EFFECT OF LASER ANNEALING ON SPECULAR AND DIFFUSE SCATTERING OF 285 GHz PHONONS AT POLISHED SILICON SURFACES

E. MOK, S. BURGER, S. DÖTTINGER, K. LASSMANN and W. EISENMENGER
Physikalisches Institut Teil 1, Universität Stuttgart, Stuttgart, FRG

Received 9 September 1985; revised manuscript received 16 December 1985; accepted for publication 23 December 1985

We have investigated the time resolved backscattering of high frequency phonons ($\geqslant$ 285 GHz) at laser annealed silicon surfaces at low temperatures. It is found that the scattering off the free surface becomes predominantly specular up to frequencies well above 285 GHz and that the anomalous transmission into liquid helium (Kapitza effect) is strongly reduced.

Introduction. In the last years several authors published backscattering experiments using phonon pulse techniques and different surface preparations in order to study the question of specular and diffuse phonon scattering at surfaces. Comparison of the backscattering from free and helium covered surfaces has shown that the diffuse part of the scattering at the free surface is strongly correlated with the anomalous high transmission of phonons into liquid helium (Kapitza anomaly), that is, much higher than it would be expected from the difference in the acoustic impedances of the solid and the helium.

Marx et al. [1] used Sn tunnel junctions with a sharp detection threshold at 285 GHz as phonon detectors to investigate silicon (100) surfaces. In their experiments the dominant process is diffuse scattering for all polishing procedures applied. By covering the surface with liquid helium or solid nitrogen the backscattering signal was strongly reduced.

On the other hand specular reflection and no reduction by helium was found by two kinds of in situ surface preparing techniques: cleaving NaF [2] and laser annealing silicon [3]. In both cases the detector was an Al tunnel junction with a detection threshold in the range of 85–110 GHz. But for Al detectors also bolometric detection of phonons with frequencies below the Al gap must be taken into account.

As shown by Burger et al. [4], with this kind of detector it is possible to obtain specular phonon reflection for low frequency phonons even at silicon surfaces polished by a standard chemical-mechanical treatment (Syton), but at higher frequencies the diffuse scattering increases. At frequencies corresponding to the detection threshold of a Sn junction detector (285 GHz) again the scattering is mainly diffuse confirming Marx's [1] results.

In this paper we describe backscattering experiments at silicon surfaces prepared by in situ laser annealing. By the use of Sn tunnel junctions we detect only frequencies above 285 GHz. Annealing the whole reflection surface resulted in nearly complete specular reflection and only small reduction of the signal by helium coverage. This corresponds to a strong reduction of the anomalous high transmission into the helium (Kapitza resistance) in a wide range of phonon frequencies.

Experimental procedure. The measuring arrangement is a modification of that described by Marx [1] and Burger [4] (fig. 1). The sample, a silicon crystal, (100) oriented, was Syton polished and fixed onto an UHV-chamber. The reflection surface of the crystal could be irradiated through an optical window with Q-switched ruby laser pulses of 50 ns duration and maximum energy of 1 J. At this pulse energy we could anneal an area of 5 mm diameter with one laser pulse with energy densities up to 3 J/cm^2 (energy density for annealing: 1.2–3.2 J/cm^2) [5]. The maximum penetration depth of the meltfront was estimated to ~0.4 μm at 1.3 K [6]. For annealing the whole reflect

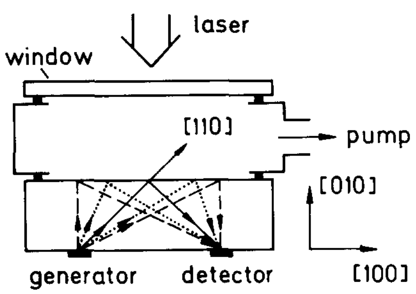

Fig. 1. Experimental arrangement. The scattering surface of the sample is part of an UHV-chamber and can be irradiated with laser pulses. Phonon paths corresponding to the signal peaks in fig. 2 are indicated. Full line: path for specular and diffuse scattering of longitudinal (peak 1) and fast transverse phonons (peak 3). Dashed lines: paths for diffuse scattering of fast transverse phonons (peak 4). Dotted lines: paths for modeconverted (long. ↔ transv.) phonons (peak 2).

ing surface at least 5 laser pulses focused on the 5 different reflection points in fig. 1 are necessary.

The 100 ns phonon pulses were generated with a constantan heater, the detector was a Sn tunnel junction.

Experimental results. Fig. 2 shows the experimental results of annealing the whole reflecting surface. Curve a shows the scattering signal from the polished silicon surface and corresponds to the signal observed by Marx [1], who explained it with diffuse reflection (max. 4% specular). In particular, the fourth pulse can be due only to diffuse scattering. Curve b shows the phonon signal after annealing. There is a large increase of the specular contributions of the signal and a strong decrease of the diffuse reflection. Even a threefold specular reflection (peak 5) appears. The third peak (ft-phonons) shows the largest change increasing up to a factor 3 corresponding to about 70% specular reflection. On the other hand the diffuse peak 4 is strongly reduced. Corresponding to the different reflection points of the peaks (fig. 1) each of them could be separately influenced by selective annealing.

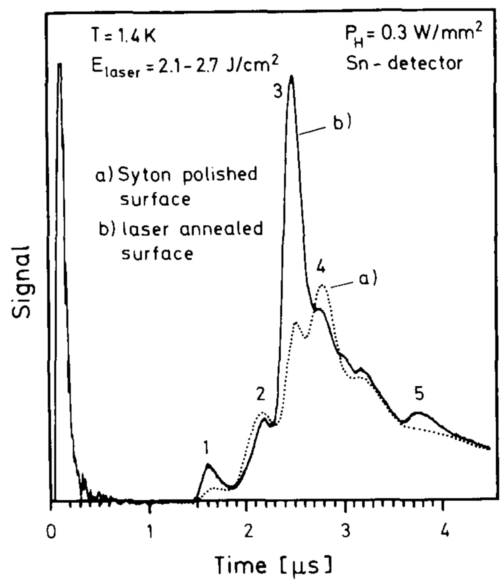

Fig. 2. Phonon backscattering signal of the polished surface (curve a) and of the laser annealed surface (curve b).

Figs. 3A and 3B show the correspondence of diffuse scattering and anomalous transmission into liquid helium (free surface curve a, helium covered surface curve b). Fig. 3A shows the backscattering signals from the polished surface. Due to predominantly diffuse scattering the signal is strongly reduced by the helium coverage. It should be noted that the reduction of the diffuse part by the helium coverage is not complete in contrast to what has been found [4] in the case of low frequency phonons. Fig. 3B shows the signals after annealing the reflecting surface. Corresponding to the change into mainly specular reflection the reduction is small but not as small as to be expected in the theoretical reflection limit. The curves in fig. 3B look quite similar to those obtained for Syton polished surfaces [4] and Al detectors (low frequencies).

For the annealed surface a much smaller "frequency" dependence of the backscattered signal could be observed (fig. 4) in varying the heater power from 0.03 W/mm^2 to 3.0 W/mm^2 as compared to the Syton polished surface.

The nearly ideal annealed surface can also be used to study the influence of different coverages under much better characterized circumstances.

For exposing the reflecting surface to air we warmed the annealed crystal up to room temperature under UHV-conditions, filled the UHV-chamber with air for 30 minutes, evacuated again to 10^{-7} Torr and cooled down to 1.0 K. Fig. 5 shows the change of the backscattering signals (same sample as fig. 3): as compared to the laser annealed surface (fig. 3B) there is

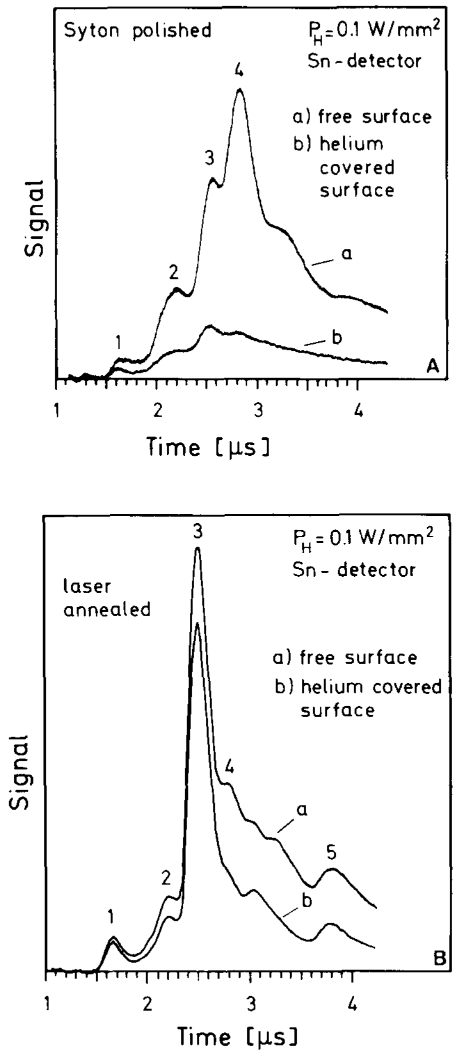

Fig. 3. (A) 285 GHz backscattering signal of the Syton polished surface without and with helium coverage (curve a: free surface, curve b: helium covered surface). (B) 285 GHz detector signal of the laser annealed surface without and with helium coverage (curve a: free surface, curve b: helium covered surface).

an increase of the diffuse scattering and a strong reduction of the specular peaks, but there is more specular reflection than in the case of the polished surface (fig. 3A). The signal from the helium covered, air exposed surface is about twice as large as that from the polished, helium covered surface (fig. 3A). This means that a laser annealed surface exposed to air shows less

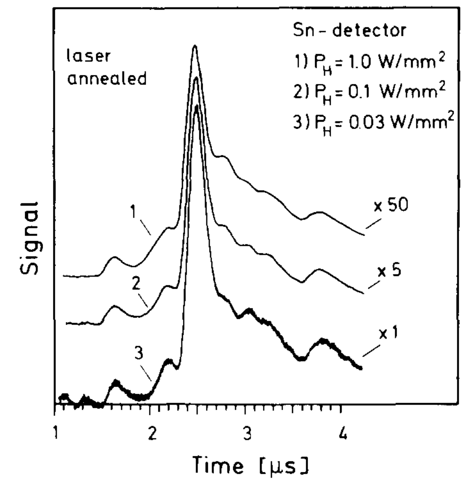

Fig. 4. The backscattering signals of the laser annealed surface show a small heater power dependence.

diffuse scattering and a smaller Kapitza anomaly than a polished silicon surface at frequencies ⩾285 GHz. Similar results for lower frequency phonons (Al detectors) were obtained by Weber et al. [3] on cleaved LiI surfaces which were exposed to air for one day. They

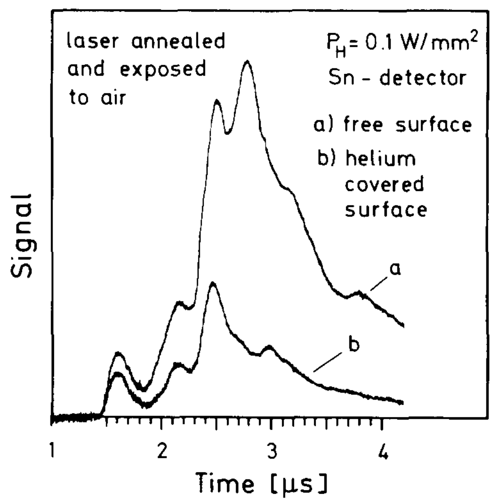

Fig. 5. The 285 GHz signals of a laser annealed surface exposed to air for 30 minutes show more specular reflection than the polished surface (fig. 3A). Curve a: free surface. Curve b: helium covered surface.

found that after the air contact the anomalous transmission into helium was greatly enhanced.

Heating the air exposed surface with laser powers below the annealing threshold ($\leqslant 1.2$ J/cm^2) had to influence on the signal. In order to reproduce the signal shape of the annealed surface it was necessary to melt again the scattering surface to a certain depth.

Conclusion. Our experiments have shown that laser annealing is a possibility to prepare in situ nearly ideal reflection surfaces even for high frequency phonons ($\geqslant 285$ GHz). After annealing we observed a large increase of the specular phonon reflection (about 70% specular reflection for the ft-phonons) and according to that the Kapitza anomaly was strongly reduced. Furthermore our experiments have shown that phonon backscattering experiments are a sensitive means to investigate the properties and the quality of laser annealed free silicon surfaces. The annealed surfaces can also be used very well to study the influence of coverages under much better characterized conditions

We would like to thank Miss G. Untereiner for the preparation of the sample surfaces.

References

[1] D. Marx and W. Eisenmenger, Z. Phys. B48 (1982) 277.
[2] J. Weber, W. Sandmann, W. Dietsche and H. Kinder, Phys Rev. Lett. 40 (1978) 1469.
[3] H. Basso, W. Dietsche and H. Kinder, in: Phonon scattering in condensed matter, eds. W. Eisenmenger et al., Springer series in solid state sciences 51 (Springer, Berlin, 1984).
[4] S. Burger, K. Lassmann and W. Eisenmenger, J. Low Temp. Phys. 61 (1985) No. 6.
[5] J.M. Poate and J.W. Mayer, in: Laser annealing of semiconductors (Academic Press, New York, 1982).
[6] R.F. Wood and G.E. Giles, Appl. Phys. Lett. 38 (1981) 422.