Characterizing MEMS Switch Reliability for Cryogenic Applications such as Quantum Computing

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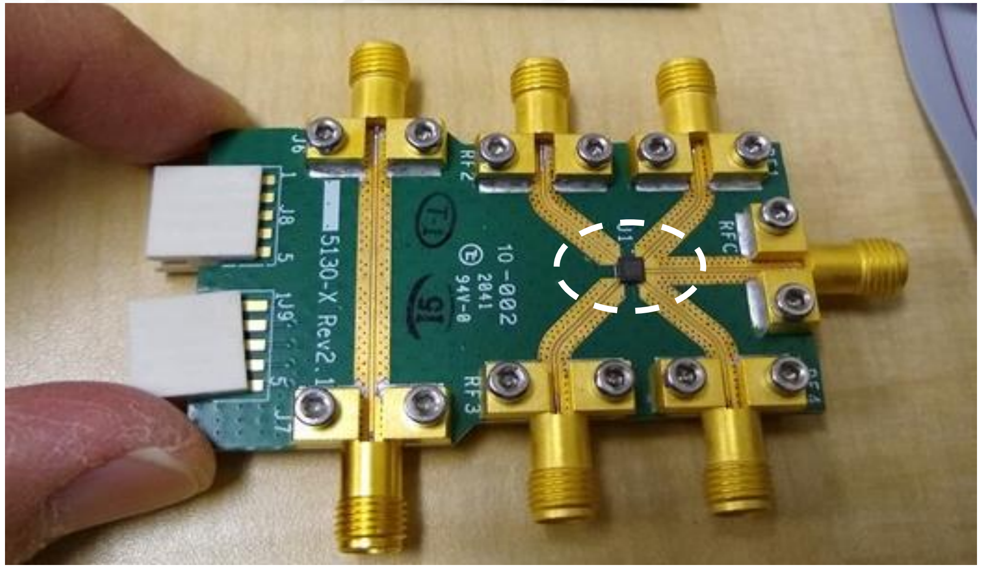
Scaling up quantum computing

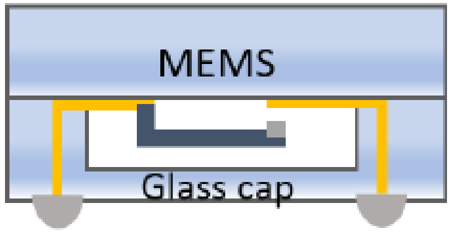
- Current quantum computers: 100's of qubits.
- Many qubit technologies, all require microwave signals to condition, initialize, and read out the qubits
- NIST: developing new microwave measurements at cryogenic (mK) temperatures, to enable $10^2 \rightarrow 10^6$ qubits to run in a dilution refrigerator
- RF MEMS switch is a critical component for NIST's cryogenic microwave measurement strategy.
  - Novel (this work): reliability data of electrostatic and/or commercial MEMS at various cryogenic temperatures

IBM quantum computer, https://spectrum.ieee.org/ibm-condor

- Low insertion loss
- High isolation
- High linearity
- Very low power consumption
- Fast switching speed
- Small size

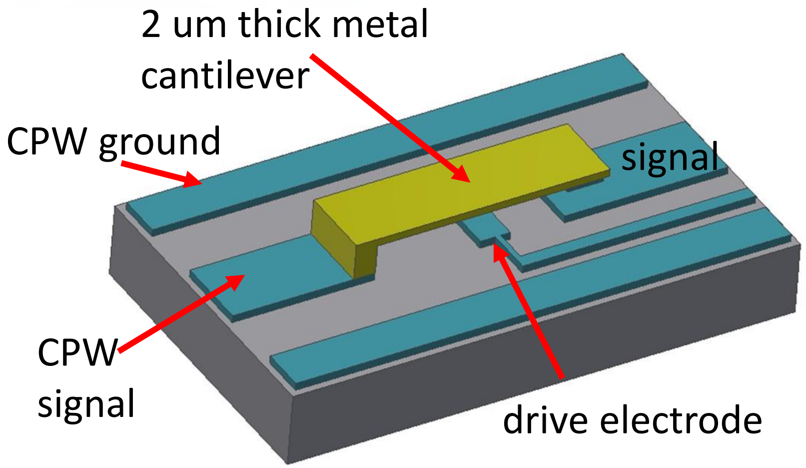


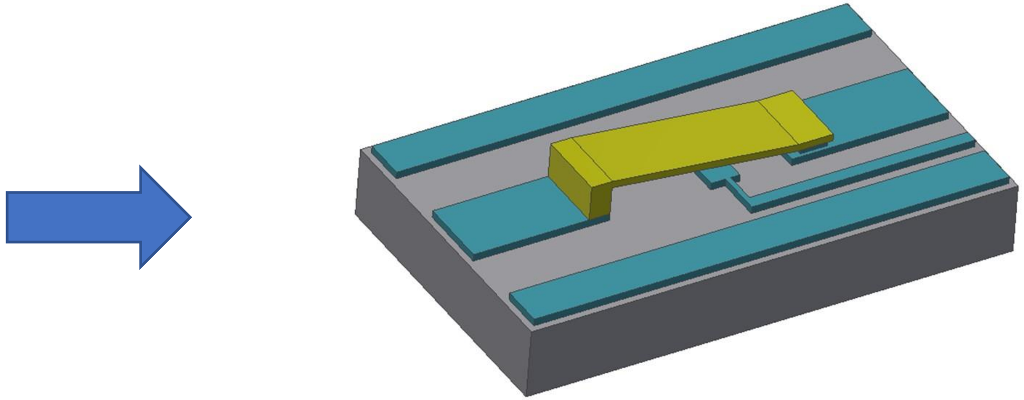
Commercial RF MEMS switch



Cross section schematic from manufacturer's data sheet

DC contact MEMS switch operation





Switch is OFF – signal is isolated

Switch is ON – signal passes through the signal line

Typical switch material: Au, 2 um thick
Typical substrate: Si, Al_2O_3,

Reliability Issues for MEMS switches at cryo temperatures

- CTE mismatches → residual stresses, change in the operating characteristics or mechanical damage/failure

- Thermal cycling → mechanical failures
- Material properties' temperature dependence (resistivity, stiffness, strain hardening)
- Plastic deformation and creep
- Contact wear degradation (DC contact switches), adhesion failures
- Dielectric charging stiction (capacitive shunt switches)
- The above can lead to varying switch characteristics over time.
- Design tradeoffs e.g. switching speed vs actuation voltage

Objectives

- Commercial MEMS switches are designed for room temperature operation

→ Goal: evaluate the reliability of commercial MEMS switches at cryogenic temperatures; provide guidance on switch lifetime and damage mitigation strategies

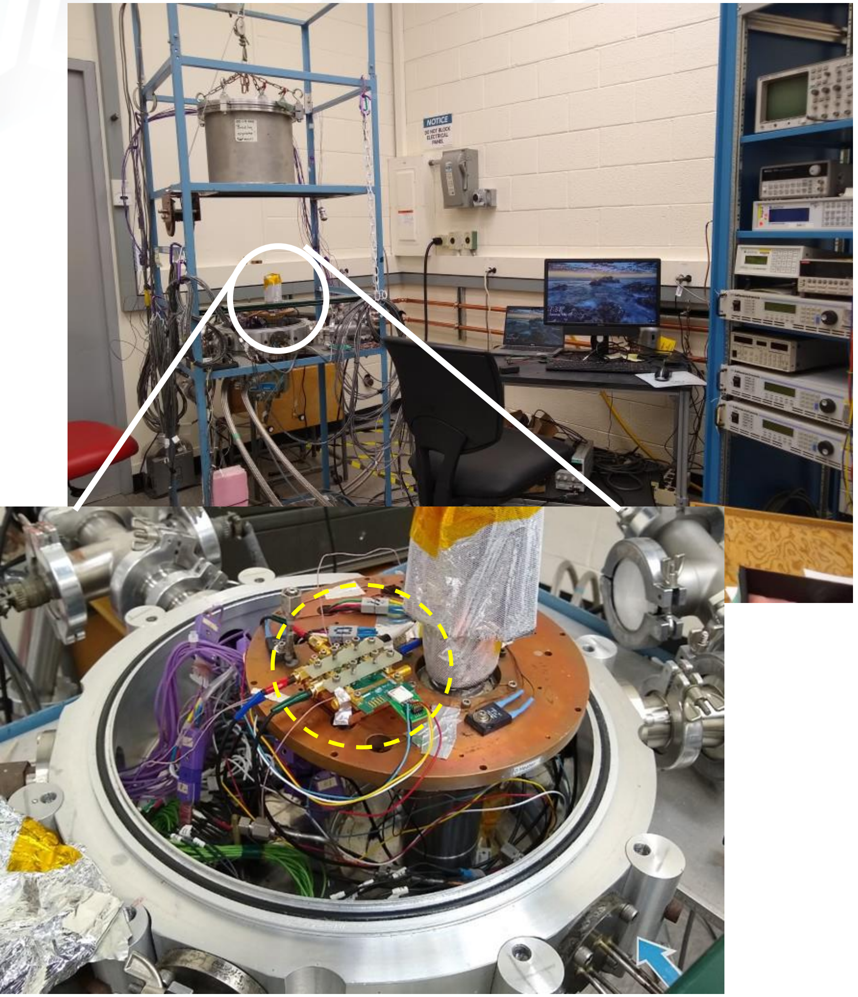
- Devices are sealed in a package ("black box"), microscopy not feasible

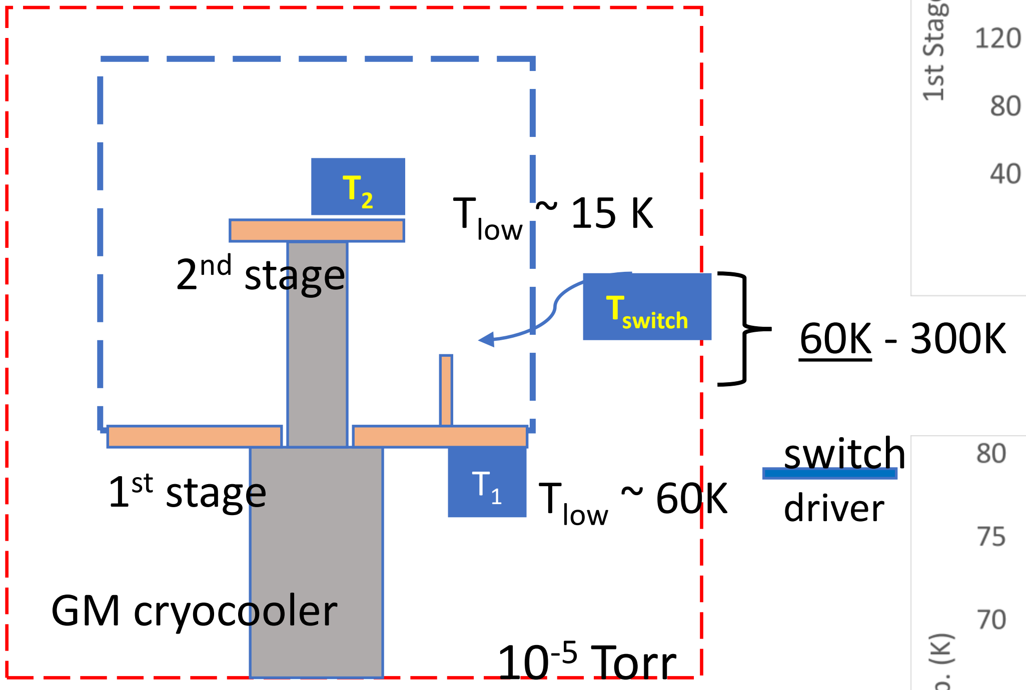
→ Objectives:

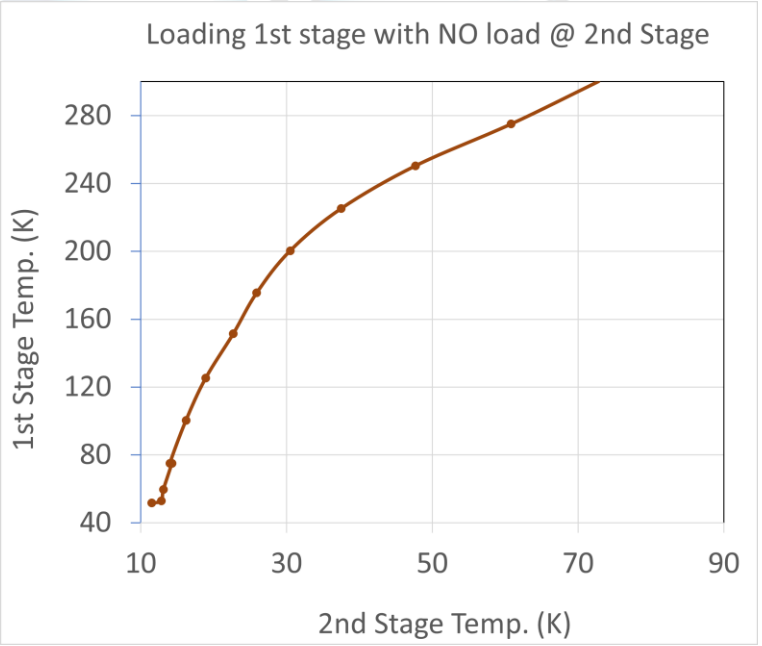
1. Develop *electrical test protocols* that are indicative of MEMS *structural reliability*
2. Develop test apparatus for various low temperatures
3. Investigate MEMS reliability from room temperature to 4 K: *Preliminary data*

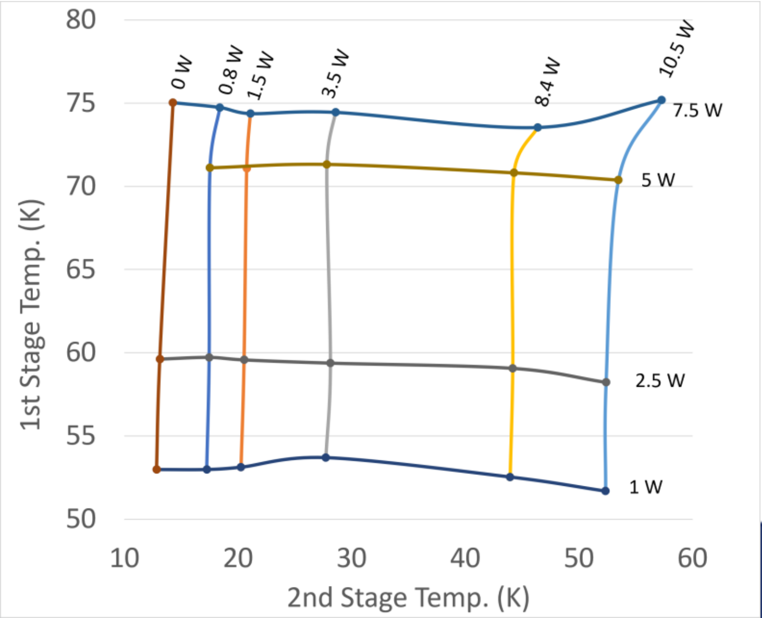
Cryostat Test Setup

- Cryostat
- Mount for MEMS
- Temperature control + measurement
- High-voltage electronics for driving MEMS
- Data acquisition

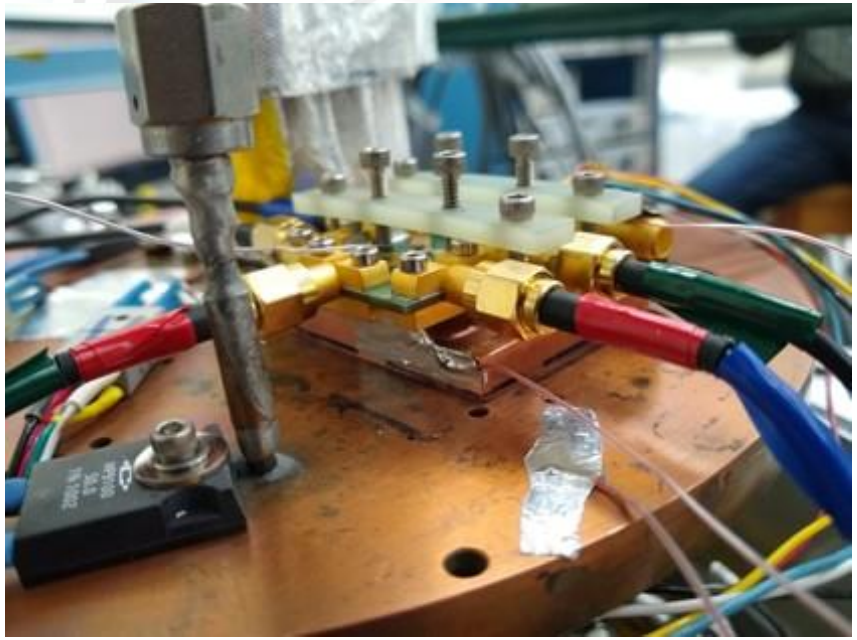


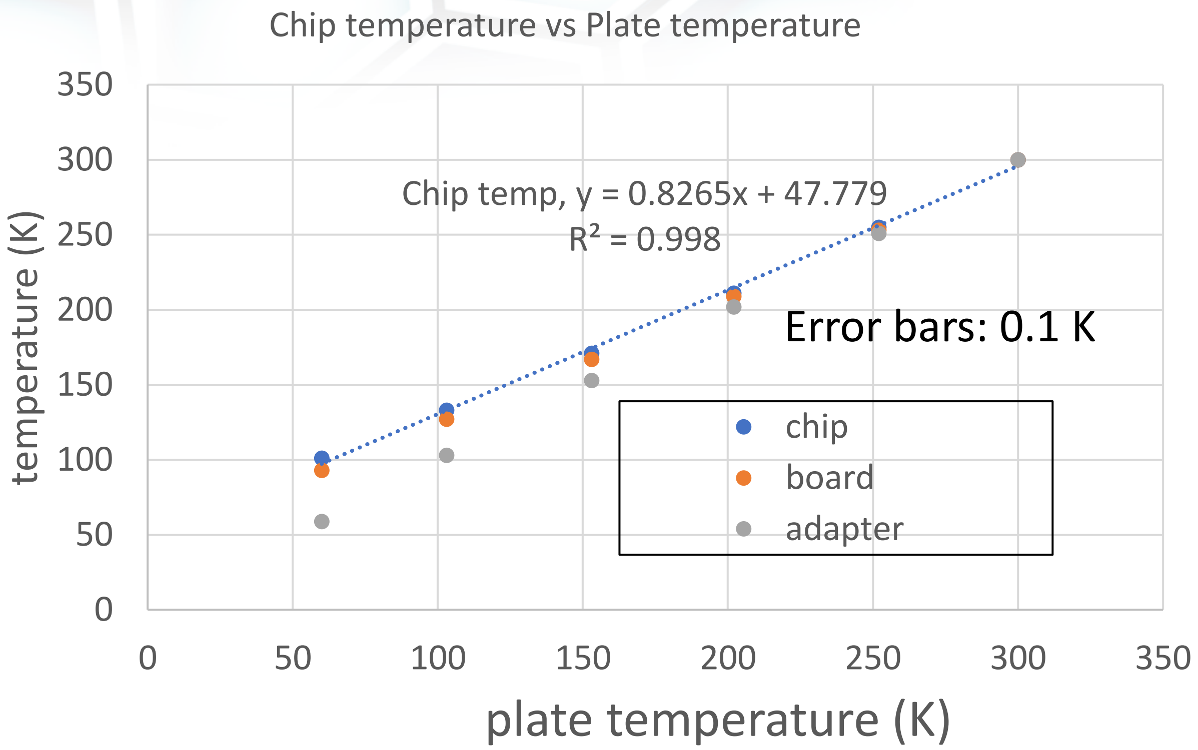






Cryostat Test Setup cont'd





Mounting of the MEMS board/chip:

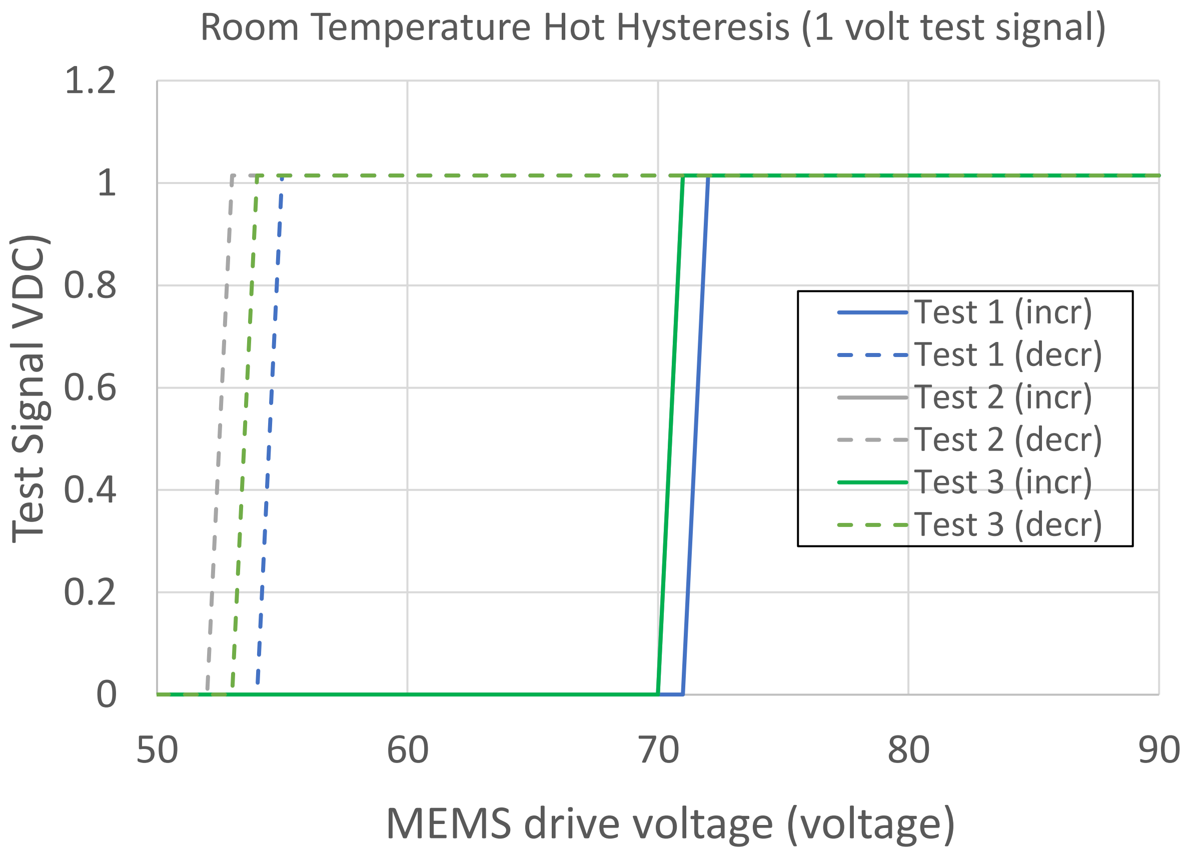
- maximize thermal conduction with electrical isolation
- Temperature measurement at various locations
  - Note: previous literature on cryogenic MEMS: convention was to assume cryostat temperature = MEMS temperature

Test protocol 1: Hot-switching, hysterises

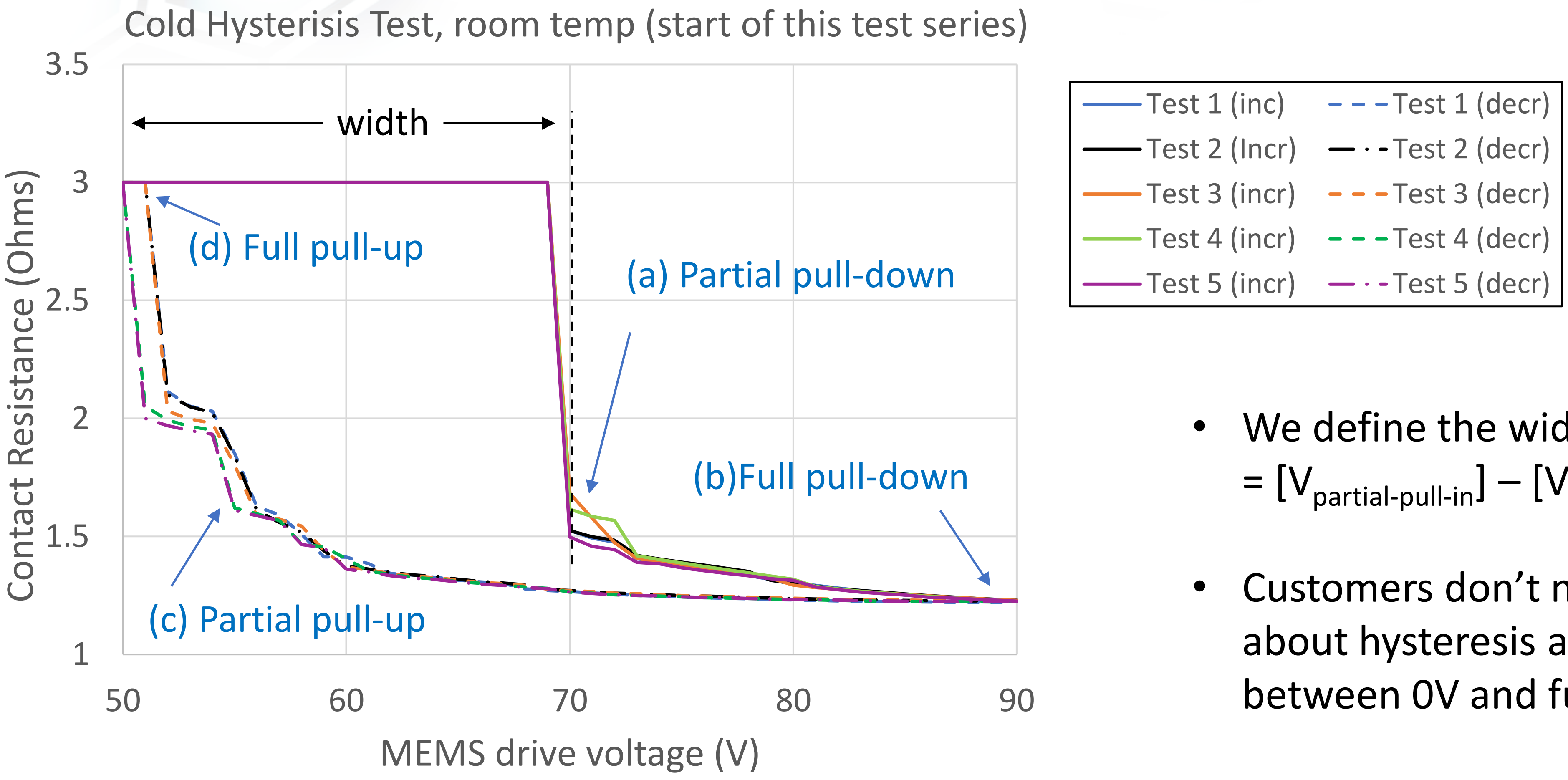
- Electrostatically-actuated MEMS cantilever beams have hysterises

- Customers don't need to worry about hysteresis as they operate between 0V and full-pull-down.

- Hot-switching hysteresis test:
  - 1 Vdc test signal
  - Sweep the MEMS drive voltage up and down
  - Measure the switch's output test signal (0 or 1 Vdc)
  - Note the MEMS drive voltage where the switch turns on/off
  - Does not give much information about the MEMS mechanical behavior.



Test protocol 2: Cold-switching, hysterises

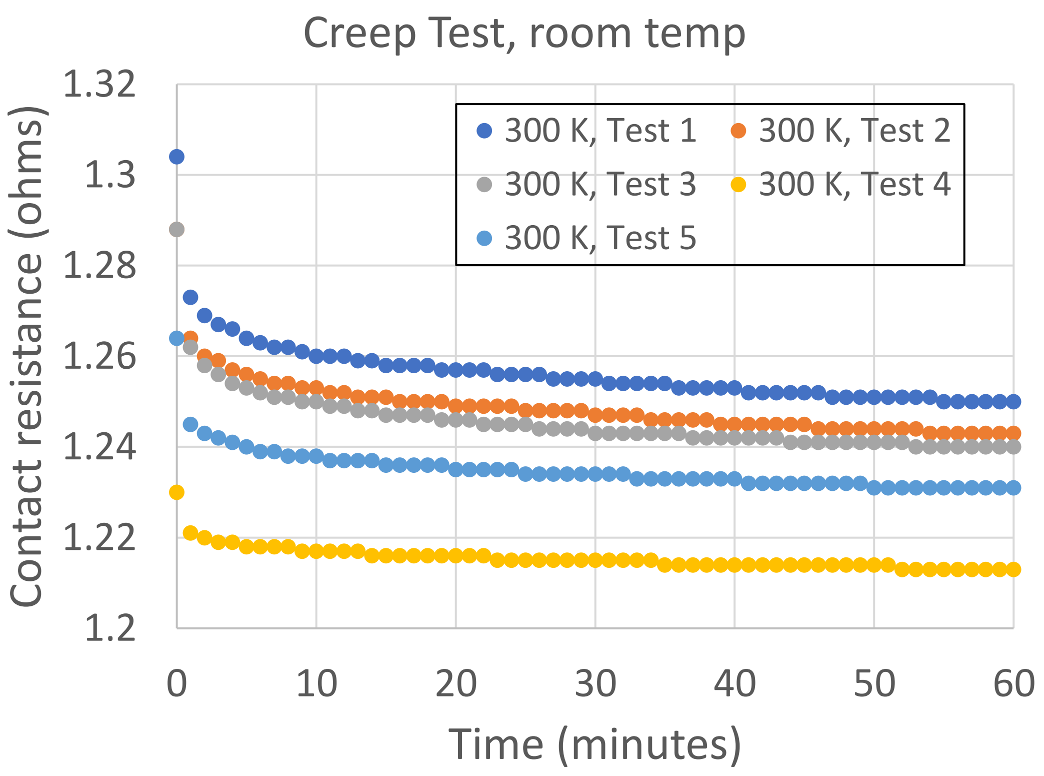


- We define the width of the curve: $= [V_{partial\text{-}pull\text{-}in}] - [V_{full\text{-}pull\text{-}up}]$
- Customers don't need to worry about hysteresis as they operate between 0V and full-pull-down.

Note: pulled-up resistance is actually infinite

Test protocol 3: “Creep”

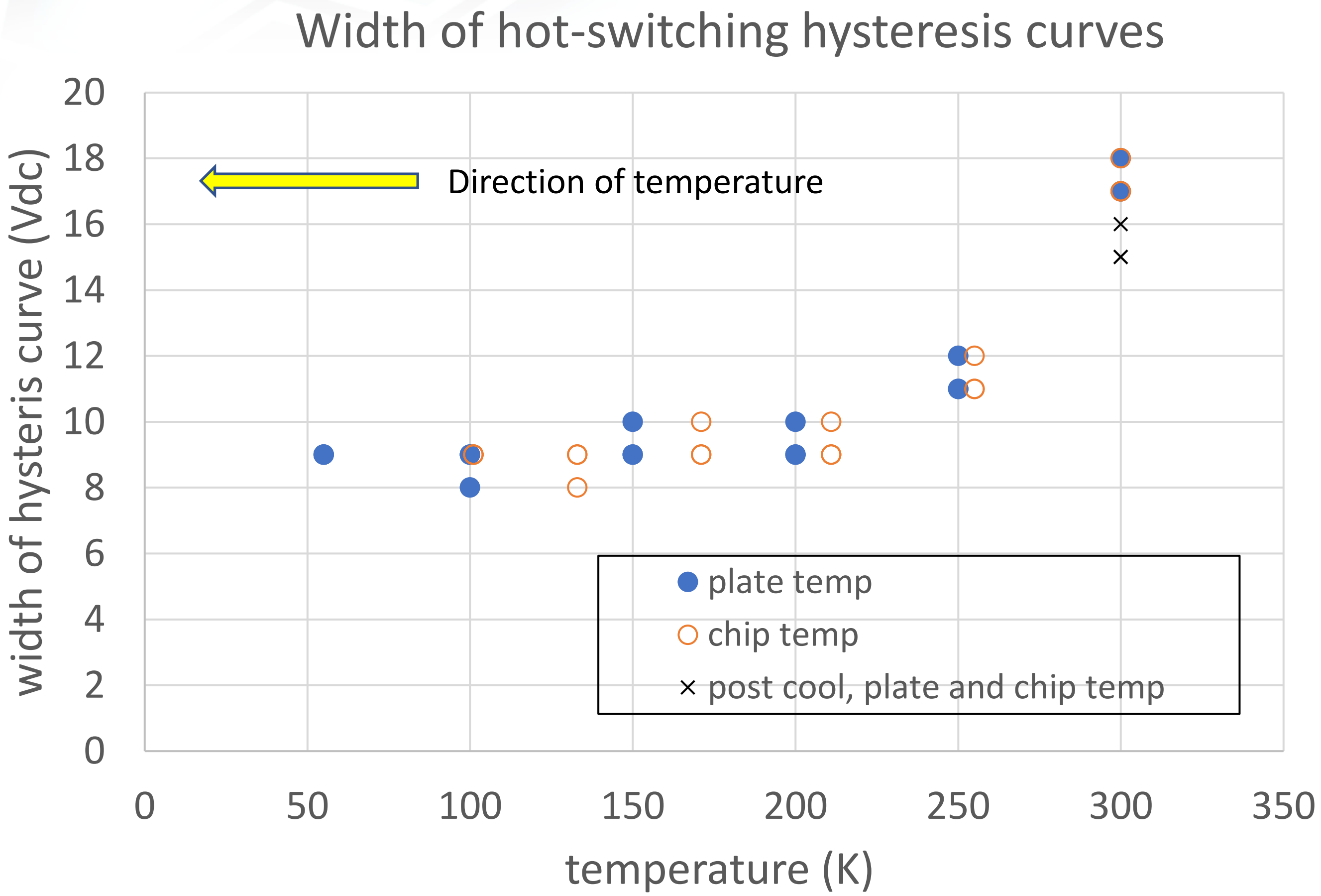
- Cold-switching test
- Turn on the switch, keep it on, measure the change in contact resistance over time. Repeat.



Observations:

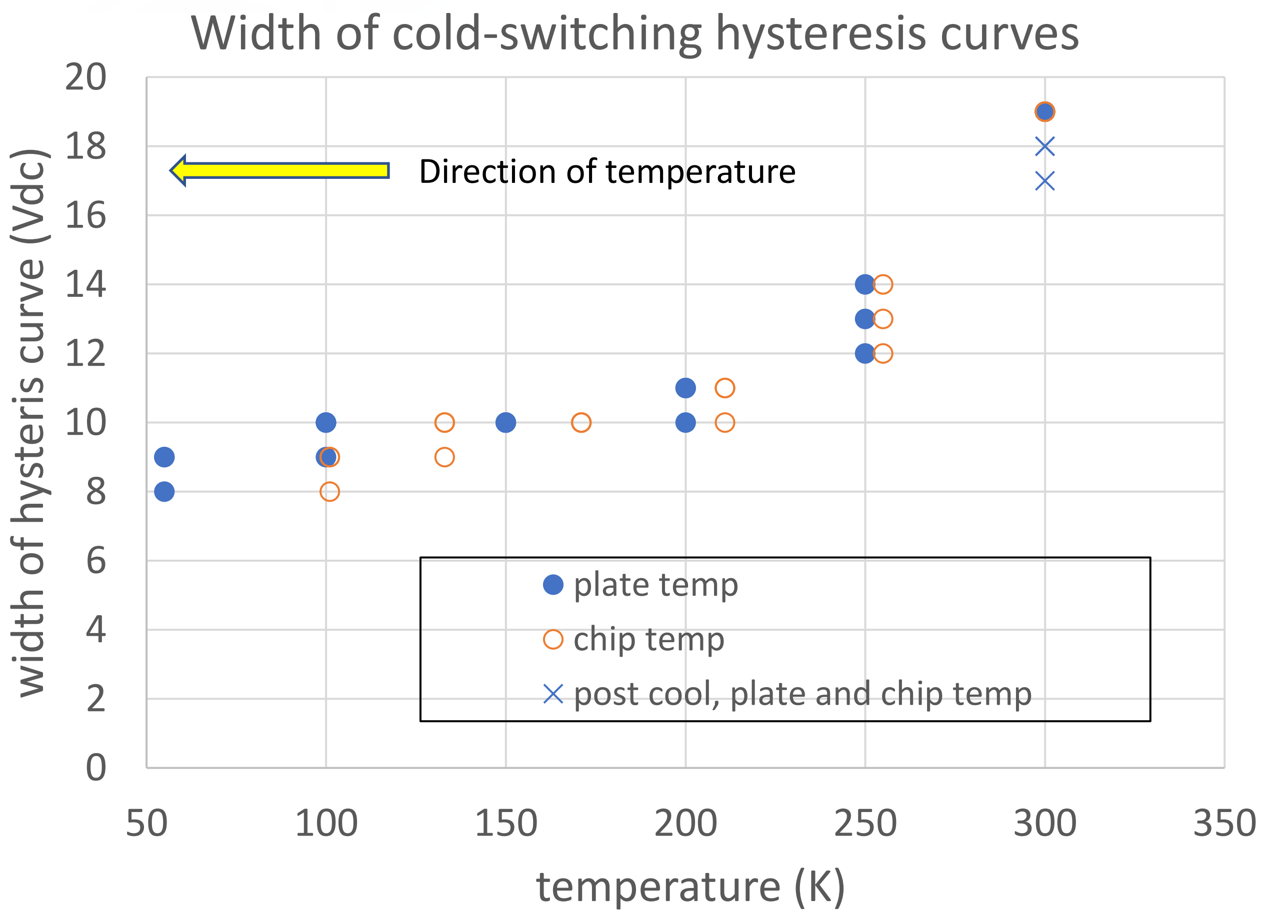
- Contact resistance decreases rapidly within 1 minute. Then gradually over the next hour.
- If the switch is then turned off and the test repeated, the new starting resistance is lower.
- If the switch is turned off and kept off. The next time it is turned on, the contact resistance is higher again.
- Consistent with the literature on MEMS switches.
- Note: even the highest contact resistance is still relatively low (less than 2 ohms).

Cryogenic Test Results: hot hysteresis



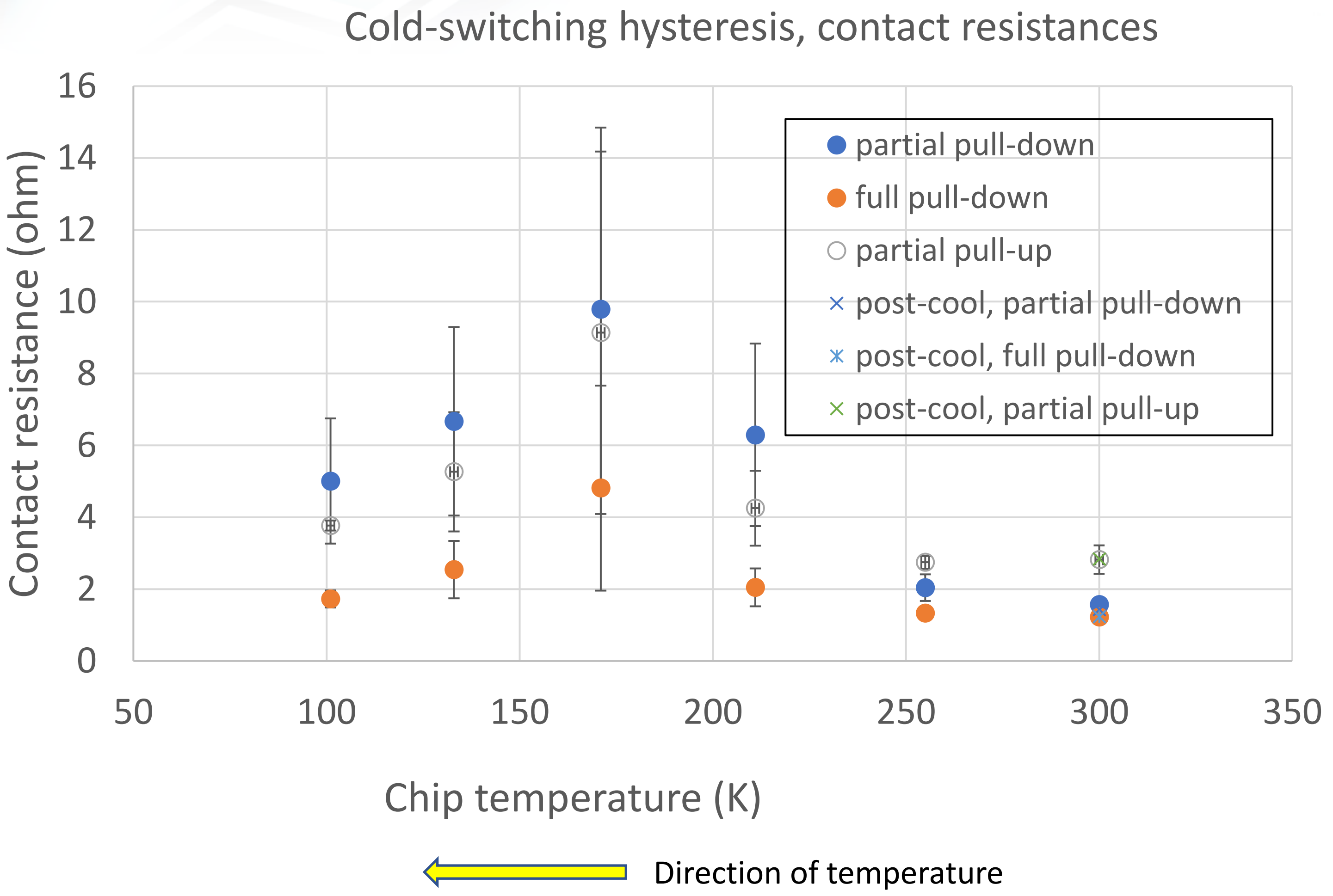
- Within each temperature there are 3 data points (3 replicate tests).
- Curve width decreases by ~30% between room temp and 250 K, then continues the trend but at slower rate
- Curve is very similar to the "cold hysteresis width vs temp" curve (repeatable performance)
- Post-cooling, the room-temp width has decreased. This is similar to the cold-hysteresis curves

Cryogenic Test Results: cold hysteresis



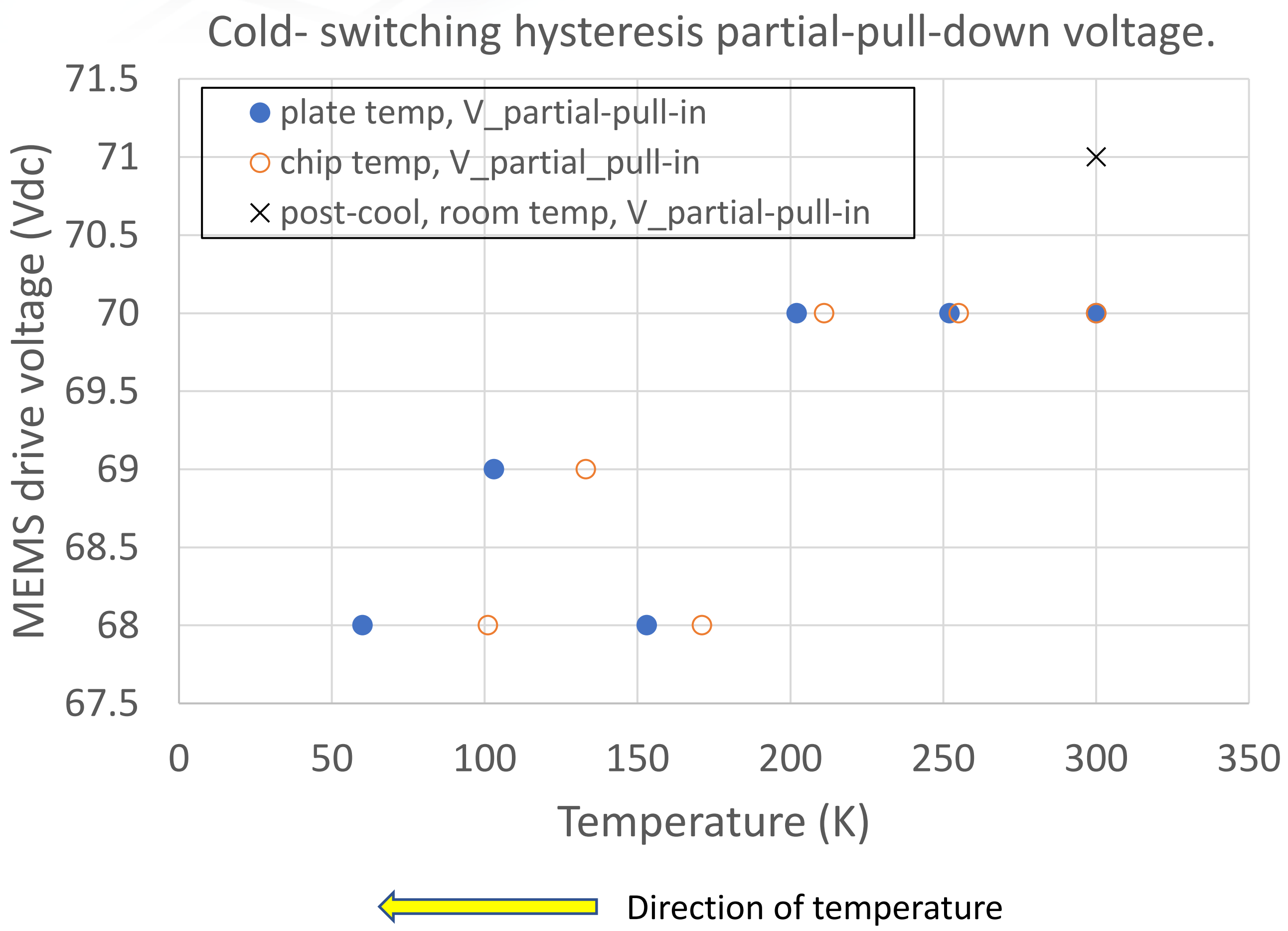
- Within each temperature there are 3 data points (3 replicate tests).
- Curve width decreases by ~30% between room temp and 250 K, then continues the trend but at slower rate
- Post-cooling, the room-temp width (similar to the hot-switching hysteresis curves)→ permanent change

Cryogenic Test Results: Cold hysteresis contact resistances



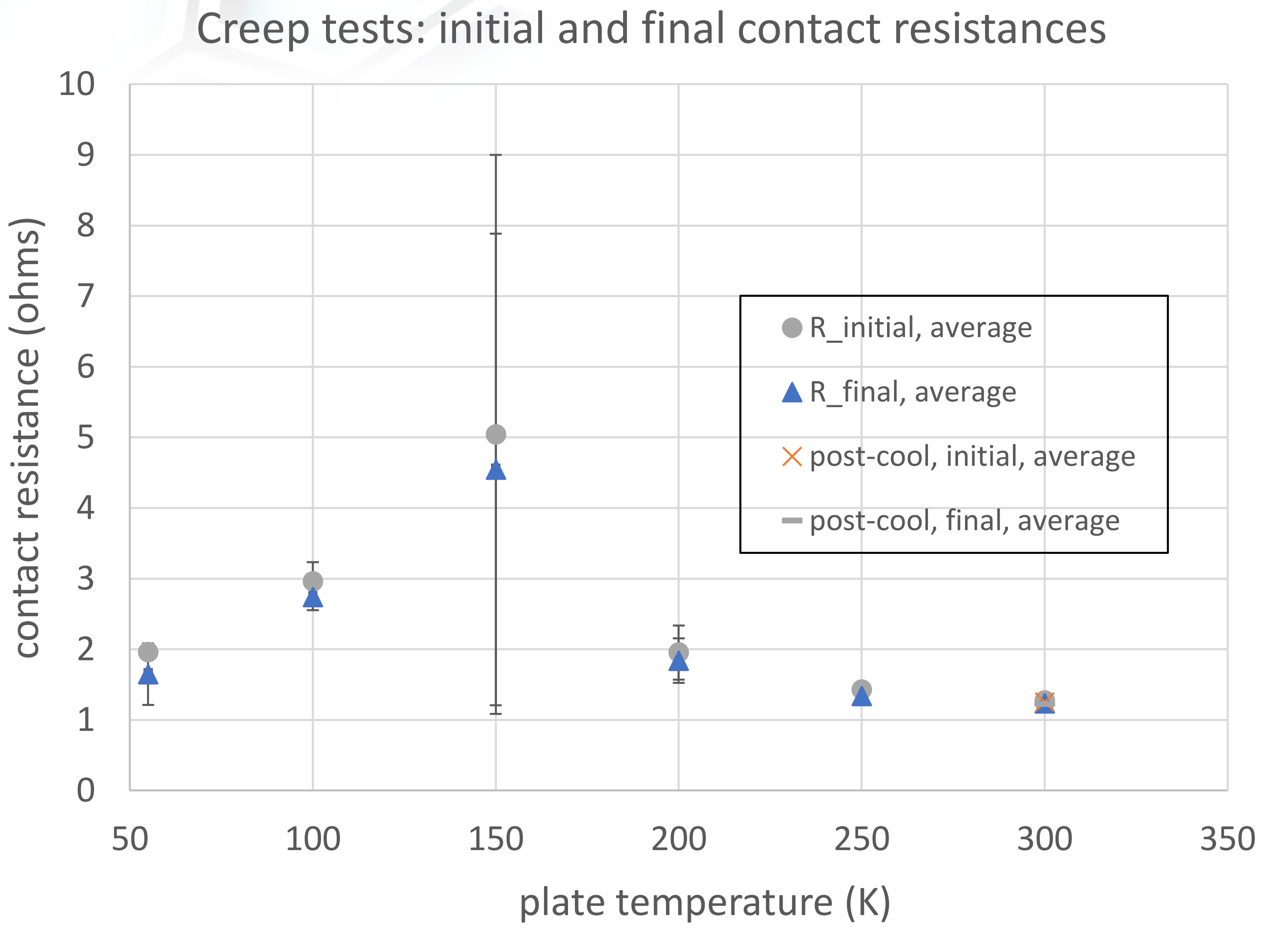
- Each data point is an average of 3 tests.
- Error bars are standard deviations
- 150 K appears to be a point of instability
- Post-cool room-temp resistance returns to pre-cool values

New slide: Constant pull-down voltage with decreasing temps; different from literature



- Whereas the literature shows increase in actuation voltage of up to 100% at cryo temps, we observe a decrease of < 5%
- Therefore, it can be said that the Menlo switch shows "practically no change" in actuation voltage with decreasing temp, which is a plus for a commercial device and is different from literature

Cryogenic Test Results: creep



- Error bars are standard deviations
- Again, 150 K appears to be a point of instability

- The shape of the curve is similar to that for the cold-switching hysteresis tests, with 150 K being a point of instability

- Post-cooling room-temperature resistances are very close to that of the pre-cooling values (no permanent change)

Summary

- Goal: evaluate mechanical reliability of commercial MEMS switches at cryogenic temperatures, for applications in quantum computing
- Developed reliability test protocols and cryogenic test apparatus
- First investigation of electrostatic and/or commercial MEMS hysteresis as function of cryo temps
- MEMS pull-down voltage ~constant down to 55 K. Opposite of literature (which shows 2X increase)
- Hysteresis curves show decrease in width with decreasing temperature
  - Most significant (~ 30 %) change is from room temp to 250 K
  - Contact resistances (cold-switching) change with decreasing temp
- Creep test
  - Contact resistances decrease over time within a single test (consistent with literature)
  - Contact resistances change with decreasing temperature
- 150 K : point of instability for hysteresis and creep tests
- Permanent change in room-temperature drive voltages and hysteresis curve widths after cooling.
- Future work:
  - Switch-response time measurements
  - Test to lower temperatures
  - Reverse the direction of the temperature change

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