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Anomalies in the internal friction and sound velocity in the high-temperature superconductor $La_{1.8}Sr_{0.2}CuO_4$

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The internal friction Q^{-1} and the Young's-modulus sound velocity v_E have been measured in $La_{1.8}Sr_{0.2}CuO_4$ using the vibrating-reed technique. Measurements were performed at a frequency of 700 Hz at temperatures between 0.2 and 100 K. A drastic change of slope in the internal friction versus temperature curve is observed at $T=44$ K just above the superconducting transition temperature $T_c=40$ K. A plateau in Q^{-1} is observed between 44 and 5 K. The sound velocity shows a decrease with decreasing temperature between 100 and 20 K and remains almost constant between 2 and 0.2 K.

The recently discovered[1] high-T_c superconducting ceramic compounds have raised a number of questions concerning the nature of the interaction responsible for superconductivity. Measurements of internal friction and sound velocity could supplement those of other properties and help to understand the mechanisms that bring about the superconducting transition.

In the present work, the vibrating-reed technique[2] has been used to obtain the Young's-modulus sound velocity (v_E) and the internal friction (Q^{-1}) of a sample of $La_{1.8}Sr_{0.2}CuO_3$, which has a critical temperature of 40 K.[3] The compound was prepared following the methods described by Cava, van Dover, Battlogg, and Rietman[4] and was then oxygen annealed for 6 h at 1000 °C. The sample was clamped at one end between copper flats and driven electrically by applying a sinusoidal voltage at a frequency $\nu/2$ between a fixed electrode and the sample. Measuring capacitively the amplitude of vibration at the free end as a function of frequency ν, the resonance curve was obtained, from which the attenuation $Q^{-1}=\Delta\nu/\nu_m$ can be deduced. If A_m is the maximum amplitude, corresponding to the resonance frequency ν_m, $\Delta\nu$ is defined as the width of the peak between the points where the amplitude falls to $A_m/2^{1/2}$. Subsequently the sample was made to oscillate at the resonance frequency by means of a tracking circuit, and changes in this frequency and amplitude were measured as a function of temperature.

The sample is a slab 1.43 cm long, 0.297 cm wide, and 187 μm thick. Its measured mass density is approximately 6.0 g/cm^3, and the resonance frequency was found to be 690 Hz. From these values a Young's modulus $E=1.9\times10^{12}$ g/cm sec^2 is obtained, which in turn gives for the Young's modulus sound velocity $v_E=5.6\times10^5$ cm/sec. The longitudinal sound velocity c_L can be deduced from this, provided the corresponding Poisson's ratio is known. No such data are available for this compound, but for reasonable assumptions of Poisson's ratio between 0.17 and 0.35, one obtains $c_L=v_E\times1.04$ and $c_L=v_E\times1.27$, respectively.

In a Debye solid, the sound velocity obtained from the specific heat c_D is given by

$$(3/c_D^3)=(2/c_T^3)+(1/c_L^3)\ , \tag{1}$$

where c_T is the transversal sound velocity. Nieva *et al.*[5] have measured $c_D=3.4\times10^5$ cm/sec from specific-heat data and Brun *et al.*[6] have obtained $c_T=3.2\times10^5$ cm/sec from Brillouin scattering of surface waves for this same compound. These numbers are all consistent with c_L obtained above and Eq. (1).

The internal friction data, deduced from the amplitude measurements, are plotted in Fig. 1 as a function of temperature. There is a decrease in Q^{-1} with decreasing temperature which follows an approximate T^2 dependence from the highest measured temperature of 90 K, until a drastic change in slope is seen at around 44 K. A

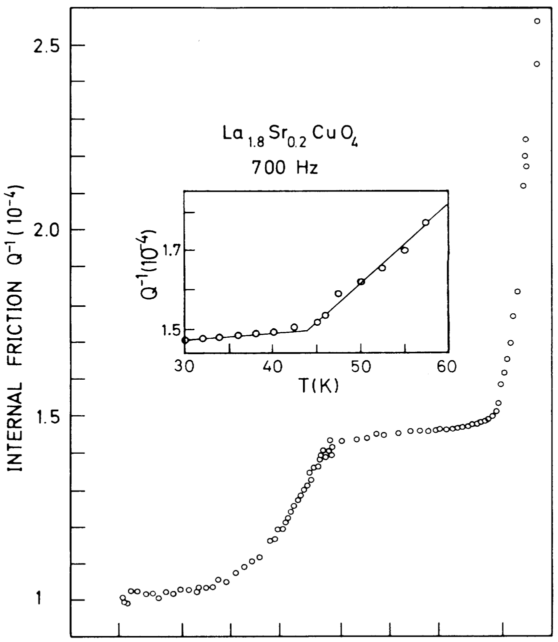

FIG. 1. Internal friction as a function of temperature. The inset shows the point at which the plateau starts. The superconducting critical temperature is 40 K for this compound.

plateau of almost constant attenuation is observed between 44 and 5 K, and then there is a further drop in Q^{-1} until a new plateau is reached at approximately 2 K. This final plateau could be explained as due to the fact that at these low values, attenuation from the clamping at the holder starts to be important. If a constant is subtracted to account for this and a logarithmic plot of Q^{-1} is drawn (Fig. 2) it can be seen that the internal friction follows an approximate $T^{1.8}$ dependence at low temperatures.

The point at which the high-temperature plateau starts is around 44 K (see inset of Fig. 1), which is somewhat higher than the T_c of the material as measured by flux expulsion and resistivity[3] and also higher than the point T_M at which the specific heat changes slope (defined in Ref. 6).

In Fig. 3 the relative change in sound velocity is plotted as a function of temperature. A decrease of the sound velocity is seen with decreasing temperature between 90 and 20 K. There is a minimum at approximately 20 K, and as the temperature is lowered further the sound velocity increases until at around 2 K, and up to the lowest measured temperature of 0.2 K the rate of increase is very slow and the velocity remains almost constant.

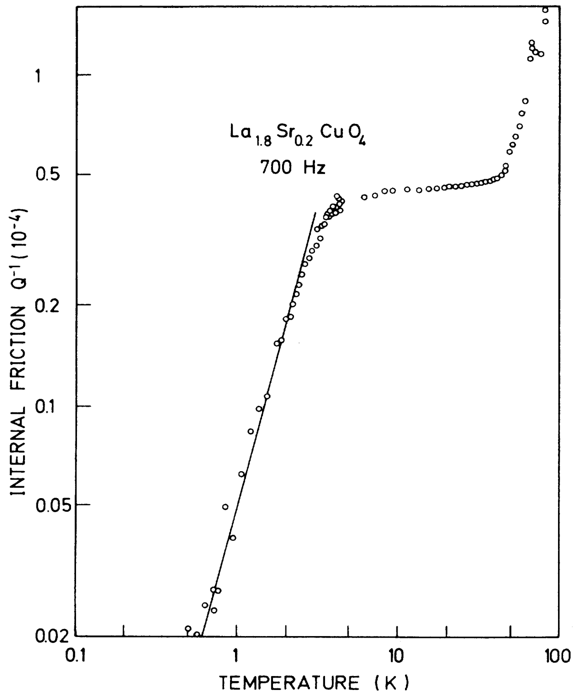

FIG. 2. Logarithmic plot of the internal friction, where the contribution due to the clamping at the sample holder has been subtracted.

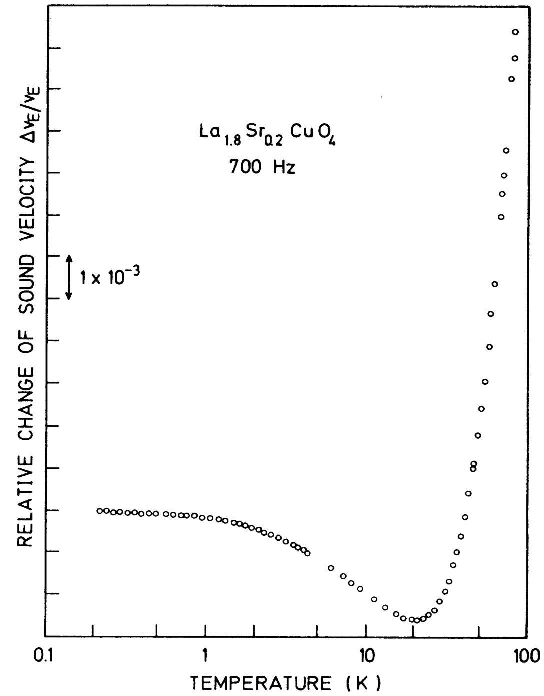

FIG. 3. Relative change in sound velocity as a function of temperature. The minimum is at 20 K. The absolute value of the sound velocity is $V_E = 5.6\times10^5$ cm/sec.

The decrease of sound velocity with temperature is seen in several amorphous dielectrics[7] in A-15 compounds such as V_3Si (Ref. 8) and also in martensitic transformations.[9] In amorphous materials the decrease is not completely understood, although in the case of vitreous silica an anomalous coefficient of thermal expansion is thought to be responsible.[7] In the A-15's and in martensites it is explained by a softening of the material preceding a structural transformation. Jorgensen *et al.*[10] in experiments with neutron scattering in a similar high-T_c ceramic ($La_{2-x}Ba_xCuO_4$) find no anomalies in the thermal expansion. If the anomalous behavior of the sound velocity is due to the softening of the material, the phase transformation present in La_2CuO_4 and inhibited by the addition of Ba or Sr (Ref. 10) could be responsible for the softening observed. The sound velocity measured at a similar frequency for the martensitic transformation in Cu-Zn-Al alloys has almost the same shape as that observed here, although of course the phase transition occurs at a higher temperature. The internal friction, on the other hand, is very different from that measured here. In the A-15's, there is a sudden stiffening of the material below T_c, and the data of sound velocity obtained here show only a very gradual change in slope at around 40 K. This could be due to the fact that the material is a granular superconductor[3] and the transition is gradual, in which case the constant sound velocity observed below 2K could indicate that the transition has been completed. With such a picture in mind the plateau in Q^{-1} could be explained if domain walls between normal and superconducting regions were moving in a dissipative way. Against this interpretation is the fact that the plateau extends from a temperature slightly above T_c to a temperature ($T = 4.5$ K) higher than that at which the sound velocity saturates.

Regarding the internal friction it is interesting to note that the order of magnitude at the plateau $Q^{-1} = 1.55\times10^{-4}$ is similar to those reported in many amorphous metals and insulators at the same frequency.[11] The plateau in attenuation or internal friction which is usually found in amorphous materials is interpreted by means of the tunneling model, in which it is assumed that tunneling systems (TS) exist which, through an interaction with the phonons, produce a relaxational absorption with a broad distribution of relaxation times. The existence of TS in this compound cannot be disregarded *a priori.* The highly probable existence of oxygen vacancies and small tetrahedral distortions of the oxygen network in this material could lead to the formation of tunneling entities as in the case of vitreous silica.[7,11] If it is assumed that only the usual TS-phonon interaction is present, then a T^3 dependence of Q^{-1} is expected to occur, instead of the $T^{1.8}$ dependence observed. Also, the change in relative sound velocity would show a maximum at the same temperature ($T=4.5$ K) as the plateau in Q^{-1} starts, instead of the saturation at low temperatures seen in Fig. 3. However, it should be taken into account that the specific heat at low temperatures[5] shows a linear behavior well below T_c and up to the lowest measured temperatures ($T=1$ K). This could be due to normal electron excitations which survive in normal regions of the sample, and the normal electrons are known to interact with the tunneling entities changing the behavior expected in an amorphous insulator or superconductor below T_c.[12] It should be noted that the coefficient of the linear term γ observed in the specific heat[5] is much greater $\gamma=1\times10^{-5}$ J/gm K^2 than the linear term which is observed typically in amorphous metals [$\gamma=3\times10^{-7}$ J/gm K^2 for amorphous $Zr_{70}Ni_{30}$ (Ref. 11)] or insulators [$\gamma=1.6\times10^{-6}$ J/gm K^2 for suprasil I (Ref. 11)] due to the TS.

The effect of oxygen content in the sample should be of importance in the formation of these tunneling systems. It has already been established[13] that it has great influence in the critical temperature, and further experiments are underway to see whether the correlation between T_c and the onset of the plateau in Q^{-1} is maintained for different oxygen contents.

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