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Electrical resistivity, Seebeck coefficient and Hall coefficient of pure thallium at 100−550 K

© A.T. Burkov, P.P. Konstantinov

Ioffe Institute, St. Petersburg, Russia
e-mail: a.burkov@mail.ioffe.ru

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Electrical resistivity, Seebeck coefficient and Hall coefficient of pure thallium were measured at temperatures from 100 K to 550 K, i.e. almost to the melting temperature of this metal. The history of the experiemental investigations of the transport properties of Tl is shortly reviewed. This is a first publication of the experimental data on the Seebeck coefficient and the Hall coefficient of Tl in such a broad temperature range.

Keywords: Electrical resistivity, Seebeck coefficient, Hall coefficient, Thallium, temperature dependences.

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Introduction

Despite the fact that thallium is an elemental metal, many properties of this element in the crystalline state, including electronic transport properties, have been poorly studied. At the same time, thallium is included in many practically important materials, as well as in compounds with interesting properties. In particular, thallium is used in the development of new high-performance thermoelectric materials based on thallium-containing compounds and multiphase composites [1,2]. Recently, thallium was used to create and study the properties of nanoclusters on the surface of semiconductor crystals as elements of new generation of microelectronics and spintronics [3,4]. At the same time, there is almost no reliable experimental data on many of the macroscopic electronic properties of thallium itself, which can be useful in such studies. In this paper, we partially compensate the lack of information about such important properties of thallium metal as Seebeck coefficient, Hall coefficient and electrical resistance.

Thallium crystallizes at 577 K, in solid state it exists in two crystalline modifications: at $T < 504$ K it is a hexagonal close-packed structure (HCP), at higher temperatures — body-centered cubic (BCC) structure [5]. Thallium is a superconductor, the superconducting transition temperature is 2.38 K [6,7]. A significant part of the experimental results on the thallium properties, available in the literature, were obtained in the first half of the last century. In addition to the crystal structure and thermodynamic properties, the electrical resistance was studied both in the crystalline phases and in the liquid state of this metal. The first measurements of the electrical resistance of thallium were made by Dewar and Fleming as early as in 1893 [8]. Electrical resistance and thermodynamic properties were studied in most detail at low temperatures in the vicinity of the transition to the superconducting state [9–12]. The electrical resistance of liquid simple metals served as a model property for testing the theory of electron transport in liquid metals [13–17], this was a stimulus for theoretical and experimental studies of crystalline and liquid monovalent and polyvalent simple metals, including thallium [12,15,18,19].

However, other transport properties — Seebeck coefficient, Hall coefficient, thermal conductivity — were studied very fragmentarily. The first information about the Seebeck coefficient of thallium is contained in Bridgman's fundamental paper on the study of the thermoelectric properties of metals and some metal alloys under pressure [20]. The Seebeck coefficient was determined for a number of metals and alloys at normal pressure at temperatures from 273 to 373 K, and the changes in the Seebeck coefficient, Peltier coefficient and Thompson coefficient were measured at hydrostatic pressure up to 12 kbar in the same temperature range. Later, the Seebeck coefficient of thallium was measured at temperatures from 273 to 573 K, i.e., for both crystalline modifications of thallium[11], but the correctness of these results raises serious doubts.

The Hall coefficient was studied very poorly. The Hall coefficient of thallium and thallium alloys with tin and indium was measured at room temperature in 1970 [21], but there is reason to believe that the sign of the coefficient was determined incorrectly. Hurd's book includes the results of measuring the Hall coefficient of thallium, and gives the value of this coefficient at room temperature [22]. The results of detailed measurements of the temperature dependence of the Hall coefficient of thallium (and many other pure metals) at temperatures from 80 to 500 K (up to 1000 K for some other metals) were published in 1988, however only in a difficult accessible preprint of the Ioffe Institute [23]. Below we present these results for thallium.

In this paper, we present the results of measurements of electrical resistance, Seebeck coefficient and Hall coefficient at temperatures from 100 to 550 K, i.e. almost to the melting point of this metal (577 K).

1. Experimental procedure

Samples for measurements in the form of plates with dimensions of about $0.5 \times 8 \times 12\,\mathrm{mm}^3$ were prepared from thallium with a purity of 99.99%. Electrical resistance and Seebeck coefficient were measured simultaneously with the setup described in Refs. 24,25 using the standard 4-probe method for measuring resistance and the differential method for measuring Seebeck coefficient. When measuring Seebeck coefficient, copper (the copper branch of copper-constantan thermocouples) was used as a reference electrode. A detailed description of the method for measuring the Seebeck coefficient and electrical resistance is given in our publications [24,25]. The error in measuring electrical resistivity is ±2%, the error in measuring of Seebeck coefficient, taking into account the uncertainty of the existing absolute thermoelectric scale, is $\pm(0.5\,\mu\mathrm{V/K} + 4\%)$.

The Hall coefficient was measured using a dual-frequency method (alternating current, alternating magnetic field), the experimental setup was described in [26]. Note that both experimental setups undergo many years of testing. The setup used for measuring Seebeck coefficient and electrical resistance participated in international interlaboratory testing (round robin test) of Seebeck coefficient measurement techniques and demonstrated high accuracy and reliability of the measurement results. Therefore, the results obtained using these devices can reasonably be considered as quite reliable.

2. Results

The results of measurements of the electrical resistance of thallium sample at temperatures from 100 to 550 K are shown in Fig. 1. Along with the results of our measurements, literature data for this temperature range are also presented. In the literature there are data for electrical resistance for temperatures from 2 K to temperatures above the melting point [10,15,19]. According to data [19] immediately before melting and immediately above the melting point, the electrical resistance is equal to 35.5 and $73.1\,\mu\Omega\cdot\mathrm{cm}$, respectively. In general, there is quite satisfactory agreement between all available results. The magnitude of the anomaly in resistance during the structural phase transition from HCP to BCC structure at 504 K according to our data is noticeably greater than in earlier measurements [11], perhaps this is due to the different purity of the metal used (Rozenbom's article [11] does not contain data on the purity of thallium used in the measurements).

The Hall coefficient is also shown in Fig. 1. We reproduce here the results obtained from a systematic study of the Hall coefficient of pure metals, which were previously published as a preprint [23]. The Hall coefficient is negative over the entire temperature range, and its amplitude strongly depends on temperature at room temperature $R_H \approx -3 \cdot 10^{-5}\,\mathrm{cm^3/C}$. At the same time, according to the data given in Khurd's book, $R_H \approx +2.3 \cdot 10^{-5}\,\mathrm{cm^3/C}$, i.e., the amplitudes are close, but the signs are opposite. According to data [21] the Hall coefficient is positive, and the amplitude at room temperature is equal to $R_H \approx 1.2 \cdot 10^{-5}\,\mathrm{cm^3/C}$. We believe that the results obtained in the paper [23] are correct; they were obtained in the course of a systematic study of the Hall coefficient of 30 pure metals, for many of which there were sufficiently detailed and reliable literature data. In all such cases, at least good qualitative agreement was observed between the literature results and the results of new measurements. The strong temperature dependence of the Hall coefficient is apparently associated with the complex electronic structure of this metal. The Fermi surface of thallium consists of sheets in 3−6 bands and contains both hole and electron surfaces [27–29]. The experimentally measured Hall effect is the mobility-weighted sum of contributions from all sheets of the Fermi surface. Because the Fermi surface of thallium contains many small features, the weighted average of the contributions to the Hall effect can vary greatly with temperature.

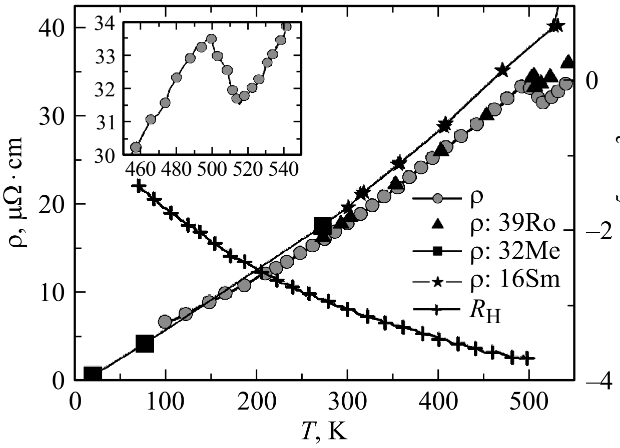

Figure 1. Electrical resistance and Hall coefficient of thallium. Our data: gray circles — electrical resistance, crosses — Hall coefficient. 39Ro — results [11], 32Me — [9], 16Sm — [18]. The inset shows the temperature dependence of electrical resistance in the vicinity of the structural transformation temperature.

The results of measurements of the Seebeck coefficient together with available literature data are shown in Fig. 2. Bridgman's results [20] are in good agreement with our data. A small difference in magnitude, almost independent of temperature, is within the experimental error of measurements of the Seebeck coefficient (see [24]). Rosenbom's results [11] differ qualitatively from both our temperature dependence of Seebeck coefficient, and from Bridgman's data. The matching of Rosenbom's data and our results at temperatures 300−400 K is accidental. Note that both the Hall coefficient and the Seebeck coefficient are sign-indicating coefficients. In this case, the Seebeck coefficient at temperatures below 350 K is positive, whereas the Hall coefficient is negative at all temperatures, i.e., over a wide temperature range, these coefficients have different signs.

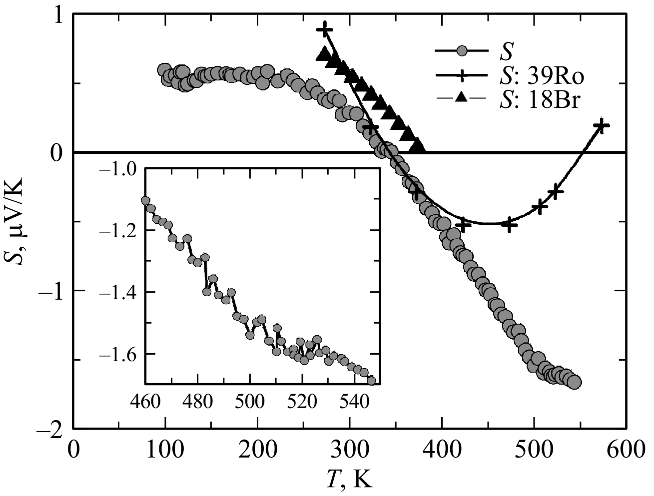

Figure 2. Seebeck coefficient of thallium. Our data: gray circles, 39Ro — results [11], 18Br — results [20]. The inset shows the temperature dependence of of Seebeck coefficient in the vicinity of the structural transformation temperature.

This situation is not unique, however. The difference in the signs of these two effects is quite often observed in metals. The most famous examples are the three noble metals: gold, silver and copper. For all three metals the Hall coefficient is negative, and the Seebeck coefficient is positive. The reason for the difference is due to different physical mechanisms of these effects occurrence. The Seebeck coefficient reflects the average energy of the diffusion flow of charge carriers, and the Hall effect is determined by the geometry of the Fermi surface and is sensitive to small parts of this surface with high curvature.

Thus, as a result of this study experimental data were obtained on the electrical resistance, Seebeck coefficient and Hall coefficients of pure thallium metal in a wide temperature range from 100 to 550 K. Experimental data on the Seebeck coefficient in such a wide temperature range are published for the first time.

Conflict of interest

The authors declare that they have no conflict of interest.

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