TRANSITION OF 280 GHz PHONONS FROM SUPERCONDUCTING TUNNELING JUNCTIONS INTO LIQUID HELIUM AND SILICON

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Comparative phonon emission experiments carries out in liquid helium and vacuum with superconducting tin–tin tunneling junctions evaporated on silicon crystals, show a transmission into helium about three times higher than the transmission into silicon.

In phonon generation and detection experiments with superconducting tunneling junctions [1] it is possible to determine the number of 2Δ phonons generated (corresponding to 280 GHz for tin) as well as the absolute sensitivity of a junction when used as a phonon detector.

Using an acoustic model of the photon radiation into the substrate, the rate of phonons to be detected can be calculated and compared with the experimental value. This permits conclusions to be drawn on phonon losses which may occur by emission into the helium bath or by thermalisation within the generator detector system.

In a superconducting junction biased at $U_G = 2\Delta/e$, pair breaking and recombination results in the generation of one 2Δ phonon per tunneling electron. The generation rate of 2Δ phonons is therefore (J_G = generator current)

$$\dot{n}_G = J_G/e\,. \qquad (1)$$

On the other hand, 2Δ phonons being absorbed in the detector by pair breaking at a rate $\dot{n}_D$ cause a stationary change δN in quasiparticle concentration [2]

$$\delta N = 2\dot{n}_D \tau_{\mathrm{exp}}\,, \qquad (2)$$

where τ_{exp} is the experimental recombination lifetime as determined from pulse decay measurements which is enhanced over the true recombination lifetime because of recombination phonon reabsorption by pair breaking [3]; τ_{exp} depends on the junction thickness and the phonon escape probability into the adjacent crystal and the helium. The change of the quasiparticle concentration δN can be obtained absolutely from the detector short circuit signal current by calibration with the thermal quasiparticle tunneling current.

The detected phonon rate $\dot{n}_D$ as obtained from eq. (2) is to be compared with a detected phonon rate calculated from $\dot{n}_G$ using the following model:

1. Emission of all primarily generated 2Δ phonons into the crystal with Lambert's cosine law corrected for phonon focusing [4] and phonon reflection at the crystal-detector interface.
2. r^{-2}-dependence of the phonon intensity.
3. Quantitative absorption of 2Δ phonons by pair breaking in the detector [5].

The results of $\dot{n}_{D,\mathrm{exp}}/\dot{n}_{D,\mathrm{calc}}$ for different junction boundary conditions are given in table 1. The results show that $\dot{n}_{D,\mathrm{exp}}/\dot{n}_{D,\mathrm{calc}} < 1$ under all conditions even under vacuum conditions. This discrepancy indicates phonon losses possibly by: phonon interaction with phonons, quasiparticles and defects; generation of surface phonons and thermalisation at interfaces; incomplete absorption inside the detector.

Comparing $\dot{n}_{D,\mathrm{exp}}/\dot{n}_{D,\mathrm{calc}}$ for liquid helium with $\dot{n}_{D,\mathrm{exp}}/\dot{n}_{D,\mathrm{calc}}$ under vacuum conditions, we find an increase by a factor 3.8. The same increase ratio is obtained for τ_{exp} (1900 nsec/500 nsec). It can be shown that in vacuum the rate of phonons detected $\dot{n}_D$ should increase in the same way as τ_{exp} of the generator. Since our detector signal $S \propto \dot{n}_D \tau_{\mathrm{exp}}$ is proportional to $\tau_{\mathrm{exp,G}}\, \tau_{\mathrm{exp,D}} = \tau^2_{\mathrm{exp}}$; we obtain:

$$S_{\mathrm{vac}}/S_{\mathrm{He}} = (\tau_{\mathrm{exp,vac}}/\tau_{\mathrm{exp,He}})^2\,, \qquad (3)$$

in agreement with the experimental values

$$\tau_{\mathrm{vac}}/\tau_{\mathrm{He}} = 3.8; \quad S_{\mathrm{vac}}/S_{\mathrm{He}} = 14\,.$$

To compare the transmission into helium with the transmission into the silicon crystal, we calculated the dependence of τ_{eff} on the junction thickness d [6] for the dominant transverse wave contribution.

For $d > l_{\mathrm{ph}}$, l_{ph} being the mean free path against

Table 1

$\dot{n}_{D,exp}$ / $\dot{n}_{D,calc}$	Substrate	Outer junction surface
0.01	Al_2O_3	He
0.03	Si	He
0.12	Si	Vacuum
0.08	Si	N_2 + vacuum

pair breaking

$$\tau_{exp}/d = 4\tau_R/l_{ph}\, l(\bar{T}_{He}+\bar{T}_{Si})\,, \qquad (4)$$

where τ_R is the true recombination lifetime [3] and

$$\bar{T} = \int_0^{\frac{1}{2}\pi} T(\varphi)\sin 2\varphi\, d\varphi$$

are averages of the transmittance probabilities $T(\varphi)$ into helium and silicon (φ = angle of incidence). Using the acoustical data of Sn and Si we get $\bar{T}_{Si} = 0.09$. This together with our experimental values for τ_{exp} in vacuum and helium respectively leads to $\bar{T}_{He} = 0.25$ (acoustic mismatch model $\bar{T}_{He} < 0.01$). This means that the emission rate of 2Δ phonons from tin junctions into helium is about three times higher than into silicon. Or: neglecting losses inside the generator we have 25% total emission into the crystal and 75% into the helium.

Since the value τ_R/l_{ph} can be obtained using detailed balance [3] and τ_{exp}/d under vacuum conditions is experimentally known, we can also determine $\bar{T}_{Si}$ from eq. (4) resulting in $\bar{T}_{Si} = 0.115$. In view of the experimental resolution of ± 20% and the neglection of the longitudinal phonon contributions this is in satisfactory agreement with the result $\bar{T}_{Si} = 0.09$ obtained from the acoustic mismatch model.

Our results strongly support the validity of the acoustic mismatch model for phonon emission from tin to silicon. In contrast to this the phonon emission from the Sn-surface into liquid helium is much higher than predicted by the acoustic model. The experiments with condensed solid N_2 on the outer junctions surface indicate that the influence on τ_{exp} and $\dot{n}_D$ may be no specific attribute to helium.

References

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