Compact stochastic modelling of memristive devices for nano-security applications

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Abstract

The memristive devices or the RRAMs are part of an emerging class of resistive devices whose resistance can be changed by applying appropriate electrical input. The switching mechanisms in these devices are intrinsically stochastic, making these devices highly suitable for hardware security applications like Physcial Unclonable Functions (PUFs), True Random Number Generators (TRNGs), and hash functions. However, accurate compact stochastic models are needed to understand these devices for hardware security applications in detail [1].

The compact stochastic models can be used to study various memristive devices, explore their electrical properties as entropy sources, and perform circuit simulations using a SPICE-like circuit simulator. Therefore, it is necessary to develop compact models that are robust, computationally inexpensive, and mimic the intrinsic stochastic behaviour of real-world memristive devices.

1D Stochastic model

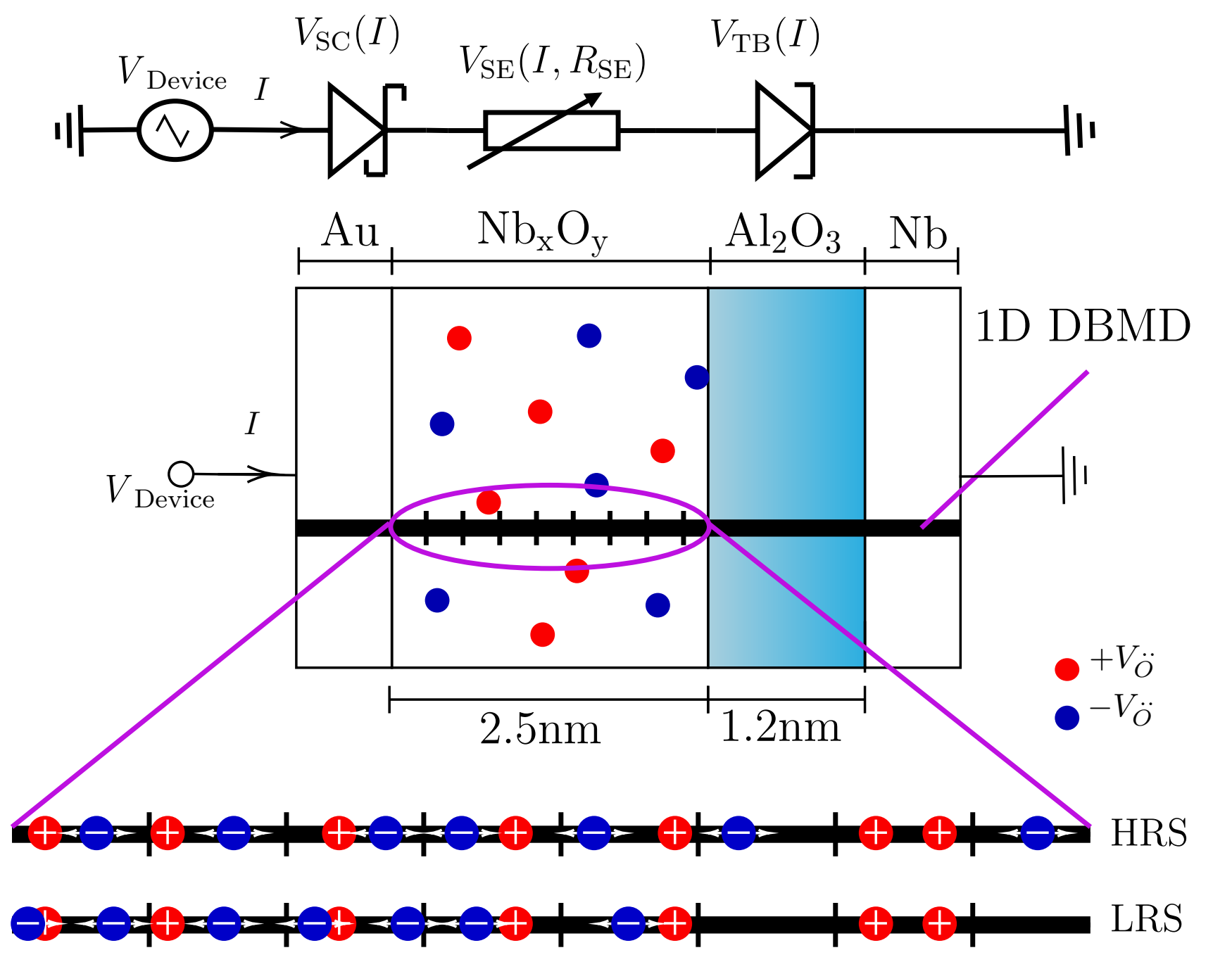
- **Cloud-In-a-Cell (CIC) scheme:** The ion transport responsible for the resistive switching is modelled by consistently coupling Newton's laws with Poisson's equation [2].
- Also known as the Particle-In-Cell (PIC) scheme.
- **Main features:**
  - ✓ Fast and computationally inexpensive
  - ✓ compatible with SPICE like simulation tools
  - ✓ includes more or less realistic physics
  - ✓ stochastic (cycle-to-cycle (C2C) and device-to-device (D2D) variability)

Device Configuration

- **Double barrier memristive device (DBMD)** [3]: $Au/Nb_xO_y/Al_2O_3/Nb$
- Switching mechanism: electric field-driven negative oxygen ions (V_o^{2-}) drift.
- Interface type device with analogous switching.

⇒ **Simulation parameters:**

Physical quantity	Value
Temperature	300K
Device area	$625\,\mu m^2$
Activation energy	0.76
Conductivity (Nb_xO_y)	$1.0 \times 10^{-4}\,\Omega m$
Length of Nb_xO_y	$2.5 \times 10^{-9}\,m$
Defect density	$5 \times 10^{20} cm^{-3}$
Tunnel barrier width	$1.1 \times 10^{-9}\,m$
Tunnel barrier height	3.2 eV
Schottky barrier height	0.98 eV
Schottky barrier ideality factor	4.2



SC : Schottky Contact, SE : Solid – State Electrolyt, TB : Tunnel Barrier

Fig 2. Charge arrangement in DBMD

Cloud-In-a-Cell (CIC) approach

⇒ **Simulation model:**

- Random distribution of ions across the computational domain.
- Electric field E is calculated using a Poisson solver.
- The electric field E is used to push the mobile ions with a certain drift velocity, v_D given by [4]

$$v_D = d p(\mathscr{E}_A) \left(\exp\left\{ \frac{|z|edE}{2k_BT} \right\} - \exp\left\{ -\frac{|z|edE}{2k_BT} \right\} \right)$$

where d=jump distance (lattice constant), z=charge number of the ion, k_B=Boltzmann constant, T=temperature, e=elementary charge, and $p(\mathscr{E}_A)$=transition probability.

⇒ **Stochasticity modelling:**

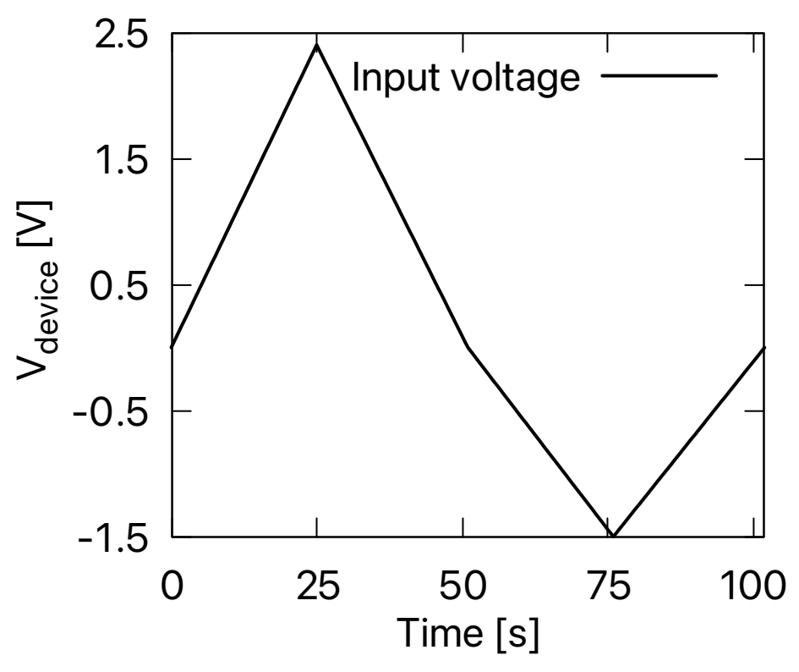
$$v_D \text{ (deterministic)} \rightarrow x_i \text{ (deterministic)} \xrightarrow[x_i = x_i(1+r\delta)]{\text{random fluctuation}} x_i \text{ (stochastic)}$$

where x_i=position of i^{th} ion, r=random number, and δ=maximum random displacement.

Results

⇒ ***I-V* Characteristics:**

The calculated *I-V* characteristics (Fig. 2b) show good agreement with the experimental [3] and kinetic Monte-Carlo (kMC) [5] simulated *I-V* characteristics shown in Fig 2a.



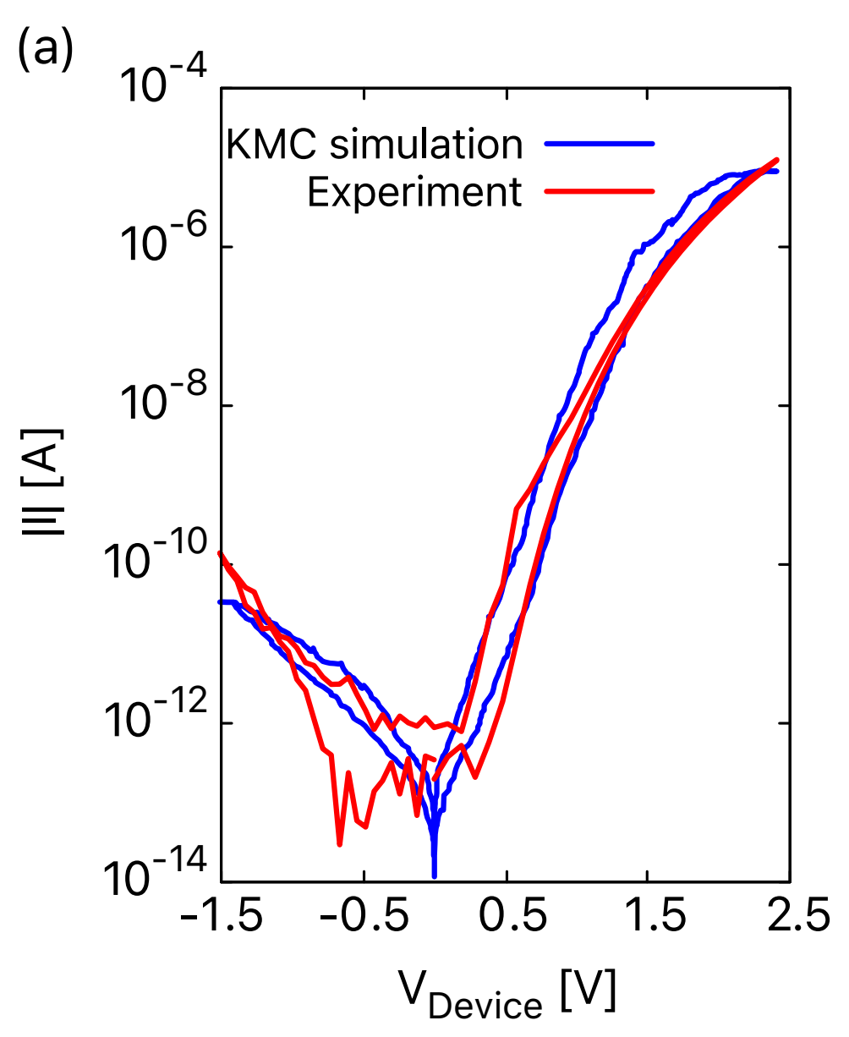


Fig 2. The *I-V* charcteristics of DBMD

⇒ **Ion transport:**

- The coloured lines represent the positions of twenty V_o^{2-} ions shown for different instants of time and voltage.
- Average distance:

$$\bar{d} = \frac{\sum_{i=1}^{N_{ions}} (\bar{x}_i - \bar{x}_{SC})}{N_{ions}}$$

x_{SC}=position of Au interface, N_{ions}=number of V_o^{2-}.

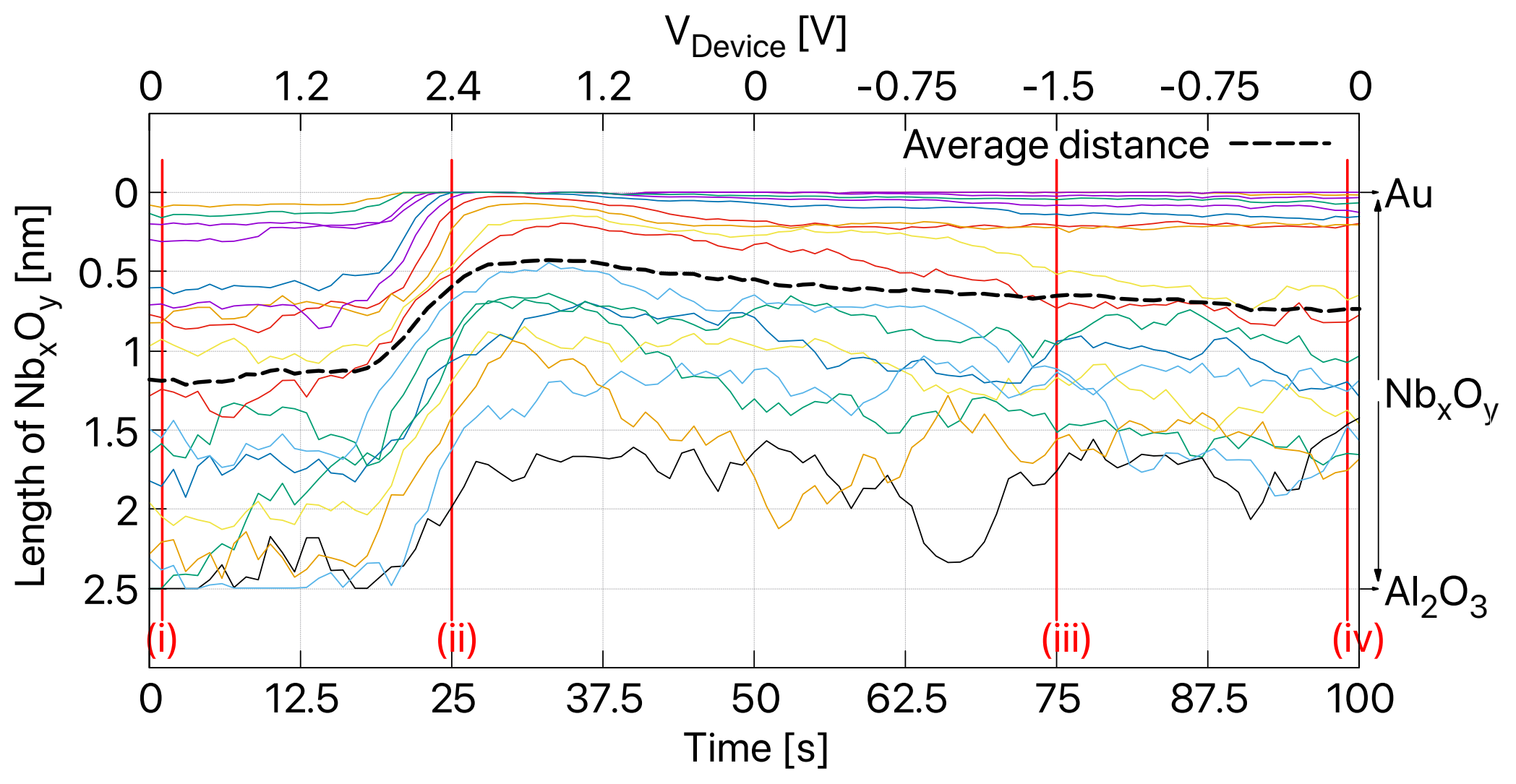


Fig 3. The ion transport shown for one input voltage cycle.

⇒ **Stochastic behaviour:**

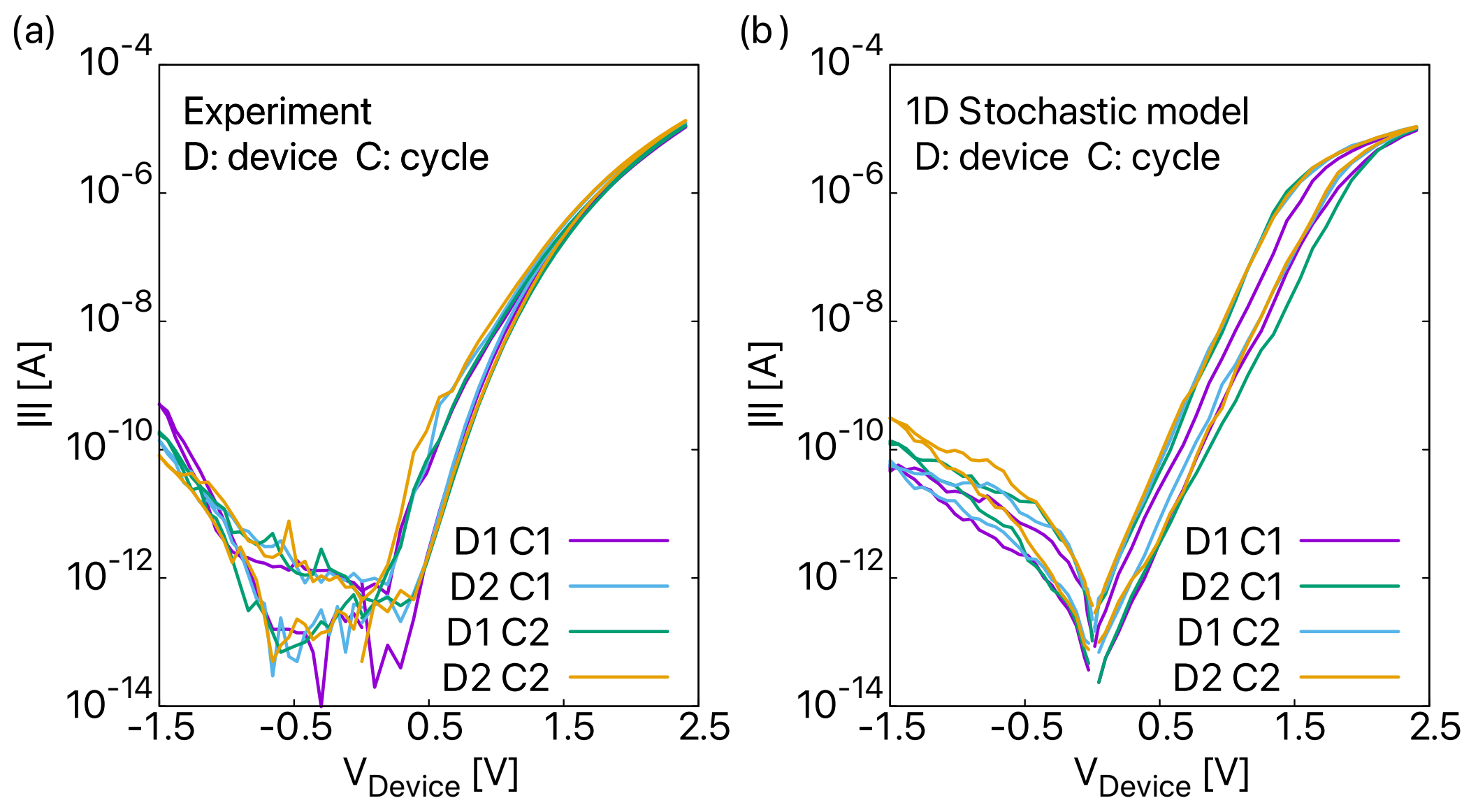


Fig 4. The *I-V* charcteristics showing stochastic behaviour of DBMD.

- **D2D variability:**
  - initial random ion arrangement
  - two devices, one input voltage cycle
- **C2C variability:**
  - artificial fluctuation of all ion positions
  - one device, two input voltage cycles

Conclusion

⇒ The work mainly focuses on **modelling** the important **intrinsic stochastic behaviour** observed in memristive devices.

⇒ The proposed **1D stochastic model** is based on CIC inspired ion transport scheme, including the physical and chemical processes responsible for resistive switching.

⇒ **The proposed model is well suited for performing circuit simulations in artificial intelligence computing, reconfigurable logic computing, or hardware security applications.**

References

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