Frequency Characterization of AlN Piezoelectric Resonators

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Abstract— **In this paper, we analyze the vibrational spectra of mechanical resonators actuated piezoelectrically with aluminum nitride (AlN) films. The microresonators consist in bimorph cantilevers with different lengths containing a piezoelectric metal/AlN/metal stack supported by a silicon nitride structural layer. The thicknesses of both the AlN and Si_3N_4 layers are varied between 0.3 µm and 1 µm to study their influence on the mechanical response of the cantilevers. The motion of the cantilevers electrically driven is first assessed by optical laser interferometry; resonant frequencies varying between 100 kHz and 8 MHz are obtained. Additionally, many of the vibrational modes are detected by measuring the changes of the electrical impedance at the resonant frequencies. The mass detection factor of the cantilevers is assessed by measuring the frequency shift after mass loading with thin SiO_2 layers. A value of 0.18 fg/Hz is obtained for vibrational modes around MHz.**

Keywords-component; AlN; mechanical resonator; electrical detection

I. INTRODUCTION

Micromechanical resonators based on cantilevers can be used as gravimetric chemical transducers as they undergo changes in their resonant frequency when loaded with an additional mass [1]. Among the different ways to promote the movement of the microstructures, piezoelectric actuation based on bimorph structures offers not only the advantage of low actuation voltages and moderate power consumptions [2], but also the possibility of detecting mechanical resonances through the measurement of the changes of the electric admittance of the piezoelectric layer [3]. Piezoelectric mechanical resonators are based on the mechanical deformations undergone by bimorph structures (piezoelectric/structural layer) as a consequence of the internal stress generated in the piezoelectric by an external electric voltage. To be used as high-resolution gravimetric transducers, high resonant frequencies are desirable, as the relative variations of the resonant frequency are proportional to the relative variations of mass [4]. Such high frequencies can be achieved either by lowering the geometric dimensions of the cantilevers or by increasing the stiffness of the structures. For a cantilever of a given size, a stiffer structure can be achieved by increasing the thickness of the different layers forming the bimorph or by using materials with higher elastic constants. Among the possible piezoelectric thin films, PZT and ZnO have been the most used in piezoelectrically actuated mass sensors [2,5,6]. In the last years, piezoelectric aluminum nitride (AlN) has become important thanks to its compatibility with conventional silicon technologies; it can be grown through a low temperature process and does not introduce incompatible ions, avoiding thus the major problems arising with other piezoelectric materials. Piezoelectric properties of AlN are similar to those of ZnO, but not as good as those of PZT; however, its high elastic constants and elevated thermal and chemical stabilities make this material very suitable for mass sensor applications.

Piezoelectric actuation offers advantages for the fabrication of low-cost mass sensors, giving the possibility of using an all-electric method for actuation and sensing, thus avoiding the complex optical procedures for the detection of motion [2]. Usually the electrical detection of movement is carried out with a pair of sensing electrodes which, along with the driving electrodes, converts the resonator into a two-port device [7]. However, it is possible to actuate and sense at the same time with just one pair of electrodes by using the inverse and direct piezoelectric effects simultaneously. In this one-port device an ac voltage applied to the driving electrodes generates the movement of the structure which, in turn, induces changes in the impedance of the piezoelectric layer measurable in the same driving electrodes. At the resonant frequencies the variations of the impedance are large enough to be used for oscillator designs.

In this communication we have analyzed the frequency response of bimorph microcantilevers containing an AlN piezoelectric capacitor acting simultaneously as actuator and detector of the movement. First, we compare the vibrational modes obtained by conventional optical interferometry with those obtained by measuring the admittance of the one-port device. Then we analyze the response of the devices to different mass loading with the aim of using them as high sensitivity mass detectors.

II. EXPERIMENTAL DETAILS

Microcantilevers of different geometries (60 µm-wide and 95 µm or 175 µm-long) were fabricated on silicon substrates using conventional surface micromachining techniques. The microcantilevers consisted in a Mo/AlN/Mo capacitor supported by a Si_3N_4 structural layer. All the films were deposited by pulsed-DC sputtering under controlled deposition conditions to minimize their in-plane residual stress. As sacrificial layer we used a 3.3 µm-thick low density silicon suboxide layer (SiO_x) sputtered in a mixture of argon and oxygen. This layer exhibited a residual stress lower than 200

MPa and a surface roughness, measured by AFM, of 5 nm rms; it was easily etched in BFH solutions at a rate of 13 µm/min in the vertical direction and 6 µm/min under the structural layer. The thickness of the Si_3N_4 layer was varied between 0.3 µm and 1 µm; its compressive residual stress of around 600 MPa was partially removed after releasing the whole structure. The piezoelectric stack was formed by an AlN film sandwiched between two 100 nm-thick Mo electrodes. A 30 nm-thick Ti layer under the Mo electrode acted both as adherent and seed layer. The thickness of the AlN film was varied between 0.3 µm and 1 µm to study its influence in the mechanical response of the cantilevers. The piezoelectric properties of the AlN were assessed through electrical response of SAW test structures made on dummy samples as described in [8]. The typical value of the longitudinal electromechanical coupling factor k_l^2 is around 1.3 %.

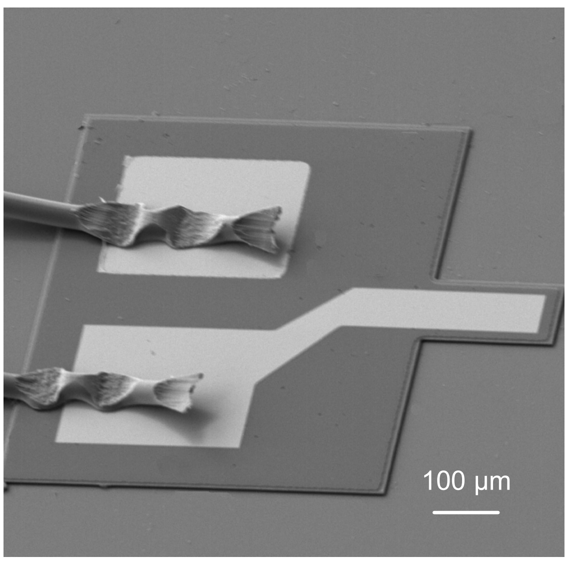

Figure 1. Example of a 95 µm-long and 60 µm-wide microcantilever.

Fig. 1 shows a SEM photograph of one of our cantilevers. The mechanical response of the devices was measured by laser interferometry. The laser beam impinged on the cantilever with a spot diameter larger than its length. The interferences of the laser beams reflected in both the mobile and the fixed parts of the device were detected with a fast Avalanche Photodiode (APD) model TIED87 whose output was amplified and fed to an Agilent ESA4402 spectrum analyzer. The microcantilevers were excited through the tracking generator of the spectrum analyzer with a signal of around 1 V of amplitude at frequencies varying between 100 kHz and 8 MHz. The electrical impedance of the devices was measured as a function of the frequency with an Agilent HP-4192A impedance analyzer. A peak voltage of 1.55 V was used for the measurement to have a similar driving than in the previous technique. The frequency range was also the same. The impedance of the cantilevers was modeled with a simple circuit consisting in capacitor in parallel with a resistor.

III. Results and Discussion

The mechanical response of the microcantilevers measured by laser interferometry has several resonances corresponding to the different vibrational modes. A typical spectrum of displacement of the cantilevers is shown in Fig. 2.

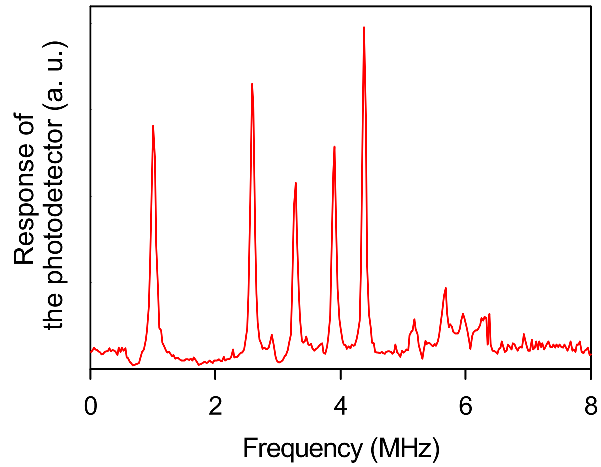

Figure 2. Mechanical response of a 95 µm-long, 60 µm-wide and 1600 nm-thick microcantilever as a function of the frequency.

The peak amplitude of the different vibrational modes is not correlated with the absolute displacement of the structure at these frequencies. As the laser beam in our experimental setup is not focused in one small dot of the cantilever, it is reflected in different areas of the mobile structure. Therefore, the spectra measured provide the frequencies of the resonant modes, but do not supply information of their relative intensities. We have observed that the high order resonant modes vary from device to device. This is due to the high sensitivity of these modes to the geometric defects of the devices. Actually, the mobile parts of our devices are not restricted to the defined cantilevers but contain also a small area of the structural layer suspended around the pillars.

The influence of the thickness of the beam in the vibrational behavior of the resonators has been investigated in two families of cantilevers of different lengths. The total thickness of the beam was increased from 600 nm to 2000 nm by increasing simultaneously the thickness of both the AlN and the Si_3N_4 layers, keeping always constant their relatives values. Fig 3 shows the variation of the resonant frequencies of the first and second resonant modes of the cantilevers as the total thickness of the beam is increased. The data in Fig. 3 demonstrate that stiffer structures exhibit always higher resonant frequencies. On the one hand, long cantilevers always vibrate at frequencies lower than short cantilevers. On the other hand, as the thickness of the structure increases, the resonant frequencies increase accordingly, regardless of the resonant mode or the geometry of the beam. All these results are well known for this kind of devices [4]. Therefore, the choice of very stiff materials, such as AlN and Si_3N_4, provides higher resonant frequencies, which is beneficial for sensor applications.

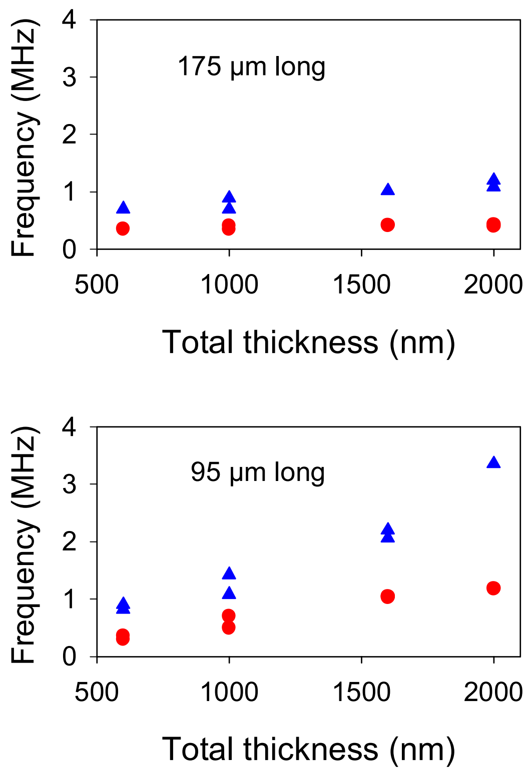

Figure 3. Resonant frequencies of the first (•) and second (▲) vibrational modes of cantilevers with different lengths (95 and 175μm) as a function of the total thickness of the beam.

As we pointed out in the Introduction, the detection of the vibrational resonances can also be carried out by means of electrical measurements. These measurements are especially convenient, since the electrical signal can be used simultaneously for excitation and detection, simplifying significantly the electronics. The admittance of the cantilevers is represented by a simple model formed by a capacitance C in parallel with a conductance G. Fig. 4 shows the variations in C and G for a given cantilever as a function of the frequency. The mechanical response of the same cantilever measured by laser interferometry is also shown for comparison. These data demonstrate that both C and G exhibit significant variations at the frequencies corresponding to the resonant modes. However, the number of modes detected by impedance measurements is clearly lower than that observed by optical interferometry.

The actuation mechanism in piezoelectric bimorph cantilevers is based on the inverse piezoelectric effect; the application of an ac electric field to the piezoelectric layer produces its elongation and, as a consequence, the bending of the bimorph. The bending of the cantilever produces in turn an additional stress in the piezoelectric material, originating a time-varying strain distribution, which, by virtue of the direct piezoelectric effect, generates localized piezoelectric fields superimposed to the ac applied field. These new time-depending piezoelectric fields produce local variations in the current density inside the piezoelectric layer. The total current, which is the magnitude actually measured by the impedance analyzer, is obtained by integrating the current density over the electrode area. The variations of the impedance should be especially important at the resonances, because the amplitudes of the vibration are greater than at other frequencies. However, depending on the shape of the vibrational mode considered, the integrated current in the piezoelectric slab may give a net term, thus giving rise to a change in the measured impedance, or it may cancel by symmetry, in which case no change in the impedance will be observed. As figure 4 shows, some modes of vibration produce greater admittance variations than others. Thus, the detection of vibrational modes by this method is very sensitive to the symmetries of each mode.

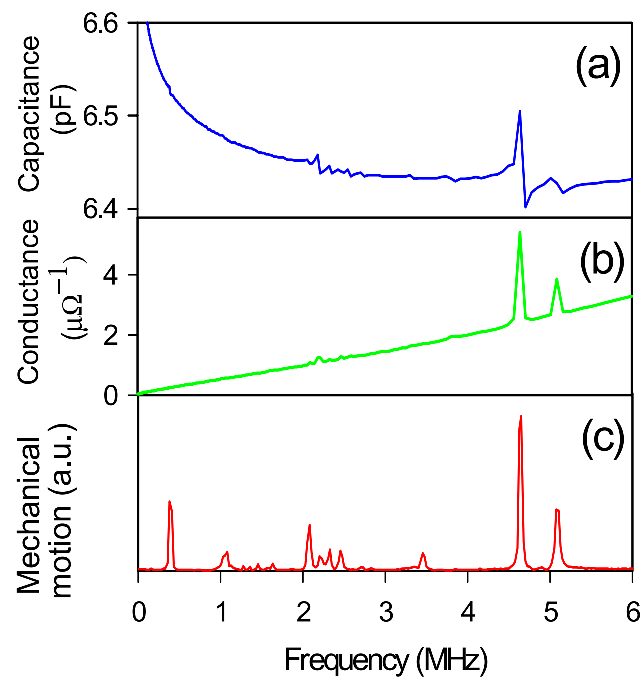

Figure 4. Frequency variation of the parallel capacitance and conductance of a typical microcantilever (175 μm-long). The mechanical response measured by laser interferometry is added at the bottom for comparison.

Finally, to demonstrate the viability of the devices presented in this work as mass sensors, we have analyzed the frequency response of a microresonator as a function of the mass loading. The total area of one resonator was loaded sequentially with SiO_2 sputtered layers of controlled thickness. The impedance spectrum was measured at the beginning of the experiment and after each deposition run. Since the area of the cantilever and the thickness and density of the deposited film are known, the mass added atop the device after each deposition can be calculated. The frequency variations in the parallel capacitance are shown in Fig. 5 for three different mass loadings. In this specific resonator, four vibrational resonances are clearly detected by impedance measurement. All the modes exhibit a significant frequency shift towards lower frequencies as the mass loading increases; this shift is greater at high frequencies. If the frequency of the resonance is depicted as a function of the mass loading, a linear behavior is observed for all the vibrational modes, as shown in Fig. 6 for the highest frequency mode (around 2.2 MHz).

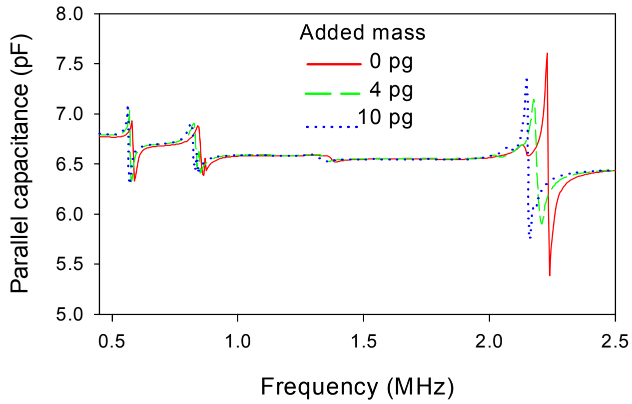

Figure 5. Frequency variation of the parallel capacitance of a microcantilever with added masses in form of thin SiO_2 films.

The value of the mass detection factor (g/Hz), defined as the inverse of the mass sensitivity (Hz/g), can be obtained from the slope of the straight line in Fig.6. The value of 0.18 fg/Hz obtained for this particular mode is in the range of the mass detection threshold for this kind of devices [9].

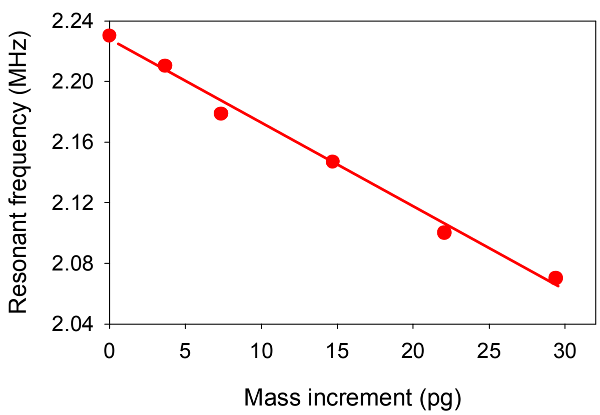

Figure 6. Resonant frequency variation of the 2.2 MHz mode as a function of the mass loading.

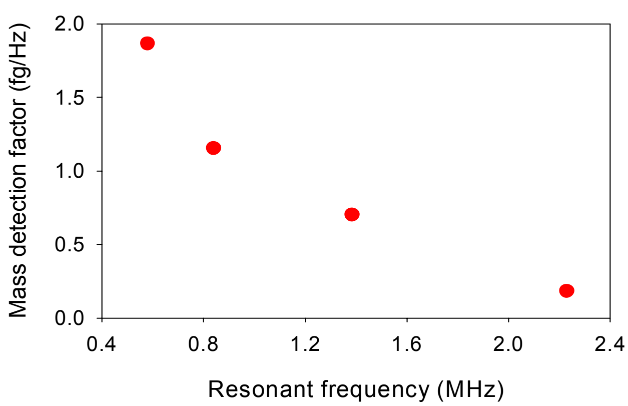

Figure 7. Mass detection factor for the four resonant modes of Fig. 5 as a function of the resonant frequency.

The mass detector factors have been obtained in a similar way for each of the modes of Fig. 5. The values are depicted in fig. 7 as a function of the resonant frequencies of the unloaded microresonator. We observe that the mass detection factor of the resonators decreases significantly at high frequencies, as theory predicts [4].

IV. Conclusions

We have studied the frequency response of piezoelectric microresonators actuated with AlN. Two types of cantilevers of different length were tested varying the total thickness of the beam. Thickening or shortening the beam produces stiffer structures with higher resonant frequencies. We have demonstrated that the vibrational behavior of the resonators can be assessed in a very convenient way trough the variations of the electrical impedance of the AlN capacitor with frequency. Using as mass sensors, these resonators exhibit mass detection factors as low as 0.18 fg/Hz for the high-frequency modes.

Aknowledgements

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