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Effect of the Phonon-Electron Interaction on Anisotropy in the Thermal Conductivity of YBCO Crystals+

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Experimental results on the anisotropic thermal conductivity κ for the directions of the a-, b- and c-axis in YBCO crystals, have been analyzed comprehensively to make clear the mechanism of the high T_c superconductivity. By comparing these results to the Tewordt and Wölkhausen (T-W) theory, the anisotropic phonon-carrier interaction coefficients γ_a, γ_b, and γ_c are evaluated. It is concluded that $\gamma_a \geq \gamma_b > \gamma_c$, and the larger the value of γ in a direction, the higher the density of the Cooper pairs in that direction. From the maximum increment of κ below T_c, $\Delta\kappa$, at each direction, phonons are concluded to be much more mobile along the ab-plane than along the c-axis.

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The interaction of phonons with carriers (holes in the case of YBCO) plays an important role to the mechanism of the high T_c oxide superconductivity. This paper describes the interaction from the view point of phonon transport, that is, the phonon thermal conductivity in the material.

We have measured the anisotropic thermal diffusivity, a, of YBCO crystals made by the QMG method [2] for the vertical and parallel directions to the c-axis by the transient method [1], and then the thermal conductivity, κ, was derived by $\kappa = aC$, where C is the specific heat per volume measured by the same apparatus. The results were compared with the Tewordt and Wölkhausen (T-W) theory [3], and the different coefficients for different scatterings have been obtained. On the other hand, Cohn et al measured the anisotropic thermal conductivity of YBCO crystals made by the self-flux method, for the a- and b-axis directions [4]. We tried to compare these results with the T-W theory to obtain the different coefficients for the above directions. Summarizing the above two results, we have the scattering coefficient of the phonon-carrier interaction, 7, in the a-, b-, and c-axis directions. In conclusion, $\gamma_a \geq \gamma_b > \gamma_c$ has been obtained, where the subscripts correspond

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to the directions of the axis. Next, the relative density of the Cooper pairs was evaluated for the a-, b-, and c-axis directions, by comparing the maximum increments of κ at a temperature below T_c, $A\kappa$, with each other. Considering the crystal structure of YBCO, phonons are concluded to be much more mobile along the Cu-0-Cu and Cu-Cu paths in the ab-plane, than along the Cu-Cu paths in the c-axis direction below T_c.

Figure 1 and 2 show the dependencies of the thermal conductivity in YBCO crystals on the temperature, measured by Cohn et al and Onuki et al, in the parallel direction to the a- and b-axis and to the ab-plane and c-axis, respectively. In the figure, solid' lines correspond to the experimental, dashed ones to the theoretical, and dot-dashed ones to the non-superconducting state obtained by using the same scattering coefficients with $g(x,y)=1$ below T_c, where $g(x,y)$ is the ratio of the phonon-carrier scattering times in the normal and superconducting states [3]. The different scattering coefficients are obtained as shown in Table I (for the Onuki et al results) and Table II (for the Cohn et al ones) by adapting the experimental results to the T-W theory, where α is the phonon scattering coefficient for point defects, β one for sheet-like defects, and γ one for the phonon-carrier interaction, μ one for the Umklapp process of phonons, and X is the factor of the scaled BCS gap. Here the coefficient, A, is related to the grain(or precipitate)-boundary scattering, and K^e is the thermal conductivity contributed by the carrier transport around 100 K, which is below 10% of the total κ in Table I and below 15% in Table II, where A and K^e

TABLE I. Different scattering coefficients obtained by adapting the Onuki et al results to the T-W theory for the directions parallel to the ab-plane and c-axis. .A and K^e are in the unit of W/m·K.

	A	α	β	γ	μ	X	K^e
ab-	80	17	15	5	7	1.3	0.25
c-	6	17	15	1	13	1.3	0.015

TABLE II. Different scattering coefficients calculated by adapting the Cohn et al results of the post anneal specimen to the T-W theory for the directions parallel to the a- and b-axis, where the value of K^e is assumed to be as same in the paper [6]. A and K^e are expressed in W/m·K.

	A	α	β	γ	μ	X	K^e
a-	560	12	0	15	56	1.3	4.4
b-	560	18	0	10	50	1.3	4.4

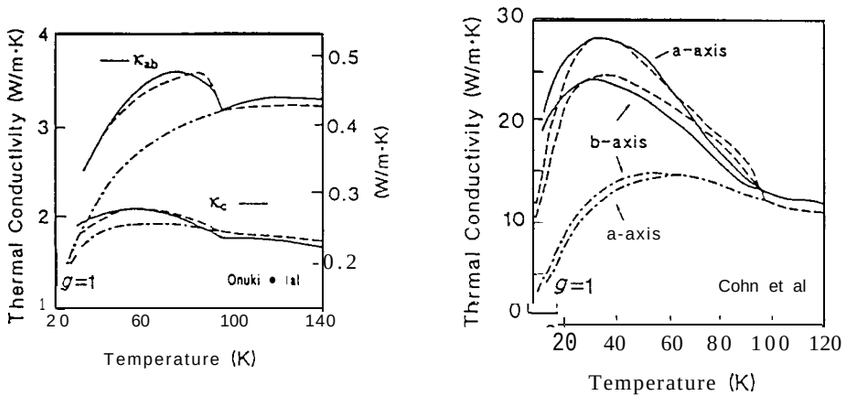

FIG.1. Temperature dependencies of experimental and theoretical results on the thermal conductivity of the YBCO single crystals due to the QMG method for directions parallel to the ab-plane and c-axis, obtained by Onuki et al, where the solid lines and dashed one correspond to the experimental and theoretical, respectively, and the subscripts ab and c refer to the directions. The dot-dashed lines are the theoretical curves of κ vs T in the non-superconducting state for each direction below T_c.

FIG.2. Temperature dependencies of experimental results on κ vs T of the YBCO single crystals due to the self-flux method for the a- and b-axis directions (solid lines). obtained by Cohn et al with the theoretical curves (dashed lines) calculated by us, where the subscripts a and b refer to the axis-directions. The dot-dashed curves are κ vs Tin th,e non-superconducting state below T_c, under assuming $g(x, y) = 1$, for each direction.

are expressed in W/m·K. In Fig. 1, a correction in the values of κ for containing the < 211 > phase of precipitates of 30% was carried out for the Pt-dopped QMG crystals used in the experiments. The coefficients in Table I differ from the corresponding values in our previous paper [1], because in this paper we adopted the same values for α and β in the cases of the ab-plane and c-axis, because of using the same specimens. From the above results, the following are concluded:

(1) The phonon-carrier interaction coefficients are different in different directions. The small value of γ in the c-axis direction should be noticed: $\gamma_a \simeq \gamma_b > \gamma_c$ is concluded for a specimen.

(2) The values of A in Table I are much smaller than those in Table II, because the grain size of the former is smaller, where we used the specimens dopped with Pt for enhancing the value of J_c[4].

(3) The value of γ depends on the density of free holes around T_c, which is increased after annealing in oxigen gas, by comparing the curves of κ vs T for the post- and pre-anneal specimens [1]. The value of γ_{ab} shown in Table I is about two times smaller than the mean value of γ_a and γ_b in Table II.

(4) The values of a and β for the dopped QMG crystals are larger than those for Cohn's self-flux crystals.

The factors, R_1 and R_2, given by,

$$R_1 = (\Delta\kappa_{ab})/(\Delta\kappa_c), \tag{1}$$

$$R_2 = (\Delta\kappa_a)/(\Delta\kappa_b), \tag{2}$$

are evaluated for Onuki's and Cohn's data, respectively, where $\Delta\kappa$ is an increment of κ caused by the creation of Cooper pairs below T_c. R_1 and R_2 are related to the ratios of density of the Cooper pairs for each direction, where the subscripts, ab, c, a, and b in $\Delta\kappa$ correspond to the ab-plane and the corresponding axis, respectively. From Figs. 1 and 2, $R_1 = 22$ and $R_2 = 1.3$ are obtained. Then the ratio, $\Delta\kappa_a : \Delta\kappa_b : \Delta\kappa_c$, is evaluated as 32 : 24 : 1 assuming $\Delta\kappa_{ab} = (\Delta\kappa_a + \Delta\kappa_b)/2$. From the result, a large amount of the Cooper pairs are created along the Cu-0-Cu and Cu-Cu chains in the ab-plane centered by an Y atom, and there is a small amount of the pairs along Cu-Cu chains in the c-axis direction, which may be emitted by tunelling from the layer centered by an Y atom to the neighbouring two layers centered by Ba atoms [5].

The different coefficients effective for the phonon thermal conductivity in the a-, b-, and c-axis directions are calculated by comparing the experimental results of Onuki et al and Cohn et al with the T-W theory.

The phonon-carrier interaction coefficient is much larger in the a- and b-axis directions than in the c-axis one for a given specimen.

The density ratio of the Cooper pairs for the above three directions is estimated from the maximum increment of thermal conductivity below T_c due to the creation of the pairs.

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