# Forming & compliance-free $HfO_xS_y/HfS_2$ memristors for machine learning & neuromorphic computing

**Aferdita Xhameni[1][2]**
AbdulAziz AlMutairi[2][3][4][5], Xuyun Guo[6], Tianyi Wen[2], Valeria Nicolosi[6] & Antonio Lombardo[1][2]
*[1] London Centre for Nanotechnology, 19 Gordon St, London, WC1H 0AH, UK.*
*[2] Department of Electronic & Electrical Engineering, Malet Place, University College London, WC1E 7JE, UK*
*[3] Department of Engineering, University of Cambridge, Cambridge, CB3 0FA, UK.*
*[4] Electrical Engineering Department, King Fahd University of Petroleum & Minerals, P.O. Box 1634, 31261, Dhahran, Saudi Arabia*
*[5] Center for Communication Systems and Sensing, King Fahd University of Petroleum & Minerals, P.O. Box 1634, 31261, Dhahran, Saudi Arabia*
*[6] School of Chemistry, Centre for Research on Adaptive Nanostructures and Nanodevices (CRANN) & Advanced Materials Bio-Engineering Research Centre (AMBER), Trinity College Dublin, Dublin 2, Ireland*
a.lombardo@ucl.ac.uk

Reducing the economic and environmental costs of modern machine learning by driving improvements in neuromorphic computing can be enabled by efficient, high-performance hardware[1]. To address this, we explore the fabrication, characterization, and simulation of memristors based on dry thermal oxidation of hafnium disulfide ($HfS_2$), a two-dimensional van-der-Waals semiconductor[2]. We develop oxide-semiconductor ($HfO_xS_y/HfS_2$) heterostructures integrated into vertical crossbar devices, enabling low-energy, forming-free, and compliance-free resistive switching. Non-volatile states are achieved with 80ns voltage pulses, maintaining an ON/OFF ratio of 102. We demonstrate multiple stable resistance states spanning three orders of magnitude by varying pulse width and height, down to <20pJ operation. Resistance states remain stable at 150°C for $10^4$s, and resistive switching persists unchanged under vacuum (8.6mbar), confirming resilience to environmental factors like water vapor and oxygen. Under potentiation and depression pulsing schemes, the devices exhibit highly linear and symmetric conductance update with minimal cycle-to-cycle variation. From this data we extract performance parameters and simulate crossbar arrays, achieving high inference accuracy in image recognition. Combined with the forming and compliance-free, stable, low-energy switching of the devices, this showcases their potential for neuromorphic computing. Finally, we investigate the mechanisms driving gradual resistive switching and the role of the semiconductor layer in tuning device conductance using technology computer-aided design (TCAD).

References

[1] A.Mehonic & A.J.Kenyon, Nature, 604 (2022) 255-260
[2] A.Xhameni, A.AlMutairi, X.Guo, I.Chircă, T.Wen, S.Hofmann V.Nicolosi & A.Lombardo, Nanoscale Horizons, (2025) Advance Article

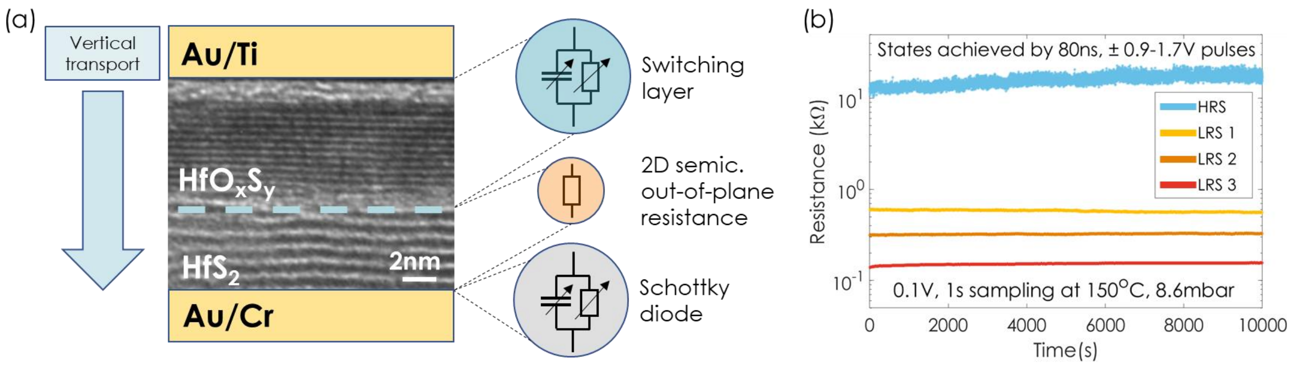


**Figure 1:** (a) Oxide-semiconductor structures integrated in vertical crossbar memristor devices, showing a highly-ordered oxide and sharp interface. (b) These devices show stable, non-volatile resistive switching at low energy without requiring electroforming or current compliance.

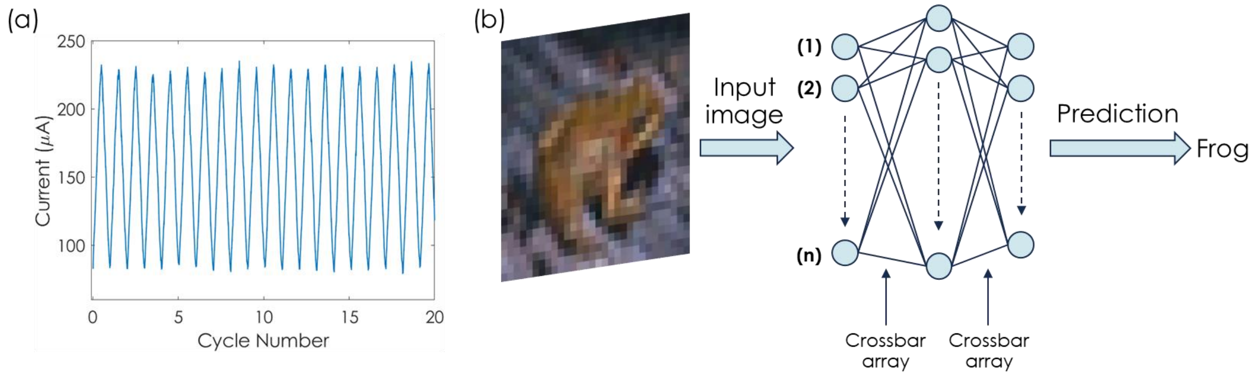


**Figure 2:** (a) Linear and symmetric potentiation and depression of $HfO_xS_y/HfS_2$ memristors from which performance parameters are extracted. (b) Image recognition performance of neural networks based on simulated crossbar arrays of these devices is evaluated.