Crossover in the Colossal Magnetoresistance Anisotropy in EuB$_6$

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Abstract. The angular dependent resistivity and magnetization have been measured on the single crystals of colossal magnetoresistance compound EuB$_6$ at temperatures $T<50$ K in magnetic fields below 80 kOe. It is found that the transition from negative (NMR) to positive (PMR) magnetoresistance $\Delta\rho/\rho(H)$ is accompanied by the change of the transverse magnetoresistance anisotropy (MRA) while the static magnetization remains to be almost isotropic. The quantitative analysis of $\Delta\rho/\rho(\phi,H_0,T_0)$ data ($\phi$ is the angle between applied magnetic field and <001> axis, the rotation axis is along <110> direction) allows to estimate a field dependence of MRA characteristic temperature $T\{K\}=8+0.4H[kOe]$, which corresponds to the change of the largest NMR amplitude from $H||<100>$ ($T<T'(H)$) to $H||<110>$ ($T>T'(H)$). A maximal amplitude of PMR established in ferromagnetic state below 12K is detected for magnetic field applied close to <111> direction. The observed change in MRA is discussed in terms of crossover from the spin polaronic regime of charge transport in paramagnetic phase to the band conductivity in magnetically ordered state.

1. Introduction
The electronic structure of europium hexaboride EuB$_6$, which is characterized by the two consecutive transitions (ferromagnetic (FM) ordering below $T_C\sim 12.5-14$ K and metal-semiconductor transition at $T_m\approx 15.7$ K), is intensively discussed during last decade. The band structure calculations [1], quantum oscillations measurements [2] and Andreev reflection study [3] favor the semimetal picture with a small overlap of the conduction and valence bands resulting to small electron/hole ellipsoids at the X points. However, the magnetotransport data [4] as well as the results of photoemission spectroscopy [5] support a semiconducting band structure in the intermediate temperature paramagnetic (PM) state of EuB$_6$. In this respect the study of angular dependent resistivity would provide an important information about both the symmetry of Fermi surface and its evolution with the onset of low temperature FM state in this colossal magnetoresistance compound.

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2. Experimental results and discussion

The combined study of transport and magnetic properties has been carried out on the single crystals of EuB₆ at temperatures 1.8-300 K in magnetic fields up to 80 kOe. The single crystals have been grown by the crucible-less inductive zone melting in argon gas atmosphere. X-ray and SEM analysis were used to control the high quality of the samples under investigation. The measurements of angular dependent resistivity $\Delta \rho / \rho (\phi, H_0, T_0)$ were produced with the help of sample rotation technique previously described in details in [6]. The temperature, field and angular dependencies of magnetization were measured on the same single crystals by using of the vibrating sample and SQUID magnetometers. The magnetic data obtained were used as reference ones to take account of the strong demagnetization effects in this FM system.

The field dependencies of magnetoresistance measured on the EuB₆ single crystal for current and magnetic field applied along <110> and <001> axes, respectively (figure 1), agree well with the previous reports [2,4]. It is seen from the data of Figure 1 that the negative magnetoresistance (NMR) dominates in the PM state of EuB₆ resulting in the colossal magnetoresistive effect in the vicinity of the FM transition. The positive magnetoresistance (PMR) is detected only in the high field limit at low enough temperatures (inset in figure 1).

A study of the angular dependent resistivity in the wide range far from magnetic and metal-semiconductor transitions allows to identify the crossover in the transverse magnetoresistance anisotropy (MRA). Particularly, the normalized resistivity data $\rho(\phi)/\rho(0)$ detected in steady magnetic field $H_0=80$ kOe (figure 2) evidently demonstrate the change of direction corresponding to the largest NMR effect from $H_0||<100>$ ($T<40$ K) to $H_0||<110>$ ($T>40$ K). Besides, an angular dependent positive contribution to magnetoresistance, which achieves the maximal values for magnetic field applied close to <111> direction, could be well resolved in the experimental data of figure 2.

To analyze quantitatively the angular dependent resistivity curves we used the equation including the second and fourth harmonics:

$$\rho(\phi)=\rho(0)(1+A_2\cos(2\phi)+A_4\cos(4\phi+\Delta \phi)), \quad (1)$$

where $\rho(0)$ is the average value of resistivity, $A_2$ and $A_4$ are the amplitudes of second and forth harmonics, respectively, and $\Delta \phi$ is the phase shift between them. The temperature dependencies of the...
corresponding parameters $A_2$, $A_4$ and $\Delta \phi$ obtained by fitting of the experimental data are presented in figure 3. The data obtained at $H_0=80$ kOe (figure 3) demonstrate the crossover in the colossal magnetoresistance anisotropy, which is characterized by the inversion of $A_2$ sign at $T \approx 40$ K. Besides, the fourth harmonic contribution $A_4$ drastically grows below 40 K dominating in the FM state at $T<10$ K (figure 3). Note also that at low temperatures the phase shift $\Delta \phi$ tends to the 45° value (inset in figure 3) that differs noticeably from the angle between <001> and <111> axes to be equal 54.7°.

When analyzing the angular dependencies of resistivity in the case of magnetic materials a special attention should be paid to the correct evaluation of demagnetization effects, which strongly reduce the internal magnetic fields in plated samples. To allow for the demagnetizing field, the angle and field dependent magnetization of the same samples used for transport measurements has been analyzed. The results distinguished an almost isotropic character of the static magnetization both in the FM and PM states so the observed MRA effects (figures 2-3) cannot be attributed to the magnetic anisotropy. Besides, the magnetization study allows us to estimate the sample’s demagnetization factors $4\pi N$ to be equal 5.22, 3.83 and 4.6 for <100>, <110> and <111> directions, correspondingly. The field dependencies of magnetoresistance $\Delta \rho/\rho(\phi,H_0,T_0)$, which were determined by taking into account the

**Figure 2.** The angular dependencies of normalized resistivity $\rho(\phi)/\rho(0)$ measured for various temperatures below 100K in steady magnetic field $H_0=80$ kOe. $\phi$ is the angle between the applied field and <001> direction, the current through the sample and the axis of rotation are parallel to <110> axis. Note the different scales upper and below the y axis brake. Dash, dotted and dash-dotted vertical lines correspondingly indicate the <110>, <111> and <110> directions.

**Figure 3.** The amplitudes of harmonic contributions to magnetoresistance estimated from the $\rho(\phi)/\rho(0)$ curves at $H_0=80$ kOe within (1). Inset shows the phase shift $\Delta \phi$ between the second and forth harmonics (see text). Dash lines correspond to $\Delta \phi=45^0$ and $\Delta \phi=54.7^0$. 
demagnetization effects, are shown in figure 4. The data of figure 4 demonstrate that the MRA detected in the PM phase is partially resulted from the demagnetization effects. In contrary, the comparison of the \( \Delta \rho/\rho \)(H) curves on the upper panel of figure 4 shows that the strong anisotropy of the positive magnetoresistance at \( T<12 \) K is an intrinsic property of the FM state of EuB\(_6\).

![Figure 4. The field dependencies of magnetoresistance estimated from the \( \Delta \rho/\rho(\phi,H_0,T_0) \) data for various orientations of the sample in magnetic field. The magnetic field values are corrected to take into account the demagnetisation fields.](image)

The \( \Delta \rho/\rho(\phi,H_0,T_0) \) data (figures 3-4) reveal a strong field dependence of the crossover temperature \( T^* \), which approximately follows the linear law \( T* \approx 8+0.4H[\text{kOe}] \). In our opinion, the explanation of the crossover in MRA observed in the PM state of EuB\(_6\) requires the adequate consideration of spin polaronic effects, which seem to result in the huge renormalization of charge carriers’ effective mass in PM phase of this compound [7]. However, more detailed measurements of transport and magnetic properties in the vicinity of FM transition are required to understand the peculiarities of crossover between the spin polaronic regime of charge transport in PM state and the band conductivity in magnetically ordered state.

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