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ACOUSTIC PROPERTIES OF HIGH T_c SUPERCONDUCTORS [1]

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The aim of the paper is to show, how the physical properties of high T_c superconductors (HTSC) are reflected in results of acoustic measurements. Because of scope of the paper, only some selected experiments are presented

HTSC can be characterised as materials

- with perovskite like structure;
- with oxygen deficit (against the stoichiometric composition);
- highly anisotropic;
- as superconductors of II. kind.

The perovskite structure is drawn in Fig.1*a*, the structure of one important HTSC - $YBa_2Cu_3O_{7-\delta}$ in Fig.1*b*.

The actual structure of HTSC consists of layers of CuO_2, MO (M = metal), and N (N=metal). These layers can be organized in many ways and many isomorphic HTSC exist. Most important from the experimental point of view remain, however, the first two discovered HTSC: $La_{1-x}Sr_xCuO_{4-\delta}$ and $YBa_2Cu_3O_{7-\delta}$. It is because these can be prepared relatively easily and in good quality.

Like some perovskites, the HTSC exhibit structural phase transitions. This tendency is further enforced by oxygen deficit (oxygen vacancies appear in CuO_2 layer).

In $La_{1-x}Sr_xCuO_{4-\delta}$, the phase transition from the tetragonal to the orthorhombic state appears. This transition occurs between 100 K and 400 K, the temperature depends on strontium content. The nature of it is the ordering of oxygen atoms in the CuO_2 layer. This phase transition was observed by ultrasonic measurement at first. It is manifested as a decrease of sound velocities of polycrystals upon cooling. It was confirmed by other (e. g. x-ray) methods later. The behaviour of sound velocities is drawn in Fig.2.

This transition can be easily traced from experiments on single crystals: The dependence of elastic constants c_{33} and c_{66} is drawn in Fig.3. The constant $c_{66} = c_{1212}$ determines the velocity of the shear wave propagating along a or b axis and polarized in the $a - b$ plane, while $c_{33} = c_{3333}$ touches sound propagation along the c-axis.

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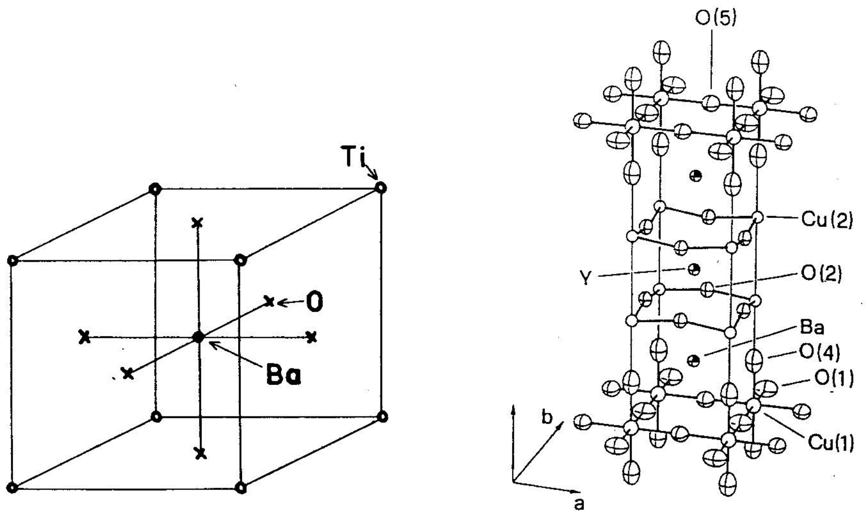

Fig. 1. *a*) The ideal perovskite structure ($BaTiO_3$), *b*) The structure of $YBa_2Cu_3O_{6.9}$, from [2]. The O(1) sites are filled from 80 percent, that makes the base for the orthorhombic distortion (lattice parameter $a > b$).

As the transition means reordering in the a-b plane, c_{66} goes to zero near the critical temperature (the lattice is unstable here), c_{33} is not affected.

In $YBa_2Cu_3O_{7-\delta}$, the tetragonal to orthorhombic transition occurs above 400°C and therefore is not easily observable in a velocity measurement; an attenuation peak was observed there.

There are several (3-4) attenuation maxima in $YBa_2Cu_3O_{7-\delta}$ between 4 K and room temperature. They are of relaxational character; their positions shift when changing the sound frequency. The activation energies were found to be 50 - 200 meV and the relaxation times are of the order 10^{-12} s. The entity, that can relax in this material with these parameters, are oxygen atoms in the CuO_2 layer. Therefore these peaks are associated with a subtle structure transition realised by oxygen reordering in the CuO_2 layer (no effect was observed in x-ray experiments).

The peak, that appears near to 220 K, is of special interest. Several other effects (in Raman spectrum, specific heat, electric conductivity) were observed near to this temperature [14]. It is also the point, where appears velocity hysteresis - see Fig.4. One possible explanation of these effects is the ferroelectric phase transition.

A decrease of velocity and a plateau of attenuation was observed at low temperature (below 1 K). This is attributed to an influence of a two level system.

The elastic moduli (bulk, shear, Young's etc.) can be determined from measured longitudinal v_l and shear v_t sound velocities. To get comparable results, the moduli must be recalculated for void-free material. Other problem is, that they depend on oxygen content, which is often only vaguely described. Even then, the

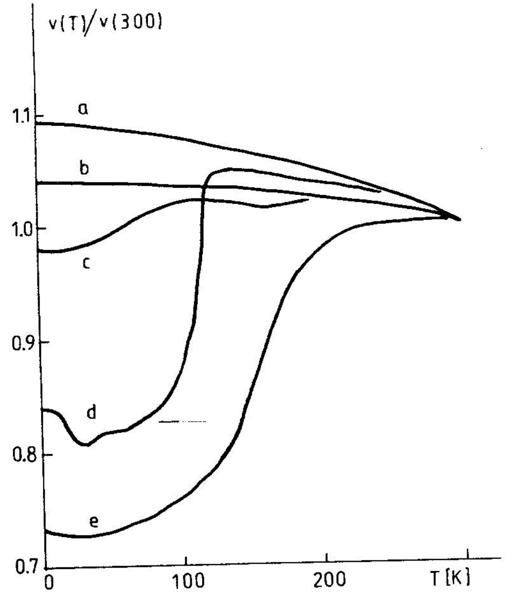

Fig. 2. The temperature dependence of longitudinal sound velocities v in polycrystalline HTSC $YBa_2Cu_3O_{7-\delta}$ (*a*), $Bi_2Sr_2CaCu_2O_8$ (*b*), $La_{1-x}Sr_xCuO_{4-\delta}$ (*e*), "parent compound" La_2CuO_4 (*c*) and perovskite $SrTiO_3$ (*d*), after [8]. The decrease of v in $La_{1-x}Sr_xCuO_{4-\delta}$ is due to the structural phase transition and does not appear in other HTSC.

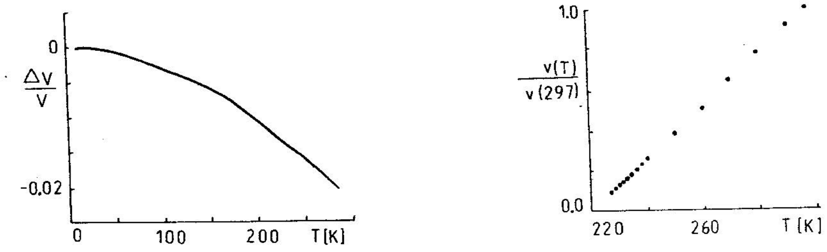

Fig. 3. *a*) The temperature dependence of longitudinal sound velocity v_{33} along the c-axis in $La_{1-x}Sr_xCuO_{4-\delta}$. There applies $c_{33} = \rho.v_{33}^2$. After [13]. *b*) The temperature dependence of shear sound velocity v_{66} in $La_{1-x}Sr_xCuO_{4-\delta}$ near the critical point. There applies $c_{66} = \rho.v_{66}^2$. After [10].

right value of the moduli is not definitively settled yet.

I will mention the bulk modulus here. This value in $YBa_2Cu_3O_{7-\delta}$ is about 100 GPa, in other HTSC less. An interesting fact is, that bulk moduli determined by high pressure experiments are markedly higher [5]. A possible explanation is a

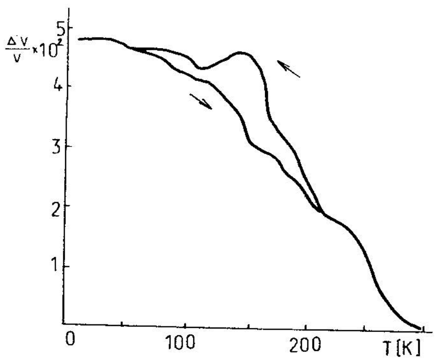

Fig. 4. Longitudinal velocity hysteresis in $YBa_2Cu_3O_{7-\delta}$. After [7].

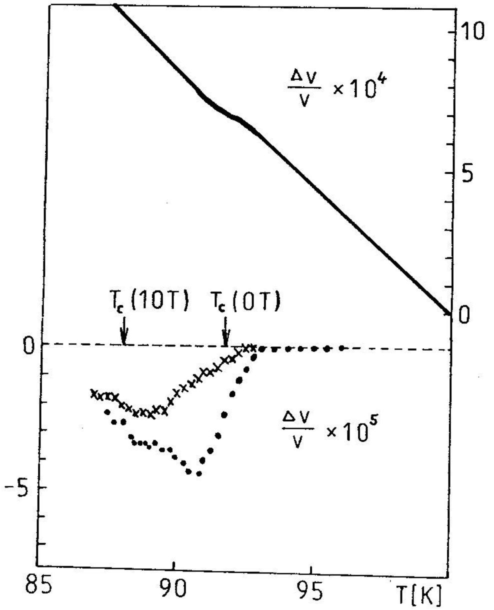

Fig. 5. The change of the longitudinal sound velocity near T_c in $YBa_2Cu_3O_{7-\delta}$. The full line shows the real change of sound velocity. The dots are for the step at T_c, when the "background" change is substracted, the crosses the same step at magnetic field of 10 T. The shift and shallowing of the velocity step is clearly visible. After [6].

steep increase of the bulk modulus with pressure.

Measurements in textured samples and in single crystals invariably show, that the elastic constants related to the $a-b$ plane are higher, than those related to the c-axis. This is due to stronger interatomic forces in the $a-b$ plane. It is in agreement with other properties of HTSC (they grow and cleave along this plane,

etc.).

The superconductive transition is connected with a decrease of the attenuation in "classical" superconductors. It is because the electrons condense into Cooper pairs and do not contribute to the attenuation any more.

The electronic part of the attenuation is proportional to the electron free path. This is very short in HTSC. Because of it, the decrease of attenuation at T_c cannot be observed in HTSC.

The superconductive transition is the phase transition of the II. order. It is connected with a step in specific heat. From it, there follows a step in elastic constants and sound velocities. A simple expression for it is [15]

$$\Delta B/B = -\frac{\Delta c_p}{T_c} B \left(\frac{\delta T_c}{\delta p}\right)^2 , \qquad (1)$$

where B is the bulk modulus, c_p specific heat and P pressure. A detailed calculation of this step is by Millis and Rabe [11]. This step of velocity is very small - of the order 10-100 ppm. Therefore it is difficult to observe it in the present samples. Several experiments show the transition very distinctly however.

HTSC are superconductors of the II. kind. It means, that they contain flux lines (FL) in suitable magnetic field. The dynamic properties of FL are very important, as they limit the practical use of a superconductor. Therefore they were intensively investigated. Acoustic methods have the advantage against other methods, that they can study FL dynamics near the equilibrium conditions. (The difference is, that the acoustic methods move the *crystal* lattice primarily, while other methods move the FL lattice.)

The behaviour of FL in HTSC is described by the thermally assisted flux flow (TAFF) model [1] (but the FL lattice melting model is still in the game also). Thermally assisted depinning of FL plays in HTSC a more important role than in "classical" superconductors, as the former have a higher critical temperature and a very short coherence length (the potential barrier, that the FL are to overcome, is proportional to the coherence length) [4].

The dependence of the sound velocity and attenuation (or damping) on temperature in a constant magnetic field (see Fig.6) can be described in the following way:

At low temperature, the FL form a regular and relatively rigid lattice. This lattice adds its strength to the crystal lattice, because of it the elastic constants (and sound velocities) are higher than those in the normal state. The FL lattice, because of its rigidity, dissipates only little the sound wave and the attenuation is small.

At higher temperature, the FL start to decouple. The sound velocity decreases. Attenuation exhibits a maximum, because of the interaction of the sound wave with weakly bound FL.

At still higher temperatures, the FL become to be unbound to the crystal lattice and the attenuation decreases.

The change of the attenuation and velocity was calculated by Pankert [12] for sound frequencies in the MHz range. For lower frequencies (vibrating reed experiments), such a simple and unified model does not exist, because of dependence on

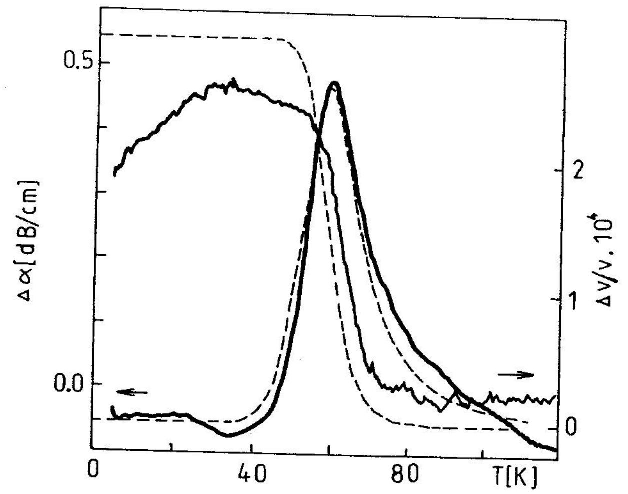

Fig. 6. The change of sound attenuation and velocity caused by the interaction with flux lines in $Bi_2Sr_2Ca_2Cu_3O_{10}$, as adapted from [9]. The full line is from experiment, the dashed line from theory.

sample dimension, sound frequency and many different modes of vibrations. The general features of the model are kept, however.

The experiments concerning propagation of surface acoustic waves are still at the beginning. Up to now, they have not shown anything what is qualitatively different from results on bulk samples.

In the paper presented, I have tried to describe the acoustic properties of high temperature superconductors. For the sake of brevity and arrangement, I have limited the discussion and mentioned only the results, that are in the accord with the prevailing view. The opposite results exist however, and it is not clear (at least in some cases), whether this is due to a low quality of the samples or to some factors, not yet understood. A more detailed discussion is in the work [3], e.g.

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