Observation of Phonon Frequency Thresholds in the Anomalous Kapitza Resistance

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Phonons emitted by superconducting tunneling junctions into insulator crystal substrates exhibit a sharp amplitude reduction above 85 GHz if the tunneling diodes are covered by ^{4}He. This is attributed to the onset of an enhanced phonon transport into helium.

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The Kapitza resistance or the thermal boundary resistance at the "real" interface between solids and liquid helium is, at least, one order of magnitude smaller than calculated in simple phonon transmission models.[1] This so-called Kapitza anomaly is still unexplained[2] with respect to its detailed microscopic origins. Significant progress has been made by the phenomenological model[3] that a violation of the k-transverse conservation rule by a lossy solid boundary explains the enhancement of the phonon transmission into the He liquid in agreement with experimental observations.[4] In fact, "ideal" crystal surfaces cleaved under low-temperature UHV conditions[5] do not show the Kapitza anomaly, whereas enhanced phonon transmission occurs after the "ideal" interfaces have been exposed to air. Finally, at sufficiently low frequencies or temperatures, the Kapitza resistance also of "real" interfaces agrees with the acoustic model.[6] Therefore, the identification of interfacial atomistic processes causing the Kapitza anomaly requires experimental studies of the frequency transition regime between regular and anomalous Kapitza resistance. Earlier experiments[7,8] indicated a smooth and structureless transition between regular and anomalous phonon reflection or Kapitza resistance in the frequency range from 20 to 200 GHz at real interfaces. This has been discussed in terms of a broad distribution of two-level systems at the solid-liquid boundary.[9-11] In our experiments we find a sharp onset in the decrease of reflectivity at about 85 GHz and additional structures at higher frequencies for a solid surface in contact with liquid or gaseous ^{4}He. This corresponds to other observations of an enhanced phonon transport from metal or isolator films into ^{4}He at the same frequencies.[12]

Our experimental arrangements are shown as insets in Figs. 1 and 2. For the generation and detection of phonons superconducting tunnel junctions evaporated on different materials (Si, Al_2O_3, GaAs) are used. It is well known that superconducting tunnel junctions emit frequency-tunable monochromatic phonons if the applied generator bias voltage (V_G) is modulated by a small ac voltage.[13,14] The frequency of these phonons is given by $\Omega_{ph} = (eV_G - 2\Delta_G)/\hbar$. In addition, superconducting tunnel junctions can be operated as quantum detectors for phonons. If the frequency of the phonons exceeds $2\Delta_D/\hbar$, the detector shows a steplike increase of the signal which remains constant until the phonon frequency reaches $4\Delta_D/\hbar$. From then on a continuous increase of the signal amplitude due to reabsorption in the detector is expected.[15]

Figure 1 shows the detector signal modulation amplitude as a function of the generator current, or the spectral phonon intensity versus frequency. The phonons are generated with a Sn junction and detected by an Al junction after propagating through a Si substrate. Cooling was provided by

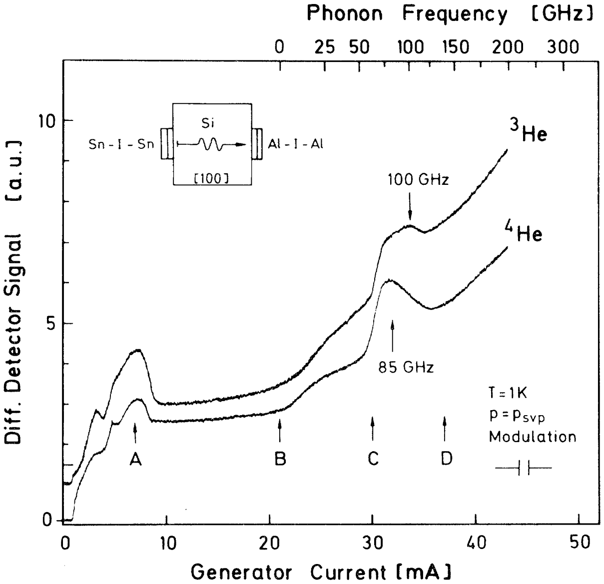

FIG. 1. Differential phonon signal of an Al detector vs the current of a Sn generator. The experimental arrangement is shown in the inset. Arrows A–D: see text. The sample is in contact with ^{3}He and ^{4}He, respectively.

^{4}He or ^{3}He gas ($T = 1$ K, $p = p_{\rm svp}$), respectively. At small currents (arrow A), some peaks due to nonlinearities in the I-V characteristic of the generator are observed. The following plateau is caused by the constant intensity of recombination phonons with fixed frequency of 285 GHz. Beginning with 0 GHz (arrow B), monochromatic phonons are generated which are already weakly detected in the Al junction operating partly as bolometer as a consequence of the high T/T_c ratio of 0.8. For phonon frequencies $\Omega_{\rm ph} > 2\Delta_D/\hbar$ (arrow C), pair breaking in the Al junction leads to a steplike sensitivity increase. At higher frequencies a significant difference in the detected phonon rate between ^{4}He and ^{3}He is observed. With ^{4}He gas in sample contact a strong decrease of the phonon signal starting at about 85 GHz is observed. After reaching a minimum at about 139 GHz the signal increases again obviously at frequencies smaller than $4\Delta_D/\hbar$ (arrow D). The decay threshold at 85 GHz is also observed with the sample immersed in liquid ^{4}He. For the sample in contact with ^{3}He gas a small decrease in the phonon signal at about 100 GHz is followed by a minimum at about 120 GHz and a smooth increase at $4\Delta_D/\hbar$. To make sure that the threshold was not caused by heating, the emitted phonon power was varied by a factor of 50 using different Ohmic Sn-I-Sn generators. Alternatively, we used the higher frequency resolution of thin Al junctions (total thickness between 250 and 500 Å) serving as phonon generators, reducing the phonon power by another two orders of magnitude. This experiment confirmed the 85-GHz threshold followed by two minima at 110 and 130 GHz. With sinusoidally modulated pulse amplitudes for the generator and sampling of the detector phonon signal we observed for all sampling times within the pulse duration the decay of the phonon signal at the 85-GHz threshold.[16,17] In repeating the experiments with different substrate materials no influence on the 85- or 100-GHz threshold in the phonon signal reduction could be observed. In contrast, the change of the boundary conditions at the free generator surface had a significant influence as already described for the contact to liquid ^{3}He. We especially observed a complete disappearance of the frequency threshold phenomena with the generator first covered with condensed nitrogen or a thin oil film and then immersed in liquid ^{4}He, or by keeping the sample under vacuum.[16,17] All these experiments together indicate that the threshold phenomena are not related to resonances in the sample or at the sample generator interface but must be caused by a frequency threshold with significant reduction of the phonon reflection at the outer generator surface in contact with liquid ^{4}He or ^{3}He, i.e., the detector signal amplitude is a direct measure for the phonon reflectivity at the He-metal boundary. We therefore conclude from our measurements that enhanced phonon transport from the metal into ^{4}He starts at about 85 GHz and reaches a maximum at about 130 GHz. A corresponding threshold of increased phonon transport into ^{3}He is found at 100 GHz.

In order to extend the frequency range of the experiment from 0 to 285 GHz we used two silicon substrates polished optically flat and fitted together with a thin acetone film in between for phonon coupling and thermalizing. As indicated in Fig. 2 (inset), superconducting Sn junctions have been used as phonon generator and detector. The generator emits monochromatic phonons both into ^{4}He and into the boundary between the two substrates. Monochromatic phonons incident at this boundary are thermalized. The reemitted "heat" leads to a signal in the Sn detector.[17] Thus, the tunneling junction together with the coupling boundary operates as a bolometer. As discussed earlier, the detector signal again corresponds directly to the reflectivity of the Sn/^{4}He interface of the generator. It must be added that smooth changes of the reflectivity cannot be detected with this arrangement. The observed signal am-

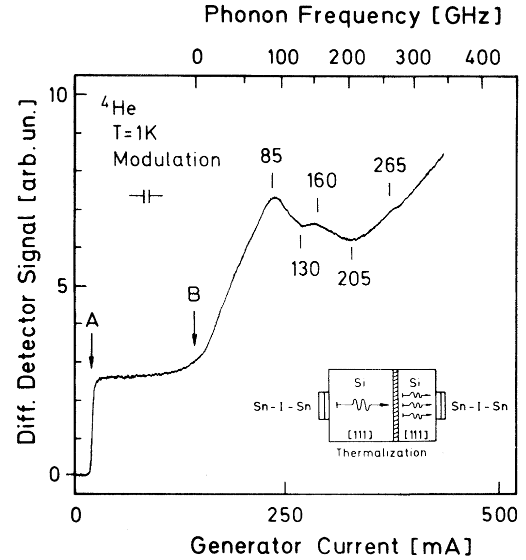

FIG. 2. Differential detector signal vs the current of a Sn generator obtained by the thermalizing arrangement (inset). (Arrows A and B: see text.)

plitude as function of the phonon frequency is shown in Fig. 2. The dc Josephson current is not suppressed by a magnetic field (arrow A). Between 0 GHz (arrow B) and 85 GHz the signal frequency dependence is almost structureless, whereas at 85 GHz a breakdown in the reflectivity is observed followed by an absolute minimum at 130 GHz. The increase of the reflectivity is interrupted at 160 GHz and at about 205 GHz the reflectivity recovers again. Another weak decrease of the phonon signal is observed at 265 GHz. By use of an Al detector with larger energy gap, these structures are also observed in measurements as in Fig. 1.

To obtain more quantitative results for the frequency dependence of the reflectivity we used a frequency-tunable phonon detector.[18,19] The measurements have been performed with a Sn generator and an Al-*I*-PbBi detector on a V^{3+}-doped Al_2O_3 crystal, with application of the modulation technique as described before but now with the variable detector frequency threshold. Since the detector sensitivity depends on the tuning bias, the always observed absorption line of the V^{3+} ion at 247 GHz (Ref. 14) serves as sensitivity reference. The ratio of the signal step at the detection onset frequency divided by the observed depth of the V^{3+} absorption line is a direct measure for the frequency dependence of the generator phonon intensity. This intensity in turn varies in proportion to the phonon reflection coefficient R at the Sn/^{4}He interface. R is normalized to R/R_0 by the step height at 75 GHz (R_0) and is shown in Fig. 3. We note that the effective reflection coefficient R/R_0 is not an absolute value which would have to be corrected by functions like phonon generation rate, detection probability, and phonon mismatch to the solid,[20] yet all these functions are monotonic and will not change the observed structures of the reflection coefficient.[17] In Fig. 3 a strong breakdown of the reflection coefficient is observed as before at 85 GHz with a minimum at about 110 GHz. The increase of the reflectivity is interrupted at about 160 and 205 GHz. The frequency dependence of Fig. 3 corresponds to Fig. 2 within the experimental errors of ±15 GHz. The decrease of the phonon signal in the described experiments implies an increase of the phonon transport through a solid/He boundary as also found in gas sound propagation[12] at about 85 GHz in ^{4}He gas and at about 100 GHz in ^{3}He.

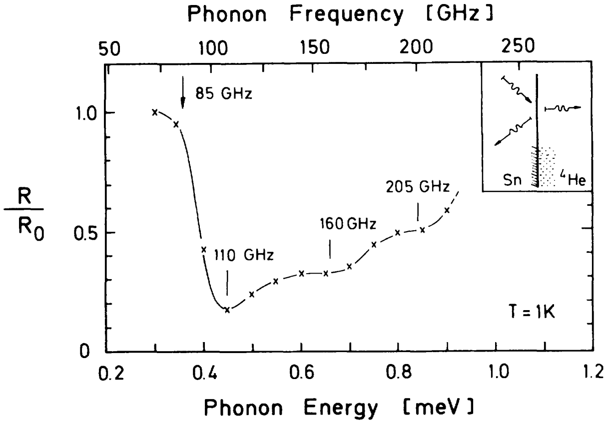

FIG. 3. Effective reflection coefficient R/R_0 vs phonon frequency. R is normalized to unity at 75 GHz (R_0). For details see text.

Summarizing, we found a strong "breakdown" of the phonon reflectivity at the solid/^{4}He boundary when the phonon frequency exceeds 85 GHz with minima at about 110, 130, 205, and 265 GHz. In the temperature range between 1.0 and 1.5 K there was no significant influence of the helium temperature on the breakdown frequency. A corresponding breakdown of the phonon reflectivity with ^{3}He gas contact is found at 100 GHz. This seems to be a property of real interfaces which are not macroscopically contaminated.

These results are to be compared with those of inelastic neutron scattering on He-layered surfaces revealing dispersionless surface excitations, roughly at the same frequencies as we observed.[21,22]

Our results may be interpreted in terms of an enhanced phonon coupling by imperfections or adatoms to excitations with characteristic frequencies in the ^{3}He or ^{4}He layers in the van der Waals potential of the real surface. Alternatively, resonant excitations[23] or two-level transitions[9,10] of the surface imperfections themselves may determine the frequencies of strong phonon coupling to the liquid ^{4}He or ^{3}He layers, respectively. For this case, our experiments indicate an additional influence of the atomic weight of ^{4}He or ^{3}He on the Kapitza threshold frequency.

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