100nm Thick Aluminum Nitride Based Piezoelectric Nano Switches Exhibiting 1mV Threshold Voltage Via Body-Biasing

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ABSTRACT

This paper reports on the first demonstration of aluminum nitride (AlN) piezoelectric logic switches that were fabricated with ultra-thin (100nm) AlN films and exhibit a 1 mV threshold voltage via the body-biasing scheme. The application of a relatively low (< 6 V) fixed potential to the body terminal of a 4-terminal switch has resulted in a repeatable threshold voltage of 1 mV. The nano-switch has been cycled to > 10⁹ cycles and, although the contact resistance was found to be high (~ 1 MΩ), the nano-films have functioned throughout to show high piezoelectric nano-film reliability.

INTRODUCTION

With the continuous scaling of the transistor the CMOS industry has recognized the emergence of some key problems that are proving to be serious obstacles to further miniaturization. Some of the major hurdles that need to be overcome involve the source-to-drain leakage in the standby state, the gate leakage because of ultra-thin dielectric layers, the inability to reduce operating power, the variation of threshold voltages over a wafer and the increasing effect of parasitics on the device performance. With miniaturization, transistors have become faster, but the gain in speed has come at a penalty in terms of standby power consumption. Also, with the CMOS transistors already switching in less than few nanoseconds, power is becoming a more relevant aspect to consider than speed. Keeping all these factors in mind the International Technology Roadmap for Semiconductors (ITRS) [1] has emphasized the need to develop alternate devices, like NEMS switches, that will consume less power in the standby state and will help in minimizing the transistor operating voltages.

Mechanical switches have been a topic of research and investment for few decades. They have nearly zero standby leakage due to the presence of an air gap between the source and the drain terminals. In addition, they are characterized by a very sharp transition between their standby and on states. This transition is not governed, as in a semiconductor, by the modulation of carriers in the channel, but by the actual mating of contacts due to mechanical motion. Therefore, mechanical switches exhibit a subthreshold slope that is orders of magnitude lower than that of CMOS devices. Because of these characteristics they are the ideal candidate to lower power consumption in the standby state and operating voltages. Most of the mechanical switches developed to date have utilized electrostatic [2-3], magnetic [4], thermal [5] or piezoelectric [6-9] actuation mechanisms. These mechanical switches have not been commercialized on a large scale as they are not as reliable and as fast as the semiconductor transistors. Micromechanical switch reliability has been limited by the very stringent requirements on the on-resistance as dictated by radio frequency (RF) applications (i.e. few Ohm of contact resistance), which have so far been the most attractive for microswitches. When we consider the same devices for implementation of mechanical computing/logic, the main design challenge resides not in the loss due to the contact resistance but the speed of operation. According to these new guidelines a mechanical switch can operate with contact
resistances in excess of 10 kΩ, therefore significantly relaxing the
dependability challenges that exist with hot switching of large currents.
Nonetheless, significant issues arise from the miniaturization of the
mechanical switches to achieve higher frequencies of operation
(approaching 100s of MHz).

For these reasons, there has been a renewed interest in the
development of fast electrostatic [10-12] and piezoelectric [9, 13-
14] nano switches. These implementations have utilized the
concept of a 4-terminal device for tuning the threshold voltage of
the switch and reducing the dynamic power consumption. Figure 1
shows an SEM of a piezoelectric nano-switch and highlights its
similarity with a 4-terminal MOSFET. Though electrostatic
actuation has been the most common method of implementing
mechanical switches, we have used piezoelectric actuation as it is
linear and can easily produce a pull-off force. Amongst the
various piezoelectric materials being commonly used for research,
Luders Zirconate Titanate (PZT) and AlN have already been
employed for fabricating mechanical switches [6-9]. Nonetheless,
PZT has the drawback that it is incompatible with present day
CMOS foundries. AlN, on the other hand, is post-CMOS
compatible, has higher dielectric strength, is amenable to scaling to
the nano-dimensions [15] and is easy to process. AlN MEMS
switches have already been used to demonstrate logic elements like
NOT [13], NAND and NOR [14] gates and prove the concept of
body biasing in 4-terminal piezoelectric devices.

The mechanical switches presented in this work have structural
AlN layers that have been scaled in thickness to 100 nm,
showing a subthreshold slope (~0.033 mV/dec) and the ability
to operate at lower supply voltages than CMOS. The use of low
supply voltages translates in greatly reduced power consumption with energy per operation in the order of few tens of nJ. The AlN
film is an order of magnitude thinner than the film used for
making switches in [13], operate with lower body-biasing voltages
(6 vs. 20 V), and especially are capable of a threshold voltage of
1 mV (w.r.t. to 30 mV in [13]). The demonstration of these nano-
switches represents a significant step forward towards the
implementation of ultra-low power mechanical computing.

![Figure 2: The zoomed-in SEM of the cross-section of the nano-
actuator shows the AlN nano-films (100nm thick) and the
sandwiching Pt films (50nm thick).](image)

**NANO-SWITCH AND BODY BIASING**

The piezoelectric switch shown in Fig. 1 is a miniaturized
version of the switch implemented earlier in [7, 13-14]. It is a
two-finger dual beam switch that has been fabricated using two
layers of 100 nm thick AlN sandwiched by three layers of 50 nm
thick Platinum (Pt) (Fig. 2). The AlN nano-films have been
deposited by Tegal Corporation, CA. The authors, in collaboration
with Tegal Corp have already demonstrated that the piezoelectric
properties of 100 nm AlN nano-films are comparable to those of
thicker AlN films. [15].

The switches presented in this work have been fabricated using
an 8-mask process on silicon wafers that is based on the
same steps presented in [14].

In this work, the scaling of the AlN films and the
consequently improved control over the actuation voltage has
enabled us to demonstrate a decrease in the threshold voltage of
the switches. This threshold voltage control has been achieved by
employing the body-biasing method [13-14]. Figure 3 explains
how the body biasing scheme can be used for accurate control of
the threshold voltage. In Fig. 3(a), the commonly used grounded
actuation mode (body terminal grounded) is shown. In this mode
the V_{th} and the Ground are able to generate the electric field
desired for actuation in the piezoelectric film. This same electric
field (as shown in Fig. 3(b)) can be obtained by fixing a bias
voltage on the set of electrodes that are grounded in Fig. 3(a). By
introducing this body-bias the required electric field for actuating
the switch is achieved by applying or gate voltage of just +100 mV
on the set of electrodes that required a gate voltage of V_{th}
in Fig. 3(a). In this example, the threshold voltage was selected to
be 100 mV, but can be adjusted to any arbitrary value by controlling
the value of the body-bias, as shown in [13-14].

In this work, V_{th} was controlled to be 1 mV. Achievement of a
1 mV threshold voltage is greatly attributed to the scaling of the
film thickness and the subsequent decrease in the required body-
biais voltage. Switches fabricated with 100 nm AlN films need a
body bias ≤ 6V whereas the devices made with 1 µm AlN needed a
bias of ≤ 20V [13] for low threshold voltage actuation. In this
specific demonstration, the change in electric filed caused by 1 mV
is ~ 30 times higher for the 100 nm AlN film based switches than
for the switches that use the thicker 1 µm AlN [13]. The higher
sensitivity of electric field to voltage variations is enabled by the
scaling of the film thickness, which simultaneously help in
reducing the body bias voltage and increase the degree of control
over actuation.

![Figure 3: Schematic representation of (a) grounded actuation
mode and (b) body-biased actuation mode.](image)

**EXPERIMENTAL RESULTS**

The device threshold voltage was measured by monitoring the
change in contact resistance while varying the gate voltage. An
Agilent E3631A DC power supply was used to apply the body-bias
voltage. An Agilent 34401A multi-meter and an Agilent 33250A
function generator were both controlled using LabView to step
through different voltages so as to study the variation of contact resistance with respect to gate voltage and applied body-bias.

Figure 4 shows the variation of the $V_{th}$ achieved by changing the body-bias. The plot shows that a threshold voltage of 1 mV has been measured. Switching occurred when the contact resistance suddenly increased to a value that was out of the range of measurement of the multi-meter. The open state value was assumed to be greater than 1 GΩ according to the specifications of the available multi-meter. From the same experiment, a value of < 0.033 mV/dec can be estimated for the subthreshold slope. This extracted subthreshold slope is comparable to those measured on similar micromechanical switches. The variation of the threshold voltage displayed in Fig. 4 is the first experimental validation that body-biasing functions, as expected, in AlN nano-films.

The nano-switch was also subjected to reliability testing to study the effect of fast and long term cycling on the Pt-Ti-Pt contact and the nano-piezoelectric film. The resonance frequency of the actuator beam was derived to be ~ 110 kHz by means of finite element analysis in COMSOL Multiphysics. For the purpose of rapidly testing for a large number of cycles the beams were
actuated above their resonance frequency, but far from any higher order modes. This was done to minimize the cross-coupling between the intended mode of actuation and other higher order modes of vibration.

Figure 5 shows the results of reliability testing of the switch operated at 500 kHz with a body-bias of 4.6 V and a square wave form of ± 2 V up to 750 million cycles. Cumulatively, the switch was tested for > 10⁷ cycles after which it failed in the closed position. This data shows that the piezoelectric nano-film functioned throughout the testing demonstrating very high nano-film reliability. Contact reliability greater than 10⁹ cycles will have to be demonstrated. Investigations on the contact wearing and its tribological properties are ongoing.

CONCLUSIONS
In summary, the first AlN piezoelectric switches that employ 100 nm thick AlN films have been demonstrated. These switches validate the use of the body-biasing technique at the nano-scale. As the thickness of the films has been scaled to the nano-dimensions the body bias voltages have been lowered to < 6 V and a better control over the actuator motion has been demonstrated. This enhanced control over switching translates into a threshold voltage of ~ 1 mV and the ability to potentially operate with supply voltages of few 10s of mV. Such supply scaling translates in several orders of magnitude reduction in active power consumption. Further scaling of these devices in the lateral dimensions will lead to the development of nanomechanical logic elements that have very low capacitance and reliably operate with extremely low supply voltages.

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