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Down-Conversion of High-Frequency Acoustic Phonons

By

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Measurements of phonon transport in amorphous media can give valuable information on the structural properties of these materials and may be of practical interest for its own concerning the question of thermalization in electronic devices. The existence of two-level systems in a-Si:H as one of these technically important materials has been concluded from measurements of dispersion and attenuation of acoustic surface waves /1, 2/. High-frequency phonon transport has been investigated in a-SiO_2 with superconducting tunnel junctions for frequency discrimination /3, 4/. Depending on the preparation technique strong frequency-dependent inelastic scattering within the layer was found for evaporated films /3/, whereas the scattering was ascribed to the film/substrate interface in the case of the more dense thermally oxidized glass films /4/. Differences in the relative importance of elastic and inelastic scattering have been found comparing SiO and a-Ge films on sapphire in a heater phonon experiment with some frequency discrimination /5/.

In the case of a-Si:H it has been found by direct comparison in /6/ that the phonon pulses excited in a-Si:H are narrower than in c-Si when detected by superconducting bolometers. This has been interpreted as a more rapid thermalization in the amorphous material. Measurements of the temporal correlation of recombination luminescence with phonon emission after pulsed optical excitation of a-Si:H on sapphire have been reported in /7/. For high excitation intensities the phonon signal was much broader than the luminescence decay. Optical excitation of crystalline semiconductors may lead to high-frequency acoustic phonon production from the rapid decay of the primary optical phonons as was shown in /8/ by $2k_F$-spectroscopy or concluded in /9/ from the pulse decay shapes for both optical and Joule heating. As a consequence there may be a complicated phonon transport which is neither ballistic nor diffuse /10/. Analogous

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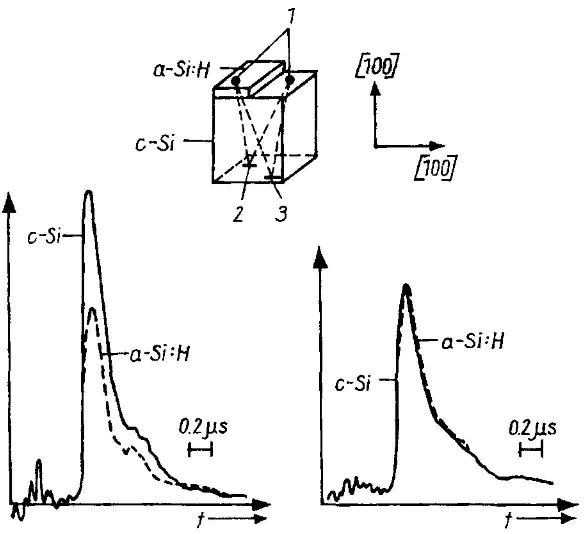

Fig. 1. Comparison of detector response for identical heater conditions; left: Sn junction, right: Al junction. The inset shows the geometry of the phonon transmission experiment in the case of ohmic heating. (1) Constantan heaters, (2) Al junction detector, (3) Sn junction detector

to /8/ and /9/ it was found in /7/ that at high laser intensities there is a broadening of the phonon signal which has been interpreted as due to phonon trapping from hot spot effects. So, for the question of phonon thermalization in a-Si:H additional spectra information is necessary.

To investigate this point further we have made measurements comparing heat pulse transmission through a-Si:H layers (thickness $\approx 1.5\ \mu m$, [H] ≈ 12 %) sputtered onto Si substrates with that through the bare substrates on crystallographically equivalent paths to minimize the intensity variation from phonon focusing. Phonon generation was either by ohmic heating or evaporated constantan films or by direct optical excitation focusing a N_2-laser beam ($\lambda \approx 0.34\ \mu m$) onto equivalent points of the covered and uncovered surfaces. As phonon detectors we take superconducting Sn tunnel junctions, sensitive for frequencies above 280 GHz or Al junctions, sensitive for frequencies above 90 GHz, and Sn bolometers at the magnetically tuned superconducting transition (T = 1.28 K with fields up to 0.1 T by means of a superconducting solenoid).

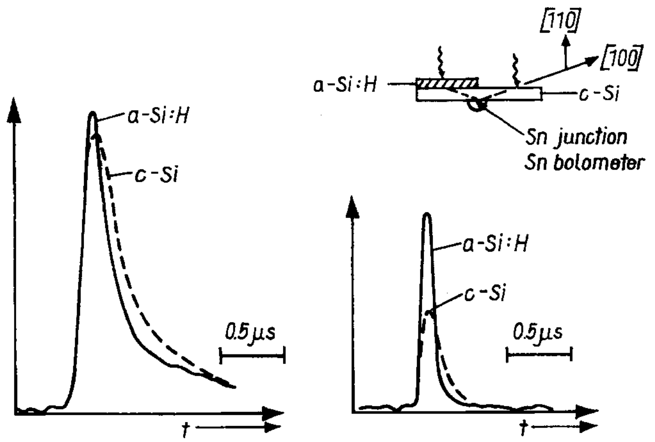

Fig. 2. Comparison of detector response for identical laser intensity; left: Sn junction, right: Sn bolometer. The inset shows the geometry of the phonon transmission experiment in the case of generation by optical excitation. (1) Sn junction, (2) Sn bolometer

In the case of the ohmic heating the constantan generators and the Sn and Al junction detectors were placed on opposite sides of a (100) Si cube of 10 mm as indicated in Fig. 1. The a-Si:H layer covering half of one surface allows the comparison of four equivalent paths. In the case of optical excitation both detectors, the Sn junction and the Sn bolometer, were at the same place (see inset of Fig. 2) in that one film could be used as a superconducting transition bolometer by magnetic tuning. Care was taken to avoid flux to be frozen in, since it would strongly reduce the junction sensitivity. The Si sample (thickness 2.8 mm) in this case was 110 oriented and the excitation points were chosen such that the propagation direction of the detected phonons was the 100 focusing direction for slow transverse phonons.

Our result in the case of ohmic heating is shown in Fig. 1. The signal from both, a-Si:H and c-Si as detected by the Al junction is practically the same in height and form (Fig. 1, right), whereas the signal through the a-Si:H layer as detected by the Sn junction is smaller by about 40 % as compared to the signal from the uncovered surface (Fig. 1, left). Since the Sn junction is sensitive only for phonons above 280 GHz this indicates a strong down-conversion of the high-frequency part of the spectrum in the a-Si:H film confirming a suggestion made in /6/ and /7/. Such a difference in the signals in principle could also be due to an unequal phonon irradiation of the detectors because of a possible slight misalignment, since phonon focusing requires critical positioning. As a check we have also measured close to the critical temperature of Sn where this junction also becomes a bolometric detector. We find that in this case both Sn junction signals become almost equal indicating that the integral irradiation of this junction from both sources is the same.

The result of the analogous experiment with optical irradiation is depicted in Fig. 2. The integrated signal in the case of bolometric detection is larger for the a-Si than for the c-Si which may be due to the difference in optical absorption and/or transformation of the optical energy into heat by radiationless processes. Also, the difference in the primary-phonon frequency distribution and consequent scattering and transport may play a role. The ratio of the integrated signals from a- to c-Si is 1.5 for bolometric and 0.9 for 280 GHz threshold detection. That is, taking c-Si as reference again a reduction of about 40 % of the high-frequency part of the signal by the a-Si:H film is also found for optical phonon excitation as for ohmic heating of a metal film. So, the higher frequencies possibly produced in the optical excitation as compared to ohmic heating /9, 11/ do not show up in the reduction factor. The signal decay is steeper for the signal from the a-Si:H layer as compared to the uncovered surface for bolometric (Fig. 2, right) as well as for high-frequency threshold detection by the Sn tunnel junction (Fig. 2, left). This finding is analogous to that of /6/ and may again be due to the difference in the primary-phonon frequency distribution and consequent scattering and transport.

These results demonstrate that phonons transmitted through thin layers of a-Si:H are strongly scattered inelastically. The same down-conversion coefficient is found for both, optically and ohmically generated phonon spectra at least for the intermediate heating intensities used here. With the experience of /4/ in mind the possible role of the a-Si/c-Si interface has to be sorted out by measuring the thickness dependence of the effect. Also, some information on the frequency dependence may be obtained from variation of the heating power.

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