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Understanding and using configurational changes in resistive switching filaments

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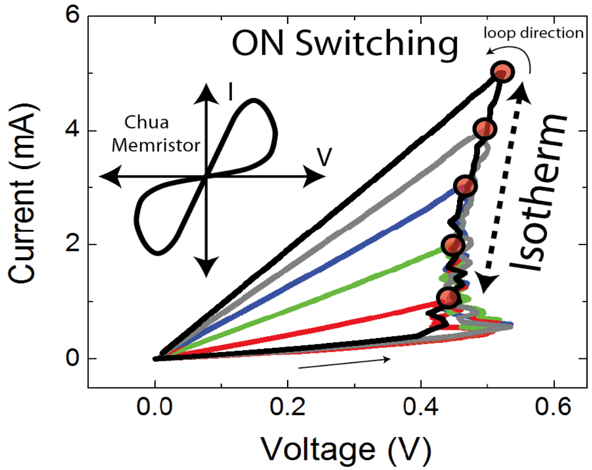
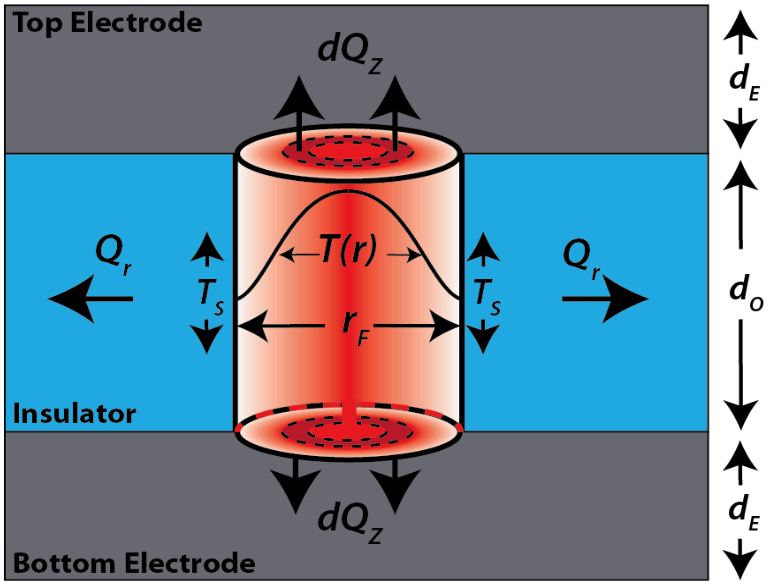
Isothermal switching suggests thermal feedback

- Common sharp IV endpoints suggest a system temperature is balanced at activation





We built a model with thermal feedback

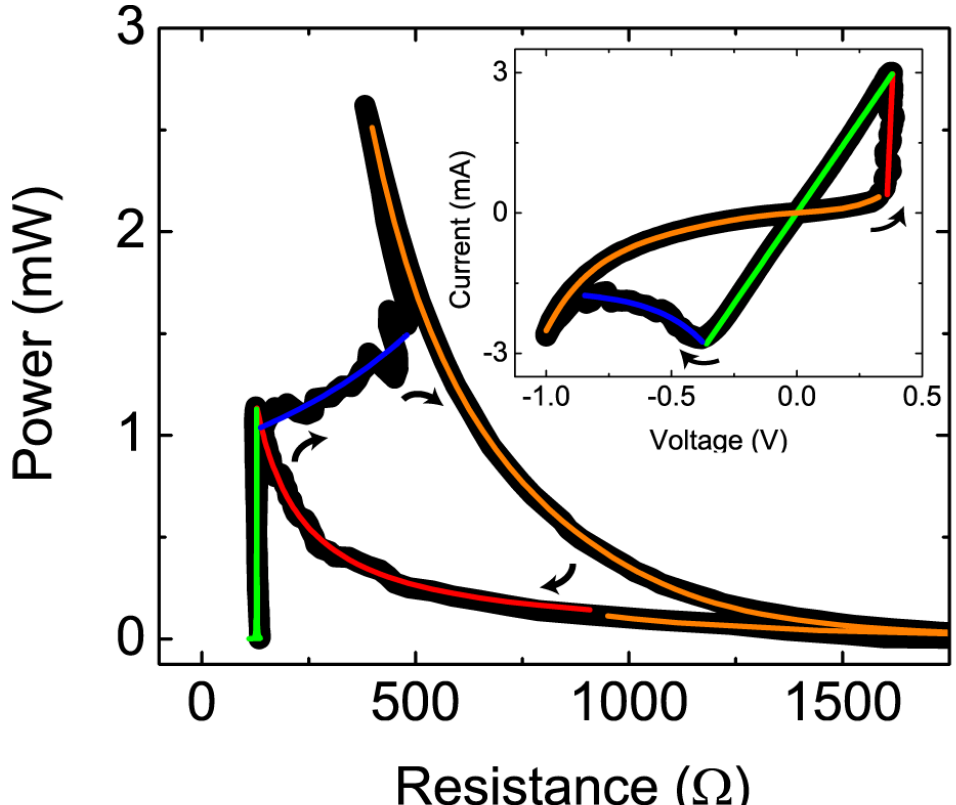
$$T_S = T_{RT} + \sigma V^2 \frac{d_E}{2k_E d_O}\left[1 - \frac{k_E}{k_F}\frac{r_F^2}{4\, d_E d_O}\right]$$

Model suggests independent control of two state variables: r and σ

$$T_S = T_{RT} + \sigma V^2 \frac{d_E}{2k_E d_O}\left[1 - \frac{k_E}{k_F}\frac{r_F^2}{4\, d_E d_O}\right]$$

1 → $$IV_r = A_r \frac{T_{crit} - T_{RT}}{R_F - R_{min}}$$

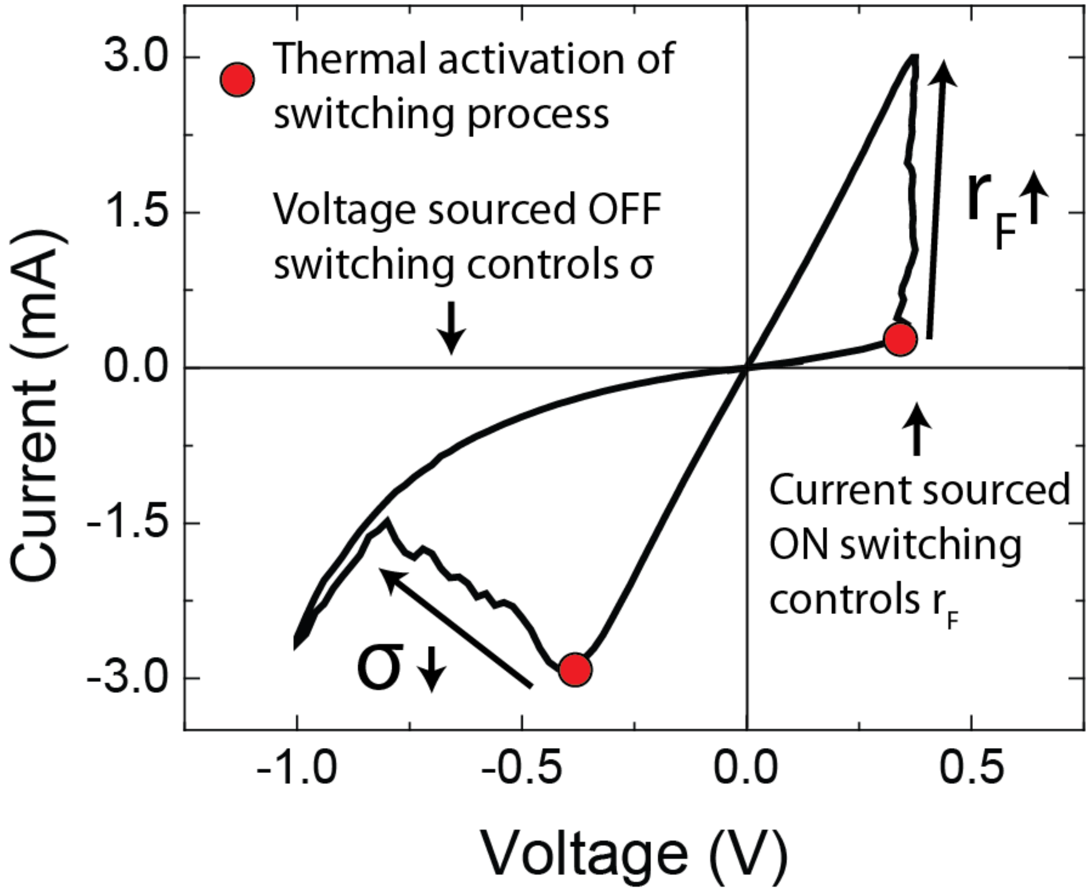
2 → $$IV_\sigma = A_\sigma \frac{T_{crit} - T_{RT}}{R_{max} - R_F}$$



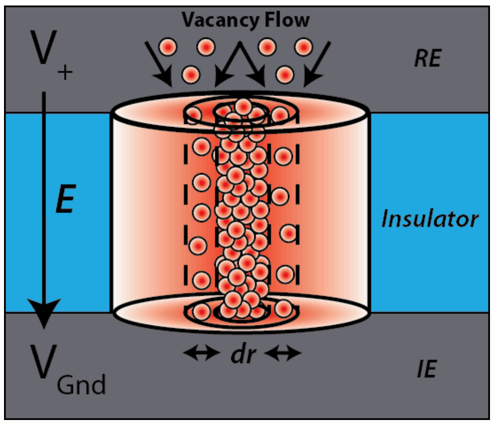
1. Allow filament radius to vary and hold conductivity constant

2. Allow filament conductivity to vary and hold radius constant

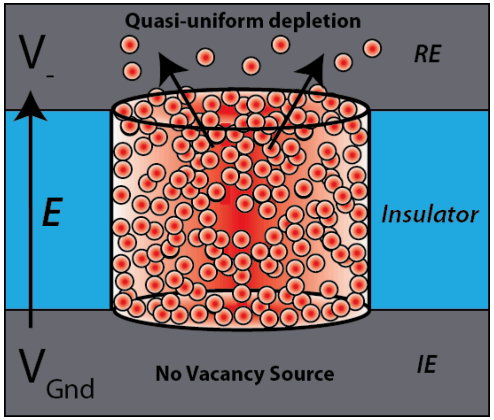
Filament configurations can be set



$$IV_r = A_r \frac{T_{crit} - T_{RT}}{R_F - R_{min}}$$



$$IV_\sigma = A_\sigma \frac{T_{crit} - T_{RT}}{R_{max} - R_F}$$



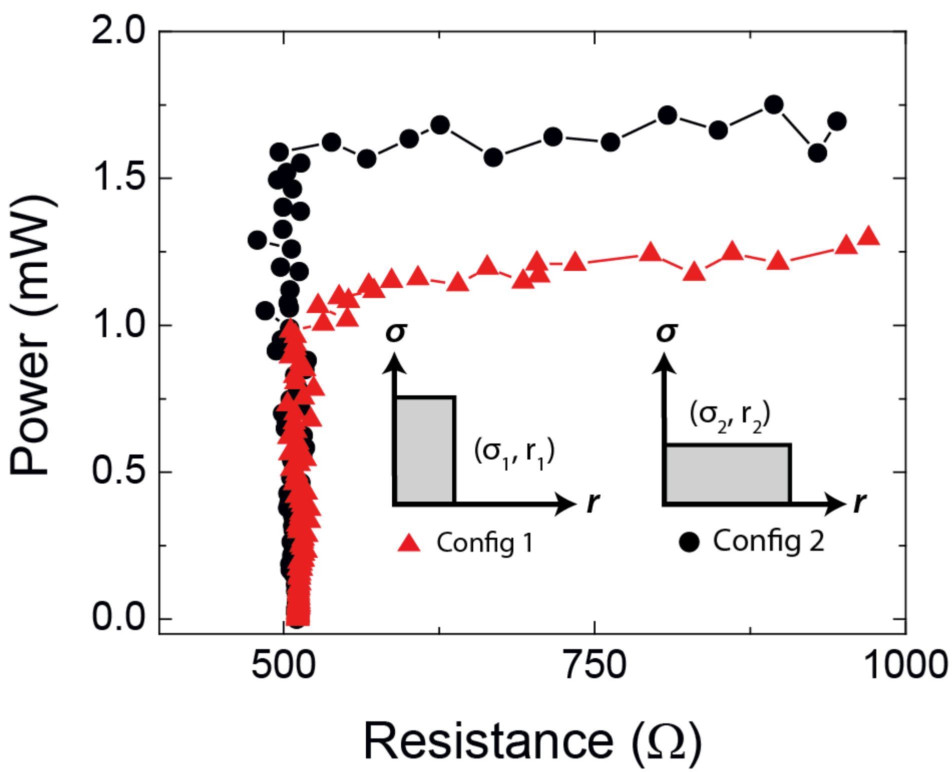
Filament configurations can be read

Model calculates required switching powers

$$T_S = T_{RT} + \sigma V^2 \frac{d_E}{2k_E d_O}\left[1 - \frac{k_E}{k_F}\frac{r_F^2}{4\, d_E d_O}\right] \Rightarrow P_{act} = \frac{(T_{Crit} - T_{RT})/R}{\frac{d_E \sigma}{2k_E d_O} - \frac{r_F^2}{8L_{WF}T_{crit}d_O^2}}$$

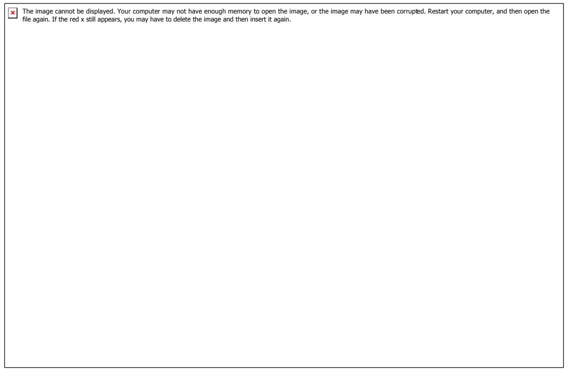
For an equivalent resistance, R, the model predicts:

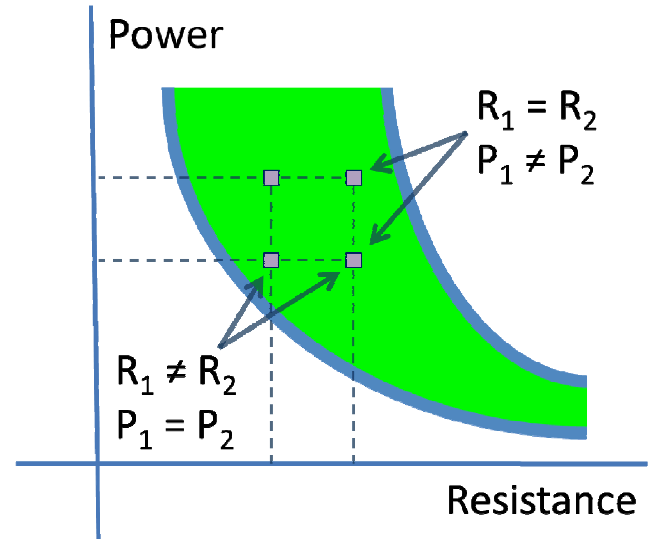
1. Small radius large conductivity → lower power to thermally activate
2. Large radius small conductivity → higher power to thermally activate



Filament configurations can store 2D info

Analog memory →
Multi-dimensional memory



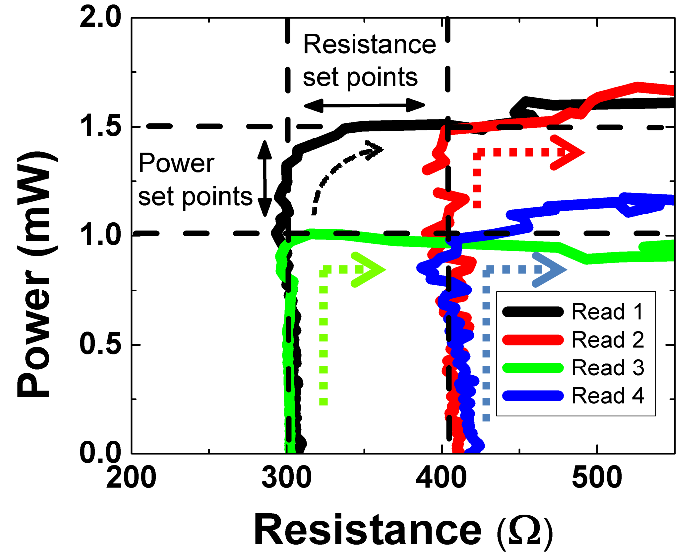


Specific microscopic conductivities and radii might change over time with aging devices

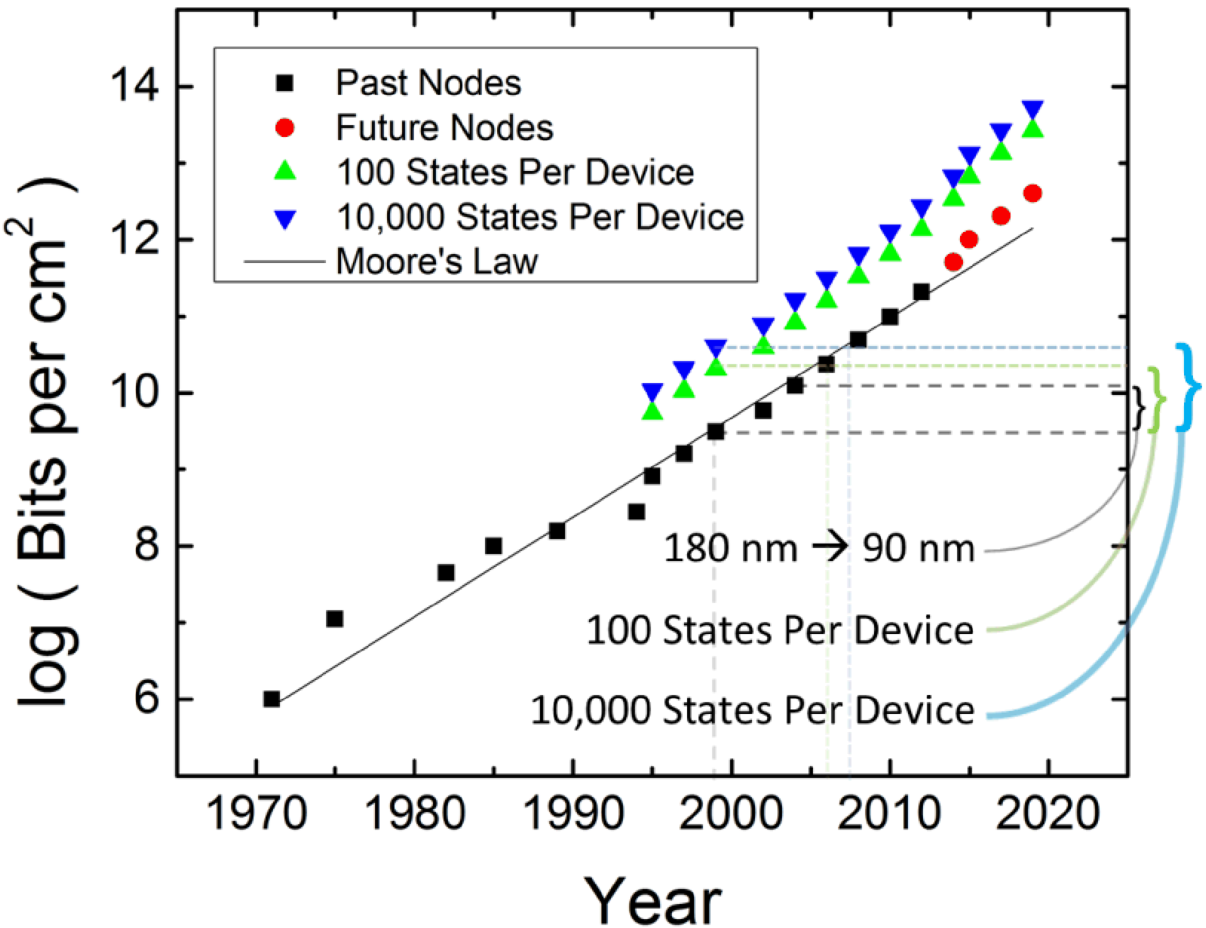
BUT

Resistances and activation powers are direct measurements, and can encode information

… so we don't need to debate microscopics



Moore’s Law (for memory) could be extended

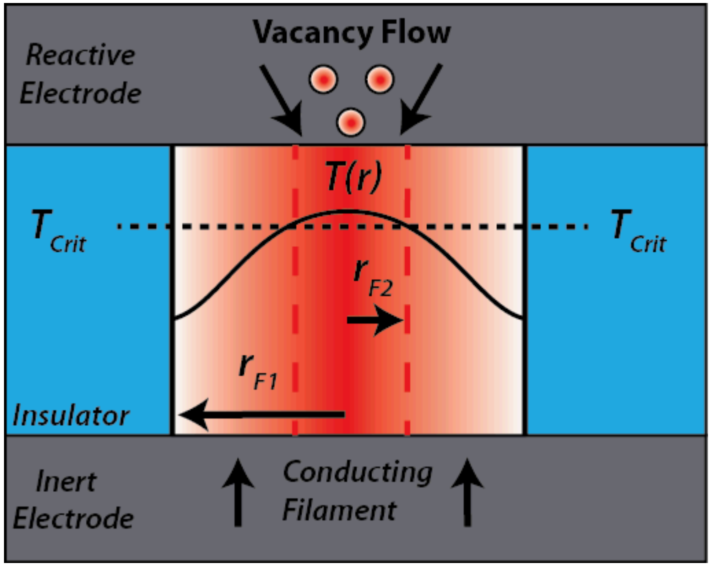


Conducting Filaments can be concatenated within themselves

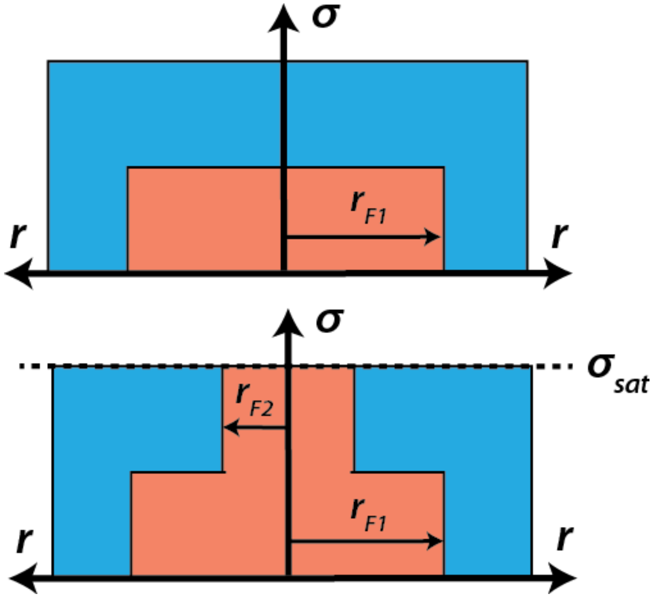
What happens if we turn the device ON after a partial RESET (partial OFF state)?

Temperature is highest in the center:

$$T(r) = \frac{\sigma V^2 r_F^2}{4 d_0^2 k_F}\left(1 - \frac{r^2}{r_F^2}\right) + T_S$$

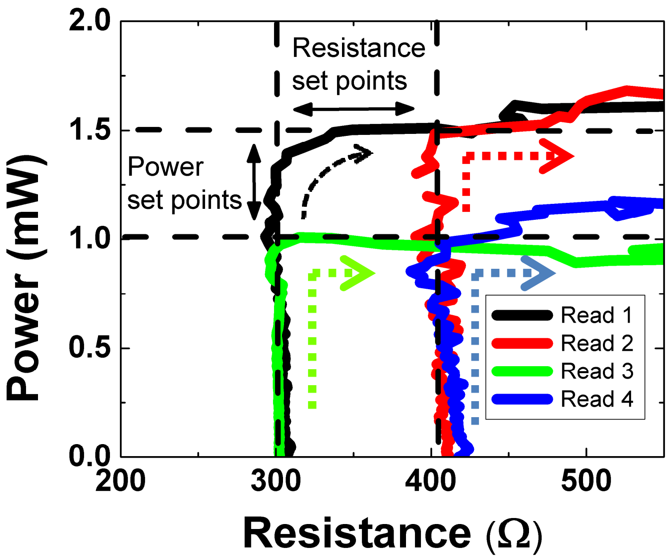


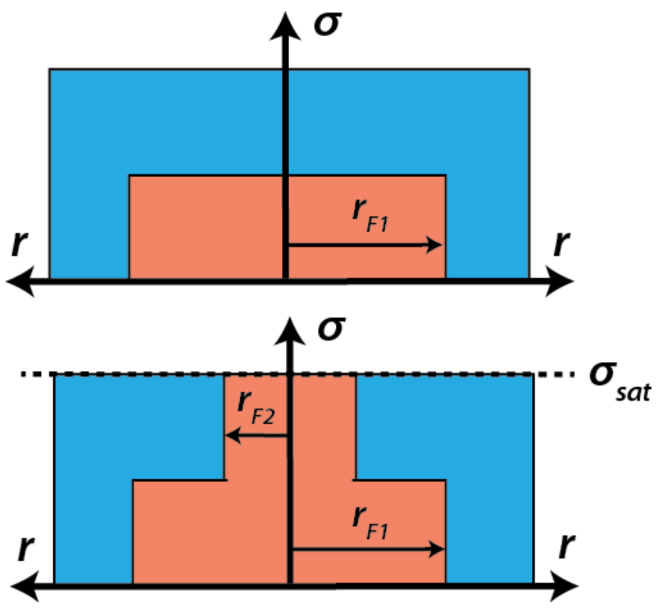
Vacancies/dopants can only flow where $T > T_{crit}$, leading to a concatenated filament

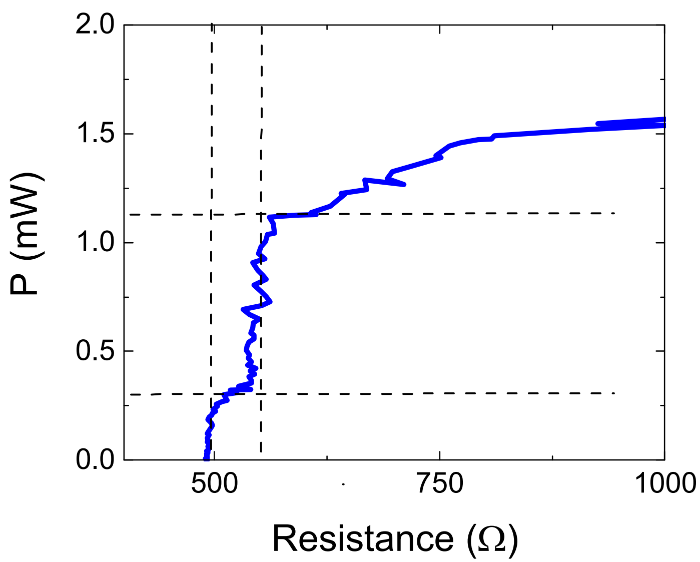


Concatenated filaments can be experimentally measured

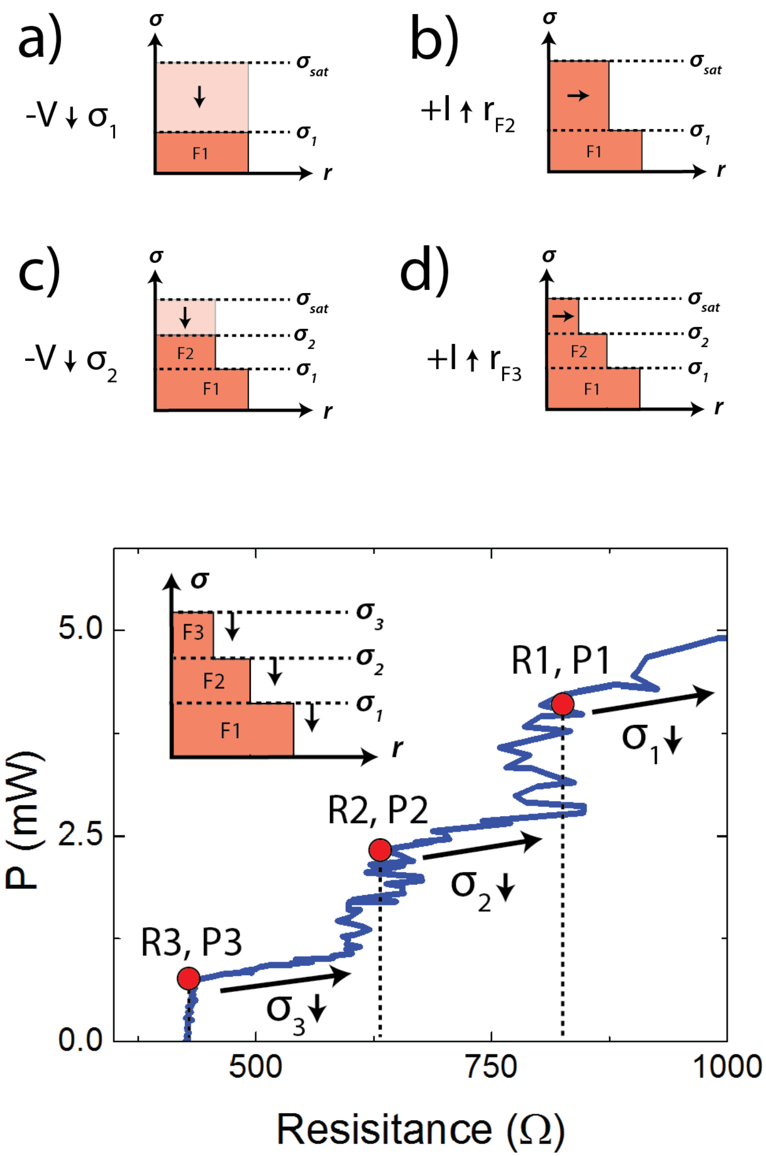
If filaments were concatenated, what would their switching profile look like?

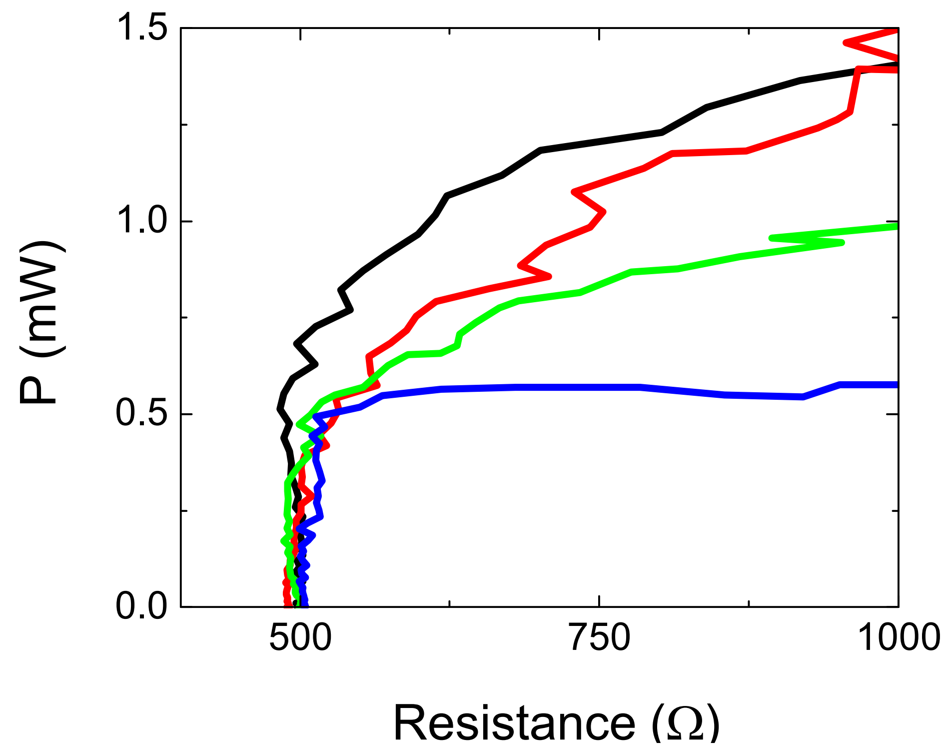






Analog radial conductivity profiles may be set

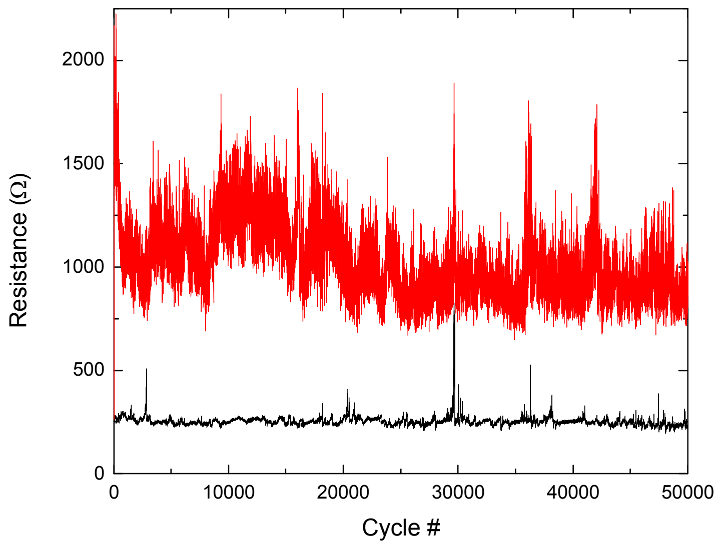


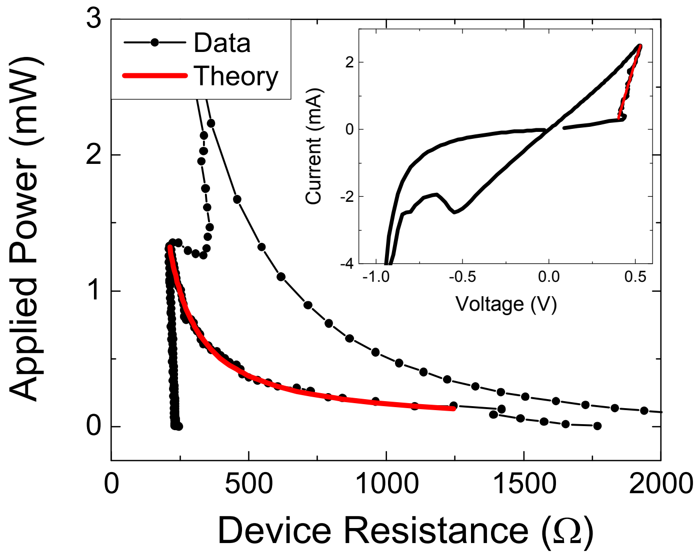


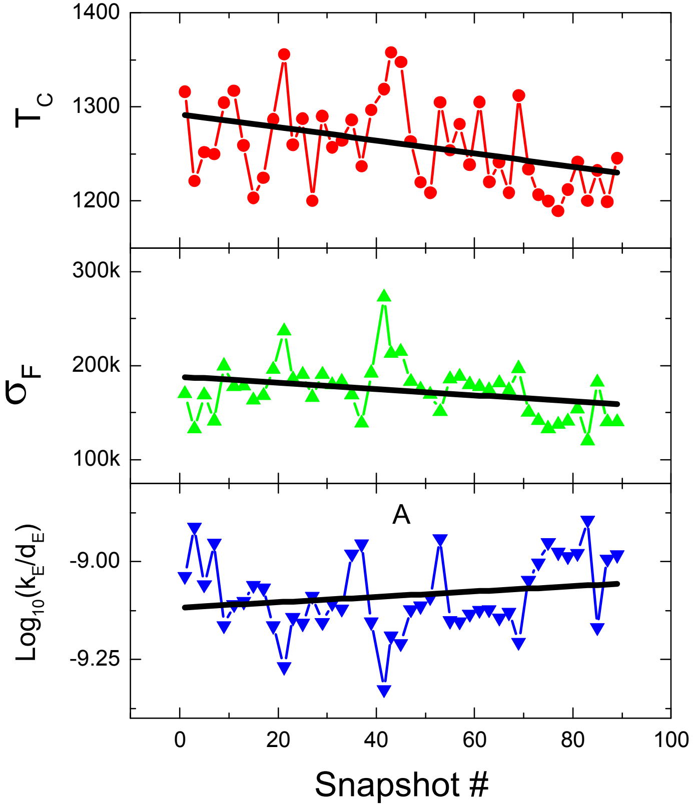
Model provides detailed filament characterization: what else can we use it for?

- Using the thermal model, a single IV loop gives a detailed filament characterization:
  - Radius
  - Conductivity
  - Activating Temperature
  - Thermal resistance

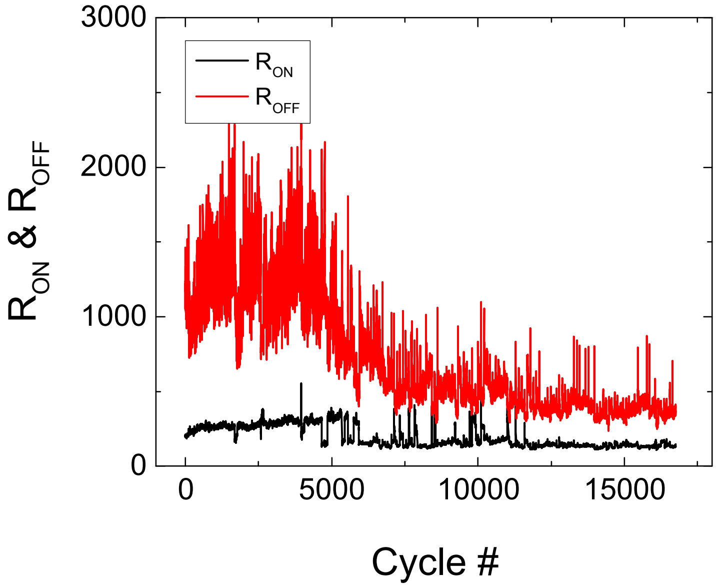
The filament can be characterized as it ages during endurance measurements

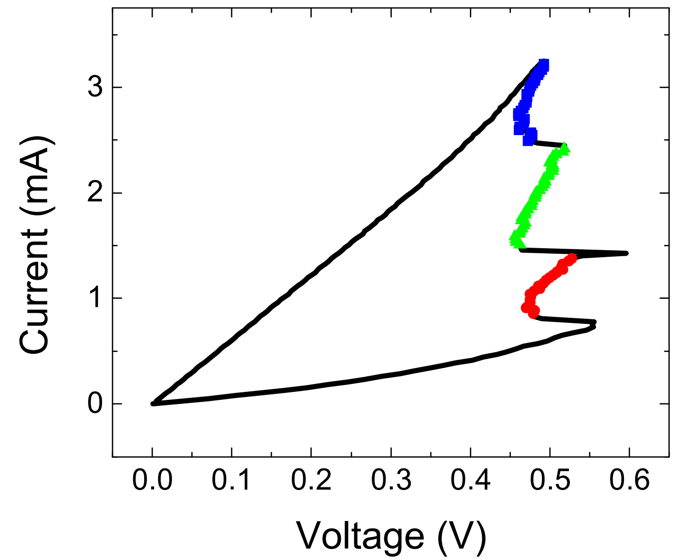


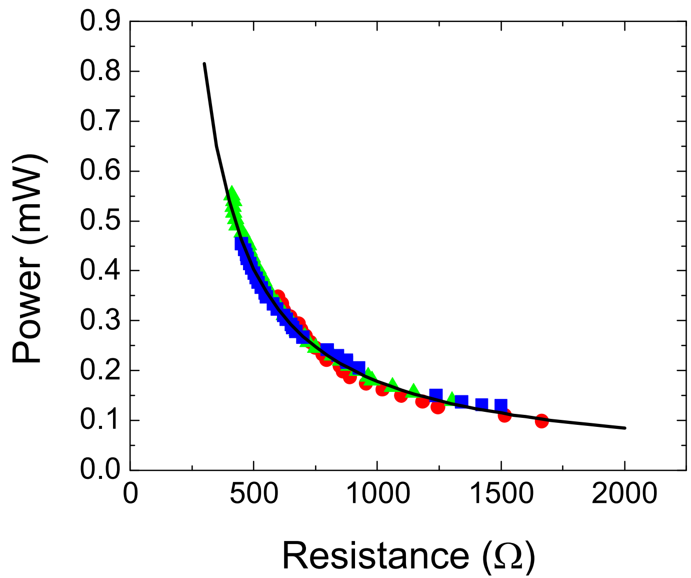




Multiple filaments can be identified and characterized simultaneously

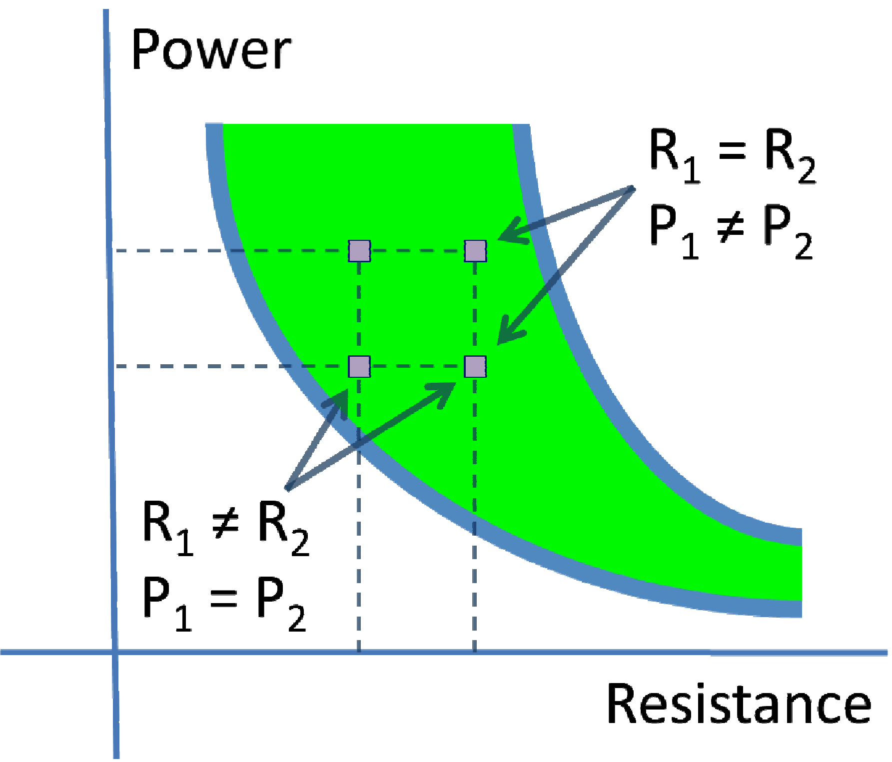


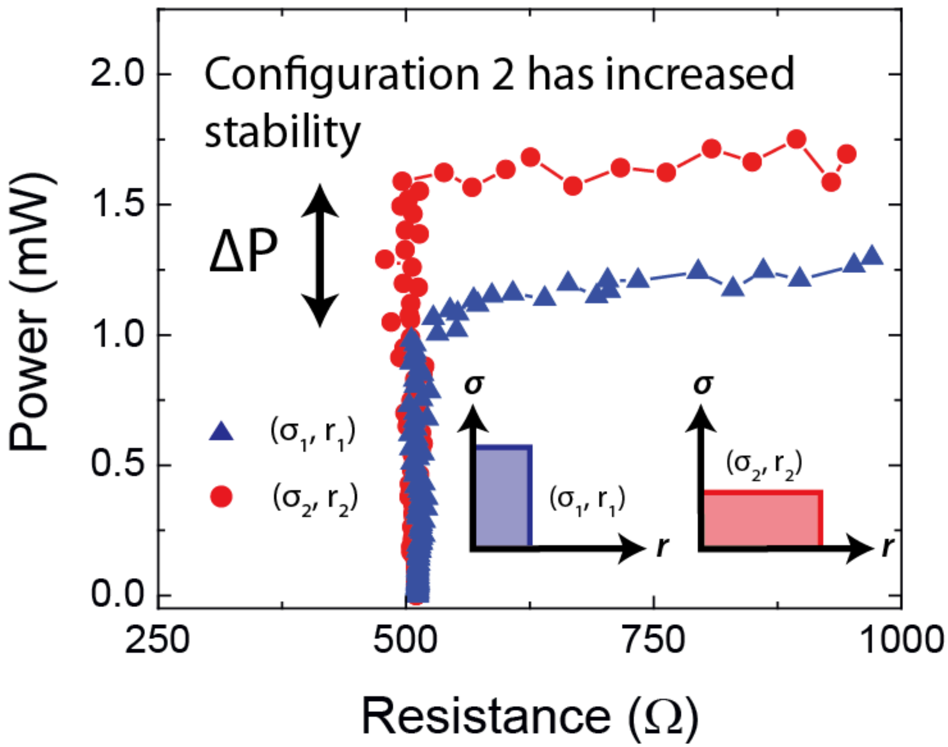




Sometimes they die very early, but analyzing IV loops with the thermal model gives good insight into their failure mechanism → multiple filaments!

Memristors → Neurons : weight change AND plasticity





Presentation Summary

- Demonstrated independent control of filament radii and conductivities predicted by thermal model
- Demonstrated 2D information writing/reading of filament configurations
- Demonstrated the ability to concatenate filaments, leading to analog control of radial conductivity profiles
- Additional model uses: characterized filament aging in real time, identified the development of multiple filaments, and mimicked neuroplasticity

Team Effort

- **Matt Marinella**
- **Conrad James**
- Jim Stevens
- Steve Wolfley
- Seth Decker
- David Hughart
- Rich Dondero
- Steve Casalnuovo
- Thomas Beechem
- Ed Bielejec
- George Vizkelethy
- Barney Doyle
- Steve Howell
- Robert Fleming
- Ed Cole
- Gaddi Hasse
- Ben Yang
- John Aidun
- Denis Mamaluy
- Harry Hjalmerson
- Mike Brumbach
- Erik Debenedictis
- Brad Aimone
- Fred Rothganger
- Brian Evans

Extending Moore's Law into Hidden Dimensions

- More Dimensions?
- New Approach to Scaling for Storage.

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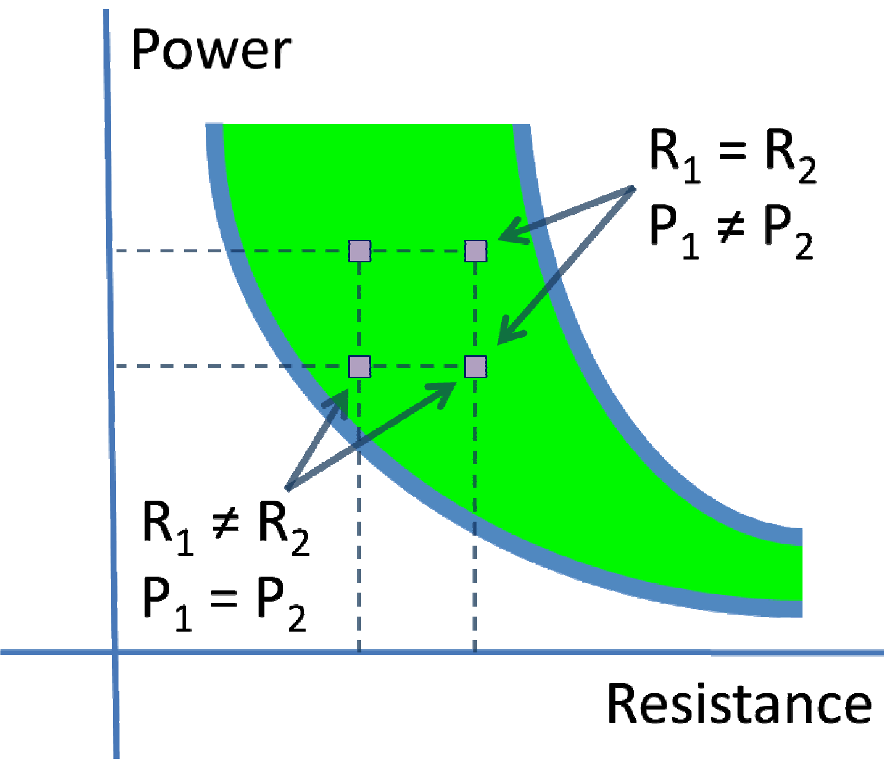
Memristors are 2-D

- Every resistance can be set in many different ways.

2-D States can be Read!

<u>2D State Writing</u>



<u>2D State Reading</u>

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Memristors are 2-D

- State density goes to N^2!
- But it's better to think of the variables as Resistance and Activation Power.