Dissipation of AFM cantilevers as a function of air pressure and metallic coating

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1 Introduction

A metallic coating of the cantilever is frequently used in most of microelectromechanical system (MEMS) and Atomic Force Microscope (AFM) sensors, which functionality is based on the mechanical movement and deformation of the cantilever. As shown by the fluctuation-dissipation theorem (FTD)[1], thermally induced mechanical fluctuations are linked to the losses of energy occurring during deformations of the systems, they determine the ultimate deflection sensitivity of these sensors and represent one of the most important noise sources. Considering only structural damping as the dissipation mechanism, Saulson[2] proposed a viscoelastic model, in which the power spectrum density (PSD) of thermal induced deflection presents a $1/f$ trend. This behavior can be seen as the signature of a viscoelastic process. Paolino[3] introduced a simple power law to describe the frequency dependence of this viscoelastic dissipation and a model that includes Sader's approach to describe the coupling with the surrounding atmosphere. He also showed that the damping is due to the metallic coating of the cantilever when viscous dissipation vanishes. As most AFM sensors require operation at atmospheric pressure, great effort has also been put into describing the effect of pressure on the resonant properties of cantilevers. Here, we study the thermal noise of AFM cantilevers, its dissipation as a function of air pressure and the associated dissipation brought by metallic coatings, we also discuss the source of internal friction attributed to these dissipations.

2 Experiments

In the Fourier space, the full model for the mechanical response function G of the force F to the deflection d can be written:

$$G(\omega) = \frac{F(\omega)}{d(\omega)} = k\left[1 - \frac{\omega^2}{\omega_0^2} + \left(i\frac{\omega}{Q\omega_0} + \phi\right)\right] \qquad (1)$$

where $\omega = 2\pi f$ the pulsation corresponding to frequency f, ω_0 the resonant pulsation, $k^*(\omega) = k(\omega)[1 + i\phi(\omega)]$ is the complex spring constant and $Q_{Sader}(\omega)$ the quality factor, both depending weakly on frequency. In vacuum, the viscous dissipation due to the surrounding air can be reduced ($Q \to \infty$), thus the dissipation is dominated by viscoelastic processes. The effective quality factor at the resonance saturates to $Q = 1/\phi(\omega_0)$. As shown in figure.1 for a gold coated cantilever, Q saturates around 4000 for pressures below 10^{-2} mbar.

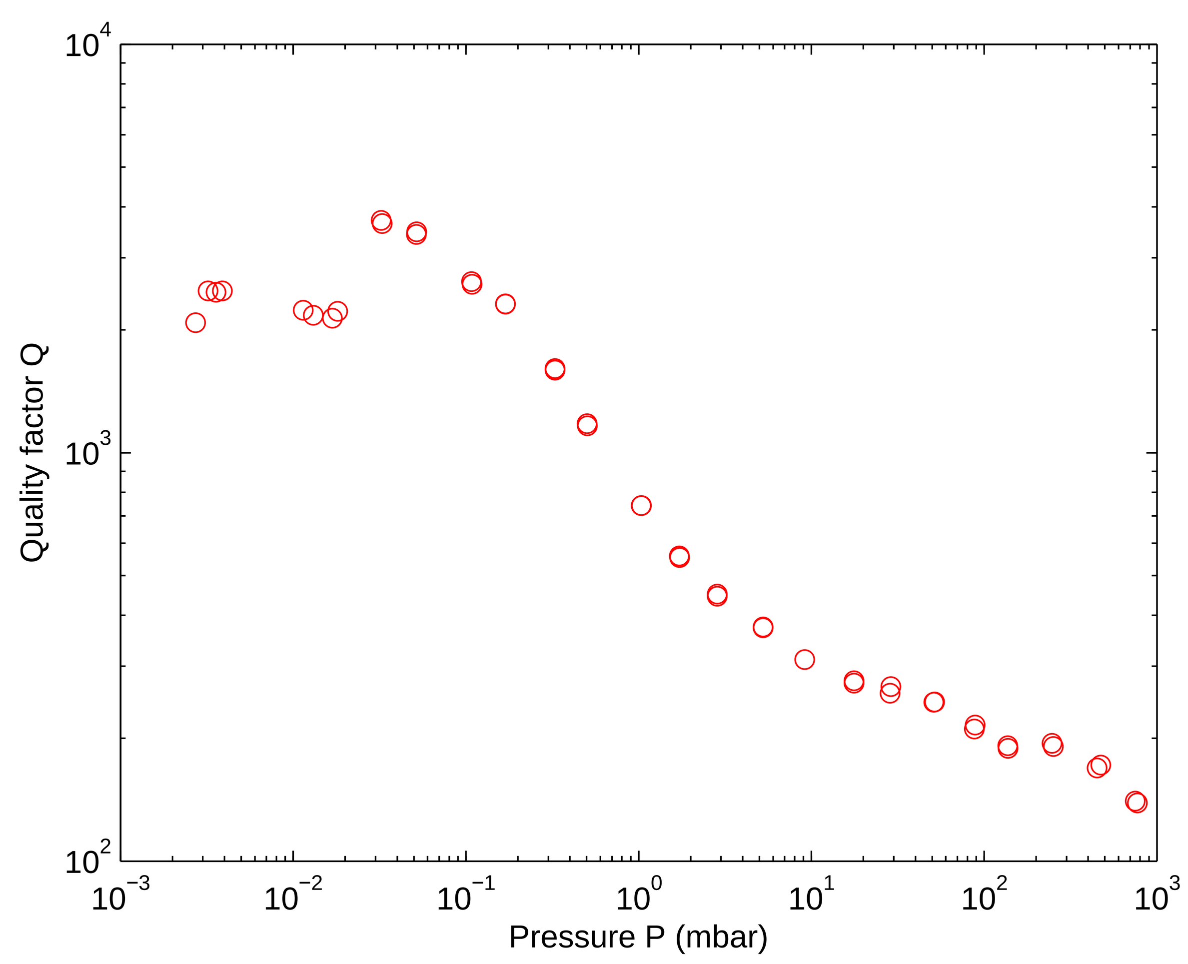

Figure 1: Quality factor for gold coated cantilever as a function of pressure.

To go further, we measure the mechanical thermal noise of metallic coated cantilevers using an innovative atomic force microscope (AFM) with a resolution down to $10^{-14} m/\sqrt{Hz}$. Thanks to this sensitivity, we are able to measure not only the thermal noise in the resonances of the cantilever but also the whole spectrum between 1 Hz and 40 kHz. We rebuild the full mechanical response function G from the measured PSD using the fluctuation dissipation therom (FDT) and the Kramers-Kronig relations. In figure2, we plot the PSD and the dissipative part of G of a gold coated cantilever for various surrounding pressures. As the pressure decreases from ambient to 10^{-3} mbar the resonance peak become shaper, which implies a larger Q. As suggested by equation (1), we clearly observe that $Im(G)$ is the sum of the two contributions. The viscous part vanishing with the pressure, at 10^{-3} mbar only the viscoelastic damping is observed.

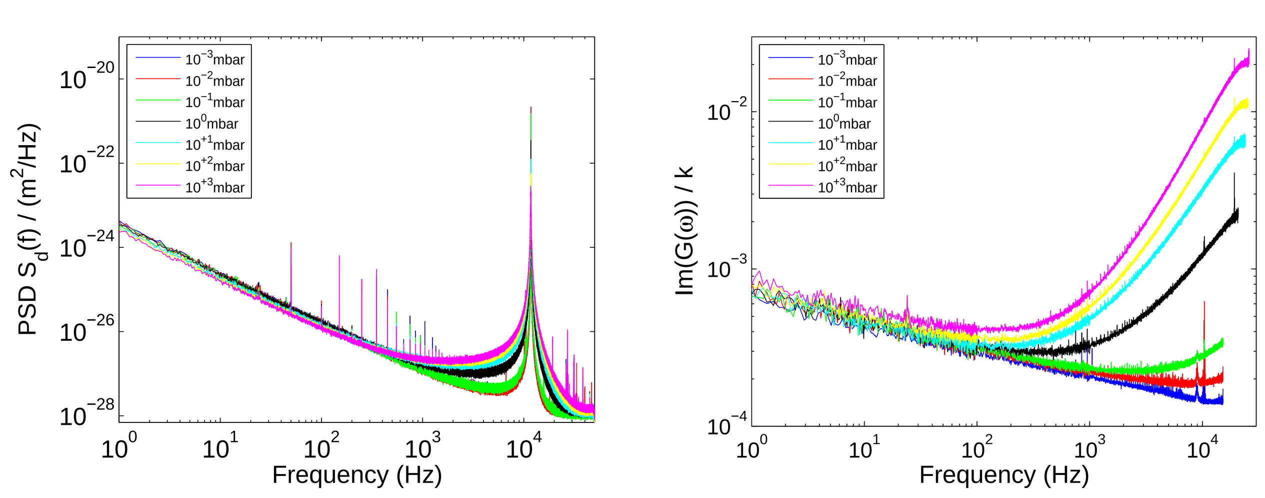

Figure 2: Power Spectrum Density (PSD) of thermally induced deflection and dissipative part of response function (G) of a gold coated cantilever at different pressures. G is reconstructed from the noise spectrums using FTD and Kramers-Kronig relations.

In figure 3, we plot $Im(G)/k$ for 3 different metallic coatings: gold (Au), aluminium (Al), platinum-iridium (PtIr). Above 1 kHz, except for the first coating (Au), dissipation due to the atmosphere is still observable. For the low frequency trend, a power law dependence with a small negative coefficient is a reasonable phenomenological model: $Im(G(\omega))/k = \phi(\omega) \to \omega^{\alpha}$. The amplitude of the viscoelastic dissipation and the value of the exponent α is material dependent: for gold and PtIr, $\alpha \sim 0.15$, whereas for aluminium, $\alpha \sim 0$.

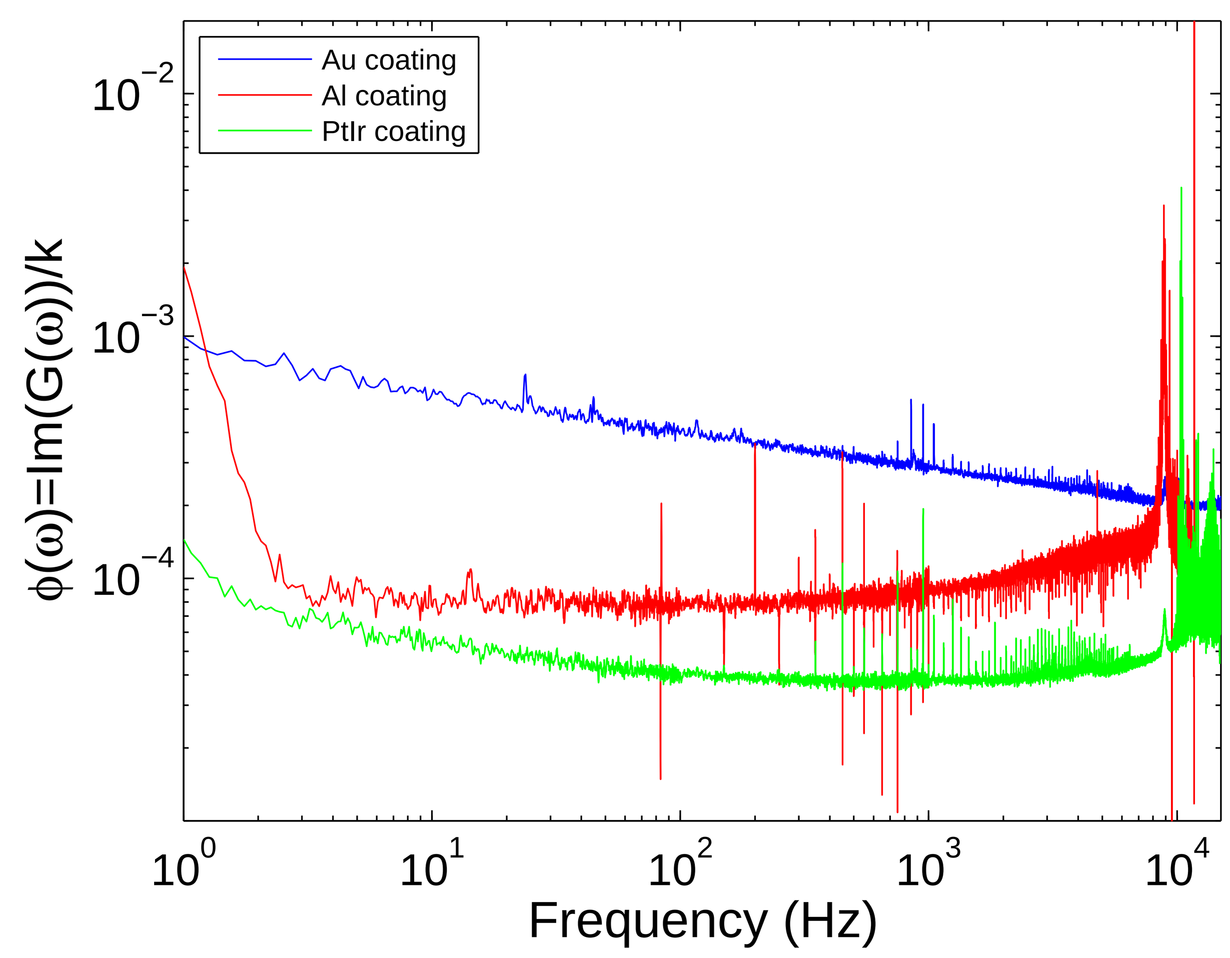

Figure 3: Dissipative part of the response function of cantilevers with Au, Al, and Pt coatings at low pressure (10^{-3} mbar). A simple power law with a small exponent accurately describe the observations at low frequency, where viscous dissipation due to the surrounding atmosphere is negligible.

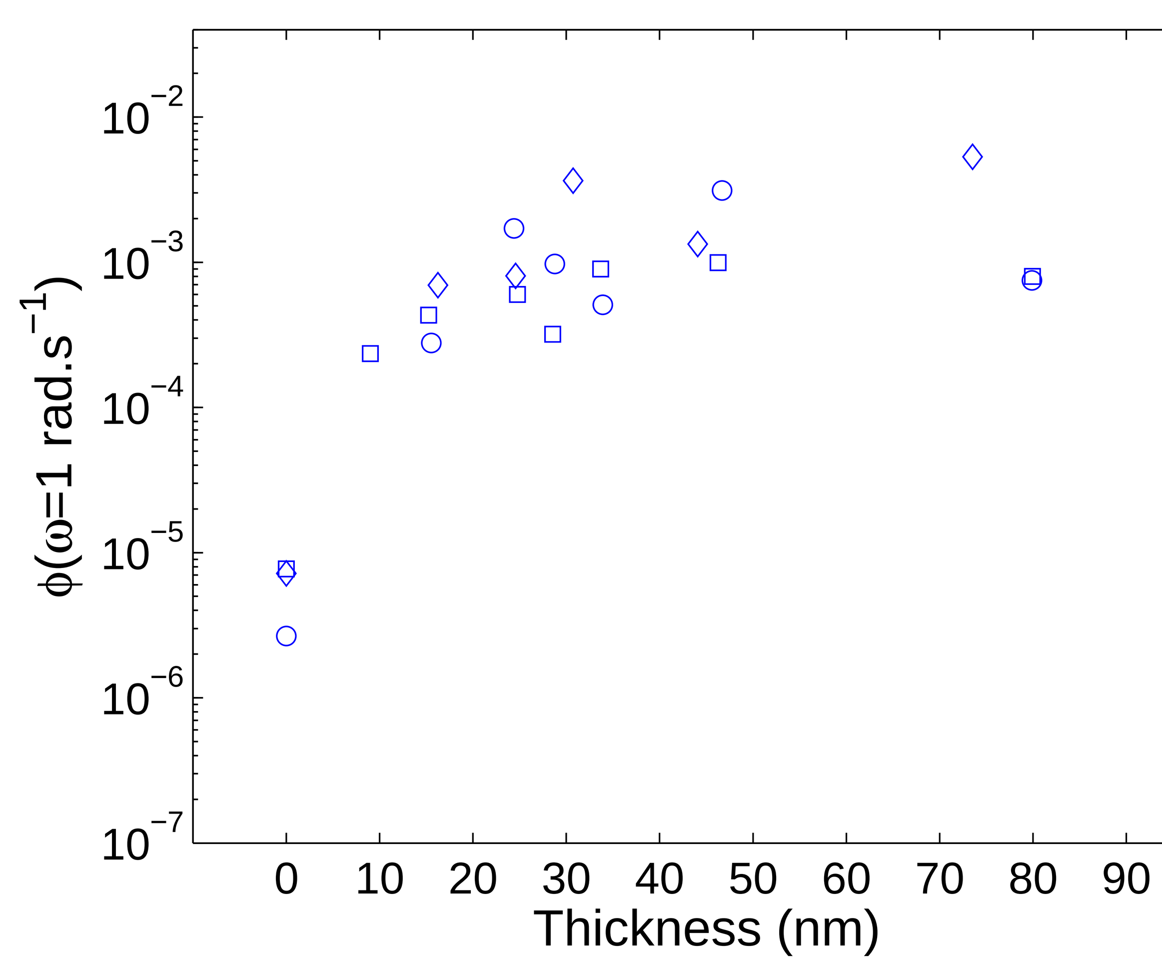

Figure 4: The loss tangent of G as a function of Au thickness

We investigate the source of such dissipation by increasing the thickness of the metallic coating evaporated onto the cantilever, and plot $\phi(\omega = 1 rad.s^{-1})$ as a function of thickness in figure 4. For gold coatings thicker than 8nm, ϕ is quite independent of thickness and of order 10^{-3}. This dissipation is much higher than that of cantilevers with only 2nm Cr coating which is usually evaporated before the gold coating to get a better adhesion. The main source of dissipation in our experiments caused by metallic coating neither comes from the interface between Cr and cantilever itself nor the bulk of gold coating but comes from the interface between gold and chromium. This may be attributed to internal friction between the two coating layers.

References

[1] Callen H B and Greene R F 1952 On a theorem of irreversible thermodynamics Phys. Rev. 86 702-10

[2] Saulson P R 1990 Thermal noise in mechanical experiments Phys. Rev. D 42 2437-45

[3] Paolino P and Bellon L 2009 Frequency dependence of viscous and viscoelastic dissipation in coated micro-cantilevers from noise measurement Nanotechnology 20 0957-4484

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