Design of a Nano-mechanical Beam Based Memory Element

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ABSTRACT

A cantilever beam based memory element is proposed which can trap static charge on a metal plate on the beam. The charge is transferred by tunneling to the metal plate from an electrode separated from it by a layer of insulation. The ON condition is represented by the deformed state of the beam when charge is placed on it and the OFF condition is represented by the relaxed state when charge is removed. Hence, the write and erase operation are performed using electrostatic actuation and the read operation is performed using piezoresistive sensing. In addition to the design and operation, the scaling aspect of the element is discussed to facilitate the fabrication of the device. Some of the advantages of this device include better speed as compared to conventional memory devices, better area density and lower power consumption.

Keywords: cantilever, mems, memory, nems

1 INTRODUCTION

Efforts to make non-volatile memory (NVM) speeds comparable to that of random access memory in order to improve processing time, have led to research and development of new types of memories with smaller dimensions, faster operation times and requiring lower power. Current Nonvolatile solid state devices have slow read and write times and require large voltage to operate. Newer technologies like Magneto resistive RAM (MRAM) [1] have faster read/write cycles of 30ns and 5ns and provide significantly higher write cycles in comparison to flash memories[2][3] but suffer from scaling limitations to higher densities. Electromechanical memories offer the advantage over conventional electronic memories in terms of charge isolation and power consumption.

A mechanical cantilever based memory element is proposed here to provide significantly faster write speeds and higher charge isolation. Aimed to comply with the International Technology Roadmap for Semiconductors (ITRS) [4] emerging memory device predictions, the device promises a significant improvement over existing non-volatile memories. However, fabrication with existing techniques is a challenge because of limitations in creating gap and metal layers of the order of few nanometers.

2 DESIGN AND OPERATION

The device consists of a SiO_2 cantilever beam. Electrostatic actuation of the cantilever beam is used to write and erase a bit value into the cell and piezoresistive sensing to read out the state stored in it. It is bistable (in states A or B) depending on presence or absence of charge as shown in figure 1.

The beam anchor consists of a Metal-Insulator-Metal-Insulator-Metal (Al-SiO_2-Al-SiO_2-Al) junction, with the middle metal electrode running along the length of the beam as shown in figure1. This structure allows charge to be placed on the beam by tunneling when a voltage is applied across the outer two plates. By allowing the thickness of the insulator between upper and middle electrodes to be small, charge can tunnel through the oxide between them. The thickness of the oxide between lower and middle plates is made large, and as a result, charge cannot tunnel through the thick oxide. Two electrode plates GND and V_{ACT} shown in figure1, serve to supply ground and actuation voltage. A folded piezoresistive strip on the top of the beam is used to sense the state of the device.

Charge is trapped on the metal plate at the bottom of the beam structure by tunneling through the metal-insulator-metal junction similar to floating gate junc-

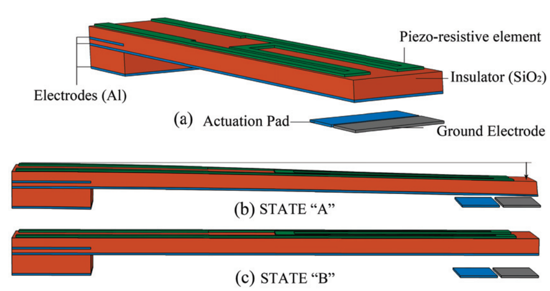

Figure 1: (a)The basic design of the nano-mechanical memory element with two states (b)deformed state - A and (c)relaxed state - B

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Table 1: Parameters for different scaled models of the cantilever memory element simulated in MATLAB

Parameters, Dependence on scaling	Scale factor,α=1	Scale factor,α=5	Scale factor,α=10
Length of beam, L_{beam} (in nm), α	120	600	1200
Width of beam, W (in nm), α	20	100	200
Thickness of beam, t (in nm), α	4	20	40
Gap in the structure, g (in nm), α	5	25	50
Length of the electrodes, L_{el} (in nm), α	10	50	100
Length of the tunnel area, L_{tunnel} (in nm), α	6.11	30.5	61.1
Maximum Stress in the device, σ_{max} (in MPascal), 1	104.16	104.16	104.16
Spring constant, K (in N/m), α	0.0139	0.0694	0.1389
Force to move to state A, F (in pN), α^2	34.7	868	3470
Charge on the beam, Q_{beam} (in C), α^2	4.42×10^{-18}	1.11×10^{-16}	4.42×10^{-16}
Isolation Capacitance, C_{iso} (in F), α^2	7.08×10^{-19}	1.77×10^{-17}	7.08×10^{-17}
Pull-in Voltage, $V_{pull-in}$ (in V), $\sqrt{\alpha}$	0.19	0.42	0.6

tions used in FLASH memories [5]. This trapped charge induces charge of opposite polarity on the ground plate causing electrostatic attractive force to act on the beam, thereby elastically deforming it. This represents state A. It should be noted here that, in this state, the air gap between the beam and the bottom electrode is not closed completely. When enough voltage V_{ACT} is applied on the actuating plate, electrostatic force pulls in the beam further down, closing the air gap completely. The free end of the beam makes contact with the GND plate, discharges instantaneously and the beam relaxes to its un-deformed state (state B). The instantaneous contact of the beam with the ground electrode leads to the flow of all the charges from the beam making the restoring mechanical force as the only force acting on the beam. Thus the contact and stiction effects can be assumed to be negligible.

3 MODELING AND ANALYSIS

As the two states A and B of the device can be represented mechanically in terms of the beam being deformed and not deformed, it is required that the device operate in the linear elastic regime, that is much below the maximum allowed linear strain.

When charge is placed on the beam and deformed at equilibrium, the beam tip is displaced by half of the gap. Two equal and opposing forces act on it are the electrostatic attractive force between the beam and the GND plate (modeled as a point force, neglecting fringing fields), and the restoring mechanical force (for which the cantilever may be modeled as a lumped second order spring mass system). This gives, for a cantilever of given dimensions, the charge on the beam interacting with the GND electrode to keep it in equilibrium. This charge in turn sets tunneling (writing) parameters like tunneling area, tunneling time and voltage applied across the tunnel junction. It can be modeled as follows in a direct tunneling regime.[6]

$$J = AE_{ox}^2 e^{\frac{-B\left[1-(1-\frac{V_{ox}}{\phi_b})^{3/2}\right]}{E_{ox}}} \quad (1)$$

where ϕ_b is the tunneling barrier and A = 1.248 x 10^{-6} A/V^2 and B = 2.334 x 10^{10} Vm^{-1} for Al-SiO_2 junction are dependent on the barrier potential and the effective mass in the oxide. The write voltage is determined by the electric field, E_{ox} as V_{write} =E_{ox}d, where d is the separation distance between the electrodes.

In order to discharge and relax the beam, voltage applied on the actuating pad to snap the beam onto the GND plate has to be slightly greater than the pull-in voltage which depends on the gap, GND electrode area and the spring constant of the cantilever.

For sensing the state of the device, piezoresistive effect is chosen because of ease in fabricating and integrating. A zigzag pattern over the area with maximum stress helps in amplifying the signal for finding the amount of deformation in the beam. Strain in the beam causes change in the resistance of the piezoresistive layer, used to sense the state of the system.

Doped Silicon is used for piezoresistive sensing because of its large gauge factor G and resistivity (ρ). It is taken that the single crystal silicon layer can be fabricated on the beam along the (1 1 1) plane, and the strain and current are observed along the $\langle 111 \rangle$ direction [7]. For the device with a scaling factor of 1, the resistivity of lightly doped silicon with Boron (1 x 10^{20} m^{-3}) is 1.33 Ohm-m [8] and gauge factor as 120 units [9].A change of 1.2 x $10^{10}\Omega$ resistance is observed for a resistance of 1.33 x $10^{11}\Omega$ for the same. The sensing amplifiers in the memory device are assumed to be sensitive enough to resolve change in current because of the change in this resistance.

3.1 Scaling

The proposed device dimensions with the $\alpha = 1$ has the dimensions in the order of few nanometers which makes it difficult to fabricate using the available technologies. A scaled up model of the same however can be fabricated by a scale factor,α to reach a desired dimension. However the tunneling junction is not be scaled due to the exponential dependence of the amount of charge on the thickness of the insulator. A scaling in the tunneling area takes care of the extra charge that should be accumulated on the beam to have a scaled electrostatic force on the beam.A few scaled models of the device were simulated using MATLAB so as to match with the technology available. The scaled models along with the different expected characteristics are listed in the table 1. The length parameters of the device and the spring constant, K of the beam are observed to scale linearly. The charge on the beam, force experienced by the beam to move to state A and the isolation capacitance are observed to increase by a α^2. The pull-in voltage required to move to state B scales by $\sqrt{\alpha}$.

3.2 Timing

The time taken to write state A in the cell depends on the time required for tunneling charge onto the plate and the time to deform the beam. Although the two events occur simultaneously, a worst case estimate is given by the sum of the time for the two events as shown in equation 2

$$t_{write1} = t_{tunnel} + t_{deformation} \quad (2)$$

The tunneling time however, dominates the write-1 time. For the device presented, it fixed at 1ns and the time to deform the beam into state A is for various scaling factors. The beam deformation time depends on the size of the beam, and is smaller for smaller device sizes. The results for the dynamic response of the beam loaded in state A, for two cases where the beam is scaled proportionally in all dimensions with scaling factors 1 and 10 is presented in figure2 for devices of different quality factors. Even for the device of length 1.2um, it is observed that its settling time is smaller by at least an order of magnitude than the time required for tunneling.

FLASH memories by comparison are slower because of the time required for tunneling for both write and erase operations. In the proposed device however, the discharge time is much smaller as it does not require tunneling and hence advantageous over conventional charge trapping memory devices. It depends only on the time to mechanically move the beam to close the air gap and relax, and hence it is a function of the voltage applied on the actuation pad, V_{ACT} and its natural frequency, w_o which depends on the size.(Equation3)

$$t_{write0} = \sqrt{\frac{27}{32}\frac{\pi}{w_o}\frac{V_{pull-in}}{V_{ACT}}} + \frac{\pi}{2w_o} \quad (3)$$

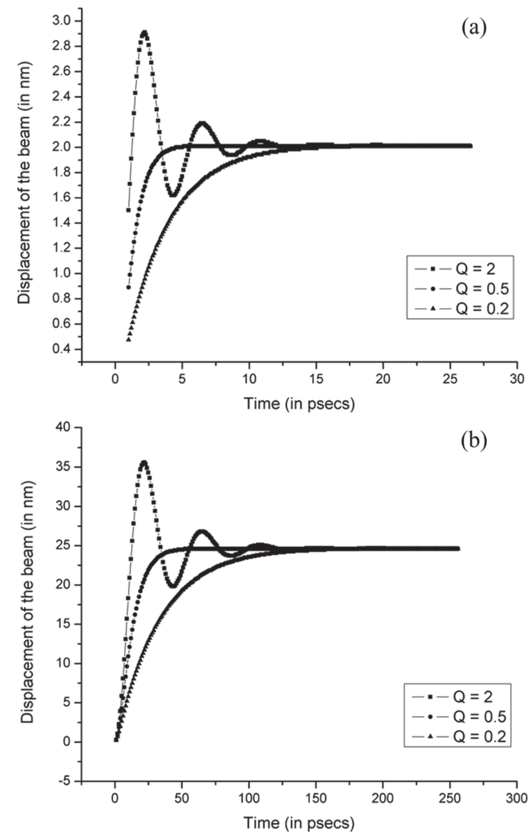

Figure 2: The time response for the cantilever to change to State A, once the charge has been placed on the beam. Time response for device with (a) $\alpha = 1$,(b) $\alpha = 10$

For the device with scaling factor, $\alpha = 1$, time for writing state A is calculated as 1.11 ns with Q of 2, assuming underdamped system to calculate the worst case time. And for writing state B, time required is calculated as 0.335ns. The speed of the sense amplifier is critical for the piezoresistive reading speed of the device.

3.3 Fabrication

The device proposed in the paper is still in its design phase and hence has many fabrication challenges to meet before being fabricated. First, the creation of the cantilever beam needs a well-defined gap of 5 nm above the ground/actuation electrodes. Another concern is the surface smoothness of the metal later below the cantilever after the sacrificial layer is removed. With advancements with Atomic Layer Deposition (ALD), very thin layer of metals can be deposited [10]. However it still remains a challenging step.

Assuming that the fabrication process will get refined over the years to come and it will be possible to overcome these limitations, the fabrication can be achieved by the steps in figure 3.

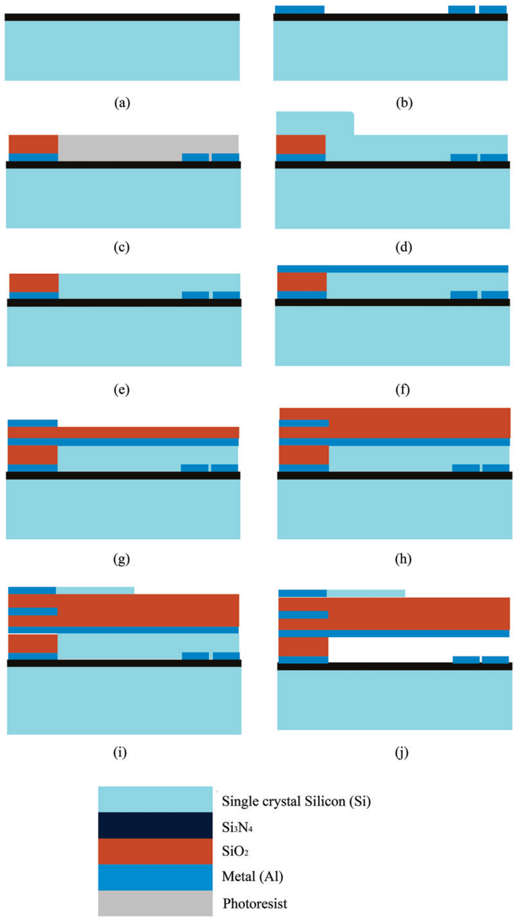

Figure 3: Fabrication steps for the cantilever based memory element. (a) The Silicon wafer is processed and a layer of Si_3N_4 is grown for isolation. (b) A layer of Al is deposited and etched to define the electrodes and actuation pads. (c) A photo-resist is then used to define the pattern for the deposition of SiO_2. (d)After the removal of the photoresist a thin sacrificial layer of Si is deposited. (e) The surface is polished using chemical mechanical polishing (CMP) and (f) a layer of Al is deposited and patterned. (g) SiO_2 is deposited over the structure and Al is again deposited followed by patterning. (h) The surface is then blasted with oxygen plasma and SiO2 is deposited over the structure. (i) Si is deposited along with the metal contacts and doped with Boron ($1x10^{20}m^{-3}$) for the purpose of piezoresistive sensing. (j) The cantilever structure is then released by XeF2 (dry etching)

4 RESULTS AND DISCUSSION

The proposed device promises a faster writing and reading times with respect to the current NVM devices. The major power consuming steps in the device are the tunneling of charges to the metal electrode and the piezoresistive reading of the state of the system. For the tunneling of charge to the electrode, the power is estimated to be 97 nW and the corresponding energy used is 9.7 x 10-17J. Further while reading the state of the beam, for a voltage of 10V, the power consumption is .75 nW.A larger value of read voltage can be used for a better resolution.

Thus the device offers a considerable advantage in performance with respect to the current technologies and can be considered a candidate for future electromechanical memories. The device parameters obtained meets the predictions for electromechanical memory devices given in the ITRS 2011 Emerging Research Devices chapter. [4]

The device proposed is a basic design of a cantilever based memory element based on charge storage and can be improved in many respects. For example, using multiple beams to store the same bit will help achieve higher reliability. Also, the charge retention on the beam for State A can be improved upon by using strips of metal instead of solid metal plate.

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