb alloys permitted to observe a number of anomalies in the thermoelectric power associated with ETT [4].

Pure and doped Bi-based thin monocrystalline wires in glass coating 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. In such wires it is methodically easy to obtain uniaxial elastic extension [6].Those wires in glass cower have high limit of the elastic tension close to the theoretical (2-2,5 % relative elongation), which is one order of magnitude higher than the value achieved in the bulk samples. [5]

This paper deals with investigation of characteristic properties of thermopower, resistance and ShdH oscillations at ETT induced by extension of Bi wires doped with acceptor (Sn) impurity.

II. EXPERIMENT

Thin wires of Bi and its alloys with 0.025at%Sn were prepared by liquid-phase casting, in a glass coating, with diameter from 100 nm to 1 μm. [6,7] The alloys with low content of the impurity were obtained by bismuth dissolution of preliminarily synthesized bulk crystals of alloys Bi-Sn of a given composition. In order to avoid the alloy oxidation the process of the wire preparation was performed in Ar atmosphere. 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 [10$\underline{1}$1] crystal direction [6].

The perfection and orientation of the samples were verified with the help of the rotation angle diagrams of transverse magnetoresistance and the Shubnikov – de Haas (ShdH) oscillations at H || I.

The excellent data reproduction of dependences of resistance R and thermopower α, as well as ShdH oscillations as a function of deformation allows to conclude that all search was made in the range of elastic deformations.

The magnetic field-dependent resistance R(H), was measured in the temperature range 4.2-300 K, and for magnetic fields of up to 14T, in a Bitter-type magnet and in a superconducting solenoid in the International High Magnetic Field Laboratory (Wroclaw, Poland).

III. DISCUSSION

The choice of composition Bi-0.025at%Sn due to the fact that according to [8, 9] at this doping, the Fermi level of T-holes located in top of the valence band at L (Fig. 1).

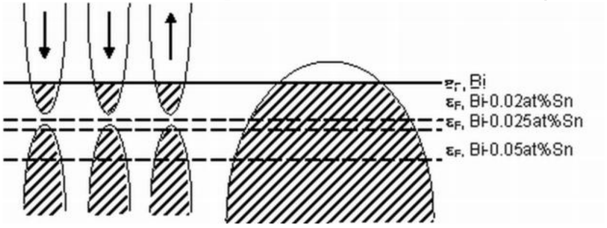

Fig. 1. Position of the Fermi level in pure and doped Bi.

Fig. 2 the variations of ShdH oscillations for longitudinal magnetoresistance in Bi-0.025at%Sn at various values of the relative extension ξ=Δl/l (l - is the initial sample length) are shown. At ξ=0 we observed only one period ShdH oscillations from T-holes (Fig. 2, curve 1).

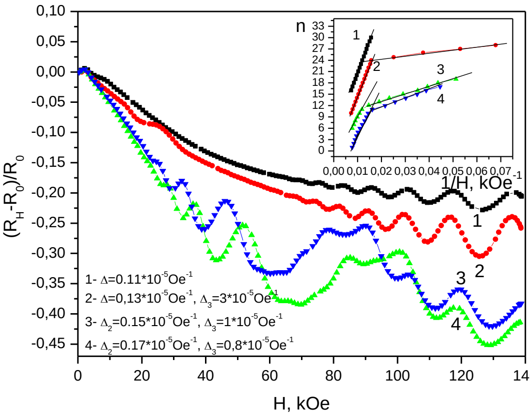

Fig. 2. Field dependences of longitudinal magneto-resistance ΔR/R(H) of Bi-0,025at%Sn nanowire, d= 0.9 μm at different values of elastic deformation: 1. ξ=0, 2. ξ =1.4%, 3. ξ =2.1%, 4. ξ =2.4% at 4.2 K. Insert: dependences of quantum number n of the ShdH oscillations on reverse field H^{-1}.

The ShdH period $\Delta^T(1/H)=0.11*10^{-5}$ Oe^{-1}, that corresponds to frequency f_0= 90.9 T.

Estimation of position of the Fermi level of T-holes ε_F^T in the frames of the two-band Kein model was calculated by the expression:

$$\varepsilon_F^T = E_{nap} - \frac{1}{2}\varepsilon_g^T + [\varepsilon_{nap}^2 + (\frac{1}{2}\varepsilon_{gT})^2]^{\frac{1}{2}} \tag{1}$$

where $E_{par} = \frac{S_T}{2\pi m_{CT}} = \frac{eh}{2\pi c} * \frac{\Delta_T^{-1}}{m_c^T}$, E_{par} is the energy in the approximation of parabolic band, ε_F^T is the energy of holes in T calculated from the top of T-band downwards, ΔE_F^{-1} is the frequency of oscillations from the minimal cross section of T-holes, ε_{gT}=200 meV according to [8], Δ_T^{-1} is the frequency of ShdH oscillations from minimum cross section Fermi surface T- holes, m_c^T - is the minimum cyclotron mass of T- holes.

The initial ε_F^T value in these wires is 59 meV (according (1)), i.e. ε_F^T is located just near the top of the band of light L- holes (Fig. 1).

During the extension of Bi-0.025at%Sn the top of the valence band of holes ellipsoid L_1 is shifted up along the energy scale. At the same time the both equivalent $L_{2,3}$ holes and electrons ellipsoids are shifted down (on the Fig. 1 the shift of the bands is indicated by an arrow).

Under the elongation we can see clear that the new Fermy surface from L-light holes appears (Fig. 2, curve 2).

It is clear from Fig. 2 that at extensions in weak magnetic fields SdH oscillations from L_1– hole ellipsoid appear, the frequency of which is increased, while the quantum limit SdH oscillations is shifted to the area of strong magnetic fields.

The deformation dependences of resistance R(ξ) and thermopower α(ξ) at different temperatures for Bi-0.025at.%Sn are shown in Fig. 3 and Fig. 4. The R(ξ) and α(ξ) behavior at extension differs significantly for pure Bi wires and for Bi-0.01 at%Sn wires [7]. As it is seen in Fig. 3, the input of holes into thermopower increases with elongation at low temperatures and the positive value of thermopower grow with the following formation of the maximum at ξ=2% relative elongation.

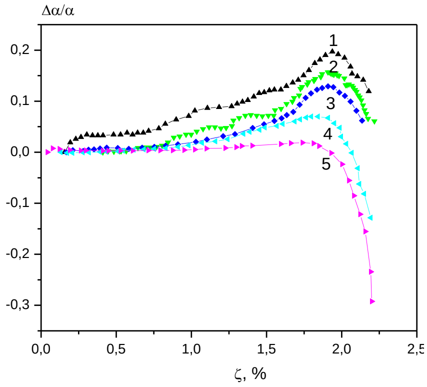

Fig. 3. Deformation dependences of thermopower α(ξ) of Bi-0,025at%Sn nanowire, d= 0.9 μm. 1- T= 8K, 2- T= 12K, 3- T= 27K, 4- T=40K, 5- T=55K.

At the same time the deformation dependences of the resistance have no features and resistance with stretching deformation monotonously increases in an interval of temperatures 4.2- 60 K (Fig. 4.)

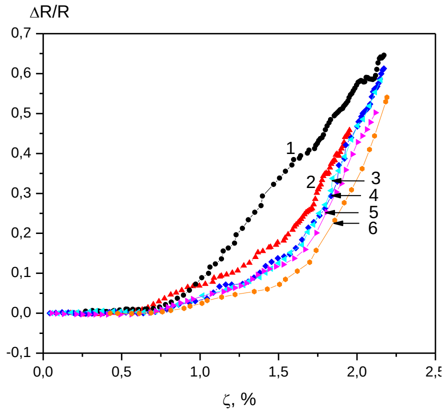

Fig. 4. Deformation dependences of resistance R(ξ) of Bi-0,025at%Sn nanowire, d= 0.9 µm. 1- T= 2.1K, 2- T= 4.2K, 3- T= 10.6K, 4- T=24K, 5- T=48K, 6- T=55K.

As it is shown in [1-3, 10] nonmonotonic dependence of α(T) and peculiarity formation on α(ξ) are connected with ETT and the appearance of the narrow channel the interband ore intervalley scattering.

At low temperatures the singularities in the thermopower and resistance at ETT induced by extension are significantly different for the cases, when the Fermi level ε_F is located in the conduction band or in the valence band of light L holes. Thus, in the first case the electron input increases with extension, but in the second case the hole one increases, i.e. the positive thermopower value becomes greater.

At the moment when L_{23} electron ellipsoids touches Fermy level T-holes, on the deformation dependences thermopower α(ξ) appears maximum of the positive polarity, which is characteristic for ETT. It is observed during appearance of the scattering selective channel $L_{2,3}$ electrons in the heavy T-band at high density states. We should note, that touching of $L_{2,3}$ electron ellipsoids happens in “cold” area at the distance ~ kT over the Fermy level T -holes, leading to maximum of positive polarity for α(ξ). During the follow up extension the contribution of $L_{2,3}$ electron ellipsoids is increased and positive contribution in thermopower is diminished.

It is shown that the high concentrations and higher temperatures leads to a reduction in the thermopower anomalies which corresponds to the exit from the ETT.

IV. CONCLUSION

In thin wires of Bi doped with Sn the peculiarities on the deformation dependences of the thermopower α(ξ) in Bi-0.025at%Sn of the thermopower were found out. The peculiarities in deformation curves of thermopower connected with electron topological transitions.The interband scattering plays key role in manifestations of above mentioned anomalies in thermopower at ETT which takes place only in doped Bi-wires at low temperatures.

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