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Piezoelectric aluminum nitride nanoelectromechanical actuators

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This letter reports the implementation of ultrathin (100 nm) aluminum nitride (AlN) piezoelectric layers for the fabrication of vertically deflecting nanoactuators. The films exhibit an average piezoelectric coefficient ($d_{31} \sim -1.9$ pC/N), which is comparable to its microscale counterpart. This allows vertical deflections as large as 40 nm from 18 μm long and 350 nm thick multilayer cantilever bimorph beams with 2 V actuation. Furthermore, in-plane stress and stress gradients have been simultaneously controlled. The films exhibit leakage currents lower than 2 nA/cm^2 at 1 V, and have an average relative dielectric constant of approximately 9.2 (as in thicker films). These material characteristics and actuation results make the AlN nanofilms ideal candidates for the realization of nanoelectromechanical switches for low power logic applications. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3194148]

The growth of the semiconductor industry has been made possible by the continuous scaling of the complementary metal-oxide semiconductor (CMOS) technology. An important aspect that hinders further reduction in the channel lengths (the length of a channel between the source and drain in a transistor) and supply voltages in metal-oxide-semiconductor field-effect transistors (MOSFET) is the passive power dissipation in the device. This power loss is experienced due to subthreshold conduction that occurs due to the presence of a physical channel in the semiconductor material for the transfer of carriers between the source and drain. Purely nanomechanical structures for implementing logic and memories[1–5] have been proposed to resolve this specific issue. The current leakage due to presence of a solid channel can be greatly reduced by replacing the channel with an air gap. This air gap can be closed by mechanical actuators, therefore significantly reducing the subthreshold slope of a conventional MOSFET.

Conventional mechanical actuation mechanisms, such as capacitive, magnetomotive, and thermoelastic, which have been used to drive nanoscale devices[6,7] have the drawback of either being nonlinear in nature or requiring high power for operation. For example, capacitive actuation, whose sensitivity depends directly on electrode area, does not scale well to submicron dimensions,[3] magnetomotive actuation needs the presence of high magnetic fields to function,[3] and thermal actuation is still comparatively inefficient at this scale.[7] On the other hand, the well-established piezoelectric actuation mechanism offers the advantages of extremely low power consumption and linear actuation.[8] In addition, the energy density per input unit voltage of piezoelectric materials is inversely proportional to the square of the film thickness. However, piezoelectric film technology scaled to nanoscale thicknesses is only in its infancy, and raises a challenge because it is hard to deposit ultrathin films that retain the properties of their thicker microscale counterparts. Studying the electromechanical properties of piezoelectric nanofilms is therefore the first step toward the realization of a structure that can be used to implement nanomechanical actuators. Furthermore, the demonstration of nanomechanical devices for logic applications dictates having simultaneously fast switching times and large deflection characteristics. The only way to preserve substantial 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 extremely small and thin at the same time. This letter reports on the implementation of ultrathin (100 nm) aluminum nitride (AlN) piezoelectric films for the fabrication of vertically deflecting piezoelectric nanoelectromechanical (P-NEMS) actuators.

Lead zirconate titanate and AlN are two commonly used piezoelectric materials that have already been used for the fabrication of actuators and microelectromechanical (MEMS) switches.[9–12] Out of these two materials, AlN stands out for its high dielectric strength, ease of deposition, and processing (involving low temperatures and nontoxic precursors), and its potential for integration with CMOS devices. AlN has previously been used for the fabrication of MEMS contour mode filters,[13] film bulk-wave acoustic resonator (FBAR) filters[14] (AlN being the material of choice for commercial FBAR production), high frequency resonators,[15] and switches.[9,10]

Scaling of piezoelectric transduction to the nanoscale has failed in the past because of degradation of piezoelectric properties due to limited orientation in thin films and increases in internal stresses (cracking and excessive deformations in released structures). The class of P-NEMS devices presented in this letter has been made possible by precise control of film quality (orientation and stress) at 100 nm thickness. Owing to optimization of the actuator design and AlN sputter technology, not only was good piezoelectric response in 100 nm thick films achieved, but bimorph actuators were formed by stacking two of these thin AlN films

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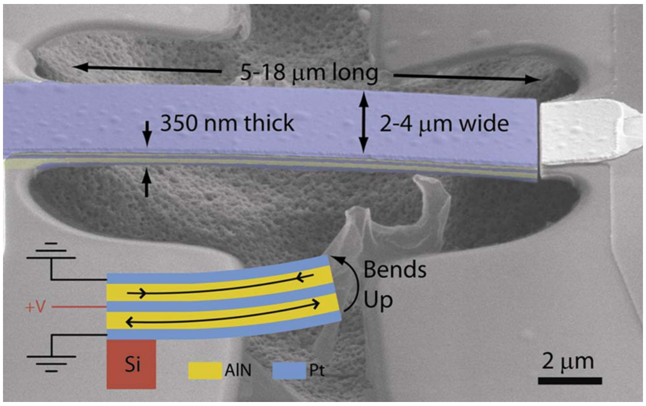

FIG. 1. (Color online) The false-colored scanning electron micrograph (SEM) was taken with the sample tilted at 52° to the horizontal. The sample was tilted to provide a three-dimensional view of the nanoactuator and show its constituent layers (350 nm thick stack formed by two 100 nm thick AlN layers and three 50 nm thick Pt layers). The released cantilevered beam also shows very small out-of-plane deflections. This is indicative of low levels of stress gradients in the nano-AlN films. The inset schematic illustrates a cross-sectional view of the stack of layers used to make the device and the operating principle of the bimorph nanoactuator.

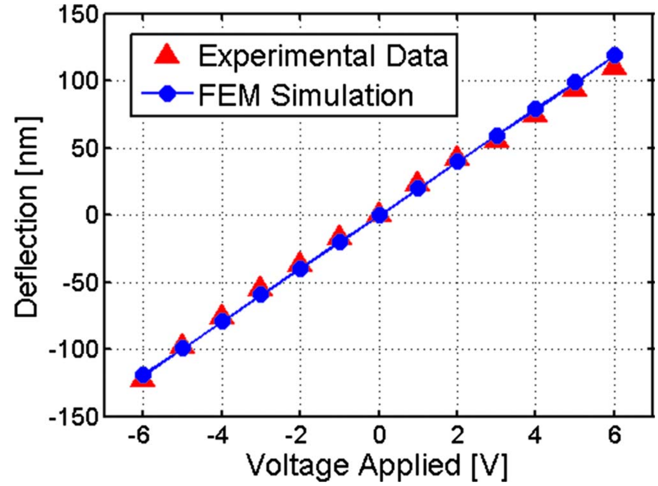

FIG. 2. (Color online) Excellent agreement exists between experimental data and FEM analysis of the vertical deflection for an 18 μm long, 4 μm wide, and 350 nm thick composite beam operated as a bimorph.

sandwiched between three layers of thin (~50 nm) platinum (Pt). The nanoactuator shown in Fig. 1 was fabricated as a beam clamped at both ends and successively cut by focused ion beam to free one end and test different length structures as bending cantilevers. Platinum electrodes were used to apply an electric field across the piezoelectric film, which causes the thin film to strain by the inverse piezoelectric effect. The basic mechanism of actuation of the beam is identical to what was demonstrated for MEMS devices:[9,10] the strains in either or both AlN layers of the structure generates a transverse moment about the neutral axis of the whole device and causes the beam to bend. The actuation voltage can be applied to each of the two piezoelectric layers separately and consequently permits the nanomechanical actuator to operate as a unimorph (single piezoelectric layer actuated) or as a bimorph (two layers actuated in opposite directions) structure. This lead to the demonstration of bimorph actuation at the nanoscale using AlN piezoelectric films that have preserved the same stress-free state and high piezoelectric coefficients of their macroscopic counterparts.

One of the biggest hurdles in the fabrication of multilayer structures is the presence of residual stress (and stress gradients) in the composite released structure. These unwanted stresses arise from both the thermal expansion mismatch between adjacent layers in the stack and intrinsic residual stresses, which can be affected by the parameters used to control the deposition of each layer. In this effort, highly *c*-axis oriented and low stress AlN thin films were deposited by a dual cathode S-Gun magnetron using ac reactive sputtering technology of Tegal Corporation.[16] It was experimentally found that both the in-plane stress and the stress gradient of AlN can be controlled by preheating the substrate before and during a fraction of the deposition process.

X-ray diffraction analysis of these thin AlN films has shown that the full width at half maximum (FWHM) varies from 2.1° to 4.4° for AlN films of thickness 100–200 nm. According to rocking curve measurements performed on films whose thickness ranged from 100 nm to 1 μm, it can be concluded that the FWHM depends on the substrate used for deposition. For example, the FWHM on bare silicon was found to be consistently lower than on patterned platinum. However, the results show that the change in FWHM does not significantly affect the piezoelectric coefficient of AlN.

Further studies were carried out to analyze the breakdown characteristics and relative dielectric constant ε_r of the thin AlN films using a capacitance test structure formed by two Pt layers (50 nm thick) sandwiching a 100 nm thick AlN layer. The *I-V* characteristics of these films, measured using a Keithley 6517A electrometer, show a low leakage current of ~2 nA/cm^2 at 1 V over a 13×13 μm area. The approximate breakdown voltage of 100 nm thick films is measured to be 12 V.

Thin film AlN offers a multitude of advantages for electrical devices operating at high frequencies, such as NEMS switches, as it possesses a relatively high dielectric strength (thus resisting breakdown) and low dielectric constant (thus requiring low power to actuate). Since AlN does not exhibit a Curie temperature, it is an ideal candidate for high temperature and high frequency applications that need low power to function. For the proposed ultrahigh frequency (i.e., 300 MHz to 3 GHz) and super high frequency (i.e., 3 GHz to 30 GHz) operations it becomes imperative to study the relative dielectric constant of AlN at high frequencies. Preliminary two-port capacitance measurements on the same structures 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.[17]

Finally, dc voltage-induced nanobeam deflections were measured by a Zygo optical profilometer in air. Figure 2 shows the excellent agreement between the predicted and measured deflection data for an 18 μm long composite nanobeam (350 nm thick with two 100 nm AlN layers, as discussed above) when operated as a bimorph. The beam exhibits linear voltage-deflection behavior, showing a deflection of ~116 nm upon the application of 6 V as compared to ~118 nm predicted by finite element method (FEM) simu-

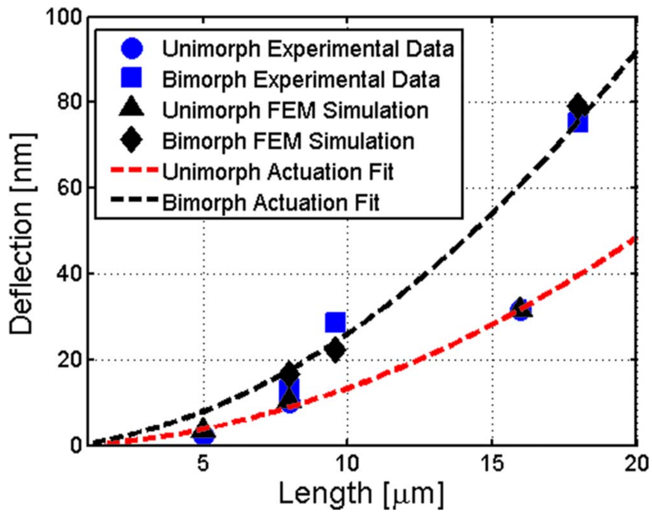

FIG. 3. (Color online) Results of deflection testing of beams of different lengths with unimorph actuation (single layer) and bimorph actuation (double layer) at 4 V and their agreement with FEM analysis. The dashed line shows the square dependence that exists analytically between tip displacement and beam length.

lations (for a rigidly fixed beam of the same dimensions) using COMSOL. 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 allows accurate prediction of the deflection behavior of AlN nanostructures by FEM simulations.

These experimental deflection measurements along with FEM simulation results and analytical solutions for the deflection of piezoelectric unimorph and bimorph beams[18] were used for extracting the experimental d_{31} piezoelectric coefficient of the ultrathin AlN films. The extracted experimental d_{31} is 1.92 ± 0.14 pC/N for the composite beam, 1.98 ± 0.16 pC/N for the top layer, and 1.89 ± 0.16 pC/N for the bottom layer. It is important to note that AlN nanoactuators offer a highly linear and reversible stroke that will greatly benefit active mechanisms for opening and closing contacts such as in piezoelectric contact switches.

Figure 3 summarizes the results for the testing of nanobeams of different lengths (5–18 μm) under unimorph and bimorph actuation at 4 V. Their deflections match well with FEM analysis and verify the dependence of deflection on the square of the beam length as predicted by conventional Euler beam-bending equations. This dependence on the square of the length shows that the piezoelectric layer generates a constant moment throughout the length of the beam.

In summary, this letter reports the implementation of ultrathin (100 nm) AlN piezoelectric films for the fabrication of vertically deflecting 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 microscale devices. The demonstrated electromechanical properties make this thin film AlN technology amenable for applications such as nanomechanical low power logic, atomic force microscopy tip transduction, nanoresonator-based sensing, and energy harvesting.

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