Low temperature damping in a nano-electro-mechanical device

Solid matter can be found in two states depending on the ordering of its atoms : Crystalline solids display a characteristic translational long-range order, whereas amorphous solids lack it. Amorphous materials are of the utmost importance scientifically and technologically. To obtain a fundamental understanding of the nature of these materials, many low temperature experiments have been done that probe dielectric, acoustic, mechanical and thermal properties. These are all macroscopic, bulk properties. To study the nature of amorphous materials at the nanometre scale, Nanometric Electro-Mechanical Systems (NEMSs) can be used. These systems are ideal tools to probe the friction processes occurring in amorphous materials.

Experimental results on amorphous materials are usually discussed in the framework of the well-known Standard Tunnelling Model of Two-Level Systems due to P.M. Anderson and W.A. Phillips. In this model, amorphous materials are assumed to contain "Two Level Systems" (TLSs) whose nature (apart from a few remarkable cases) is essentially unknown. The distribution of the energy splitting between the two levels is assumed to be very broad, and can be modelled by a constant density-of-states n. The TLSs are assumed diluted enough to be independent. All properties are then described by two parameters: the density of states n and a second parameter g, the strength of the coupling to phonons and/or electrons. As concerns the mechanical damping, of interest in our experiments, the attenuation mechanism is thus essentially the energy flow from the mechanical mode to the phonon bath through the Two Level Systems.

Fig. 1: Scanning Electron Microscope (SEM) image of a silicon NEMS sample of "goalpost" type. The 7 µm long "paddle" bar is 150 nm thick x 250 nm wide, and 30 nm of aluminum is evaporated on the top surface. It vibrates out-of-plane thanks to the electromagnetic excitation force (magnetomotive scheme).

While providing the proper phenomenological grounds for the understanding of experimental data, the model is far too simplistic and some theorists have challenged the existence of any TLSs at all. The key to a proper understanding seems to be in the coupling mechanism between individual Two Level Systems or any other possible entities responsible for the low-energy properties. Estimates for the typical length scale marking the crossover between correlated and truly independent Two Level States are about 1 µm. This is well within the NEMS fabrication range.

Dedicated NEMS resonator devices can be viewed as probes sensing the friction processes occurring in their constitutive materials. To date, only a few experiments on the mechanical friction at low temperature (down to 20 milliKelvin) in amorphous NEMSs, using only a few different amorphous materials, are available in the literature. The overall features among published data look qualitatively the same, but no quantitative consensus exists. Furthermore, NEMSs have displayed much worse mechanical quality factors than bulk structures, a fact that is not yet properly justified but is certainly linked to the TLS to TLS interaction length.

When the mechanical material of the NEMS is a dielectric (silicon, silicon dioxide, silicon nitride...), a conducting overlayer is usually added on the structure. This metal can be either normal or superconducting, but in either case it influences the friction mechanisms. This fact, which had been overlooked in the literature up to now, has been very clearly demonstrated by our group. We have shown that, by switching the aluminium metal from normal to superconducting using an external magnetic field as a "control-knob", the friction experienced by a silicon NEMS (the vibrational device shown in Fig. 1) is greatly reduced (see the linewidth data of Fig 2).

One explanation for the phenomenon is a renormalization of the interactions among Two Level Systems in our samples due to the nearby presence of the metal, in particular with its conduction electrons. The exact nature of these TLSs remains a puzzle (are they on the surface? within the aluminium?), but clearly we have demonstrated that the electronic degree of freedom of the NEMS has to play a role in the damping mechanism. This information should be a new key to help "crack" the long-standing mystery of the TLS nature of amorphous materials.

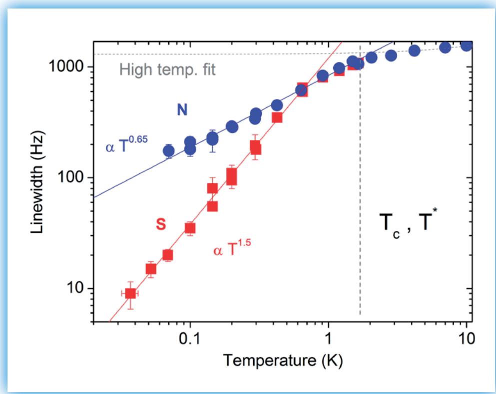

Fig. 2: An aluminium coated Si cantilever structure reaches quality factors $f/\Delta f$ of order one million around 20 mK, exceptional for a mechanical mode resonating around 10 MHz. N and S denote measurements with the Al in normal and superconducting states, while T^* (which happens to coincide with T_c, aluminium's critical temperature) marks the beginning of the damping decrease as T is reduced.

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FURTHER READING

Evidence for the Role of Normal-State Electrons in Nanoelectromechanical Damping Mechanisms at Very Low Temperatures
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