# HIGH FREQUENCY PHONON EMISSION FROM SUPERCONDUCTING Al-TUNNELLING JUNCTIONS

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In single particle tunneling between identical superconductors phonons are generated by relaxation - and recombination transitions /1/ of injected quasiparticles. Phonon detection /1/ is mediated by the breaking of Cooper-pairs by phonons with energy exceeding the superconducting energy gap $2\Delta_D$. This leads to an increase of the quasiparticle population and a corresponding contribution to the tunneling current in the thermal tunneling regime $0 < eV < 2\Delta_D$ (V = battery voltage).

Voltage tunable phonon absorption spectroscopy /2/ makes use of the sharp upper limit of the continuous relaxation phonon or phonon Bremsstrahlung spectrum /2/ at the energy $\Omega = eV - 2\Delta_G$. In strong coupling superconductors as Sn and Pb the accessable energy range extends from zero energy to the gap energy $2\Delta_G$ since phonon reabsorption by Cooper-pairbreaking /3/ prevents the escape of relaxation phonons with higher energy than $2\Delta_G$. In weak coupling superconductors as Al, phonon reabsorption is reduced and in addition injected quasiparticles have relatively long relaxation time constants leading to quasiparticle diffusion from the barrier to the substrate boundary before phonon emission by relaxation takes place /4/. This results in a finite phonon escape probability also at energies exceeding the limit of $2\Delta_G$ as has been given evidence in experiments /4/ /5/ using Al junctions as phonon generator and Sn junctions as detector. At these high phonon energies the shape of the spectrum at the upper edge $eV - 2\Delta_G$ is changed as compared to the simpler steplike behavior /3/ for maximum energies below $2\Delta_G$.

Theoretical and experimental information on the high energy phonon spectrum at finite temperature or quasiparticle occupation is important for spectroscopic applications but also gives valuable insight into the different quasiparticle transitions.

The relevant quasiparticle transition processes leading to different contributions to the phonon spectrum are indicated in Fig. 1 as follows:

A: recombination of quasiparticles at the gap edge leading to phonon emission at $2\Delta_G$;
B: relaxation of quasiparticles injected from completely occupied states leading to a continuous spectrum with cutoff at $\Omega = eV - 2\Delta_G$;
C: direct recombination of the same quasiparticles with e.g. thermally excited quasiparticles resulting in a continuous spectral background with a peak at $\Omega = eV$;
D: relaxation of quasiparticles injected from thermally occupied states also resulting in a peak $\Omega = eV$;
E: direct recombination of quasiparticles injected from thermally occupied states. The peaklike phonon contribution slightly above $\Omega = eV + 2\Delta_G$ has a sharp <u>low</u> frequency cutoff at $\Omega = 2\Delta_G + eV$ /6/ /7/.

Within the limits of the BCS approximation the complete spectrum can be obtained quantitatively by numerical convolution procedures /4/ /5/, as shown in Fig. 2, where the contributions of the transitions B, C, D are clearly depicted. The contribution of process E is too small as to appear on this scale, also the major contribution to transitions resulting from recombination of already relaxed quasiparticles, i.e. secondary transitions, is not shown. The calculation has been also extended to the normal conductor limiting case for T = 0 introduced in Fig. 2 by dotted lines. In this case the sharp upper frequency edge is changed to a linear intensity decay cutting the zero level at $\Omega = eV$.

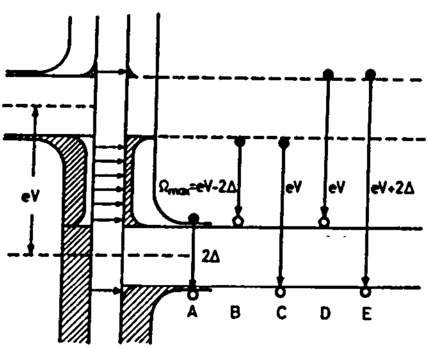


Fig. 1 Quasiparticle Transitions and Phonon Energies, c.f. text. Ref. /6/

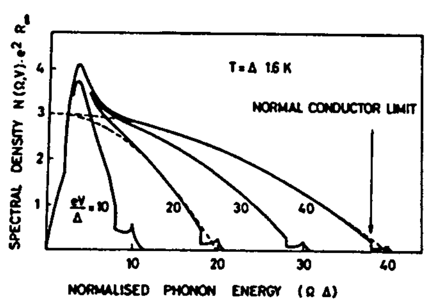


Fig. 2 Calculated Generator Phonon Spectrum. Ref. /5/

For experimental comparison an Al generator and a Sn detector with Si-substrate have been used /6/ /7/. The signal derivative with respect to the generator - current (or voltage) as function of the generator voltage, as shown in Fig. 3 /7/, has the same shape as the calculated spectrum but with inverted energy scale. This can be interpreted in terms of the sharp detector sensitivity threshold at $\Omega = 2\Delta_D$ and the common modulation technique by superimposing a small pulse or AC signal on the generator DC voltage. The detector modulation signal then corresponds to the first signal derivative with respect to the generator voltage. As can be seen from Fig. 2 a small change in the generator voltage produces an almost parallel shift of the spectrum to higher energies. The resulting change in the detector signal under this condition is determined by the spectral intensity at the threshold frequency $\Omega = 2\Delta_D$. The spectral structures of Fig. 2 are found in Fig. 3: The steep signal rise at $eV = 2\Delta_{Sn} + 2\Delta_{Al}$ corresponds to the onset of the main relaxation process B at $\Omega = eV - 2\Delta_G = 2\Delta_D$; the maximum at $eV = 2\Delta_{Sn}$ corresponds to processes C and D with $\Omega = eV$; the smaller maximum at $eV = 2\Delta_{Sn} - 2\Delta_{Al}$ is clearly revealed at higher amplification and reflects process E with $\Omega = eV + 2\Delta_G$ /6/ /7/. The weak oszillatory structure at $eV = 2\Delta_{Sn} + 2\Delta_{Al}$ can be attributed to longitudinal phonon interferences in the generator film of 1125 Å total film thickness. Time of flight pulse separation indicates that only longitudinal phonon interferences are observed. With larger film thickness values the interference structure disappears.

For spectroscopic applications the modulation method for taking the first signal derivative $di_s$: dV /2/ is appropriate for a gen-

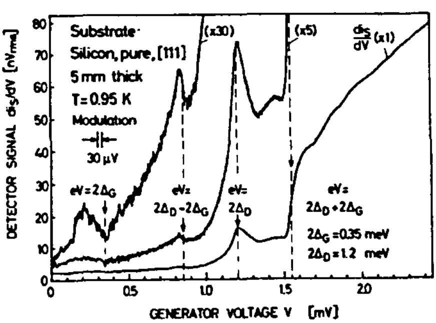


Fig. 3 Differential Signal for an Al-Generator and Sn-Detector on Pure Si Substrate. $2\Delta_{Al} = 0.35$ meV, $2\Delta_{Sn} = 1{,}2$ meV. Ref. /7/

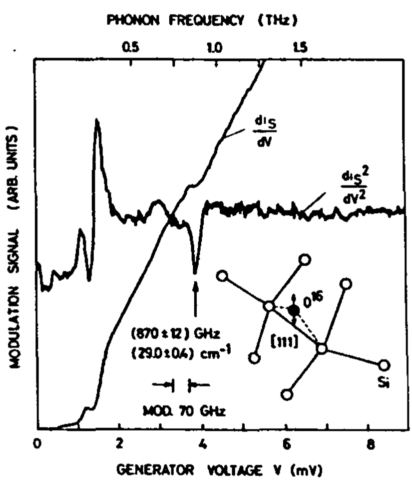


Fig. 4 Phonon Absorption in Si: O, Al-Generator and Sn-Detector. Ref. /5/

erator spectrum with a large step at the high frequency cutoff at $\Omega = eV - 2\Delta_G$. Under this condition the modulation results in a narrow effective phonon band at $\Omega = eV - 2\Delta_G$. In the limit of very high generator voltages compared to $\Delta_G$ the cutoff step at $eV - 2\Delta_G$ is reduced in height and becomes comparable to the thermal structures. This situation can be approximated by the normal conductor spectrum. It can be demonstrated /5/ /6/ that this spectrum also results in a narrow effective phonon band if the A.C. modulation technique is extended to the second derivative of the detector signal $d^2i_s : dV^2$ by recording the second harmonic of the detector modulation.

This method has been used in measurements of the phonon resonance scattering of oxygen impurities in silicon /5/, as shown in Fig. 4. Again an Al generator and a Sn detector were evaporated on the doped Si crystal. The structures of the first signal derivative at low generator voltages correspond to the results in Fig. 3. In addition, a pronounced plateau appears at 3.9 meV as expected for the oxygen resonance scattering. In the limit of high generator voltages the signal derivative approaches a linear dependence on voltage in accord with the detector sensitivity increasing in proportion to phonon energy. Phonons of energy $\Omega > 4\Delta_D$ are reabsorbed by pairbreaking and the succeeding relaxation of quasiparticles gives rise to additional phonons of $2\Delta_D$.

The second signal derivative $d^2i_s : dV^2$, introduced in Fig. 4, reveals the absorption maximum in the proper shape indicating that the generator spectrum at these energies $eV \gtrsim 24\Delta_G$ can be approxi-

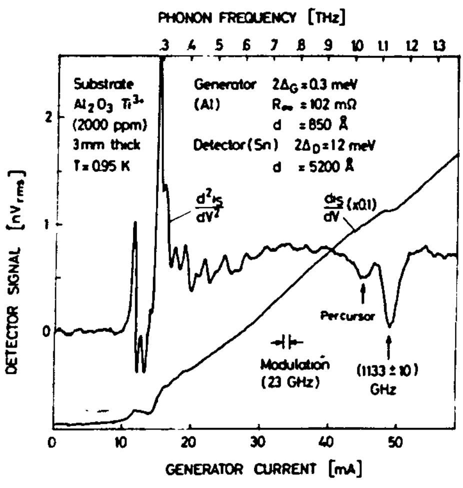


Fig. 5 Phonon Absorption in $Al_2O_3:Ti^{3+}$, Al-Generator and Sn-Detector. Ref. /7/

mated by the normal conductor limiting case. The resonant frequency of the oxygen atom results with 870 ± 12 GHz in good agreement with far infrared data /5/.

Evidence for phonon emission from Al-junctions at still higher frequencies has been found by W. Forkel very recently in using resonant scattering by electronic transitions between ground state levels of $Ti^3$ in $Al_2O_3$ /7/. The result of the experiment being similar to the one discussed before, is presented in Fig. 5. The first and second signal derivative show strong absorption at the phonon energy $\Omega = eV - 2\Delta_G$ corresponding to a frequency of 1133 ± 10 GHz in close agreement with the far infrared value /8/ of 37.8 $cm^{-1}$. The precursor of the absorption line in the second derivative results from a smaller phonon contribution at $\Omega = eV$, being detected as a consequence of the high experimental resolution. The observed linewidth of 55 GHz exceeds the experimental resolution of 23 GHz and also the linewidth of far infrared absorption. This may be due to the high Ti concentration of nominally 0.2 %. The second derivative also shows strong oscillations in the range of the detector energy gap structure resulting from longitudinal phonon interferences in the generator film of 850 Å total thickness. The sound velocity results with $6.3 \cdot 10^5$ cm/s in agreement with the bulk value.

Besides its application to phonon spectroscopy the observed high energy phonon escape from Al-tunneling junctions is expected to provide more information on the absolute strength of the phonon - electron interaction in Al.

I wish to thank W. Forkel, K. Laßmann and M. Welte for valuable discussions. Recent experimental results /7/ were kindly supplied by W. Forkel prior to publication. Financial support by the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

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