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PHONON POLARIZATION FROM PHONON IMAGING

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Résumé - Les interactions sélectionnées par la polarisation des phonons de haute fréquences (10^{11} Hz) avec les défauts de cristaux peuvent être caractérisées par "phonon imaging".

Abstract - Polarization-selective scattering of high-frequency (10^{11} Hz) phonons by defects can be characterized by phonon imaging.

The type of method one chooses to study propagation and scattering of acoustic phonons depends greatly on the desired frequency range. For example, ultrasonic experiments generally employ megahertz to gigahertz waves generated coherently by rf transducers. In contrast, phonons in the gigahertz to terahertz (10^{12} Hz) range are frequently studied by thermal conductivity and heat-pulse methods. The heat-pulse technique involves time-of-flight detection of incoherent, non-equilibrium phonons, as first demonstrated in solids by von Gutfeld and Nethercot /1/ in 1964. Heat-pulse experiments are generally conducted at low temperatures (< 10 K) in order that the ballistic mean free path of high-frequency phonons exceeds the dimensions of a macroscopic crystal.

To good approximation both ultrasonic pulses and ballistic heat pulses travel at the same velocity, despite their three-order-of magnitude difference in frequency. /2/ Ultrasonically one produces a particular acoustic mode, wavevector, and polarization, whereas, in a heat pulse all modes, wavevectors, and polarizations are generated. One of the features of the heat-pulse method is that longitudinal and transverse modes can be separated by their differing time of flights across the crystal. This is an advantage over thermal conductivity measurements, which involve an average over all modes. But strictly speaking the polarization, or displacement vector, of a given phonon is not selectable in a conventional time-of-flight experiment. Thus, the use of heat pulses to study polarization-sensitive scattering processes would seem to be limited.

This limitation can be overcome by examining the angular distribution of heat flux. Basically, the energy flux emanating from a point source of heat is highly anisotropic, due to phonon focusing, /3/ and the resulting intense structures in the heat-pulse pattern can be readily identified with phonons of given mode, wavevector-direction, and polarization. The identification requires a straightforward calculation of the heat flux, based simply on continuum elasticity theory and the known elastic constants of the particular crystal.

The experimental measurement of phonon flux versus propagation angle is achieved by a recent extension of the heat-pulse technique known as phonon imaging. /4/ In this method a heat source (laser pulse) is raster-scanned across one face of the crystal and a small bolometer detects the phonons arriving at a fixed point on the opposite face. Experimental details may be found in the references. /4,5/

A phonon image of LiF reported by Northrop, Cotts, Anderson and Wolfe /5/ is shown in Fig. 1a. From a phonon focusing calculation of this crystal, it is known that the intense horizontal (H) and vertical (V) ridges are due to fast transverse (FT) phonons, and the bright diamond at the center is due to slow transverse (ST) phonons. This calculation also gives polarization information. For example, the polarization vector of the horizontal (vertical) FT ridge is vertical (horizontal), as indicated by the white arrows.

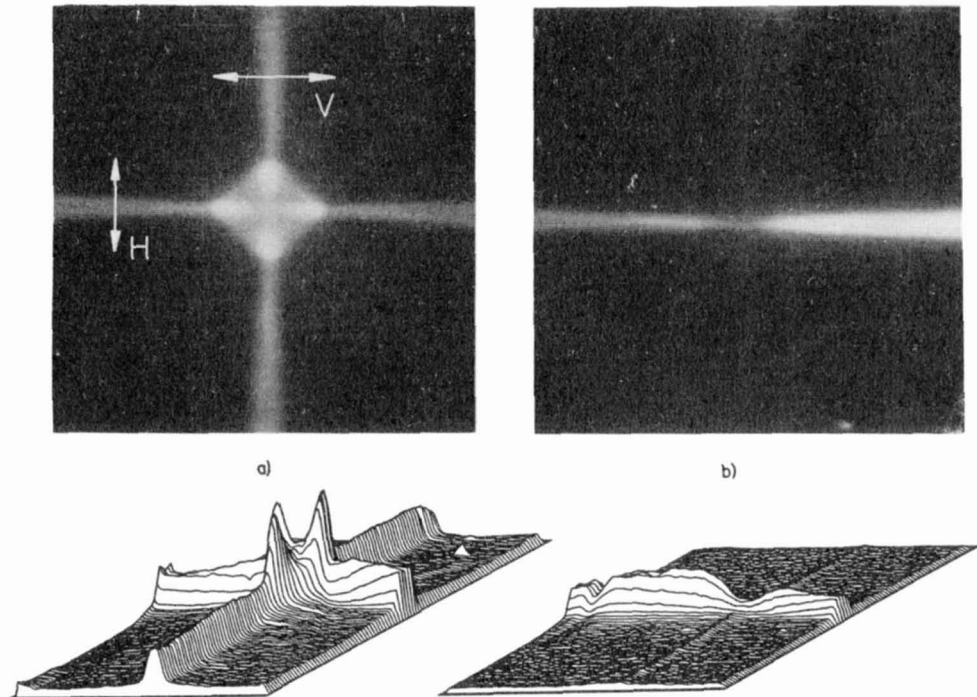


Fig. 1 - (a) Ballistic phonon image of heat-pulses in undeformed LiF at $T = 2.2$ K. (Ref. 5.) The center of the photo corresponds to phonons propagating along $[100]$. The image spans 80° in propagation direction from left to right. The brightest regions demark flux singularities resulting from phonon focusing, as discussed in Ref. 4. Hidden-line drawing shows relative intensities. (b) Image of LiF crystal deformed as in Fig. 2.

If a selected orientation of dislocations are introduced into the crystal by plastic deformation, qualitative changes occur in the ballistic heat-flux pattern, /5/ as shown in Fig. 1b. This sample was deformed 10% along the $[100]$ axis, which introduces $[110]$ and $[\bar{1}\bar{1}0]$ slip planes, as indicated in Fig. 2. The resulting heat-flux pattern displays a complete absence of ST phonons. Also missing are the FT phonons in the vertical ridge. Remarkably, the horizontal FT ridge remains, indicating that these phonons with vertical polarization are relatively unscattered by the dislocations. In effect, the deformed crystal is acting as a phonon polarizer. A detailed analysis by Northrop et al /5/ showed that this behavior was predictable using Granato's fluttering-string model for phonon-dislocation scattering./6,7/

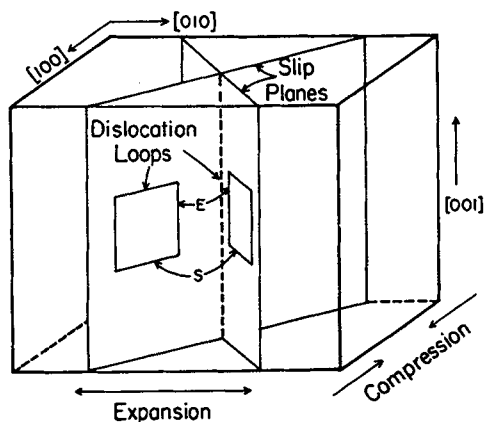


Fig. 2 - Illustration of slip planes induced by compressive force along $[100]$, while the crystal is allowed to expand along $[010]$. Loops of edge and screw dislocations are shown. In the phonon imaging experiments, the front (100) face is covered with a metal film, and a superconducting bolometer is deposited at the center of the rear $(\bar{1}00)$ face.

This type of experiment indicates that the phonon imaging method has great potential for probing the interaction of high-frequency phonons with extended defects. One drawback, however, is that the heat-pulse method involves a rather broad distribution of phonon frequencies; the maximum frequency in a 10 K Planck distribution is 600 GHz. Potentially, superconducting tunnel-junctions or optical detectors can be used to achieve frequency selection.

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