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Low temperature mechanical energy dissipation phenomena in praseodymium-doped yttrium superconductors

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Abstract

Studies of the anelastic properties of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ceramics ($0 \leqslant x \leqslant 1$) were performed. The internal friction and Young modulus measurements were carried out by the vibrating reed technique in the temperature range from 20 to 180 K. The measurement frequency was in the range 90–760 Hz. The aim of this work was to investigate the influence of praseodymium content on the anelastic properties of 1–2–3 material.

The main phenomena which are caused by doping with praseodymium can be seen in the low temperature part of the internal friction spectra (20–40 K). The maximum at about 40 K, known as maximum 1 in the spectra of yttrium 1–2–3 material, gradually decreases with increasing praseodymium content. Relaxation processes located in the conducting planes, possibly electronic phenomena, have been considered as an origin of maximum 1. The samples which contained more than 50% Pr showed another low temperature maximum 25–30 K. This maximum also reflects thermally activated relaxation phenomena. Its estimated activation energy is very low (0.03 eV). The common feature of all the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples regardless of the dopant content is the presence of internal friction maxima observed in our frequency range at 80 and 100 K (maxima 3 and 4 in the spectra of 1–2–3 material). These processes were not significantly affected by the presence of praseodymium.

1. Introduction

Although anelastic properties of the $Y_1Ba_2Cu_3O_{7-\delta}$ superconductor have been extensively studied for the last 6 years, none of the low temperature relaxation phenomena observed in this material has been unambiguously explained. Various mechanisms of relaxation have been considered. These include atom movements [1, 2], off-symmetry relaxation [3], dislocation relaxation [4] and electronic processes [5, 6].

As is well known, superconductivity in $Y_1Ba_2Cu_3O_{7-\delta}$ is suppressed by substitution of yttrium by praseodymium. On the other hand, the non-superconducting $Pr_1Ba_2Cu_3O_{7-\delta}$ material has the same crystal structure as its superconducting counterpart $Y_1Ba_2Cu_3O_{7-\delta}$, with only subtle crystallographic differences [7, 8]. Thus $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ offers a promising opportunity of studying whether the electronic properties themselves influence the internal friction spectra of these materials.

In this work we report the results of internal friction measurements performed on a series of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples ($x=0.0$, 0.1, 0.2, ..., 1.0).

2. Experimental details

The $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ceramics were prepared from a stoichiometric mixture of dried Pr_6O_{11}, Y_2O_3, $BaCO_3$ and CuO powders. The sintering procedure consisted of three stages carried out in air: (1) 915 °C, 20 h; (2) 930 °C, 20 h; (3) 930 °C, 20 h. Finally the samples were pressed into pellets and annealed at 935 °C in flowing oxygen for 96 h and then cooled down within 12 h.

The measurements of anelastic effects were conducted by the vibrating reed technique in the temperature range 20–180 K. The measurement frequency was in the range 90–760 Hz. The samples had the shape of

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thin plates (the average dimensions of the samples where about 30 mm × 5 mm × 0.4 mm). They were rigidly clamped at one end and vibrations were caused by an electrostatic force applied to the free end. The amplitude of oscillations was about 10 μm, corresponding to a value of strain amplitude of about 5×10^{-6}. The rate of temperature increase was 0.8 K min^{-1}. The decrement of the amplitude decay was calculated by the least-squares method, fitting to a few hundred subsequent amplitudes. The approximate height of loss maxima was estimated on the basis of the internal friction spectra analysis performed in terms of a single-relaxation-time Debye process [9]. An exponential temperature dependence of the internal friction background was assumed.

The superconducting transition temperature was determined by the shielding effect method. The magnetic shielding effect was measured with two coaxial coils placed on opposite sides of the sample. One was supplied with a.c. current (1 kHz) while the resulting voltage was measured on the other. The magnetic shielding was examined simultaneously with the internal friction measurements. The transition temperature of the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples decreased with increasing praseodymium content and was consistent with that obtained by other authors [10, 11].

3. Results and discussion

The internal friction spectra obtained for $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples containing various amounts of praseodymium ($x=0$, 0.3, 0.6 and 0.9) in the temperature range 20–180 K are shown in Fig. 1. All maxima present in the spectra shift with the

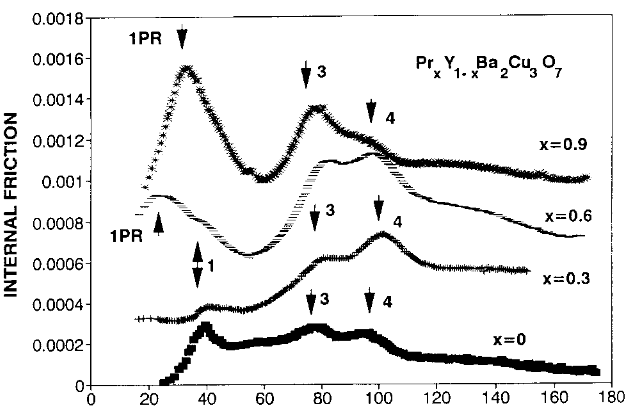

Fig. 1. Temperature dependence of internal friction in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples ($x=0$, 0.3, 0.6 and 0.9). The spectra were taken at measurement frequencies $f=210$ ($x=0$), 278 ($x=0.3$), 247 ($x=0.6$) and 257 Hz ($x=0.9$). In order to avoid overlapping of the spectra, the curves corresponding to $Y_{0.7}Pr_{0.3}Ba_2Cu_3O_{7-\delta}$, $Y_{0.4}Pr_{0.6}Ba_2Cu_3O_{7-\delta}$ and $Y_{0.1}Pr_{0.9}Ba_2Cu_3O_{7-\delta}$ are shifted upwards by 0.0003, 0.0006 and 0.0009 respectively.

vibration frequency (*e.g.* maximum 1PR in the $Y_{0.1}Pr_{0.9}Ba_2Cu_3O_{7-\delta}$ sample shifts by 5.7 K when the frequency changes from 95 to 702 Hz); therefore they reflect thermally activated relaxation processes. The narrow frequency range available in our experiments prevented us from determining the exact values of activation energy. Nevertheless, we estimated the activation energies of the processes in the $Y_{0.1}Pr_{0.9}Ba_2Cu_3O_{7-\delta}$ material. These results as well as the known values of activation energy in yttrium 1–2–3 superconductor are presented in Table 1. The relaxation parameters of maximum 4 in $Y_{0.1}Pr_{0.9}Ba_2Cu_3O_{7-\delta}$ were determined with the largest error, because this peak overlaps both maximum 3 and a wide maximum at about 130–150 K (an effect which we consider non-intrinsic to the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ material).

It can be seen from Fig. 1 that the presence of praseodymium in the samples affects the low temperature part of the spectra (20–40 K). The low temperature maximum, known as maximum 1 in the $Y_1Ba_2Cu_3O_{7-\delta}$ material ($T\approx32$–40 K), gradually decreases with increasing praseodymium content (*e.g.* $Q^{-1}=3.3\times10^{-4}$, 1.5×10^{-4} and 0.4×10^{-4} for $x=0.0$, 0.3 and 0.6 respectively). On the other hand, another low temperature maximum (maximum 1PR at $T\approx25$–30 K) occurs in the $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ samples for $x\geqslant0.5$. Peak 1 PR grows significantly with increasing Pr content ($Q^{-1}=6.7\times10^{-4}$ and 8×10^{-4} in $Y_{0.1}Pr_{0.9}Ba_2Cu_3O_{7-\delta}$ and $Y_1Ba_2Cu_3O_{7-\delta}$ respectively). Its approximate activation energy is very low (0.03 ± 0.02 eV), even lower than that characteristic of maximum 1 in the $Y_1Ba_2Cu_3O_{7-\delta}$ superconductor. We believe that the diminishing of maximum 1 as a result of doping with praseodymium supports the idea that an electronic relaxation in the conducting planes might be responsible for this effect [5]. It is known from optical data that with an increase in praseodymium concentration the density of free carriers decreases from approximately 1×10^{21} cm^{-3} in $Y_1Ba_2Cu_3O_{7-\delta}$ to less than 1×10^{19} cm^{-3} in $Pr_1Ba_2Cu_3O_{7-\delta}$ [14]. A decrease in the charge carrier concentration would lead to a reduction in the electronic relaxation process intensity. It should be stressed that the apparent relationship between the carrier concentration (T_c) and the height of maximum 1 in 1–2–3 superconductors described above is not an exceptional one. On the contrary, it seems to be a rule. Such a behaviour has been observed in 1–2–3 and 1–2–4 yttrium superconductors doped with iron [15]. Another example of maximum 1 diminishing as a result of a decrease in hole concentration is the case of 1–2–3 material with reduced oxygen content [16]. The low value of activation energy (0.07 eV) is also consistent with the interpretation of maximum 1 as an electronic relaxation process, although it does not rule out other models.

TABLE 1. Estimates of activation energy of relaxation processes in $Y_{0.1}Pr_{0.9}Ba_2Cu_3O_{7-\delta}$ (processes 1Pr, 3 and 4). Also shown for comparison are values of activation energy of relaxation processes in $Y_1Ba_2Cu_3O_{7-\delta}$ (processes 1, 3 and 4) [12, 13, 5]

Material	Activation energy (eV)			
	Process 1	Process 1PR	Process 3	Process 4
$Y_1Ba_2Cu_3O_{7-\delta}$	0.07	–	0.16	0.2
$Y_{0.1}Pr_{0.9}Ba_2Cu_3O_{7-\delta}$	–	0.03 ± 0.02	0.18 ± 0.06	0.3 ± 0.1

The nature of the new low temperature process observed in $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ for $x \geqslant 0.5$ is not known. However, it is worth noting that from approximately this amount of praseodymium a subtle change in the CuO_2 plane structure has been detected by neutron diffraction measurements [7]. Such a change might develop conditions for a new relaxation phenomenon in the planes.

The high temperature part of the internal friction spectra of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ does not seem to be affected significantly by the praseodymium atoms. Maxima 3 and 4 can be seen in all the spectra. Within experimental error their activation energies are close to those characteristic for the yttrium 1–2–3 material. The intensities of processes 3 and 4 change from sample to sample in the range from 2×10^{-4} to 4×10^{-4}. No systematic tendency which could be linked to the change in praseodymium content has been detected. These maxima have been interpreted as being caused by relaxation processes in the CuO chains [3]. Doping with praseodymium does not change the structure of the chain planes except for causing some disorder in these planes. Hence the above results neither support nor contradict this hypothesis.

4. Conclusions

The studies of anelastic properties of $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ceramics ($0 \leqslant x \leqslant 1$) showed that doping with praseodymium influences the low temperature part of the internal friction spectra. On the basis of results presented as well as the experiments reported previously, we have considered an electronic relaxation process located in the conduction planes as a possible source of maximum 1.

It should be mentioned that many high temperature cuprate superconductors show a low temperature relaxation process [4, 5, 16, 17]. What is more interesting, the intensity of this effect in $La_{2-x}Ba_xCuO_{4-\delta}$ and $La_{2-x}Sr_xCuO_{4-\delta}$ materials also seems to depend on the free-carrier concentration [17]. We believe it is possible that such electronic phenomena which occur in the conduction planes might be a common feature of cuprate conductors or superconductors. We think this is worth further study.

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