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EMISSION OF HIGH FREQUENCY RELAXATION PHONONS BY SUPERCONDUCTING ALUMINIUM TUNNELLING JUNCTIONS

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Résumé. — Jusqu'à maintenant on ne pouvait pas observer l'émission des phonons de relaxation ayant une énergie $E > 2\,\Delta$ par des jonctions tunnel supraconducteurs d'étain, parce que la réabsorption de ces phonons dans le générateur est trop forte. Alors nous reportons sur des expériences dans lesquelles nous avons observés l'émission des phonons de relaxation ayant une énergie $E > 2\,\Delta$ par des jonctions tunnel supraconducteurs d'aluminium. Nous discutons les conditions nécessaires pour l'émission des phonons de relaxation de hautes fréquences.

Abstract. — Up to now the emission of relaxation phonons of energy $E > 2\,\Delta$ by tin tunnelling junctions could not be observed by reason of the strong reabsorption of such phonons in the generator junction. We now report experiments in which the emission of relaxation phonons of energy $E > 2\,\Delta$ by aluminium tunnelling junctions is observed. The conditions necessary for the emission of high frequency relaxation phonons are discussed.

It was first pointed out by Eisenmenger and Dayem [1] that superconducting tunnel junctions could be used as phonon generators. The measurements showed [1], [2], that the phonon spectrum radiated by such a diode consists mainly of two parts : a « monochromatic » peak at energy $E = 2\,\Delta$ due to the recombination of quasiparticles and a continuum of relaxation phonons with a sharp high frequency cut off at $E = eU - 2\,\Delta$ (U = generator voltage). In addition, the experiments showed, that in Sn-I-Sn diodes for $eU > 4\,\Delta$ most of the phonons with $E > 2\,\Delta$ become reabsorbed within the generator film by pair-breaking and subsequent decay of the secondary quasiparticles under emission of low energetic phonons. The last result was confirmed by experiments by Eisenmenger [3] and Narayanamurti [4], in which no phonons of energy $E > 2\,\Delta$ leaving a Sn-generator junction could be observed. We now report on the observation of phonons of energy $E > 2\,\Delta$ radiated by Al-I-Al tunnelling junctions.

We used a Sn-I-Sn tunnelling junction as phonon detector. Both the Al-I-Al generator and the Sn-I-Sn detector junction were evaporated onto opposite faces of a sapphire plate (3 mm thich, c-cut). The experiments were performed at $T = 1.0$ K ; at this temperature $2\,\Delta_{\mathrm{Al}} = 0.28$ meV, $2\,\Delta_{\mathrm{Sn}} = 1.16$ meV. The tin detector responds only to phonons of energy $E \geqslant 2\,\Delta_{\mathrm{Sn}}$, therefore, only phonons of energy $E \geqslant 8.4\,\Delta_{\mathrm{Al}}$ can be observed. Under pulsed generator current conditions the first derivative of the detector signal with respect to the generator current, i. e. the differentiated transmission-reception characteristic (DTRC) was directly measured by means of a sampling and modulation technique.

Figure 1 shows the phonon spectrum due to first step relaxation of quasiparticles calculated according to the theoretical results of Tewordt [5]. The main features of this spectrum are : a decaying slope towards higher phonon energies, a sharp cut off at energy $E = eU - 2\,\Delta$ and a high energetic precursor with maximum energy $E = eU$ due to tunnelling and relaxation of thermally excited quasiparticles. (Also the direct recombination of quasiparticles of energy $E = eU - \Delta$ yields a contribution to the phonon spectrum with maximum energy $E = eU$.) On account of this phonon spectrum, one would expect the first onset of the signal at a generator voltage $eU = 2\,\Delta_{\mathrm{Sn}}$ and the main onset at $eU = 2\,\Delta_{\mathrm{Sn}} + 2\,\Delta_{\mathrm{Al}}$. Correspondingly the DTRC is expected to show a predominant steplike signal increase at $eU = 2\,\Delta_{\mathrm{Sn}} + 2\,\Delta_{\mathrm{Al}}$.

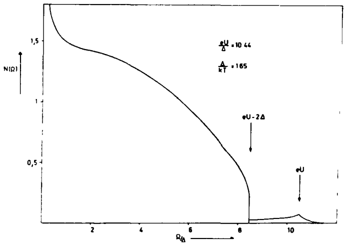

FIG. 1. — Calculated first step relaxation phonon spectrum.

We have measured the DTRC of two pairs of junctions (Fig. 2 and 3). We observed the first onset at $eU = 2\,\Delta_{Sn}$ and the second onset at $2\,\Delta_{Sn} + 2\,\Delta_{Al}$ respectively at $2\,\Delta_{Sn} + 1.3\,\Delta_{Al}$. After the second onset there is a steep approximately linear signal increase without steplike features. In the case of the second measurement, the generator current at $eU = 2\,\Delta_{Sn} + 1.3\,\Delta_{Al}$ is relatively close to the critical current. This may locally cause a decrease of the generator gap, which can explain the onset at $2\,\Delta_{Sn} + 1.3\,\Delta_{Al}$ instead of $2\,\Delta_{Sn} + 2\,\Delta_{Al}$. In addition, our relatively high $t = T/T_c$ and the quasiparticle injection by the tunnelling current results in a high quasiparticle density in the generator diode, primarily filling up states near the gap edge. On account of this, the step in the DTRC is rounded off. Summarizing, the onset of the signal at well-defined generator voltages $eU > 4\,\Delta_{Al}$ gives evidence of the emission of relaxation phonons of energy $E > 2\,\Delta_{Al}$.

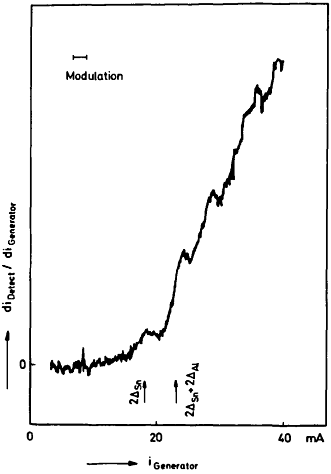

FIG. 2. — Differentiated transmission reception characteristic A ; $T = 1.0$ °K.

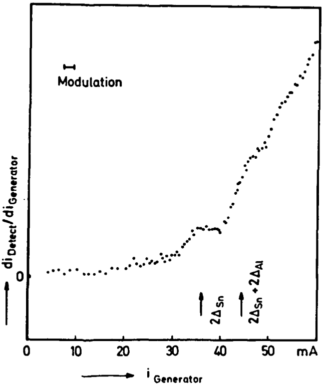

FIG. 3. — Differentiated transmission reception characteristic B ; $T = 1.0$ °K.

We now discuss the conditions necessary for the emission of relaxation phonons of energy $E > 2\,\Delta$ (Fig. 4). WKB-calculations yield the selection rule for the tunnelling process, that the electronic k-vector must be perpendicular to the barrier [6]. Further, from the k-conservation rule applied to the relaxation process it follows that the phonon is emitted at finite angle to the electronic k-vector. If the relaxation time τ_R of the quasiparticle is smaller than the mean time τ_{el} between two elastic collisions of the quasiparticle, the phonons may be emitted only in directions with angles exceeding the critical angle of internal total reflection at the Al-sapphire boundary. Therefore, the primary phonons cannot escape into the sapphire. In the case $\tau_R > \tau_{el}$ quasiparticles change their direction before relaxation takes place and phonons are emitted isotropically. Under these conditions high phonon escape probability into the sapphire results if the film thickness d is small compared to the phonon mean free path Λ against reabsorption. Otherwise, the diffusion length δ of quasiparticles must be larger than $d - \Lambda$. The diffusion length is determined by $\delta = l_{el}\sqrt{\tfrac{1}{3}\,\tau_R/\tau_{el}}$; $l_{el} = \tau_{el} \cdot v_F$ being the quasiparticle mean free path with respect to elas-

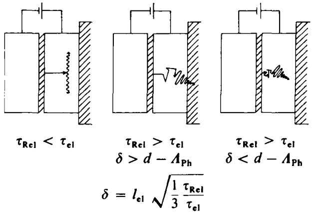

FIG. 4. — Schematic illustration of the discussion of conditions necessary for the emission of high frequency relaxation phonons.

tic collisions. We estimate that in Al $\tau_R/\tau_{el} \approx 10\,000$ for the emission of phonons of energy $2\ \Delta_{Sn}$ and in Sn for the emission of phonons of energy $2\ \Delta_{Pb}$ $\tau_R/\tau_{el} \approx 10$. Although the ratio τ_R/τ_{el} in the case of aluminium three orders of magnitude more favorable than in the case of tin, the fact, that no relaxation phonons of energy $E > 2\,\Delta_{Sn}$ emitted by Sn-diodes could be observed, cannot be explained without assuming a mean free path for high energetic phonons in tin of less than 700 Å [7].

In the case of our second measurement we have calculated the absolute detector signal current using our phonon escape model for the Al-junction. The absolute phonon sensitivity of the detector junction was determined by the temperature dependence of the thermal tunnelling current. Taking into account contributions of phonon reabsorption in the generator as a consequence of the finite film thickness and the critical angle of total internal reflection, the agreement between our calculation and experiment is within a factor of 10. Considering the uncertainty in the determination of the mean free path of phonons and the ratio τ_R/τ_{el}, this result can be regarded as satisfactory.

We think that high energy relaxation phonon emission above the superconductor energy gap may be of considerable value in using a superconductor tunnelling junction as phonon source with voltage tunable upper phonon energy edge for phonon absorption spectroscopy.

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DISCUSSION

K. RENK. — Which frequency can you reach, 10^{12} Hz ?

M. WELTE. — Up to now we used generator diodes of relatively low resistance in order to study carefully the structures at $2\,\Delta_{Sn}$ and $2\,\Delta_{Sn} + 2\,\Delta_{Al}$. In these experiments the upper limit (about 500 GHz) was given by the critical current of the generator junction. Higher frequencies can simply be reached by using Al junctions of higher resistivity. The reported method should also work at 10^{12} Hz, but we did not yet try it at this frequency.

V. NARAYANAMURTI. — What is your estimate of the highest frequency relaxation phonons one can generate in Al ?

M. WELTE. — On account of the uncertainty in the determination of the phonon mean free path Λ and the diffusion length δ it is in the moment difficult to calculate the high frequency limit for high phonon escape rates from Al-junctions. Extrapolating the ultrasonic attenuation data at even higher frequencies and taking into account the quasi-particle energy dependence of δ we estimate that also at phonon frequencies of 10^{12} Hz the escape condition $\Lambda + \delta > d$ should be fulfilled for film thicknesses of 1 000 Å.

C. ELBAUM. — On the matter of singularities at $2\,\Delta$ and $4\,\Delta$, the calculations seem to have been based on the B.C.S. density of states — « real metal » effects are expected to sharpen these singularities — have these effects been taken into account ?

M. WELTE. — The calculations are based on the theoretical results for finite temperature of Tewordt ; these formulas contain only the B.C.S., density of states. In the case of aluminum this seems to be a good approximation because aluminum is a very « B.C.S. like » superconductor.

H. KINDER. — Real metal effects can enhance the edge of the spectrum but cannot produce a singularity.

A. LONG. — Has the speaker performed any time resolution measurements to determine the relative proportions of longitudinal and transverse phonons in the flux ?

M. WELTE. — No the signal to noise ratio is not adequate.