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Kapitza Resistance of Laser-Annealed Surfaces

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Our understanding of the phonon processes at the interfaces between two media is still quite rudimentary. Particularly notorious is the Helium-solid interface, where the accoustic impedances differ by a large amount. It is well known that the Kapitza resistance, i.e. the thermal boundary resistance between Helium and a solid, is usually up to 100 times smaller than predicted by the acoustic theory as formulated by Khalatnikov [1]. However, it was shown by J. WEBER et al. [2] that there was no discrepancy at surfaces of freshly cleaved crystals, i.e. at surfaces of exceptional good quality. Thus it is clear that surface irregularities must be responsible for the anomalous Kapitza resistance. Little progress has been made, however, in the understanding of how these irregularities mediate the anomalously strong phonon transmission.

In this Paper we describe a technique which allows the in situ modification of a surface. Simultaneously the phonon loss into Helium can be measured. From the effect of the surface modifications on the phonon losses, we can gain insight into the nature and the role of the surface irregularities.

We use the method of laser annealing which was introduced recently [3]. This technique uses high-power light pulses from a ruby laser to irradiate a Si surface. The energy of the pulse is sufficient to melt momentarily a thin (less than 5000 Å thickness) surface layer. It is known from several studies [3] that the molten layer recrystallizes in the same structure as the bulk and that the surface is free of impurities.

Our experimental set up is shown in Fig. 1.a. We used a vacuum chamber which was immersed in liquid Helium at 1 K. The sample, a Si crystal, (100) oriented, of 4 mm thickness, was sealed to one side of the chamber. The test surface of the sample was at the vacuum side. It was polished by the supplier and without visible scratches. The phonon generator and the detector were placed about 0.5 mm apart on the outer side of the cystal. As generator we used a Sn film which was heated by irradiation with light pulses from an HeNe laser. We assume that the emitted phonon spectrum has a broad frequency band with a maximum at 2Δ, the energy gap of the Sn. We used phonon pulses of 100 ns duration. These pulses were, after reflection from the test surface, detected with an Al tunnel junction. The intensity of the reflected phonons depends , of course, on the losses at the test surface. The relative signal change during filling the chamber with Helium could be measured with about 1 % precision. The reproducibility of the total sensitivity after a laser annealing of the test surface was about 30 %.

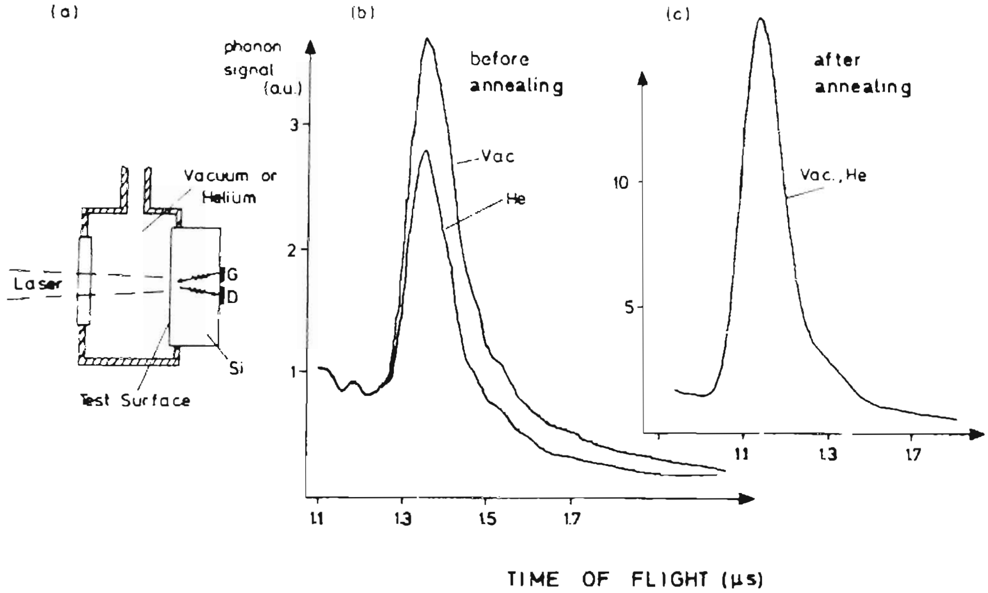

Fig.1 (a) Sample setup. Phonon pulses before laser annealing (b) and after annealing (c)

The ruby laser which we used for the annealing provided pulses of 40 ns duration (TEM_{00} mode). From experiments with room-temperature Si, we concluded that an area of 0.12 mm^2 could be annealed with one laser pulse, i.e. over this area was the energy density above the annealing threshold of 1 J/cm^2 [3]. Thus the energy of our laser was too small to anneal the whole test surface with one laser pulse. Therefore we used an optical scanning apparatus to move the laser beam across the test surface. With this method many annealed spots could be placed next to each other which barely overlapped.

The experimental results are shown in Figs. 1.b and 1.c. The intensities of the reflected phonons are plotted vs their respective times of flight. Due to phonon focusing transverse phonons only were detected. The two traces in Fig. 1.b were obtained before the annealing. The loss of intensity between the chamber being evacuated (vac) and filled with Helium (He) was as expected for a "standard" Si surface [4]. The trace in Fig. 1.c was measured after annealing an 8 mm^2 area in the center of the test surface. Strikingly the reflected phonon intensity increased enormously (about fivefold). Note the different scales at the y-axis. Probably this increase was due to the transition from diffusive to specular reflection of the phonons. Similar strikingly no difference between the traces was discernible if the chamber was evacuated or filled with Helium. That means that the anomalous Kapitza transmission disappeared. From this result we conclude that laser annealed surfaces are as good as the cleaved ones of J. WEBER et al. [2].

In the next step we contaminated the test surface by irradiating the In seal between the Si crystal and the vacuum chamber several times with the ruby laser. The result is shown in Fig. 2.a. The absolute height of the phonon pulse was now considerably decreased indicating that the phonons were now again nonspecularly reflected. The pulse shape, however, differed from that of the virgin state. It exhibited now a pronounced tail. Similarly to the virgin state of the test surface, the anomalous Kapitza transmission

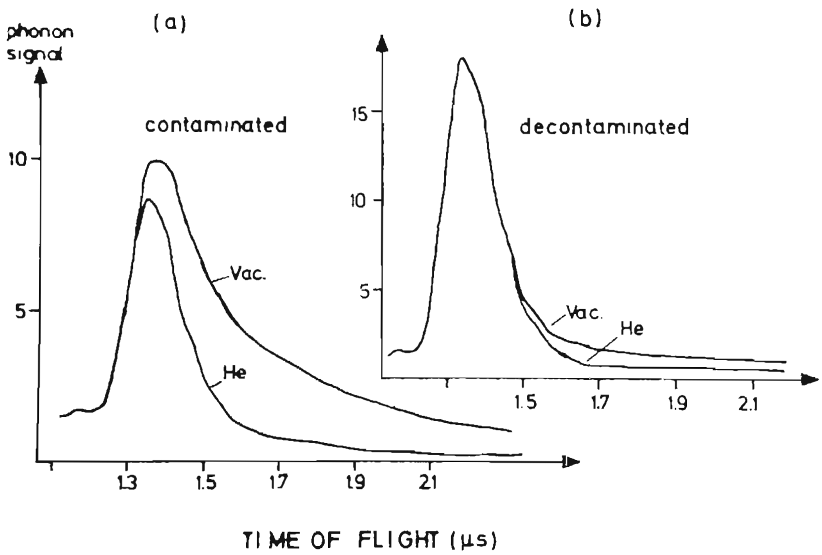

Fig.2 Phonon echoes after contaminating (a) and consequent decontamination by laser annealing (b)

returned. Particularly the phonons in the tail were lost if the chamber was filled with Helium.

With a repeated laser annealing we could decontaminate the surface again. This time we annealed an area of only $1mm^2$. Nevertheless both the tail and the phonon loss into the Helium disappeared almost completely. This shows that the tail was not due to phonons travelling along long path lengths under oblique angles which would lead to long times of flight. The tail must rather have been due to a time delay in the contaminant.

At the moment the exact chemical nature of the contamination is not known. It could be evaporated and recondensed water or In metal itself. The different phonon-pulse shapes obtained with the virgin and with the contaminated surface indicate different origins of the anamolous Kapitza transmission in the two cases.

In conclusion we have shown that phonon-ideal surfaces can be prepared with laser annealing. The possibility of repeated contamination and annealing will very likely start a completely new branch of surface studies with phonons. With this technique we have demonstrated for the first time that the anomalous Kapitza transmission can be induced by condensing impurities on the interface between the solid and the Helium. It is noteworthy that the existence of such impurities is a prerequisite for a recent model [5] of the anomalous Kapitza transmission.

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