Anomalous behavior of phonon spectrum near 2.5-order phase transition

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By the method of electron tunneling we have found a nonlinear behavior of the phonon frequencies of indium fused with tin. We discussed the possible causes of these anomalies, and also their influence on the critical temperature of the superconducting transition.

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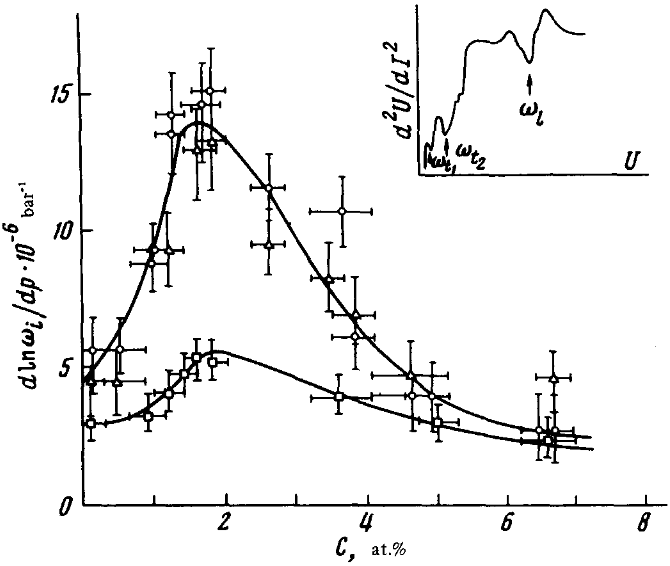
A change in the topology of the Fermi surface causes anomalies of thermodynamic and kinetic characteristics of a metal (phase transition of order 2.5).[1] According to the theory of Makarov and Bar'yakhtar,[2] such topological changes determine also the nonlinear course of the critical temperature T_c of the superconductor. The already available numerous experimental results on the influence exerted on T_c by small additions of impurity and by pressure[3] are qualitatively well described by the theory of[2], which takes into account only the change in the electronic spectrum. Nonetheless, attention is called to the correlation between the nonlinear change of the lattice parameters and the number of electrons per atom.[4] On the basis of such information, which is independent of[2,3], it can be assumed that anomalies appear in the phonon spectrum in the course of the topological transition, and this undoubtedly should be taken into account when changes in T_c are considered.

Using this idea, we have undertaken a tunnel investigation of the phonon spectra of In—Sn alloys in the region of the topological transition. Information on the change of the characteristics frequencies of the spectrum of the lattice vibrations $\omega_t^{cr}=\omega(q_{cr}) : \omega_{t_1}=3.2$ meV and $\omega_{t_2}=4.6$ meV, corresponding to the transverse modes of the vibrational spectra, and on the change of the longitudinal frequency $\omega_l=13.4$ meV, was extracted from the tunnel plots of $d^2/U/dI^2$ against U, obtained at 1.4 °K.

The film tunnel junctions $Al—Al_2O_3—In_{1-x}Sn_x$ ($x\approx 0—6$ at.%) were prepared and measured by a procedure described in[5]. To reveal weak nonlinearities, we measured also the dependence of the derivatives $d\omega_i^{cr}/dp$ on the tin concentration. The experiments were performed in a high-pressure cell using a kerosene-oil mixture as a transmitting medium at pressure 2—3 kbar, when the changes of the observed frequencies in the region of the topological transition exceeded the measurement error. The pressure was determined from the superconducting transition temperature of the indium with an error of 100 bar.

Melting produces strong changes in the nonlinear components of characteristics of the oscillation frequencies of the crystal lattice of the indium. The figure shows the measured values of $d\ln\omega_i^{cr}/dp(c)$. The corresponding values of these quantities $d\omega_{t_1}/dp=(1.8\pm0.5)\times10^{-5}$ meV/bar, $d\omega_{t_2}/dp=(2.0\pm0.5)\times10^{-5}$ meV/



Concentration dependences of $d\ln\omega_i/dp$ for In—Sn alloys (0—ω_{t_1}; Δ—ω_{t_2}; □—ω_l). Insert—typical form of d^2U/dI^2 vs. U tunnel characteristic.

bar, and $d\omega_l/dp = (4.0 \pm 0.6) \times 10^{-5}$ meV/bar for pure indium, agree with the published data.[6]

Let us consider the possible causes of the appearance of anomalies in the $\omega_i(c)$ dependences. In principle this fact could be treated as a direct consequence of electron-photon interaction, which changes when a new electron cavity appears at a certain point $\mathbf{p}_k$. However, using the explicit expression for the renormalization of the phonon frequency $\delta\omega$,[7] we find that to explain such large experimental values of $\delta\omega$ it is necessary to assume that the following inequality holds: $\epsilon_{\mathbf{p}_k} + \hbar\mathbf{q}^{cr} - \epsilon_{\mathbf{p}_k} \leq \hbar\omega_{cr}$. It seems highly unlikely that such a relation can be satisfied for three different values of $\mathbf{q}_{cr}$. It is not excluded, however, that for indium the three observed characteristics frequencies ω_{t_1}, ω_{t_2}, and ω_l can correspond to one and the same wave vector $\mathbf{q}_{cr}$.

Of no little importance in the considered phenomenon is the interaction of the Fermi surface with the boundaries of the Brillouin zone.[4] It leads to a restructuring of the Fermi surface itself, and can also change the lattice parameters and its vibrational spectrum. In this case not only the individual characteristic frequency, but also the phonon spectrum of the crystal should move nonlinearly. Favoring this assumption is the behavior of the speed of sound in In-Sn alloys in the same concentration region.[8] It is also possible that in the region of the topological transition the thermodynamic stability of the lattice varies and causes an isomorphic phase transition of first order.

In order to estimate the contribution of the phonons to the nonlinear part of the variation of the derivative dT_c/dp, it suffices to differentiate the well known McMillan formula for T_c with respect to pressure as a parameter. The obtained relation connects $d\ln T_c/dp$ with the derivative $\gamma^* = d\ln\omega_i/dp$ average over the spectrum. Using $(d\ln T_c/dp)_{lin} = -15.6\times10^{-6}$ bar^{-1},[9] we obtain the following value for the linear component of the generalized Gruneisen parameter $\gamma^*_{lin} = 4.6\times10^{-6}$ bar^{-1}. Since this quantity agrees with the experimental data, the initial formula can be used for an estimate of the nonlinearity in $d\ln T_c/dp$. The nonlinear components of $d\ln\omega_i/dp$ (see the figure) will make a noticeable contribution to the irregular behavior of $\delta(d\ln T_c/dp)$. The change of the lattice quantity, due only to phonons, is negative and reaches at the maximum a value that lies in the range from -0.8×10^{-5} bar^{-1} to -3.4×10^{-5} bar^{-1}. At the same time, the experimentally observed values of $\delta(d\ln T_c/dp)$ are always positive and reach values 0.17×10^{-5} bar^{-1}.[9] It follows therefore that the experimentally measured $\delta(d\ln T_c/dp)$ curve is actually due to the contribution of two terms: positive due to electrons and negative due to phonons. Allowance for only the first term in the reduction of the experimental data leads to inaccuracies in the determination of the band-structure parameters.

The considerations advanced above as well as the results of our experiments indicate that to develop a consistent theory of influence of the topological transition in the electronic spectrum on the critical temperature of a superconductor, it is necessary to take into account both the electron and phonon mechanisms. It must be noted, however, that the observed changes of the phonon spectrum in the region of the phase transition of order 2.5 cannot be explained at present unambiguously from the point of view of the known concepts.

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