Analog Switching in SiOx:Cu Memristors: Bridging Fabrication and Functionality through a Holistic Perspective

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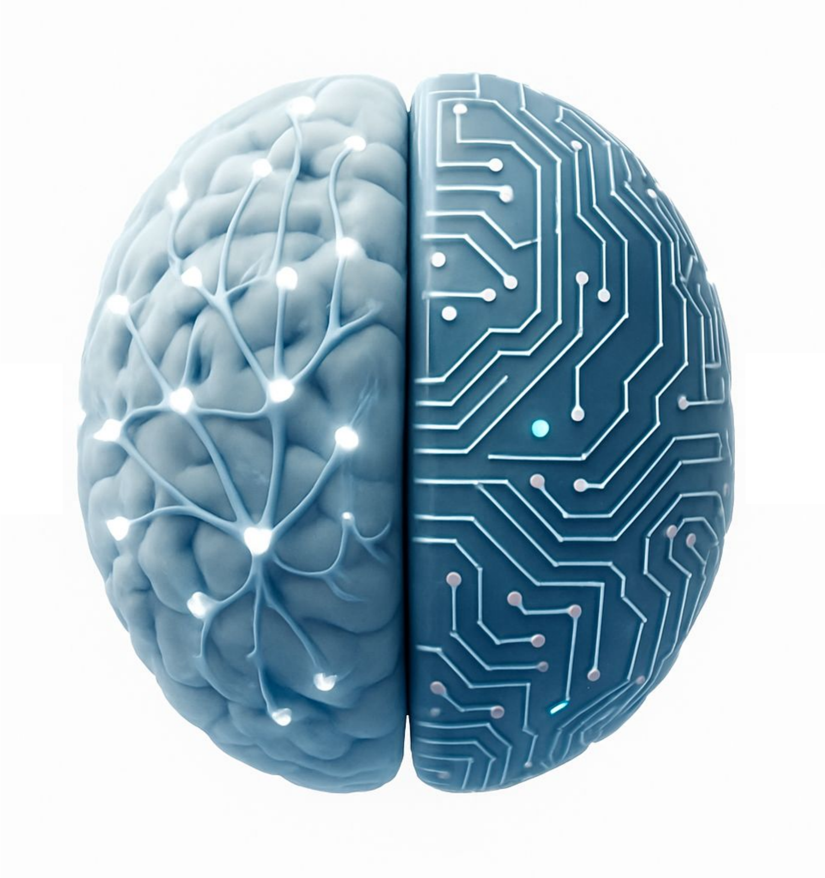
[1]Ruhr University Bochum, [2]Kiel University

Goal: brain-like processing in hardware
(neuromorphic engineering)



<u>Motivations</u>

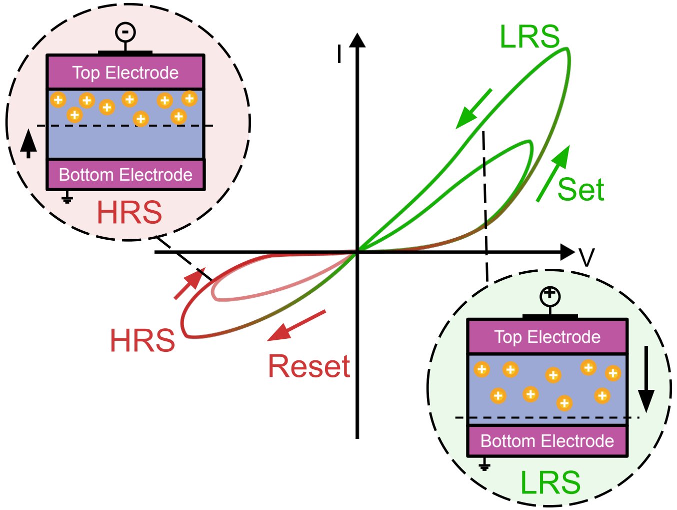
- Incomparable energy efficiency
- Parallel and real-time processing
- Robustness and adaptability

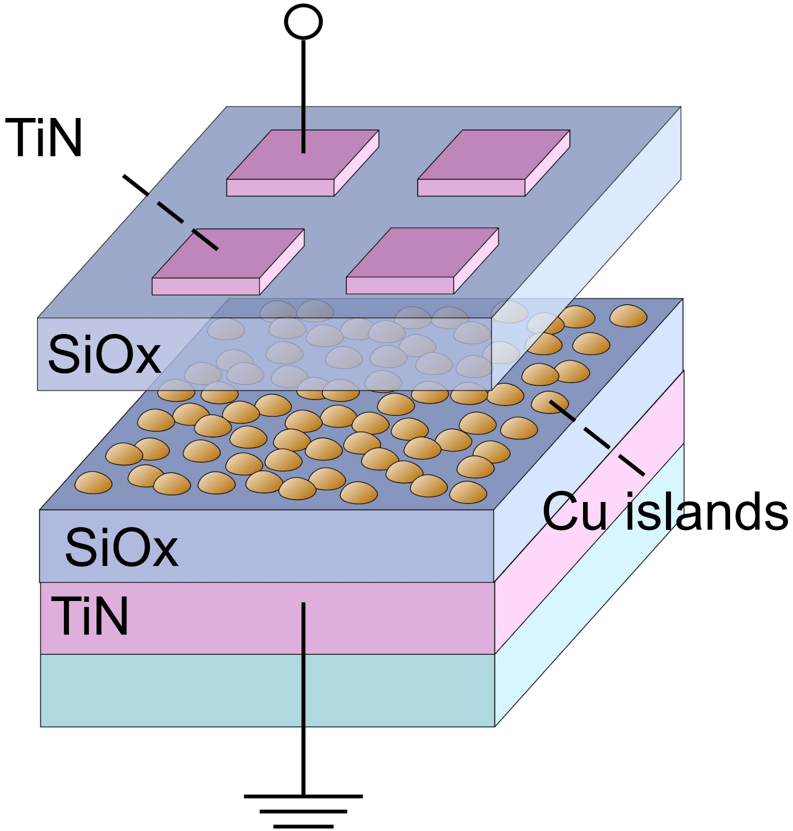
<u>Key element:</u> **memristor**
Synapse-like analog switching
(for microelectonics)

Illustration generated with assistance of GPT-5

Memristor developed at Kiel University[1]

- Analog switching at ~ 1 V
  (highly energy efficient)
- CMOS compatible
  (transfer and scalable)
- Simple design and fabrication
  (series of sputter deposits)





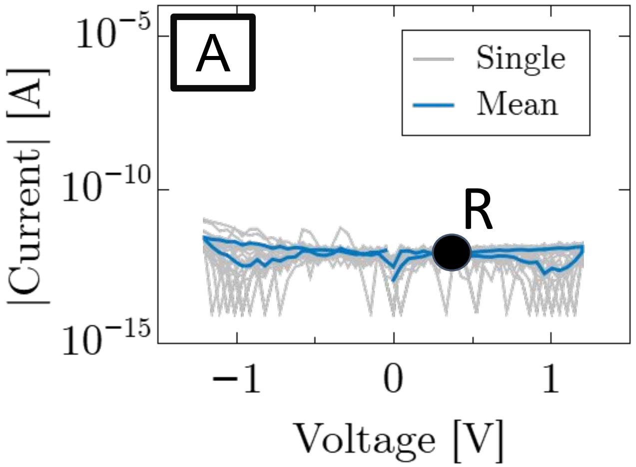
[1]Lamprecht et al., Adv. Eng. Mater. 27, 2401824 (2025)

What happens during manufacture?

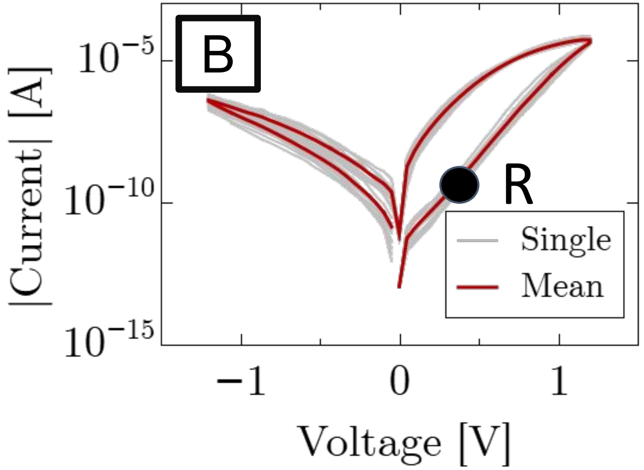
After 3 years of fabrication:

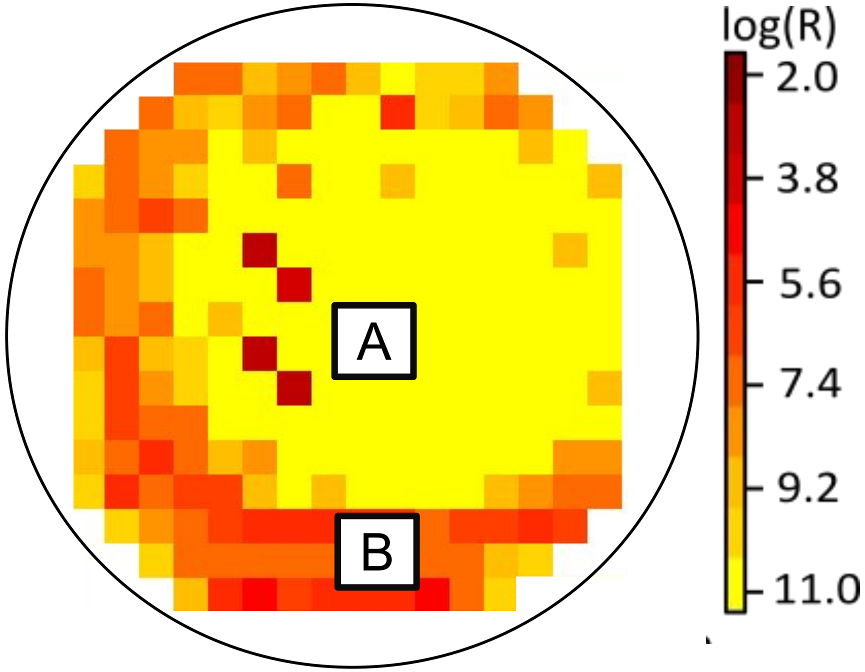
- > 50,000 devices (≈ 50 wafer)
- High device-to-device variability
- Unclear effect of process parameters

capacitive



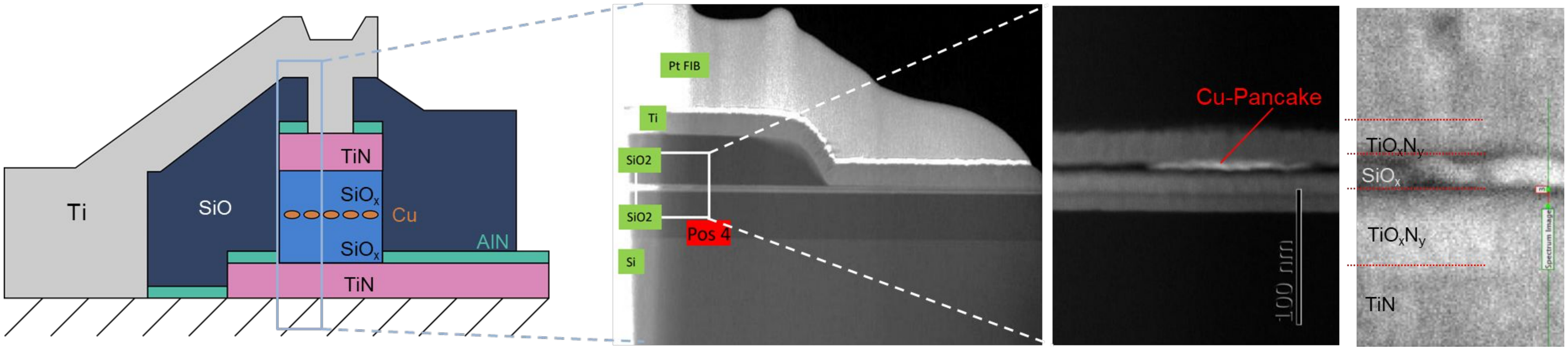
analog





exemplary wafer map
(oversimplifying: *I*-*V* → R)

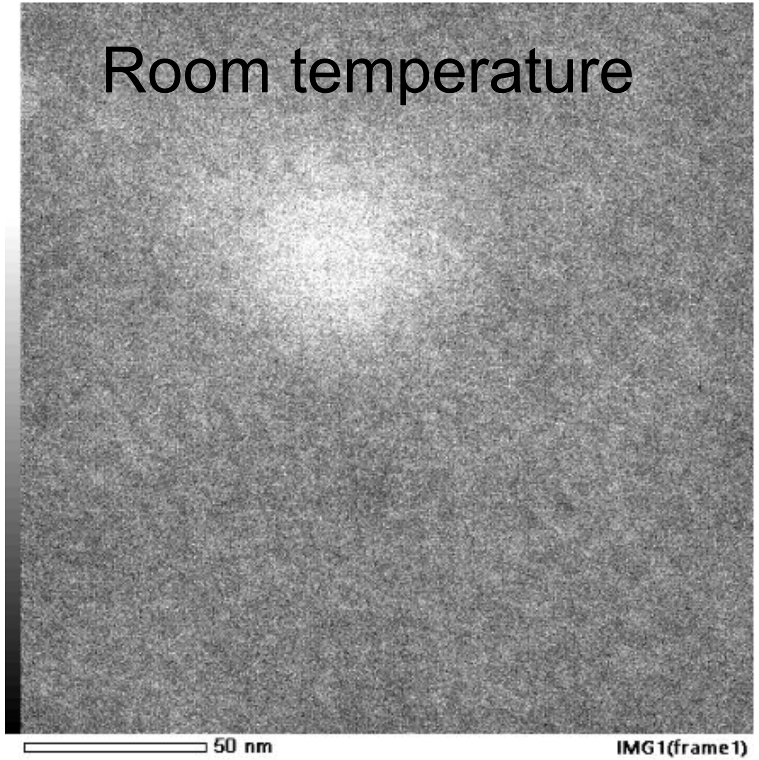
What happens during manufacture?

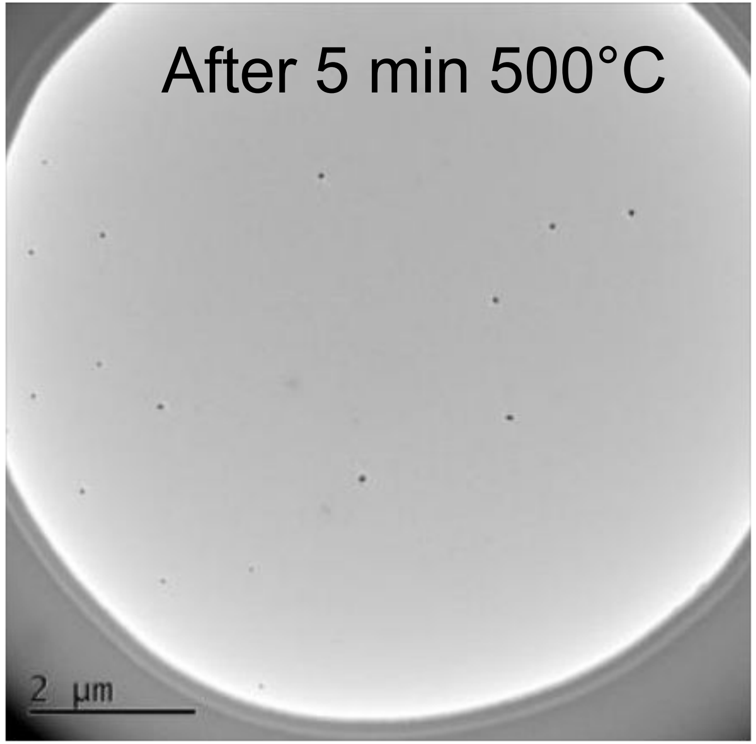


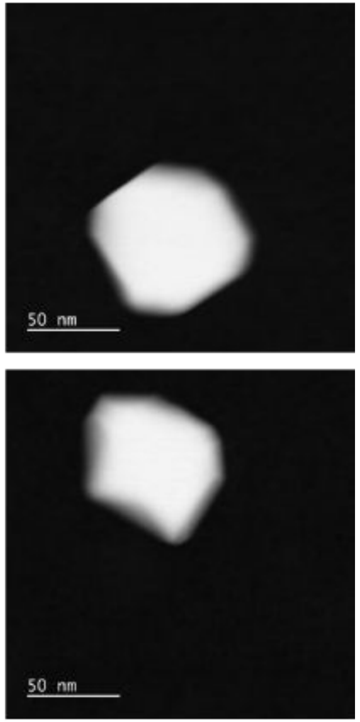
Method: TEM analysis

Result: Large Cu agglomerations

What happens during manufacture?



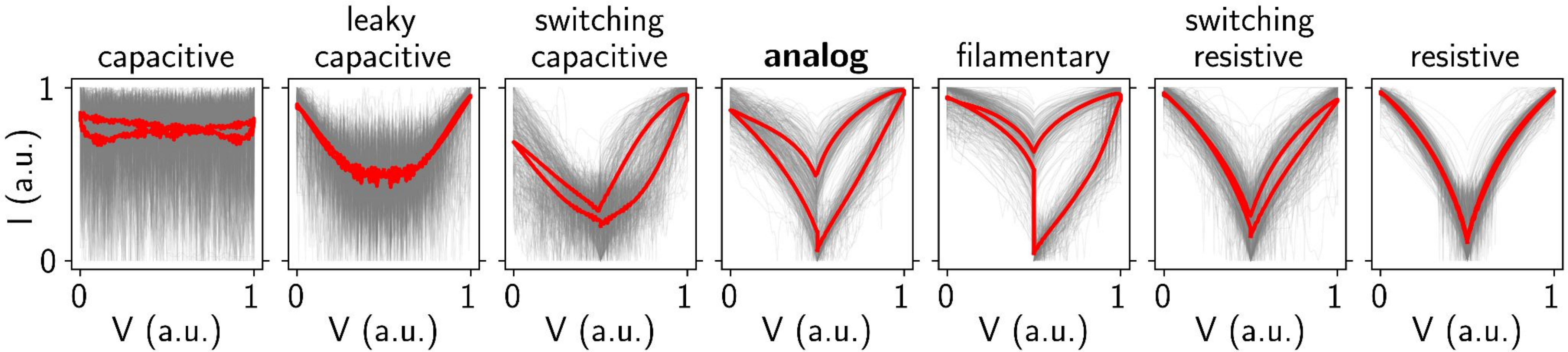




<u>Method:</u> TEM in situ heating

<u>Result:</u> Large Cu agglomerations through **volumetric processes**

Establishment of a comprehensive overview

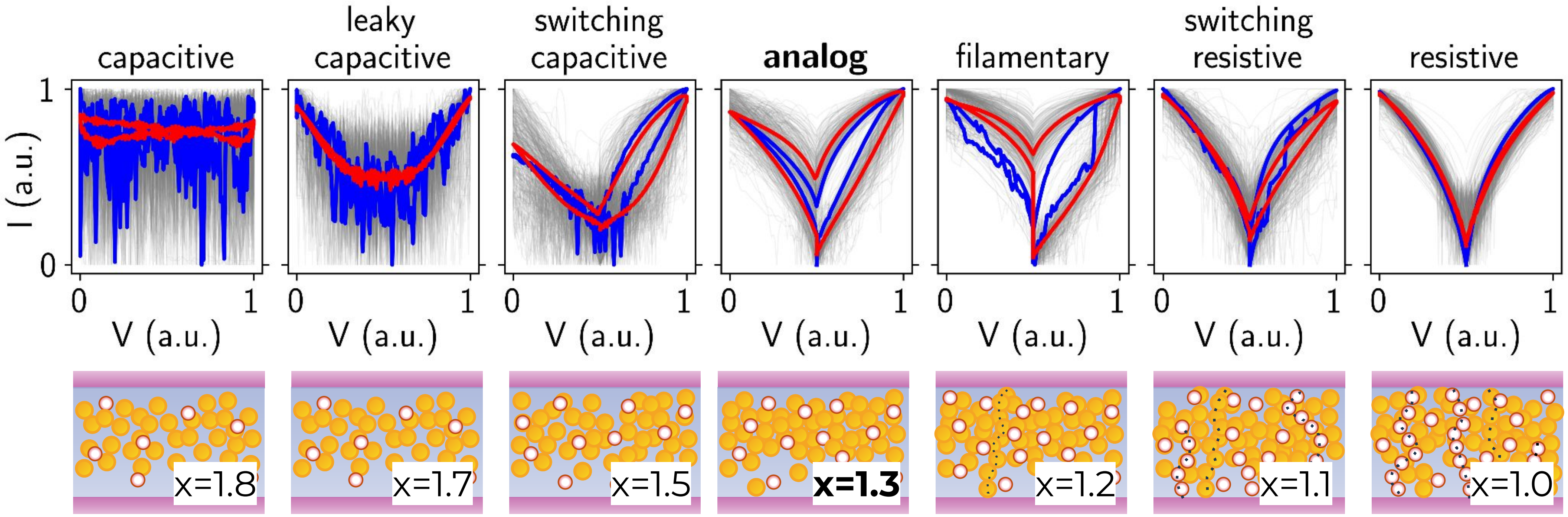


Method: clustering (self-organizing map[1]) and cluster aggregation

Result: 7 labelled clusters instead of > 50,000 *I-V* curves

[1]Kohonen, Biological cybernetics 43, 59-69 (1982)

Understanding nanoelectronic processes



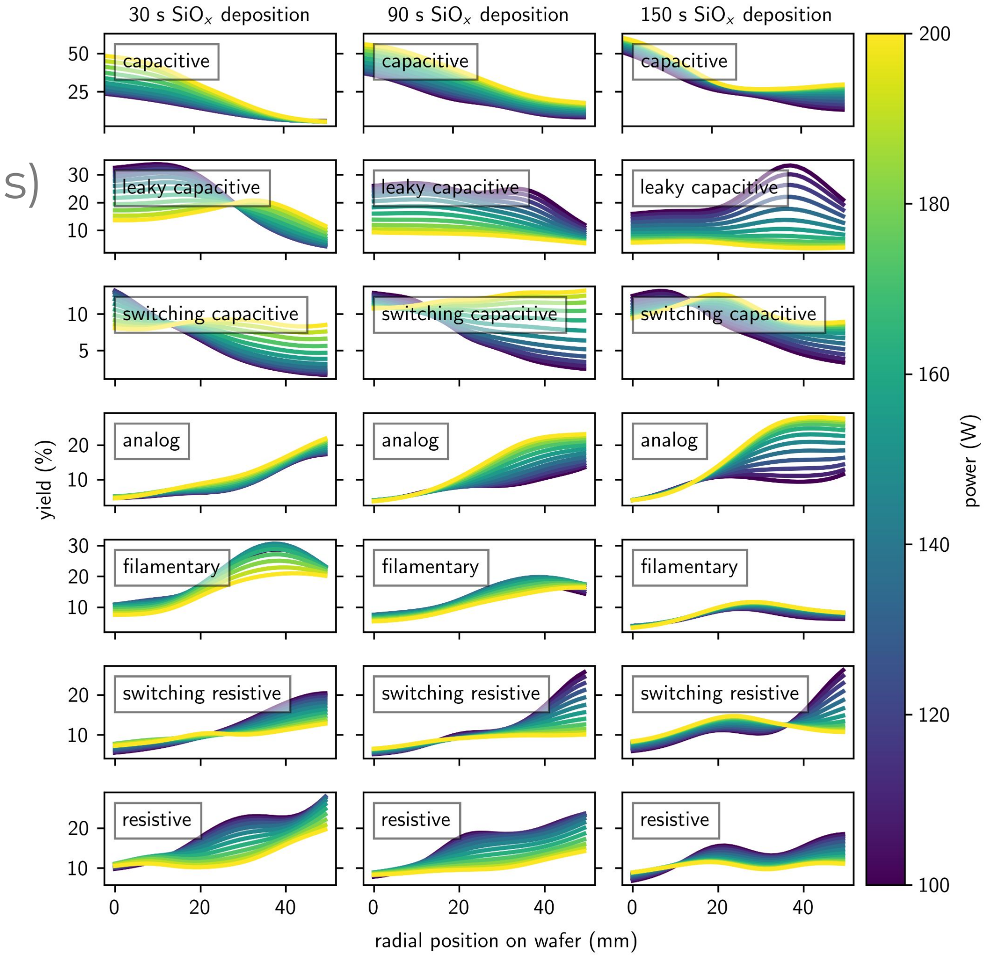
Method: Cloud-in-a-Cell based 1D simulation[1] (inspired by plasma PIC)

Result: mobile oxygen vacancies (deep traps) and large immobile Cu agglomerations (shallow traps) enable **analog** characteristics

[1]based on Yarragolla et al., J. Appl. Phys. 131, 134304 (2022)

Understanding plasma processing (process parameters)

Method
Kernel density estimations[1]
(data homogenization / removal of sampling bias)



[1]implemented in scitkit-learn: Pedregosa et al., JMLR 12, pp. 2825-2830, 2011

Understanding plasma processing (process parameters)

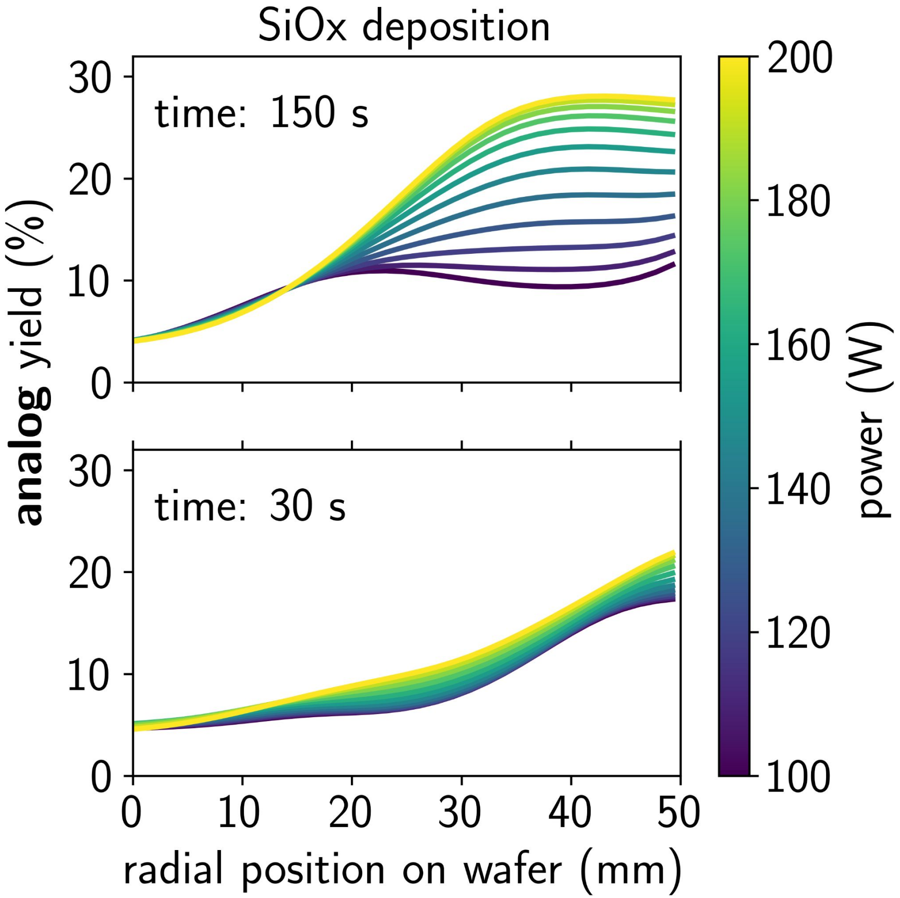
Method

Kernel density estimations[1]

(data homogenization / removal of sampling bias)

Results (maximizing **analog** yield)

- Greater power
  (x↓ and compressive stress ↑)
- Radial position > 20 mm
  (unclear)



[1]implemented in scitkit-learn: Pedregosa et al., JMLR 12, pp. 2825-2830, 2011

Understanding plasma processing (plasma dynamics)

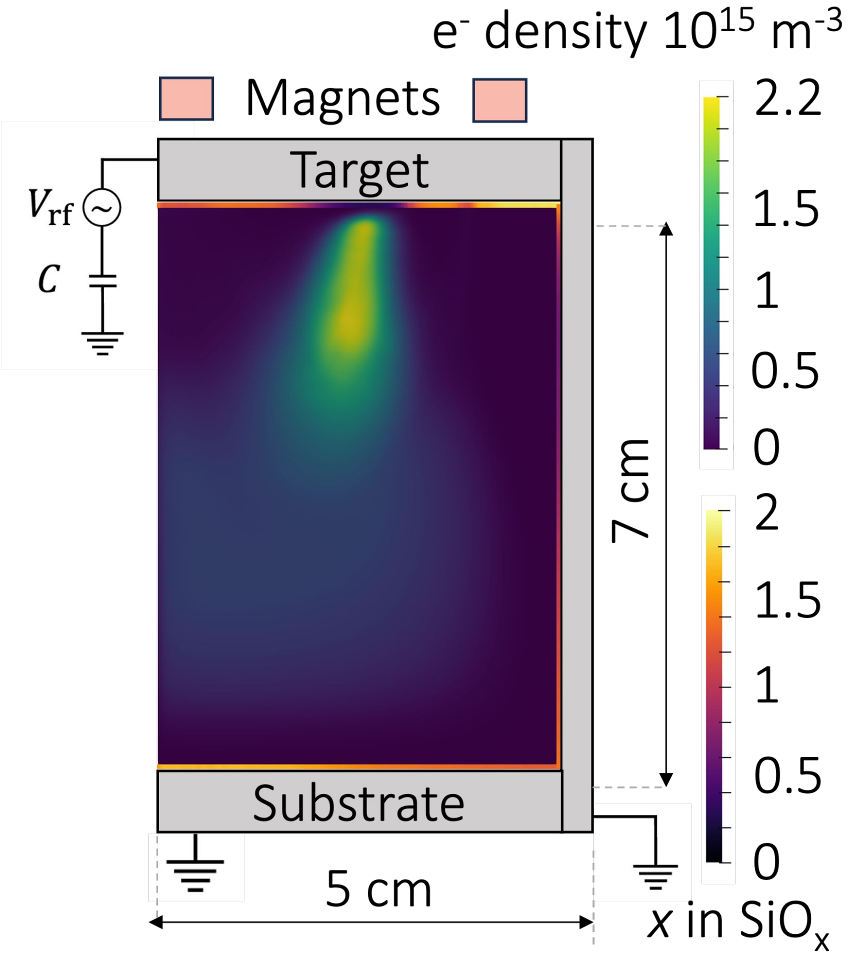
Method

Hybrid PIC simulation

(Ar/O_2, 5% O_2, 0.5 Pa, V_{rf}=300 V, V_{SB}=-140 V)

Results

- Greater power
  (x↓ and compressive stress ↑)
- Radial position > 20 mm
  (unclear)



Understanding plasma processing (plasma dynamics)

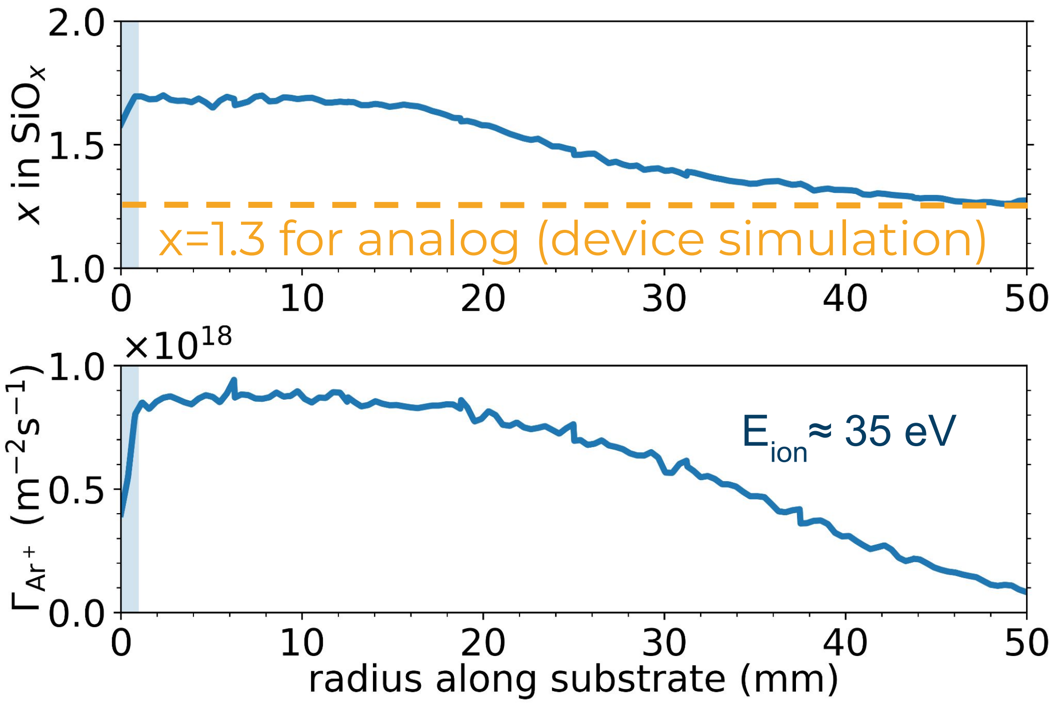
<u>Method</u>

Hybrid PIC simulation

(Ar/O_2, 5% O_2, 0.5 Pa, V_{rf}=300 V, V_{SB}=-140 V)

<u>Results</u>

- Greater power
  (x↓ and compressive stress ↑)
- Radial position > 20 mm
  (x↓ and Γ_{Ar+}↓)



Understanding plasma processing (ion bombardment)

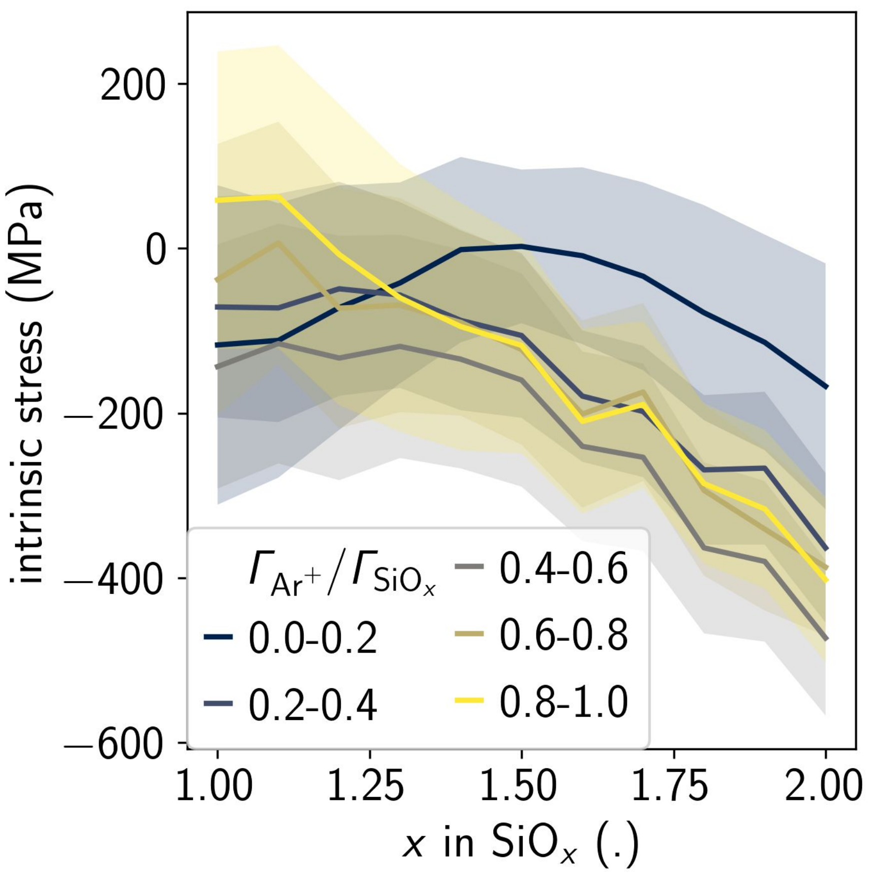
Method

Reactive molecular dynamics

(ReaxFF/ZBL potential)

Results

- Greater power
  (x↓ and compressive stress ↑)
- Radial position > 20 mm
  (x↓ and Γ_{Ar+}↓)
- Variations in stress
  (on the mesoscale)



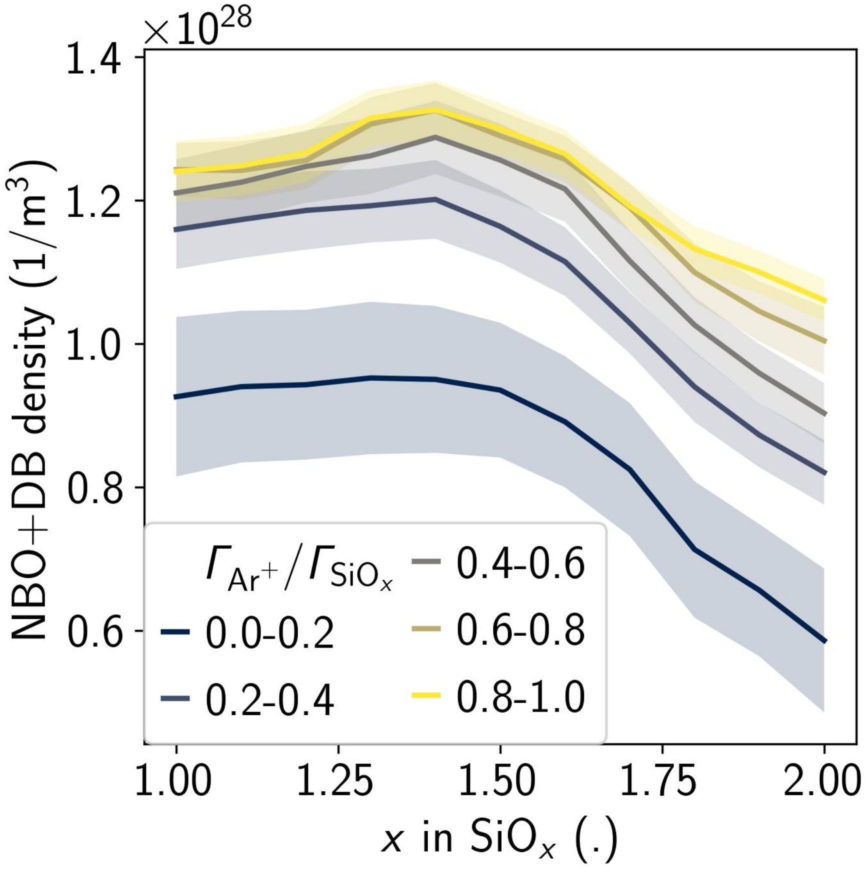
Understanding plasma processing (ion bombardment)

Method

Reactive molecular dynamics
(ReaxFF/ZBL potential)

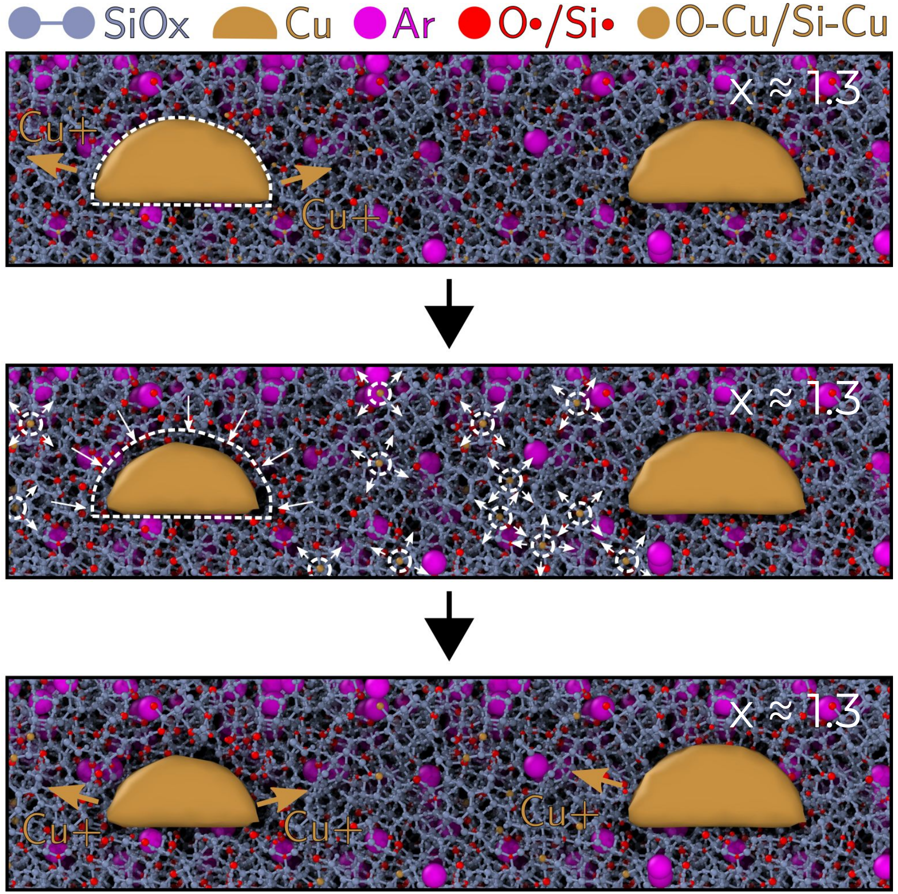
Results

- Greater power
  (x↓ and compressive stress ↑)
- Radial position > 20 mm
  (x↓ and Γ_{Ar+}↓)
- Variations in stress
  (on the mesoscale)
  - Non-bridging oxygen (NBO)
  - Dangling bonds (DBs)
  - Entrapped Ar / structural changes



Chain reaction

1. Formation and diffusion of Cu+
   (strong dependence on the local environment)
2. Relaxation of Cu+ and DBs / NBOs
   (buildup of local stress / strain)
3. Repeat but with strained SiOx
   (triggering the dissolution of other Cu islands)



DB: dangling bonds; NBOs: non-bridging oxygen

What happens during manufacture? (conclusion)

Chain reaction

1. Formation and diffusion of Cu+
   (strong dependence on the **local environment**)
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   (buildup of local stress / strain)
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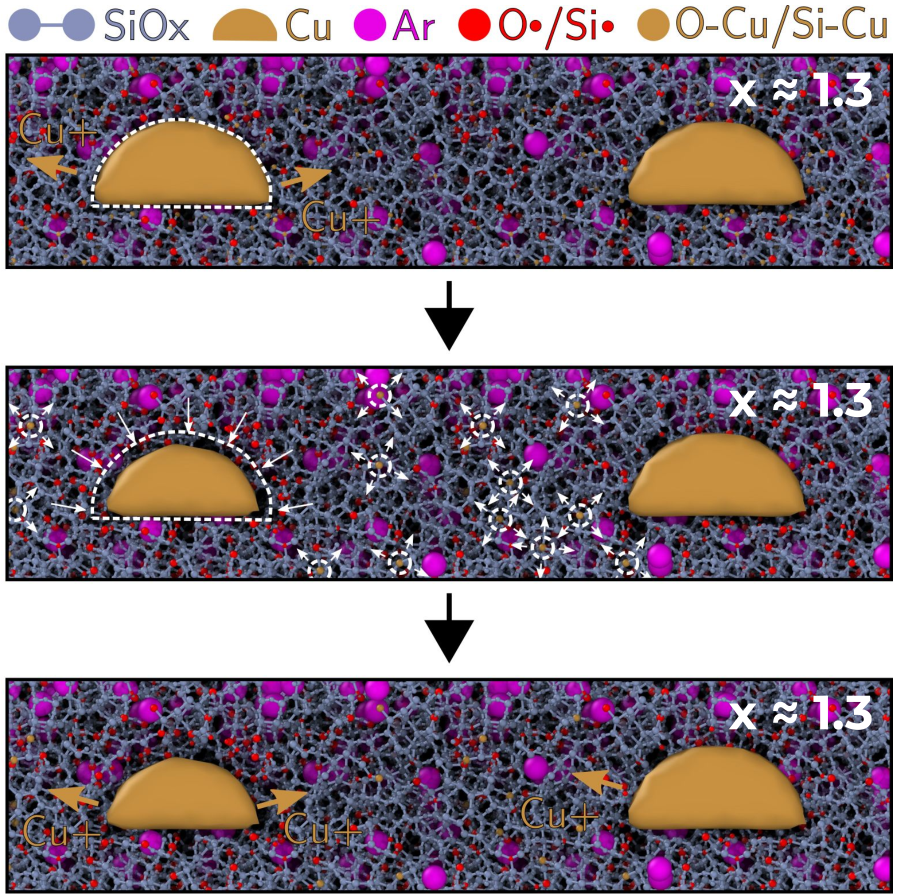

Local environment defined by

- Macroscale plasma non-uniformity
- Mesoscale stress modulation
- Nanoscale variation in system state
  (i.e., composition, defects, density, stress)

DB: dangling bonds; NBOs: non-bridging oxygen

Acknowledgement

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