Design and Fabrication of Aluminum Nanoelectromechanical Switches

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Abstract:

In integrated circuits, nanoelectromechanical (NEM) switches are advantageous because they have nearly zero power dissipation in their off state. An energy recoverable design that stores elastic energy in the mechanical switch can further lower operating voltage. In this project, we constructed a lateral cantilever beam that switches between two symmetric sense electrodes (drains) when voltage is applied to two symmetric drive electrodes (gates). To avoid conductivity issues of silicon beams, we used aluminum to construct our device on a quartz substrate. Silicon was used as a sacrificial release layer for the aluminum. Though we were not able to finish fabricating a device, we ultimately aim to use our design to achieve a significant decrease in switching voltage as compared to a traditional NEM switch.

Introduction and Background:

Currently, most logic operations in electronic devices are performed by transistors, which dissipate power in their off state. As transistors have gotten smaller, this power leakage problem has resulted in large amounts of wasted energy [1]. Nanoelectromechanical (NEM) switches provide lower power alternatives to transistors by taking advantage of mechanical properties to reduce the two main components of standby power dissipation: I_{off} (off-state current) and V_{DD} (operating voltage).

Figure 1 shows our NEM switch design, consisting of a cantilever beam, a source electrode, and two sets of gate and drain electrodes. The beam switches to a drain due to an electrostatic force once a sufficiently high voltage, $V_{pull\text{-}in}$, is applied to the corresponding gate. When the gate voltage is lowered, the beam stays attached to the drain due to attractive surface forces until it releases at some lower $V_{pull\text{-}out}$. Because the beam is physically detached from the drain when it is not pulled in, I_{off} is zero.

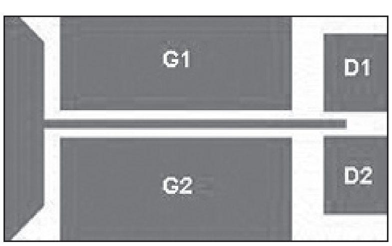

Figure 1: Generalized design for a lateral cantilever beam switch, with a source electrode and two gates (G) and drains (D).

To further reduce power dissipation, parallel electrode designs take advantage of energy recoverable operation (ER) [2]. To understand ER, consider a swing set (Figure 2): initializing a swing from rest requires pulling it with a certain force F1. After release, one can hold it at the other side using a greatly

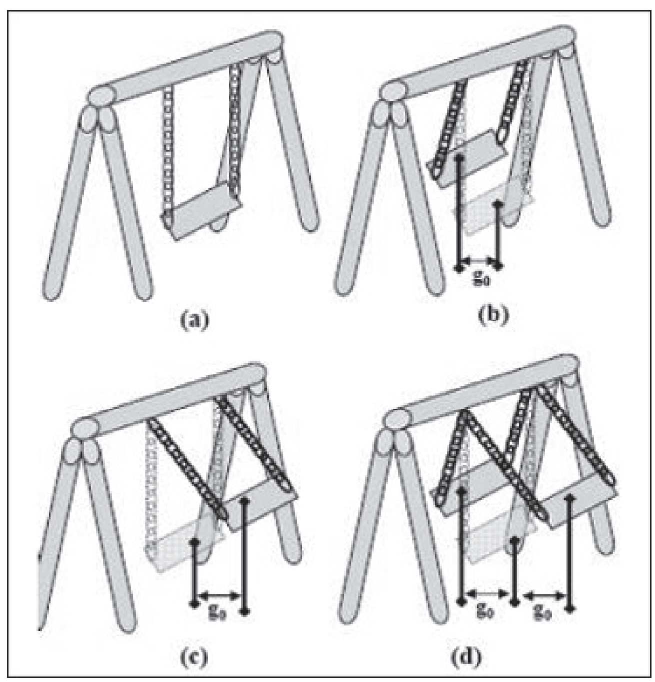

Figure 2: Swing set analogy for energy recoverable operation of lateral NEM switches.

reduced force F2 << F1. Similarly, a parallel electrode switch is initialized to one drain at a relatively high $V_{pull\text{-}in}$. Stored elastic energy switches the beam to the opposite drain at $V_{pull\text{-}out}$, where the beam can be held at a lower V_{hold} << $V_{pull\text{-}in}$. In other words, after initialization, our switch operates at significantly reduced V_{DD}.

Previous switches fabricated with this design used silicon as the structural layer. However, silicon forms a layer of insulating oxide when exposed to air, whose thickness requires significantly higher drain biases, decreasing energy efficiency. We used aluminum, which forms thinner, self-limiting native oxide layers. Aluminum is also a metal, whose conductivity makes it easier to pass current. Further, aluminum processes are low-temperature and back-end-of-line (BEOL) compatible, broadening the range of applications for these devices.

Procedure:

We first designed a lithography mask of an array of devices that varied beam-to-gate overlap (12 to 19.5 μm) and beam-gate gap (500 or 600 nm). Simulation of our standard device using a parallel plate model showed that as beam-to-gate overlap increases, switching time increases, whereas pull-in voltage decreases.

To fabricate, we deposited a sacrificial polysilicon layer on top of a quartz substrate. We used metal sputtering to deposit 0.7 μm of aluminium, which we patterned with photolithography and etched using a chlorine-based reactive ion etch. Photoresist was removed with a piranha clean and our devices were released dry using xenon difluoride.

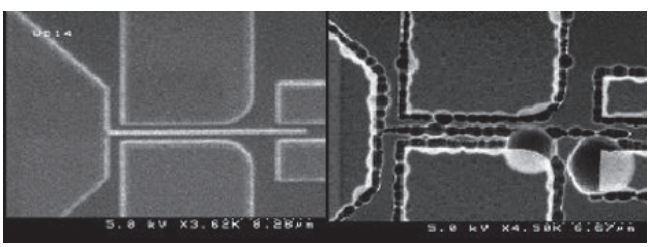

Figure 3: SEM image of unreleased device (left) versus device after 72 seconds of xenon difluoride release (right).

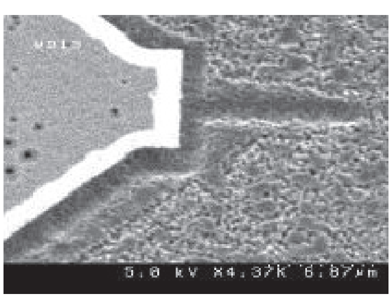

Figure 4: SEM image of device without beam after 90 seconds of xenon difluoride release.

Results:

We were unable to successfully release an aluminum device because our structural layer was etched away after exposure to xenon difluoride. Scanning electron microscope (SEM) images of two devices show that the aluminum layer begins being eaten away at 72 seconds of release (Figure 3) and the beam disappears completely after 90 seconds (Figure 4).

Discussion and Future Work:

Our results were unexpected because xenon difluoride should not attack aluminum. We initially suspected that the release step, which is highly exothermic, melted away the aluminum. However, running the release with less heat by adding nitrogen flow and delays between etching cycles yielded the same results. The most plausible explanation is that the structural layer deposited was not 100% aluminum, but a mixture of aluminum and silicon.

Once we fabricate successfully released devices, we will test them by ramping gate voltage and looking for the voltage ($V_{pull\text{-}in}$) at which current starts to flow between the beam and the corresponding drain. We will then sweep the voltage in the other direction to see when the drain current returns to zero, indicating pull-out.

Conclusion:

Aluminum NEM switches with cantilever beams laterally situated between parallel electrodes can greatly reduce both active and standby power dissipation. We modeled, designed, and fabricated such devices. However, we were unable to release a device; future work will involve determining why the xenon difluoride release step was unsuccessful. Ultimately, we hope these devices can use energy recoverable operation to run on significantly reduced voltages.

Acknowledgements:

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References:

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[2] Akarvardar, K., D. Elata, R. T. Howe, and H. S. P. Wong; "Energy-reversible complementary NEM logic gates"; Device Research Conference, pp. 69-70 (2008).