Galvano-Magnetic Properties and Shubnikov de- Haas Effect of Te- Whiskers

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***Abstract* — The work is devoted to investigation of the peculiarities of magnetoresistance, Hall effect and Shubnikov de Haas oscillations in Te- whiskers. Te- whiskers was prepared from vapor- gas phase on the substrate pure tellurium and grown naturally of the walls of a crucible in the course of growing Te single crystals by the Chochralski method. The measurements of the galvanomagnetic properties and Shubnikov de Haas oscillation correspond to the notion of the occurrence of the effect of intraband magnetic breakdown when two different quasi-classical cyclotron trajectories coexist simultaneously in a magnetic field. This effect is a consequence of the presence of the saddle point in the dispersion law of the tellurium valence band.**

***Index Terms* — Intraband breakdown, saddle point, Te- whiskers.**

I. INTRODUCTION

Unique physical properties involve research people long time because of anisotropy of structure and a difficult energy spectrum of carriers in it.

Low-dimensional structures based on Te-whiskers are of special importance. Whiskers as subjects of physical investigations possess unique properties: high chemical purity, perfect structure of bulk and surface, small dimensions, and high strength close to theoretical limit.

One of interesting peculiarities of tellurium is that it possesses only hole conduction at low temperatures. All impurities in tellurium generate acceptor conductivity irrespective of the doping element valence [1, 2].

Residual impurities and structural defects, resulting in the break of covalent bonds, being filled by the conductivity band electrons, as the reason of the hole conduction of tellurium [3-5].

It is known that whisker crystals (WC) grown from vapor-gas phase have more perfect crystalline structure. Thanks to the high more perfection of the crystalline structure the effect of dislocations forming in the bulk on the electric conduction must be negligible. Moreover, when WC are grown from the vapor-gas phase, there takes place an additional refinement, even in the case, when tellurium WC is grown of a sufficiently pure material.

The study of tellurium WC, in addition to the elucidation of the growth mechanism and their electric properties, is important because it supplements our knowledge about WC possessing a great mechanical strength and higher elastic deformation limit, resistance to oxidation, to dissolving, etc.

The purpose of the given researches is influence of mechanisms leading to appearance of unusual electro-physical properties in perfect whiskers of Te.

II. EXPERIMENT

An p-type single crystals in the form of solid hexahedral cylinders ore the ones with inside holes having hexahedral form was prepared from vapor-gas phase on the substrate from pure tellurium. Te- single crystals grown too naturally on the walls of a crucible in the course of growing Te single crystals by the Chochralski method.

The parent single-crystal had a form of a hollow hexagonal prism with a hex-shaped hole. At the liquid nitrogen temperature (77 K), one profile plane was cut from such a hexahedron. Characteristic sizes of the sample were as follows: length (l) l = 1.7 mm, width (b) b = 0.104 mm, and thickness (d) d = 0.021 mm. Current and potentiometric contacts were prepared for the sample. The galvanomagnetic effects were measured at helium temperatures (4.2-1.5 K) in a superconducting solenoid up to 14 T and at alternating current with a frequency of 13 Hz. The magnetic field induction axis was parallel to the broad part of the sample and perpendicular to the C_3 axis

($C_3 \perp B$). The distance between the measuring probes along the sample was 0.44 mm; the distance between the Hall probes was 0.021 mm. The signal of the Hall effect and magnetoresistance was measured by a Lockin Ampifier DSP 7265 digital instrument.

The measurements were carried out in the International Laboratory of Strong Magnetic Fields and Low Temperatures, Wroclaw, Poland.

III. RESULTS AND DISCUSSIONS

Figures 1 and 2 show characteristic dependences of voltages of the Hall effect and magnetoresistance for one pair of the measuring contacts (the 34-contact pair for the Hall effect; the 35-pair for the magnetoresistance) measured at T = 4.2 K.

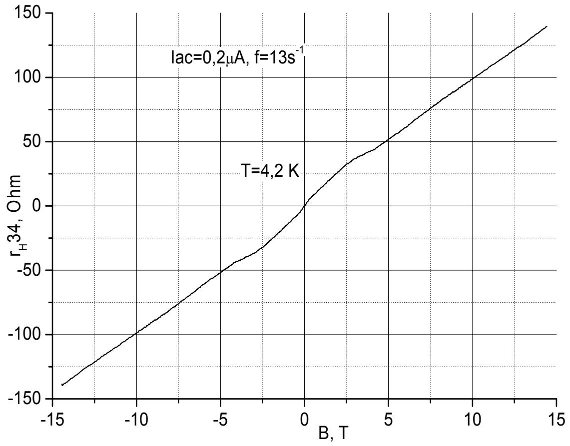

Fig. 1. Dependences of the Hall effect in the whisker on magnetic field induction.

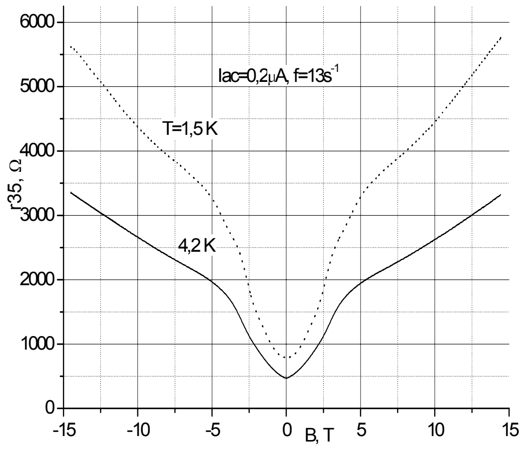

Fig. 2. Dependence of the whisker resistance on magnetic field induction.

First of all, it should be mentioned that the Hall effect sign corresponds to the conductivity of hole current carriers. Using the given dependences, it is easy to determine the concentration and the Hall mobility of current carriers in the sample under study. It is known that the Hall coefficient (R_H) can be determined from measurements of the Hall effect by the formula:

$$R_H = \frac{r_H S}{d_H B}, \qquad (1)$$

where r_H is the Hall effect resistance ($r_H = \frac{U_H}{I}$), U_H is the Hall effect measuring signal, S is the sample cross-sectional area, I is the sample current, d_H is the distance between the Hall probes, and B is the magnetic field induction.

The R_H coefficient is related to the concentration of the hole current carriers by the simple relation [6]

$$R_H = \frac{A}{pec}, \qquad (2)$$

where p is the hole concentration, e is the electron charge, c is the sound velocity, and A is the Hall-factor depending on degree of hole degeneration, scattering mechanism, and magnetic field value.

In weak magnetic fields (μB<<1, where μ is the hole mobility, and B is the magnetic field induction) for the case of nondegenerate statistics (ε_F /kT <<1, where ε_F is the Fermi energy value, kT is the heat energy of hole gas) the expression for A [6] is as follows

$$A = \frac{3\sqrt{\pi}}{4} \times \frac{\Gamma(2r+3/2)}{\Gamma^2(r+2)}, \qquad (3)$$

where $\Gamma(2r+3/2)$ is the gamma-function, and r is the scattering mechanism parameter. In the case of impurity ion scattering r = 2, and in weak magnetic fields A = 1.93.

In strong magnetic fields (μB>>1) irrespective of degree of hole degeneration and scattering mechanism parameter A = 1; therefore, expression (2) transforms into (4):

$$R_H = \frac{1}{pec}, \qquad (4)$$

The Hall mobility was calculated by the formula:

$$\mu = R\,\sigma \qquad (5),$$

where R is the Hall coefficient, σ is the specific conductivity at zero magnetic field:

$$\sigma = \frac{I\,l}{U\,S}, \qquad (6),$$

where U is the voltage on the potential probes situated along the sample, l is the distance between the probes, S is the sample cross section, and I is the sample electric current value.

As result of the calculation, the hole concentration in strong magnetic field (B >> 0) appeared to be $p_{4,2K} \approx 1,0\times10^{15}$ cm^{-3}; the mobility $\mu \approx 3540$ cm^2/V s. This value of concentration of free current carriers in single-crystal Te corresponds to the case of degenerate statistics, i.e., ε_F/kT >> 1. With the use of calculated value, it is easy to find that, at a value of magnetic field induction higher than 3 T, the Landau quantization of the energy spectrum of degenerate holes in the sample under study must occur (quantization condition is μB >1); herein, Shubnikov-de Haas oscillations of the magnetoresistance effect must be observed [7]. In Fig. 2, the oscillating component of the magnetoresistance effect becomes appreciable as the experiment temperature decreases to 1.5 K; it is properly resolved (Fig. 3) at numerical differentiation of the dependences shown in Fig. 2.

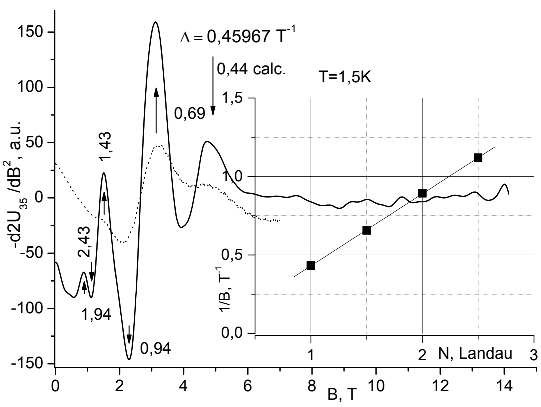

Fig. 3. The solid line is a result of the numerical differentiation of the magnetoresistance signal measured at T = 1.5 K (Fig. 2).

The dashed curve is a result of the subtraction of the 4th degree polynomial function from the measured dependence. The arrows denote the positions of extreme points; the numbers stand for Landau level numbers; Δ is the oscillation period on the reversed magnetic field scale. The inset shows the position of the first four extreme points on the reversed magnetic field scale.

One can see that the position of the extreme points on their sequential number of the appearance on the reversed magnetic field scale is in a good agreement with the linear dependence. This fact means that the found oscillations are the Shubnikov-de Haas oscillations. The observed splitting of the Landau zero level corresponds to the notion of the occurrence of the effect of intraband magnetic breakdown when two different quasi-classical cyclotron trajectories coexist simultaneously in a magnetic field [8]. This effect is a consequence of the presence of the saddle point in the dispersion law of the tellurium valence band [9].

In the range of weak magnetic fields ($B \rightarrow 0$), the effect of negative magnetoresistance is observed (Fig. 3); the specific features of its manifestation have been analyzed in detail in [10, 11].

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