An observation of second sound in sapphire

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The propagation of acoustic oscillation modes in sapphire was investigated by using the method of heat pulses. In addition to ballistic phonon propagation, the propagation of heat in the form of "second sound" was observed for the first time. The relaxation times of the resistive and normal phonon scattering processes are estimated.

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In spite of the fact that the existence of second sound in single crystals of solid dielectrics was predicted in 1947,[1] this effect was first observed[2] in 1966 in single crystals of solid He^4, which, as is well known, has a high degree of isotopic purity, and somewhat later in NaF single crystals grown and purified under special conditions.[3] Although after solid He^4 single crystals of Al_2O_3 have the most suitable isotopic composition for observation of second sound, this effect thus far has not successfully been observed in sapphire,[4–6] presumably because of the imperfect ions in the crystals investigated.

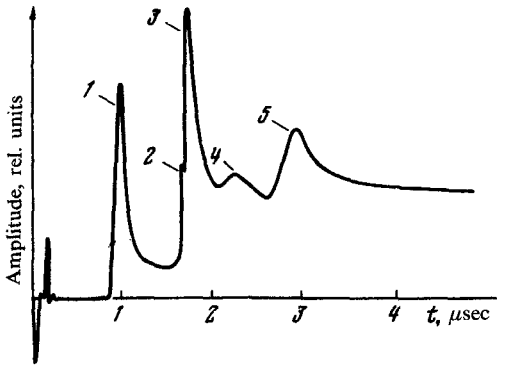

FIG. 1. Heat pulses in sapphire at $T = 3.4$ K. The power of the input pulses is 12 W/mm^2.

We decided to return to this problem, using single crystals to investigate the propagation of heat pulses in sapphire. The crystals had been prepared for laser technology, where strict requirements are imposed on their purity and perfect structure.

We investigated cylindrical samples 15 mm in diameter and 10.4 mm in length with a 6° angle between the C axis and the generatrix of the cylinder. The faces of the samples were mechanically polished to optical purity. Then the samples were annealed at 800° C for 4 hours. The heater and the detector, whose dimensions were 0.3×1 mm, were sprayed on the opposite faces of the sample using the method of thermal sputtering in a vacuum. The heater, a gold or copper film, has a resistance of $\approx 50\ \Omega$ at 4.2 K. An indium film, which became superconducting in the neighborhood of 3.4 K with a transition width of 0.1°, was used as the detector. The detector temperature was maintained in a range where the detector sensitivity was $\approx 3 \times 10^2\ \Omega$/deg. The sample, the heater, and the detector were in close contact with the liquid helium. Current pulses 10–100 nsec in duration and up to 40 V were fed to the heater at 100-Hz frequency. With a proper displacement current (1–5 μA) the bolometers operated in an almost linear transitional region without saturation in the entire range of power supplied to the generator. The voltage generated as the response of the detector to the incident phonon flux was amplified by a wide-band amplifier and directed to the oscillograph. In addition to visual observation of the signals, they were also recorded on an X-Y recorder.

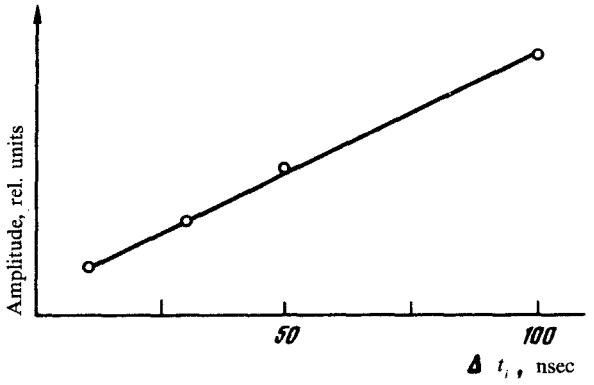

FIG. 2. Dependence of the pulse amplitude of the second sound on the duration of the heater current pulses.

Figure 1 shows a typical heat pulse in sapphire. The time lag in the appearance of the first peak (arrival time) corresponds to the transmission time of longitudinally polarized phonons (L modes) in the ballistic regime at a propagation rate of 11.35×10^5 cm/sec. The second and third peaks are associated with the arrival of transversely polarized phonons (T_1 and T_2 modes) in the ballistic regime. Their propagation velocities were 6.35×10^5 and 6.05×10^5 cm/sec, respectively. We attribute the appearance of the fourth pulse to the arrival of phonons reflected once from the side surface of the cylindrical sample. The location of the maximum of this pulse corresponds to mirror reflection of the incident ballistic phonon with its polarization changed by reflection (L modes into a T mode or T modes into an L mode) and propagation of the reflected phonon in the ballistic regime. The smearing of this peak is due to the rough reflection surface. The location of the maximum of the fifth pulse corresponds to the arrival of a group of phonons with a propagation velocity equal to 3.5×10^5 cm/sec. The acoustic oscillation modes cannot propagate in sapphire at such low velocities.[7] We suggest that this peak is produced by propagation of heat in the form of second sound. In fact, the heat propagation velocity in the second-sound regime is given by[8]

$$v_{II}^2 = \frac{1}{3}\sum_i c_i^{-3} \Big/ \Big(\sum_i c_i^{-5}\Big), \tag{1}$$

where c_i is the velocity of sound of the ith polarization.

Substituting the measured propagation velocities of the longitudinal and transverse phonons into expression (1), we can see that the velocity of second sound in sapphire for the given crystallographic direction is equal to 3.67×10^5 cm/sec. Notice that this value is close to the measured propagation velocity of heat, which produces the fifth peak.

According to Ackerman and Guyer,[8] the expression for the time dependence of the temperature in a thermal wave at a distance L from the heater is

$$T(L,t) = \frac{\delta T_0 \Delta t_i}{6\pi}\left(\frac{10\pi}{\tau_N t}\right)^{1/2}\exp\left(-\frac{t}{2\tau_R}\right)\exp\left\{-\frac{(L-v_{II}t)^2}{6/5\, c^2 \tau_N t}\right\}, \tag{2}$$

where δT_0 is the initial rise in the temperature of the heater above the temperature of the crystal, Δt_i is the duration of the current pulse of the heater, t is the time, τ_R is the time scale of resistive scattering processes, τ_N is the time scale of normal scattering processes, v_{II} is the velocity of the second sound, and c is the average velocity of sound in the Debye approximation. As follows from Ref. 2, the amplitude of the temperature wave must be a linear function of the duration of the current pulse of the heater. The measured dependence of the pulse amplitude of the second sound on the duration of the current pulse is shown in Fig. 2 and its behavior corresponds to expression (2). To plot this dependence we had to reconstruct the true shape of the second-sound signal which, as Fig. 1 shows, is observed against a background diffusive heat flux. To isolate the background, we recorded the signal of the heat pulse for long periods of time.

If we then use the solution of the equation for the diffusive heat flux:

$$T(L,t) \sim t^{-3/2} \exp\left(-\frac{L^2}{1/3\, r_R\, c^2\, t}\right) \tag{3}$$

and vary the value of τ_R, we can obtain agreement between the calculated curve and the shape of the heat pulse observed experimentally. The best fit is obtained for τ_R equal to 3×10^{-7} sec.

As follows from Ref. 2, the halfwidth of the second-sound pulse depends on the time scale of the normal scattering processes. A comparison of the profiles of the temperature wave with the observed shape of the second-sound signal for $\tau_R = 3\times10^{-7}$ sec and different values of τ_N shows that Eq. (2) closely approximates the observed pulse shape if τ_N is equal to 4×10^{-9} sec.

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