Metal oxide-based structures for novel computing paradigm concepts

Robert Mroczyński

Warsaw University of Technology, Institute of Microelectronics and Optoelectronics
Koszykowa 75, 00-662 Warsaw, Poland

Corresponding author's e-mail address: ***robert.mroczynski@pw.edu.pl***

This work summarizes the recent results devoted to the materials engineering, optimization, and subtle characterization of structures and devices based on ultrathin oxide materials. These materials fabricated employing low-temperature methods show great potential in new concepts for logic and memory devices, e.g., neuromorphic or brain-inspired computing, as possible candidates for emulating artificial synapses and constructing artificial neural networks. The presented results were performed by joint research teams representing the Institute of Microelectronics and Optoelectronics and the Centre of Advanced Materials and Technologies of Warsaw University of Technology. Both groups implement broad research concerning technology, characterization, and diagnostics of materials, structures, and semiconductor devices. Recently, joint fundamental studies related to materials engineering of different oxide and nitride materials were performed to fabricate structures and devices exhibiting resistive switching properties compatible with BEOL conditions. The test structures are based on metal oxides, also with the inclusion of semiconductor nanocrystals, ferroelectrics, and classical silicon oxide in the ultrathin regime. Advanced and subtle electrical characterization, including typical DC current-voltage characteristics analysis, small-signal and pulse measurements, and complex impedance spectroscopy, were performed to identify investigated structures' transport mechanisms. Moreover, the structural investigations support the obtained data to fully understand the switching properties and electrical behavior of fabricated devices.

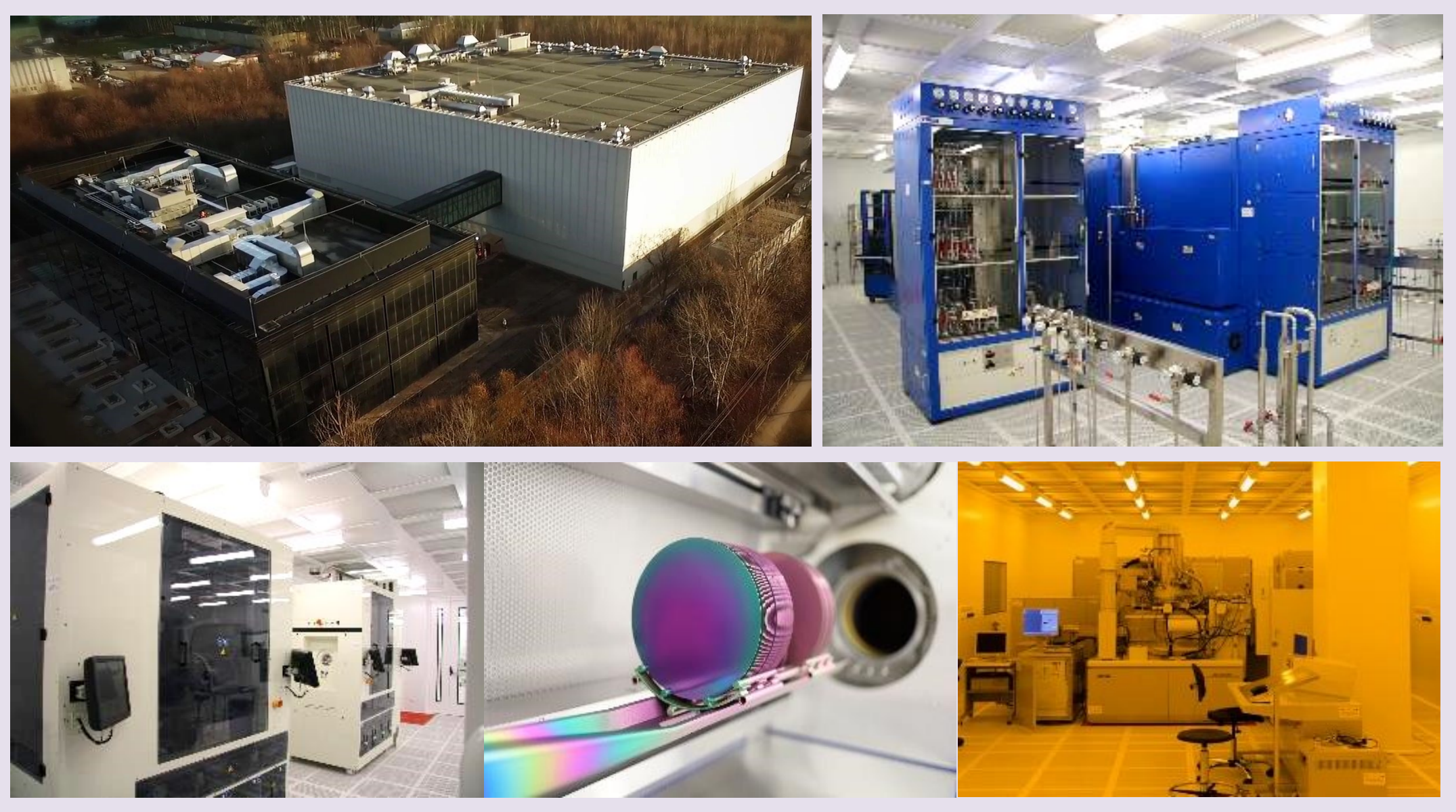
Access to the unique research infrastructure

INSTITUTE OF MICROELECTRONICS AND OPTOELECTRONICS

- Research clean-room facility with the full lineup of processing tools compatible with 4-inch substrates
- Fabrication of thin and ultrathin materials using low-temperature methods, i.e., PVD, PECVD, ALD
- Wet and dry etching (RIE) employing fluorine- and chlorine-based plasma
- Photolithography (CD ~1 um)
- Electrical characterization – Keithley 4200SCS and Keysight B1500A system equipped with FORMFACTOR PM8 station with ProbeShield enclosure

CENTRE OF ADVANCED MATERIALS AND TECHNOLOGIES

- State-of-the-art infrastructure with stable and repeatable technology
- Technology equipment compatible with wafer sizes from 4- up to 8-inch substrates for collaboration with Universities, RTOs, and pilot line production
- Microelectronics, photonics, and microsystems applications
- Separate (to avoid cross-contamination issues) technology platforms: (i) Si-compatible technology, and (ii) Wide-bandgap semiconductor technology



Materials engineering and technology of memory structures and devices

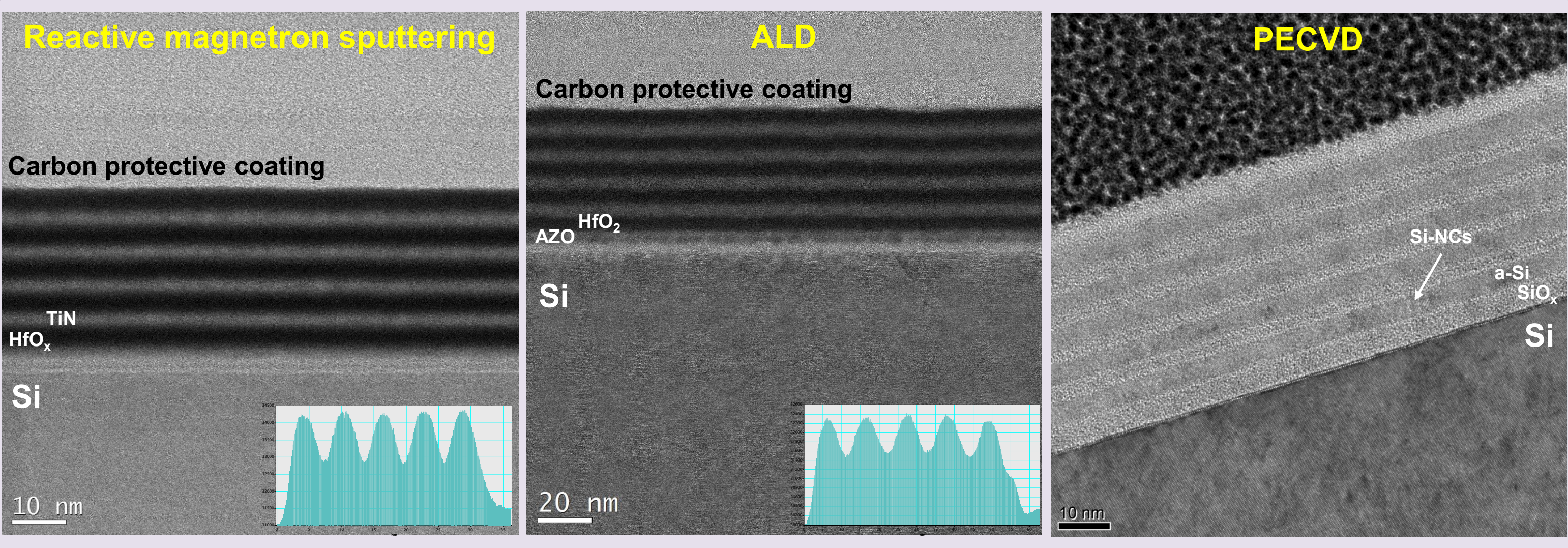


Figure 1. HRTEM cross-sections of periodic structures based on selected ultrathin materials formed by low-temperature methods.

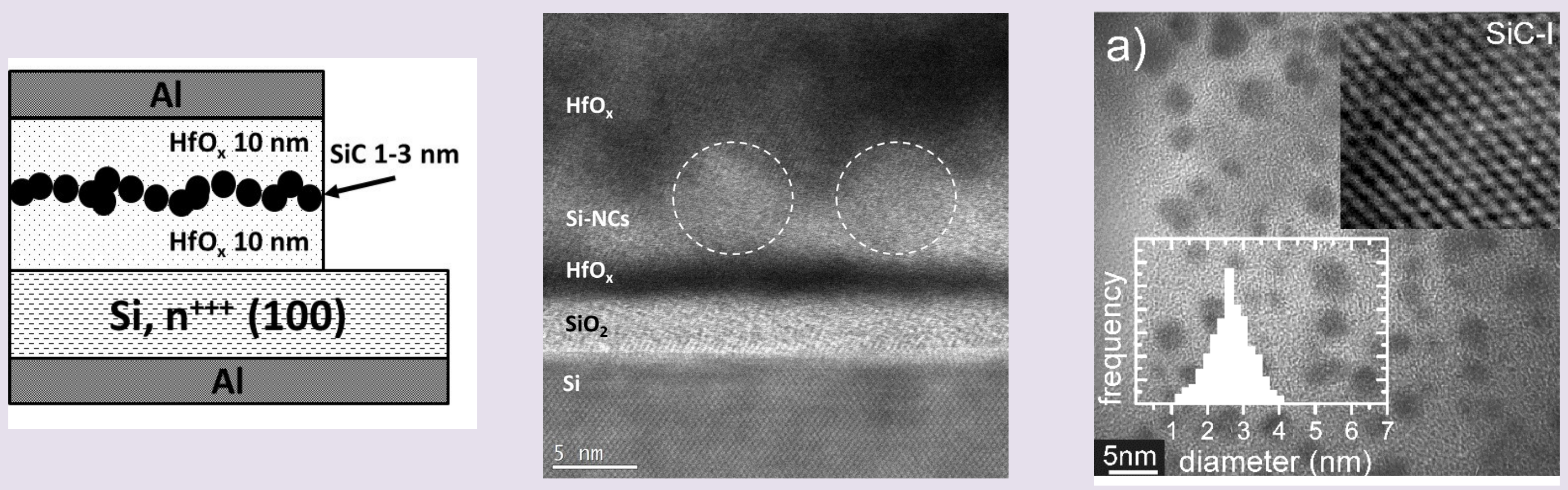


Figure 2. Schematic cross-sections of MIM structures with SiC-NCs embedded in HfO$_x$ ensembles.

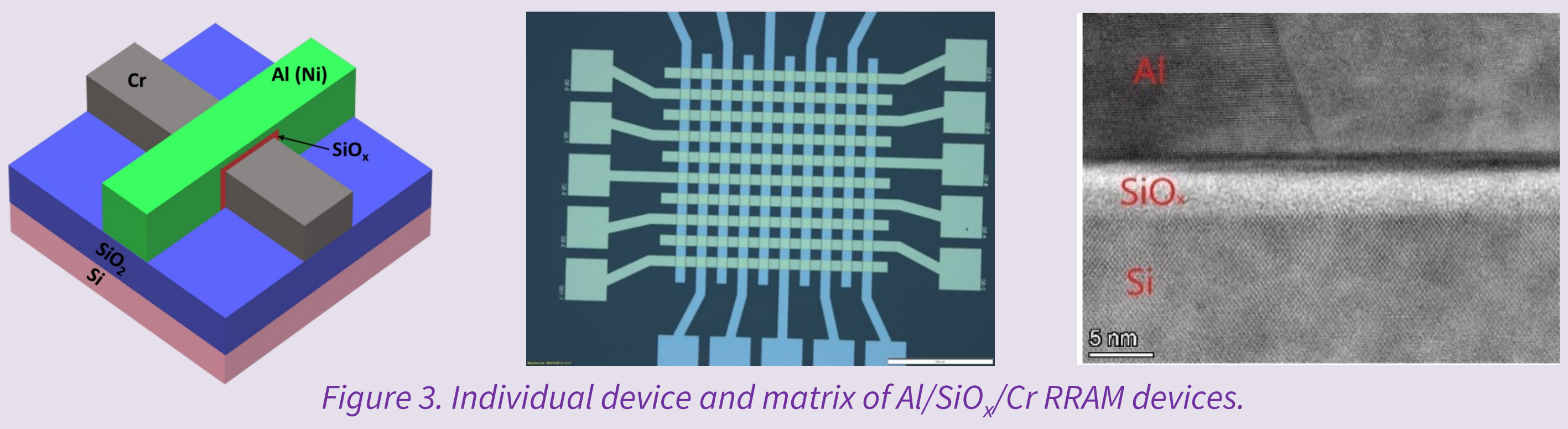


Figure 3. Individual device and matrix of Al/SiO$_x$/Cr RRAM devices.

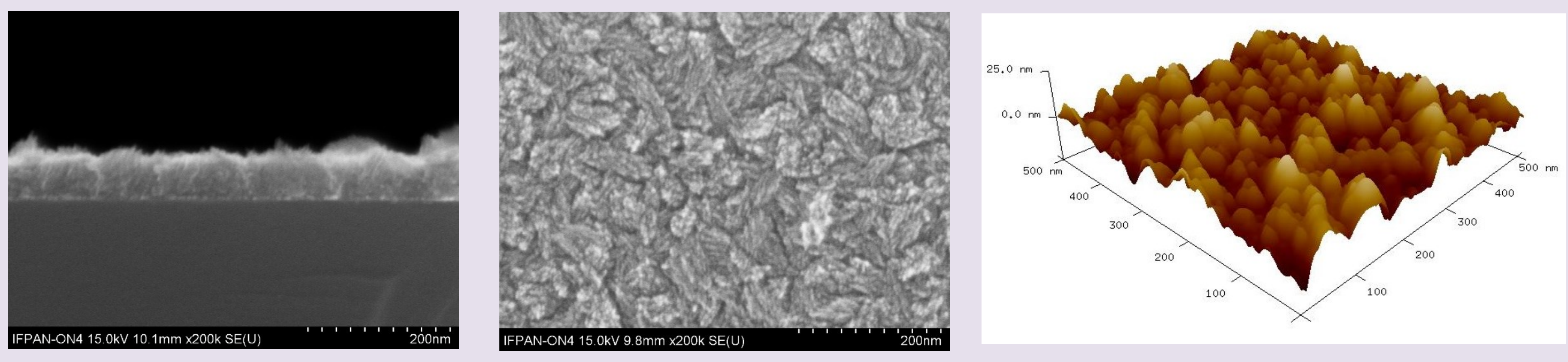


Figure 4. SEM and AFM images of hydrothermally formed CuO films.

- Competencies in the fabrication of thin and ultrathin materials with tailored properties fabricated employing low-temperature methods compatible with BEOL conditions, e.g., reactive magnetron sputtering (PVD), Atomic Layer Deposition (ALD), or Plasma-Enhanced Chemical Vapor Deposition (PECVD) – Fig. 1.
- Successful implementation of designed technologies in the processing sequence of different memory devices, e.g., RRAM structures based on hafnia films with the inclusion of semiconductor nanocrystals (Fig. 2) or matrices of MIM devices with SiO$_x$ films (Fig. 3)
- Significant support by the comprehensive structural investigations of investigated materials and structures (Fig. 4)

Electrical characterization and modeling

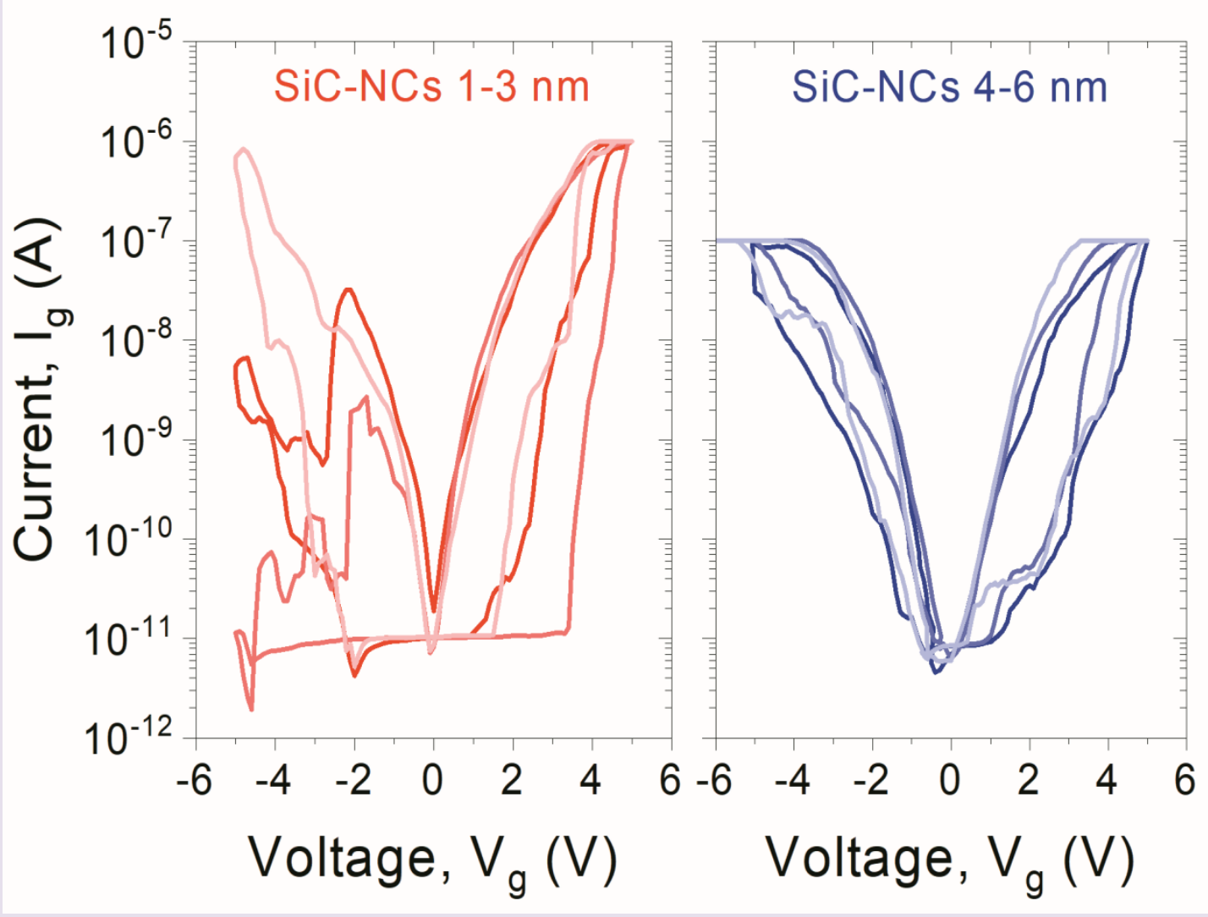


Figure 5. Basic resistive switching curves of MIM devices with SiC-I (1–3 nm) and SiC-II (4–6 nm) NCs.

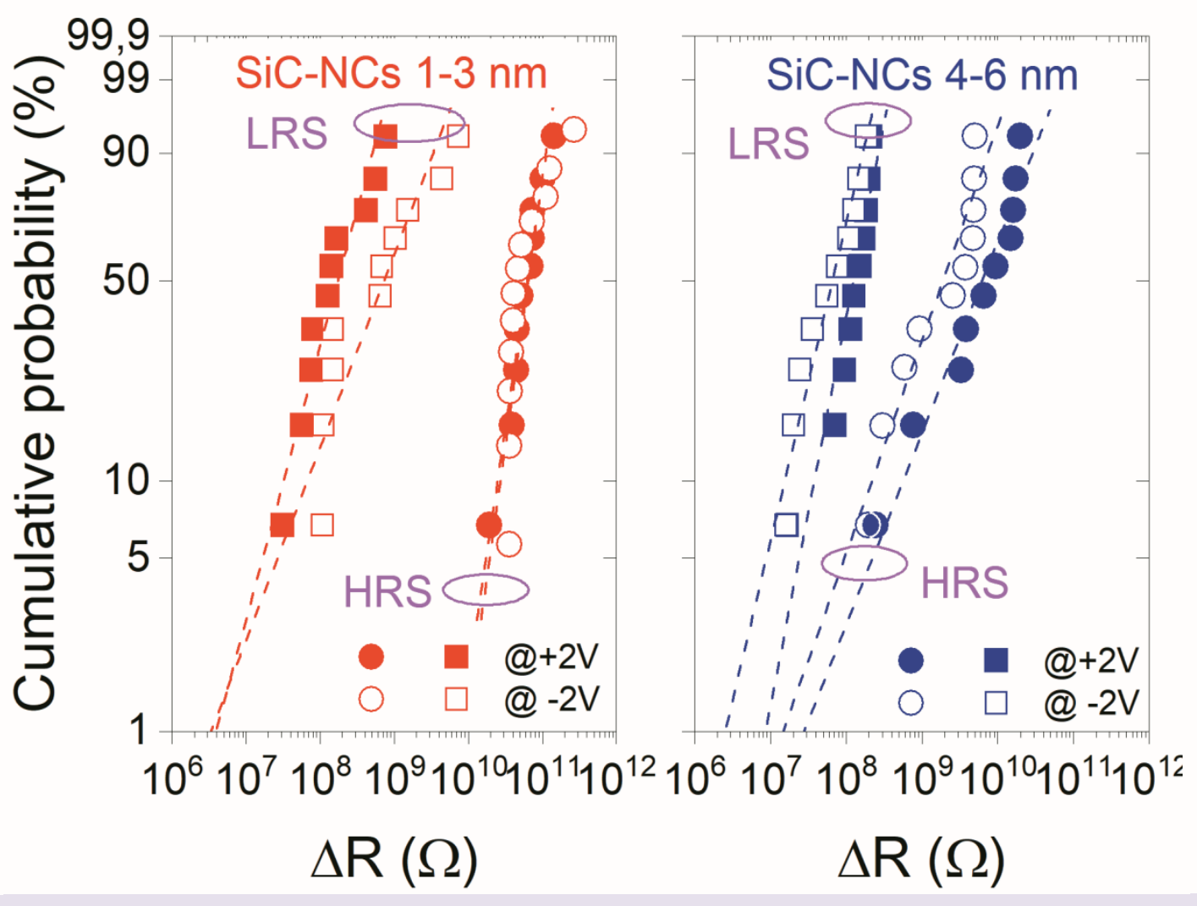


Figure 6. Cumulative plot of retention expressed as resistance changes within the time; resistance values were taken for all devices at V_g = +/−2 V.

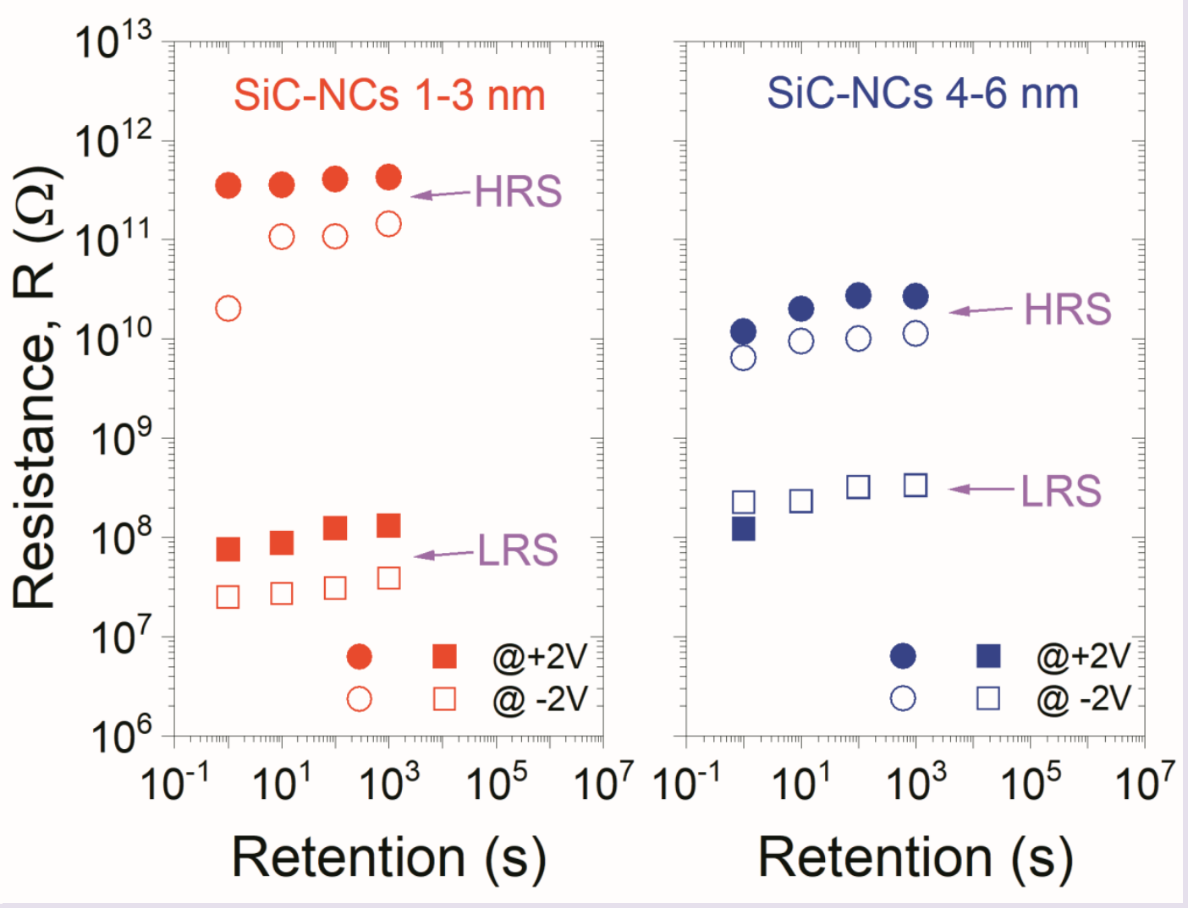


Figure 7. Retention characteristics of RRAM structures with SiC-NCs; resistance values were taken at V_g = +/−2 V.

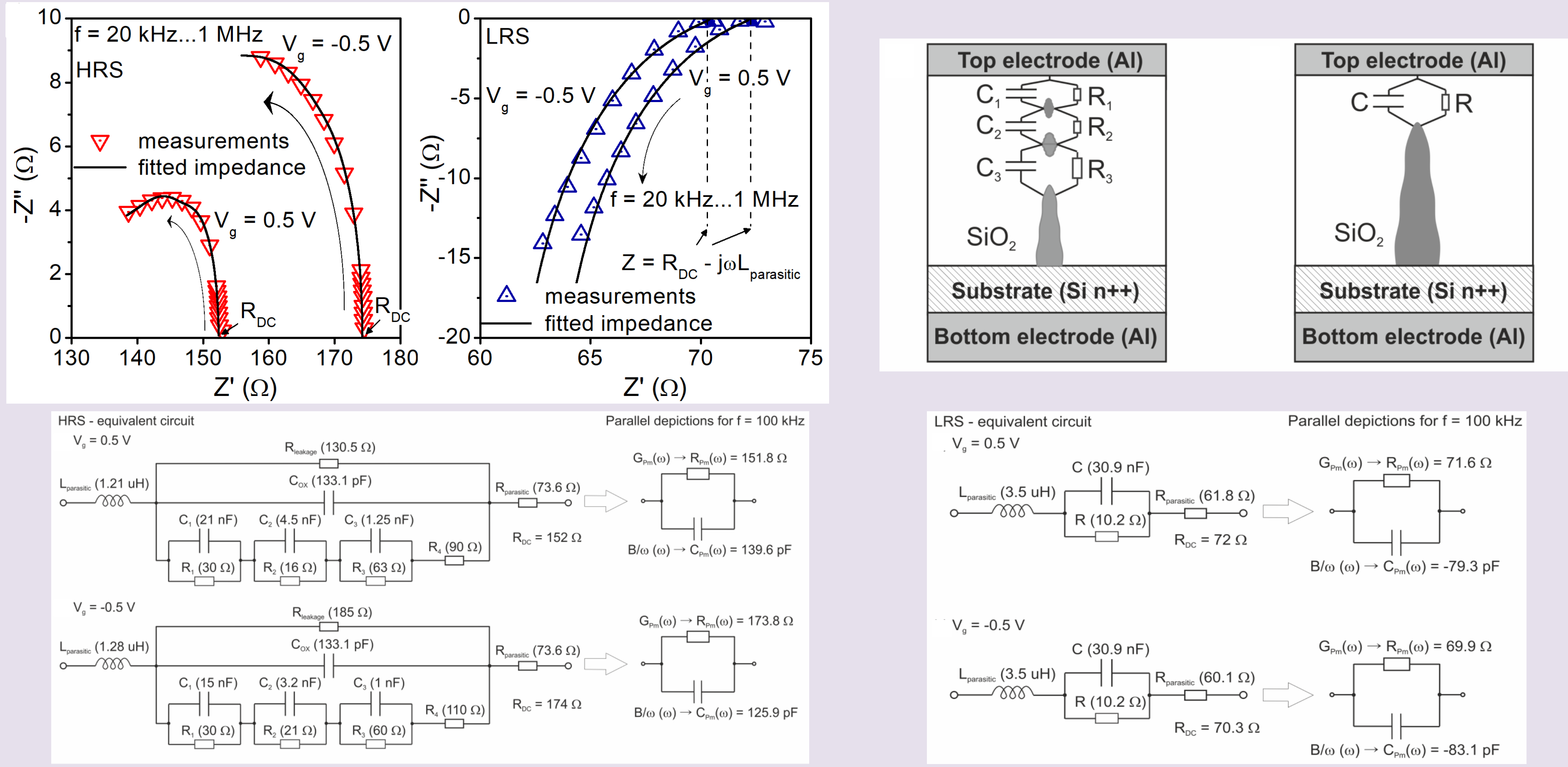


Figure 8. Complex impedance spectra of investigated structures for a frequency range of 20 kHz – 1 MHz at different gate bias voltage values in HRS and LRS and electrical equivalent circuit for the measured device in LRS/HRS at V_g = +/− 0.5 V.

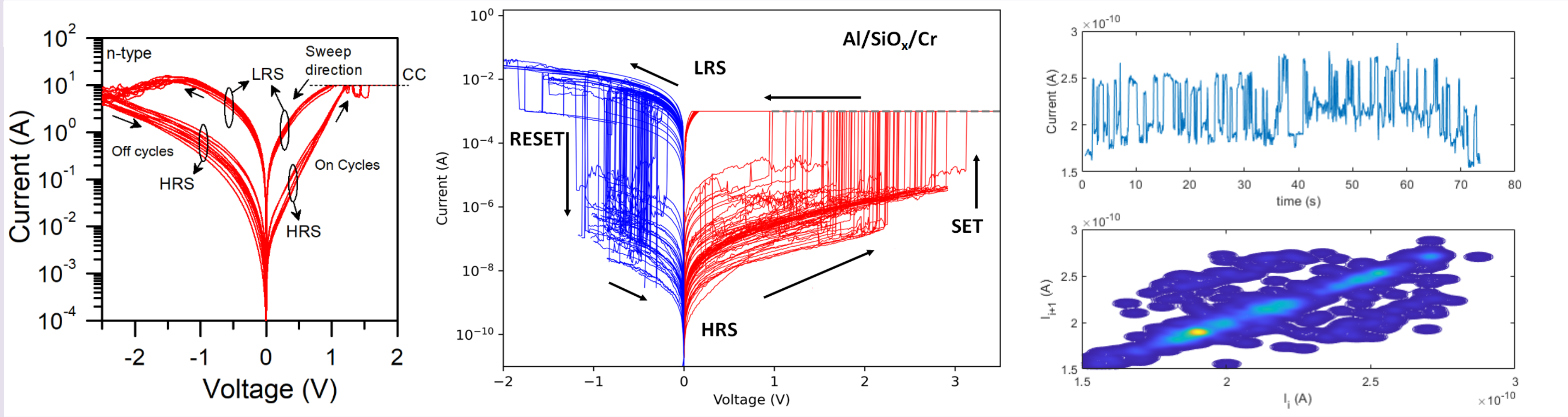


Figure 9. Resistive switching curves of Al/SiO$_x$/n^{++}-Si and Al/SiO$_x$/Cr MIM devices with current trace of TiN/SiO$_x$/n^{++}-Si structure with weighted Time Lag Plot of RTN.

- Performed electrical characterization provides initial information about the electrical behavior and performance of examined structures and devices (Figs. 5–7)
- Complex impendence spectroscopy characterization allows for deeper understanding of switching properties and filament formation during the structure operation (Fig. 8)
- Statistical analysis and high-resolution pulse measurements allows for identification of potential application in scaled memory devices and novel computing paradigm concepts (Fig. 9)

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