Origin of Discontinuous Negative Differential Resistance in Metal-Oxide-Metal Devices

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Metal-oxide-metal cross-bar devices that exhibit current-controlled negative differential resistance (CC-NDR) can be used to fabricate nanoscale oscillators, and are of interest as a fundamental building block for brain-inspired neuromorphic computing. For devices based on binary metal-oxides the CC-NDR response is typically manifest as S-type current-voltage characteristic that can be attributed to an increase in the oxide conductivity due to local Joule heating. However, recent studies have shown that such devices also exhibit a range of more complex behaviour that may provide additional functionality. These include an abrupt 'snap-back' response, as well as compound characteristics comprising various combinations of S-type and snap-back characteristics. Understanding such behaviour is complicated by the fact that conductivity changes can involve a combination of electronic and thermal processes, material-specific phase transitions (e.g. crystallization or metal-insulator transitions) and non-uniform current distributions.

This presentation summarises our current understanding of the mechanisms underpinning the snap-back and compound CC-NDR modes and shows how this understanding can be used to develop devices with new functionality [1]. Specifically, we combine electrical, physical and thermal characterisation of NbOx-based devices to understand the origin of the CC-NDR modes and their dependence on material and device parameters (e.g. oxide stoichiometry, electrode metal, film thickness, device area). These results are then compared with the predictions of an electro-thermal model of filamentary conduction that employs a core-shell structure to represent conduction in the filamentary path (core) and the surrounding oxide film (shell). These results show that both the snap-back and compound CC-NDR characteristics can be explained by current redistribution between the core and shell regions, with the snap-back response resulting from an abrupt current bifurcation process in which the current distribution separates into regions of low and high current density. Further analysis shows that the criterion for bifurcation is determined by the relative magnitudes of the shell-resistance and the NDR of the core region. Based on this understanding, we demonstrate how the asymmetric contact resistance of a Schottky-barrier contact can be used to construct devices with a bias-polarity dependent CC-NDR response [2].

Significantly, the results of this study demonstrate that a diverse range of CC-NDR responses can be explained by a relatively simple model that accounts for current redistribution within metal/oxide/metal device structure. Within this framework, the continuous S-type and abrupt snap-back CC-NDR responses have the same physical origin, precluding the need to invoke addition mechanisms such as an insulator-metal transition.

[1] Nandi, S.K., et al., Advanced Functional Materials, 2019. 29 (50).
[2] Nath, S.K., et al., Physical Review Applied, 2020. 13(6).

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