Enhancement of thermal conductivity in the superconducting state of Co-doped BaFe$_2$As$_2$

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Abstract. We report the thermal conductivity in Co-doped BaFe$_2$As$_2$ at under-, optimal-, and over-doping levels. We find the enhancement of the thermal conductivity divided by temperature $\kappa/T$ in the superconducting state at all doping levels, which is strikingly similar to those observed in the strongly correlated superconductors, such as high-$T_c$ cuprates and heavy fermion systems. We also find that the enhancement of $\kappa/T$ is strongly suppressed by applying magnetic fields. The analysis based on the vortex-scattering model unveils that the enhancement of $\kappa/T$ originates from the steep increase of the quasi-particle mean-free path possibly due to the reduction of the inelastic scattering in the superconducting state. Strong enhancement of $\kappa/T$ of over-doping level may suggest that quasiparticle population still remains even at low temperatures.

1. Introduction
Since the discovery of iron-based superconductors LaFeAs(O,F) with $T_c = 26$ K [1], the high temperature superconducting mechanism has attracted great interest. To elucidate the pairing mechanism, it is important to investigate the superconducting gap structure closely associated with the superconducting pairing interaction. Theoretically, fully gapped $s$-wave state with opposite signs between different Fermi surfaces $s_{\pm}$ wave has been proposed [2]. Although several experiments in favor of $s_{\pm}$ wave have been reported, recent studies suggest that in some iron-based superconductors, e.g., BaFe$_2$(As,P)$_2$ [3], the gap is nodal on a part of the Fermi surface, and the gap structure in iron-based superconductors is still controversial. To elucidate the details of superconducting gap structure, heat transport is very useful because heat transport is well known to provide valuable information on the low-energy excitation of quasiparticles in the superconducting state and scattering mechanism in the normal state, which is also closely associated with pairing interaction. In order to clarify the details of superconducting gap structure and scattering mechanism, we measure the thermal conductivity for Co-doped iron-arsenide BaFe$_2$As$_2$ under magnetic field.

2. Experimental
Single-crystalline samples of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ were grown by the FeAs/CoAs self-flux method and their fundamental properties are reported in Ref [4, 5]. A mixture with a ratio of Ba : FeAs/CoAs = 1 : 5 was placed in an alumina crucible. The whole assembly was sealed in a large silica tube, and heated up to 1150 °C and kept there for 10 h followed by slow cooling.
down to 800 °C at a rate of ~ 2 - 5 °C/h. The average Co concentration in each batch was determined by energy dispersive X-ray spectroscopy measurements. For thermal transport measurements, crystals with typical dimensions of ~ 2 × 0.3 × 0.03 mm³ were used. A one-heater-two-thermometer steady-state method was used to measure thermal conductivity. Heat current was aligned within the ab plane of the sample and the magnetic field is applied along the c axis. The same contacts and gold wires were used to measure the resistivity of the sample by a standard four-contact method.

3. Results and Discussion

Figure 1 shows the temperature dependence of thermal conductivity divided by temperature $\kappa/T$ for $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$ under several magnetic fields. Below $T_c = 13.4$, 23.1, and 12.5 K for $x = 0.045$, 0.070 and 0.113 obtained from zero resistivity, respectively, $\kappa/T$ shows a strong enhancement, especially in over-doped sample. In the normal state above $T_c$, at $x = 0.045$ and 0.113, a broad peak around $T \sim 15$ K is observed. While the broad peak is robust against applying magnetic field, the strong enhancement below $T_c$ is drastically suppressed by magnetic fields for all doping levels. We note that the enhancement of thermal conductivity below $T_c$ is observed in strongly correlated materials such as high temperature cuprate superconductors [6] and heavy fermion superconductors [7].

To extract the electronic contribution to the heat transport, we analyze the thermal conductivity using the vortex scattering model in the mixed state [8]. In this system, total thermal conductivity is given by the sum of electronic and phononic parts, $\kappa = \kappa_{el} + \kappa_{ph}$. For $x = 0.045$, we assume that magnon contribution to the heat transport is negligibly small because the present temperature $T \lesssim 10$ K and field range $\mu_0 H < 9$ T is much smaller than the energy scale of antiferromagnetic excitation $\sim k_B T_N \sim 80$ K. In the vortex scattering model, $\kappa$ is written by

$$\kappa(T, H) = \frac{\kappa_e(T, 0)}{1 + \alpha(T)|H|} + \kappa_{ph}(T),$$

where $\alpha = \ell_0 \sigma_{tr}/\phi_0$ with $\sigma_{tr}$ the vortex cross-section presented to an incident quasiparticle. The eq. (1) is obtained assuming the Matthiesen’s rule in magnetic field, $1/\ell = 1/\ell_0 + 1/\ell_v$, where $\ell_0$ is quasiparticle mean free path in zero field and $\ell_v = 1/n_v \sigma_{tr} = \phi_0/\sigma_{tr} H$ is mean free path
The present results indicate that quasiparticle population for strongly suppressed [9]. 

\[ \ell \propto (\text{quasiparticle population}) \]

may be unlikely because more introduction of Co atoms increases number of scattering centers.

The analysis based on the vortex scattering model, \( \kappa(T, H) = \kappa_c(T, 0)/(1 + \alpha(T)/H) + \kappa_{ph}(T) \). Insets show the temperature dependence of \( \alpha(T) \).

modulated by vortices. We note that phonon contribution is not affected by magnetic field.

Figure 2 shows the field dependence of the thermal conductivity. From a fit to the data using eq. (1), we can obtain \( \kappa_c, \kappa_{ph}, \) and \( \alpha \). Figure 3 shows the temperature dependence of \( \kappa_c/T \) and \( \kappa_{ph}/T \) at zero field in the superconducting state obtained from the analysis based on the vortex scattering model. For comparison, total thermal conductivity at zero field is also plotted. In addition, we plot \( \kappa_c/T \) and \( \kappa_{ph}/T \) in the normal state obtained from the assumption of the validity for Wiedemann-Franz law, \( \kappa_c/T = L_0/\rho \), and \( \kappa_{ph}/T = \kappa/T - L_0/\rho \), where \( L_0 \) is the Lorenz number. Obtained \( \kappa_c/T \) and \( \kappa_{ph}/T \) in the superconducting state at all doping levels are smoothly connected with those in the normal state obtained from Wiedemann-Franz law, which strongly indicates that the present analysis is valid. \( \kappa_{ph}/T \) for all doping levels show peaks around \( T \sim 15 \) K regardless of the superconducting and normal state. We note that the lattice contribution should not be changed drastically by a small amount of Co substitution. Therefore, these results strongly suggest that the broad peak in the normal state at under- and over-doping level originates from the lattice contribution.

We discuss the origin of the enhancement of \( \kappa/T \) below \( T_c \). The analysis based on the vortex scattering model indicates that enhancement of \( \kappa/T \) stems from increase of \( \kappa_c/T \) as shown in Fig. 3. The enhancement of \( \kappa_c/T \) can be explained as follows. Insets of Fig. 2 show the temperature dependence of fitting parameter \( \alpha(T) \) for Ba(Fe\(_{1-x}\)Co\(_x\))\(_2\)As\(_2\) with \( x = 0.045, 0.070, \) and 0.113. \( \alpha(T) \) increases with decreasing temperature, which indicates that enhancement of electronic contribution \( \kappa_e/T \) originates from the increase of quasiparticle mean free path \( \ell_0 \), possibly due to the reduction of inelastic scattering in the superconducting state because \( \alpha(T) \) is proportional to \( \ell_0 \).

We comment on the stronger enhancement in \( \kappa_c/T \) for \( x = 0.113 \) than those for \( x = 0.045 \) and 0.070. \( \kappa_c/T \) for \( x = 0.113 \) is enhanced up to at least about five times as large as that in the normal state while \( \kappa_c/T \) for \( x = 0.045 \) and 0.070 increases by a factor of about three. This may be unlikely because more introduction of Co atoms increases number of scattering centers. In fact, for Zn-doped YBCO, where Zn atoms act as scattering centers, enhancement of \( \kappa \) is strongly suppressed [9]. \( \kappa_c/T \) is proportional to (quasiparticle population) \( \times \) (mean free path). The present results indicate that quasiparticle population for \( x = 0.113 \) still remains even at \( T_c/5 \) and the increase of mean free path overcomes the reduction of quasiparticle population.

**Figure 2.** Magnetic field dependence of the normalized thermal conductivity \( \kappa(H)/\kappa(0) \) for Ba(Fe\(_{1-x}\)Co\(_x\))\(_2\)As\(_2\) with \( x = (a) 0.045, (b) 0.070, \) and \( (c) 0.113 \). Lines are fits to the data by the vortex scattering model, \( \kappa(T, H) = \kappa_c(T, 0)/(1 + \alpha(T)/H) + \kappa_{ph}(T) \). Insets show the temperature dependence of \( \alpha(T) \).
with decreasing temperature, which imply that the superconducting gap structure is anisotropic and/or nodal. We note that the heat transport measurements along c axis suggest the presence of nodes in gap for over-doped sample [10].

4. Summary
We report the heat transport for the Co-doped iron-arsenide BaFe$_2$As$_2$ at under-, optimal-, and over-doping levels. We find that thermal conductivity $\kappa/T$ shows a enhancement below $T_c$ at all doping levels and a broad peak exists above $T_c$ at under-and over-doping levels. The detailed analysis based on a vortex scattering model in the mixed states reveals that the obtained enhancement in $\kappa/T$ below $T_c$ originates from a increase of quasiparticle mean free path and the broad peak above $T_c$ is due to the phonon contribution. Strong enhancement of $\kappa_e/T$ for over-doping level may suggest that quasiparticle population still remains even at $T_c/5$.

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