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PHONON IMAGING

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Abstract.- Investigations of phonon propagation and scattering in solids use either coherent microwave phonons or incoherent phonons in the form of heat pulses[1] generated by current flow through thin metallic films and bolometer detection, or monochromatic incoherent phonons generated and detected with superconducting tunneling junctions[2]. Applying these techniques to a perfect single crystal, quantitative measurements require knowledge on phonon propagation in anisotropic media. In contrast to optic properties the acoustic propagation in anisotropic media is much more complicated by the large number of elastic constants. An additional complication arises if the dispersion of acoustic phonons is included. Whereas the propagation of coherent phonons is simply described by the anisotropic constant-energy surfaces in q-space, the propagation of incoherent phonons (generated by a point source) is determined by the distribution of group velocities. These distributions were first calculated by Taylor, Maris and Elbaum[3] with the result that specific propagation directions and modes show strong and sharply peaked intensity maxima. This phenomenon was called "phonon focussing". In later work also names as phonon channeling, phonon caustics etc. have been used. The pronounced sharpness of these distributions with strong intensity changes within angles of 1 degree raised strong experimental and theoretical interest for a more complete spacial description, or for imaging the phonon distributions. First, three-dimensional directivity patterns were obtained by computer analysis[4]. More recently, direct measurements of phonon intensity distributions[5] and, for instance, measurements with computer-aided spacial display[6] of the phonon intensity have led to impressive phonon images on crystal surfaces. Alternatively, it is also possible to obtain direct phonon images[7], observing the thickness increase of a superfluid ^{4}He-film on the crystal surface by the fountain effect in regions of high phonon intensity. In this lecture the fundamentals of phonon focussing and phonon imaging techniques will be reviewed.

1. Introduction.- Phonon transport in solids by heat conduction is well-known as a quasi-equilibrium situation in which local thermal equilibrium is established by Normal and Umklapp processes. The heat flow vector is related to the temperature gradient by a second rank tensor equation, resulting in isotropic heat conduction for cubic crystals. At low temperatures phonon scattering by Normal and Umklapp processes becomes negligibly small, resulting in nonequilibrium phonon transport by ballistic-acoustic propagation. Stress and strain in the

acoustic waves are related by a 4th rank tensor which can be reduced to a 6 by 6 second rank tensor, resulting in 21 independent elastic coefficients for crystals of lowest symmetry. Cubic symmetry requires only three independent elastic coefficients still with a strongly anisotropic angular dependence of sound velocities for all three phonon modes. The angular dependence of sound velocity in general leads to very characteristic angular intensity variations and even singularities if phonons are excited incoherently by a point-like source. This phenomenon is called phonon focussing and is experimentally observed in all phonon propagation experiments using heater /bolometer configurations for phonon generation and detection. The same holds for phonon experiments with superconducting tunneling junctions or point-like phonon generation by optical excitation.

2. Nonequilibrium Ballistic Phonon Transport.- The first ballistic phonon pulse experiment was performed by Nethercot and von Gutfeld[1]. In this experiment, Fig. 1, phonons were pulse-excited at one surface of

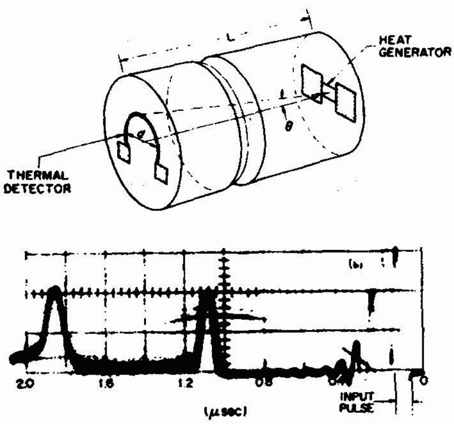

Fig. 1 Heat pulse method.
Top: c-sapphire crystal with phonon generator and detector.
Bottom: Detected phonon pulse signals at 1.2 K.
From right to left: Electric coupling signal, longitudinal phonon signal, transverse phonon signal.
After R.J. von Gutfeld and A.H. Nethercot, Ref. 1

a c-cut sapphire by an evaporated metal heater and detected by a superconducting bolometer at the opposing surface. The observed signals show the expected acoustic times of flight, however, the signal amplitude ratio between transverse (degenerate) and longitudinal phonons by phonon density of states arguments should be much larger than found in the experiment. Similar unexpected results for signal amplitude ratios are observed in phonon pulse experiments with superconducting tunneling junctions[2]. In principle, this could be explained by mode-dependent phonon scattering or -attenuation during propagation. But changing the propagation distance should influence these ratios. This, however, was not observed; instead the signal amplitude ratios were found to be strongly dependent on the propagation direction within the crystal. The experimental findings were properly explained as "phonon focussing"; i.e. a strong angular dependence of ballistic phonon intensities caused by crystal anisotropy; in the now classical work of Taylor, Maris and Elbaum[3]. Phonon focussing later has also been named phonon - channeling, - caustics, - catastrophe. Phonon focussing can be explained by the nonspherical phonon momentum surface at constant frequency, $\omega(q) = \text{const.}$ for different phonon modes. Fig. 2 shows a section of this surface for the slow transverse, ST-mode in silicon. Since energy propagation, ac-

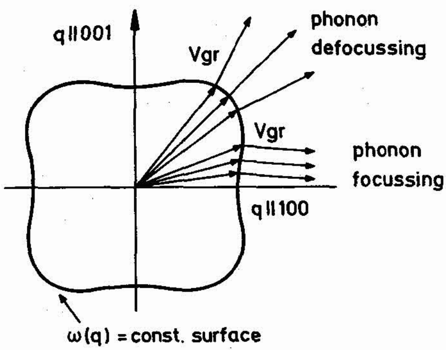

Fig. 2 Phonon focusing is shown to be caused by many q-states contributing to one group velocity from areas of the slowness surface $\omega(q)$ = const. with small curvature. Example: 100 ST-mode-cross section for cubic crystals.

cording to the group velocity $v_{gr} = \frac{\partial\omega}{\partial q}$ is normal to the $\omega(q)$ = const. surface, it is evident that for regions with zero curvature (Gaussian curvature) a large number of q-states contributes to phonons with the same group velocity. Assuming equilibrium phonon occupation for all q-states, this results in high incoherent ballistic phonon intensities;

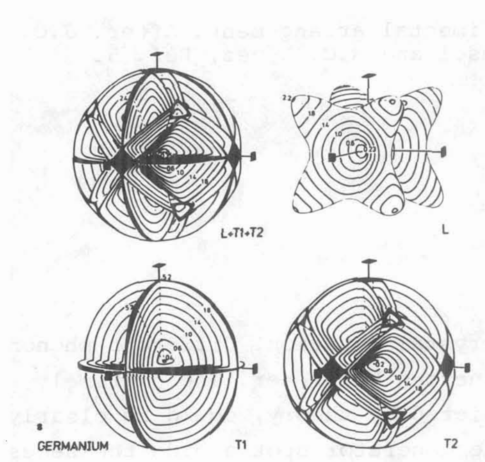

Fig. 3 Calculated phonon intensity surfaces for Ge. After F. Rösch and O. Weis, Ref. 4.

i.e. "phonon focussing" in the corresponding direction. In contrast, regions of strong curvature lead to phonon "defocussing". The $\omega(q)$ = const. surface is called "slowness surface", since the phase velocity is small for large phonon momentum q. Based on the work of Taylor, Maris and Elbaum[3], Rösch and Weis[4] performed computer calculations of the directivity pattern of phonon intensities caused by phonon focusing for several crystal systems. One example is shown for Ge in Fig. 3, by which the surprisingly high intensities for different modes and directions are visualized. Especially for fast transverse FT-modes and slow transverse ST-modes sharp focussing plains and also cusp structures are obtained.

3. Experiments on Directivity Patterns of Ballistic Phonon Propagation and Imaging of Phonon Intensity Distributions.- Stimulated by phonon intensity measurements in pulse experiments and the phonon wind influence on the dynamics of electron-hole droplets in semiconductors, recent experimental activity for investigating phonon focussing was forced. Indirect evidence for phonon focussing was found in phonon reflection and back-scattering experiments by Marx et al[8] and by Taborek and Goodstein[9]. First direct measurements of the angular intensity distribution of ballistic phonons propagating in Ge were performed by Hensel and Dynes[5], as shown in Fig. 4. Phonons were excited by a pulse

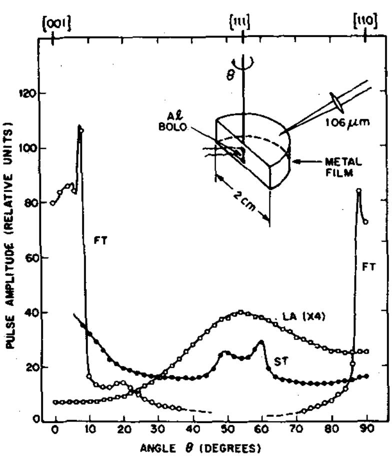

Fig. 4 Angle dependence of the phonon focusing in the $(1\bar{1}0)$ plane of Ge for LA, FT and ST-modes. Insert: Experimental arrangement. After. J.C. Hensel and R.C. Dynes, Ref. 5.

laser beam, moving the hot spot by crystal rotation. Different phonon modes were detected by one superconducting bolometer. The extremely high peaks for FT and ST modes, predicted by theory, could be clearly observed. The technique of moving the generator spot avoids the necessity for an array of detector bolometers.

Northrop and Wolfe[6] were able to "image" the angular phonon intensity distributions in two dimensions by computer-aided visualization. Instead of crystal rotation, the movement of the laser excitation spot was achieved by x-y scanning with the help of two galvanometer mirrors. For detection, again one fixed bolometer was used. Selection of different modes is possible by delay-time-controlled signal-sampling. The very impressing phonon image, Fig. 5, obtained for Ge is equivalent to a

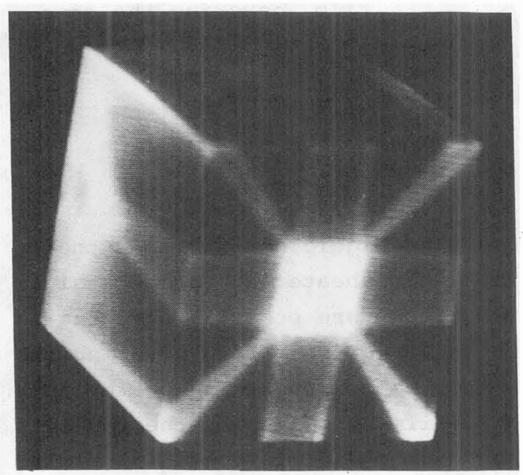

Fig. 5 Phonon focusing image for a 1 cm^3 Ge crystal, obtained by computer-aided image construction, using bolometer heat pulse detection. Phonon pulse generation was performed with a pulsed laser and x-y scanning of the laser focus on the crystal surface. After G. Northrop and J. Wolfe, Ref. 6.

fixed phonon excitation point and a movable detector or an array of many detectors. This image is in full agreement with calculations[3,4,5,6], see also Fig. 3. The extremely high accuracy and angular resolution of less than 1 degree is demonstrated in Fig. 6 for a larger Ge-crystal,

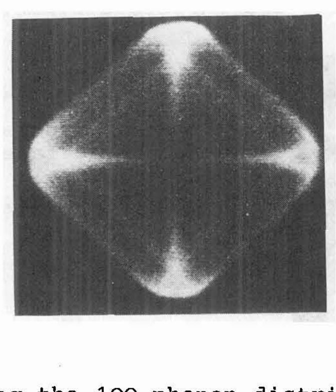

Fig. 6 High resolution (0.4°) phonon focusing image of the ST-mode near the |001| axis of Ge. Bright square-width 15°. Computer-aided image construction. After G. Northrop and J.P. Wolfe, Ref. 6

showing the 100 phonon distribution in detail. Northrop and Wolfe[6] demonstrated these very complex structures again to be in agreement with theory.

A different technique[7] of visualizing angular phonon distributions makes use of the fountain pressure in the superfluid ^4He-film covering the crystal surface. The experimental arrangement is shown in Fig. 7,

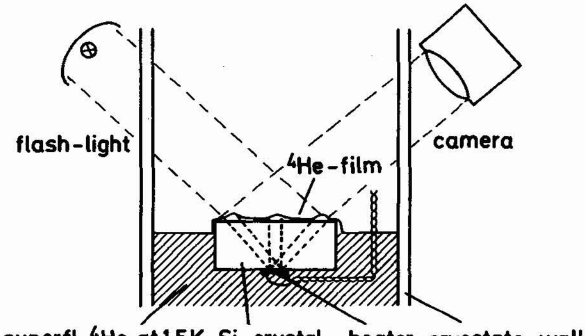

Fig. 7 Experimental arrangement for directly imaging phonon focusing by the fountain pressure in the superfluid ^{4}He-film, covering the crystal sample. After W. Eisenmenger, Ref. 7.

the silicon crystal being partly immersed in liquid helium below the λ point. Phonons are generated by a small area heater at the crystal backside. When the heater is operated, phonons are propagating along the focusing direction and absorbed in the superfluid film covering the upper crystal surface. In these areas the temperature is raised by appr. 10^{-4} K, leading to an increase of the He-film thickness by the fountain pressure. This kind of image conversion can be used to obtain directly visible phonon distribution patterns. The crystal surface is intentionally contaminated by condensed air or lampblack, increasing the optical contrast and enhancing the critical film flow velocity which sets an upper limit for film thickening by the fountain pressure, since in regions of increased film thickness evaporated helium must be replenished by superfluid film flow. The phonon distribution photographed for a 111 silicon crystal is shown in Fig. 8, revealing the threefold symmetry

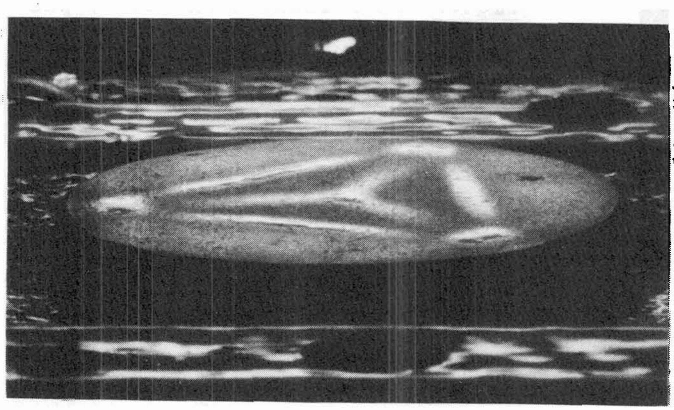

Fig. 8 Phonon focusing image at the surface of a (111)-Si-crystal. After W. Eisenmenger, Ref. 7.

and the phonon focusing structures expected from theory, c.f. Fig. 3. Corresponding pictures have been obtained for Ge crystals and it was also possible to photograph these distributions under vertical direction. An easy comparison with theory is possible by computer calculation of the surface phonon distribution for the crystals used by a Monte-Carlo-Method[10]. The corresponding result for silicon 111 is shown in Fig. 9.

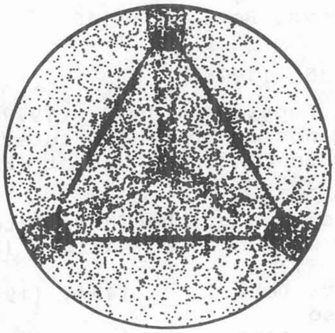

Fig. 9 Monte-Carlo simulation of the phonon focusing image in Fig. 9. After D. Marx, Ref. 10.

4. Conclusions.- Phonon imaging demonstrates the strongly anisotropic angular distributions of phonon intensities in nonequilibrium ballistic propagation, well in accord with theory and based on classical elastic theory now elaborated in detail by computer calculations. These findings are very important for absolute phonon intensity and propagation measurements which are evidently strongly influenced by phonon focusing in all crystals even in those which show little deviation from a spherical slowness surface, such as e.g. sapphire. The same applies to quantitative phonon reflection and scattering experiments and studies as to how phonon focusing images change under the influence of frequency dispersion[11] at high frequencies. Phonon imaging may also be applied for investigations of impurity, isotope and on general imperfection scattering, leading to smeared-out images. Therefore, phonon imaging appears as an important experimental tool in nonequilibrium ballistic phonon physics.

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