Scalable Fabrication of Vertically Arranged Bi_2Se_3 Crossbar Arrays of Memristors towards Neuromorphic Control Applications

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As the classical von-Neumann computing architecture approaches its performance ceiling, a variety of non-conventional devices are proposed for realizing neuromorphic circuits that could provide fast and energy-efficient in-memory computing.[1, 2] Memristors are one of the promising candidates for this competition. The memristor families based on transition metal oxides such as TiO_x, TaO_x, WO_x, and HfO_x have been widely investigated.[2, 3] Recently, memristive switching devices based on two-dimensional (2D)-layered transition metal dichalcogenides (TMDCs) have been reported, focusing on demonstration of proof-of-concept devices or implementation of 2D memristive devices under the state-of-the-art settings for operating filamentary memristors.[4, 5] These 2D-material-based memristive devices have been also investigated for several unique or new properties in comparison with oxide-based memristors, including significantly improved level of interconnectivity among multiple devices, the higher biological similarity for emulating real neuron functions, and the controllable long-term and short-term memory behaviors.[6, 7] However, most circuital demonstrations so far utilizing 2D materials employ methods such as mechanical exfoliation that are not up-scalable for wafer-level fabrication.[8] Thus, one of the imperative research efforts seeks to fabricate the vertically arranged crossbar arrays of 2D-material-based memristors which performs multiply and accumulate (MAC) operation between the hidden nodes output voltage and memristor conductance.

In the conventional oxide-based memristor fabrication process, initially, the bottom electrode is deposited on the substrate, and then an insulating layer is deposited over the entire exterior of the bottom electrode (BE). However, unlike oxide layer depositions capable of large area growths, most 2D material growth techniques typically generate isolated few-layer islands across the substrate surface, resulting in shorted nodes over crossbar arrays (**Figure 1a**). In this work, we present a study on the scalable fabrication of vertically arranged 2D material-based crossbar arrays of memristors. **Figure 1b** schematically illustrates the site-selective growth of the Bi_2Se_3 features through a physical vapor deposition (PVD) combined with the metal deposition and photolithography. Within the Au-coated sites, 2D hexagonal-shaped Bi_2Se_3 nanosplates are preferentially formed. The Au-guided PVD growth formed 2D-layered hexagonal Bi_2Se_3 nanoplates via the vapor-solid-solid (VSS) mechanism, in contrast to the 1D Bi_2Se_3 nanoribbons grown on the catalyst-free Si/SiO_2 substrates via a vapor-liquid-solid (VLS) mechanism.[9] We have fabricated 6 x 6 vertically arranged Bi_2Se_3 Crossbar Arrays (**Figure 1c**). **Figure 1d** shows the SEM image of as-grown Bi_2Se_3 features on Au electrodes, and the insets display the zoomed view of the 2D layered hexagonal nanoplate structures of Bi_2Se_3 as well as the corresponding EDS image, which confirm the uniform growth over the BE, effectively preventing formation of shorted nodes in the large-area crossbar array structure.

This work provides a useful guideline for fabricating crossbar arrays of memristive devices based on 2D layered semiconductors, which could be deployed for making synaptic nodes in hardware-based artificial neural networks or neuromorphic sensory devices capable of sensing spatiotemporal events.

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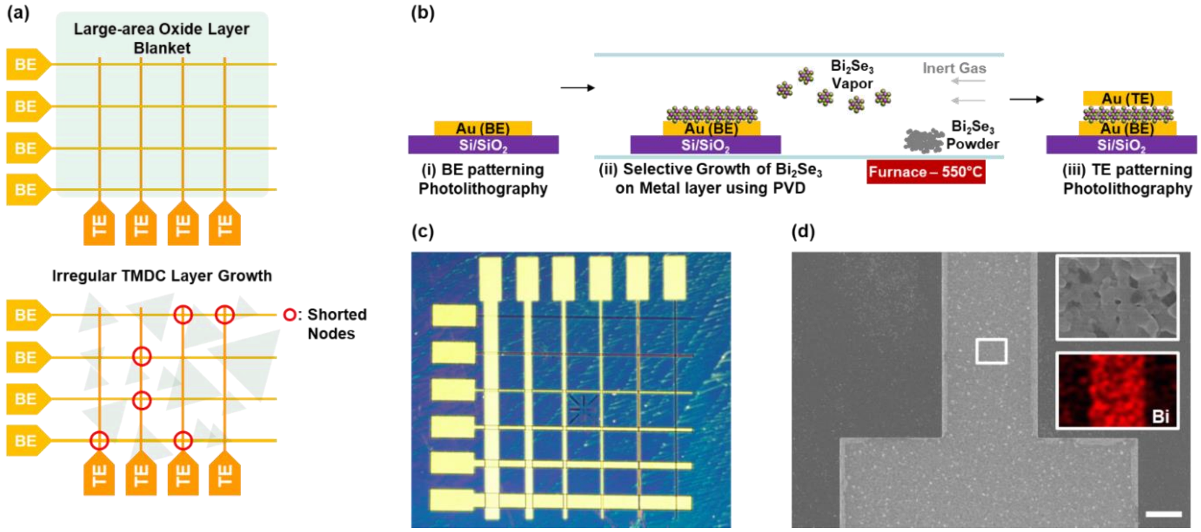

Figure. 1 (a) Illustrations of conventional oxide-based memristor crossbar arrays and TMDC-based memristor crossbar arrays with defects of shorted nodes; (b) illustration of the vertically arranged Bi_2Se_3 memristor crossbar arrays fabrication process: (i) patterning bottom electrodes (Au) using photolithography, (ii) PVD process for the metal-selective deposition of Bi_2Se_3 layer, and (iii) patterning top electrodes (Au) using photolithography; Microscopic characterizations of vertically arranged Bi_2Se_3 memristor crossbar arrays: (c) optical micrograph of an as-fabricated Bi_2Se_3 memristor crossbar arrays; (d) SEM micrograph of a metal-selectively deposited Bi_2Se_3 layer (scale bar: 1μm). Insets: A zoomed image of Bi_2Se_3 layer and EDS elemental mapping of Bi, respectively.

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