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Molecular adhesion controlled microelectromechanical memory device for harsh environment data storage

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This work demonstrates a cantilever based electrostatic microelectromechanical system device operating as a memory element. Volatile and non-volatile functions are engineered by manipulating molecular adhesion force through contact dimples and restoring force using the cantilever design. For non-volatile *RESET* operation, a method of detaching the cantilever with 3 V pulsating DC signal at 1 MHz is proposed. *SET/RESET* cycles are performed up to 10^3 times at 300 °C without any performance degradation. A writing speed of up to 0.94 μ s is achieved, which is faster than conventional high temperature flash memories. With demonstrated attributes, the fabricated device offers excellent potential for harsh environment data storage applications. © 2014 AIP Publishing LLC.

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FLASH memory is the mainstream technology for NVM, while other emerging NVM technologies include Resistive RAM (R-RAM), Magnetic RAM (M-RAM) and Phase-Change RAM (PCRAM). The aforementioned NVMs are prone to data loss at higher temperatures (>100 °C).^{1–3} Microelectromechanical systems (MEMS) devices are known to work in harsh environment (extreme temperature/radiation/vibration). Recently, high temperature non-volatile memory operations have been demonstrated using anchored cantilever and teeter-totter MEMS switches.^{4,5} The data retention was obtained through van der Waals force⁶ holding the actuated switch to the contact electrode. Although, desired properties were obtained, both the cantilever and teeter-totter devices used additional electrodes to perform the memory *RESET* operation.

This letter presents a memory device which uses precisely controlled molecular adhesion force for data retention and method for *RESET* operation. The presented *RESET* operation does not require additional electrode and thus saves significant area in device design. The precise control of the molecular adhesion force is achieved by manipulating the total contact area of the cantilever using sub-micron size contact dimples. Volatile and non-volatile memory operations are demonstrated up to 300 °C.

The memory operation is performed on vertically-movable cantilever structure by electrostatic force. Under the applied electrostatic force, the cantilever bent down and touches the contact pad. The cantilever remains in contact position till electrostatic and molecular adhesion force together are higher than the cantilever restoring force. When the electrostatic force is removed and molecular adhesion force is lower than the cantilever restoring force, the cantilever returns to non-contact position and the device operates like a volatile memory. However, with the increase in the cantilever contact area, the molecular adhesion force

overcomes the cantilever restoring force and the cantilever remains in contact with the pad and device operates like a non-volatile memory.

The cantilever is detached from the contact pad by applying a chain of DC voltage pulses to the contact terminal. The pulse based detachment mechanism allows single electrode to execute *SET/RESET* operation and offers a significant advantage in reducing device footprint compared to the double sided electrode structure.⁴ Molybdenum (Mo) is chosen due to its high melting point (2610 °C), robustness, small wear out, and good thermal conductivity.^{7,8} Theoretical formulation is employed to design the volatility and non-volatility function of the memory devices explained in the next paragraph. The experimental results confirm that the molecular adhesion force can be leveraged to develop power efficient MEMS memory (volatile and non-volatile) devices.

The MEMS memory devices consist of three terminals (gate, source, and drain) as shown in Fig. 1(a). The movable cantilever (source electrode) is positioned above the actuation (gate electrode) and the contact (drain electrode) pads. When a potential (greater than cantilever's pull-in voltage) is applied between the source and gate electrodes, the cantilever pulls in to the contact pad. The gate electrode is covered by 50 nm thick aluminum oxide (Al_2O_3) to prevent the cantilever from touching the gate during the pull-in operation. It is assumed that the contact between the source and drain is ohmic due to the pure Mo electrodes. To study the molecular adhesion force effects on the volatility of the MEMS devices, various square dimple structures (contact) are designed at the cantilever's tip as shown in Figs. 1(b) and 1(c). The size of each square dimple is 500 nm $\times$ 500 nm. Four kinds of devices (M1 ~ M4) are designed and their dimensional parameters are summarized in Table I. The parameters are cantilever width (w), actuation length (W), cantilever length (L), cantilever thickness (h), actuation gap (d_0), and the number of dimples.

The device operation (*SET/RESET*) is determined by the combination of three forces (electrostatic forces, molecular

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FIG. 1. An illustration of the cantilever device with (a) the top view, (b) the cross section view of non-volatile memory device with 25 (5×5) dimples and (c) the cross section view of volatile memory device with 9 (3×3) dimples.

adhesion forces and restoring forces). The molecular adhesion force between the metal contacts is proportional to the number of dimples. To implement volatile operation, the cantilever is designed to have high restoring force and low molecular adhesion force while low restoring and high molecular adhesion force are employed for non-volatile operation. Cantilevers with high restoring force and low molecular adhesion force are designed with relatively shorter cantilever lengths and with fewer dimples (M1 and M2 in Table I). Decreasing the cantilever length increases the restoring force and reducing the number of dimples reduces the molecular adhesion forces. Conversely, device M3 and M4 are designed with longer beam lengths to reduce the cantilever restoring force and more dimples to increase the molecular adhesion force. By controlling the number of dimples and the cantilever length, the proposed MEMS memory devices exhibit either volatile or non-volatile characteristics. As described earlier, the three forces determine the memory phenomenon for MEMS cantilever device, and the operation principle is illustrated in Fig. 2.

TABLE I. The cantilever design parameters for device M1 to M4 are as summarized.

Device type	M1	M2	M3	M4
w (μm)	2	2	2.5	3.5
W (μm)	13.5	14	23	31
L (μm)	18	19	30	40
h (μm)	0.3	0.3	0.3	0.3
d_0 (μm)	0.5	0.5	0.5	0.5
Dimple No.	9		25

FIG. 2. Major forces are electrostatic, restoring and adhesion. (a) Electrostatic force is applied at gate terminal. (b) Source makes contact with drain under the electrostatic force. (c) Non-volatility: Source remains in contact with drain when the electrostatic force is removed and molecular adhesion force is larger than cantilever restoring force. (d) Volatility: Source deactuates when cantilever restoring force is larger than molecular adhesion force.

The electrostatic force is determined by the standard parallel plate capacitor theory

$$F_{elect} = \left(\frac{1}{2}\right) \frac{\epsilon_0 W w V^2}{d^2}, \quad (1)$$

where W represents the gate length, w is the cantilever width, d indicates the bent cantilever gap from the bottom electrode, ϵ_0 is the vacuum permittivity, and V is the applied bias.⁹ The fringing field effect of the device is assumed to be negligible.

The mechanical bending of the cantilever follows the conventional spring force $F = k(x)$, which is exponentially proportional to the cantilever's deflection. The cantilever restoring force is expressed by the following equation:

$$F_{spr} = k(d_0 - d), \quad (2)$$

$$k = \frac{E w h^3}{4 L^3}, \quad (3)$$

where E represents the Young's Modulus of the cantilever, h is the cantilever's thickness, w is the beam width and d_0 the original cantilever's gap distance.^{9,10}

The analytical model of the adhesion force was reported to be dependent on the surface roughness.⁶ The molecular adhesion force (F_{adh}) and the adhesion energy (Γ) can be written as follows:

$$F_{adh} = \frac{2\Gamma A \alpha}{d_{vdw}}, \quad (4)$$

$$\Gamma = \frac{A_{Hamaker}}{12\pi D_{rms}^2}, \quad (5)$$

where A is the contact area, d_{vdw} is the van der Waals distance, D_{rms} is the root mean square surface roughness of Mo, α is the correction function,^{3,11} and $A_{Hamaker}$ ($16.2\text{--}45.5 \times 10^{-20}\text{J}$) is the hamaker constant for metal.^{12,13} The surface roughness D_{rms} was extracted from atomic force microscopy (AFM) scan.

The cantilever pull-in voltage is obtained by equating the electrostatic force (F_{elec}) and cantilever restoring force (F_{spr}). It was reported that abrupt switching occurs when a cantilever is bent to less than two third of its original gap distance and F_{elec} is larger than F_{spr} .¹⁴ The pull-in voltage (when $L = W$) is expressed by the following equation:

$$V_P = \sqrt{\frac{2Eh^3d_0}{8.37\epsilon_0 W^4 \left(\frac{5}{6d_0^2} + \frac{0.19}{d_0^{1.25}W^{0.75}} + \frac{0.19}{d_0^{1.25}W^{0.75}} + \frac{0.4h^{0.5}}{d_0^{1.5}w} \right)}}. \quad (6)$$

In the designed devices (M1-M4), the most critical parameter contributing to the pull-in voltage variation is the cantilever length. Also, it was theoretically reported that with all parameters (h , d , and w) kept constant, pull-in voltage (V_P) increases significantly by reducing the cantilever length.⁹ Similar relation could be observed for cantilever restoring force (F_{spr}) as given in Eq. (2), where F_{spr} decreases when cantilever length increases. Longer beams (M3 and M4) result in lower V_P and F_{spr} compared to shorter beams (M1 and M2) containing higher V_P and F_{spr} . Therefore, longer beams (M3 and M4) are designed to demonstrate non-volatility, whereas shorter beams (M1 and M2) exhibit volatile functionality.

The cantilever device was fabricated on 8 in. silicon wafer. PECVD silicon nitride (Si_3N_4) and ALD aluminum oxide (Al_2O_3) were deposited for dielectric isolation. PVD Mo was deposited and patterned to form the bottom gate and the contact pad electrodes. 50 nm Al_2O_3 was deposited and patterned for electrical isolation of the gate electrode. Sacrificial PECVD SiO_2 was then deposited and planarized by CMP to eliminate topography. The contact dimples were patterned on the SiO_2 surface and etched to stop on Mo. Thin layer of SiO_2 was again deposited before patterning and etching SiO_2 to create the cantilever's anchor. PVD Mo was then deposited and patterned to form cantilever electrode. The device was finally placed in VHF to remove the sacrificial SiO_2 .

SEM images of the suspended cantilever and contact structures are shown in Fig. 3(a). The cantilever is designed with the length and width of $30\text{ }\mu\text{m}$ and $2.5\text{ }\mu\text{m}$, respectively. The designed air gap between the cantilever and the bottom electrode was 500 nm with 25 (5×5) contact dimples at the tip of the cantilever for devices M3 and M4 as shown in Fig. 3(b). Fig. 3(c) shows the tip of M1 and M2 devices with 9 (3×3) dimples. The surface roughness of Mo is extracted from atomic force microscopy (AFM) using Veeco dimension 5000 and the measured D_{rms} of 2.878 nm is as shown in

FIG. 3. (a) SEM image of the MEMS cantilever after the VHF release process. (b) Device M3, M4 comprises 25 contact dimples which allow enough adhesion force to perform non-volatile operation. (c) Device M1, M2 has 9 contact points, where molecular adhesion force was not enough to overcome cantilever restoring force and device acts as volatile memory.

Fig. 4. The required value of D_{rms} for achieving the adhesion energy of $\Gamma = 0.986\text{ mJ/m}^2$ is calculated by Eq. (5). This corresponds to the molecular adhesion force of $0.171\text{ }\mu\text{N}$ for each dimple as described in Eq. (4) with $d_{vdw} = D_{rms}$ and $\alpha = 0.1$.^{3,16} As a result, the implemented 9 and 25 dimples generate the molecular adhesion force of $1.15\text{ }\mu\text{N}$ and $0.43\text{ }\mu\text{N}$, respectively.

The pull-in voltage measurement results for volatile (device M1) and non-volatile (device M3) memories are illustrated in Fig. 5. I/V measurement are conducted at 25°C , 150°C , and 300°C . As expected, pull-in voltage is found to decrease with increase in temperatures. For device M1, Fig. 5(a) shows the pull-in voltage of 10.34 V (300°C), 10.89 V (150°C), and 11.38 V (25°C). The pull-out voltages are observed to be 7.37 V (300°C), 6.82 V (150°C), and 6.55 V (25°C). The pull-in voltages of device M3 are observed to be 11.52 V (300°C), 13.47 V (150°C), and

FIG. 4. AFM scan of Mo surface roughness result. D_{rms} of 2.878 nm obtained.

Device M1

For dimple = 9

$$F_{adh} = 0.15\text{ }\mu\text{N}$$

$$F_{spr} = 0.38\text{ }\mu\text{N}$$

$$F_{spr} > F_{adh}$$

Device M3

For dimple = 25

$$F_{adh} = 0.43\text{ }\mu\text{N}$$

$$F_{spr} = 0.10\text{ }\mu\text{N}$$

$$F_{spr} < F_{adh}$$

FIG. 5. I/V measurement for memory device at 20 °C, 150 °C and 300 °C with (a) Volatile memory device and (b) non-volatile memory device. The pull-in voltage reduces for both kinds of memory devices at higher temperatures. For each design, 5 individual devices are characterized to confirm the volatile (device M1 & M2) and non-volatile (device M2 & M4) behavior.

13.81 V (25 °C) as shown in Fig. 5(b). There is no pull-out observed after removing the actuation voltage, and it confirms the non-volatility for the device M3.

After performing the *SET* operation on the non-volatile memory devices (M3 and M4), the cantilever release (*RESET*) operation is performed by a vibrational release technique. From the experiment, square pulses of 1 MHz with 3 V in amplitude are applied to the drain electrode while the gate/source electrodes are connected to ground terminal. The applied pulses pull down the cantilever at short intervals and eventually lead the cantilever to vibrate. The amplitude of pulses is kept smaller than the cantilever pull-in voltage to avoid the pull-in condition. The vibration amplitude gradually grows by applying suitable voltage pulses close to the resonance frequency of the cantilever. The increasing vibrational force together with the cantilever restoring force eventually overcomes the molecular adhesion force, and brings back the cantilever to its unstuck position. Although the actuation electrode controlled cantilever *RESET* theory was reported earlier,¹⁵ the contact electrode based cantilever detachment proposed in this work is reported and needs further investigation to validate the accurate mechanism.

Fig. 6 illustrates the *SET/RESET* cycling behavior of volatile memory (device M1) at 300 °C. The *SET/RESET* operation is performed for 10^3 cycles and measured with semiconductor device analyzer. An input pulse ($V_{G,pulse}$) is applied at gate electrode as shown in Fig. 6(a) and the current output response is observed at drain electrode as shown in Fig. 6(b). The *SET* operation on device M1 is performed by applying 12 V pulse for 1 ms duration. It is then followed with *RESET* operation by applying 0 V pulse for subsequent 1 ms. Furthermore, the switching time is experimentally measured to determine the *SET* response speed of device M1 at 25 °C, 150 °C, and 300 °C. Tektronix AFG3102 dual channel arbitrary/function generator is used to generate actuation pulses at gate electrode, and output signal is observed at drain electrode. All the signals are collected and time delay is recorded by Tektronix DPO7054 Digital Phosphor Oscilloscope. Fig. 6(c) shows the switching time of 0.94 μ s at 300 °C. The switching time slows down to 1.16 μ s at 150 °C and 1.77 μ s at 25 °C.

For non-volatile memory (device M3), the *SET* operation is performed at 300 °C by applying 12 V pulse for 1 ms.

FIG. 6. Volatile memory device cycling and response speed graph, (a) voltage pulse input to gate terminal, (b) current output at source terminal, (c) *SET* response speed at 300 °C.

The *SET* pulse is applied and measured with semiconductor device analyzer. Subsequently, the *RESET* operation is performed by applying a series of pulses (3 V with 1 MHz frequency) using a function generator for next 1 ms. After *RESET*, the device is connected back to semiconductor analyzer for again applying and measuring the actuating pulse. The *SET/RESET* operation is performed for 5 cycles, and data are shown in Figs. 7(a) and 7(b). With the similar method used for volatile memory device, Fig. 7(c) shows the 0.95 μ s switching time measured at 300 °C. At 150 °C, the switching time slows down to 1.63 μ s and further to 2.31 μ s at 25 °C.

The summary of the volatile and non-volatile memories is presented in Fig. 8. Based on molecular adhesion force (F_{adh}) and cantilever restoring force (F_{spr}), the gradient line

FIG. 7. Non-volatile memory device cycling and response speed. (a) Voltage pulse input to gate terminal. (b) Current output at drain terminal. (c) *SET* response speed at 300 °C.

FIG. 8. Summary of the balancing forces for MEMS memory devices. For non-volatile memory device, the adhesion force is greater than restoring force. For volatile-memory device, the restoring force is greater than adhesion force.

separates the graph into two, with adhesion force dominant at upper portion of the graph and restoring force dominant at the lower portion of the graph. Non-volatile memory (M1 and M2) lies in the adhesion force dominant region and the volatile memory (M3 and M4) in the restoring force dominant region. The error bar (vertical line along the middle point of each device) plotted represents the error contributed by $A_{Hamaker}$ constant of metal in the range of $16.2\text{--}45.5 \times 10^{-20}$ J.

This paper demonstrated MEMS volatile and non-volatile memory devices through precise control of molecular adhesion force and cantilever restoring force. *I/V*, *SET/RESET* cycling, and switching speed characterization results were obtained at ambient (25 °C) to high temperatures (150 °C, 300 °C). The devices has demonstrated the *SET* and *RESET* operations up to 10^3 times at 300 °C. The response time of 0.94 μs was observed at 300 °C for volatile memory device. The non-volatile memory device showed the response time of 0.95 μs. The cantilever detachment was demonstrated through applying reset pulses at contact electrode. This offers potential *RESET* phenomenon not only for

the proposed MEMS memory devices but also for many other MEMS actuators.

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