Acoustic characteristics and structural features of the vibration spectrum of the $La_{2-x}Sr_xCuO_4$ ($x=0$ and 0.2) lattice and the $YBa_2Cu_3O_y$ ($y=6$ and 7) lattice

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(Submitted 21 July 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 6, 326–329 (25 September 1988)

In the compounds $La_{2-x}Sr_xCuO_4$ ($x = 0, 0.2$) and $YBa_2Cu_3O_y$ ($y = 7,6$) the temperature-dependent variation of the absorption of longitudinal sound, $\alpha(T)$, and the variation in its velocity, $S(T)$, are similar when $x = 0$ and 0.2 and $y = 6$ and 7. The anomalous temperature behavior of α and S is attributable to the interaction of sound with the soft optical modes.

There is now no agreement regarding the behavior of the temperature dependence of the acoustic characteristics of high-T_c superconductors. This lack of agreement stems primarily from the discrepancy in experimental data.[1–10] For example, strong anomalies in the velocity of sound, S, or its absorption near T_c were observed in some

 0021-3640/88/180359-06$01.00

studies[5,6] but not in others. Considerable latitude in the interpretation of the results is also attributable to the fact that measurements were usually carried out with single samples, complicating the choice between the various models. We report here the results of an experimental study of the acoustic characteristics of $YBa_2Cu_3O_y$ with $y = 7$ and 6 and $La_{2-x}Sr_xCuO_4$ with $x = 0.2$ and 0, including a single crystal sample. Such a complex study has heretofore not been performed.

The measurements were carried out at frequencies of 20 and 50 MHz by means of the standard pulsed method with a pulse length of 1–1.5 μs. The use of signal–comparison electronic circuit allowed us to measure the velocity of sound with a relative error of $\sim 10^{-2}\%$ and the absorption coefficient with a relative error of $\sim 10^{-1}$ dB/cm. At temperatures above 150 K the measurement accuracy decreased because of the appearance of the temperature-dependent contact background. The disk-shaped samples of thickness 1.5–3 mm were protected against the penetration of contact lubricant into the bulk of the material. During thermal cycling from 4.2 K to 250 K the samples exhibited no hysteretic effects or jumps in the sound velocity or absorption. We studied textured ceramic samples with the C axis running in the direction of the propagation of sound. In the case of $YBa_2Cu_3O_7$ we used one sample in which the value of y was changed by annealing it in a vacuum. A 3×3-mm wafer of thickness 2.5 mm was cut out perpendicular to the C axis from the original La_2CuO_4 orthorhombic single crystal with the axes $a = 5.3845$ Å, $b = 5.35228$ Å, and $C = 13.1490$ Å, with a $< 5'$ disorientation of the units.

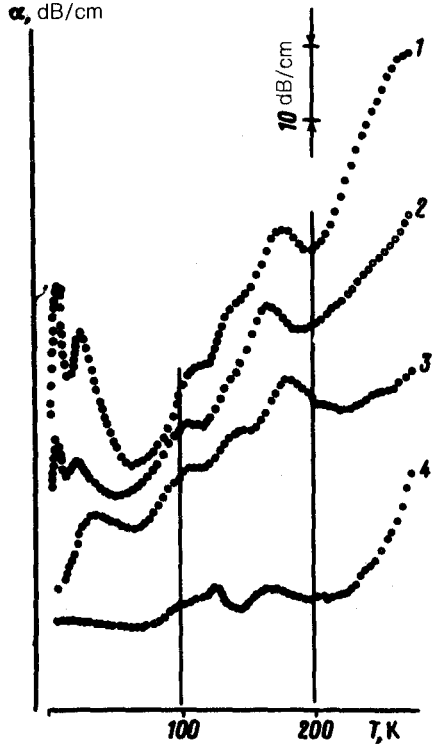


FIG. 1. Temperature dependence of the absorption of sound: La_2CuO_4 (ceramic) 1—50 MHz; 2—20 MHz; 3—$La_{1.8}Sr_{0.2}CuO_4$—50 MHz; 4—La_2CuO_4 (single crystal) 50 MHz. The sound is directed along the C axis.

In the case of the samples of the lanthanum system the curves which describe the change, at $T \gtrsim 50$ K, in the sound absorption as a function of temperature, $\alpha(T)$, exhibit at temperatures of 100–120 K and 160–170 K (Fig. 1) features in the form of absorption peaks amounting to 5–10% of the temperature-independent background (~ 50 dB/cm). The position of the peak shifts slightly down the temperature scale as the frequency of sound decreases (compare curves 1 and 2). At $T \leqslant 25$ K the amplitude of the structural features in a first approximation changes in proportion to ω, rather than in proportion to ω^2, as predicted by Lifshitz and Pitaevskiĭ.[12] The sample containing strontium is a superconductor with $T_c = 38$ K. At $T \approx T_c$ this sample (curve 3) does not exhibit an unusual behavior of the absorption; specifically, at $T \lesssim T_c$ the value of α does not decrease appreciably, as is typically the case in ordinary superconductors.

At temperatures $T \lesssim 50$ K the $\alpha(T)$ curve for a La_2CuO_4 ceramic sample differs markedly from a similar curve for a single crystal (Fig. 1). This difference evidently stems from the crystallographic absorption anisotropy. At temperatures of 6–30 K, for example, anomalies similar to those found in the ceramic sample were also observed in a bulk single crystal when the sound was propagated at an angle to the C axis.

The sound velocity in the lanthanum samples (Fig. 2) increases by $\sim 10\%$ as the temperature is lowered below $T \sim 200$ K and peaks at ~ 120 K. It then decreases by 1% in single crystals and by 5 or 6% in ceramics as the temperature of 50 K is approached. Since the $S(T)$ curve for a superconducting ceramic is similar to that of a nonsuperconducting ceramic, there is no reason to regard it as a "precursor" of the superconducting transition. A similarity of the $\alpha(T)$ and $S(T)$ curves for insulating

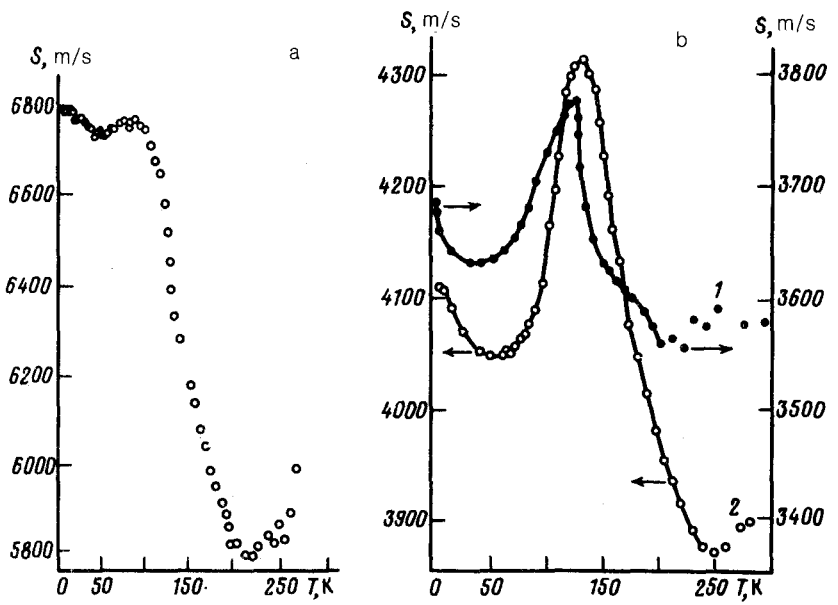


FIG. 2. Velocities of sound in the lanthanum system. (a) Single crystal (50 MHz); (b) curve 1—La_2CuO_4 (points); curve 2—$La_{1.8}Sr_{0.2}CuO_4$ (circles).

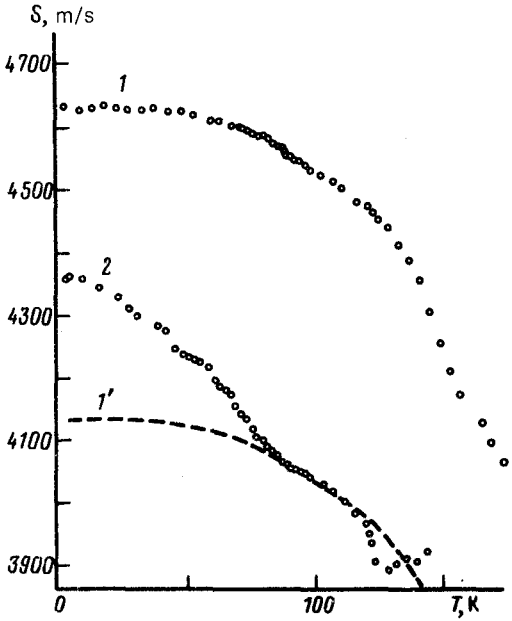
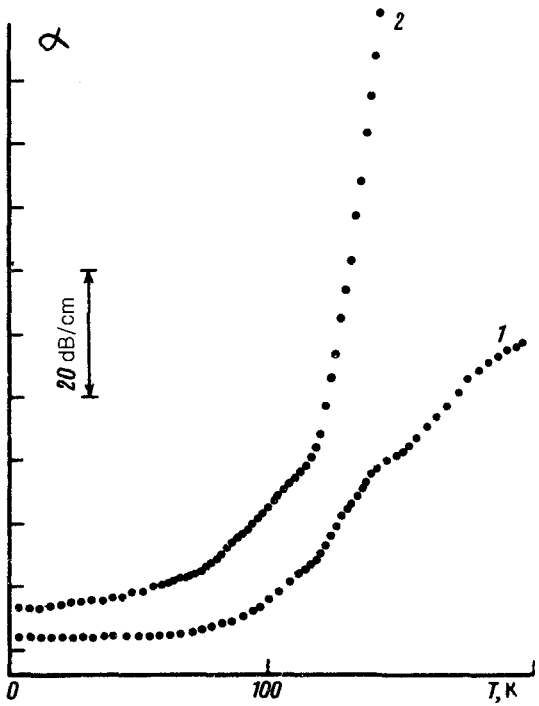


FIG. 3. Acoustic characteristics of $YBa_2Cu_3O_y$; curves 1 and 1′—ceramic with $y = 6$; curve 2—ceramic with $y = 7$. Curve 1′ illustrates a relative variation of S.



and metal-like samples suggests that conduction electrons contribute negligibly to the acoustic properties of lanthanum compounds. The estimate of the electron-dependent attenuation of sound, reported by us elsewhere,[3] is clearly too high.

The $YBa_2Cu_3O_y$ compound with $y = 7$ is a superconducting orthorhombic modification and this compound with $y = 6$ is an insulating tetragonal modification. In this experiment we used the same sample in the measurements, and the effect of the complicating factors was minimal. The transition from the orthorhombic phase to the tetragonal phase is accompanied by an increase in the sound velocity by 10 or 12% and by a decrease in the $\alpha(T)$ and $S(T)$ curves in the range of temperature variation from 4.2 K to 150 K (Fig. 3). Similar results were obtained in Ref. 10, which became known to us during the writing of this paper. It is pertinent to note that only a quantitative change of the $\alpha(T)$ and $S(T)$ curves was observed in this case.

Taking all the experimental results which we have obtained into account, we see that the acoustic characteristics are insensitive to the change in the composition of the compounds studied. This circumstance is in favor of the assumption that the possible structural transitions are not a factor which determines the specific features on the $\alpha(T)$ and $S(T)$ curves. At the same time, the lattice vibration spectrum changes only slightly with the composition of the materials under study, as follows from the neutron measurements.[11] The factor responsible for the anomalies on the $\alpha(T)$ and $S(T)$ curves is evidently traceable to the particular way in which the sound interacts with the internal vibrations of the lattice of these compounds. As we know,[12] if the sound-induced deformation of the lattice causes the vibration frequency to change, the presence of nonuniform processes leads to the absorption of sound as a result of a redistribution of the thermal energy among the various vibration modes. The magnitude of the absorption is determined by the many-photon processes of the energy exchange among the various vibration modes which are resolved in energy, momentum, and vibration polarization. In a material with a perovskite structure,[13] the soft optical modes, whose energy varies as a result of deformation, are primarily responsible for the absorption of sound.

In a "lanthanum" system the optical mode with $\epsilon_0 = 10$ meV, whose existence has been confirmed by neutron experiments,[14] is primarily responsible for the absorption of sound. At higher energies the modes with $\epsilon_0 = 30$ and 45 MeV are responsible for the absorption of sound. The presence of these modes can be deduced from the calculation of the dispersion curves for this compound[15] and from the optical data.[16] The displacement of the characteristic energies in the spectrum with the temperature, which we have observed, is additional proof of the fact that these modes are soft. In all these modes the oxygen complexes vary in various degrees.

The interaction of sound with the soft optical modes also leads to a change in its velocity. A gradual "freezing out" of the optical oscillations as the temperature is lowered leads to an increase in the sound velocity because of the increase in the lattice rigidity. From this viewpoint, a change in the behavior of the $\alpha(T)$ and $S(T)$ curves for "yttrium" ceramics upon removal of oxygen can naturally be linked with a corresponding decrease in the spectral density of the vibration modes of the oxygen-containing complexes which are responsible, in particular, for the temperature profiles of these quantities.

All the results obtained by us can thus be explained, at least qualitatively, in terms of the interaction of sound with the soft optical modes of the compounds which we have studied. A quantitative explanation is complicated by the presence of several soft modes and by the fact that the anisotropy of the compounds studied by us must be taken into account.

We wish to thank V. P. Seminozhenko for support.

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Translated by S. J. Amoretty