LOW VOLTAGE PIEZOELECTRIC NEMS RELAYS FOR ULTRALOW POWER DIGITAL CIRCUITS

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ABSTRACT

The paper presents the design, synthesis, and characterization of the first piezoelectric nanoelectromechanical relays with sub-1-Volt actuation (850 mV). The relays are normally closed and exhibit high mechanical restoring forces at relatively low voltage. This is enabled by (i) employing ultrathin piezoelectric aluminum nitride film (10 nm) with high *c*-axis orientation and controlled residual stress, (ii) demonstrating a relay design with a stress-compensating geometry, and (iii) optimizing the thicknesses of the layers forming a four-layer unimorph actuator. The relays exhibit a very low energy dissipation per switching cycle (46 aJ), an extremely small subthreshold slope (0.015 mV/dec), and a low contact resistance (16 kΩ).

INTRODUCTION

NEMS relays have been proposed as very promising successors or hybrid complements to metal-oxide-semiconductor field-effect transistors (MOSFETs) [1]. The fundamental physics of MOSFETs limit their further scaling due to the sharp increase in static power consumption and the inability to lower the supply voltage below few 100s of milliVolts [2]. NEMS relays, however, have been demonstrated to implement digital logic [3, 4] and memory [5-6] elements with low leakage and extremely steep subthreshold slope. They are also more suitable for harsh environments compared to MOSFETs [7]. Despite these merits, the high voltage presently used to drive NEMS relays (2.5-22 V) stands against their use in ultralow-power applications. Although electrostatic NEMS relays were recently demonstrated to operate at 0.4 V [8], piezoelectric relays with sub-1-Volt actuation have never been reported. Two main challenges stand against achieving low actuation voltage in miniaturized piezoelectric relays: (i) synthesizing ultrathin piezoelectric films with high quality, and (ii) controlling the stress-induced deflection in the multi-layer stack of piezoelectric actuators to maintain few nanometers height switching gaps. An actuation voltage smaller than 1 V could not be achieved even for aggressively scaled piezoelectric NEMS relays which use ultrathin (25 nm) AlN films and ~28 nm switching gaps [9].

This work reports the design and fabrication of normally closed (NC) piezoelectric NEMS relays which exhibit an actuation voltage smaller than 1 V. The relays are formed by the thinnest to date piezoelectric AlN films (10 nm) and use a stress-compensating geometry and an optimized unimorph actuator to maximize the restoring mechanical forces.

RELAY DESIGN AND OPERATION

The NC relay has four terminals: source, drain, gate, and body (see Fig. 1), and is based on piezoelectric unimorph actuators. The relay makes use of a stress-compensating geometry, and consists of three suspended beams placed next to each other (Fig. 1a and b). The center beam carries the piezoelectric actuator and the metal tip (the conductive channel) in the longitudinal direction of the beams while the two outer symmetric beams carry the source and drain bottom contacting metals in the transverse direction. The outer beams are connected together by an insulating layer of AlN, hence forming a folded beam structure surrounding the center actuator

(see Fig. 1c). We refer to this arrangement as a triple-beam structure. From a stress perspective, the triple beam geometry resembles a differential topology. The residual stress and stress gradient of the center beam are an average of the stresses of the outer beams, independently of whether the stresses of the outer beams are equal or different. Consequently, the stress-induced deflection of the center beam is an average of the deflections of the outer beams. This compensates the differences in stresses between the three beams and maintains the nanometer height switching gaps. Note that the relay geometry makes use of curved beams which average the in-plane stresses in *x* and *y* directions simultaneously between the center and outer beams across the whole beams' length. This in turn reduces further the displacement difference due to any stress asymmetry in the three beams. Rectangular beams, however, would compensate only the stress in either *x* or *y* directions. FEA simulations were performed for the proposed triple beam structure under different residual stresses using COMSOL. Fig. 1b shows an example of these results where the left, center and right beams with respective residual stresses of 230, 140 and 35 MPa exhibit comparable deflections.

Figure 1: NC NEMS relays based on the triple-beam geometry: (a) SEM images of as fabricated piezoelectric NC relay using 10 nm thick AlN films; (b) FEA simulation showing the stress-induced deflections for the three suspended beams; (c) cross sections describing the layer stack of the beams and the relay structure.

In NC relays, the tip contacts the source and drain upon releasing the device without any applied voltage (*i.e.* the relay is normally *on* as shown in Fig. 2). In order to achieve that, the residual stresses in the layers forming the beams were reduced, yet kept large enough to yield a higher divergence in the stress levels

of the three beams than the stress margin that can be compensated by the triple beam geometry. This margin depends also on the initial switching gap determined by the thickness of the sacrificial layer. For the switches realized in this work, the residual stresses of the AlN and Pt films were -250 and ± 75 MPa, respectively and the sacrificial layer thickness was 60 nm. To turn off the relay, a small restoring force is required to overcome only the stress asymmetry in the three beams (in addition to surface adhesion), hence a low actuation voltage is expected.

Figure 2: Magnified SEM image of the contact area for a fabricated NC relay. The tip contacts the source and drain upon releasing the device due to asymmetric in-plane stresses.

We performed a FEA simulation to determine the stress-induced z-deflections for the three beams forming the relay shown in Fig. 1a. The analysis made use of the measured residual stress values for AlN and Pt (mentioned above), and assumed a 20% variance in the stress levels between the three beams. An initial gap of 60 nm (the sacrificial layer thickness) was included between the metal tip and the source and drain contacting metals. Also, no contact pair was defined between the tip and the source and drain in order to determine the deflection of the center beam at the contact area. The simulation shows that the z-deflections at the contact area for the left, center and right beams are 2.079, 1.986 and 2.035 μm , respectively (see Fig. 3). In other words, the z-position of the metal tip is 93 and 49 nm below the source (left beam) and drain (right beam), respectively, hence forming a NC relay. The simulation highlights also that if the residual stress of AlN and Pt is reduced to -50 MPa, and the stress variation between the three beams is decreased to 5%, a normally open (NO) relay with 8 nm switching gap can be obtained.

Figure 3: FEA simulation for the residual stress-induced deflections in the synthesized NC relays. The measured residual stresses for the sputtered AlN and Pt films were used in simulation.

The NC relay demonstrated in this study uses a four-layer piezoelectric unimorph actuator (see Fig. 4a). The actuator consists of a piezoelectric film (AlN) sandwiched between two metal electrodes (the gate and body), and bonded to an elastic layer (AlN). Applying an electric field between the body and gate terminals generates a lateral strain in the piezoelectric film. Due to the constraint imposed by the elastic layer, the lateral strain is translated to a transverse moment around the neutral axis of the actuator's stack causing a bending motion. The direction of the electric field across the piezoelectric film determines the bending direction of the actuator. In the synthesized NC relay, the actuator bends in the upward direction upon applying the actuation voltage, which pulls the tip (the conductive channel) far from the source and drain, hence turning the relay off (Fig. 4a). Removing the applied voltage causes the actuator to return to its original position, shortening the source and drain. Thus, the gate-body potential difference is used to create or remove a conducting channel between the source and drain via a metal tip.

Figure 4: Cartoon schematic describing the operating principle of piezoelectric (a) NC and (b) NO relays.

The thicknesses of the elastic layer (the bottom AlN) and the Ti/Pt electrodes forming the piezoelectric unimorph actuator were optimized to maximize the electromechanical coupling. As a result, the synthesized NC relay exhibits high mechanical restoring force at relatively small voltage. Therefore, a low actuation voltage can be achieved. This analysis was performed using FEA simulation and a complex analytical model that considers all layers in the actuator stack [10]. Here it is worth mentioning that the optimization goal of the unimorph actuators used to realize NC and NO relays is different. In NC relays, the initial switching gap, g_0 , is 0 nm (i.e. the relay is in the *on* state as fabricated as highlighted in Fig. 4a). The thicknesses of the layers forming the actuator are optimized to result in a maximum restoring force in order to break the contact during the opening of the relay at small voltages. In a NO operation (Fig. 4b), the initial g_0 is larger than 0 nm, and the actuator has to close this gap to turn the relay on. In this case, the thicknesses of the actuator's layers are selected as a compromise between generating maximum displacement and maximum contact force. This is required to assure that the relay can be turned on using a small voltage while exhibiting a low contact resistance.

FABRICATION PROCESS FLOW

The relays were fabricated using a seven masks process as described in Fig. 5. The most critical and new step in the process with respect to what was reported in [9] was the reactive sputtering of highly *c*-axis oriented 10 nm thick AlN films with controlled

residual stress over ultrathin Pt layers (5 nm). A two-step deposition recipe was developed to sputter AlN using a dual cathode S-Gun magnetron source. Each step exhibited a different process work point on the hysteresis curve of the magnetron discharge via changing the N₂ and Ar partial pressures to provide better conditions for AlN nucleation on the ultrathin Pt surface. The in-plane stress of the AlN films was controlled via modifying the Ar flow gradually during the reactive sputtering process.

Figure 5: The fabrication process described at the cross section M1-M2 shown in Fig 1a: (a) Sputter 10 nm AlN seed layer on (100) Si substrate, sputter and pattern Ti/Pt (2/5 nm) layers using lift-off to define the actuator's bottom electrode; (b) deposit 10 nm piezoelectric AlN film using reactive sputtering, open vias (not shown) in the AlN using the AZ400K developer to access the bottom electrode; (c) deposit and pattern Ti/Pt layers to define the actuator's top electrode and the source and drain; (d) define the lateral dimensions of the relay by AlN etching using Cl₂/BCl₃/Ar chemistry; (e) sputter and pattern a sacrificial layer of amorphous Si (60 nm) by lift-off, deposit and pattern a Pt layer via lift-off to define the tip and contact pads, define release openings using a photoresist mask; (f) etch the sacrificial layer and the Si substrate using XeF₂ to release the relay and remove the photoresist by plasma ashing.

Figure 6: HRTEM image showing the layer stack of the piezoelectric unimorph actuator used to realize the NC relays.

Cross-sectional high-resolution transmission electron microscopy (HRTEM) image of the four-layer piezoelectric actuator used to realize the NC relays is shown in Fig. 6. The image highlights the high *c*-axis orientation and the fine columnar grain structure of the synthesized 10 nm AlN films. This can be observed for the piezoelectric film (top AlN) as well as the elastic layer (bottom AlN). Moreover, the arrangement of the lattice planes in the grown ultrathin AlN film can be seen, and emphasize the continuous lattice microstructure within a single grain from the AlN/Pt interface up to the film surface. The full width at half maximum (FWHM) of x-ray diffraction rocking curve measurements around the diffraction peak of AlN (0002) for the sputtered 10 nm films is 4.7°. Also, the deflection profiles of the synthesized four-layer unimorph actuators were measured under different applied voltages using an optical profilometer. These measurements were fitted to the computed deflections from the analytical model in [10] in order to calculate the d_{31} piezoelectric coefficients for the sputtered piezoelectric films. The extracted d_{31} coefficient for the synthesized 10 nm AlN films is -1.75 pC/N, which is 91% of the reported d_{31} value for 1 μm thick and highly oriented AlN films. This clearly highlights the significance of the developed two-step recipe for the reactive sputtering process.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 7a presents typical I-V measurements for the synthesized NC relays based on 10 nm thick piezoelectric AlN films. The measurements were done in ambient air using the body-biased actuation method [11]. The shown turn-off voltage sweeps were recorded while the body terminal was biased using different voltages. The role of the bias applied to the body, V_B , is to increase the mechanical restoring force of the actuator (see Fig. 1 and 4a) so that a small complementary voltage applied to the gate terminal (V_G) can break the contact and turn the relay off. The gate voltage at which the relay is turned off is called the threshold voltage, V_{th} . As shown in the figure, V_{th} can be precisely tuned and reduced to few millivolts via adjusting V_B . The relay exhibits an actuation voltage ($V_{act} = V_{th} - V_B$) of 850 mV and a source-drain resistance of 16 kΩ (Pt-to-Pt contact).

The average V_{th} measured under different V_B for the demonstrated NC relays is plotted in Fig. 7b. The linear dependence of V_{th} on V_B is obvious. For comparison, the measurements of a NO relay which uses 25 nm thick piezoelectric AlN film and 28 nm switching gap is also plotted in the figure [9]. Thanks to the scaling of the AlN film thickness to 10 nm and the proposed NC design demonstrated in this work, the relays exhibit an actuation voltage smaller than 1 V compared to 1.6 V for the NO relays. A comparison between the synthesized NC relays in this study and prior work on NO AlN relays is summarized in Table 1. The sub-1-Volt actuation of the NC switch designated as S1 comes with more than 3X reduction in the relay active area compared to S2, the NO relay that used 25 nm AlN films. The NC relays exhibit also a very high I_{on}/I_{off} ratio (10^8) and an extremely small subthreshold slope (0.015 mV/dec), three orders of magnitude smaller than what is achieved by state-of-the-art MOSFETs.

The extremely small data dispersion in the measured V_{th} at a given V_B for the demonstrated NC relays (Fig. 7b) indicates the weak influence of the contact's surface adhesion on the switching process (*i.e.* negligible hysteresis). Moreover, the precise control of V_{th} in the range of few millivolts highlights the possibility of performing the switching function with just few millivolts. The NC piezoelectric relays demonstrated here have superior performance compared to the reported sub-1-Volt electrostatic relays [8] which exhibit unstable I-V characteristics and a high subthreshold slope

of 10 mV/dec. The NC relays have a relatively small actuator's footprint and an extremely small V_{th} , which lead to a greatly reduced switching energy. For example, when $V_G = 10$ mV (more than one order of magnitude larger than the minimum V_{th} shown in Fig. 7a), the computed energy consumed per switching event is 46 aJ. This calculation assumes charging and discharging of an equal size gate. However, the active area of the NC relays is much larger than the active area of MOSFETs. A scaling analysis of AlN relays shows that the footprint of these devices could be reduced to 0.16 μm^2 if 1 nm thick piezoelectric AlN films were to be used. In this case, the actuation voltage could be scaled to 41 mV.

Figure 7: (a) The turn-off voltage sweeps of piezoelectric NC relays measured in ambient air using the body-biased method. The source-drain potential difference, V_{DS} , was 100 mV, and the minimum used V_G step was 0.1 mV. (b) The average measured V_{th} at different V_B for the demonstrated NC relays. The results of prior work on NO relays which use 25 nm AlN piezoelectric films is also plotted for comparison.

CONCLUSION

We demonstrated normally closed NEMS relays which use a stress compensating structure and 10 nm thick piezoelectric AlN films. The relays are the first to exhibit an actuation voltage smaller than 1 V, and are capable of performing reliable switching with just few millivolts thanks to their extremely small subthreshold slope. The active area and actuation voltage of the demonstrated NC relays are respectively three and one orders of magnitude smaller compared to the normally open relays formed by 250 nm thick piezoelectric AlN films. These results clearly

highlight the significant potential of scaling the AlN film thickness as well as employing the NC relay geometry. We believe this work has paved the way toward building ultralow-power microprocessors and low voltage memories.

Table 1: Summary of the measured data for the demonstrated NC relays and a comparison to prior work on AlN relays. The switches are referenced as S1, S2 and S3. Note that S is the subthreshold slope and R_c is the source-drain resistance. The contact area of S1 is 2.4 μm^2 .

Switch (NC or NO)	S1 (NC) This work	S2 (NO) [9]	S3 (NO) [11]
t/g_0 (nm)	10/0	25/28	250/400
V_{act} (V)	0.85	1.63	8.45
Active area (μm^2)	58	187	40000
I_{on}/I_{off}	10^8	10^7	10^7
S (mV/dec)	0.015	0.033	0.065
R_c (kΩ)	16	5.14	0.02

REFERENCES

- [1] O. Y. Loh and D. E. Horacio, "Nanoelectromechanical contact switches," *Nature Nanotech.*, vol. 7, pp. 283-295, 2012.
- [2] S. G. Narendra and A. Chandrakasan, "Leakage in Nanometer CMOS Technologies," Springer, New York, 2006.
- [3] J. Jeon, V. Pott, H. Kam, R. Nathanael, E. Alon, and T. J. K. Liu, "Perfectly complementary relay design for digital logic applications," *IEEE Electron. Dev. Lett.*, vol. 31, pp. 371-373, 2010.
- [4] R. Proie, R. Polcawich, J. Pulskamp, T. Ivanov, and M. Zaghloul, "Development of a PZT MEMS switch architecture for low-power digital applications," *J. of Microelectromech. Syst.*, vol. 20, pp. 1032-1042, 2011.
- [5] K. Akarvardar and H. S. Wong, "Ultralow voltage crossbar nonvolatile memory based on energy-reversible NEM switches," *IEEE Electron. Dev. Lett.*, vol. 30, pp. 626-628, 2009.
- [6] W. Xiang and C. Lee, "Nanoelectromechanical torsion switch of low operation voltage for nonvolatile memory application," *Appl. Phys. Lett.*, vol. 96, Art. # 193113, 2010.
- [7] T. Lee, S. Bhunia, and M. Mehregany, "Electromechanical computing at 500°C with silicon carbide," *Science*, vol. 329, pp. 1316-1318, 2010.
- [8] J. O. Lee, Y. H. Song, M. W. Kim, M. H. Kang, J. S. Oh, H. H. Yang, and J. B. Yoon, "A sub-1-volt nanoelectromechanical switching device," *Nature Nanotech.*, vol. 8, pp. 36-40, 2013.
- [9] U. Zaghloul and G. Piazza, "10–25 nm piezoelectric nano-actuators and NEMS switches for millivolt computational logic," in *Digest Tech. Papers MEMS'13 Conference*, 2013, pp. 233-236.
- [10] D. L. DeVoe and A. P. Pisano, "Modeling and optimal design of piezoelectric cantilever microactuators," *J. Microelectromech. Syst.*, vol. 6, pp. 266-270, 1997.
- [11] N. Sinha, T. Jones, Z. Guo, and G. Piazza, "Body-biased complementary logic implemented using AlN piezoelectric MEMS switches," *J. of Microelectromech. Syst.*, vol. 21, pp. 484-496, 2012.

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