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Electrical Resistivity and Charge Density of Bismuth Telluride Doped with Erbium

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The electric properties of a single crystal bismuth telluride doped with a small concentration of Erbium, $Bi_{2-x}Er_xTe_3$ with x = 0.002, are investigated as a function of temperature. The resistivity was obtained by using the van der Pauw method. The measured electrical resistivity is 78 μΩcm at 4.2 K. The charge density of $Bi_{2-x}Er_xTe_3$ is found to be $2 \times 10^{19}/cm^3$ at 4.2 K. It turns out that $Bi_{2-x}Er_xTe_3$ is a *p*-type semiconductor. It is discussed that the high mobility and less density support that $Bi_{2-x}Er_xTe_3$ is a potential sensor with high energy resolution. Comparison with an established material (i.e. Au:Er alloy) is also discussed.

Key words : $Bi_{2-x}Er_xTe_3$ single crystal, electric property, resistivity, charge density

1. Introduction

The properties of a dilute concentration of Er in a host material of Au, Au:Er have been intensively studied [1, 2]. One of the applications of Au:Er is cryogenic particle detectors for high resolutions and low threshold. The ground state of the Er^{3+} ions in the Au lattice field is G_7 Kramer's doublet with g = 6.8. The zero-field splitting is about 15 K (10.4 cm^{-1}). Below 1 K the magnetization is determined by the ground state under small magnetic fields less than 0.01 T. The magnetization change of Au:Er due to an absorption of a particle is the primary mechanism of a particle detection. There is, however, a factor limiting a lager concentration of Er to the application. The exchange interactions between the magnetic ions, dipole-dipole interactions and Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions limit the optimal concentration to 1000 ppm at 100 mK and 0.01 T. The RKKY interaction in Au:Er is found to be 5 times greater than the dipole-dipole interaction. The preparation of a single crystal bismuth telluride doped with a Er, $Bi_{2-x}Er_xTe_3$ is motivated by the fact that the RKKY interactions can be significantly reduced in $Bi_{2-x}Er_xTe_3$ due to a small number of charge carriers.

A V-VI compound of $Bi_{2-x}Er_xTe_3$ is a semiconductor with an indirect band gap, $E_g \approx 0.15$ eV. Its unit cell is rhombohedral containing 3 molecules. It can be either *n*-type or *p*-type depending on the relative ratio of the elements and adding impurities. $Bi_{2-x}Er_xTe_3$ is a well-known material for its thermoelectric properties. The observations of Shubnikov-de Haas (SdH) and de Haas-van Alphen (dHvA) oscillations initiated the studies of its band structure. The existence of double balance and double conduction bands was suggested [3-5]. The evidence of six-fold degeneracy on conduction band minimum and valence band maximum was also investigated [6, 7].

In the present experiment, the electrical resistivity and charge carrier density of $Bi_{2-x}Er_xTe_3$ single crystal are measured between 4.2 K and room temperature. The electric properties of $Bi_{2-x}Er_xTe_3$ is compared with the Au:Er alloy. The application of $Bi_{2-x}Er_xTe_3$ crystal was also proposed as a sensor material with high resolution.

2. Experiment

A single crystal of $Bi_{2-x}Er_xTe_3$ with 0.2 mole percent of Er was grown by Czochralski method [8]. The characteristic crystallographic axis, *c*-axis, of the rhombohedral structure is easily determined by its cleavage planes. The crystal orientation was confirmed with a Laue x-ray diffraction pattern.

A thin square piece with 2 mm^2 area was cut from a cleaved $Bi_{2-x}Er_xTe_3$ slab. The thickness of the square slab was estimated to be 83 μm from the weight. The density of $Bi_{2-x}Er_xTe_3$ is 7.74 g/cm^3. Its molar volume is 103.5 cm^3. Four electrical contacts were made with a cryogenic silver epoxy at each corner of the square slab. At the each

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corner the epoxy was applied on not just one side but the other side and the short edge to prevent abnormal charge accumulation in a thin plane which might be caused by possible poor electrical connections to neighboring ones.

3. Results and Discussion

Fig. 1 shows the measured electrical resistivity for the temperature range of 4.2 K ~ room temperature. The electric resistivity was obtained using the van der Pauw method. The resistivity of $Bi_{2-x}Er_xTe_3$ is 78 μΩcm at 4.2 K as shown in Fig. 1. The resistivity of the crystal increases with temperature as usual.

The Hall measurement was carried with magnetic fields applied up to 1 T along the crystallographic *c*-axis of the $Bi_{2-x}Er_xTe_3$ crystal. This was repeated for the different combination of current voltage leads and the opposite direction of the magnetic field to cancel out geometrical offsets. The measured Hall voltage was *p*-type. The effective charge carrier density at different temperatures is shown in Fig. 2. Unlike one band gap semiconductor, the carrier density increases as the temperature decreases in $Bi_{2-x}Er_xTe_3$ crystal. However, this measurement does not have enough information for quantitative arguments on the band structure. One interesting point of the measurement is that the charge carrier density tends to saturate to a value at low temperatures as well as at high temperatures. It is indeed an important result because it can be extrapolated to the region of temperatures where the low temperature detectors are active.

The single crystal of $Bi_{2-x}Er_xTe_3$ with x = 0.002 had six

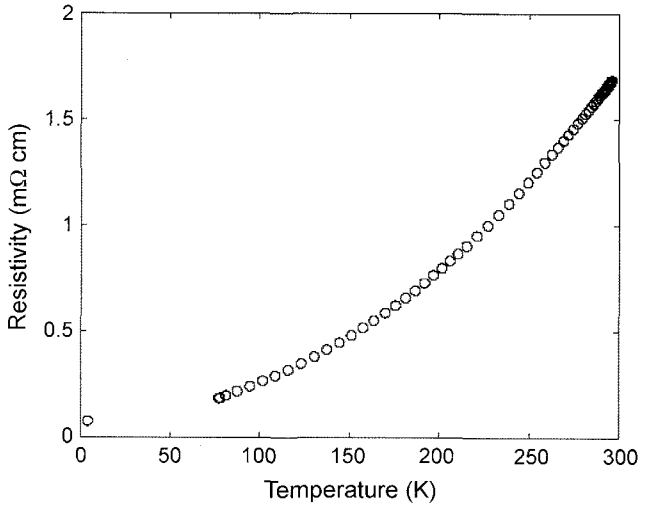

Fig. 1. Measured resistivity of $Bi_{2-x}Er_xTe_3$ single crystal as a function of temperature.

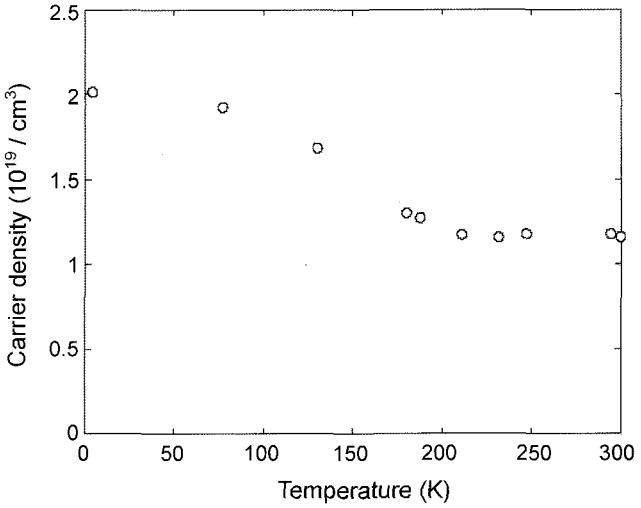

Fig. 2. Charge carrier density of $Bi_{2-x}Er_xTe_3$ single crystal as a function of temperature.

times larger resistivity than that of Au:Er at 4.2 K. In the case of Au:Er a linear contribution of Er contribution in electrical resistivity is found to be 6.7 μΩcm per % [9]. It should be noted that the molar volume of $Bi_{2-x}Er_xTe_3$ is about ten times lager than that of Au. It is not clear that the measured resistivity at 4.2 K is due to the impurities or the smaller number of charge carriers. Interestingly, the mobility is rather high. The high mobility together with the measured resistivity can provide fast enough thermalization inside $Bi_{2-x}Er_xTe_3$ single crystal at a particle detection.

The charge density of $Bi_{2-x}Er_xTe_3$ is 3 orders smaller comparing to Au:Er. This significantly suppresses the RKKY interaction which is indirectly mediated by the charge carriers between magnetic ions. If the dipole-dipole interaction is the major exchange interaction, the optimal concentration of Er can be 5 times larger than that of Au:Er if apparent magnetic moments is in the same order in both cases. This indicates that $Bi_{2-x}Er_xTe_3$ may provide better resolutions than Au:Er when it is designed in an optimal condition.

The magnetic proprieties of $Bi_{2-x}Er_xTe_3$ is still open to study. The ground state of Er in the crystal field of Bi_2Te_3 and zero-field splitting are the important parameters to use $Bi_{2-x}Er_xTe_3$ as a particle detector. The exchange interactions between the magnetic ions also need to be measured for further studies on this subject.

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