ULTRA THIN ALN PIEZOELECTRIC NANO-ACTUATORS

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ABSTRACT

This paper reports the first implementation of ultra thin (100 nm) Aluminum Nitride (AlN) piezoelectric layers for the fabrication of vertically deflecting nano-actuators. An average piezoelectric coefficient (d_{31}~ - 1.9 pC/N) that is comparable to its microscale counterpart has been demonstrated in nanoscale thin AlN films. Vertical deflections as large as 40 nm have been obtained in 18 μm long and 350 nm thick cantilever beams under bimorph actuation with 2 V. Furthermore, in-plane stress and stress gradients have been simultaneously controlled. Leakage current lower than 2 nA/cm^2 at 1 V has been recorded and an average relative dielectric constant of approximately 9.2 (as in thicker films) has been measured. These material characteristics and preliminary actuation results make the AlN nano-films ideal candidates for the realization of nanoelectromechanical switches for low power logic applications.

KEYWORDS

NEMS, nano-actuators, piezoelectric film, Aluminum Nitride, AlN thin film, stress.

INTRODUCTION

The ever shrinking size of CMOS components and the need to achieve higher device densities have been the strongest motivators for the growth of the semiconductor industry. This push for technological growth is hindered by power dissipation due to subthreshold conduction and short-channel effects that occur when the devices are made to function in the nm-regime. The issues that exist at this scale can be resolved by utilizing purely mechanical structures for implementing logic and memories [1-5].

MOSFETs use a channel in the semiconductor material for the transfer of carriers between the source and drain. The physical presence of a solid channel causes subthreshold leakage that can be greatly reduced by replacing the channel with an air gap. This air gap can be closed by purely mechanical means, therefore reducing the subthreshold slope of a conventional MOSFET, which is instead limited by the thermal distribution of carriers in the channel.

Conventional mechanical actuation mechanisms, like capacitive, magneto-motive and thermoelastic that have been used to drive nanoscale devices [6, 7] have the drawback of either being non-linear in nature or requiring high power for operation. For example, capacitive detection does not scale well in the sub-micron dimensions [3], magneto-motive actuation needs the presence of high magnetic fields to function [3] and thermal actuation is not very efficient, although it scales favorably [7]. On the other hand, the well established piezoelectric actuation mechanism offers the advantages of extremely low power consumption and linear actuation. In addition, the energy density per input unit voltage of piezoelectric materials increases with the square of the film thickness.

The implementation of nanomechanical devices for logic applications dictates having fast switching times and large deflection characteristics, simultaneously. The only way to preserve high mechanical responsiveness along with high operating frequencies is to scale both the thickness and the length of the device; *i.e.* the device would have to be very small and thin at the same time. This paper reports on the first implementation of ultra thin (100 nm) Aluminum Nitride (AlN) piezoelectric films for the fabrication of vertically deflecting Piezoelectric NanoElectroMechanical (P-NEMS) actuators.

ALN FILMS: EFFECTS OF SCALING AND EXPERIMENTAL CHARACTERIZATION

Lead Zirconate Titanate (PZT) and AlN are two of the most commonly used piezoelectric materials and have already been used for the fabrication of actuators and MEMS switches [8-10]. Out of these two materials AlN stands out for its high dielectric strength, ease of deposition and processing, and its potential of integration with CMOS devices.

Scaling of the thickness of piezoelectric materials into the nano realm without experiencing degradation in the orientation and piezoelectric properties has been one of the biggest hurdles in the fabrication of P-NEMS. Another cause of failure in the past was the increase in internal stresses (cracking and excessive deformations in released structures) in the nano-films. This paper presents a new class of P-NEMS devices that have been made possible by precise control of film quality (orientation and stress) at 100 nm thickness. Not only was good piezoelectric response achieved in 100 nm thick films, but also bimorph actuators formed by stacking two of these thin AlN films sandwiched between three layers of thin (~ 50 nm) Platinum (Pt) (Figure 1) have been demonstrated. Platinum electrodes were used to apply an electric field across the piezoelectric film, which causes the thin film to strain by the reverse piezoelectric effect. The basic mechanism of actuation of the beam is identical to what was demonstrated for MEMS devices [8, 9]. The actuation voltage can be applied to each of the two piezoelectric layers separately and consequently permits to operate the nanomechanical actuator as a unimorph (single piezoelectric layer actuated) or as a bimorph (two layers are actuated in opposite directions) structure. This is the first demonstration of bimorph actuation via AlN piezoelectric films at the nanoscale that have also preserved the same stress free and high piezoelectric coefficients of its macroscopic counterparts.

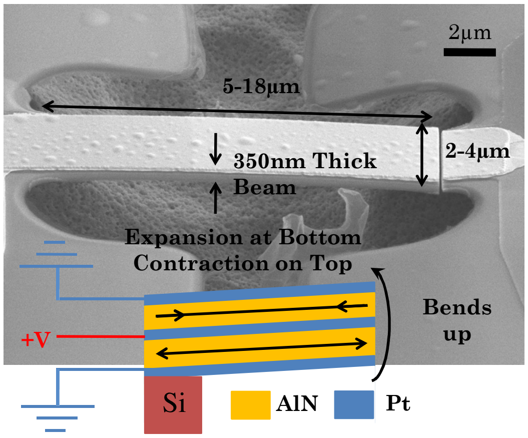

Figure 1: Scanning Electron Micrograph of a free cantilever beam showing small deflections when released. This is indicative of low levels of stress gradients in the nano (100 nm thick) AlN films. The figure also illustrates the stack of layers used to make the device and the operating principle of the bimorph nano-actuator.

The presence of residual stress is a certainty in any multi-layered released structure. This residual stress becomes a bigger hurdle when the films are scaled to the nano-dimensions and leads to excessive curling and, in extreme cases, cracking of the released film. This unwanted stress arises from both the thermal mismatch between the adjacent layers in the stack and from the parameters used to control the deposition of each layer. In this project, highly c-axis oriented and low stressed AlN thin films were deposited by a dual cathode S-Gun magnetron using AC reactive sputtering technology of Tegal Corporation [11]. It was experimentally found that both the in-plane stress and the stress gradient of AlN can be controlled by pre-heating the substrate before and during a fraction of the deposition process. Figure 2 shows the results of optimization of in-plane stress and stress gradients for 200nm thick AlN films.

X-Ray Diffraction (rocking curve) analysis of thin AlN films has shown that the full-width half maximum (FWHM) of the (002) diffraction peak varies from 2.1° to 4.4° for AlN films with thicknesses ranging from 100 to 200 nm. According to measurements performed on micron thick films and 100 nm thin films, it can be concluded that the FWHM has a dependence on both the thickness of the film being deposited and the substrate used for deposition. FWHM degrades with decreasing film thickness and is generally lower on single crystal surfaces (such as Silicon).

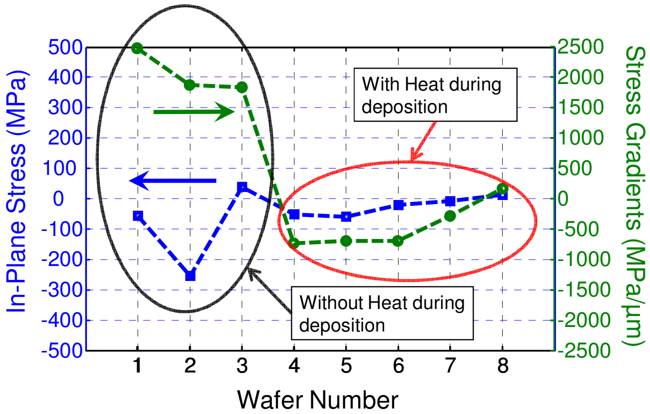

Figure 2: The plot presents the stress optimization performed for minimizing both the in-plane stress and the stress gradient for 200nm thick films.

Experimental characterization of the thin AlN films was carried out to analyze the breakdown characteristics and relative dielectric constant, ε_r, using a capacitance test structure formed by two Pt layers (50 nm thick) sandwiching a 100 nm thick AlN layer. The I-V characteristic of these films (Figure 3), measured using a Keithley 6517A Electrometer, shows a low leakage current of ~ 2 nA/cm^2 at 1V for a 13 x 13 µm area. The approximate breakdown voltage of 100 nm thick films has been measured to be 12 V.

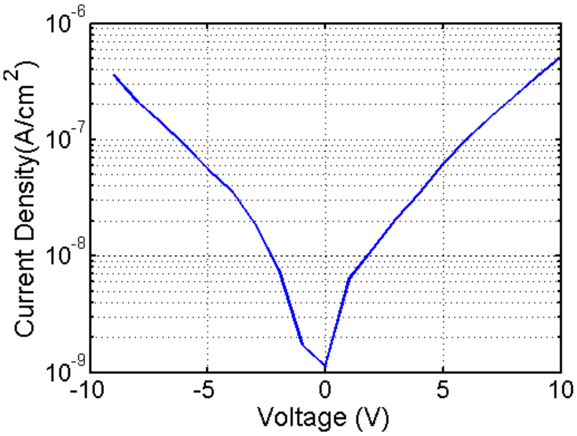

Figure 3: I-V characteristics of a 100 nm thick AlN film showing low leakage current of ~ 2 nA/cm^2 at 1V for an area of 13x13 µm.

Thin film AlN offers a multitude of advantages for electrical devices, like NEMS switches, resonators and filters, operating at high frequencies as it possesses high dielectric strength and low dielectric constant. As AlN has already been successfully used for the fabrication of MEMS contour mode filters [12], FBAR Filters [13], high frequency resonators [14] and switches [8, 9] it becomes even more advantageous to scale these devices down so as to achieve even higher levels of miniaturization. To enable this proposed Ultra High Frequency (UHF) and Super High Frequency (SHF) operation it becomes imperative to study the relative dielectric constant of AlN at high frequencies. Preliminary 2-port capacitance measurements on the same structures that were used for the leakage measurements were performed in a Lakeshore RF probe station with an Agilent PNA-L N5230 network analyzer. An identical open structure was de-embedded from the direct measurements and the resultant admittance was fitted to an equivalent series LC-circuit. An average value of 9.2 was measured for the dielectric constant. This value is similar to what has been recorded for thicker AlN films.

We conclude that, despite the enormous challenges in controlling film stress, quality and orientation, the deposition of thin AlN films below 200 nm with electromechanical properties comparable to microscale counterparts is possible.

VERTICALLY DEFLECTING NANO-ACTUATORS

A 5-mask post-CMOS compatible process (Figure 4) was employed to fabricate the nano-actuators. The fabrication steps are very similar to the process that was previously used for the realization of AlN-based MEMS switches [8, 9].

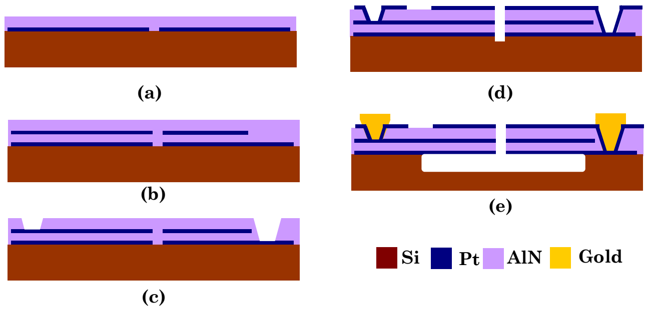

Figure 4: Schematic of the fabrication process used for the making of the NEMS AlN devices. (a) 100nm of AlN was deposited on 50 nm of Pt. (b) Second layer of 100nm of AlN was deposited on another intermediate 50 nm layer of Pt. (c) Vias are opened using KOH based developer, which gives access to bottom and middle Pt. (d) Top layer of 50nm of Pt is deposited and AlN is etched. In this case the gap between the beams was made using a FIB. This gap can be easily included in the design of the actuator and fabricated during the dry-etch of AlN. (e) 200nm of gold is deposited to fill the via and achieve a better electrical contact. Structures are released using a XeF_2 vapor phase release.

The scaling of both the AlN films and the device dimensions called for a more accurate control of the process parameters than what is usually required for MEMS scale structures. On the other hand, the use of thin AlN films simplifies the dry-etch step (Cl_2/BCl_3 based dry etch of AlN), which does not require the use of an oxide hard mask, and can be performed with hard-baked photoresist (~2.2µm thick). The nano-actuator shown in Figure 1 was fabricated as a beam clamped at both ends and was successively cut by Focused Ion Beam (FIB) in order to free one end and test different length structures as cantilevered benders.

DC voltage-induced nano-beam deflections were measured by a Zygo optical profilometer. Figure 5 shows the deflection profiles for an 18 µm long beam under bimorph actuation (*i.e.* both layers were used for actuation). The beam showed a deflection of ~ 116 nm upon the application of 6 V as compared to ~118 nm predicted by FEM simulations (using COMSOL).

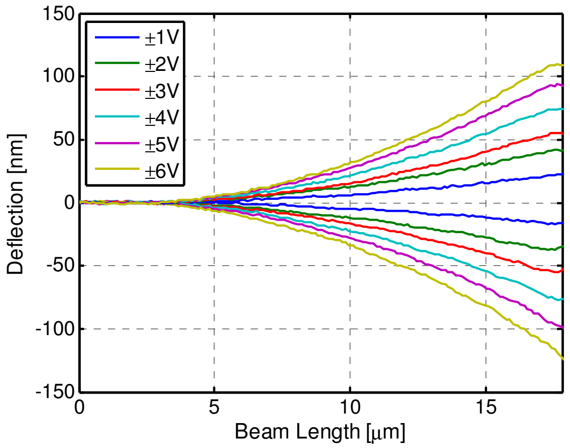

Figure 5: Deflection profiles for an 18µm long, 4 um wide and 300 nm thick beam subjected to bimorph actuation.

Figure 6 shows the excellent agreement between the predicted and measured deflection data for an 18 µm long nano-beam (350 nm total thickness) when operated as a bimorph. Both layers of AlN have also been individually actuated and the deflection measurement for each individual layer closely matches the FEM predictions. The agreement between simulation and experimental data gives us the ability to accurately predict the deflection behavior of AlN nano-structures by FEM simulations.

These deflection measurements along with analytical solutions for the deflection of piezoelectric unimorph and bimorph beams [15] were used for extracting the d_{31} piezoelectric coefficient of the ultra-thin AlN film. The extracted experimental d_{31} is - 1.92 pC/N for the composite beam, -1.98 pC/N for the top layer and -1.89 pC/N for the bottom layer. This confirms that both layers have good electromechanical properties. Furthermore, the perfectly linear and reversible stroke offered by the AlN nano-actuators (Figure 5) provide for additional robustness and reliability in devices that can benefit from active mechanisms to open and close contacts such as in NEMS switches.

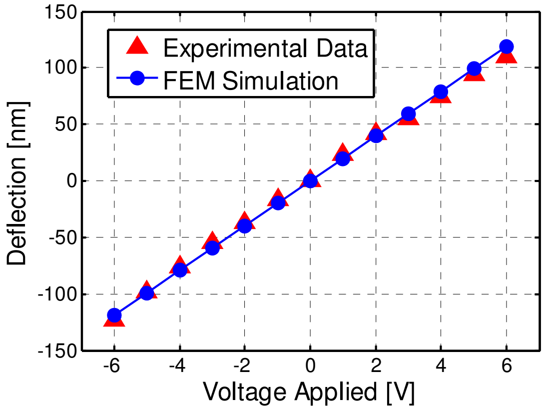

Figure 6: Excellent agreement exists between experimental data and FEM analysis (using COMSOL) of the vertical deflection for an 18µm long, 4µm wide and 350nm thick beam operated as a bimorph.

Figure 7 summarizes the results for the testing of three nano-beams of different lengths (5-18 um) under unimorph actuation at 6 V. Their deflections match well with FEM analysis and verify the dependence of vertical displacement on the square of the beam length as predicted by conventional Euler beam-bending equations.

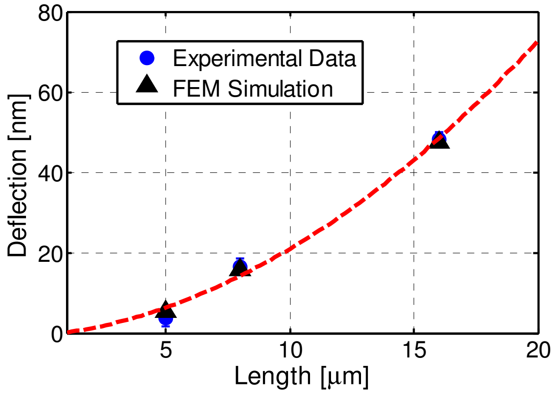

Figure 7: Results of deflection testing of three beams of different lengths (single layer actuation) at 6V and their agreement with FEM analysis. The dashed line (fitted curve) shows the square dependence between displacement and beam length.

CONCLUSIONS

This paper reports the first implementation of ultra thin (100 nm) Aluminum Nitride (AlN) piezoelectric films for the fabrication of vertically deflecting P-NEMS devices. The optical interferometric measurements of the deflection of the nanoactuators match closely with the FEM simulations. Electrical properties of the films were measured and found to be similar to micro-scale devices. The demonstrated electromechanical properties make this thin-film AlN technology amenable for applications such as nanomechanical low-power logic, AFM tip transduction, nanoresonator-based sensing and energy harvesting.

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