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Robustness of nano-electromechanical switches against mechanical shock and vibration loads

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Abstract

Nano-electromechanical (NEM) switches offer significant potential for future computing and memory applications due to their low power consumption and ability to operate in high-temperature and radiation-harsh environments. However, there is a lack of studies on the robustness of NEM switches under mechanical loads. In this study, we investigated the performance of 3- and 7-terminal NEM relays under mechanical shocks up to 5000 g and vibrations up to 70 g. The results demonstrate that devices maintain mechanical functionality, with some variations in the electrical characteristics. These findings underscore the potential of NEMS technology for reliable operation in harsh environments, paving the way for their possible integration into next-generation electronic devices.

1. Introduction

The rapid technological advancement of connected devices has led to an increasing demand for electronic devices that can operate reliably under extreme conditions. This is particularly true for applications in the Internet of Things (IoT), aerospace, and industrial electronics, where devices are often exposed to high temperatures, radiation, and other harsh environmental factors. Traditional solid-state electronic components, such as transistors, face significant challenges in these environments due to their inherent limitations in temperature and radiation tolerance. As a result, there is a growing interest in exploring alternative technologies that can offer enhanced reliability and performance under such conditions.

One promising technology that has garnered significant attention is nanoelectromechanical (NEM) relays. NEM relays are miniature mechanical switches that operate by physically making and breaking electrical contacts. Unlike traditional transistors, NEM relays have zero leakage current, a steep subthreshold slope, and the ability to function at elevated temperatures and radiation levels. These characteristics make NEM relays particularly well-suited for applications requiring high reliability in harsh conditions and low power consumption [1][2][3][4], as seen in the nuclear industry, radiotherapy, industrial Xray instruments, and data logging, processing and control applications at high temperatures.

The potential of NEM relays to serve as the building blocks for non-volatile memory (NVM) in harsh environments is especially noteworthy. Non-volatile memory retains data even when power is removed, making it an essential component in many electronic systems. However, existing NVM technologies, such as EEPROM and flash memory, are limited by their susceptibility to high temperatures and radiation. NEM relays, with their inherent radiation hardness and high-temperature capability, offer a promising solution to these challenges [5] .

Despite the advantages of NEM relays, their widespread adoption has been hindered by concerns about their reliability. The mechanical nature of NEM relays introduces unique failure mechanisms that are not present in traditional solid-state devices. For instance, the physical contact between the relay's moving parts can lead to wear and degradation over time, affecting the relay's performance and longevity. Additionally, the robustness of NEM structures against mechanical loads is of particular concern, as they contain long suspended beams and other complex structures. The scope of the current work is to investigate the effects of the mechanical loads on the structural integrity and electrical performance of the NEM relays.

2. NEM switches and their operation principle

Typical NEM relays operate by applying an electrostatic force to a movable beam, causing it to deflect and make contact with an electrode. This

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physical contact allows current to flow, effectively turning the switch "on". When the electrostatic force is removed, the beam returns to its original position through spring action in the beam, breaking the contact and turning the switch "off". Fig. 1 shows the schematics of a basic 3-terminal (3T) in-plane NEM relay investigated in the present study. All of the relay structures and electrodes are fabricated on the device silicon layer of a silicon-on-insulator (SOI) wafer. After the device features are patterned and etched, the beams are suspended by etching away the underlying buried oxide layer. A layer of blanket gold (~ 50 nm) was deposited on top of the entire NEM structure in order to improve the contact resistance between the tip of the beam and the counter drain electrode and to coat the electrode pads.

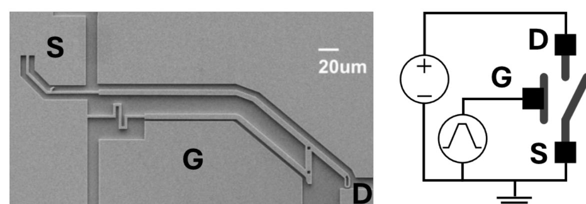

Fig. 1. Micrograph of a 3T NEM relay with Gate (G), Drain (D), and Source (S) terminals, and test circuit where the gate voltage is ramped up and down with a drain bias.

This relay is actuated by applying a voltage between the gate and source (beam): a gradually increasing positive voltage is applied to the gate, while the source is always kept grounded to minimize the possibility of out-of-plane bending. When the applied gate-source voltage reaches the pull-in voltage (V_{p-i}) of the relay, a connection is established between the beam tip and drain. By applying a positive voltage bias on the drain and monitoring the drain-source current, a switching event can be detected electrically.

Another type of NEM device investigated in this study is a 7-terminal (7T) relay shown in Fig. 2, which is fabricated using the same process as for 3T relays. The beam is rotated either clockwise or anticlockwise by applying the actuating voltage to one of the two gate electrode pairs: clockwise by actuating gate pair PG1+AG1, for the beam tip to land on drain D1, and anticlockwise by applying a voltage to gate pair PG2+AG2, for the opposing beam tip to land on drain D2. The hinge portion of the circular beam is designed to be soft enough that the adhesion force at the contact after rotation is greater than the restoring spring force. Thus, the beam stays switched even when the gate voltage is reduced to zero. This results in a non-volatile device that serves as the storage device in memory applications. If, on the other hand, the beam pulls out before the gate voltage is reduced to zero, the relay is a standard switch (i.e. volatile device, like the 3T switch described above). For non-volatile devices, to switch the state and rotate the beam to the other drain, a voltage is applied to the opposing pair of gates.

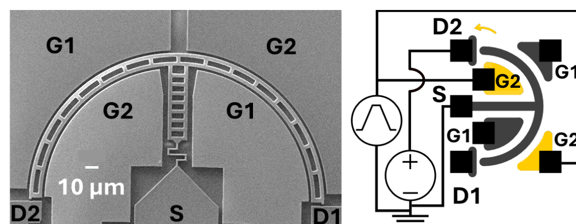

Fig. 2. Micrograph of a 7T NEM relay with Gate (G1, G2), Drain (D1, D2) and Source (S) terminals, and test circuit where the gate voltage is ramped up and down for anticlockwise rotation with a bias on D2.

More details on the design, fabrication and electrical characterisation of the studied 3T and 7T NEM relays can be found in [4][6]. The critical dimensions of the NEM devices presented in this work are of the order of ~1 μm. The overall lifetime of these switches' is typically a few tens of cycles. Therefore, each electrical test consisted of just one switching cycle to ensure that the possible cycling lifetime issues do not compromise the results of the mechanical robustness tests.

3. Mechanical shock robustness

Mechanical shock tests were carried out in ambient conditions on unpackaged 1 cm × 1 cm dies containing 28 3T switches and 56 7T switches. The switches were electrically characterised prior to the shock tests. The chip was then subjected to two sequential shock loads: 1000 g peak acceleration (pulse duration 1 ms), and 5000 g peak acceleration (pulse duration 0.2 ms). Electrical characterisation was performed after application of each shock. The first shock level of 1000 g was chosen as a qualification requirement based on the MIL, JEDEC and ESA qualification standards [7][8][9]. The second shock level of 5000 g, the maximum achievable with our equipment, was applied to investigate the devices' robustness against severe mechanical shock conditions that are far beyond the qualification requirement. For each load level a total of 30 mechanical shock pulses were applied comprising 5 shock pulses in each of the 6 primary directions (Z+, Z-, Y+, Y-, X+, X-).

Electrical characterisation results obtained on the tested 3T switches show that all 18 tested switches stayed operational after both shock tests (see Table 1). Some variations in the pull-in and pull-out voltages were observed, especially after the tests at 5000 g. However, such variations were observed in multiple batches of NEM devices tested with Au as the contact solution and are thus not considered as failures. Our experience of characterising such switches shows that

devices with Au contact coatings exhibit drift in the pull-in and especially pull-out voltages from cycle to cycle, which can be attributed to wear out of the contact material, changing of the contact surface roughness, or changes in the surface properties of the Au coating caused by repeated impacts and joule heating. Thus, these variations cannot be conclusively attributed to the applied shock. Fig. 3 shows a typical example of the electrical characterisation of a 3T switch before and after the shock test at 1000 g. The step-like changes in the drain-source current (red curve) occur at the pull-in voltage of 37 V when the device switches to the "on" state during the gate voltage ramp-up, and at the pull-out voltage of 34 V when the device is switched back to the "off" state during the gate voltage ramp-down. Both pull-in and pull-out voltages stayed almost identical before and after the test.

Table 1. Summary of the electrical characterisation results of the tested 3T switches before the mechanical shock test, after the test at 1000 g, and after the test at 5000 g.

Parameter	Initial	After 1000 g	After 5000 g
Working device count	18	18	18
$V_{p\text{-}i}$ [V]	37 – 38	37 – 38	37 – 46
$V_{p\text{-}o}$ [V]	32 – 37	30 – 37	18 – 35

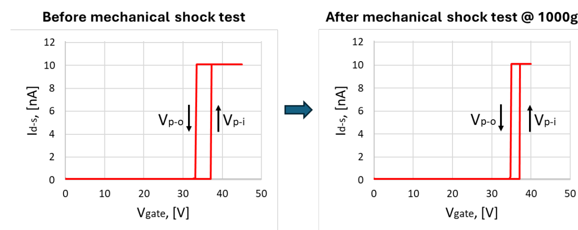

Fig. 3. Example of the electrical characterisation of a 3T switch before and after the shock test at 1000 g.

Characterisation results obtained on the tested 7T switches show that all 39 working devices stayed mechanically operational after the tests at 1000 g and 5000 g. As mentioned above, the 7T switches can exhibit two possible behaviours: non-volatile and volatile. Based on our experience with characterising 7T devices, a given chip would generally have a mix of both types of behaviours. Furthermore, a given switch may even change its behaviour from volatile to non-volatile and back during programming and re-programming cycles. Therefore, both types of behaviour after the shock tests are accepted as pass conditions, given that their occurrence confirms the mechanical functionality of the NEM structure, which is the main focus of the current investigation. Any change in the electrical behaviour is likely related to the quality of the contact between the tip of the source beam and the drain electrode. Alternative contact coatings with better performance are currently under investigation (see also Conclusions).

Fig. 4 shows a typical example of the electrical characterisation of a non-volatile 7T switch before and after the shock test at 5000 g. The initial state of the switch is "neutral", i.e. it is not switched to either of the two possible "on" states. First, the voltage on gate pair 2 is ramped up to program "state 2", which is retained upon ramping the gate 2 bias down to 0 V (see Fig. 2 for test configuration). Then, the voltage on gate pair 1 is ramped up to re-program the switch from the "state 2" to "state 1", which is also retained upon ramping the gate 1 voltage down to 0 V. After the initial characterisation prior to the shock test the 7T switch stayed in the non-volatile "state 1". After the shock test the state was, however, reset to "neutral". Then the switch could be programmed again to "state 2" and re-programmed to "state 1" in the non-volatile manner. It is therefore important to note that despite the switch withstanding the mechanical shock of 5000 g and retaining its functionality, the state of the non-volatile switch is not kept after the shock test. This is true for all tested 7T switches that exhibited a non-volatile behaviour. Design optimisations and alternative contact coatings are being investigated to overcome this problem.

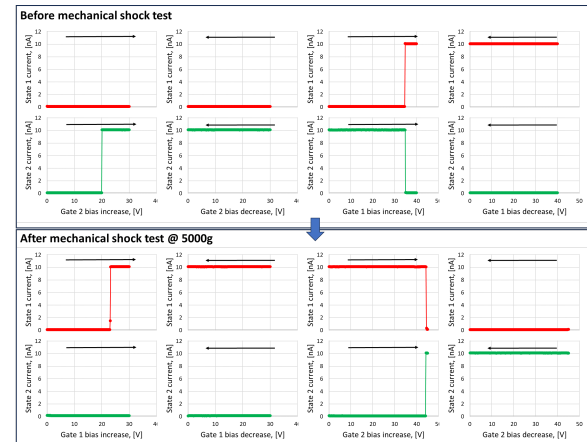

Fig. 4. Example of the electrical characterisation of a 7T switch before and after the shock test at 5000 g. Red curve: drain1-source current, green curve: drain2-source current.

4. Mechanical vibration robustness

Mechanical vibration tests were carried out on another chip with 3T and 7T NEM switches. As before, the switches were electrically characterised prior to the vibration tests. The chip was then subjected to two sequential mechanical vibration tests: random vibration with rms acceleration of ~45 g, followed by a sine sweep vibration with peak acceleration of 70 g. Electrical characterisation was

performed after each vibration test. The chosen vibration levels are at least as demanding as the most severe conditions prescribed in the MIL [11], JEDEC [12] and ESA [13] qualification standards. Each vibration test was performed sequentially in 3 axes: Z, Y, and X. The test frequency range was 10-2000 Hz and the duration was 15 minutes in each direction.

Electrical characterisation results obtained on the tested 3T switches (see Table 2) show that 7 out of 8 switches could withstand both random and sine sweep vibrations. One of the switches failed to actuate after the sine sweep vibration test. The observed one failure could have also occurred from the possibly low cycling reliability of this switch. High resolution optical microscopy investigation of the switch did not reveal any physical damage caused by the vibrations. Thus, it can be considered as a non-representative outlier. Similar to the mechanical shock tests, some variations in the pull-in and pull-out voltages were observed.

Table 2. Summary of the electrical characterisation results of the tested 3T switches before the vibration tests, after the random vibration, and after the sine sweep vibration.

Parameter	Initial	After random vibration	After sine sweep vibration
Working device count	8	8	7
V_{p-i} [V]	37	37 – 39	36 – 37
V_{p-o} [V]	13 – 33	12 – 39	17 – 37

Characterisation results obtained on the tested 7T switches show that all 41 working devices stayed mechanically operational after both vibration tests. Similar to the shock test results, the 7T switches exhibit a mixture of volatile and non-volatile electrical behaviours. Despite maintaining mechanical functionality, the devices may change their electrical behaviour from volatile to non-volatile and vice versa, as well as not retaining the programmed state (in the case of the non-volatile switches)

5. Conclusions

Mechanical shock and vibration tests clearly indicate very good structural robustness of the NEM devices against mechanical loads. Among about 100 tested devices subjected to 4 types of tests only one mechanical actuation failure was observed, which cannot be attributed to the mechanical stress tests with any certainty due to poor cycling characteristics of the tested batch. Subsequent optical inspection did not show any physical damage, suggesting this is an outlier. All other tested 3T and 7T switches maintain their mechanical ability to actuate after the application of harsh mechanical loads, such as shocks up to 5000 g and vibrations up to 70 g. However, changes of the electrical behaviour from non-volatile to volatile and vice versa were observed for 7T switches. These observations suggest that the surface adhesion force at the contact was insufficient to keep the beam switched against the g force encountered in acceleration and shock tests. Based on our experience of prior electrical tests carried out on these devices, the main cause of the failures is likely related to the utilized Au contact coating that is not optimal for the NEM switches. Au is soft and prone to deformation and wear, especially in moving MEMS parts thus leading to the deterioration of the contact stability with time. Further improvements of the switches including use of nanocrystalline graphite and Ru as alternative contact coatings, and miniaturization to reduce the beam mass, are expected to provide significant improvements.

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References

[1] S. Rana, et al., Nanoelectromechanical relay without pull-in instability for high-temperature non-volatile memory, Nature Communications 11, (2020), 1181.
[2] Y. Li et al., Integrated 4-terminal single-contact nanoelectromechanical relays implemented in a silicon-on-insulator foundry process. Nanoscale, 15.43, (2023), 17335-17341.
[3] Q. Tang et al., Energy Consumption in Micro-and Nanoelectromechanical Relays, IEEE Transactions on Electron Devices, 72.4, (2025), 1969-1976.
[4] J. D. Reynolds et al., Single-contact, four-terminal microelectromechanical relay for efficient digital logic. Advanced Electronic Materials, 9.1, (2023), 2200584.
[5] M.K. Kulsreshath et al., Digital Nanoelectromechanical Non-Volatile Memory Cell, IEEE Electron Device Letters, 45.4 (2024), 728-731.
[6] D. Pamunuwa et al., Theory, Design, and Characterization of Nanoelectromechanical Relays for Stiction-Based Non-Volatile Memory, Journal of Microelectromechanical Systems, 31.2, (2022) 283-291.
[7] MIL-STD-883K test method 2002, 2016.
[8] JESD22-B104C, 2004.
[9] ESCC-2269000 test 8.3.5.3.1 (ii), 2018.
[10] MIL-STD-883K test method 2007, 2016.
[11] MIL-STD-883K test method 2026, 2016.
[12] JESD22-B103B, 2006.
[13] ESCC-2269000 test 8.3.5.3.1 (v), 2018.