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A. I. Golovashkin and G. P. Motulevich. Electron and Phonon Characteristics of Nb_3Sn. Optical and tunnel investigations of the superconducting Nb_3Sn, which has high critical parameters, were carried out in the Optics Laboratory of the Lebedev Physics Institute.

1. The Nb_3Sn films were prepared by simultaneous evaporation of Nb and Sn in a vacuum of 5×10^{-6} mm Hg[1,2]. It turned out that an ultrahigh vacuum is essential to obtain Nb_3Sn films with extremely high critical parameters. The film thicknesses were 0.03–2 μ. The main measurements were performed on films 0.5–2 μ thick. The films had mirror surfaces. The surface layer was not distorted by hardening or by oxidation, so that the optical constants and the tunnel characteristics pertain to the undistorted metal. The static characteristics practically coincided with the characteristics of the bulk metal. An x-ray investigation of the samples has shown that they contain only the A-15 phase. The superconducting transition temperature was $T_c = 17.3 - 18.3$°K. The width of the transition was $\Delta T = 0.1 - 0.3$°K. The critical-current density was $j_c \gtrsim 5 \times 10^5$ A/cm^2 in a zero magnetic field.

2. The optical constants n and κ ($n - i\kappa$ is the complex refractive index) were measured by a polarization method in the wavelength interval $\lambda = 0.4 - 10\ \mu$[3]. The dielectric constant $\epsilon = n^2 - \kappa^2$ and the optical conductivity $\sigma = 2n\kappa/\lambda$ were calculated.

The contributions to ϵ and σ from the conduction electrons and to interband transitions were separated. The following characteristics of the conduction electrons were obtained: conduction-electron concentration $N = 1.1 \times 10^{22}$ cm^{-3}, $N/N_{val} = 0.04$ (N_{val} is the concentration of the valence electrons), average electron velocity on the Fermi surface $v_F = 0.48 \times 10^8$ cm/sec, total area of Fermi surface $S_F = 1.1 \times 10^{-37}$ g^{2}cm^2 sec^{-2}, and effective electron collision frequency $\nu = 1.85 \times 10^{14}$ sec^{-1}. The small value of N is due to the large number of Bragg planes intersecting the Fermi surface. (The Fermi surface is intersected by 102 planes constituting six physically nonequivalent systems).

The characteristics obtained for the interband transitions are listed in Table I. In the table, ω_{max} is the frequency corresponding to the maximum of the interband-transition band, σ_{max} is the conductivity at the frequency ω_{max}, ν_g is a dimensionless relaxation parameter[4], and V_g are the Fourier components of the pseudopotential and correspond to the Bragg planes with indices g. The six principal bands of the interband conductivity were determined experimentally. The number of the bands and the values of V_g point to a hybridization of all the valence electrons and to applicability of the pseudopotential approximation. The optical data show that the density of the electronic states near the Fermi surface is not anomalously large. This seems to contradict the results of measurements of the specific heat, and the reason for the contradiction are discussed below.

Optical measurements have made it possible to determine the electron-phonon interaction constant λ_{ep}.[5,6] For our Nb_3Sn layers we obtained $\lambda_{ep} = 0.46$. Using McMillan's formula for T_c,[7] we obtain $\mu^* = -0.12$. The negative value of the effective Coulomb potential μ^* can indicate the presence of an additional non-phonon superconductivity mechanism, or an appreciable increase of λ_{ep} with decreasing temperature[1], or else that McMillan's formula does not hold for Nb_3Sn.

3. We measured the dependence of I, dI/dV and d^2I/dV^2 on V (I is the tunnel current and V is the voltage) for tunnel junctions of Nb_3Sn with Pb, Sn, Al, and Nb_3Sn. The tunnel barriers were either the natural oxide of Nb_3Sn or Al_2O_3 layers. We investigated both freshly prepared and electrically polished Nb_3Sn films. The electron mean free path in these films was ~ 100 Å. Four values of the energy gap 2Δ were obtained and are given in Tbble II[8]. The maximum of the tunnel density of states occurs in the region of the second and third gaps ($2\Delta_{eff} = 1.9$ meV). The ratios $2\Delta/kT_c$ for all the gaps were smaller than predicted by the BCS theory. One gap was anomalously small. The presence of different gaps is apparently connected with the anisotropy of the Nb_3Sn gap.

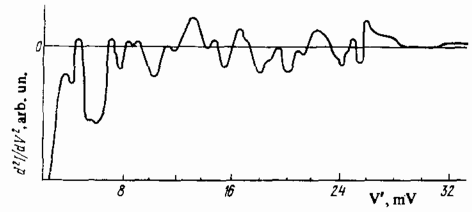
Information on the effective phonon spectrum of Nb_3Sn was obtained from the plot of d^2I/dV^2 against V, which is shown in the figure[9]. The minima of d^2I/dV^2 correspond to the maxima of the function α^2F, where F is the phonon density of states and α is the effective electron-phonon coupling constant. It is seen from the figure that the phonon spectrum of Nb_3Sn is complicated and consists of 12 maxima. Some of them are low-

TABLE I. Parameters of interband transitions of Nb_3Sn

Band number	$\hbar\omega_{max}$, eV	ν_g	σ_{max}, 10^{14} sec^{-1}	$\lvert V_g \rvert$, eV	g	Band number	$\hbar\omega_{max}$, eV	ν_g	σ_{max}, 10^{14} sec^{-1}	$\lvert V_g \rvert$, eV	g
1	0.155	0.2	37.0	0.07	110	4	0.95	0.7	10.5	0.32	211
2	0.21	0.3	45.0	0.09	220	5	1.8	0.3	9.0	0.76	210
3	0.40	0.08	8.5	0.19	310	6	3.0	0.25	8.5	1.30	200

TABLE II. Energy gaps of Nb_3Sn at $T \approx 2$°K

Gap number	$\frac{2\Delta}{e}$, mV	$\frac{2\Delta}{kT_c}$	Gap number	$\frac{2\Delta}{e}$, mV	$\frac{2\Delta}{kT_c}$
1	4.70±0.04	3.0	3	1.50±0.04	1.0
2	2.24±0.04	1.4	4	0.36±0.04	0.2



Dependence of d^2I/dV^2 on V' for the $Nb_3Sn-Al_2O_3-Nb_3Sn$ tunnel junction. Abscissas—$V' = V-2\Delta_{eff}$, where V is the voltage and $2\Delta_{eff} = 1.9$ meV is the effective energy gap of Nb_3Sn.

frequency. Each group of maxima of α^2F corresponds to an $F(\omega)$ maximum obtained from the results of neutron measurements[10].

4. The presence of low-frequency maxima in the phonon spectrum makes the Debye approximation unsuitable for practical use. In the calculation of the specific heat, the low-frequency maxima lead to the appearance of a term linear in the temperature and connected with the lattice. This circumstance is usually disregarded, and this greatly exaggerates the electronic density of states. It appears that this is the main cause of the aforementioned discrepancy between the optical data and the results of specific-heat measurements.

The electron and phonon spectra of Nb_3Sn turned out to be more complicated than for ordinary metals. This calls for a special check on the validity of McMillan's formula for T_c.

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V. M. Galitskiĭ, V. F. Elesin, D. A. Kirzhnits, Yu. V. Kopaev, and R. Kh. Timerov, Feasibility of Superconductivity in Nonequilibrium Systems with Repulsion. It is known that the size of the superconducting gap Δ in the simplest model[1], when the effective electron-phonon coupling constant g corresponds to attraction ($g < 0$) and is constant in the interval $\pm\omega_D$ near the Fermi level, is determined by the following expression:

$$1 = -g \int_0^{\hbar\omega_D} d\epsilon\, [1-2n(\epsilon, T)]\, (\epsilon^2+\Delta^2)^{-1/2}, \qquad (1)$$

where $\hbar\omega_D$ is the limiting phonon energy, $n(\epsilon, T)$ is the quasiparticle occupation function, and T is the temperature.

The critical superconducting transition temperature T_c is determined by condition (1) if we put in the latter $\Delta = 0$.

In the equilibrium state and in the absence of an external source at $T = 0$ we have $n = 0$ for all ϵ. An increase of n under the influence of the external source leads to a suppression of the superconductivity[2]. On the other hand, it is seen from (1) that for a system that is nonsuperconducting ($g > 0$) under normal conditions ($n < 1/2$) a superconducting state ($\Delta \neq 0$) is possible if $n > 1/2$ is produced under the influence of the external source. Since n characterizes the filling of the electronic states above the gap Δ and of the hole states below the gap, it follows that $n > 1/2$ corresponds to the condition of inverted population.

The last condition can be satisfied for the semiconductor model of Fig. 1, which is considered in[3], if the time τ_E of the intraband energy relaxation is much shorter than the time of interband recombination through the dielectric gap Eg. The superconducting state is possible in this case if $Eg < \Delta_0$, where

$$\Delta_0 = \frac{2\mu^2}{\hbar\omega_p} \exp\left(-\sqrt{\frac{g_1^3}{g_0^4} - \frac{\pi}{4} - \frac{1}{g_0}}\right),$$

μ is the Fermi quasilevel of the electrons in the conduction band and of the holes in the valence band, ω_p is the plasma frequency; the quantities g_0 and g_1 characterize respectively the intraband and interband Coulomb interactions.

The superconducting gap is produced not at the Fermi quasilevels ($\pm\mu$), but near the band extrema. It is known that for a bound state to be produced it is necessary that the potential and kinetic energies have opposite signs. Under equilibrium superconductivity conditions, the pairing takes place with attraction between the electrons near the Fermi level, corresponding to a loss of kinetic energy. In a state with inverted

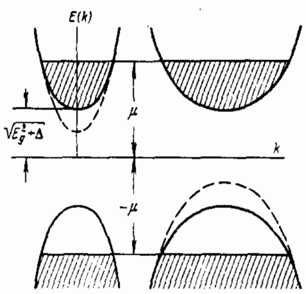

FIG. 1. (Δ_0^2 is designated by Δ).