Low temperature resistivity studies of SmB$_6$: Observation of two-dimensional variable-range hopping conductivity

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Abstract

We studied electrical resistance of a single-crystalline SmB$_6$ sample with a focus on the region of the "low-temperature resistivity plateau". Our observations did not show any true saturation of the electrical resistance at temperatures below 3 K down to 70 mK. According to our findings, temperature dependence of the electrical conduction in a certain temperature interval above 70 mK can be decomposed into a temperature-independent term and a temperature-activated term that can be described by variable-range hopping formula for two-dimensional systems, exp[-$(T_0/T)^{1/3}$]. Thus, our results indicate importance of hopping type of electrical transport in the near-surface region of SmB$_6$.

Keywords: SmB$_6$, Kondo insulator, variable-range hopping

1. Introduction

Heavy fermion semiconductor samarium hexaboride, SmB$_6$, attracts attention of researchers for more than half a century. Its fascinating physical properties are very interesting not only because of long-lasting fundamental questions, but also from application point of view [1–10]. Electrical resistivity of high-quality SmB$_6$ samples shows a rapid increase with decreasing temperature below 50 K, and surprisingly, it shows tendency to saturate at very high residual value $\rho_0$ at the lowest temperatures, below $\approx 4$ K [2, 9, 10], while the corresponding residual conductivity $\sigma_0 = 1/\rho_0$ is less than the minimum metallic conductivity $\sigma_{min}$ defined by Mott [11]. Thus, in case of metallic conductivity, such unusually low $\sigma_0$ would require a mean free path of itinerant conduction electrons to be less than the interatomic spacing [2, 9]. This unphysical requirement has been a subject of a long-standing controversy whether SmB$_6$ in the ground state is a metal or an insulator, although, in principle, it clearly indicates that electrical transport in SmB$_6$ cannot be assigned to any metallic-type conductivity that would be homogeneous in the whole volume of the material.

The strange low-temperature behavior of SmB$_6$ has been associated with existence of a metallic surface, whereas nontrivial topological surface states [12–15], as well as trivial polarity-driven ones [16] have been proposed to exist there. Valence-fluctuation induced hopping transport [17] represents another possibility to explain the electrical transport in SmB$_6$ at the lowest temperatures, while this scenario moreover predicts enhanced conductivity of the near-surface layer, resembling the typical feature of topological insulators [17]. In principle, all above mentioned scenarios can coexist, but up to now a convincing association of experimentally observed electrical conductivity of SmB$_6$ at lowest temperatures with a specific mechanism(s) is still missing.

A persuasive conclusion about the origin of the resistivity saturation in SmB$_6$ unconditionally requires detailed studies of electrical transport at lowest temperatures allowing to identify corresponding conduction mechanism(s). In this work we report electrical resistance studies of single crystal SmB$_6$ focusing on the low-temperature region below 3 K.

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2. Materials and Methods

The SmB$_6$ single crystal was grown by the zone-floating method. The studied sample (the same one as used in our previous studies [18]) was cut in a bar-shape geometry in the (1 0 0) direction. Electrical resistivity was measured below 3 K down to 70 mK in a home-made dilution $^3$He-$^4$He minirefrigerator. Four probe ac resistance measurements were done by LR-700 AC Resistance Bridge (Linear Research, USA) in a non-shielded laboratory. Temperature was determined utilizing a calibrated (Cernox) thermometer (Lake Shore Cryotronics, USA).

3. Results and discussion

Previously we studied electrical resistivity of the same SmB$_6$ sample in the temperature interval between 4 K and 100 K [18]. As we reported there [18], the resistivity below 50 K shows a large increase with decreasing temperature and has a tendency to saturate at a high residual value at the lowest temperatures [18]. Two regions with different activation energies were found in the temperature dependence of the resistivity $\rho(T) \propto e^{W/k_B T}$ ($k_B$ is Boltzmann constant and $W$ is an activation energy), namely $W = 5.2$ meV for the interval of 6 - 10 K and $W = 5.6$ meV between 18 K and 30 K [18]. Now we have focused on the temperature interval from 3 K down to 70 mK. As can be seen in Fig. 1, the obtained data show no saturation in the investigated temperature range (despite to indication based on the previous measurements above 4 K [18]). Instead of this, two inflex points in the $\rho(T)$ curve have been found in this temperature interval, which can be considered as a sign for different dominating transport regimes below and above 1 K. (Such resistivity behaviour qualitatively resembles one of another single crystalline sample of SmB$_6$ prepared by the same technology process [10].)

As reported by many authors before, the low-temperature dependence of the electrical resistance, $R(T)$, can be in case of SmB$_6$ described by the two-channel model [6–10], e.g. in the form

$$R(T)^{-1} = R_n^{-1} + R_a^{-1} \times \exp(-W_n/kT),$$

(1)

where $W_n$ is activation energy associated with temperature activated transport of the bulk, and parameters $R_n^{-1}$ and $R_a^{-1}$ are constants characterizing temperature non-activated and temperature activated contribution to the conduction, and are usually associated with metallic nature of the surface and insulating bulk, respectively. Our experimental data, depicted in Fig. 1, also indicate presence of temperature activated transport at lowest temperatures, below 0.5 K. Therefore we have made attempts to fit the data below 0.5 K using Eq. 1. However, we have found out that this type of regression formula is not suitable, and another model of electrical transport needs to be considered to describe the data.

Another mechanism of temperature activated electrical conductivity, typical for heavily doped and amorphous semiconductors at low temperatures, is variable-range hopping (VRH) between localized states in the vicinity of the Fermi level [11, 19]. In the most general form the resistivity in such case is given by

$$\rho(T) \propto \exp\left[(T_0/T)^p\right],$$

(2)

where $p$ depends on the dimensionality, $d$, of the system and the energy distribution of the density of localized states in the vicinity of the Fermi level. If the density of localized states near the Fermi level is constant or depends only slowly on energy, then $p = (d + 1)^{-1}$ [19], thus for $d = 3$ the temperature dependence of the resistivity follows the Mott’s law, i.e. $\rho(T) \propto \exp\left[(T_0/T)^{1/3}\right]$. Supposing that the electrical conduction of the studied SmB$_6$ sample can be described by the two-channel model, where one channel represents temperature non-activated contribution, and the second one is of a VRH type then it should be true that

$$R(T)^{-1} = R_n^{-1} + R_{3D}^{-1} \times \exp\left[-(T_{3D}/T)^{1/4}\right],$$

(3)

where parameters $R_{3D}^{-1}$ and $T_{3D}$ are constants characterizing VRH contribution to the bulk conduction, and $R_n^{-1}$ has similar meaning as in Eq. 1 (and in Eq. 4 below). It has been noticed that (significantly) increased
concentration of lattice imperfections, which may play role of hopping centers, is expected in the near-surface region of SmB$_6$, and therefore a strong enhancement of the conductivity in this region is expected [17]. Supposing that this near-surface region can be treated as a 2D layer, the resulting conduction can be written in the form

$$R^{-1}(T) - R^{-1}_n = R^{-1}_{2D} \times \exp\left[-\left(T/T_D\right)^{1/3}\right],$$

where $R^{-1}_{2D}$ and $T_D$ are constants characterizing VRH transport in this near-surface region.

Attempts to fit the experimental data at lowest temperatures using the regression formula expressed by Eq. 3 did not provided satisfactory result, thus indicating absence of VRH type of transport in the bulk of the sample at lowest temperatures. On the other hand, performed numerical analysis revealed that regression formula in the form of Eq. 4 is suitable for the fitting. As can be seen in Fig. 2, where the resistance data are plotted in coordinates $\ln(1/R - 1/R_n)$ versus $T^{-1/3}$, Eq. 4 provides excellent description of the data at temperatures below 0.45 K. The resulting fitting parameters $R_n = 710 \, \Omega$, $R_{2D} = 632 \, \Omega$ and $T_D = 6.85 \times 10^{-4} \, \text{K}$ were obtained based on the fit of the data from the temperature interval of 0.09 - 0.4 K. In accordance with the discussion above we take this as evidence that VRH transport in the near-surface region, being a consequence of significantly higher concentration of lattice imperfections in this region, is dominating temperature activated conduction mechanism in SmB$_6$ below $\approx 0.45 \, \text{K}$.

Now, let us focus on the data above 1 K. Several authors modeled electrical resistivity data of SmB$_6$ at
temperatures above 2 K by a formula equivalent to Eq. 1 [6–10]. However, performing numerical analysis of our data we have found out that although this formula is appropriate for a rough description of the experimental data at temperatures approaching 3 K, there is a systematic deviation of the fit by this type of formula from the experimental data. This can indicate that the temperature dependent two-dimensional VRH, which dominates at the lowest temperatures, is not negligible neither at temperatures approaching 3 K, so consideration of two-dimensional VRH is still needed to describe the electrical transport in SmB$_6$ above 1 K. Therefore we analyzed the conduction data above 1 K using a combination of Eq. 1 and Eq. 4 in the form

$$R(T)^{-1} = R_{a}^{-1} + R_{2D}^{-1} \times \exp\left[\left(-\frac{T_{2D}}{T}\right)^{1/3}\right] + R_{a}^{-1} \times \exp(-W_{a}/kT),$$

(5)

Indeed, taking into account not only the contribution due to the temperature activated conduction in the bulk (and the temperature non-activated term), but also the term due to the two-dimensional VRH, has lead to finding a proper fit of the data in the temperature range of 1.25 - 2.5 K. It is demonstrated in Fig. 3, where logarithm of the conduction data after subtraction of two-dimensional VRH contribution, $R_{2D-VRH}^{-1} = R_{2D}^{-1} \times \exp\left[-\left(\frac{T_{2D}}{T}\right)^{1/3}\right]$, and temperature non-activated conduction, $R_{a}^{-1}$, as determined from the data between 0.09 K and 0.4 K is plotted versus $T^{-1}$. The activation energy determined as the slope of the linear fit of the data from Fig. 3 in the range between 1.25 K and 2.5 K is $W_{a} = 0.32$ meV. We
associate this energy with the impurity-to-band activation energy of impurities (and lattice imperfections) forming the impurity band in the forbidden gap of SmB$_6$. (Note that $W_a$ is nearly one order of magnitude less than the energy of activation process governed by the forbidden gap, $W$, determined for this sample previously [18].)

Analysis performed above indicates that electrical transport in SmB$_6$ above 1 K can be adequately explained considering two temperature activated terms, which we predominantly associate with the conduction of the bulk, $R_a^{-1} \times \exp(-W_a/kT)$, and the two-dimensional VRH conduction in the near-surface region, $R_{2D}^{-1} \times \exp[-(T_{2D}/T)^{1/3}]$. The additional temperature non-activated term ($R_n^{-1}$) can be in accordance with existing models ascribed to metallic surface states, which can be either trivial [16] or topologically protected [12–15], or alternatively it can be associated with valence-fluctuation induced hopping transport [17].

4. Conclusions

Performed electrical resistance studies of the single-crystalline SmB$_6$ sample reveal that there is no true saturation of the electrical resistance down to temperature as low as 70 mK. The electrical conduction in a
certain temperature interval above 70 mK can be described by the two-channel model with a temperature independent (metallic-like) term and temperature activated term corresponding to variable-range hopping conduction in two-dimensional systems, which can be associated with an enhanced conduction in the near-surface region. The three-channel model, considering moreover temperature activated conduction from the bulk, is needed to describe the experimental data above 1 K. Our results moreover indicate that precision resistance measurements down to millikelvin temperatures are needed for reliable conclusions about the ground state of SmB$_6$.

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