Interaction of electrons with thermal phonons in $YBa_2Cu_3O_{7-\delta}$ films at low temperatures

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The time of the electron-phonon coupling, τ_{eph}, in YBaCuO films, a measure of the relaxation time of the resistance of a superconductor in the resistive state, has been determined from the radiation-induced increase of the resistance at low temperatures. The fitted results obtained by these methods show that the relaxation of the resistance in the resistive state is attributable to the cooling of the electron subsystem relative to the phonon subsystem. The time τ_{eph}, inversely proportional to the temperature, was found to be 80 ps at $T = 1.6$ K and 5 ps at $T = 30$ K.

The study of the scattering of charge carriers plays an important role in research on the physics of high-T_c superconductors. The data on the temperature-dependent part of the resistance, the thermal conductivity, the thermal emf, and the fluctuation phenomena allow, however, many different interpretations as to the choice of the mechanism for inelastic electron scattering and allowance for transport phenomena and umklapp processes. It is thus clearly of considerable interest to determine the cooling rate of the electron subsystem, which is governed exclusively by electron-phonon coupling, relative to phonons. It was previously found that at liquid-helium temperatures the time required for electron-phonon coupling, τ_{eph}, measured under conditions of slight deviation from equilibrium as the time scale for the relaxation of the resistance of a superconductor in the resistive state, is an order of magnitude shorter in YBaCuO films than that for conventional superconductors.[1,2] In the present letter we report the results of an experimental study of the temperature dependence of τ_{eph} on the basis of direct measurements of the relaxation rate of the resistance and nearly steady-state measurements of laser-induced increase of the resistance.

For conventional superconductors these methods give self-consistent results for τ_{eph} which are comparable to those obtained by other methods.[3] The use of these methods for high-T_c superconducting films, however, yields substantially different results. In the case of conventional superconductors the phonon temperature stabilization at liquid-helium temperatures (i.e., the warming of only the electron subsystem) was achieved because of the small thickness (d) of the films: The time scale of phonon-electron scattering, $\tau_{phe}(T)$, in this case must be shorter than that of the escape of a thermal phonon from the film, $\tau_{es} \propto d$. As the temperature is raised, however, this condition breaks down, and we see from steady-state measurements an overall heating of the film. If, on the other hand, the phonon specific heat is greater than the electron specific heat, the phonons in the film may function as a heat sink in the case of short-lived phenomena in the electron subsystem (whose typical time constant is shorter than the effective time of τ_{phe}).[1,2]

In the experiment we used films of the $YBa_2Cu_3O_{7-\delta}$ composition of thickness 0.1–1 μm, obtained by laser evaporation and magnetron sputtering of Al_2O_3 or BaF_2 substrate with sublayers of ZrO_2, MgO, and $BaSrTiO_3$. The width of the superconducting transition, which began at about 92 K, was ~ 10 K. The samples were strips of width 0.5 mm and length 4 mm. We measured the response of the sample which was connected to a current generator. The response was in the form of a laser-induced variation of the voltage across the sample, ΔU, as a function of temperature $T = 1.5$–90 K, current $I = 0$–10 mA, and magnetic field $B = 0$–5 T, in the wavelength range $\lambda = 3$–0.3 mm, with $\lambda = 0.8$ μm. We also measured the current-voltage characteristics and the T-vs-V slope, $dU/dT = I \times dR/dT$.

Two methods were developed for the measurement of short relaxation times: In the first method we used a semiconductor heterolaser with a pulse length of 20 ps, while in the second we used a backward-wave-tube laser with a continuously tunable frequency f of an amplitude-modulated light, from low frequencies to 12 GHz. In the pulse method, however, a high sensitivity cannot be obtained even with the use of gate integration, because of the large spacing of pulses and because of their insufficient stability. As a result, the minimum power level per pulse that can be measured is several orders of magnitude greater than that measured in the case of sinusoidal modulation and does not allow us to study the linear relaxation. We have therefore used primarily the second method,[4] in which one of the two identical backward-wave tubes was tuned to a particular frequency, while the other was continuously tuned by the supply voltage. The detection was carried out at the beat frequency f. If the relaxation is described by the time τ, we have $\Delta U(f) = \Delta U(0)[1 + (2\pi f\tau)^2]^{-1/2}$.

The results of the measurements show, in general, that two phenomena coexist in the investigated wavelength range: the Josephson effect is seen at the weak intergranular links and electron heating occurs when the grains are in the resistive state. The granularity of the film and the properties of the grain boundaries determine the region these phenomena dominate. In the single-crystal region of a film or at the grain boundaries the Josephson effect is absent and only electronic heating prevails. Figure 1, for example, shows the curves of $\Delta U(I)$ for a granular film at $T = 4.2$ K, $B = 0$, and $B = 3$T for various wavelengths of light. In the long-wavelength part of the spectrum the Josephson effect is dominant at the weak intergranular links. The behavior of the Josephson effect is typically characterized by a shift of the maximum of ΔU, which is proportional to the frequency, by the ΔU peaks at the Shapiro steps, and by other effects. In this case the electronic heating dominates at $\lambda \leqslant 0.4$ mm and $B = 0$ and in the entire range of wavelengths when the Josephson effect is suppressed by the magnetic field. The latter circumstance governed one of the conditions under which τ_{eph} was measured: Although the results presented below were obtained in a magnetic field $B = 3.5$ T, in several cases they agree with the results obtained at $B = 0$.

Figure 2 shows the values of τ_{eph} for one of the test samples. These values were obtained directly from the $\Delta U(f)$ plots in the temperature interval 1.5–4.2 K. At $T > 4.2$ K we see that τ_{eph} is less than 20 ps, lying outside the range amenable to measurement.

The calculation of τ_{eph}, which makes use of the quasi-steady-state technique, is based on the energy-balance equation with a coefficient of heat transfer from electrons

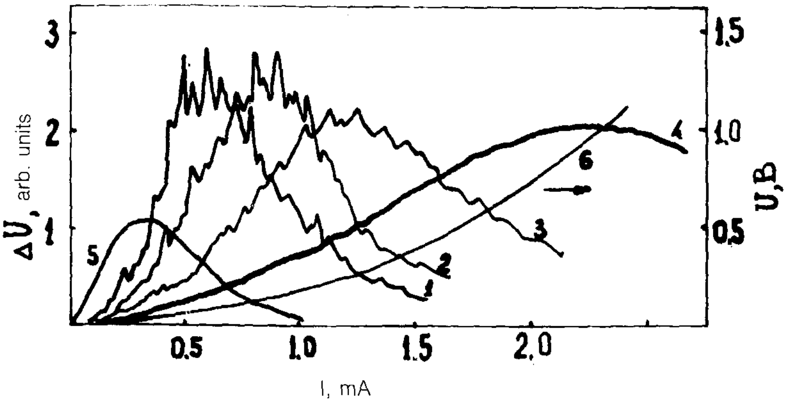

FIG. 1. The plots of $\Delta U(I)$ for various wavelengths of light, λ(mm), at $T = 4.2$ K and $B = 0$. *1*—2.2; *2*—1.3; *3*—0.8, *4*—0.3 and 8×10^{-4}; curve *5*—the behavior of $\Delta U(I)$ at 4.2 K and $B = 3$ T for various wavelengths; curve *6*—typical *I–V* characteristic.

to phonons, $G_e = c_e/\tau_{eph}$ (Ref. 3). We thus can write

$$\Delta U(f) = \frac{dU}{dT} P \frac{\tau_{eph}}{c_e} [1 + (2\pi f\tau)^2]^{-1/2}, \tag{1}$$

where P is the radiation power absorbed per unit volume, and $c_e = \gamma T$ is the electron specific heat. The temperature dependence of τ_{eph} is determined according to (1) to be $\tau_{eph}(T) \propto T\Delta U \times (\partial U/\partial T)^{-1}$, where ΔU was measured at $f = 100$ MHz. The $\tau_{eph}(T)$ curve in Fig. 2 is linked with the value of τ_{eph} measured at 4.2 K. Also shown in Fig. 2 are the results of the measurements of dU/dT and ΔU using similar samples, which were taken from Ref. 5 and which we analyzed. The authors of that study[5] attributed

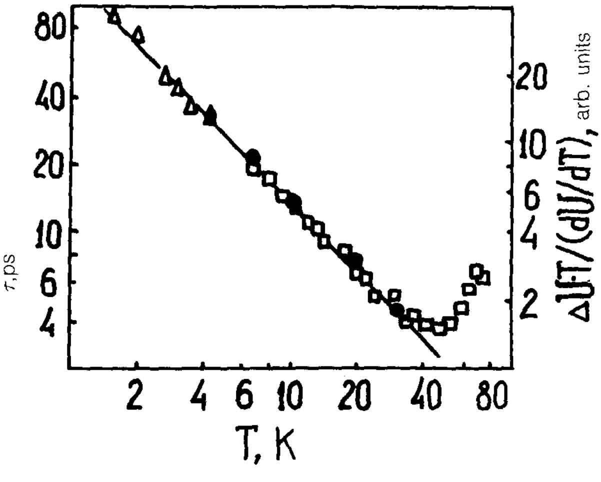

FIG. 2. The curve of $\tau_{eph}(T)$. Δ—The values of τ determined from the curves of $\Delta U(f)$; O—the curve of $\Delta UT \times (dU/dT)^{-1}$ is linked with the value of τ at $T = 4.2$ K; □—the same curve plotted using the data of Ref. 5. The solid line corresponds to the $\tau_{eph} \propto T^{-1}$ curve.

their results to the bolometric effect. We have already noted,[1,2] however, that the relaxation time which was measured directly is at least an order of magnitude shorter than the minimum bolometric time, τ_{es}, measured for these films, that this time does not depend directly on the film thickness or on the acoustic matching of the film and the substrate, and that it is therefore of a nonbolometric nature. At liquid-nitrogen temperatures the tails on the $\Delta U(f)$ curves at low frequencies, $f < 1$ MHz, show that the bolometric effect cannot be described by a single time constant, and that this effect is determined by the heat conductivity of the substrate. An increase in $T\Delta U \times (\partial U/\partial T)^{-1}$ at $T \geqslant 40$ K (Fig. 2) apparently cannot be attributed to the temperature dependence of τ_{eph}. It stems from the measurement of ΔU at insufficiently high modulation frequencies,[5] at which the bolometric effect manifests itself.

The consistent results obtained by the two methods of determining τ_{eph} are evidence that the energy relaxation is uniform in nature, i.e., these results show that diffusion of quasiparticles is not a dominant factor in the relaxation process.

The most important result of our study is the observation of the temperature dependence $\tau_{eph} \propto T^{-1}$ which can be accounted for on the basis of the several attempts to explain in terms of electron-phonon coupling the linear temperature dependence of the resistance which was observed in films of superconducting cuprates (including those with a low T_c), beginning with the liquid-helium temperatures. The simplest explanation of the dependence $\tau_{eph} \propto T^{-1}$ is provided by the scattering of electrons by flexural oscillations, consistent with the dispersion relation $\omega \propto q^2$ (Ref. 6), which can be defined as the complex structure of the cuprates and as the morphology of the film itself.

The study of τ_{eph} in high-T_c superconducting films is also of interest from the practical standpoint, because such a study would make it possible to predict the properties of various detecting and switching devices.[2]

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