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Reflection of Phonons at Interfaces between Silicon and Solid Hydrogen and Deuterium*

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The reflection of phonons at an interface between a silicon crystal and solidified hydrogen and deuterium has been investigated by the heat-pulse method. The reflection coefficients are found to be much smaller than predicted by the acoustic-mismatch theory.

According to the theory of Khalatnikov,[1] the thermal boundary resistance (Kapitza resistance) at an interface between two materials occurs because phonons attempting to pass from one medium to the other are reflected by the mismatch in the acoustic properties of the media. Experimental investigations of the thermal boundary resistance[2] have traditionally measured either (1) the resistance at the interface between a classical solid (e.g., silicon or copper) and liquid ^{3}He or ^{4}He, or (2) the resistance between two classical solids. In experiments of type (1) a wide variety of solids has been investigated. In every case, the measured Kapitza resistance has been considerably smaller, by up to a factor of 100, than the value predicted by the acoustic-mismatch theory, except at very low temperatures ($T<0.1°$K). On the other hand, in experiments of type (2) involving two classical solids, the results have been in generally good agreement with the acoustic-mismatch theory. One could speculate, therefore, that the anomalously small value of the Kapitza resistance to liquid helium is an effect unique (a) to liquids, (b) to helium, or (c) to any material in which quantum effects are important. Folinsbee and Anderson[3] have shown that the Kapitza resistance to liquid and solid helium are of the same order of magnitude, indicating that speculation (a) is incorrect. To decide between (b) and (c) one must study a quantum system other than helium. A convenient measure of the importance of quantum effects is de Boer's "quantum parameter" Λ^*. Λ^* is defined by

$$\Lambda^* = h/\sigma(m\epsilon)^{1/2},$$

where σ and ϵ are the range and strength, respectively, of the interatomic potential, and m is the molecular mass. Materials for which $\Lambda^* \leqslant 0.5$ are classical in the sense that zero-point motion makes only a small correction to the lattice dynamics.[4] For ^{3}He and ^{4}He Λ^* is 3.08 and 2.68, respectively. The only other materials with $\Lambda^* > 1$ are H_2 and D_2, for which Λ^* has values 1.73 and 1.22. We report here measurements for these solids. In order to make a comparison, data were also taken for liquid and solid ^{4}He, and for solid neon ($\Lambda^* = 0.59$).

The experiments used the heat-pulse technique instead of the traditional dc-heat-flow Kapitza-resistance measurement. Using this method, one can study the reflection coefficient of phonons of a particular polarization, whereas the dc method averages over phonon polarizations. The experimental arrangement (Fig. 1) was similar to that of Guo and Maris.[5] The silicon crystal and sample chamber, surrounded by a vacuum space, were in thermal contact with a helium pot. The temperature was controlled by pumping on the pot and by varying the current through an attached resistance heater. At the beginning of the experiment the sample chamber A was under vacuum. A pulse of phonons was generated at the lower face of the silicon by Joule heating of a thin film of Constantan. Some of these phonons were reflected from the upper face of the silicon and detected by one of two thin-film superconducting bolometers on the lower face. Separate echoes were observed corresponding to longitudinal and transverse phonons, and also to phonons whose time of flight indicated that they had undergone

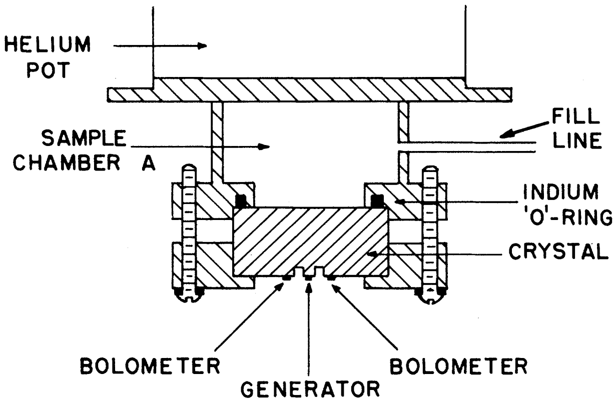

FIG. 1. Experimental apparatus.

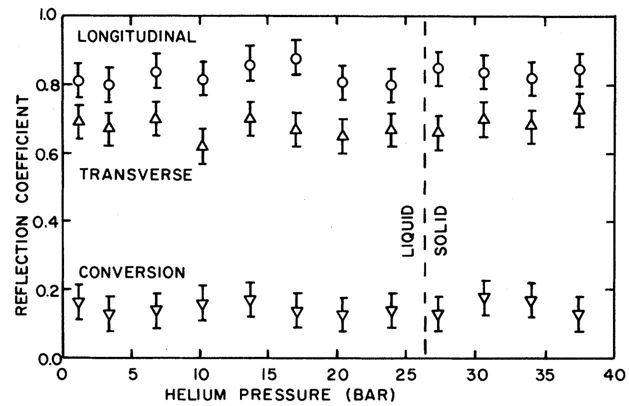

FIG. 2. Reflection coefficient for phonons incident on a {111} face of silicon covered by liquid or solid ^{4}He as a function of the pressure applied to the helium. The ambient temperature is 1.4°K and the temperature of the phonon generator is 6.0°K.

mode-conversion at the upper surface. Helium, hydrogen, deuterium, or neon were then introduced into A, producing either a solid or liquid in contact with the upper surface of the silicon, depending upon the applied pressure and the temperature. The reduction in amplitude of the phonons detected by the bolometer could then be used to find the reflection coefficient of the phonons at the interface between the silicon and the material condensed in A. Measurements of the reduction in pulse amplitude were made for the longitudinal, transverse, and mode-conversion pulses. For each condensed gas, several runs were performed. The variations in the measured reflection coefficients were generally less than ±0.05. All data presented in this paper were taken on a silicon crystal with {111} faces. The end faces of this crystal had been polished with successively finer grades of alumina powder down to 0.3 μm. The ambient temperature was between 3.0 and 3.2°K, except for most of the liquid and solid helium runs. For these it was 1.3–1.8°K. The temperature of the Constantan generator[6] was typically 6–7°K.

The experimental results for the reflection coefficients are summarized in Table I. Also shown are theoretical reflection coefficients for longitudinal and transverse phonons calculated from the acoustic-mismatch theory under the assumption that the reflecting surface is flat on the scale of the acoustic wavelength.[7] The spread in theoretical values occurs because the orientation of the solidified gas crystals is unknown, and because phonons are incident on the interface over a small but finite range of angles. No theoretical value is given for the mode-conversion phonons. The mode-conversion phonons arise primarily because of surface roughness, and so it is difficult to use the acoustic-mismatch theory to calculate a reflection coefficient for this signal. The principle features of the results are as follows:

(1) The reflection coefficients for H_2 and D_2 are much smaller than the acoustic-mismatch values, particularly for transverse phonons. The experi-

TABLE I. Reflection coefficients for phonons incident on a {111} face of silicon covered by various condensed gases. Experimental results have an uncertainty of ± 0.05.

Material	Λ* Quantum parameter	Longitudinal Theory	Longitudinal Exp.	Mode-conversion Exp.	Transverse Theory	Transverse Exp.
Liquid ^{4}He	2.68	0.99	0.83	0.14	1.00	0.65
Solid ^{4}He (30 bar)	2.68	0.98	0.85	0.14	0.98	0.68
Solid H_2	1.73	0.96	0.81	0.16	0.96	0.67
Solid D_2	1.22	0.92	0.77	0.15	0.92	0.69
Solid Ne	0.59	0.71± 0.03	0.55	0.15	0.68± 0.10	0.59

mental accuracy is not sufficient to detect any difference between H_2 and D_2.

(2) The results for liquid ^{4}He are similar to earlier measurements.[5] The reflection coefficients for liquid ^{4}He at saturated vapor pressure and solid ^{4}He at 30 bar are equal; this is in agreement with the recent measurements of Folinsbee and Anderson.[3] We have also measured the reflection at intermediate pressures and found that there is no measurable discontinuity when solidification occurs (Fig. 2).[8]

(3) For Ne the agreement with the acoustic-mismatch theory is much better, although the reflection coefficient for longitudinal phonons is still significantly less than the theoretical value.

(4) In all cases the mode-conversion phonons have a very small reflection coefficient.[9]

In summary, these experiments strongly suggest that anomalously small reflection coefficients (and, by implication, anomalously small Kapitza resistances) are characteristics of systems in which quantum effects are important. The similarity[10] of the results for liquid and solid ^{4}He, solid H_2, and solid D_2 indicates that the unknown mechanism which causes the anomalous energy transfer is probably the same in all of these systems.

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[10] The similarity of the reflection of phonons from ^{4}He, H_2, and D_2 could be further established by comparing the frequency dependence of the phonon reflection coefficients from the three systems. For ^{4}He [see C. H. Anderson and E. S. Sabisky, in *Physical Acoustics*, edited by W. P. Mason and R. N. Thurston (Academic, New York, 1971), Vol. 8, p. 1; H. Kinder and W. Dietsche, Phys. Rev. Lett. 33, 578 (1974)] the phonon reflection coefficients agree with the acoustic-mismatch theory below a frequency of 40 GHz and fall to approximately 0.5 at frequencies of 100 GHz and higher. It is expected that the reflection coefficients from solid H_2 and D_2 also decrease with increasing frequency over some range of phonon frequencies.