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Mechanical shock and vibration testing of volatile and non-volatile nanoelectromechanical switches

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Abstract:	Nanoelectromechanical (NEM) switches are promising for ultra-low-power electronics in harsh environments due to their zero leakage current and radiation hardness. However, their mechanical robustness under extreme loads remains insufficiently studied. This work investigates the performance of 3-terminal and 7-terminal NEM relays subjected to mechanical shocks up to 5000 g and vibrations up to 70 g. All tested devices retained mechanical functionality, confirming excellent structural integrity. Electrical characterization revealed variations in pull-in and pull-out voltages and loss of programmed states in 7T relays, although their non-volatile capability remained intact. These instabilities are primarily attributed to the soft Au contact coating, which is prone to wear and deformation. The findings highlight the suitability of NEM technology for harsh environments and point to future improvements through more suitable contact materials and device miniaturization.

----------------------- REVIEW 1 ---------------------

This paper presents an investigation of the mechanical shock and vibration robustness of nano-electromechanical switches (NEMS). 3-terminal and 7-terminal NEMS are evaluated after 1000g and 5000g shock test and after random vibration followed by sine sweep vibration. Only electrical characterization is performed, using the pull-in and pull-out voltages. The authors state that these voltages stay "almost identical" before and after the tests, which lead them to the conclusion that the NEMS have a good structural robustness. One electrical failure (out of 100 tested) is classified as "infant mortality", and the authors speculate that the Au contact coating is the main cause of the failure.

1. Looking at the results in more detail, several questions arise. Only a range of pull-in and pull-out voltages is presented in the tables, but it's not clear how many measurements have been performed before and after the tests, and there is no indication of the variance of the measured values. This would be important since the authors remark that "variations are normal for the developed NEM devices". If variations are normal, they should be presented in detail, e.g. by measurement series of at least 20 switching cycles before and after the mechanical/vibrational test.

The overall lifetime of these switches ranges from a few cycles up to 1000 cycles with a typical value of a few tens of cycles. Therefore, when performing the mechanical robustness tests we had to make sure that any failures (if observed) are due to the impact of the mechanical loads and are not caused by the possible low "natural lifetime". Thus, each electrical test consisted of just one switching cycle, which is sufficient to verify the mechanical functionality of the switch. The manuscript was updated to incorporate this information (page 2), with the following sentence:

"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."

The observed variation of the pull-in and pull-out voltages before and after the test is comparable to their variation during the lifetime cycling tests. Examples are given in the tables below. For the sake of keeping the manuscript within the 4 page limit we can not present these tables in the text, but they can be incorporated in the manuscript if accepted for the extended journal publication.

Table A. Variation of the pull-in and pull-out voltages of 3T switches before and after the mechanical shock tests at 1000g.

Device ID	**Before test**		**After test**		**Result**
	Vp-i, [V]	Vp-o, [V]	Vp-i, [V]	Vp-o, [V]	

B01	37	33	37	35	Pass
B02	37	33	37	36	Pass
B03	37	34	37	35	Pass
B05	37	32	37	36	Pass
B06	37	35	37	33	Pass
B07	37	37	37	34	Pass
B10	37	33	37	30	Pass
B11	38	36	38	35	Pass
B13	37	35	37	36	Pass
B14	37	36	37	35	Pass
B15	37	35	37	34	Pass
B16	37	36	37	37	Pass
B20	37	34	37	34	Pass
B21	37	34	37	35	Pass
B22	37	34	37	33	Pass
B24	38	36	38	35	Pass
B25	38	36	38	34	Pass
B26	37	32	37	37	Pass

Table B. Variation of the pull-in and pull-out voltages for a representative 3T switch during switching cycling (first 20 cycles and the last successful cycle No. 77).

Cycle No.	Vp-i, [V]	Vp-o, [V]	Result
01	37	32	Pass
02	37	36	Pass
03	37	37	Pass
04	37	35	Pass
05	37	36	Pass
06	37	34	Pass
07	37	36	Pass
08	37	37	Pass
09	37	32	Pass

10	37	35	Pass
11	37	35	Pass
12	37	36	Pass
13	37	34	Pass
14	37	33	Pass
15	37	28	Pass
16	37	35	Pass
17	37	28	Pass
18	37	18	Pass
19	37	36	Pass
20	37	35	Pass
77	37	35	Pass
78	Not possible to switch		Fail

2. The authors describe that the 7-terminal devices change their behavior from volatile to non-volatile and back, but quantitative information about this behavior is missing, too.

The intended functional behaviour of the 7T switches is non-volatile, but variations in the surface adhesion force at the contact can result in volatile behaviour. (the full details of how this switch works is detailed in ref [6] of the paper: D. Pamunuwa et. al, "Theory, Design, and Characterization of Nanoelectromechanical Relays for Stiction-Based Non-Volatile Memory," in *Journal of Microelectromechanical Systems*, vol. 31, no. 2, pp. 283-291, April 2022, doi: 10.1109/JMEMS.2021.3138022.).

However, in both cases the switch is functional. The scope of this paper was to address the effect of the mechanical loads on the robustness of the switches, i.e. to check if their functionality is preserved after subjecting them to the mechanical loads, which is addressed on page 3.

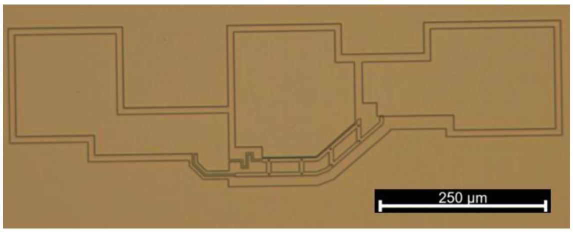
3. In the section "conclusion", the additional failure mode of contact stiction is mentioned – this mode should already be presented in the results section.

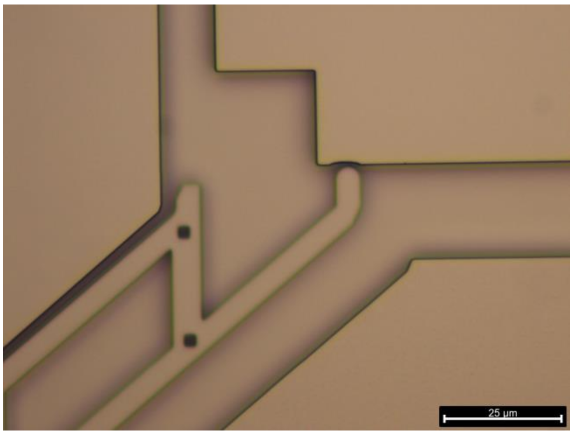
Thank you for pointing this out. This was due to an oversight as this failure mode was observed for other switch types, which were finally not included in this paper. We have removed it from the conclusions and modified the text (page 4).

4. Concerning the "infant mortality" case, it is methodically flawed to characterize the failure as non-representative outlier without any further physical characterization. Methods like optical microscopy, infrared microscopy or SEM are available which

would allow a more detailed evaluation of the failed part. Physical characterization might answer the question whether the failure rate of 1% is acceptable in this state of development or not and whether the use of Au is really the root cause of the problem.

This comment is indeed very relevant, and we are happy to share with the reviewer more information and context about this failed sample. The overall yield of operational 3T switches from the chip for the vibration test was 29% (only 8 out of 28 switches were functional). This yield is rather low, e.g. as compared to the yield of 64% for the chip subjected to the shock tests. A low yield of operational switches usually correlates with a low overall cycling lifetime. Therefore, the observed single failure could not be reliably attributed to the vibration tests. In the revised paper we have addressed this point in more detail and removed the term "infant mortality" (page 4). We have performed high resolution optical microscopy on this switch after the failure, which showed no physical damage or any other structural issues that could be attributed to the vibrations:





An additional sentence with the results of the optical microscopy on the failed switch was added to the text (page 4). The images can be included in the full version of the paper:

"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."

The conclusions also has additional clarifications:

“ … 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.”

The following statements have also been added:

“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.”

“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.”

---------------------- REVIEW 2 --------------------

The manuscript presents interesting findings on 7T device performance, yet a few aspects require minor revisions to enhance clarity and strengthen the overall reliability of the conclusions.

1. Device Stability: The observed instability in the electrical behavior of the 7T structures, particularly the loss of the non-volatile state following mechanical shock, raises concerns regarding the robustness of the devices. Add just one sentence discussing about the underlying mechanisms of this failure

Review 1 raised a similar point in comment 2. As per the response there, the intended functional behaviour of the 7T switches is non-volatile, but due mostly to variations in the surface adhesion force at the contact, the behaviour can be volatile. Nevertheless, , in both cases the switch is functional, and the scope of this paper was to address the effect of the mechanical loads on the robustness of the switches, i.e. to check if their functionality is preserved after subjecting them to the mechanical loads, which is addressed on page 3. As requested, we have added this clarification in the paper.

2. Contact Material: The use of gold (Au) contacts, while common in nanoscale device research, is known to result in variable contact resistance over time. This limits the strength of the long-term performance claims. The authors are encouraged to briefly acknowledge this limitation or suggest possible mitigation strategies.

A discussion on the drawbacks of Au as contact coating material and alternatives has been included in the conclusions (page 4).

3. Incomplete Experimental Data: The reference to data on nanoscale devices as "to be added" suggests that the experimental section is not yet complete. Finalizing and incorporating this data is essential before publication to ensure the experimental validation is comprehensive.

We will be happy to add more experimental data in the extended version of this paper for the journal publication. As mentioned in the replies to the Reviewer 1, we could add the following:

- Tables with the details on pull-in and pull-out voltages
- Additional discussion on the electrical performances of 7T switches
- Optical microscopy images on the only failed sample, confirming no physical damage to it

4. Figure Legibility: Figure 4 refers to red and blue traces but it is red and green.

The mistake is corrected (blue -> green), thank you! We have also re-worked Figure 3 for better quality.

5. Lastly, while the references are mostly consistent, aligning them fully with the ESREF 2025 guidelines (and ensuring compatibility with Elsevier's style in the event of journal extension) is recommended. This includes standardizing abbreviations, adding missing publication years for standards, and including titles where possible. (ex. [5] M.K. Kulsreshath et al., IEEE Electron Device Letters, 2024, vol. 45, no. 4, 728. Add title "Digital Nanoelectromechanical Non-Volatile Memory Cell")

Thank you for pointing this out. The publication years and paper titles are added to the references and follow Elsevier's numbered style.

----------------------- REVIEW 3 ---------------------

In this work the authors investigate the functionality of NEM relays , 3T and 7T after sequential mechanical shocks of 1000 g and 5000 g and also after sequential mechanical vibrations one random with a peak amplitude of 45 g and the other of a sine form with peak amplitude of 70 g. The frequencies of the mechanical vibrations were within the range of 10-2000 Hz.

In both cases the devices were functional after the application of the mechanical shocks or vibrations with some modifications of the parameters of their function.

This work is interesting and certainly within the scope of ESREF regarding reliability issues of NEMS.

1. Why the authors used accelerations of 1000 g and 5000 g , or the mechanical vibrations described in the abstract? Is there any protocol these NEMS should follow? How is this related to the application of such NEMS?

The first level of 1000g was set as a qualification requirement for the developed devices. It was chosen to ensure the compliance with the Telcordia and MIL-883 standards (first severity level). The second level of 5000g corresponds to the maximum reachable acceleration with our equipment. This level ensures the compliance with the highest requirements of ESA and JEDEC standards. This information is on pg 2, Section3.

2. It would be very interesting to see how the dimensions of the NEMS to the scale of 100 nm will affect the functionality of the device as the authors promise to demonstrate in the final paper.

Unfortunately, our current advances with nm-sized switches do not allow carrying out the mechanical tests because of insufficient switching cycling reliability (typically about 10 cycles). The cycling reliability shall be improved to at least a few tens of cycles to enable the mechanical robustness tests without being potentially compromised by the low switching cycling reliability. This work is currently in progress.

3. It would be nice in the final article in the introduction to see some more information regarding the importance of such NEMS through examples of applications.

Examples of applications are added in Introduction on page 1.

4. Also, the authors should comment on how such devices particularly the non-volatile relays can be improved regarding their reliable functionality.

The two main strategies too improve the switch performance is to optimise the design dimensions (i.e. by miniaturisation) and to use a contact coating with better properties. Both approaches are currently being explored. The are mentioned in the

Conclusions (page 4) in a substantially revised section (see also response to comment 4 of reviewer 1).

5. In figures 3 and 4 the numbers on the axes and the letters should be larger in order to be readable. Please do so.

Figure 3 was completely re-worked to improve its quality. The font size in Figure 4 was also increased slightly. This big figure is meant to have two-column width, but we had to confine it to one column width to meet the 4-page space requirements. If the paper is accepted for the extended journal publication, Figure 4 will be two-column wide.

6. I suggest an oral presentation of this nice work.

We would be pleased to make an oral presentation.

----------------------- REVIEW 4 ---------------------

The authors investigate the robustness of NEM switches under mechanical shocks up to 5000g and vibrations up to 70g. The results, based on 100 tested devices, show that the functionality of the NEM switches is maintained.

This work is of interest for the community of NEMS designers, well-writen and organized. I recommend this paper for the ESREF 2025 conference.

Here are my remarks / questions :

1. Have the NEM switches been packaged? if not, did you perform the tests in a vacuum chamber ?

The investigated NEM switches were not packaged and were tested at the bare die level. Packaging of the switches is a planned project activity after the switch design is finalized and the switches exhibit sufficient reliability. The switches were tested in ambient conditions as thy are intended to operate in non-hermetic packages. This information was added to the manuscript (start of Section 3 on pg 2):

“Mechanical shock tests were carried out in ambient conditions on unpackaged 1 cm × 1 cm dies containing 28 3T switches and 56 7T switches”

We acknowledge that this indeed might affect the quality of the contact coating. Wafer-scale hermetic packaging is also foreseen at the later stages of the project.

2. Did you perform the test at wafer level ?

No, they were performed on unpackaged 1cm x 1 cm dies containing 28 3T switches and 56 7T switches. This is clarified in the manuscript, as per the response to comment 1 above.

3. What is the thickness of the gold deposited on top of the entire NEM structure (3T NEM relay) ?

The thickness of the Au coating was about 50 nm. This information is included in the manuscript.

---------------------- REVIEW 5 --------------------

The experimental procedure is well organized, and the manuscript well prepared and written. Despite this there are technical points needed to further improve the whole presentation of work.

1. The figures showing the pull-in and pull-out process are not clear, hence in the final paper this issue needs to be considered.

This point was also raised by the Reviewer 3. Figure 3 was completely re-worked to improve its quality. The font size in Figure 4 was also increased slightly. This big figure is meant to have two-column width, but we had to confine it to one column width to meet the 4-page space requirements. If the paper is accepted for the extended journal publication, Figure 4 will be two-column wide.

2. Physics of the decrease of pull-in and pull-out voltages with stress needs to be discussed and related to material wear out in the final paper not to be left as a simple statement.

A certain variation of the pull-in and pull-out voltages is very typical for our NEM switches with Au contact coating. This variation is observed before and after the mechanical tests (as presented in the manuscript), but also during continuous switching cycling of the switches in ambient conditions. This variation is caused by the changing conditions of the contact between the tip (source) and the drain. Any local effects, such as wear out of the contact material, or changing of the contact surface roughness affect the electrical properties of the switch. This discussion was added to the manuscript (page 2). Please see also reply to comment 4 of Reviewer 1.

3. Finally, as the authors pointed out in the manuscript more information is expected in the final paper.

This point was also raised by the Reviewer 2. We will be happy to add more experimental data in the extended version of this paper for the journal publication. As mentioned in the replies to other Reviewers, we could add the following:

- Tables with the details on pull-in and pull-out voltages
- Additional discussion on the electrical performances of 7T switches
- Optical microscopy images on the only failed sample, confirming no physical damage to it

Highlights

- NEM relays were subjected to mechanical shock loads up to 5000 g and vibration levels up to 70 g.
- All tested 3T and 7T relays retained their mechanical functionality after the applied shock and vibration stresses.
- Cycle-to-cycle variations of pull-in and especially pull-out voltages were confirmed to be intrinsic device behaviour.
- 7T switches exhibited transitions between volatile and non-volatile states due to contact interface variability.
- Au contact coatings were identified as a key limitation, motivating ongoing development of improved contact materials.

Mechanical shock and vibration testing of volatile and non-volatile nanoelectromechanical switches

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Abstract

Nanoelectromechanical (NEM) switches are promising for ultra-low-power electronics in harsh environments due to their zero leakage current and radiation hardness. However, their mechanical robustness under extreme loads remains insufficiently studied. This work investigates the performance of 3-terminal and 7-terminal NEM relays subjected to mechanical shocks up to 5000 g and vibrations up to 70 g. All tested devices retained mechanical functionality, confirming excellent structural integrity. Electrical characterization revealed variations in pull-in and pull-out voltages and loss of programmed states in 7T relays, although their non-volatile capability remained intact. These instabilities are primarily attributed to the soft Au contact coating, which is prone to wear and deformation. The findings highlight the suitability of NEM technology for harsh environments and point to future improvements through more suitable contact materials and device miniaturization.

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, 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 when powered down, 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. This paper extends our previous work to investigate the effects of the mechanical loads on the structural integrity and electrical performance of the NEM relays [6].

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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 physical contact allows current to flow, effectively turning the switch "on". When the electrostatic force is removed, the beam returns to its original position [7] through spring action in the beam, breaking the contact and turning the switch "off". Fig. 1 shows the schematic 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.

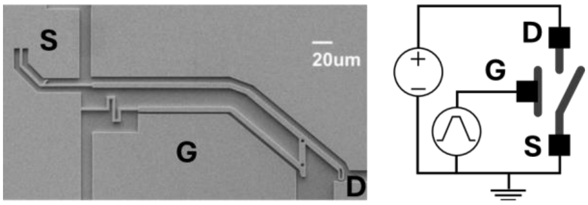

Fig. 1. Micrograph of a 3T NEM relay with Gate (G), Drain (D), and Source (S) terminals, and test circuit where the gate voltage is ramped up and down with a drain bias.

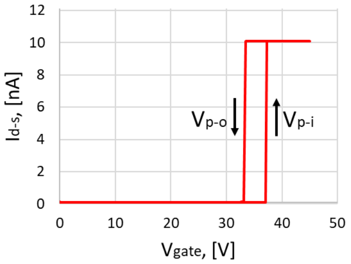

Fig. 2. Electrical characterisation of a 3T switch.

This relay is actuated by applying a voltage between the gate and source (beam): a gradually increasing positive voltage is applied to the gate, with the source 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 (see Fig. 2). By applying a positive voltage bias on the drain and monitoring the drain-source current (I_{d-s}), a switching event can be detected electrically as a step-like increase of I_{d-s}. Subsequently, the gate-source voltage is gradually decreased until the beam pulls out at the pull-out voltage (V_{p-o}), and I_{d-s} goes back to zero.

Another type of NEM device investigated in this study is a 7-terminal (7T) relay shown in Fig. 3, fabricated using the same process as for 3T relays. All 7-T devices start in a “neutral” state, with the beam in the centre. In the first programming cycle the beam is rotated either clockwise or anticlockwise by driving one of 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 opposite beam tip to land on drain D2. To achieve non-volatile functionality, 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 (see actuation of “state 1” in Fig. 4, where the device is rotated clockwise). This type of NEM relay 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 (see actuation of “state 2” in Fig. 4, where the beam is rotated anticlockwise), the relay is volatile, like the 3T switch described above. For non-volatile devices, to switch the state and rotate the beam to the opposite drain, a voltage is applied to the opposing pair of gates, which is termed reprogramming. Two reprogramming schemes can be identified: the force (and voltage) required to pull the beam out of contact can either be greater or less than the force (and voltage) required to switch the beam from the neutral state to a drain. In the first scheme, the beam pulls out and switches to the other state without any further increment in the gate drive. This behaviour can be seen in Fig. 4 where “state 1” is non-volatile, and actuation to “state 2” occurs after pull out. This work only used devices of this reprogramming type (see [7] for more details on how the 7-T switch works). It can also happen that a device designed to be non-volatile, because of deviations in fabrication, can become volatile. Comparison of the electrical characterisation of volatile and non-volatile states in 7T switches is shown in Fig. 4.

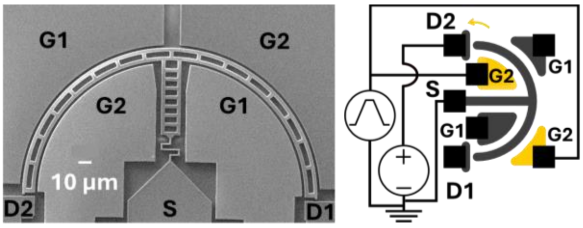

Fig. 3. Micrograph of a 7T NEM relay with Gate (G1, G2), Drain (D1, D2) and Source (S) terminals, and test circuit where the gate voltage is ramped up and down for anticlockwise rotation with a bias on D2.

More details on the design, fabrication and electrical characterisation of the studied 3T and 7T NEM relays can be found in [4][7]. 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. It is important to note that even at room temperature, the electrical characteristics of the NEM relays can show notable cycle-to-cycle variations. In particular, the pull-in voltage $V_{p\text{-}i}$ of a given 3T switch typically varies within approximately ±2 V, whereas the pull-out voltage $V_{p\text{-}o}$ exhibits a considerably broader range, often spanning from about 18 V to 37 V. Such variations are intrinsic to the mechanical nature of the contact interface and may arise from minor changes in contact surface roughness, adhesion conditions, or residual stress relaxation within the beam structure.

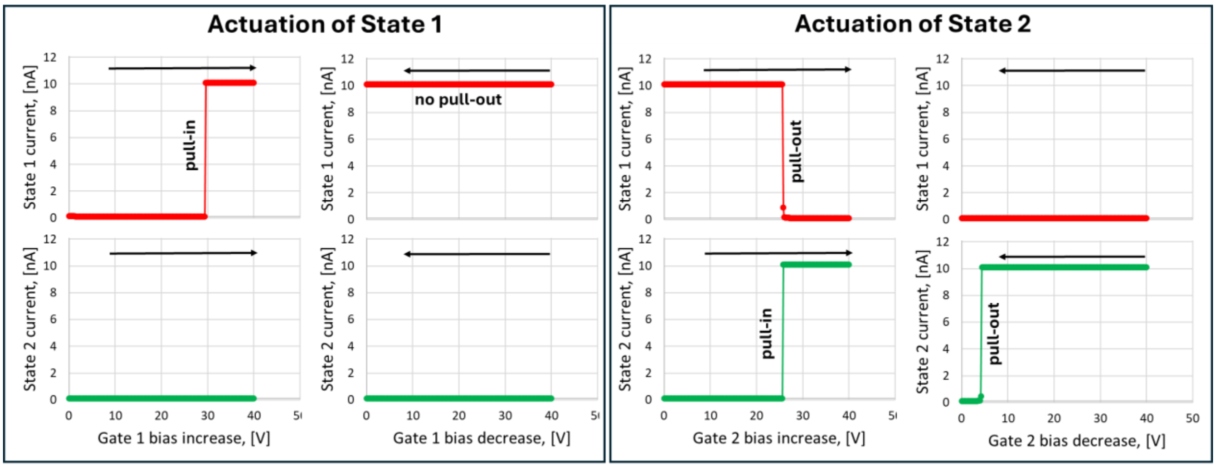

Fig. 4. Electrical characterisation of a 7T switch. State 1 shows non-volatile behaviour, while State 2 is volatile.

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 [8][9][10]. 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. Some variations in the pull-in and pull-out voltages were observed, especially after the tests at 5000 g (see Table 1). However, such variations are not considered failures, as similar behaviour has been consistently observed in multiple batches of NEM devices with Au contact coatings during cycling tests at room temperature. 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. 5 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 34-35 V when the device is switched back to the "off" state during the gate voltage ramp-down. The pull-out voltage slightly changed (34 V before the shock test and 35 V after the shock test), whereas the pull-in voltage stayed almost identical (37 V).

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.

Device ID	Initial (V_{p-I} / V_{p-o})	After 1000 g (V_{p-I} / V_{p-o})	After 5000 g (V_{p-I} / V_{p-o})
B01	37 V / 33 V	37 V / 35 V	37 V / 33 V
B02	37 V / 33 V	37 V / 36 V	37 V / 27 V
B03	37 V / 34 V	37 V / 35 V	37 V / 26 V
B05	37 V / 32 V	37 V / 36 V	37 V / 22 V
B06	37 V / 35 V	37 V / 33 V	37 V / 35 V
B07	37 V / 37 V	37 V / 34 V	37 V / 22 V
B10	37 V / 33 V	37 V / 30 V	37 V / 34 V
B11	37 V / 36 V	37 V / 35 V	37 V / 28 V
B13	37 V / 35 V	37 V / 36 V	37 V / 18 V
B14	37 V / 36 V	37 V / 35 V	37 V / 23 V
B15	37 V / 35 V	37 V / 34 V	37 V / 21 V
B16	37 V / 36 V	37 V / 37 V	37 V / 25 V
B20	37 V / 34 V	37 V / 34 V	37 V / 21 V
B21	37 V / 34 V	37 V / 35 V	37 V / 25 V
B22	37 V / 34 V	37 V / 33 V	37 V / 22 V
B24	37 V / 36 V	37 V / 35 V	37 V / 23 V
B25	37 V / 36 V	37 V / 34 V	37 V / 23 V
B26	37 V / 32 V	37 V / 37 V	37 V / 19 V

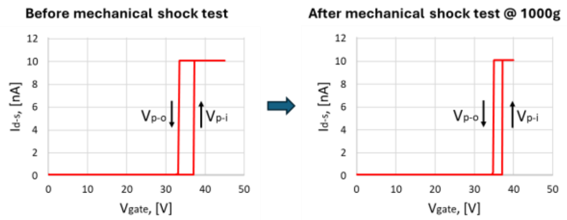

Fig. 5. Example of the electrical characterisation of a 3T switch before and after the shock test at 1000 g.

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. This behaviour is closely related to the same physical mechanisms that cause variations in the pull-in and pull-out voltages. Minor changes in the contact surface conditions – such as local deformation or wear of the Au coating, variations in adhesion forces, or small shifts in surface roughness – can alter the balance between the restoring spring force of the beam and the adhesion force at the contact. As a result, the device may intermittently exhibit either volatile or non-volatile behaviour depending on the precise state of the contact interface during a particular switching event. 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).

Among the 39 tested 7T switches, 6 devices remained volatile throughout all mechanical shock tests, 4 devices consistently retained their non-volatile behaviour after each test stage, while the remaining 29 devices exhibited transitions between volatile and non-volatile states. Fig. 6 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 latched 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.

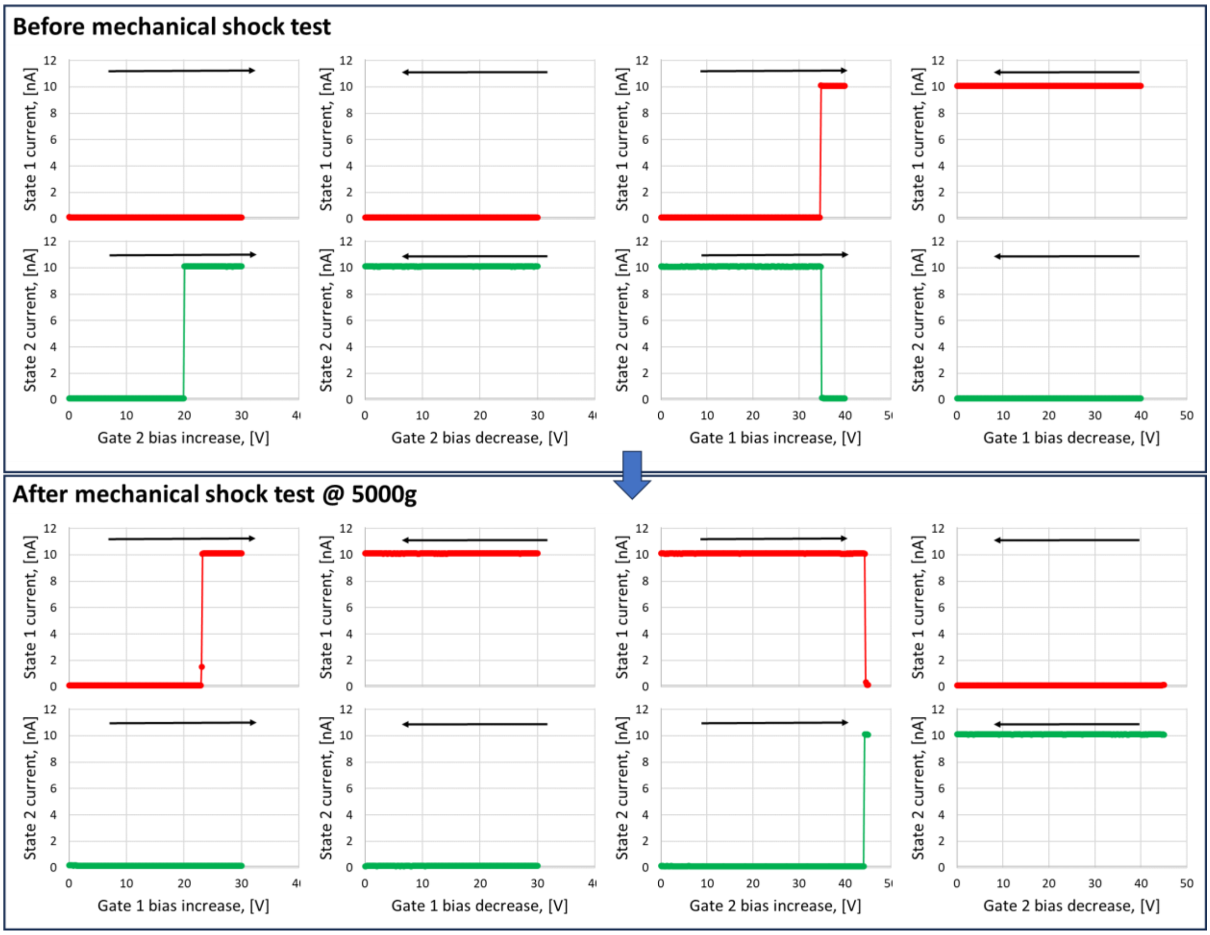

Fig. 6. Example of the electrical characterisation of a 7T switch before and after the shock test at 5000 g. Red curve: drain1-source current, green curve: drain2-source current.

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 [12], JEDEC [13] and ESA [14] 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. Similar to the mechanical shock tests, variations in the pull-in and pull-out voltages were observed. One of the switches failed to actuate after the sine sweep vibration test. The overall yield of operational 3T switches on the chip used for the vibration tests was 29% (8 out of 28 switches), which is relatively low compared to the 64% yield obtained for the chip subjected to the shock tests. A low initial yield typically correlates with reduced overall cycling reliability, as devices from such batches often exhibit premature degradation of the contact interface or beam anchoring regions. Notably, the failed sample was located in a chip area with an even lower local yield, where most neighbouring switches were non-functional already prior to testing. Consequently, the single observed failure cannot be reliably attributed to the applied vibration loads but is more likely linked to the inherently limited cycling reliability of the devices from this particular chip region. High-resolution optical microscopy inspection of the failed switch did not reveal any visible physical damage to the beam, anchors, or contact region (see Fig. 7). No signs of fracture, delamination, or permanent deformation were detected, further supporting the conclusion that the observed failure is unrelated to the applied vibration loads and can be regarded as a non-representative outlier.

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.

Device ID	Initial ($V_{p\text{-}I}$ / $V_{p\text{-}o}$)	After random vibration ($V_{p\text{-}I}$ / $V_{p\text{-}o}$)	After sine sweep vibr. ($V_{p\text{-}I}$ / $V_{p\text{-}o}$)
B12	37 V / 35 V	37 V / 32 V	43 V / 33 V
B17	37 V / 25 V	39 V / 39 V	fail to actuate
B20	37 V / 17 V	37 V / 29 V	37 V / 37 V
B21	37 V / 33 V	39 V / 12 V	37 V / 33 V
B24	37 V / 32 V	37 V / 16 V	36 V / 27 V
B25	37 V / 16 V	37 V / 17 V	36 V / 21 V
B26	37 V / 15 V	38 V / 32 V	37 V / 17 V
B27	37 V / 31 V	37 V / 18 V	37 V / 33 V

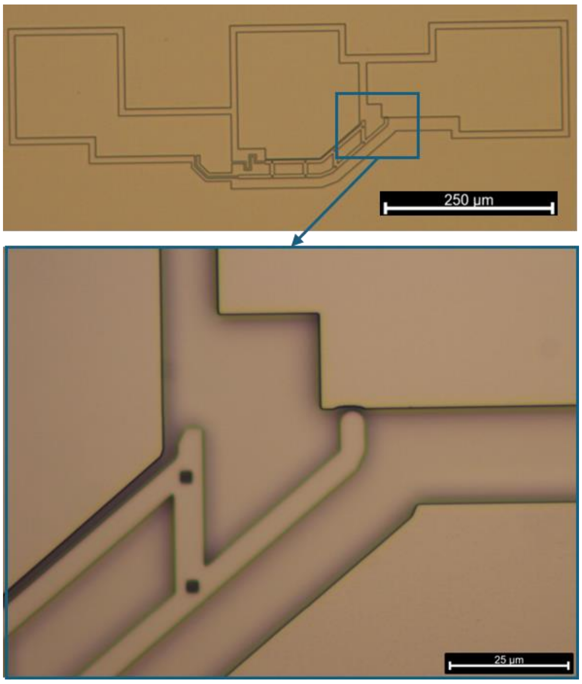

Fig. 7. High-resolution optical microscopy inspection of the switch B17 that failed to actuate after the sine sweep vibration test.

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. Of the 41 tested 7T switches, 17 devices remained volatile throughout both mechanical vibration tests, only 2 retained stable non-volatile behaviour, and the remaining 22 exhibited intermittent transitions between volatile and non-volatile operation. All 7T devices exhibiting non-volatile behaviour before and after the mechanical tests did not retain their programmed state following testing. Specifically, during the pre-test electrical characterization, the switches were set to a defined non-volatile state. However, after the mechanical tests, this programmed state was lost, and the switches reverted to their neutral state. Despite this, post-test electrical characterization confirms that the devices remain non-volatile. This indicates that while the switches can reliably maintain programmed states during electrical characterization, the application of mechanical loads (shocks or vibrations) causes a loss of the programmed state without affecting the inherent non-volatility of the device.

5. Conclusions

Mechanical shock and vibration tests confirm excellent structural robustness of NEM relays. Out of ~100 devices subjected to shocks up to 5000 g and vibrations up to 70 g, only one actuation failure occurred, likely unrelated to mechanical stress. All other 3T and 7T switches retained mechanical functionality after testing.

Electrical behaviour, however, showed variability. For 7T relays, mechanical loads caused loss of the programmed state, even though the devices remained non-volatile. This indicates that shocks and vibrations affect state retention but not the fundamental non-volatility of the device. Variations in pull-in and pull-out voltages were also observed, primarily due to the soft Au contact coating, which is prone to deformation and wear especially in moving MEMS parts thus leading to the deterioration of the contact stability with time.

Overall, the results demonstrate that NEM technology can withstand extreme mechanical conditions, making it promising for harsh-environment electronics. Future improvements – such as replacing Au with more suitable coatings (e.g., nanocrystalline graphite or Ru) and reducing beam mass through miniaturization – are expected to enhance state retention and long-term reliability.

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Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.