Mechanical detection and mode shape imaging of vibrational modes of micro and nanomechanical resonators by dynamic force microscopy

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Abstract. We describe a method based on the use of higher order bending modes of the cantilever of a dynamic force microscope to characterize vibrations of micro and nanomechanical resonators at arbitrarily large resonance frequencies. Our method consists on using a particular cantilever eigenmode for standard feedback control in amplitude modulation operation while another mode is used for detecting and imaging the resonator vibration. In addition, the resonating sample device is driven at or near its resonance frequency with a signal modulated in amplitude at a frequency that matches the resonance of the cantilever eigenmode used for vibration detection. In consequence, this cantilever mode is excited with an amplitude proportional to the resonator vibration, which is detected with an external lock-in amplifier. We show two different application examples of this method. In the first one, acoustic wave vibrations of a film bulk acoustic resonator around 1.6 GHz are imaged. In the second example, bending modes of carbon nanotube resonators up to 3.1 GHz are characterized. In both cases, the method provides subnanometer-scale sensitivity and the capability of providing otherwise inaccessible information about mechanical resonance frequencies, vibration amplitude values and mode shapes.

1. Introduction

Micro and nanoelectromechanical resonators are attracting a growing interest for both basic research and technological applications [1]. A limiting factor for the development of these systems is the difficulty of characterizing of their dynamical properties. Detecting very small vibration amplitudes at very high frequencies becomes is a highly nontrivial task, particularly when the dimensions of the resonant device are in the nanometer-scale. Optical detection methods do not provide enough lateral resolution here, and electrical techniques can not provide information about actual vibration amplitude values or mode shapes.

As an alternative, atomic force microscopy (AFM) imaging methods can provide otherwise inaccessible information about micro and nanoelectromechanical systems (MEMS and NEMS), such as their actual vibration amplitudes, mode shapes or power dissipation mechanisms. In this work, we demonstrate the use of different bending modes of an AFM cantilever to simultaneously obtain the
topography and mechanical vibration amplitude of resonant MEMS & NEMS with sub-nanometer scale sensitivity. Here we demonstrate this method by its application to two different systems: a film bulk acoustic micromechanical resonator (FBAR) and a multiwall carbon nanotube (CNT) nanomechanical resonator. While both have resonance frequencies in the RF range (MHz-GHz), these two devices have very different properties: FBARs are very stiff systems, several tens of micron large, that vibrate in thickness acoustic modes with amplitudes up to several nanometers; CNT resonators are nanometer-scale systems several orders of magnitude more compliant, that vibrate in bending modes with amplitudes up to a few hundreds of picometers. Our results point out that the proposed method is applicable to arbitrarily large resonant frequency systems and it is appropriate for a broad range of NEMS and MEMS devices.

2. Experimetal set-up

FBAR technology is among the most successful applications of RF-MEMS for frequency-control in wireless electronics [2]. The FBAR device used in this work is shown in Fig. 1(a). The resonator consists of a suspended piezoelectric AlN, pentagonal-shaped membrane sandwiched between metal electrodes. The structure has a main thickness-extensional mode at 1.6 GHz in which the device undergoes out-of-plane motion with an amplitude of up to a few nanometers.

Carbon nanotubes offer unique mechanical properties for their application in ultrasensitive mass or force sensor devices [3]. Our resonators are based on multiwall nanotubes synthesized by arc-discharge evaporation. The nanotubes are connected to two Cr/Au electrodes patterned by electron-beam lithography on a Si substrate with a 1 µm thermal silicon dioxide layer [figure 1(a)]. The nanotube is released from the substrate by HF etching. The nanotubes are driven by applying a DC + AC signal to the device sidegate or backgate electrodes.

In our experiments, the tip is scanned in amplitude modulation dynamic force microscopy mode (AM-DFM). Although contact mode AFM can in principle be also used for detecting nanomechanical vibrations [4], it is known that dynamic mode operation minimizes tip-surface interaction forces [5], which here contributes to maximize sensitivity and minimize perturbation of the sample device vibration. In our method, the amplitude of the cantilever oscillation driven at any of its first two bending modes is used for feedback control and topography imaging. The resonators are fixed to a home-made chip carrier with 50 ohm transmission lines and are driven by an amplitude modulated signal with a carrier frequency at or near its resonant frequency. The modulation frequency $f_{\text{mod}}$ is set to match any of the first two bending modes of the AFM cantilever that is not used for feedback control, which is not externally driven. However, this mode is excited due to the interaction between the tip and the vibrating surface of the resonator, and its amplitude can be measured with an external lock-in amplifier. In air, the quality factor of both cantilever modes is high enough to prevent mechanical coupling between them. Each mode can actually be considered as a separate cantilever that can be used whether for topography imaging or vibration amplitude detection. The cantilevers used in
the experiments have a nominal spring constant around 1-2 N/m and resonant frequencies of the first two modes $f_1$ and $f_2$ around 50-70 kHz and 400-500 kHz, respectively.

In the case of the FBAR, we use the first cantilever mode for feedback control and the second one for detecting its vibration amplitude. In the case of the CNT, we inverse the set-up and use the second cantilever mode for feedback control and the first one for vibration amplitude detection. In both cases, the resonant frequency of the sample resonators lays in the MHz or GHz range. This is much higher than the resonant frequencies $f_1$ and $f_2$ of the cantilever. However, modulating the amplitude of the resonators vibration allows the tip to be sensitive to the effective position of the resonator surface, which is given by the envelope of the vibration. With $f_{\text{mod}} = f_1$ or $f_{\text{mod}} = f_2$, the tip is subject to quasi-periodic excitation due to its interaction with the resonators vibration envelope, which produces the excitation of the corresponding cantilever eigenmode.

3. Film Bulk Acoustic Resonator

Fig. 2 shows the results of the characterization of the FBAR. Figs. 2(a) and 2(b) are the topography and amplitude image, respectively, obtained at resonance, on the 80x80 $\mu$m area of the resonator membrane indicated in Fig. 1(a). The image shows the usual features observed on FBAR vibrations [6]: the so-called main pancake mode is identified as a central amplitude maximum that decays towards the borders of the resonator. In addition, a superimposed shorter wave-length pattern, corresponding to a simultaneously excited parasitic mode, is also observed. The mechanical frequency response displayed in Fig. 3(c) shows the main resonance peak at 1.595 GHz. Additional peaks at lower frequencies corresponding to lateral modes are also identified. Amplitudes in the sub-nanometer scale were detected at 1.6 GHz with a lateral resolution limited by the tip radius, typically below 50 nm.

In this case, the first AFM cantilever mode is used for topography imaging and the second for amplitude detection [7]. This configuration implies to set a large modulation frequency so that $f_{\text{mod}} = f_2$, typically above 400 kHz. This presents two important advantages. First, image acquisition time, which is limited by lock-in detection at a reference frequency given by $f_{\text{mod}}$ is several times faster than by setting $f_{\text{mod}} = f_1$. Such difference becomes important when imaging large active area resonators such as the FBAR. The images of figure 2 where obtained in 7 minutes. The second advantage concerns thermomechanical effects in this type of resonators [8]. When an RF driving signal is applied to the FBAR, part of the energy is absorbed by the membrane and converted into heat. As a result, the membrane undergoes periodic thermal expansion at a frequency given by $f_{\text{mod}}$. However, faster
modulation frequencies decrease the magnitude of temperature fluctuations of the membrane and minimize thermally induced vibrations that can eventually mask the observed RF vibration.

4. Carbon nanotube resonator

Figure 3 shows the results obtained on a CNT resonator composed of a nanotube with 770 nm length and 8.4 nm width. Figures 3(b) to 3(d) show the mode shapes obtained for the fundamental, second and third order bending modes of the resonator at 0.154, 0.475 and 1.078 GHz. Figures 3(e) to 3(g) display 3d topography plus amplitude merged images, which allow to identify the bending mode profile. Figure 3(h) shows the resonance curve obtained for the highest resonance frequency detected on a CNT resonator in our experiments, corresponding to 3.12 GHz. By means of the effective signal-to-noise ratio optimization provided by our lock-in detection scheme, we were able to detect vibration amplitude values down to a few picometers.

Remarkably, both the bending profiles and resonance frequency values are consistent with what is expected from elastic beam theory for a double clamp beam with the material properties of CNTs [9]. For instance, the theoretical ratio between the second and third to the first bending mode resonance frequencies of a double clamped beam with rigid clamps are \( f_2/f_1 = 3.1 \) and \( f_3/f_1 = 5.4 \). In the case shown in figure 3, we find \( f_2/f_1 = 2.8 \) and \( f_3/f_1 = 7.0 \), which is consistent with the theoretical values. The deviation is attributed to lack of rigidity of the clamping ends.

In opposition to the previous case, here we use the second eigenmode of the cantilever for feedback control and the first one for vibration amplitude detection. In this case, the small scan area required and the absence of thermally induced motion in the nanotube makes no advantageous use of the opposite configuration. On the other hand, the first cantilever eigenmode has a spring constant
which is more than 10 times softer than that of the second, which contributes to minimize any perturbation to the nanotube vibration. Further optimization of the measurements is achieved by setting a cantilever setpoint amplitude very close to the free amplitude, typically around 50 nm.

5. Conclusions.

In summary, we have described an AM-DFM based method for detecting and imaging mechanical vibrations in MEMS and NEMS devices with sub-nanometer-scale sensitivity. The method is applicable regardless of the device resonant frequency, and it has been demonstrated here for the characterization of a microscale FBAR resonator and a nanoscale CNT resonator.

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References

[1] Ekinci K L and Roukes M L 2005 Rev. Sci. Instrum. 76 061101-12
[2] Ruby R, Bradley P, Larson J D and Oshmyansky Y 1999 Electron. Lett. 35 794-5
[3] Sazonova V, Yaish Y, Ustunel H, Roundy D, Arias T A and McEuen P L 2004 Nature 431 284-7
[4] Safar H, Kleiman R N, Barber B P, Gammel P L, Pastalan J, Huggins H, Fetter L and Miller R 2000 Appl. Phys. Lett. 77 136-8
[5] San Paulo A and Garcia R 2000 Biophys. J. 78 1599-605
[6] San Paulo A, Quevy E, Black J, Howe R T, White R and Bokor J 2007 Microelectron. Eng. 84 1354-7
[7] San Paulo A, Black J, White R M and Bokor J 2007 Appl. Phys. Lett. In print
[8] San Paulo A, Liu X and Bokor J 2005 Appl. Phys. Lett. 86 84102-4
[9] Garcia-Sanchez D, San Paulo A, Espladiu M J, Perez-Murano F, Forro L, Aguasca A and Bachtold A 2007 Physical Review Letters In print