JOURNAL DE PHYSIQUE *Colloque* C4, *supplément au n°* 10, *Octobre* 1972, *page* C4-29

EXPERIMENTAL RESULTS ON ABSOLUTE PHONON DETECTION SENSITIVITY OF SUPERCONDUCTING TUNNELLING JUNCTIONS

J. TRUMPP, P. EPPERLEIN and K. LASSMANN

Physikalisches Institut der Universität Stuttgart, Germany

Résumé. — Pour la génération et détection des phonons de 300 GHz on emploie des jonctions tunnel d'étain supraconducteur. Il est possible d'obtenir la sensibilité absolue pour la détection des phonons. Ainsi on peut comparer le nombre des phonons détectés avec celui des phonons engendrés. Le résultat, en connexion avec des mesures de la constante de temps de la jonction en dépendence de son épaisseur indique qu'il y a plus de phonons rayonnés dans l'hélium qu'on le supposait à partir d'un simple modèle acoustique.

Abstract. — Superconducting tin tunnelling junctions are used for generating and detecting 300 GHz phonons. The absolute phonon detection sensitivity can be obtained, making possible a comparison of the number of phonons detected to the number of phonons generated. This, together with measurements of the dependence of junction time constant on its thickness, gives an indication that far more phonons are radiated into liquid He than is expected from a simple acoustic model.

A superconducting tunnelling junction is a simple device for generating and detecting quasi-monochromatic phonons of a frequency corresponding to the energy gap 2Δ of the superconductor [1]. For example, tin-tin junctions are operating at 2.85×10^{11} Hz- (Besides, there is also a continuous spectrum with a variable upper edge [2], [3], [4].)

In the following we are showing that the number of 2Δ-phonons generated as well as the absolute sensitivity for phonons detected by such a junction can be obtained, thus allowing conclusions to be drawn on attenuation and scattering losses in a generator-detector setup. With tin-junctions evaporated on sapphire and silicon crystals immersed in liquid He II, we find strong evidence for a large fraction of phonons to be radiated into the helium.

If a superconducting junction is biased at $2\Delta/e$, pair breaking takes place in the tunnelling process giving one excitation on each side of the barrier per tunnelling electron and thus one recombination phonon. The generation rate of 2Δ phonons is, therefore, simply

$$\dot{n}_{\mathrm{ph}} = \frac{i_{\mathrm{G}}}{e}, \qquad (1)$$

where i_{G} is the current in the generator junction (apart from a small correction for some extra current which in good junctions is of the order of 1 %).

If a junction is biased at a voltage $U < 2\Delta/e$ the temperature dependent part of the tunnelling current is proportional to the (temperature dependent) concentration of excited quasiparticles N_{T}

$$i_{\mathrm{T}} = N_{\mathrm{T}}\, C(U, T) \qquad (2)$$

where $C(U, T)$ is an effective tunnelling constant. At low temperatures

$$N_{\mathrm{T}} = N_0 \sqrt{2\,\Delta k T \pi}\, \mathrm{e}^{-\Delta/kT}, \qquad (3)$$

where N_0 is the density of states at the Fermi level (with both spin states included). Plotting i_{T} as a function of $\sqrt{T}\,\mathrm{e}^{-\Delta/kT}$, we get a straight line, which shows that the temperature dependence of $C(U, T)$ and of $\Delta(T)$ as well is negligible. N_0 in our films we have confirmed by a new technique [5] to be the same as for bulk material from specific heat measurements. Therefore, from the slope

$$\frac{\partial i_{\mathrm{T}}}{\partial(T^{1/2}\,\mathrm{e}^{-\Delta/kT})} = C(U, T)\sqrt{2\,\Delta k \pi} \qquad (4)$$

$C(U, T)$ can be obtained.

Now, if 2Δ phonons are absorbed by the junction at a rate $\dot{n}^{*}_{\mathrm{ph}}$ the stationary change in quasiparticle concentration is given by

$$\delta N = 2\,\dot{n}^{*}_{\mathrm{ph}} \cdot \tau_{\mathrm{exp}}, \qquad (5)$$

where τ_{exp} is an effective recombination time constant [6], which is obtained in a pulse experiment. It can be assumed, that this extra concentration distribution relaxes to a thermal one in a time short compared to τ_{exp} [7]. Therefore, we may write

$$\delta i_{\mathrm{T}} = \delta N C(U, T) = 2\,\dot{n}^{*}_{\mathrm{ph}}\, \tau_{\mathrm{exp}}\, C(U, T) \qquad (6)$$

with the same tunnelling constant as in (1).

So far, we have managed to relate the generator current to the rate $\dot{n}_{\mathrm{ph}}$ of phonons generated and, on the other hand, the receiver current to the rate $\dot{n}_{\mathrm{ph}}^{*}$ of phonons absorbed in the detector. We are left with the problem of relating $\dot{n}_{\mathrm{ph}}$ to $\dot{n}_{\mathrm{ph}}^{*}$, that is to find out which fraction of the phonons generated in the emitter will be absorbed in the detector.

We have made this comparison for a series of experiments with tin junctions evaporated on sapphire or silicon rods, axis being c or [111] direction respectively. Lengths varied from 3 mm to 10 mm ; the end faces were mechanically polished optically flat. Junction dimensions were typically $1 \times 1\ \mathrm{mm}^2 \times 3\,000$ Å. The rods were immersed into He II.

Superficially, the setup looks like a classical ultrasonic experiment, were a transmitter and a receiver are bonded onto a crystal and the attenuation in the material is found from the exponential decay of the echo train. The most important difference is, that we are here working with incoherent phonons radiated from the emitter with a characteristic similar to Lambert's cosine law, so that echoes will become very small from geometric spreading and would also mix with multiple sidewall reflections making an evaluation very difficult.

For a calculation of $\dot{n}_{\mathrm{ph}}^{*}$ we will make the following assumptions to be discussed below :

1) All phonons will be radiated into the crystal with a Lambert's cosine radiation characteristic modified by the boundary conditions of the perfectly smooth surfaces [8]. Phonon focussing is accounted for [9].

2) No phonon scattering or attenuation will take place within the crystal or at its boundaries.

3) Phonons incident on the crystal junction boundary will be reflected corresponding to the acoustic mismatch model. Each phonon transmitted will be absorbed within the receiver junction to excite a Cooper pair.

The figure for $\dot{n}_{\mathrm{ph}}^{*}$ thus obtained has to be compared to that deduced from measurement. Our findings are that only a fraction of appr. 1 % (sapphire) resp. 2.5 % (silicon) independent of temperature and crystal length are detected by the receiver. The question arises which of the above-mentioned assumptions fail. We have not yet experimental data isolating all possible effects. So far, we can only make some estimates :

From an analysis of our measurements of the dependence of the inherent junction time constant τ_{exp} on its thickness we see that

a) The mean free path of $2\,\Delta$-phonons against attenuation by excited is much greater than our junction thicknesses, so that attenuation within the emitter is not important. This is consistent with extrapolations of ultrasonic experiments at much lower frequencies.

b) The mean free path of $2\,\Delta$-phonons against pairbreaking is comparable or smaller than junction thickness ; which means that most of them will be absorbed in the receiver by pairbreaking.

c) Radiation into liquid helium is much higher than would be expected from a simple acoustic mismatch model. Assuming that the latter will be valid for the junction/crystal boundary the junction surface looking to the helium makes a loss corresponding to a transmission of about 75 %. This means that only 25 % of the phonons generated will be radiated into the crystal. We are preparing an experiment with the crystal in vacuum for comparison.

Attenuation within the crystals can be excluded since no dependence on length is to be seen ; also extrapolation of ultrasonic data gives very long mean free paths.

Attenuation in a surface region, damaged by mechanical polishing, cannot completely be excluded. We are about to compare different polishing surface treatments.

Finally, a lack of « overlap » of the spectral distribution of the emitted phonons with the detector sensitivity must be considered in principle. From our experiments so far there is no indication for this ; but we are preparing more detailed experiments on this problem.

From the foregoing estimates we see that the junction surface in contact with He II contributes an unexpected large loss of phonons. However, taking this into account the remaining discrepancy between calculation and experiment amounts to a factor of five to ten.

Note added in proof. — By comparing τ_{exp} and the detected signal height when measuring in liquid He or vacuum we found in our latest experiment results confirming our foregoing estimations. This means, that the transmittance for $2\,\Delta$ tin phonon radiation into the He is 0.25 where as the transmittance into silicon is found to be 0.12 close to the theoretical value of 0.09.

References

[1] Eisenmenger (W.), Dayem (A. H.), *Phys. Rev. Lett.*, 1967, **18**, 125.

[2] Kinder (H.), Lassmann (K.), Eisenmenger (W.), *Phys. Lett.*, 1970, **31A**, 475.

[3] Welte (M.), Lassmann (K.), Eisenmenger (W.), this volume, p. 25.

[4] Kinder (H.), this volume, p. 21.

[5] Lassmann (K.), Sonnenberg (K. H.), Eisenmenger (W.), to be published.

[6] Rothwarf (A.), Taylor (B. N.), *Phys. Rev. Lett.*, 1967, **19**, 27.

[7] Tewordt (L.), *Phys. Rev.*, 1962, **128**, 12.

[8] Weis (O.), Angew (Z.), *Phys.*, 1969, **26**, 325.

[9] Taylor (B.), Maris (H. J.), Elbaum (C.), *Phys. Rev.* 1971, **B 3**, 1462.

DISCUSSION

A. F. G. WYATT. — What was the surface preparation of the Si ? The mechanical polishing could well cause surface damage which would cause diffusion of the phonons in the surface layer.

J. TRUMPP. — The surfaces were polished with diamond powder of different grain sizes (3 μ ... 0.75 μ) moving the crystal on pellon disks. With the smallest grain size we polished the surfaces long enough to be sure that defects in the surface layer are only due to the smallest grain. The depth of residual scratches was lower than 500 Å.

A. LONG. — Have you a value for $\overline{\overline{T}}$ for the tin-sapphire interface ?

J. TRUMPP. — Theoretical value 0.085.