Physica C 469 (2009) 106–110

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

# Hump structure below $T_c$ in the thermal conductivity of $MgB_2$ superconductor

R. Lal [a], Arpita Vajpayee [a], V.P.S. Awana [a,*], H. Kishan [a], A.M. Awasthi [b]

[a] National Physical Laboratory, Dr. K.S. Krishnan Marg, New Delhi 110012, India
[b] UGC-DAE Consortium for Scientific Research, University Campus, Khandwa Road, Indore 452017, India

ARTICLE INFO

*Article history:*
Received 25 November 2008
Accepted 12 December 2008
Available online 24 December 2008

*PACS:*
74.70.Ad
74.25.Fy

*Keywords:*
$MgB_2$
Thermal conductivity

ABSTRACT

A reasonable cause of absence of hump structure in thermal conductivity of $MgB_2$ below the superconducting transition temperature ($T_c$) lies in the appearance of multigap structure. The gaps of lower magnitude can be suppressed by defects so that this system becomes effectively a single-gap superconductor. When such a situation is created, it is hoped that thermal conductivity ($\kappa$) will show hump below $T_c$. Proceeding along these lines, a sample of $MgB_2$ with a relatively higher residual resistivity $\rho_o = 33.8\ \mu\Omega$ cm has been found to show a hump structure below $T_c$. The actual electronic thermal conductivity $\kappa_{el}$ of this sample is less than that expected from the Wiedeman–Franz law by more than a factor of 2.6 in the considered temperature range.

Modifying the Wiedeman–Franz law for the electronic contribution by replacing the Lorenz number $L_0 = 2.45 \times 10^{-8}\ \mathrm{W\,\Omega\,K^{-2}}$ by an effective Lorenz number $L_{eff}$ ($<L_0$) we have obtained two sets of $\kappa_{el}$, namely those with $L_{eff} = 0.1L_0$ and $0.2L_0$. Corresponding to these two sets of $\kappa_{el}$, two sets of the phonon thermal conductivity $\kappa_{ph}$ are obtained. $\kappa_{ph}$ has been analyzed in terms of an extended Bardeen–Rickayzen–Tewordt theory. The main result of this analysis is that the hump structure corresponds to a gap ratio of 3.5, and that large electron-point defect scattering is the main source of drastic reduction of the electronic thermal conductivity from that given by the usual Wiedeman–Franz law.



## 1. Introduction

The $MgB_2$ superconductor was discovered by Nagamatsu et al. [1] in 2001. It involves two types of carriers – one corresponding to the two-dimensional (2D) $\sigma$ band, and the other corresponding to the three-dimensional (3D) $\pi$ band [2]. The dominant effect of superconductivity takes place only in the $\sigma$ band [2], although $\pi$ band also takes part in the superconductivity [3]. The interaction responsible for the superconductivity is the electron–phonon interaction [2,3]. In the normal state the resistivity of the $MgB_2$ metal is also caused by the electron–phonon interaction in a defect-free sample [4]. There has been an intensive study of almost all the types of physical properties of the $MgB_2$ superconductor in both the super conducting and normal states, and thus sufficient progress has been made to understand the behavior of this compound [5]. In particular, the thermal conductivity has been investigated by a large number of workers [6–16] by considering various forms of the $MgB_2$ system, like different defect levels, different types of doping, and single or polycrystalline samples. The studies of the thermal conductivity ($\kappa$) of $MgB_2$ made by Sologubenko et al. [9,13], Wu et al. [15] and Anshukeva et al. [16] is limited to low temperatures ($T \leqslant 100$ K) only and in these studies $\kappa$ increases with temperature $T$ within the considered temperature range. Other authors [6–8,10–12,14] have studied the thermal conductivity up to much higher temperature range ($T \leqslant 250$ K [7], $T \leqslant 275$ K [10,11], $T \leqslant 300$ K [6,8,12,14]). The general behavior of $\kappa$ with $T$ is that initially $\kappa$ increases with $T$ attaining a maximum value at some temperature $T_{max}$. The values of $T_{max}$ are 112 K, 118 K, 66 K, 66 K and 66 K for the samples of Refs. [6–8,10,11], respectively. The behavior of the $MgB_2$ sample of Ref. [12] is quite complicated, and we have considered only the MgB11-15 sample of Ref. [11]. The samples of Ref. [14] does not show any maximum in $\kappa$ till $T = 300$ K. The MGB-TS sample of Ref. [10] also does not show any maximum till 275 K. Another general feature of $\kappa$ is that in some cases [6,7,14], $\kappa$ increases with $T$ near room temperature, while in another cases [8,11] $\kappa$ continues to decrease after $T_{max}$ up to the highest measured temperature.

It is well established that the superconducting state of the $MgB_2$ superconductor shows two finite gaps at the Fermi energy at $T = 0$ K [17–20]. One of these gaps corresponds to the $\sigma$ band, while the other to the $\pi$ band. From a superconductor of finite gap(s) we expect according to BRT theory [21,22] a hump below $T_c$ in the thermal conductivity. But a weak hump is reported only by Anshukeva et al. [16] below $T_c$, as none of the other existing reports [6–15] show a hump structure in thermal conductivity below $T_c$. Various authors interpret the absence of a hump structure in $\kappa$

* Corresponding author. Tel.: +91 11 45608329; fax: +91 11 45609310.
*E-mail address:* awana@mail.nplindia.ernet.in (V.P.S. Awana).
*URL:* http://www.freewebs.com/vpsawana/ (V.P.S. Awana).

0921-4534/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2008.12.005

below $T_c$ in various ways. It has been argued in particular by Sologubenko et al. [8] that absence of the hump structure is possible if the energy gap is about three times smaller than the values given by the original Bardeen–Cooper–Schriffer (BCS) theory [23]. But the reported energy gap at zero temperature, $2\ \Delta(0)$ is found to be 4.1 $k_BT_c$ by Chen et al. [17], and 4.3 $k_BT_c$ by Lui et al. [3] for the $\sigma$ band. This means that the superconducting energy gap is certainly much larger than one third of the BCS gap $2\Delta_{BCS}(0) = 3.5k_BT_c$. Other possible reason for absence of the hump structure is that the electron–phonon interaction is much weaker than phonon-defect scattering. This is shown to be incompatible with the situation that exists in $MgB_2$ [8]. Yet another possible reason is that the phonon contribution to the thermal conductivity is small near $T_c$. This is also shown incompatible with the situation of $MgB_2$ [8]. At present the most reasonable source of absence of hump structure below $T_c$ in $MgB_2$ is the possibility $MgB_2$ is a multigap superconductor [3,8].

The multigap structure of the superconductivity of $MgB_2$ may correspond to the clean limit [3] or dirty limit [24] depending upon the nature of the sample. For a $MgB_2$ sample of residual resistivity $\rho_o = 2.0\ \mu\Omega$ cm, Sologubenko et al. [8] find $\ell \approx 800$ Å. The coherence length of the polycrystalline sample of $MgB_2$ is $\xi \approx 52$ Å [25]. This means $MgB_2$ will no more be in the clean limit if $\rho_o$ is enhanced by a factor of 15 or more, i.e. if $\rho_o \geqslant 30\ \mu\Omega$ cm. When this condition is met we hope the multigap nature of the superconducting state to change to a single-gap case, thereby making it possible to observe a hump in $\kappa$ *vs.* $T$ below $T_c$. On these lines we have prepared a sample of $MgB_2$ with $\rho_o = 33.8\ \mu\Omega$ cm, and have indeed observed a clear hump in $\kappa$ *vs.* $T$ curve below $T_c$. Here it may however be noted that the MGB-TS sample of Putti et al. [10] corresponds to $\rho_o = 39.0\ \mu\Omega$ cm. Despite this these authors have not observed any hump in the thermal conductivity below $T_c$.

## 2. Experimental data

Synthesis of polycrystalline bulk sample of $MgB_2$ is described by Awana et al. [26]. Micro-structural details and measurements of various physical properties, including X-ray diffraction, magnetization, electrical resistivity and thermal conductivity are also described in Ref. [26]. For clarity here we reproduce the behavior of XRD, magnetization, electrical resistivity and thermal conductivity in Figs. 1 and 2. The resistivity has been measured up to 300 K and the thermal conductivity has been measured from 18 K to 300 K. The micro-structural analysis of Awana et al. [26] shows that the grains of $MgB_2$ have excellent connectivity, and in particular there is no evidence of cracks in the system. Thus the present thermal conductivity data corresponds to the actual behavior of the $MgB_2$ sample. The fact that the observed thermal conductivity appears to be lowest than those of other authors [6–16] does not point to any inconsistency. This is because the residual resistivity $\rho_o$ is much higher in the present case than most of the other reports [6–16]. In fact, we found that the present value of $\rho_o$ is comparable to the MGB-TS sample of Putti et al. [10] where $\rho_o = 39.0\ \mu\Omega$ cm. Thus we should compare our $\kappa$ results with those of these authors only. When we do so, it turns out that the values of $\kappa$ are 3.1 W/m K and 4.5 W/m K at $T = 25$ K and 100 K, respectively, in the present case, while the corresponding values of $\kappa$ for the MGB-TS sample of Putti et al. [10] are 2.0 W/m K and 6.1 W/m K. Obviously these values are comparable, signifying that low value of $\kappa$ in the present case are due to higher $\rho_o$, and not due to cracks, etc.

## 3. Results and discussion

From the magnetization of Fig. 1 we find that the present sample of $MgB_2$ superconducts at $T_c = 37.3$ K. From the peak of the

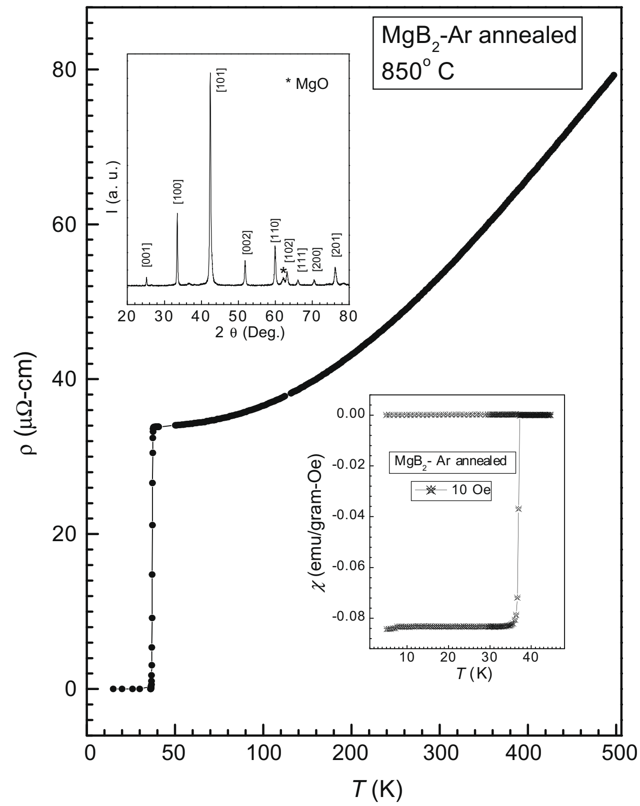


**Fig. 1.** Observed resistivity $\rho(T)$ of the $MgB_2$ sample up to 300 K. The upper inset shows the X-ray diffraction, and the lower inset shows the magnetization $M$ for $T \leqslant 45$ K.

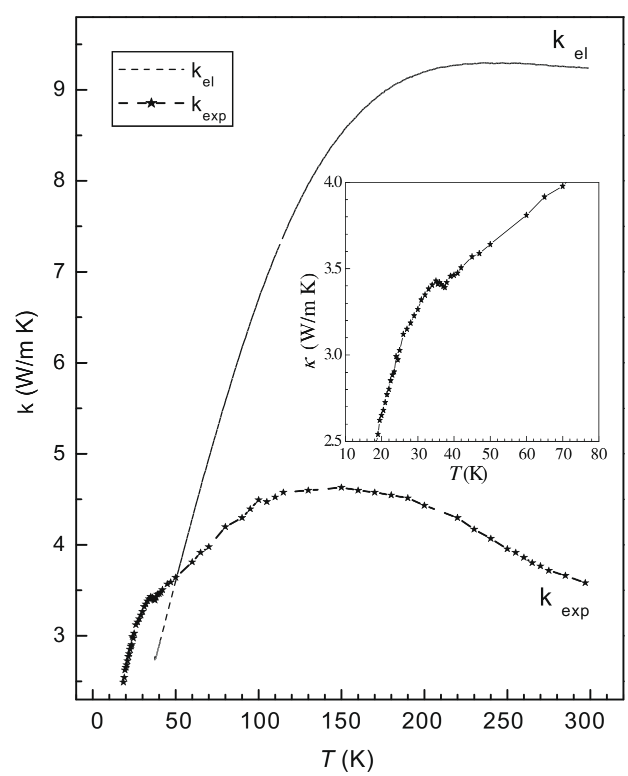


**Fig. 2.** Observed thermal conductivity $\kappa$ of the $MgB_2$ sample from 18 K to 300 K. The dashed line corresponds to the electronic thermal conductivity $\kappa_{el} = L_oT/\rho(T)$. The inset shows the thermal conductivity near the superconducting transition temperature $T_c$.