Critical-Cone Channeling of Thermal Phonons at a Sapphire-Metal Interface

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A new structure has been observed in the phonon focusing pattern of a highly polished sapphire crystal with a metalized surface. It corresponds to a concentration of transverse phonons close to the critical cone for mode conversion between transverse and longitudinal waves. This wave-vector channeling effect is interpreted in terms of evanescent longitudinal waves at a weakly bonded sapphire-metal interface.

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In recent years, phonon-imaging techniques have demonstrated the complex directional character of heat-pulse propagation in crystals at low temperatures.[1-3] As a result of elastic anisotropy the wave vector $\vec{k}$ and ray vector $\vec{V}$ of a phonon are not in general collinear, and this results in pronounced anisotropies in energy flux even for an isotropic distribution of phonon wave vectors, an effect known as phonon focusing. Singularities in flux (caustics) are a prominent feature in the observations and, for phonon frequencies of less than about 500 GHz, are entirely explicable in terms of the bulk properties of the medium. In this paper we report the observation of pronounced flux anisotropy which is due not to the usual focusing of ray vectors, but to a sharp concentration of phonons around certain directions in $\vec{k}$ space. This wave-vector–channeling effect originates at the interfaces between the crystal and its heater and detector films (see below), and is sensitive to the crystallographic orientation and quality of those crystal faces. Simple acoustic mismatch theory[4] predicts some nonuniformity in the distribution of phonon $\vec{k}$'s crossing these interfaces, but does not account for the prominent features which we report here.

Our experimental technique is similar to that used in earlier work.[2] In the present case, 100-ns heat pulses are generated by modulating a 200-mW Ar^+ laser at a repetition rate of 100 kHz. The beam is focused to about 50 μm and raster scanned across the highly polished face of a sapphire disk covered by a 2000-Å Cu film. A $50 \times 50\ \mu m^2$ superconducting Al bolometer, evaporated on the opposite face and biased near its superconducting transition temperature ($T = 1.6$ K), detects the phonons propagating across the sample. The signal is amplified and sampled by a boxcar integrator with its gate set to detect both transverse-acoustic phonon modes. The integrated phonon intensity is then stored for each x-y position of the heat pulse in the form of a 256×256 array which can then be displayed on a video monitor.

One of our experimental ballistic phonon images for sapphire (Al_2O_3) is shown in Fig. 1(a). Most of the bright features seen in the photograph are due to classical phonon-focusing singularities. To isolate this bulk propagation effect we have generated the theoretical phonon focusing pattern shown in Fig. 1(b), using previously measured values of the elastic constants[5] and assuming an isotropic distribution of $\vec{k}$ vectors. Essentially the same pattern of caustics is evident in both the experimental and theoretical images. Also present in the lower portions of these figures are two sloping ridges with large but nonsingular intensity. There is, however, a striking feature appearing in the experimental image which is not predicted by the theory: This is the oval-shaped band or "halo" of high intensity, which makes four small loops where it passes through pairs of slow transverse (ST) wave caustics.

Great simplification is effected by translating the halo into a $\vec{k}$-space distribution of ST phonons and thereby removing the distorting effects of bulk focusing. The loops are eliminated, and the $\vec{k}$-space distribution that results is found to be sharply peaked in directions lying very close to the critical cone for mode conversion between ST and longitudinal (L) waves at the crystal surface. The critical cone condition is portrayed schematically in Fig. 2(a), which shows a section of a constant-frequency surface in wave-vector space. An outgoing ST wave on the critical cone has wave-vector component in the surface equal to that of an L wave which has a *ray vector*, $\vec{V}_L$, along the surface. The *wave vector*, $\vec{k}_L$, of that L wave is in general inclined to that surface. This critical cone condition is identical to that encountered in seismology, where a longitudinal wave front moving *along* a surface is able to produce a headwave composed of secondary transverse wavelets propagating into the solid.[6] This

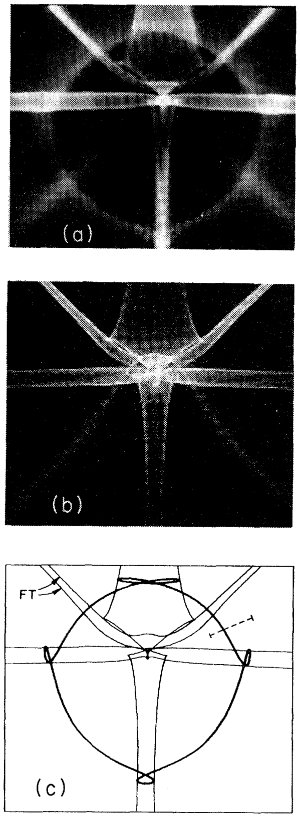

FIG. 1. (a) Ballistic phonon image for sapphire at 1.6 K with faces cut in the [1$\bar{1}$02] direction, referred to conventional hexagonal axis. Bright regions indicate directions of high phonon flux. The image represents a ±32° horizontal scan with the [1$\bar{1}$02] direction at the center of the pattern. The time gates of the boxcar integrator are set to accept the ST and FT modes. (b) Calculated phonon focusing pattern for sapphire for the same situation as in (a). (c) ST critical-cone contour (heavy line) superimposed on a map of the caustics for sapphire. The FT caustics are identified, and all the remaining caustics are ST. The scan line for Fig. 3(a) is indicated by the dashed line.

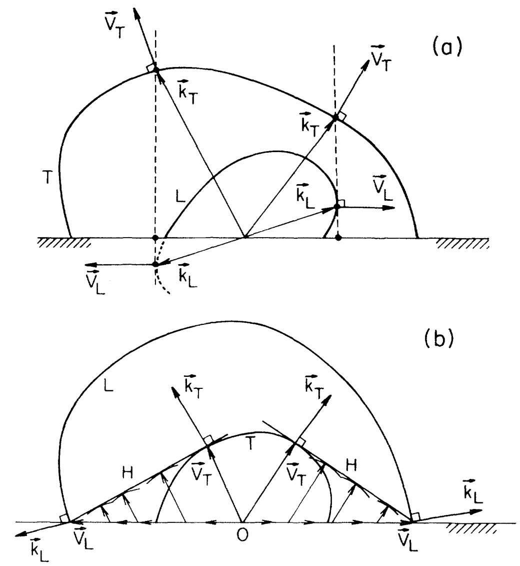

FIG. 2. Two complementary schematic views of the critical-cone condition in $\vec{k}$ space and the head-wave reconstruction process in real space. (a) A section through a constant-frequency surface showing the conditons on $\vec{k}_T$, $\vec{k}_L$, and $\vec{V}_L$. (b) A headwave (H) composed of secondary T wavelets radiated from a surface as a result of the passage of a faster-traveling L wave front along that surface.

headwave generation process is illustrated in Fig. 2(b).

Because sapphire is only mildly anisotropic it turns out that the critical cone in $\vec{k}$ space is within a few degrees of being circular, with half-angle equal to $\theta_c \approx \arcsin(V_{ST}/V_L) \approx \arcsin(C_{44}/C_{11})^{1/2} \approx 33°$. Figure 1(c) shows the contour (heavy line) formed by the ray vectors of this critical cone of $\vec{k}$'s, superimposed on a map of the caustics for sapphire. Comparison with Fig. 1(a) shows that the location of this contour is in good agreement with the experimental halo.

An important prediction of this idea is that the shape and position of the channeling pattern with respect to the phonon-focusing structure should be different for surfaces of different crystallographic orientation. This is found to be true experimentally: The channeling pattern in general does not resemble a circle, but it is always accurately predicted by the critical-cone condition described above. Critical-cone channeling is also observed for L to fast-transverse (FT) conversion. For the orientation of Fig. 1, the FT channeling pattern is much weaker than the ST halo. The reason for this is that the phonons comprising the FT pattern all happen to have polarization vectors pointing very nearly perpendicular to the sagittal plane of the $\vec{k}$'s. Such phonons are expected to participate relatively weakly in mode conversion and so show little sign of critical-cone effects. We have found that the simple expedient of resolving the transverse-wave polarization onto the L-wave polarization and squaring is able to account fairly accurately for the relative intensities of the ST and FT channeling patterns in the different orientations.

To show the magnitude of the critical-cone channeling effect we plot, in Fig. 3(a), the phonon flux variation as the propagation angle, θ, is scanned across the halo [i.e., a line scan in Fig. 1(a) as depicted in Fig. 1(c)]. The halo intensity

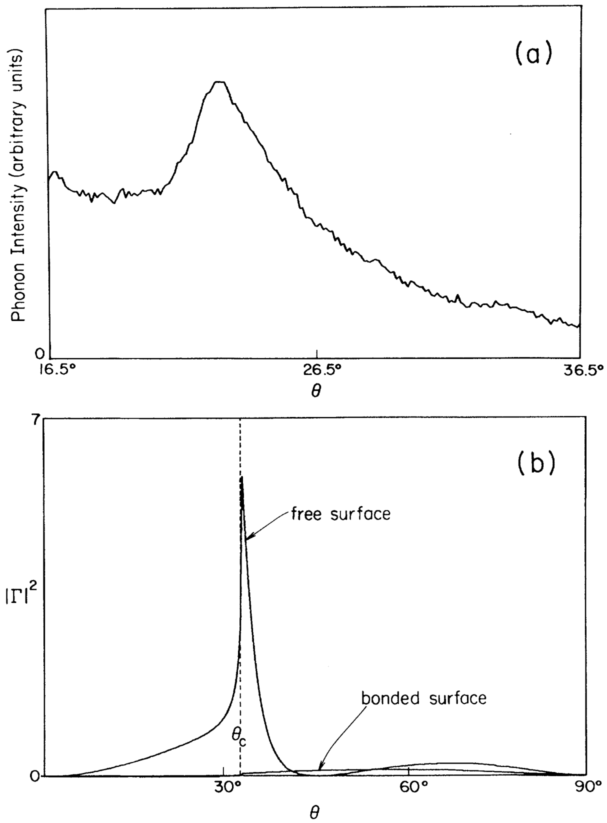

FIG. 3. (a) A line scan taken across the halo showing intensity variation with direction. The location of the scan line with respect to the phonon caustics is shown in Fig. 1(c). As a result of focusing the real-space position of the halo is shifted from ~33° to ~22°. (b) Mode conversion from transverse to longitudinal waves.

corresponds to about a factor of 2 increase in flux over the background. We find that simple acoustic mismatch theory, based on the usual assumption of two perfectly bonded media, yields a barely perceptible feature at the critical angle which is far too faint ($\lesssim 1\%$) to account for the size of our effect.

A key to the $\vec{k}$-channeling mechanism is provided by plotting the variation of the squared amplitude, $|\Gamma|^2$, of an L wave resulting from mode conversion of a vertically polarized unit-amplitude T wave incident on a *tractionfree* sapphire surface. This is shown in Fig. 3(b), which has been calculated taking sapphire to be elastically isotropic. As can be seen there is a pronounced angular resonance lying just beyond the critical angle and hence corresponding to *evanescent* L waves confined to the surface. As with the experimental curve, Fig. 3(a), the peak is skewed, rising more steeply on the inside. Significantly, this resonance is almost completely absent when, as shown in Fig. 3(b), the sapphire is taken to be perfectly bonded to a Cu film!

Thus it would appear that high-frequency phonons perceive the sapphire and metal as being weakly bonded to each other, and that those phonons with $\vec{k}$'s near the critical cone and with polarization vectors close to the sagittal plane are able to make use of a resonant coupling to evanescent L modes at the sapphire surface to enhance their transmission probability across the interface.

The process is similar to the phenomenon of ultrasonic critical angle reflectivity.[7,8] There are, however, novel and distinctive features in the present case. It is the nature of the coupling between the two media which appears to be crucial rather than bulk attenuation and, as discussed above, the "surface" wave that mediates the process is not the Rayleigh mode but an evanescent longitudinal wave.

Another important issue is the quality of the sapphire surface. Our crystals are optical windows: A roughness test with a 2.5-μm diamond stylus showed a variation in elevation of less than 100 Å.[9] The phonons that cross this surface are generated as a heat pulse with Planck temperatures of order 10 K, and so have wavelengths on the order of 100 Å. It is noteworthy that, from the standpoint of critical-cone channeling, these phonons behave as though the surface were flat. We have found that by roughening the radiator surface with a 1-μm diamond polish, a decrease by about a factor of 2 in the halo intensity, relative to the background, is brought about. This sensitivity of the halo to surface damage on a microscopic scale would appear to be an important practical characteristic.

In summary, we have observed for the first time a ballistic phonon signal that is intrinsic to the radiator and detector interfaces. It is located near the critical cone for mode conversion from T to L waves and is evidently mediated by evanescent L waves in the crystal. This critical-cone channeling would appear to constitute a sensitive probe of crystalline surface quality and also of the bonding of metal to crystal surface. We anticipate that the study of such wave-vector channeling will provide important clues to the long-standing problems of phonon-boundary scattering.

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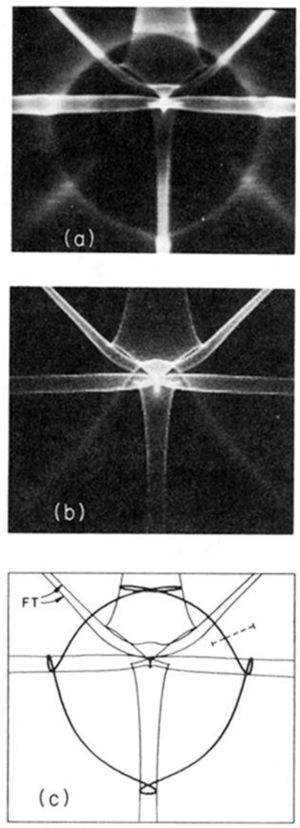
[9]These are standard optical windows obtained from Insaco Inc., Quakerstown, Pa. The final polishing stages were 3-μm diamond lap and then Syton mechanical-chemical polish. We examined the surface with an electron microscope and at ~ 0.2-μm resolution no structure was observable.



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