EFFECTIVE QUASIPARTICLE RECOMBINATION TIMES AND ELECTRONIC DENSITY OF STATES AT THE FERMI LEVEL IN SUPERCONDUCTING FILMS

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Résumé.— Les temps de recombinaison des quasiparticules, mesurés directement dans des jonctions tunnel supraconductrices d'étain et d'aluminium, correspondent assez bien aux valeurs, calculées d'après le modèle ray-on-acoustique d'Eisenmenger et al. τ_{exp} décroît dans les jonctions d'aluminium granuleuses. Les temps, mesurés au plomb, indiquent des pertes des 2 ϕ -phonons à l'intérieur du volume du film. La densité d'état électronique sur le niveau de Fermi N_0 dans les films d'étain, de plomb et d'aluminium diffère moins que 5 % de N_0 de la matière massive.

Abstract.— Quasiparticle recombination times τ_{exp} , directly measured in evaporated superconducting Sn- and Al-tunnel junctions, show reasonable agreement with the values calculated on the basis of the ray-acoustic trapping lifetime model of Eisenmenger et al. τ_{exp} decreases in O_2 -perturbed granular Al-junctions. In Pb the measured times indicate 2 ϕ -phonon volume losses. The electronic density of states at the Fermi-Level N_0 in Sn-, Pb- and Al-films differs less than 5 % from N_0 of the corresponding bulk material.

STATEMENT OF PROBLEMS.— The indirect steady-state method for measuring τ_{exp} in a sandwich-structure of two tunnel junctions requires the knowledge of N_0 as resulting from heat-capacity measurements of the clean bulk material [1]; alternatively, also the band-structure quantity [2] has been used. The samples, in contrast, consist of vacuum-deposited films of microcrystalline structure, usually with high disorder. Consequently, the question arises for the value of N_0 in disordered metal films. We here report on direct measurements of τ_{exp} in superconducting Sn-, Al- and Pb-tunnel junctions and a new experimental technique to determine N_0 in thin films. Comparisons between the measured τ_{exp} and calculations based on the ray-acoustic trapping lifetime model of Eisenmenger et al. [3] have been made in the linear thickness (d) range of τ_{exp} assuming the validity of the relation $\Lambda_V \gg \Lambda_W$ between the mean free paths of 2 ϕ -phonons due to reabsorption (Λ_W) and bulk loss processes (Λ_V).

EXPERIMENTAL PROCEDURE.— An expression for the absolute determination of N_0 has been derived from the relations for the BCS density N_{th} of thermally excited quasiparticles, the lifetime τ_{exp} from the rate equations of Rothwarf-Taylor [4], and the excess quasiparticle density δN under a stationary injection rate I_0 . This expression contains the quantities T , Δ , I_0 , $\tau_{\text{exp},0}$ (at $\delta N/N_{\text{th}} \ll 1$), and $\delta N(t=0)/N_{\text{th}} = X(t=0)$. These values can be obtained from a single symmetric tunnel junction, i.e. Δ and

T from the current-voltage characteristic and $X(0)$, $\tau_{\text{exp},0}$ form the time decay of δN . Current pulses were used for the generation of δN . δN was determined experimentally from the change of the tunnelling current in the thermal tunnelling regime at voltages $0 < U < 2\Delta/e$, i.e. $\delta N/N_{\text{th}} = \delta i/i_{\text{th}}$. A mean least-squares fit of the nonexponential decay function $X(t)$, calculated from the rate equations, on the experimental decay curves supplies values for $X(t=0)$ at the switch-off time $t=0$ of the injection pulse and for $\tau_{\text{exp},0}$.

EXPERIMENTAL RESULTS.— **TIN:** (figure 1) The measured $\tau_{\text{exp},0}$ is $\tau_{\text{exp},0} = \tau_0 T^{-1/2} \cdot e^{\Delta(T)/k_B T}$ with $\tau_0 = 0.58$ ns and $\Delta(T) = \Delta_0 = 585 \mu\text{eV}$. From the cal-

Fig. 1 : Experimental quasiparticle recombination time vs $1/T$ for a superconducting Sn-tunnel junction immersed in liquid ^4He . Quasiparticle excitation by current ($\circ$), laser (+). Quasiparticle excitation by current ($\circ$), laser (+). Symbol $\bullet$ corresponds to a run with trapped magnetic flux (0.2 G). Overinjection by the "two-particle current" i_{2p} at the biasing point $U_B = 0.8 \text{ mV} > \Delta/e$ has been considered.

calculation results $\tau_0 = 1.1$ or 0.6 ns according to the used average phonon transmission coefficient $0.25/5/$ or $0.5/6/$ at the boundary Sn/He. $\tau_{exp,o}$ doesn't depend on quasiparticle excitation by current and laser pulse at the same sample. The "two-particle current" i_{2p} has to be considered as an injection current with $I_0 = i_{2p}/eV_{Tu}$ (V_{Tu} = junction volume). At low temperatures $\tau_{exp,o}$ is reduced by trapped magnetic flux (vortices). A reduced reemission and reabsorption of 2Δ -phonons is the "vortices-doped" films is responsible for this effect. The average value for N_0 (with both spins) in the evaporated Sn films was determined to $(2.71 \pm 0.06) 10^{22} [eV cm^3]^{-1}$ compared to the bulk value $2.77 \times 10^{22} [eV cm^3]^{-1} / 7/$.

ALUMINIUM.- With increasing perturbation of the films by oxygen background evaporation $\tau_{exp,o}$ and the average grain size $\bar{D}$ ($2000 \dots 130 \text{ \AA}$) decrease, the transition temperature T_c and the energy-gap Δ_0 increase (figure 2). The decrease of $\tau_{exp,o}$ at the junction with $T_c = 1.85 \text{ K}$ cannot be explained with the dependence $\tau_{exp,o} \propto d/\Delta^2$. Possible reasons are an enhanced 2Δ -phonon escape by diffuse phonon scattering at the microcrystalline, irregular junction boundaries and an increase of the electron-phonon coupling $\alpha^2(\omega)$. The measured recombination time for an "undisturbed" sample ($T_c = 1.23 \text{ K}$, $d = 5000 \text{ \AA}$) amounts to $\tau_{exp,o}/d = (0.024 \pm 20 \text{ \%}) [s/cm]$ at $T = \Delta/4 k_B$ and $\Delta = 200 \text{ \mu eV}$; the calculated time is $\tau_{exp,o}/d = (0.031 \pm 30 \text{ \%}) [s/cm]$. Within $1.23 \text{ K} \leq T_c \leq 1.85 \text{ K}$ the mean value for N_0 in the films varies between 3.3 and $(3.4 \pm 0.05) \times 10^{22} [eV cm^3]^{-1}$ (bulk value : 3.45×10^{22}). The observed T_c -enhancement in the granular films can be completely attributed to the quantization of the phonon states in the small grains $/8/$.

LEAD.- The measured $\tau_{exp,o}$ meets the exponential temperature dependence above $T = 1.8 \text{ K}$ with $\tau_0 = 0.08 \text{ ns}$ (figure 3). The calculation, however, supplies $\tau_0 = 1.35 \text{ ns}$. This difference indicates 2Δ -phonon volume losses ($\Lambda_V \gg \Lambda_W$ invalid). The N_0 value in the films agrees with that in the bulk $(4.4 \times 10^{22} [eV cm^3]^{-1})$.

Fig. 2 : Experimental recombination time vs $\Delta/k_B T$ for three tunnel junctions with different degrees of perturbation and direct contact to liquid ^4He

Fig. 3 : Experimental recombination time vs $\Delta/k_B T$ for a Pb-tunnel junction under vacuum conditions

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