Phonons have a longer life than expected

Control of thermal transfer and the design of new nanostructured thermoelectric materials are now main issues for microelectronic devices. Heat is carried predominantly by phonons in semi-conductors and thus the knowledge of their meanfree path (MFP) is a very important issue. However, this parameter is still largely unknown: a kinetic theory of heat conductivity leads to a MFP of 40 and 20 nm in Si and GaAs respectively. Nevertheless, recent thermal conductivity measurements with a thermoreflectance method suggest that the MFP may have values over a few orders of magnitude and that phonons with MFP exceeding 1 µm at room temperature contribute to a large extent to heat transfer[1]. The research group « Acoustique pour les Nanosciences » at the Paris Institute of Nanosciences has just made a breakthrough by performing the first accurate and direct measurement of phonon MFP in GaAs in the frequency range 0.2-1 THz.

Since a few years at INSP and in collaboration with the LPN, we have developed methods to perform experiments of longitudinal acoustic wave propagation, at very high frequencies up to one Terahertz. Acoustic transducers are GaAs/AlAs superlattices, whose period defines emission and detection frequencies. Three experimental configurations, described on figure 1, have been used for the whole frequency range from 0.2 to 1 THz. The large number of periods of the superlattice was the key point to obtain a large dynamical range in the acoustic wave amplitude measurement. This allowed the precise measurement of the acoustic attenuation from 10K up to 70 K.

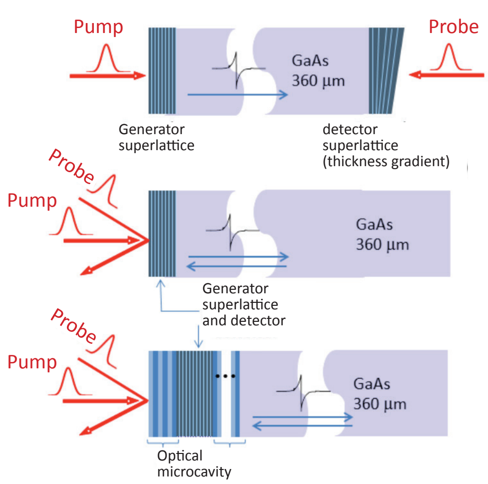

Figure 1
Experimental configurations that have been used for MFP measurements.

1 Role of Low-Energy Phonons in Thermal Conduction. C. Herring, Phys. Rev. 95, 954 (1954).

As shown in figure 2, the attenuation always increases with temperature at any frequency as expected (figure2a). However a plateau appears between 0.7 and 1 THz in the frequency dependence (figure2b), after a range where the attenuation classically increases as the square of the frequency (full line plot). This result was quite unexpected but we could nevertheless explain it within the classical scheme of phonons interactions. In the temperature range which has been investigated, the processes with the largest probability involve 3 phonons. Wave vectors and energy conservation laws for these processes are a very strong constraint for low energy phonons. Herring has shown that the main processes for a longitudinal wave were inelastic scattering by a transverse phonon with a wave vector close to a high symmetry axis. Indeed, close to such directions, a weak removal of transverse modes degeneracy allows the coupling of a low energy longitudinal wave with large wave vectors transverse phonons whose density of states is large. Paradoxically, the mechanism which makes these processes very efficient for a low frequency longitudinal wave could also explain their breakdown when this frequency increases beyond a few hundreds of GHz : indeed the transverse phonons frequency cutoff, which is pretty low in covalent semi-conductors (such as GaAs or Si), is rapidly reached. The other interaction processes compensate this breakdown which results in the plateau we observed in our experiments between 0.7 and 1 THz.

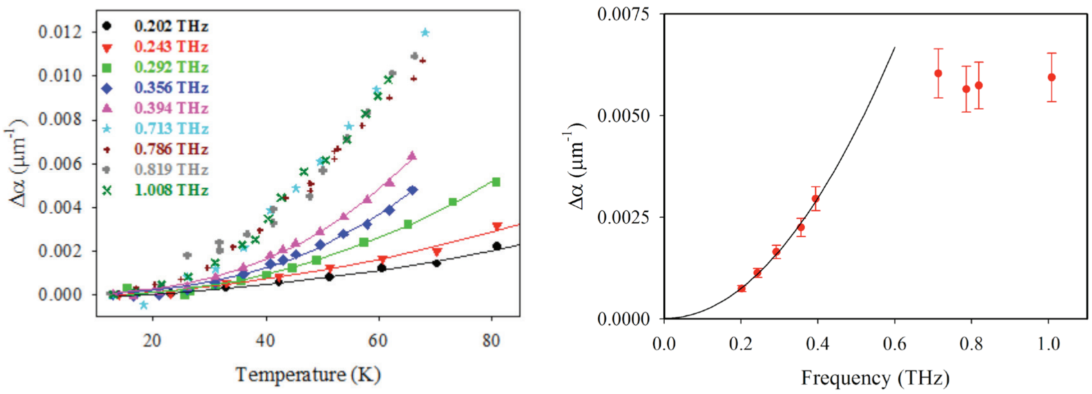

Figure 2

Relative variation of acoustic attenuation as a function of temperature (a) and frequency (b).

Thus, due to Herring processes breakdown, subterahertz phonons lifetime can be much longer than expected and an extrapolation at room temperature predicts in particular a MFP of 10 µm for a 1 THz longitudinal wave in GaAs.

These results bring a direct proof of the significant contribution of subterahertz phonons in heat transfer. Thus, it's crucial to take into account these very large MFP for a good understanding of thermal transfer in nano- and micro-structures. An accurate determination, by ***ab-initio*** calculations, of phonon dispersion curves and phonon-phonon coupling parameters in various materials would allow studying to what extent this result holds.

Reference

"Direct measurement of coherent subterahertz acoustic phonons mean free path in GaAs"
R. Legrand, A. Huynh, B. Jusserand, B. Perrin, A. Lemaître
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Contact

Bernard Perrin : Bernard.Perrin@insp.jussieu.fr