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Fluctuation induced conductivity of polycrystalline MgB_2 superconductor

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Abstract We report fluctuation-induced conductivity (FIC) of the polycrystalline MgB_2 superconductor in the presence of magnetic field. The results are described in terms of the temperature derivative of the resistivity, $d\rho/dT$. The $d\rho/dT$ peak temperature observed for $H = 0$ Tesla at 39 K remains very distinct under applied fields of 6 Tesla and 8 Tesla at 22 and 20 K respectively. Aslamazov and Larkin (AL) equations are used to explain the anisotropic nature of the polycrystalline MgB_2. The effective coherence length, ξ_p (0) determined experimentally is 55.17 Å, which roughly matches with previously reported experimental work.

Introduction

The recently discovered MgB_2 [1] superconductor exhibits the order parameter fluctuations as we increase the magnetic field. Several experimental studies of specific heat [2], critical current density [3], Raman scattering [4] and magnetoresistivity [5] have been reported so far. Fabris and co-workers [6] reported the temperature derivative of the resistivity of MgB_2 system near the transition temperature. MgB_2 engrosses a simple hexagonal structure (AlB_2-type space group P6/mmm) comprising graphite type B layers interleaved with Mg layers [7]. The lattice parameters are $a = 3.086$ Å and $c = 3.524$ Å. Band structure calculations reveal that, while strong covalent B–B bonds are retained, Mg is fully ionized [8]. The interlayer separation of B–B plane is equal to $a/\sqrt{3} \sim 1.782$ Å, while the Mg–Mg distance in the plane is equal to lattice constant a. The charge carriers are situated in essentially two-dimensional (2D) bands derived from the σ bonding $p_{x,y}$ orbitals of boron, and in one electron and one hole band derived from the π-bonding p_z orbitals of boron. There is considerable experimental evidence (boron isotope effect [9], scanning tunneling experiments [10], negative pressure coefficient of T_c [11]) that a conventional phonon-mediated pairing mechanism can account for the superconducting properties of MgB_2, in which a key role is played by the 2D σ-band of $p_{x,y}$ orbitals within the boron layers.

A two-gap model was innovated to explain the mechanism of critical field, specific heat and tunneling. σ and π bands [12] have very distinct character to each other. σ bands being of hole type while the π bands belong to electron type. These two bands may actually be associated to the two peculiar superconductive gaps, Δ_σ and Δ_π. It has been discussed that the B–B planes are similar to the $Cu–O_2$ planes in high T_c cuprates [13]. Sidorenko deals with an experimental investigation of the resistive transition broadening of the MgB_2 thin films using by thermally activated flux flow (TAFF) mechanism [14].

In this paper, we grope the fluctuation-induced conductivity (FIC) in polycrystalline samples of pristine MgB_2 in presence of anomalous magnetic field ($H = 0$ T, 6 T and 8 T). There is no exact theory available so far which can describe the FIC of the polycrystalline sample but here we

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have discussed the modified Aslamazov and Larkin (AL) equations, which are explained by Ghosh et al. [15] to analyze the FIC of the polycrystalline samples. Sample was prepared by the standard solid-state reaction technique. The results are endorsed in terms of the temperature derivative of the resistivity, $d\rho/dT$. A clear single peak structure is observed in $d\rho/dT$ vs. T plot as the strong applied field of 6 T and 8 T.

Experimental details

Our MgB_2 samples were synthesized by encapsulation of well mixed and palletized high quality (above 3 N purity) Mg and B powders with some added Mg turnings in a soft Fe-tube and its subsequent heating to 750 °C for two and half hours in an evacuated (10^{-5} Torr) quartz tube and quenching to liquid-nitrogen temperature. Resistivity measurements are carried out by four-probe technique under applied field of up to 8 Tesla.

Theoretical formulations

MgB_2 possesses simple hexagonal structure with anisotropic conductivity. The pure MgB_2 manifests that Mg–B bond length, B–Mg–B and Mg–B–Mg bond angles do not correlate with T_c, suggesting that these notions do not perturb the transition temperature [16] while Mg–Mg and B–B bonds are the critical structural parameters that correlate with T_c. Thermodynamic fluctuations prevail due to the change in number of Cooper pairs in these planes. It has been explicitly revealed that the B–B planes are akin to the Cu–O_2 planes in high T_c cuprates [13]. In these planes when variation in number of Cooper pairs occurred, then thermodynamic fluctuations produces. Yet, the resistivity of the chains does not vary with the applied temperature it concludes that the fluctuation is absent in B–Mg–B and Mg–B–Mg chains of pristine MgB_2, which can emphatically contribute to conductivity. The conductivities along a and b directions are given by $\sigma_a = \sigma_{pl}$ and $\sigma_b = \sigma_{pl} + \sigma_{ch}$. Here σ_{pl} and σ_{ch} show the conductivities of B–B planes and chains, respectively. Now the fluctuations of the above conductivities can be written as

$$\Delta\sigma_a = \Delta\sigma_{pl}, \tag{1}$$

$$\Delta\sigma_b = \Delta\sigma_{pl} + \Delta\sigma_{ch}. \tag{2}$$

It is found that the energy gap is absent in the conductivity of the chain of MgB_2 superconductor. It may be argued that there is no contribution of the chain in the FIC. So, we use $\Delta\sigma_{ch} = 0$. From the above Eqs. (1) and (2), we find

$$\Delta\sigma_b = \Delta\sigma_a. \tag{3}$$

We have taken into account the polycrystalline sample of MgB_2 as minuscule spherical grains that are randomly oriented in the entire system [17]. The FIC is described experimentally from the relation

$$\Delta\sigma = \frac{1}{\rho_m} - \frac{1}{\rho_n} \tag{4}$$

Here ρ_m and ρ_n are the measured resistivity and resistivity smear out from the extrapolation from nth order polynomial at the same temperature, respectively. $\Delta\sigma$ is confined in the substantial B–B layers of the MgB_2 superconductors. So, we may precursor the polycrystalline sample to be a system of minuscule spherical grains where a and c directional FIC are randomly oriented. By using the concern electrostatic equation embodied with Green function formalism, we find the FIC of the polycrystalline sample in 2D and 3D limit as follows:

$$\Delta\sigma_p^{2D} = \frac{1}{4}\left\{\frac{e^2}{16\hbar d}\in^{-1}\left[1+\left(1+\frac{8\xi_c^4(0)}{d^2\xi_{ab}^2(0)}\in^{-1}\right)^{1/2}\right]\right\}. \tag{5}$$

$$\Delta\sigma_p^{3D} = \frac{e^2}{32\hbar\xi_p(0)}\in^{-1/2}, \tag{6}$$

where the reduced temperature $\in = (T - T_c^{mf})/T_c^{mf}$ and T_c^{mf} is the mean field critical temperature of the polycrystalline sample which can be obtained from peak of the $d\rho/dT$ vs. T plot and ξ_p (0) is an effective characteristic coherence length which may be used as an independent parameter for characterizing the polycrystalline samples. It may be represented as

$$\frac{1}{\xi_p(0)} = \frac{1}{4}\left[\frac{1}{\xi_c(0)} + \left(\frac{1}{\xi_c^2(0)} + \frac{8}{\xi_{ab}^2(0)}\right)^{1/2}\right]. \tag{7}$$

We can calculate the value of ξ_p (0) from Eq. (7) by substituting ξ_c (0) and ξ_{ab} (0). Using the Ginzburg-Landau (G-L) mean coherence length, $\xi(T) = \xi_0 (1 - T/T_c)^{-0.5}$, one finds ξ_{ab} (0) = 70 Å and ξ_c (0) = 40 Å. Equations (5–7) are taken from the reference [14]. The fluctuation conductivities of Eqs. (5) and (6) are equal to crossover temperature, T_0^p . At this temperature the sample tolerate neither 2D nor 3D and given by

$$T_0^p = T_c\left[1+\frac{\xi_p^2(0)}{d^2}\left(1+\frac{\xi_p^2(0)}{16\xi_{ab}^2(0)}\right)\right], \tag{8}$$

It is clear from the theoretical as well as experimental observation that ξ_p (0) ≪ ξ_{ab} (0), Eq. (8) reduces to the Eq. (9).

$$T_0^p = T_c\left[1+\left(\frac{\xi_p(0)}{d}\right)^2\right], \tag{9}$$

We purport the above-described formalism to emphasize the FIC in anomalous magnetic fields.

Results and discussion

The resistivity versus temperature measurements under different magnetic field 0 T ≤ H ≤ 8 T for polycrystalline MgB_2 superconductor is shown in Fig. 1. These results endorse that as the magnetic field increases the transition temperature, T_c of sample decreases correspondingly. These plots also show the deviation from the temperature, T_B. We assume that T_B is that temperature from where the plot shows the non-linearity. It is to be noted that in Fig. 1 plot show the linearity from T_B = 300 K to T_B = 200 K and become non-linear beyond this temperature limit. T_B is assumed to be the temperature below which the establishment of Cooper pair formation starts. The different transition temperatures at different magnetic fields are shown in Table 1. Inset of Fig. 1 depicts the magnifying plot of resistivity versus temperature near the transition temperature of MgB_2 system.

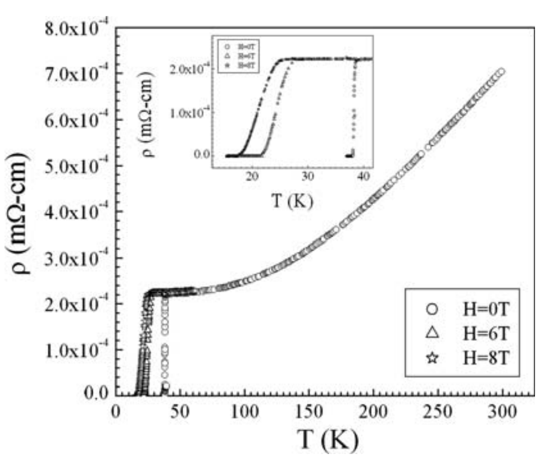

Fig. 1 Temperature dependence of resistivity plot for polycrystalline MgB_2 system in 0 T ≤ H ≤ 8 T, inset shows the extended part of the same

Table 1 T_c (K), $T_c^{mf}(K)$ and $T_B(K)$ of polycrystalline MgB_2 sample at different magnetic fields

MgB_2 sample	T_c (K)	T_c^{mf} (K)	T_B (K)
H = 0 T	39.0	73.8	200
H = 6 T	22.0	24.4	200
H = 8 T	20.0	20.8	200

Figure 2 shows the plot of temperature derivative of the resistivity for polycrystalline MgB_2 in different magnetic fields. From the peaks of these curves T_c^{mf} (mean field critical temperature) have been taken into account. The peak at H = 6 T has resemblance with the peak at H = 8 T but observed after some shifting, there is no similar fluctuation of peak observed at H = 0 T. The fluctuation at H = 0 T for $T_c^{mf} = 73.8\,K$ is very distinct from 6 T and 8 T and most probably originated from the temperature fluctuation between the sample and the thermometer. The T_c^{mf} for H = 6 T and 8 T are observed at 24.4 K and 20.8 K, respectively. The transition temperature, T_c, observed at H = 0 T, 6 T and 8 T are 39, 22 and 20 K, respectively. Inset of Fig. 2 shows the extended part in the vicinity of transition temperature of MgB_2 system under applied magnetic fields.

Figure 3 endorses the relation between $\Delta\sigma$ ∈ and $\in^{-1}$. We have taken that $d \gg \xi_c^2$ (0)/ξ_{ab} (0) then recalling the first order term in Eq. (5) we find

$$\Delta\sigma_p^{2D} = A \in^{-1} + B \in^{-2} \tag{10}$$

where A and B are temperature independent factors determined as

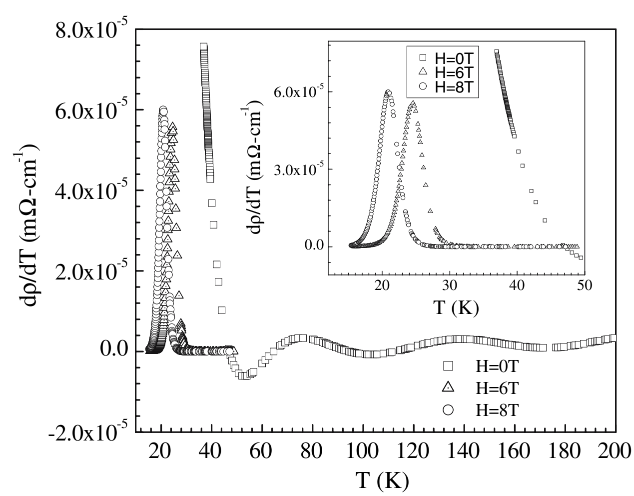

Fig. 2 Temperature derivative of the resistivity for polycrystalline MgB_2 in different magnetic fields, inset shows the extended part of the same

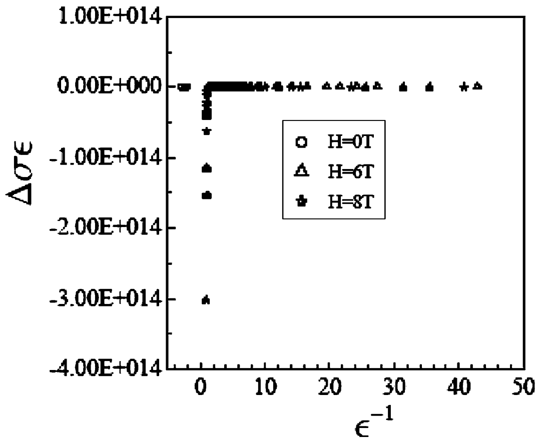

Fig. 3 The variation of $\Delta\sigma \in$ vs. $\in^{-1}$ of polycrystalline MgB_2 in anomalous magnetic fields

$$A = \frac{e^2}{32\hbar d}, \tag{11}$$

$$B = \frac{e^2 \xi_c^4(0)}{16\hbar d^3 \xi_{ab}^2(0)} \tag{12}$$

It is to be noted that if $A \gg B$, then the fluctuation observed in the vicinity of higher temperature would be 2D in nature because of the high anisotropic nature of the samples. If $A \ll B$, the exponent becomes –2 which belongs to the zero-dimensional (0D) fluctuations.

To elaborate the second term of Eq. (10) we plotted the $\Delta\sigma \in$ vs. $\in^{-1}$ in Fig 3, this plot becomes linear when the inverse of reduced temperature, $\in^{-1}$ decreases. Several studies have been done to determine the coherence length of the MgB_2 single crystal. For the single crystal of MgB_2 superconductor the coherence length in *ab* and *c* direction are ξ_{ab} (0) = 70 Å and ξ_c (0) = 40 Å, respectively [18]. From the Eq. (7), the effective coherence length, ξ_p (0) for polycrystalline sample of MgB_2 superconductor is determined experimentally to be 55.17 Å, which is approximately equal to the experimental value 50 Å [19]. The presumption of minuscule spherical nature of the grains might affect the evolution of ξ_p (0).The detailed discussion of our experimental work of temperature derivative of the resistivity for polycrystalline bulk MgB_2 in different magnetic fields is presented in Ref. [20].

Conclusions

From the detailed discussion of temperature derivative of resistivity we recognize the FIC in the vicinity of transition temperature of polycrystalline MgB_2 superconductor. Temperature dependence of resistivity at 6 T and 8 T are distinct to each other. The peaks obtained in Fig. 2 clearly explained the anomalous behaviour of temperature dependence of resistivity at 6 T and 8 T by T_c^{mf}. As magnetic field increases the T_c and T_c^{mf} decreases but T_B remains constant up to 200 K. Here we employed the modified AL equations for polycrystalline MgB_2 system. It is evident that anomalous fluctuations of the resistive transition have been observed in several high temperature cuprate superconductors [21], which are electronically and structurally much more complex than MgB_2. The experimentally estimated effective coherence length in this paper is roughly matched with the previous calculated experimental work [9].

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