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Special Topic: Two-dimensional Materials and Devices

Sub-1-nm-node beyond-silicon materials and devices: Pathways, opportunities and challenges

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With the increasing demand for processing massive amounts of data and information in the post-Moore era, higher demands are being placed on the performance of integrated circuits (ICs). Miniaturizing the size of transistors and increasing their integration has been the main driver for the development of ICs in recent decades. However, the development of traditional silicon-based ICs has reached a bottleneck due to the limits of the miniaturization of silicon-based materials. Two-dimensional (2D) semiconductors and their devices represented by transition metal dichalcogenides (TMDCs) semiconductors provide new opportunities to break the performance improvement bottleneck of silicon-based ICs. Unlike silicon-based materials, 2D semiconductors naturally have atomic-scale thickness while being immune to short-channel effects, paving the way for the development of post-Moore 1-nm-node ICs. Furthermore, the rich physical properties of 2D semiconductors also provide the flexibility to design diverse and novel devices promising to drive transformative developments in the ICs industry. Therefore, 2D semiconductors and devices are strong candidates for ICs to enter the 1 nm node. Recently, a variety of wafer-level high-performance 2D semiconductors preparation methods have been developed, providing material assurance for ICs applications. As for the basic devices, the performance of individual devices such as on-off ratio, on-state current, and contact resistance meet the performance requirements of the International Roadmap for Devices and Systems (IRDS) for 1-nm-node logic devices. In terms of circuit integration, applications from simple transistors to combinational logic circuits have been realized, driving their practical application in the ICs industry. Based on the above progress, 2D materials, especially 2D TMDCs, are considered one of the most competitive new beyond-silicon materials and will be applied to post-Moore ICs in 2028.

To promote the further development of 2D semiconductors, we have organized a special topic on “Two-dimensional Materials and Devices” in *National Science Open* (NSO). The topic will focus on key issues in 2D semiconductors and functional devices research. We have invited eight scientists from different fields to present their latest research findings and prospective analyses of 2D materials systematically.

Effective preparation of high-quality 2D semiconductors is a prerequisite in their research explorations.

Liu's group [1] developed an ultrafast growth strategy for high-quality iodine-assisted MoS_2, which greatly improves the performance of 2D devices. To truly harness the enormous potential of 2D semiconductors with high integration, Wang's group [2] successfully achieved 2-inch single-crystal epitaxial $MoSe_2$ growth. Because of their ultra-thin nature, the substrate highly modulates the epitaxial growth process of 2D materials. Liu *et al*. [3] summarized the model of 2D material-assisted epitaxy and detailed the improved crystal quality and target functional applications, providing a blueprint for developing 2D material-assisted epitaxy for research applications.

The direct integration of wafer-level 2D semiconductors into traditional transistor architectures cannot meet the needs of future high-performance ICs, and the development of next-generation ICs requires the design of new devices. Zhang *et al*. [4] reviewed the custom design of building powerful computing-capability TMDCs transistor development, guiding the development of powerful computing-capability ICs. Bao's group [5] designed a 2T1C DRAM architecture for in-memory computation, providing an alternative approach to efficiently process massive data computing tasks and break the memory barrier.

As the demand for IC applications has increased, the development of new functional 2D devices has emerged as an important aspect and key direction for 2D material development in the post-Moore era. As discussed by Xiong's group [6], the spin-orbit coupling of 2D magnetic materials provides a promising area for the development of spintronic and magnetoelectronic devices. Because of their unique physical properties, 2D materials have a broad range of prospects for constructing new optoelectronic devices. Zhang's group [7] discovered type-IV excitons in a multi-valued bilayer MoS_2, making the type-IV excitons in this system an emerging platform for building state-of-the-art optoelectronic devices. Furthermore, as in the 2D material-based ion transport channels analyzed by Ren's group [8], the use of 2D materials brings new research ideas in the areas of energy storage and conversion, seawater desalination, and biological systems.

As the space for this special topic is limited, we cannot list all the recent progress made in the field of 2D materials and devices. However, we believe that this topic will contribute to the advancement of research on 2D semiconductors and devices by providing valuable information and perspectives, further promoting innovation and breakthroughs in this exciting area. Finally, we would like to express our gratitude to all the authors, reviewers, and editorial staff for their excellent support and contributions in preparing this topic.

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