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A methodology for evaluating MEMS switch reliability at cryogenic temperatures

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Abstract. Current commercially available Micro Electromechanical Systems (MEMS) switches are designed to operate within a limited range of temperatures near room temperature, thus their long-term performance at lower temperatures requires more investigation. We developed a set of reliability test methods for MEMS at cryogenic temperatures. We demonstrate measurements of the commercial MEMS switches' hysteresis curve widths, contact resistances, and switching times, at up to ten equilibrium temperatures from room temperature down to 18K. We also performed these characterizations as a function of the number of switching cycles, for up to 1 million cycles at temperatures of 18K and 50K. These test methods may potentially help provide MEMS manufacturers and users with data for device development, and for developing guidelines for MEMS cryogenic applications.

1. Introduction

Radio frequency (RF) switches made using MEMS (microelectromechanical systems) technology offer many advantages over traditional larger switches, such as smaller size, lower weight and power consumption, faster switching speeds, lower insertion loss and higher linearity. Recent reviews of RF MEMS switch technology and applications can be found in Refs [1, 2]. Typical applications, such as in telecommunications, involve room temperatures but there has also been interest in custom fabricating MEMS switches for cryogenic applications with temperatures of 1 - 10K, [3-7]. The current work is part of a larger program aimed at developing new microwave measurements for quantum computing [8]. Commercial MEMS switches are designed for room temperature operation so their long-term reliability at cryogenic temperatures needs investigation, whereby we define "reliability" as not only catastrophic failure where the switch no longer opens or closes, but as the intermediate path where the electromechanical characteristics change with temperature and time, which can lead to performance degradation. Furthermore, commercial MEMS are also packaged by the manufacturers in sealed hermetic chip housings, which prevents use of optical metrology and other methods requiring direct access to the chip.

To this end, we have developed a cryogenic test chamber and a set of DC electrical test protocols for evaluating the reliability of MEMS switches over a range of cryogenic temperatures. We demonstrate our metrology on commercially obtained (fully packaged) MEMS switches. In our previous work we reported initial details of our apparatus and test protocols and demonstrated extensive measurements first on one MEMS switch [9] and then on four identical MEMS switches in the same package [10], with both sets of tests conducted at six steady state temperatures down to 55K. These tests revealed subtle differences in the electromechanical response of identical devices within the same package and the effects of cryogenic temperature operation versus cryogenic cooling without cryogenic operation.

In the present work, we show further refinement of our instrumentation and test methods by testing two identical sets of MEMS switches simultaneously at several temperatures down to 18K, and adding new measurements of the switching speed, and the effect of cycling the switches on and off at the cryogenic temperatures.

2. Experimental Methods

2.1 Devices under test

To demonstrate our cryogenic MEMS reliability test methods, we purchased two identical sets of MEMS switches from a commercial vendor and ran tests on them. Each set consists of a 2.5 mm x 2.5 mm hermetically sealed housing containing four identical MEMS switches. Each chip package was mounted by the manufacturer on identical printed circuit boards (PCB's) with dimensions 1.5 x 2.5 inches (38.1 x 63.5 mm) and with RF transmission lines and SMA (SubMiniature version A) connectors. Each board came with a separate and identical PCB containing the control circuitry to turn each switch on and off. We used the manufacturer's control board only during our high-cycling tests (see Sections 3.2 and 3.4).

Both sets were purchased three years before the present work, and labeled as boards "A" and "B". We designate each switch by its board and number, i.e., "A1" refers to switch #1 on board A. We reported preliminary results of our cryogenic tests on Switch A1 two years ago at CEC/ICMC 2023 [9]. We then reported our test results for Switches A1, A2, A3, and A4 last year at the ASME IMECE 2024 conference [10]. The minimum test temperature in both cases was 55K. Board A was tested again this year down to a temperature of 18K. Board B, by contrast, remained in its box from the manufacturer and was stored at room temperature in a typical office environment until tested for the first time this year down to a temperature of 50K.

2.2 Cryogenic test apparatus

Figure 1a shows our Gifford-McMahon (GM) cooled test chamber and the MEMS control and data acquisition system, and Fig 1b shows one of the MEMS boards mounted inside the chamber. We reported the details of this test setup in our previous works [9, 10] in which we had used only the first cooling stage. In the current work we have further developed the test apparatus by adding the second cooling stage to cool and test two MEMS boards simultaneously.

We mounted board A to the second stage (see Fig 1b) and board B to the first stage, which cooled to minimum temperatures of 18K and 50 K, respectively. Each MEMS board was held with GTA bars to machined copper thermal adapters designed to provide thermal contact while ensuring electrical isolation. As in our previous work, thermocouples were attached to each stage, and to each PCB, and to the top of each chip package. Our earlier work [9] showed the typical steady state temperatures reached at these locations for the first stage. In the present work, all temperatures referred to hereafter are the stage temperatures. All, circuitry, electronics and instrumentation were located outside the chamber.

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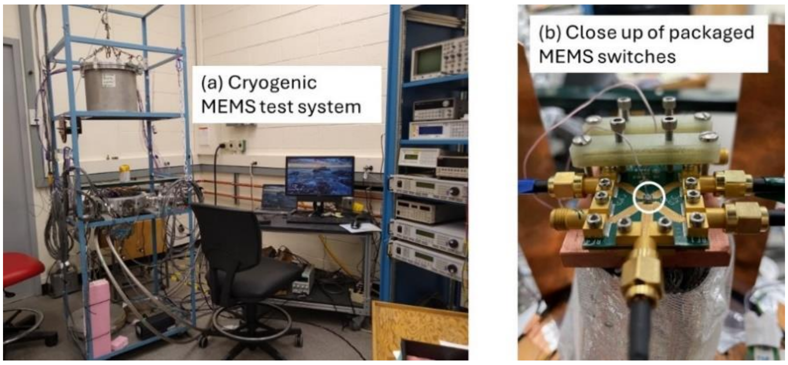

Figure 1. Photographs of (a) the cryogenic MEMS test system and (b) close up of one of the commercial MEMS boards mounted inside the chamber. Circled is the 2.5 mm x 2.5 mm hermetically sealed chip

2.3 Test protocols

As in our earlier work, we cooled the MEMS boards to several pre-selected and adjustable steady-state temperatures, and at each temperature we ran several types of DC electrical tests on each switch.

For the current test series, the chamber was first pumped down to a pressure of about 1E-4 Torr (0.013 Pa). Then an initial set of characterization tests was run on switches A1, A2, A3, B1 and B2 sequentially, at room temperature. These tests were the cold-switching hysteresis test, hot-switching hysteresis test, and “creep” test, these test protocols were described in our earlier work [9]. We then added new measurements of the switching times. Both boards were simultaneously cooled, and at each equilibrium temperature the above tests were repeated on each switch. The temperatures for the first stage (board B) were: 250K, 200K, 150K, 100K, 50K. The corresponding temperatures of the second stage (board A) were: 130K, 50K, 30K, 22K, 18K. After the characterizations at the lowest temperatures were completed, the cryostat was shut off and the system allowed to naturally warm up to room temperature. A final set of characterizations was then repeated on each switch at room temperature again. The test data for each switch at each temperature (including the pre-cool and post-cool room temperature) were recorded by a data acquisition system with custom software to automate the operation of the tests as well as record the raw data and temperatures.

When the characteriztion tests at all temperatures were completed, we then added a new test protocol, described in Section 3.2 and 3.4, which we call the “high-cycle tests”. Here the switches were kept at temperatures of 18K (board A) or 60K (board B) while being cycled on and off at a rate of 7 kHz. We re-measured each device’s hysteresis, creep, and switching speed characteristics after every 100,000 cycles.

3. Results

3.1 Hysteresis width vs. temperature

Figure 2 shows a typical hysteresis curve measured on a switch (in this case, A1 at room temperature). As described in our earlier work [9], we sweep the drive voltage from 0V to 90V and back, in steps of 1 V, while measuring the switch’s contact resistance in a four-probe configuration.

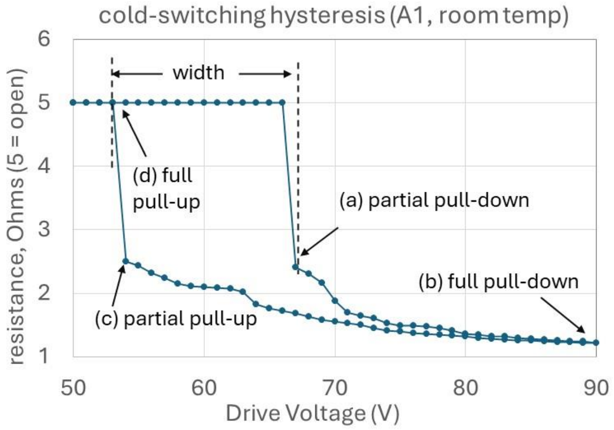

Figure 2. Typical hysteresis curve measured for one switch, from [9, 10]. To improve the clarity of the plot, we arbitrarily assigned a value of 5 Ohms when the contact resistance was infinite. The contact resistance was measured using a four-probe configuration.

A typical DC-contact MEMS switch is a thin-film metal cantilever beam which, in the "off" state, is suspended over the substrate, resulting in an open circuit. At a critical threshold voltage, the beam collapses to contact the substrate which closes the switch, we call this critical voltage the "partial pull-down voltage", shown as point (a) in Fig 2. When the voltage further increases the beam makes firmer contact with the substrate due to the higher electrostatic force, and the contact resistance reaches a steady state minimum which we call the "full pull-down" condition, labeled as (b). Full pull-down for the switches in this work was consistently reached by 90 V. When the voltage is decreased, the electrostatic force decreases leading to increasing resistance, corresponding to (b) to (c) in Fig 2. Eventually a new threshold voltage is reached whereby the mechanical restoring force of the beam, due to its material elasticity, overcomes the electrostatic force and the beam fully releases from the substrate leading to infinite resistance again, corresponding to (d). In our tests we define the hysteresis width as $V_{partial\_pull\text{-}down} - V_{full\_pull\text{-}up}$ or $V_a - V_d$. Figure 3 shows the variation of the hysteresis widths measured for five switches at each temperature.

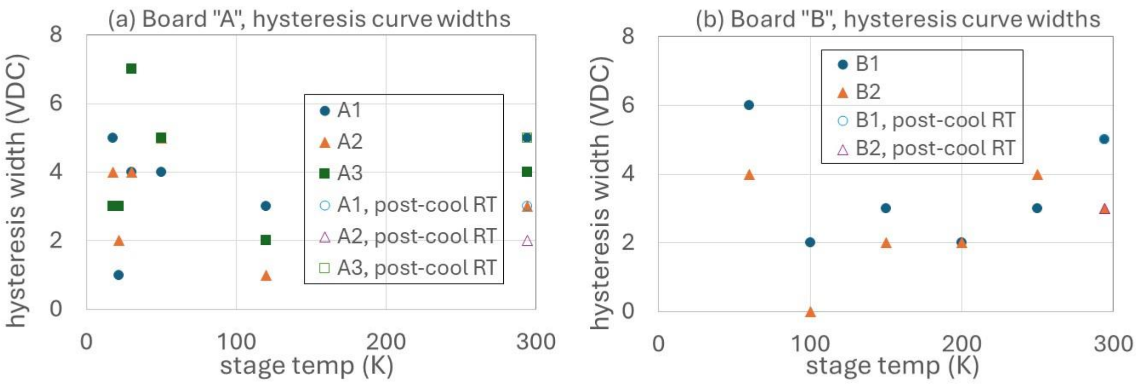

Figure 3. Graph of cold-switching hysteresis curve width vs. temperature. The direction of the test is from room temperature toward decreasing temperature, followed by the post-cooling room temperature. The uncertainties in the voltage and temperature are 0.1 V and 1 K, respectively.

The plots for all the devices in Fig 3 show a "U" shape in the first regime from room temperature down to ~50K, with the minimum hysteresis width occurring in the temperature range of 100-150K. This trend was also observed in our previous tests on board A [10] (However, when switch A1 was initially tested prior to that, its hysteresis width had decreased monotonically with decreasing temperature down to 55K [9].) For all switches, at temperatures above the inflection range of 100 - 150K the hysteresis curves are relatively smooth, but are less smooth when the temperature drops below this inflection range, with the curves measured within the inflection range being the most uneven, as shown in Figure 4 for one representative switch.

As shown in Fig 3, when the switches were gradually warmed back up to room temperature, some showed hysteresis widths near their initial (pre-cooled) values (A3, B1 and B2), while other devices showed slightly different hysteresis widths compared to their pre-cooled values (A1 and A2), which might indicate permanent deformation in the switch material.

Note that in Fig 4, the minimum hysteresis width, which occurs in the temperature range of 100 - 150K, is as small as 1V. The pull-down voltages for all switches ranged from approximately 65V at the lowest temperature to 70V at room temperature. The pull-up voltages varied more with temperature and account for the "U" shape in Fig 3 and the narrowing of the hysteresis curves.

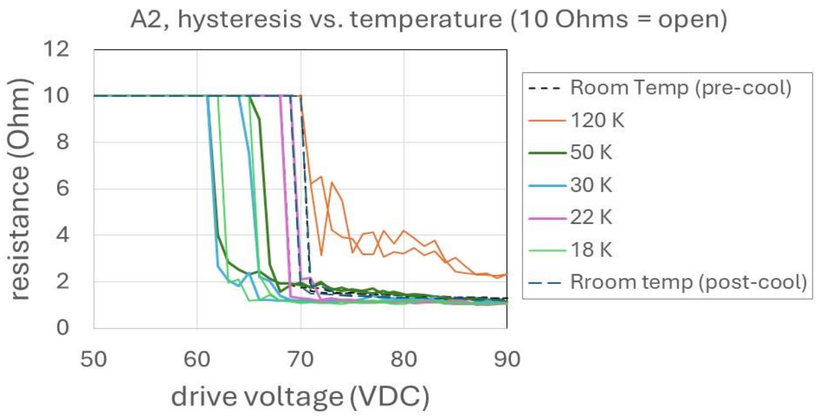

Figure 4. Hysteresis curves for one switch at different temperatures. Plots for all other switches are similar. At the inflection temperature the curves are the most uneven. At temperatures above that, the curves are smooth.

The hysteresis curves in general also appear to narrow over time. When switch A1 was first tested extensively two years prior to the present work, its hysteresis width at that time [9] was approximately 3X larger than its current value in Fig 3 above, at all test temperatures. A1's previous hysteresis width values are also 3X higher than that of all other switches in the present work, at all temperatures, including the "B" switches which were operated for the first time in the present test series. The increase in pull-up voltage, in general, might thus be due to an increase in moisture content inside the chip packages over time, perhaps as a result of microscopic leaks or diffusion. For example, it has been found that the surface charge distribution and charge dissipation rate of electrostatic actuators varies with humidity, with faster charge decay occurring at higher relative humidity [11]. These hysteresis tests might be a way to detect that effect in packaged MEMS switches.

Contact resistances corresponding to $V_{partial\text{-}pull\text{-}down}$ followed different trends for the two boards. The "A" devices showed monotonic increase and wider variation in resistance as temperatures dropped, from 2-3 Ohms at room temperature to 2-9 Ohms at 18K. The "B" devices, on the other hand, showed increase in resistance from 2 Ohms at room temperature to 11 Ohms when cooled to 200K, but then decreased when cooled further, reaching ~2 Ohms again at 60K. (Note that these are the resistances at *partial* pull-down, not at full pull-down whch are lower.) By contrast, Brown et. al [6] found their commercial but unpackaged MEMS switches (from a different vendor) exhibited decreasing contact resistance with decreasing temperature down to 77K.

3.2 Hysteresis widths after 1 million on/off cycles at cryogenic temperature

Figure 5 shows the hysteresis curve widths, and the contact resistances at partial pull-down, for the five switches before they were cycled on and off, and after 100,000 on/off cycles, and after 1 million cycles, all at cryogenic temperatures. 90 V drive voltage was used to ensure full pull-down during cycling. The hysteresis widths of all devices converged to a value of 4 - 5V after 1 million cycles. All devices were still fully operational after 1 million cycles at 18K (board A) and 50K (board B), but the contact resistances and hysteresis widths differed from their pre-cycled values at those temperatures. For comparison, Benoit et. al [7] found their (unpackaged and non-commercial) MEMS switches had lifetimes of 6 million cycles at liquid He temperature.

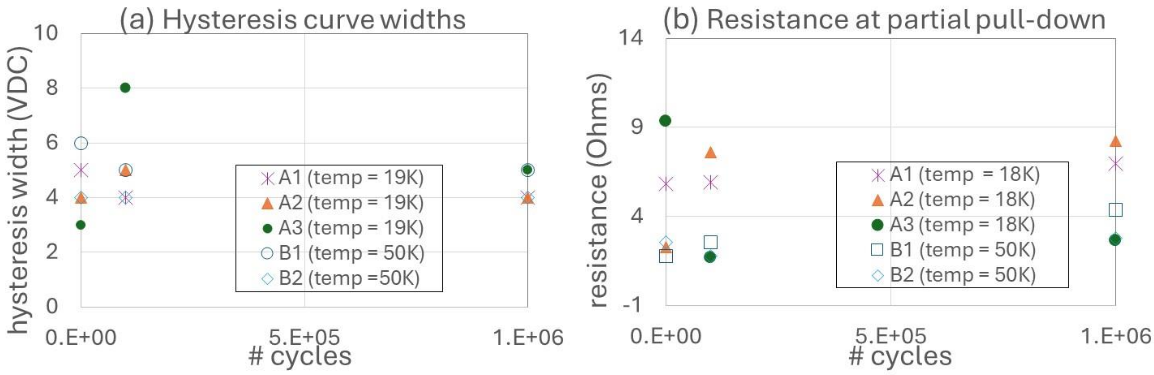

Figure 5. High cycle tests at temperatures of 18K (board A) and 50K (board B). The hysteresis curve width (a) and contact resistance (b) were measured after every 100,000 cycles. The values before cycling, after the first 100,000 cycles and after 1 million cycles are plotted. Where the open circles/squares are not visible on the graph, it is because they are directly overlaid on top of the other data points.

3.3 Switching times vs. temperature

We measured the time for each MEMS switch to turn on and off at each temperature. For this hot-switching test, a 0.5 VDC carrier signal was input into the MEMS switch. The switch was cycled on and off at a frequency of 0.5 Hz using a square wave from 0-90V. The drive voltage and carrier signal were recorded at a sampling rate of 100 kHz. Figure 6 shows typical measurements for one switch at 18K. The “rise time” is the time for the carrier signal to reach its full value of 0.5 V after the drive voltage is turned on. The “fall time” is the time taken for the carrier signal to decrease to 0V after the drive voltage is turned off. Plots for all the other switches, at all temperatures, appear similar.

Figure 7 shows that the rise times of the carrier signal, for all the switches across all temperatures, ranged from 10-40 μs whereas the time for the drive voltage to reach 90V was 50 μs. The carrier signal’s rise time is less than that of the drive voltage because the MEMS partially pull-down at ~60-70V, as shown in Figs 3 and 4. The MEMS’ fall times are on the order of 1-2 ms for all temperatures.

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3.4 Switching times after 1 million on/off cycles at cryogenic temperature

Figure 8 shows the rise and fall times of switches A1, A2, and B1 measured before cycling, after 100,000 cycles, and after 1 million cycles, with both the cycling and the switching time measurements done at cryogenic temperatures. Since the resolution of the measurement was 10 μs, the longer rise time after 1 million cycles (Fig 8a) is within the measurement uncertainty. Fig 8b shows ~ 10% decrease in fall times after 1 million cycles.

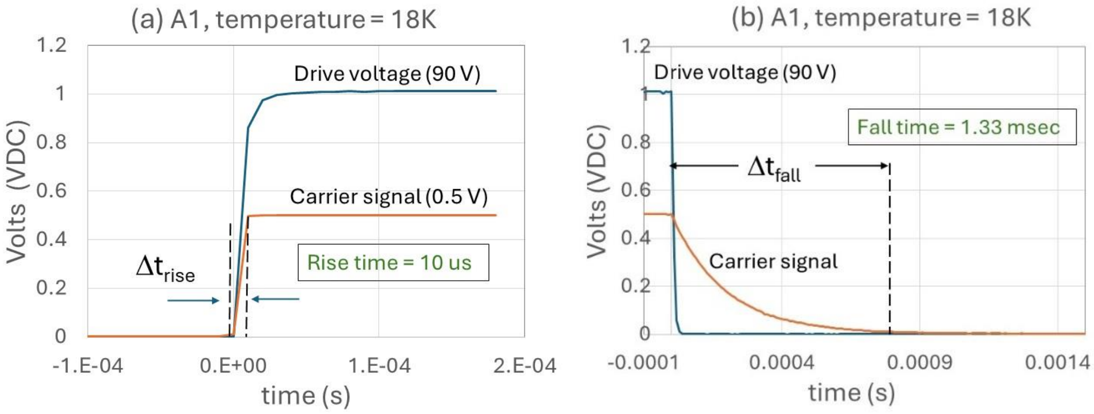

Figure 6. Rise time and fall time of a typical MEMS switch (switch A1) at temperature18K. Plots for all other switches at all temperature are similar.

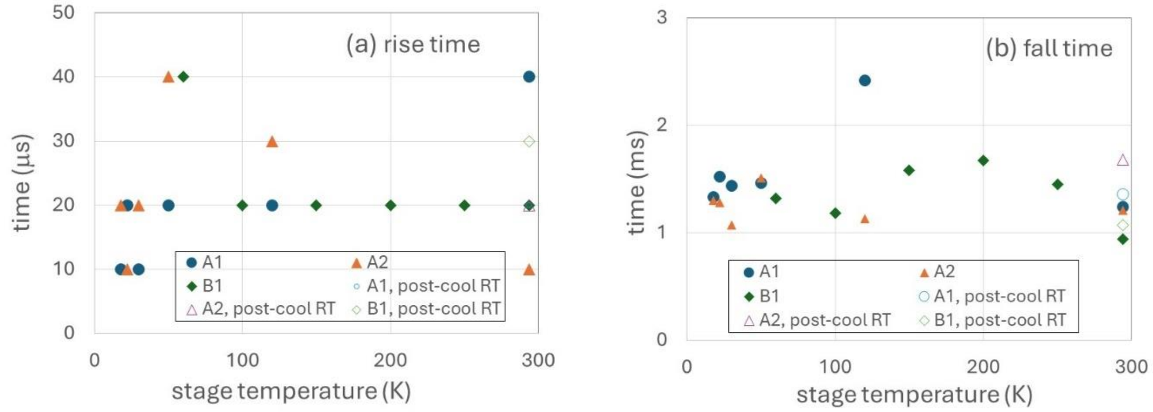

Figure 7. Summary of rise- and fall times for each switch at each temperature. The direction of the test is from room temperature toward decreasing temperature, followed by the post-cooling room temperature. The uncertainty in the time is 10 μs. Where open circles/triangles are not visible is when it is directly overlayed on top of other data points.

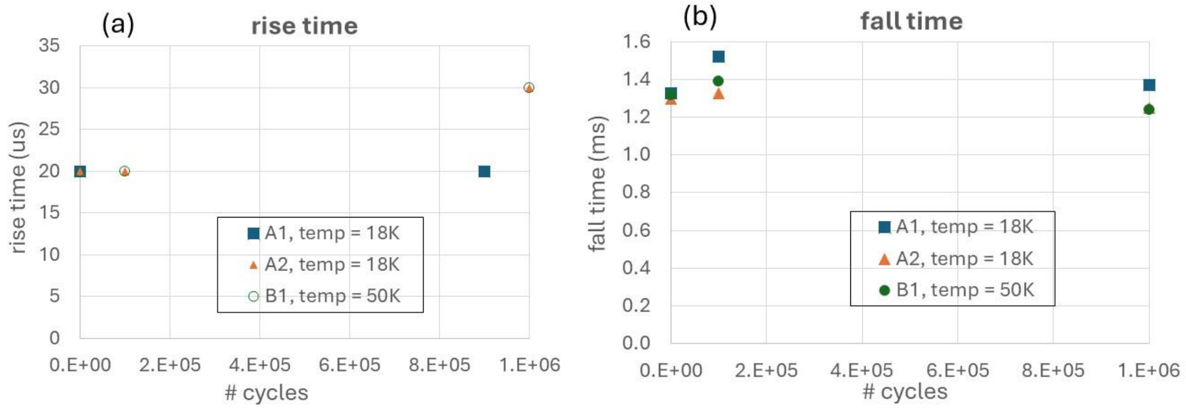

Figure 8. High cycle tests at temperatures of 18K (board A) and 50K (board B). The rise times (a) and fall times (b) of three switches are shown. Their values before cycling, after the first 100,000 cycles, and after 1 million cycles are plotted. Where the open circles are not visible on the graph, it is because they are directly overlaid on top of the other data points.

The manufacturer's specification sheet shows device lifetime of more than 3 billion cycles to failure at room temperature, with failure defined as the switch being stuck closed. So far we have cycled the switches for 1 million cycles at cryogenic temperatures, and measured gradual changes in their hysteresis, creep and switching time characteristics. Future work will consist of more cycles at cryogenic temperature, with periodic characterization tests, until failure is reached.

4. Summary

We described our test apparatus and protocols for measuring changes in MEMS switches' electromechanical characteristics from room temperature down to 18K and demonstrated these methods on two sets of identical commercially available switches. We showed a subset of our test methods and data, with a focus on the changes in the MEMS' hysteresis curve width and switching speed as a function of cryogenic temperature and number of actuation cycles at low temperatures. Our test methods, and the representative data we obtained, could potentially assist MEMS manufacturers with developing their device designs and fabrication processes, and provide their customers with guidance on device operation at cryogenic temperatures.

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