Extinction of the Kapitza Anomaly for Phonons along the Surface Normal Direction

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We have succeeded in extinguishing the anomalous Kapitza transmission of phonons whose wave vector is normal to a surface treated by conventional means and handled in air. In the same experiments, phonons approaching the surface with oblique wave vectors are anomalously transmitted. We argue that these results demonstrate that the Kapitza anomaly is due to surface defects which couple to the phonon strain field.

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For the past ten years phonon-pulse experiments, both in reflection and in transmission, have been used to study the Kapitza anomaly.[1] These experiments have shown that, contrary to the expectations of conventional elastic theory, transverse as well as longitudinal phonons are transmitted across interfaces between solids and liquid helium with anomalously large efficiency.[2]

We have studied the transmission from liquid helium of phonons propagated along the Si(111) direction. Previous studies in this geometry have found pulses due to longitudinal and slow transverse phonons with the same 1:3 ratio expected from phonon focusing in the crystal.[3-5] In this paper we show, however, that for longer-wavelength phonons, the longitudinal transmission at that interface can be extinguished while the transverse transmission is less attenuated. The observation is significant because, in this orientation, longitudinal phonon modes propagate parallel to their wave vectors and hence do not strain the surface. By contrast, transverse phonon modes have wave vectors oblique to their direction of propagation and hence do strain the surface. Our observations therefore imply that surface strain is a key mechanism of the Kapitza anomaly. This result was predicted by a model due to Kinder,[6] who pointed out that the Kapitza anomaly can be accounted for by surface defects which couple to the phonon strain field and to the excitations of liquid helium.

Our experiment is essentially similar to previous ones,[3-5] except that we used phonons transmitted into instead of out of the crystal. The geometry is shown in the inset of Fig. 1. A thin-film evaporated-Constantan heater (0.3×0.3 mm^2) on a Plexiglas substrate is spaced a few micrometers from the optically polished surface of a Si crystal (15 mm diam., 4 mm thick) by means of evaporated-indium tabs. Energy from the heater traverses the intervening liquid helium via second sound, arriving at the crystal surface where it can excite phonons by means of the Kapitza anomaly. Those phonons which propagate along the (111) direction are monitored by an Al-oxide–Al detector junction (1 mm diam). Longitudinal and transverse pho- are distinguished by their times of flight.

For a given heater pulse, this geometry produces about the same signal size as the more conventional one in which the heater and detector are interchanged. However, in that case, the heater creates hot phonons in the crystal which are converted to low-temperature heat in the liquid helium before reaching the detector. In the present arrangement, the heater energy is immediately converted to low-temperature heat (second sound) and therefore excites only low-frequency pho-

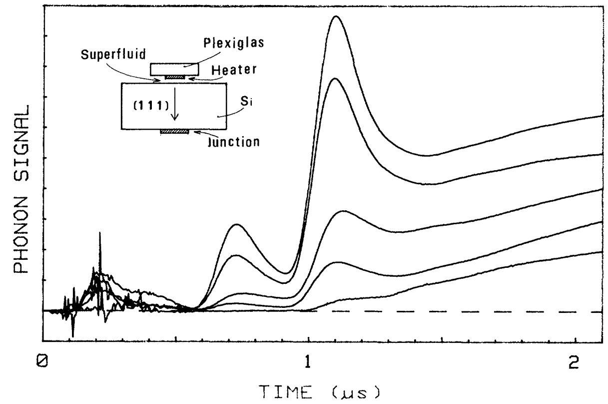

FIG. 1. Phonon-pulse signals for the same heater power (4 W), but different surface preparations, as explained in the text. The first (smaller) peak is due to longitudinal phonons, and the second is due to slow transverse phonons in each case. Note the extinction of both longitudinal and transverse phonons even at this high heater power. Inset: experimental geometry (not to scale).

nons in the crystal. We are therefore able to obtain a substantial signal comprised of low-frequency, long-wavelength phonons ($\hbar\omega/k_B \lesssim 2.2$ K). Our purpose in producing these long-wavelength phonon pulses was to probe the behavior of the Kapitz anomaly on the scale of irregularities of an ordinary surface (i.e., one that is handled in air rather than being prepared *in situ*).

Figure 1 shows an example of our experimental results. All the traces shown are time-of-flight signals at the same junction, all at ambient temperature 1.2 K, with 100-ns pulses of 14-V amplitude in the 50-Ω heater (i.e., 4 W). They differ only in the treatment history of the Si surface. From the lowest trace to the highest, the Si surface was treated as follows: (1) etched in nitric acid followed by HF, distilled-water rinse, and optical-paper wipe; (2) same, then rinsed with a drop of isopropyl alcohol; (3) same after some further exposure to air and possibly pump oil; (4) re-etched as above, but not wiped; (5) same, but wiped with optical paper. These traces, which are a direct indication of anomalous Kapitza transmission through a single surface, show that the anomaly depends sensitively on subtle and as-yet uncontrolled and unknown details of surface handling and history. They also show that the transmission technique is a sensitive indicator of the degree of Kapitza anomaly.

Figure 2 shows the same data plotted in a different way. Here all the traces have been scaled such that the peak due to transverse phonons has the same height. By contrast, the longitudinal (L) peak varies from a height consistent with zero up to about 20% of the transverse (T) peak height. In other data, the L/T ratio of 0.33 observed by previous investigators was reached at higher heater power in the sample showing the largest overall signal. Moreover, for each sample, the L/T ratio was monotonically heater-power dependent, showing complete extinction of the L peak below some threshold power in each case. Figure 3 shows a low-power (2-V pulses) signal from surface 3 above, together with the 14-V signal for the same surface, repeated from Figs. 1 and 2. Here the extinction of the L pulse at low power is clearly evident.

We can summarize these observations by saying that anomalous Kapitza transmission is lower for both modes at lower heater power and hence for lower-frequency, longer-wavelength phonons. In addition, the L pulses always decrease faster than the T pulses, falling below our ability to detect when the T signal is still quite substantial.

In previous experiments the Kapitza anomaly has been successfully extinguished only at surfaces that had been freshly cleaved[7] or laser annealed[8] *in situ*. Although these experiments made it clear that the phenomenon is due in some way to the nonideality of the surface, they did not reveal the mechanism of the anomaly, which is present in all ordinary samples handled in conventional ways. The surface treatments in this paper are comparable to those normally used in phonon-pulse experiments and thermal-Kapitza-resistance studies. Thus our ability to reduce or eliminate the anomaly in a selective way affords a unique opportunity to examine the systematics of the phenomenon.

Next we discuss the results in terms of existing theories. Khalatnikov's theory[9] is certainly not applicable here, since we are dealing with a dirty surface.[1] Moreover, this theory cannot explain the extinction of the longitudinal pulse. Shiren[10] has suggested that surface roughness diffracts phonons from the liquid helium into the solid. This theory does not yield any

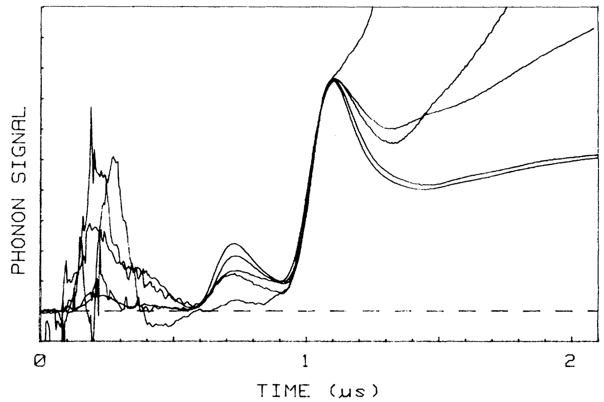

FIG. 2. The same data as in Fig. 1 but scaled to have the same transverse peak height. The smallest signal has been multiplied by a factor of 16. The longitudinal pulse is extinguished even more strongly than the transverse one.

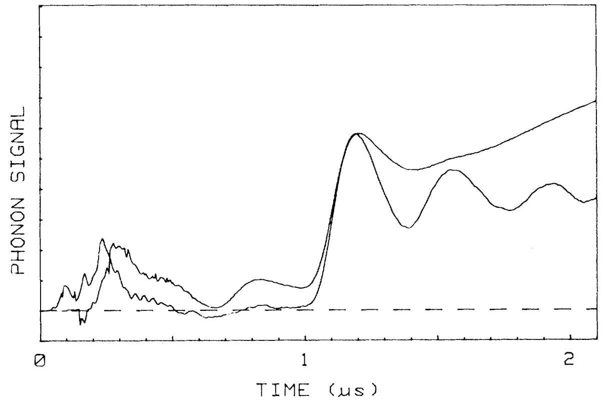

FIG. 3. Comparison of a 4-W pulse and a 0.08-W pulse for the same sample (No. 3), scaled to the same T peak height. The L pulse is extinguished in the 0.08-W pulse (which also has second-sound echoes). The 4-W pulse is repeated from Figs. 1 and 2.

strong dependence on the direction of the transmitted phonons, nor does it predict the frequency- and roughness-dependent L/T ratio that we observe. Vuorio[11] has proposed that impurities form an acoustic matching between the two media; in effect, this means that the coupling between the host crystal and the surface impurities is inertial. Again, there is no strong variation with the angle and polarization of the phonons transmitted into the solid, and our results cannot be explained.

However, our results are predicted by the defect model proposed by Kinder,[6] and in fact, this prediction motivated us to do the present experiment. Kinder has argued that all ordinary surfaces are characterized by the presence of localized defects, e.g., two-level states with random excitation energies, whose phenomenological behavior is well known from the study of bulk glasses. These defects are excited by the rotons and phonons (i.e., the second-sound pulse) incident from the helium side. Subsequently, the excited defects relax, with a certain probability, by phonon emission into the solid.

The angular distribution and polarization distribution of these emitted phonons reflects the type of defect-phonon interaction. In the case of inertial coupling, only a weak angular dependence is expected. If the coupling is via the phonon strain, i.e., by deformation-potential interaction (like in bulk glasses), then one must take into account that the strain field of the phonon eigenmodes of the solid is modified at the surface by the boundary condition. Because of the strong acoustic mismatch between helium and the solid,[9] the surface can be considered to a good approximation as being force free, as far as the defect-phonon interaction is concerned. This boundary condition has the consequence that the phonon eigenmodes of the solid with normal wave vectors have a node of the strain field at the surface, while phonon eigenmodes with oblique wave vectors have nonvanishing strain components at the surface. Therefore, phonons with normal wave vectors cannot interact with surface defects, and the spontaneous emission by excited defects into these modes is forbidden.

This argumentation is strictly valid only for $q_\perp d \ll 1$, where d is the thickness of the defect layer, including the mean amplitude of any surface roughness, and $q_\perp$ is the normal component of the wave vector of the phonon mode considered. With increasing $q_\perp d$, the defects extend beyond the node at the surface and begin to feel the strain field of the phonon states. Thus the emission becomes increasingly allowed, even into phonon states with normal q. Correspondingly, the emission into phonon states with small angles to the normal increases as well.

In summary, the defect model predicts, for a thin layer on a smooth surface, that the phonon intensity emitted into the solid should vanish for normal wave vectors and remain finite for oblique angles. For larger $q_\perp d$, the intensity should increase for both normal and small oblique angles.[12]

In order to keep the experiment simple and clear-cut, we have chosen the (111) plane of Si for the surface and a propagation direction normal to this plane. As already mentioned, the longitudinal phonons then have normal wave vectors, while the slow transverse modes have angles of $\sim 10°$ and $20°$.[13] Our results are then readily understood in view of the above discussion. Figure 1 shows the variation of the emission probability with the layer thickness d at constant power, i.e., constant q. Figure 2 shows that the variation is stronger for the L mode because it is forbidden for $d \cong 0$. Finally, Fig. 3 shows the effect of increasing power, i.e., increasing q at a single surface, i.e., constant layer thickness d.

We conclude that the behavior is consistent with the model of surface defects which interact by deformation-potential coupling with the phonons of the solid. On surfaces prepared by conventional means and handled in air, the defects form a layer whose thickness can be comparable to the wavelength of the phonons in the solid. Our new technique will permit study of those layers in detail in future experiments.

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