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Electrical detection of the mechanical resonances in AlN-actuated microbridges for mass sensing applications

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We report the fabrication and frequency characterization of mechanical resonators piezoelectrically actuated with aluminum nitride films. The resonators consist of a freestanding unimorph structure made up of a metal/AlN/metal piezoelectric stack and a Si_3N_4 supporting layer. We show that the electrical impedance of the one-port device can be used to assess the vibrational behavior of the resonators, provided that the modes do not exhibit specific symmetries, for which the impedance variations cancel. Frequency shifts arise when loading the resonators with small masses. As gravimetric sensors, the microbridges exhibit mass sensitivities of 0.18 fg/Hz for vibrational modes around 2 MHz. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2924284]

Micromechanical resonators based on freestanding unimorph structures (cantilevers and bridges) can be used as gravimetric chemical transducers as they undergo changes in their resonant frequency when loaded with an additional mass.[1] 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.[2] High resonance frequencies are obtained in stiffer structures, which can be achieved by decreasing the dimensions of the devices,[3] or by increasing either the elastic constants of the materials involved[4] or the stress of the layers.[5]

Among the different ways used to produce the movement of the freestanding microstructures, piezoelectric actuation offers the advantage of low actuation voltages and moderate power consumptions.[6] Piezoelectric flexural resonators are based on the mechanical bending experienced by unimorph structures (piezoelectric/structural layer) when an external field perpendicular to the surface is applied. The electric field induces a longitudinal extension (or contraction) of the piezoelectric layer, proportional to the piezoelectric coefficient d_{31}. The internal in-plane stress built in this piezoelectric layer produces the bending of the freestanding structure in the vertical direction.[2] Lead zirconate titanatc (PZT) and ZnO have been the piezoelectric layers of choice in the last years for piezoelectrically actuated devices.[7–9] The recent advances in AlN films for acoustic wave devices, such as bulk acoustic wave,[10] surface acoustic wave (SAW),[11] or contour mode[12] resonators, suggest their use in piezoelectric mechanical resonators;[4] AlN films are fully compatible with conventional silicon micromachining technologies and offer interesting properties for mass sensor applications, such as high chemical and thermal stabilities and good piezoelectric properties.

An interesting characteristic of piezoelectrically driven resonators is the possibility of detecting the mechanical resonances through the changes of the electric admittance of the piezoelectric layer;[13] this provides an all-electric method for actuation and sensing thus avoiding the complex optical procedures for the detection of motion. By simultaneously using the inverse and direct piezoelectric effects, a single pair of electrodes is required for both actuation and sensing, providing a one-port device: the electrical signal is simultaneously used for excitation and detection, which significantly simplifies the electronics.

In this letter, we report the fabrication and characterization of mechanical microresonators piezoelectrically actuated with an AlN layer, which simultaneously acts as actuator and detector of the motion. We show that most of the vibrational modes detected by conventional optical interferometry can also be assessed by measuring the electrical admittance of the one-port device. We investigate the possibility of using these freestanding structures as high sensitivity gravimetric sensors by analyzing the frequency response of the devices after different mass loading.

Freestanding microbridges of different geometries were fabricated on silicon substrates using conventional surface micromachining techniques following the procedure described in a previous work.[14] The microstructures consisted in a Mo (150 nm thick)/AlN (800 nm thick)/Mo (150 nm thick) stack supported by an 800 nm thick Si_3N_4 structural layer (see Fig. 1). A 30 nm thick Ti layer under the Mo bottom electrode acted both as adhesion and seed layer to promote the growth of well oriented AlN films. All the films were deposited by pulsed dc sputtering under controlled deposition conditions to minimize their in-plane residual stress. The structural layer had a compressive residual stress of around 600 MPa, which was partially removed after releasing the whole structure. 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 surface roughness, measured by atomic force microscopy (AFM), of 5 nm rms; it was easily etched in buffered hydrofluoric acid solutions at a rate of 13 μm/min in the vertical direction and 6 μm/min under the structural layer. The longitudinal piezoelectric coefficient, d_{31}, was assessed through the electrical measurements of SAW delay lines built on top of AlN films of identical characteristics than those used for devices fabrication, following the procedure previously described.[15] A d_{31} mean value of 1.6 pm/V was derived from

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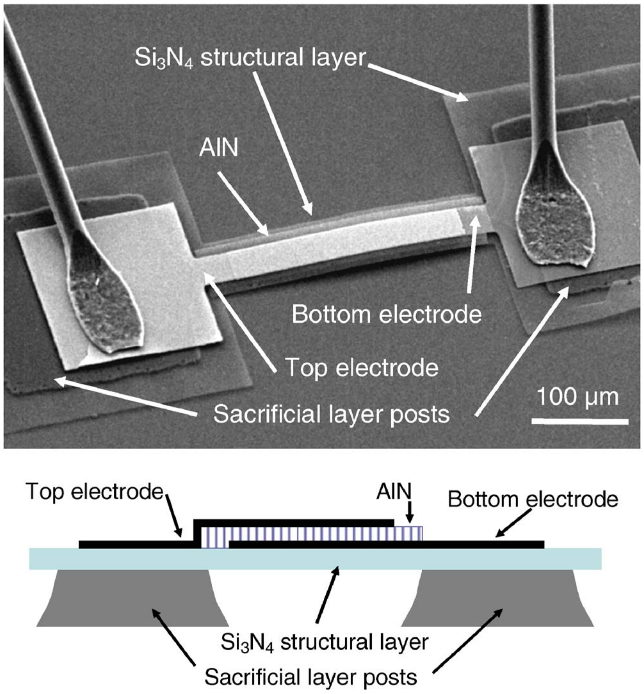

FIG. 1. (Color online) Picture of 300×60 μm^2 microbridge obtained by scanning electron microscopy (SEM) and a schematic side view of the device.

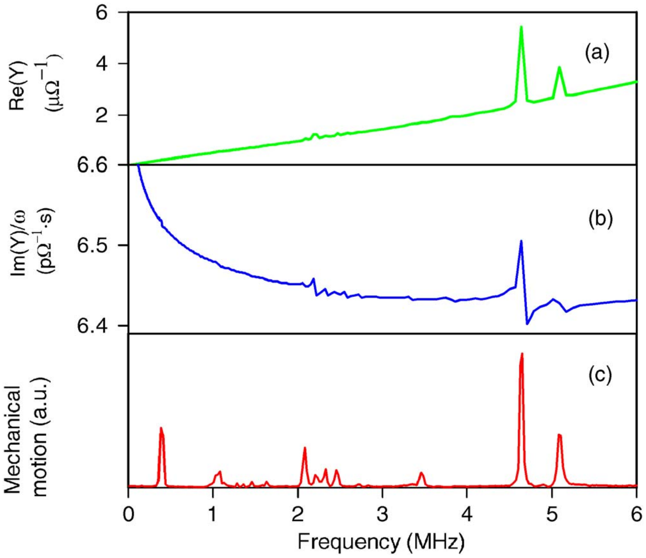

FIG. 2. (Color online) Real part (a) and imaginary part divided by the angular frequency (b) of the electrical admittance, and mechanical motion measured by laser interferometry (c) as a function of frequency, for a typical 175×60 μm^2 microbridge.

the longitudinal electromechanical coupling factor (k_l^2) obtained from the SAW devices.[16]

A first assessment of the mechanical response of the devices was obtained by laser interferometry. The laser beam impinged on the microstructures with a spot diameter larger than their lengths. The interferences of the laser beam reflected in both the mobile and the fixed parts of the device were detected with a fast avalanche photodiode model TIED87 whose output was amplified and fed to an Agilent ESA4402 spectrum analyzer. The microresonators 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 vibrational resonances were also assessed through electrical measurements. The electrical impedance of the devices was measured as a function of the frequency with an Agilent HP-4192A impedance analyzer in the same frequency range, using a driving voltage of amplitude similar to the value used in the previous described experiment.

Figure 2 shows the vibrational spectrum of a microbridge assessed by optical and electrical techniques. The vertical displacement, measured by optical interferometry, provides the resonance frequencies of the different vibrational modes. We verified that stiffer structures obtained either by increasing the thicknesses of the freestanding beam or by decreasing its length provided higher resonant frequencies. Coinciding with the resonance frequencies, significant variations of the real and imaginary parts of the electrical admittance were observed. However, fewer modes were detected by impedance measurements than by optical interferometry. This can be explained as follows. The actuation mechanism in piezoelectric unimorph structures 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 unimorph. The bending of the beam produces in turn an additional stress in the piezoelectric material, originating a time-varying strain distribution, which, by 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 actually the magnitude 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 any other frequencies. 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. However, this term may be cancelled by symmetry, in which case no change in the impedance will be observed, as shown by Vazquez *et al.*[17] for commercial AFM cantilevers with piezoelectric actuation with ZnO. As Fig. 2 shows, some modes of vibration do not produce admittance variations. In a previous work,[18] we reported the modal analysis by finite elements modeling of similar microbridges. The analysis showed that most of the experimentally measured resonant modes could be predicted by the theoretical model. Besides, it also revealed the existence of vibrational modes with a significant lack of symmetry, which are the best candidates for admittance analysis.

To demonstrate the viability of using these devices as mass sensors, we analyzed the frequency response of a typical microbridge as a function of the mass loading. The total area (500×100 μm^2) of the microbridge was sequentially loaded with SiO_2 sputtered layers of controlled thickness, which produced mass increments in the picogram range. The mass density and deposition rate of the sputtered SiO_2 films were previously determined using thicker films deposited on 100 mm Si wafers by weighting the substrates before and after the deposition and measuring the thicknesses of the layers with a profilometer. The estimated error in the mass loading is below 15%. The impedance spectrum of the resonators was measured before starting the loading process and after each deposition run. Figure 3 shows the imaginary part

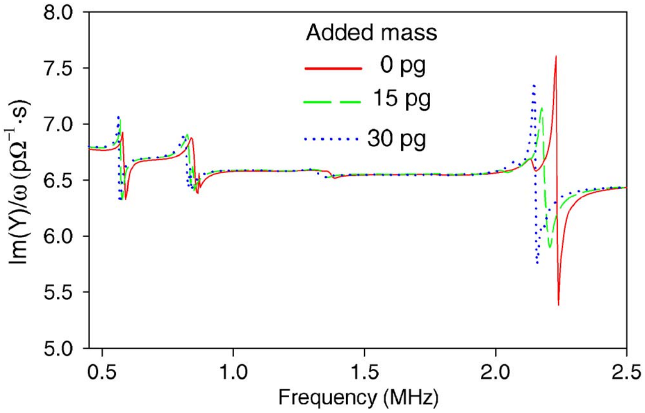

FIG. 3. (Color online) Imaginary part of the electrical admittance divided by the angular frequency as a function of frequency for a $500\times 100\ \mu\mathrm{m}^2$ microbridge with different added masses.

of the admittance divided by the angular frequency measured in the resonator before and after three different mass loadings. Four vibrational resonances are clearly detected by impedance measurement in this specific resonator. All the modes exhibit a significant frequency shift toward lower frequencies as the mass loading increases. This shift is more significant 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. 4 for the higher frequency mode (2.23 MHz). The value of the mass sensitivity (g/Hz) can be obtained from the slope of the straight lines in Fig. 4.[19] The values obtained are 0.18, 0.70, 1.15, and 1.87 fg/Hz for the 2.23, 1.39, 0.84, and 0.58 MHz modes, respectively. The value of the highest resonant mode is in the range of the mass detection threshold for this kind of devices.[8] We observe that the mass sensitivities of the resonators significantly improve at high frequencies, as predicted by theory.[13]

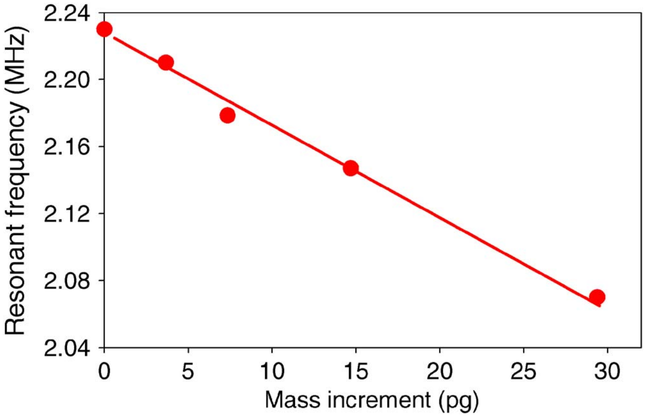

FIG. 4. (Color online) Resonance frequency of the 2.23 MHz mode of a $500\times 100\ \mu\mathrm{m}^2$ microbridge as a function of the mass loading.

In conclusion, we have fabricated and characterized piezoelectric microresonators actuated with AlN. 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 sensitivities of as low as 0.18 fg/Hz for the high-frequency modes.

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[1] S. Hosaka, T. Chiyoma, A. Ikeuchi, H. Okano, H. Sone, and T. Izumi, Curr. Appl. Phys. **6**, 384 (2006).
[2] V. Cimalla, F. Niebelschütz, K. Tonisch, C. Foerster, K. Brueckner, I. Cimalla, T. Friedrich, J. Pezoldt, R. Stephan, M. Hein, and O. Ambacher, Sens. Actuators B **126**, 24 (2007).
[3] N. V. Lavrik and P. G. Datskos, Appl. Phys. Lett. **82**, 2697 (2003).
[4] A. N. Cleland, M. Pophristic, and I. Ferguson, Appl. Phys. Lett. **79**, 2070 (2001).
[5] J. H. Lee, T. S. Kim, and K. H. Yoon, Appl. Phys. Lett. **84**, 3187 (2004).
[6] J. D. Adams, G. Parrot, C. Bauer, T. Sant, L. Manning, M. Jones, and B. Rogers, Appl. Phys. Lett. **83**, 3428 (2003).
[7] J. H. Park, T. Y. Kwon, H. J. Kim, S. R. Kim, D. S. Yoon, C.-I. Cheon, H. Kim, and T. S. Kim, J. Electroceram. **17**, 565 (2006).
[8] W. Pang, L. Yan, H. Zhang, H. Yu, E. S. Kim, and W. C. Tang, Appl. Phys. Lett. **88**, 243503 (2006).
[9] S. Vicknesh, S. Tripathy, V. K. X. Lin, S. J. Chua, B. Kumar, and H. Gong, Appl. Phys. Lett. **90**, 091913 (2007).
[10] R. Lanz and P. Muralt, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **52**, 936 (2005).
[11] C. Caliendo, Appl. Phys. Lett. **83**, 4851 (2003).
[12] G. Piazza and A. P. Pisano, Sens. Actuators, A **136**, 638 (2007).
[13] W. Y. Shih, X. Li, H. Gu, and W. H. Shih, J. Appl. Phys. **89**, 1497 (2001).
[14] J. Olivares, E. Iborra, M. Clement, L. Vergara, J. Sangrador, and A. Sanz-Hervás, Sens. Actuators, A **123-124**, 590 (2005).
[15] E. Iborra, L. Vergara, J. Sangrador, M. Clement, A. Sanz-Hervás, and J. Olivares, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **54**, 2367 (2007).
[16] A. Sanz-Hervás, M. Clement, E. Iborra, L. Vergara, J. Olivares, and J. Sangrador, Appl. Phys. Lett. **88**, 161915 (2006).
[17] J. Vazquez, P. Sanz, and J. L. Sánchez-Rojas, Sens. Actuators, A **136**, 417 (2007).
[18] J. Olivares, J. Malo, S. González, E. Iborra, I. Izpura, M. Clement, A. Sanz-Hervás, J. L. Sánchez-Rojas, and P. Sanz, Proc. SPIE **6186**, 61860K (2006).
[19] S. Shin and J. Lee, J. Korean Phys. Soc. **49**, S608 (2006).