Correlation of sputter deposition parameters with current-voltage ($I$-$V$) characteristics in double-barrier memristive devices

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Neuromorphic computing

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Neuromorphic computing

- Hardware realization of **bio-inspired systems** (neurons and synapses)
- **Fundamental differences to conventional computers:**
  - Representation of **information by relative values of analog signals**
  - **Co-localization of memory and computing** (avoid von Neumann bottleneck)
- **associative tasks** like pattern recognition

- **real-time**
- **energy efficient**
- **parallel**

C. Mead, Proceedings of the IEEE 78 (1990)
J. Yang et al., Nanotechnology 8 (2013)
A double-barrier memristive device (DBMD)

- Strong I-V non-linearity and asymmetry
- Self-rectifying
- Interface-based switching → analog
- Voltage threshold for switching
- No electro-forming

A double-barrier memristive device (DBMD)

Tunnel barrier

Al | Al₂O₃ | NbOₓ | Au

1.3 nm | 2.5 nm

Schottky barrier

Coupled mechanisms by ultra-thin solid state electrolyte
Unsupervised learning with DBMDs – mixed-signal implementation

Unsupervised learning with DBMDs – mixed-signal implementation

Pulse generating unit

Current measurement (I-to-V converter)

Voltmeter

Analog signals

Control signals

16x16 crossbar

Fabrication of DBMDs

• DC-magnetron sputtering

• Nb is sputtered in an Ar / O₂ gas mixture (poisoned mode) \( \rightarrow \) NbOₓ

• 100 mm targets and 100 mm wafers

➢ No homogeneous layers across one whole wafer \( \rightarrow \) variable \( I-V \) curves
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  - Performance of neuromorphic systems crucial depend on the individual I-V characteristics
    → tailoring of I-V curves possible if impact of deposition parameters is understood
$I$-$V$ characteristics of a whole 100 mm wafer

- **R @ +1.6 V**
  - Low to high color gradient

- **R @ -1.6 V**

- **Position on wafer (mm)**
  - Range from -40 to 40

- **Current density** $|J|$ vs. voltage $V$ for three different sections (1, 2, 3)
  - Scales range from $10^{-16}$ to $10^{12}$ A/μm²

- **Current density** $|J|$ vs. voltage $V$ for section 4
  - Scales range from $10^{-16}$ to $10^{-6}$ A/μm²
Measurement of plasma parameters during DC magnetron sputtering of NbO\textsubscript{x}

- Energy flux by heating of a floating copper plate

Voltage sweep on probe and measuring the current
- Electron temperature ($T_e$)
- Floating potential ($\Phi_{fl}$)
- Plasma potential ($\Phi_{pl}$)
- Ion Current
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plasma engineered devices
Correlations of plasma parameters and memristive behaviour
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- $\Phi_{fi}$ resembles $R$ for positive bias within +/- 25 mm

- No correlation for outer area, e.g. at +/- 30 mm
Correlations of plasma parameters and memristive behaviour

- Maxima of $T_e$ at position of high resistive devices without memristive behaviour
- Center comparable to edge
Correlations of plasma parameters and memristive behaviour

- Maxima of $T_e$ at position of high resistive devices without memristive behaviour
- Center comparable to edge
- Broadening of $I$-$V$ curve
Correlations of plasma parameters and memristive behaviour

- Energy flux at substrate surface is important for film properties → density, stoichiometry, morphology etc.

- Superposition of several parameters leading to needed layer properties
Correlations of plasma parameters and memristive behaviour

- High energetic negative ions at race-track position

- Can influence electronic properties due to defect creation

→ e.g.: higher resistance of Al-doped ZnO

Sputtered from Zn target in Ar / O₂ atmosphere


Electron energy loss spectroscopy of O-K edge (EELS)
By transmission electron microscopy (TEM)

EELS of O-K edge
• NbO₂ or Nb₂O₅ in the center $\rightarrow$ insulating oxidation states
• Suboxide at race-track position $\rightarrow$ lower oxidation state (signal strength small) $\rightarrow$ NbO is metallic conductor

Reference spectra: Bach, EELS investigations of stoichiometric niobium oxides and niobiumbased capacitors, PhD thesis, university of Karlsruhe
Kinetic Monte Carlo Simulations


- lumped element circuit model is consistently coupled with 3D kinetic Monte Carlo model for the ion transport
- **drift of charged point defects within the NbO}_x is the key factor for the resistive switching behavior** → oxygen (vacancies) **modify the local electronic interface states** → **change of resistance**

New simulations (T. Mussenbrock and S. Dirkmann):
- Higher defect concentration → “bigger” $I$-$V$ hysteresis
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![Graph showing I-V characteristics with different defect concentrations.](image-url)
Thank you for your attention!

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