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PROPAGATION OF HIGH-FREQUENCY PHONONS IN THIN SiO FILMS AT 60 mK (*)

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Résumé. — A l'aide d'une jonction tunnel supraconductrice, nous étudions la propagation de phonons de haute fréquence engendrés par un émetteur de chaleur, à travers une couche mince de SiO déposée sous vide. Les expériences montrent que le SiO contient des systèmes à deux niveaux d'énergie supérieure à 360 μeV . On observe des temps de *transit* extrêmement longs et une saturation de l'absorption des phonons.

Abstract. — By means of a superconducting tunnel junction we study the propagation of heater generated high-frequency phonons through a thin evaporated SiO film. The experiments suggest that SiO contains two-level systems with energies above 360 μeV . Extremely long *transit* times and saturation of the phonon absorption are observed.

Most of the peculiar properties of amorphous dielectrics at low temperatures [1] are well explained by the tunneling model [2]. This model is based on the idea that phonons in glasses are resonantly scattered and trapped by so-called two-level systems (2LS). Some parameters of these 2LS such as the density and the coupling to the phonons have been determined from ultrasound measurements [3]. Still little is known, however, about the energy range over which these 2LS exist. Ultrasound measurements are limited to rather low frequencies (< 30 GHz) and thus cannot provide this information.

Specific-heat measurements do not give much information either. Nevertheless, the linear temperature dependence for temperatures $T < 0.5$ K indicates that 2LS exist up to energies of at least 100 μeV , the dominant phonon energy at 0.5 K. At temperatures above 0.5 K the contribution of 2LS to the specific heat cannot be discerned from the phonon contribution which grows as T^3 .

In this paper we investigate by means of a novel measuring technique whether the energy range of the 2LS extends beyond 360 μeV . We generate the high-frequency phonons by means of an electrically pulsed constantan heater (0.1 μm thick). This heater generates a broad spectrum of phonons. The phonons

emitted by the heater propagate through a thin film of glass (SiO, 0.6 μm thick). At the opposite face of the film a superconducting aluminium tunnel junction detects only those phonons which have an energy high enough ($> 360 \mu\text{eV}$) to break up Cooper pairs. In this way we are able to specifically study the propagation of the high-frequency phonons (> 90 GHz). The junction, the glass and the constantan film are evaporated as successive layers onto a {111} face of a silicon single crystal (8 mm thick). The crystal serves as a stable support of the thin layers and provides good thermal contact with the mixing chamber of the dilution refrigerator. Onto the opposite face of the crystal an identical heater is evaporated for reference purposes. Both {111} faces are kept in vacuum. For the glass we choose SiO, because it evaporates at a relatively low temperature and does not destroy the tunnel junction. The amorphous nature of the film was verified by X-ray diffraction measurements.

Typical responses of the junction to some heat pulses (100 μs duration) are displayed as a function of time in figure 1. The crystal was kept at a temperature of 60 mK. The signal shapes are not reminiscent of simple integration. Nevertheless we checked that the shapes are not due to trivial integration in the detector or to slow heating of the silicon crystal. We measured the detector time constant to be 5 μs . This is much shorter than the signal risetimes observed. We exclude crystal heating because the reference

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FIG. 1. — Detector response to 100 μ s long heat pulses with different powers : 390 nW/mm², 690 nW/mm², 1.1 μ W/mm² and 4.3 μ W/mm².

FIG. 2. — Detector response to 4 μ s long heat pulses with powers of 39 μ W/mm² and 11 μ W/mm² (trace 1), and with powers of 0 μ W/mm² and 11 μ W/mm² (trace 2).

heater at the opposite crystal face needs a much larger power to yield the same signal amplitude and also because the time constant for heating is observed to be much longer.

We analyse the signal shape as follows. A transit time of 0.1 ns is required for the phonons to propagate ballistically through the glass film. However, no signal is observed during the first microseconds. Therefore we conclude that the mean free path for phonons with frequencies above 90 GHz must be less than the film thickness (0.6 μ m). This is much shorter than the value extrapolated from the highest frequency (9 GHz) measured so far [4]. The short mean free path implies strong 2LS-phonon coupling and thus a short relaxation time T_1 . Probably the long signal risetimes observed arise from phonon resonance trapping in the SiO.

In a second kind of experiment we feed two short pulses (4 μ s) instead of a single long pulse into the heater, an intense one followed some 50 μ s later by a weak one. Both pulses are clearly detected by the junction (Fig. 2, trace 1). If we apply, however, only the second (weak) pulse, without giving the larger pulse first, a much smaller signal is observed (Fig. 2,

trace 2). This effect is certainly not due to a nonlinear response of the detector. Signals generated with the reference heater at the opposite crystal face add linearly.

The observed phenomenon is strongly reminiscent of saturation of 2LS as was observed in ultrasound experiments [1]. However, one would not expect that a Planck-like heater spectrum would saturate 2LS as long as $kT_{\text{heater}} < (\hbar\omega)_{2\text{LS}}$. (For our experiment we calculate $(\hbar\omega)_{2\text{LS}} > 5 kT_{\text{heater}}$.)

Probably the observed saturation indicates that somehow the high- and the low-energy 2LS are strongly coupled. However in ultrasound experiments only a weak mutual interaction between 2LS of different energies has been found [1].

In conclusion our experiments have indicated the existence of 2LS above 360 μ eV in SiO. Furthermore the experiments have shown that in SiO the mean free path of high-frequency phonons (> 90 GHz) is much shorter than 0.6 μ m. The double-pulse experiment suggests that saturation of 2LS also occurs with heat pulses.

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