Design optimization of pulsed-mode electromechanical nonvolatile memory

Pott, Vincent; Vaddi, Ramesh; Chua, Geng Li; Lin, Julius Tsai Ming; Kim, Tony Tae-Hyoung

2012

<https://hdl.handle.net/10356/98616>

<https://doi.org/10.1109/LED.2012.2201440>

© 2012 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at DOI: [<http://dx.doi.org/10.1109/LED.2012.2201440>].

Downloaded on 26 Apr 2023 15:43:52 SGT

Design Optimization of Pulsed-Mode Electromechanical Nonvolatile Memory

Vincent Pott, *Member, IEEE*, Ramesh Vaddi, *Member, IEEE*, Geng Li Chua, Julius Tsai Ming Lin, *Member, IEEE*, and Tony T. Kim, *Member, IEEE*

Abstract—Storage-layer-based nonvolatile memory (NVM) devices, such as Flash, ferroelectric RAM, or magnetic RAM, have limited reliability at high temperature (HT, $T > 200^\circ\text{C}$). On the contrary, storage-layer-free NVM devices based on a bistable nanoelectromechanical (NEM) mechanism and adhesion forces show excellent reliability at HT. This letter presents design optimization of an electrostatic NEM NVM device. The SET/RESET principle is based on the pulsed-mode switching of a mechanically free electrode (the shuttle), which is placed inside a guiding pod, having two stable positions. Based on the shuttle kinematic equation, this letter derives key design and operation parameters, particularly optimization in terms of switching speed and switching energy. The small footprint of the shuttle NEM NVM makes it applicable to ultracompact and reliable data storage at HT.

Index Terms—High-temperature (HT) electronics, nanoelectromechanical (NEM) systems, nonvolatile memory (NVM).

I. INTRODUCTION

COMMERCIAL nonvolatile memory (NVM) devices typically fail at high temperature (HT). The market-dominant Flash technology demonstrates remarkable performances in terms of density and reliability but cannot permanently store data if the chip is exposed to HT (typically, $T > 200^\circ\text{C}$) [1]. Similar issues appear in all *storage-layer-based* NVM devices, including magnetic RAM [2] and ferroelectric RAM [3], even if their physical data lost mechanisms are different.

To address this concern, *storage-layer-free* NVM devices based on electromechanical multistability have been investigated for data storage at HT [4], [5]. However, microelectromechanical systems suffer from poor area efficiency due to anchoring. The 9F^2 three-terminal *shuttle memory* [6] alleviates this issue by proposing an anchorless disk-shape electrode, where only electrostatic actuation and adhesion forces control

Fig. 1. (a) Top-view layout of the three-terminal nanoelectromechanical (NEM) memory. AA' 3-D cross sections in the (b) down ($I_{DS} > 0$) and (c) up ($I_{DS} = 0$) states.

TABLE I
PULSED-MODE SWITCHING OPERATION OF THE NVM DEVICE

Logic	Applied voltage	Effect
Switching to gate	$V_D = V_S = 0$ $V_G = V_P$ (pulse)	V_P : Pull-out voltage
Switching to S/D	$V_D = V_S = V_P$ $V_G = 0$	Switching to both drain and source
Read	$V_D = V_R$, $V_S = 0$ $V_G = 0$	V_R : Read voltage ($V_R \ll V_P$) down: $I_{DS} > 0$, up: $I_{DS} = 0$
Hold	$V_D = V_S = V_G = 0$	Adhesion: non-volatility

Fig. 2. Switching time and switching energy plots, as a function of V_G -pulse duration. Shuttle parameters are $A = 4 \mu\text{m}^2$ and $d_{\text{shuttle}} = 300 \text{ nm}$. Shuttle metal density is $16.6 \times 10^3 \text{ kg/m}^3$ (shuttle mass $m = 2 \times 10^{-14} \text{ kg}$). Technology gap is $d_{\text{gap}} = 100 \text{ nm}$, and applied bias are $V_G = 10 \text{ V}$ ($0 < t < T_{\text{pulse}}$), and $V_D = V_S = 0$.

the switching of the cell. Based on Newton's motion equation, the kinematic of the shuttle has been analytically solved [6].

This letter presents a complete design analysis of the shuttle geometry and its associated pulsed-mode operation. Impacts of design parameters per switching cycle are discussed.

Manuscript received April 20, 2012; revised May 10, 2012.

This work was supported by the Science and Engineering Research Council, Agency for Science, Technology and Research (A*STAR), under Grant 102-165-0088. The review of this letter was arranged by Editor M. Jureczak.

V. Pott and J. T. M. Lin are with the Institute of Microelectronics, Agency for Science, Technology and Research (A*STAR), Singapore 117685 (e-mail: pottv@ime.a-star.edu.sg).

R. Vaddi and T. T. Kim are with the Division of Circuits and Systems, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798.

G. L. Chua is with the Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117583.

Fig. 3. Product of switching time and switching energy as a function of V_G -pulse duration T_{pulse} . Variable parameters are (a) shuttle area A , (b) shuttle electrode thickness d_{shuttle} , (c) actuation gap d_{gap} , and (d) actuation pulse amplitude V_G . Design of experimental constant values are $A = 4 \mu\text{m}^2$, $d_{\text{shuttle}} = 300 \text{ nm}$, $d_{\text{gap}} = 100 \text{ nm}$, and $V_G = 10 \text{ V}$.

II. STRUCTURE AND OPERATION OF THE NEM NVM

A sketch of the shuttle memory with double gap is shown in Fig. 1. The anchorless electrode is controlled by the drain (V_D), source (V_S), and gate (V_G) pulsed-mode voltages. The two stable positions (see Table I) of the anchorless electrode (planar area A , thickness d_{shuttle} , and mass m) are either up to the gate electrode or down to both source and drain electrodes. Reading is done by probing source-to-drain current I_{DS} with the shuttle serving as a switchable electrode.

A source/drain-to-gate switching cycle consists of the following: 1) shuttle capacitive charging ($V_G > V_P$, $V_D = V_S = 0$) until the shuttle-to-gate electrostatic force overcomes adhesion forces; 2) shuttle liftoff; 3) V_G -bias turnoff during the transfer; 4) shuttle landing toward the gate electrode; and 5) shuttle discharging.

III. IMPACT OF DESIGN PARAMETERS

The minimum switching voltage $V_P > V_G$ to initiate shuttle liftoff is given by

$$V_P = 4d_{\text{gap}} \cdot \sqrt{\frac{\Gamma \cdot \alpha}{d_{\text{vdw}} \cdot \epsilon_0}} \quad (1)$$

where Γ , α , and d_{vdw} represent parameters related to surface properties [6], [7]; ϵ_0 is the dielectric constant of vacuum; and d_{gap} is the fabricated shuttle to fixed electrode distance.

Adhesion forces between conductive surfaces are reported to increase with temperature and, therefore, to enhance the storage principle, which is an opposite trend to *storage-layer-based* NVM.

The shuttle's motion equation $x(t)$ is given by (2), whose analytical solution is solved in [6]. Thus

$$m \cdot \frac{d^2 x(t)}{dt^2} = \frac{q_{\text{bottom}}^2}{2 \cdot \epsilon_0 \cdot A} - \frac{q_{\text{top}}^2}{2 \cdot \epsilon_0 \cdot A} \quad (2)$$

where q_{bottom} and q_{top} are the net induced charges over the bottom and top surfaces of the metallic shuttle, respectively. From (2), both switching time and switching energy are extracted and plotted in Fig. 2.

Switching bias V_G must be turned off (or reduced to $V_G < V_P$) during the mechanical transfer to avoid any electrostatic pendulum effect [8]. As adhesion will slightly vary from one surface to another, a high-voltage pulse $V_G \gg V_P$ is suggested to ensure proper switching (i.e., ability to switch all bits, even those having stronger adhesion). Furthermore, a *high-voltage/short-duration* switching pulse is also ideal to prevent shorts between the gate and the drain or the source, in the case of shuttle tilting due to the irregular adhesion force.

A speed-energy metric [9] to optimize the design and its pulsed-mode operation is proposed. Fig. 3 highlights variation effects in shuttle area A , shuttle thickness d_{shuttle} , actuation gap

Fig. 4. (a) Representation of tilt angle θ . (b) Tilt angle θ versus air gap d_{gap} for long ($L = 2 \mu\text{m}$) and short ($L = 200 \text{ nm}$) shuttle geometries.

d_{gap} , and pulse amplitude V_G on the product of the switching time and the switching energy.

The optimal pulse duration is typically 15% longer than the minimum required pulse duration. This observation is similar for all simulated plots. An optimal design should have a small area and thin shuttle, as well as small actuation gaps.

As aforementioned, a design limiting factor is the potential shuttle tilt θ . Geometry parameters include shuttle diameter L and thickness d_{shuttle} , as well as actuation gap d_{gap} . Fig. 4 illustrates an exemplary geometry of a tilted shuttle and the dependence of θ on L , d_{shuttle} , and d_{gap} .

The geometry relation and its solved θ -angle analytical solution are given, respectively, in

$$L \cdot \sin \theta + d_{\text{shuttle}} \cdot \cos \theta = 2 \cdot d_{\text{gap}} + d_{\text{shuttle}} \quad (3)$$

$$\theta = \sin^{-1} \left(\frac{2 \cdot d_{\text{gap}} + d_{\text{shuttle}}}{\sqrt{L^2 + d_{\text{shuttle}}^2}} \right) - \tan^{-1} \left(\frac{d_{\text{shuttle}}}{L} \right). \quad (4)$$

To avoid possible gate-to-source/drain shorts during switching, the shuttle should be designed to minimize its θ -angle. From (4), we deduce that the smaller the actuation gap, the smaller the θ -angle.

Tilting occurs in the case of uneven adhesion forces. If adhesion is not overcome on one side of the shuttle electrode, then there is a risk of permanent gripping, as illustrated in Fig. 4(a). A high-voltage pulse $V_G \gg V_P$ is applied to ensure minor variations in adhesion forces will not cause tilting. The high-voltage pulse will also reduce switching time, but at the expense of energy consumption, as shown in Fig. 3(d).

The maximum adhesion force between two hard surfaces in contact is directly proportional [7] to adhesion energy Γ , which

is given by

$$\Gamma = \frac{A_{\text{metal}}}{12 \cdot \pi \cdot D_{\text{rms}}^2} \quad (5)$$

where A_{metal} is the Hamaker constant of the metal, and D_{rms} is the roughness of the surface. Therefore, the variation of pull-out voltage δV_P is directly related to the variation of surface roughness δD_{rms} by

$$\delta V_P = \frac{1}{\delta D_{\text{rms}}^2}. \quad (6)$$

A hard and smooth conductive surface will ensure proper switching with minimal risk of tilting and no plastic deformation of electrodes.

IV. CONCLUSION

This letter has presented the impact of both geometry parameters and associated pulsed-mode control of an electrostatic anchorless NVM device. A small area ($A < 0.25 \mu\text{m}^2$) and thin ($d_{\text{shuttle}} < 100 \text{ nm}$) shuttle electrode, which is guided between scaled-down vacuum gaps ($d_{\text{gap}} < 50 \text{ nm}$), is the most efficient design for speed-energy optimization. Limits of shuttle scaling from shuttle tilt analysis are derived, and it shows the importance of low surface roughness. The removal of mechanical anchors warrants better scalability and operability for data storage at HT.

REFERENCES

- [1] K. Grella, H. Vogt, and U. Pachen, "High temperature reliability investigations of EEPROM memory cells realised in silicon-on-insulator technology," in *Proc. HiTEN*, Jul. 2011, pp. 221–225.
- [2] K. Lee and S. H. Kang, "Design consideration of magnetic tunnel junctions for reliable high-temperature operation of STT-MRAM," *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 1537–1540, Jun. 2010.
- [3] D. A. Kamp and A. D. DeVilbiss, "A high-rel embedded ferroelectric memory," in *Proc. NVMTS*, Nov. 2007, pp. 56–59.
- [4] B. Halg, "On a micro-electro-mechanical nonvolatile memory cell," *IEEE Trans. Electron Devices*, vol. 37, no. 10, pp. 2230–2236, Oct. 1990.
- [5] R. Gaddi, C. Schepens, C. Smith, C. Zambelli, A. Chimenton, and P. Olivo, "Reliability and performance characterization of a MEMS-based non-volatile switch," in *Proc. IRPS*, Jun. 2011, pp. 171–176.
- [6] V. Pott, G. L. Chua, R. Vaddi, J. M.-L. Tsai, and T. T. Kim, "The shuttle nanoelectromechanical nonvolatile memory," *IEEE Trans. Electron Devices*, vol. 59, no. 4, pp. 1137–1143, Apr. 2012.
- [7] F. W. DelRio, M. P. De Boer, J. A. Knapp, E. D. Reedy, Jr., P. J. Clews, and M. L. Dunn, "The role of van der Waals forces in adhesion of micromachined surfaces," *Nat. Mater.*, vol. 4, no. 8, pp. 629–634, Aug. 2005.
- [8] K. Asano, "On the theory of an electrostatic pendulum oscillator," *Amer. J. Phys.*, vol. 43, no. 5, pp. 423–427, May 1975.
- [9] L. M. Castaner and S. D. Senturia, "Speed-energy optimization of electrostatic actuators based on pull-in," *J. Microelectromech. Syst.*, vol. 8, no. 3, pp. 290–298, Sep. 1999.