文章编号：1001-9014(XXXX)XX-0001-04

DOI：10. 11972/j. issn. 1001-9014. JIMW. 2026166

A universal epitaxy platform for bismuth-based crystals

Wang Weijun[1,2], Ho Johnny Chung Yin[1,2,3,4]

(1. Department of Materials Science and Engineering, City University of Hong Kong, Kowloon 999077, Hong Kong SAR, China;
2. State Key Laboratory of Terahertz and Millimeter Waves, City University of Hong Kong, Kowloon 999077, Hong Kong SAR, China;
3. Institute for Materials Chemistry and Engineering, Kyushu University, Fukuoka 816-8580, Japan;
4. Shenzhen Research Institute, City University of Hong Kong, Shenzhen 518057, PR China)

Abstract: This work reports a universal epitaxy strategy on K^+-free mica surfaces, enabling the general synthesis of nine distinct millimetre-scale bismuth-based chalcogenide and oxychalcogenide single crystals on a single low-cost substrate. The platform further demonstrates high-performance photodetectors and imaging arrays, paving a new route for integrated optoelectronics based on multifunctional two-dimensional material systems.

Key words: Bismuth chalcogenides, chemical vapor deposition (CVD), interface engineering, millimetre-scale single crystals, photodetectors

PACS:

A material family that intrinsically hosts topological, high-mobility semiconducting and ferroelectric properties offers a unique platform for next-generation electronics and optoelectronics. Among two-dimensional materials, bismuth-based chalcogenides and oxychalcogenides (e. g., Bi_2X_3, Bi_2O_2X, and Bi_2XO_5, X = Se, Te) stand out by combining multiple functionalities within a single, chemically related system[1-3]. Yet, for years, a fundamental bottleneck has stalled its progress: each compound demanded its own growth recipe, and most relied on specific, lattice-matched substrates[4-6]. Writing in *Nature Communications*, Zhao and co-workers[7] now report a groundbreaking chemical vapour deposition (CVD) strategy that overcomes these limitations. Based on their previous breakthrough achievements in the epitaxial growth of wafer-scale topological materials[8], the authors now combine elemental precursors with a K^+-free mica surface to achieve, for the first time, the paradigm-shifting general synthesis of nine distinct millimeter-scale single crystals, including topological insulators, high-mobility semiconductors, and ferroelectrics/dielectrics, all on the same low-cost substrate. This work represents a milestone in the scalable integration of multifunctional bismuth-based materials.

The key insight lies in re-engineering a common material: fluorophlogopite mica. Freshly cleaved mica appears atomically flat, but the authors discovered that randomly distributed K^+ ions remain on the surface, acting as diffusion barriers (Figs. 1a and b). A mild pre-annealing step removes these ions, creating a truly uniform growth template that enhances adatom mobility and facilitates large-domain growth. Using this approach, they successfully synthesized 1 mm Bi_2Se_3 (Fig. 1c) and other Bi-based single crystals. With this template, the team uses elemental bismuth and chalcogen (Se or Te) together with finely tuned oxygen partial pressures to "dial-in" the desired phase. By simply adjusting the O_2 concentration, they can switch between Bi_2Se_3, $Bi_3O_{2.5}Se_2$, Bi_2O_2Se (Fig. 1d), and by substituting Se with Te or a Se-Te mixture, they obtain Bi_2Te_3, the alloy $Bi_2Se_xTe_{3-x}$, and even the ferroelectric Bi_2TeO_5. Unlike established two-dimensional families such as Mo-S, graphene, B-N or In-Se systems, the Bi-O-Se family uniquely integrates multiple functionalities, including semiconducting, ferroelectric, dielectric, topological, and metallic behaviours (Fig. 1e). Moreover, the nine compounds grown here reach lateral dimensions substantially larger than previously reported, marking a clear advance in domain size control (Fig. 1f).

Beyond synthesis, the authors demonstrate the practical utility of their platform. They fabricate high-performance photodetectors and, more importantly, a fully functional 8×8 photodetector array (Figs. 1g and h) directly on the mica substrate, achieving high-fidelity imaging across visible, near-infrared and communication wavelengths (Fig. 1i). This transition from discrete components to a scalable imaging system validates the platform's readiness for integrated optoelectronics.

The work stands out for its universality and simplicity. Previous landmark studies achieved wafer-scale epitaxy of individual bismuth compounds on perovskite substrates (e. g., $SrTiO_3$) or on sapphire[6], but each substrate was optimal for only one or two phases. Here, for the first time, nine distinct functional phases are grown

on a single, inexpensive mica substrate – a genuinely substrate-agnostic approach that does not require lattice matching. This breakthrough opens up entirely new avenues for systematic materials discovery and device prototyping.

Looking forward, several directions are worth pursuing. Scaling the K^+-free mica platform to wafer dimensions would be a natural next step for industrial compatibility, possibly by using larger-area mica sheets or by adapting the method to flexible substrates. The ability to grow multiple phases on the same substrate also opens the door to monolithic integration – for example, combining a high-mobility channel (Bifree mica platform to wafer dimensions would be a natural next step for industrial compatibility, possibly by using larger-area mica sheets or by adapting the method to flexible substrates. The ability to grow multiple phases on the same substrate also opens the door to monolithic integration – for example, combining a high$_2O_2Se$) with a ferroelectric gate dielectric (Bi_2SeO_5) or with a topological insulator for spin-charge conversion. Importantly, the broad spectral response and excellent photodetection performance demonstrated in this work suggest immense potential for emerging applications such as vision restoration in Brain-Machine Interface (where high-sensitivity, flexible photodetectors are needed to mimic retinal functions) and high-sensitivity mid-wavelength infrared gas detection (exploiting the tunable bandgap of Bi-based alloys to target characteristic absorption lines of greenhouse gases and volatile organic compounds). Further optimisation of device contacts and encapsulation could also enhance performance. Moreover, band engineering designs such as unipolar barrier structures[9] offer additional routes to improve Bi-based photodetectors. Nevertheless, by solving the foundational synthesis problem, Zhao and colleagues provide a versatile materials platform that will catalyse research across condensed matter physics, semiconductor engineering and photonics.

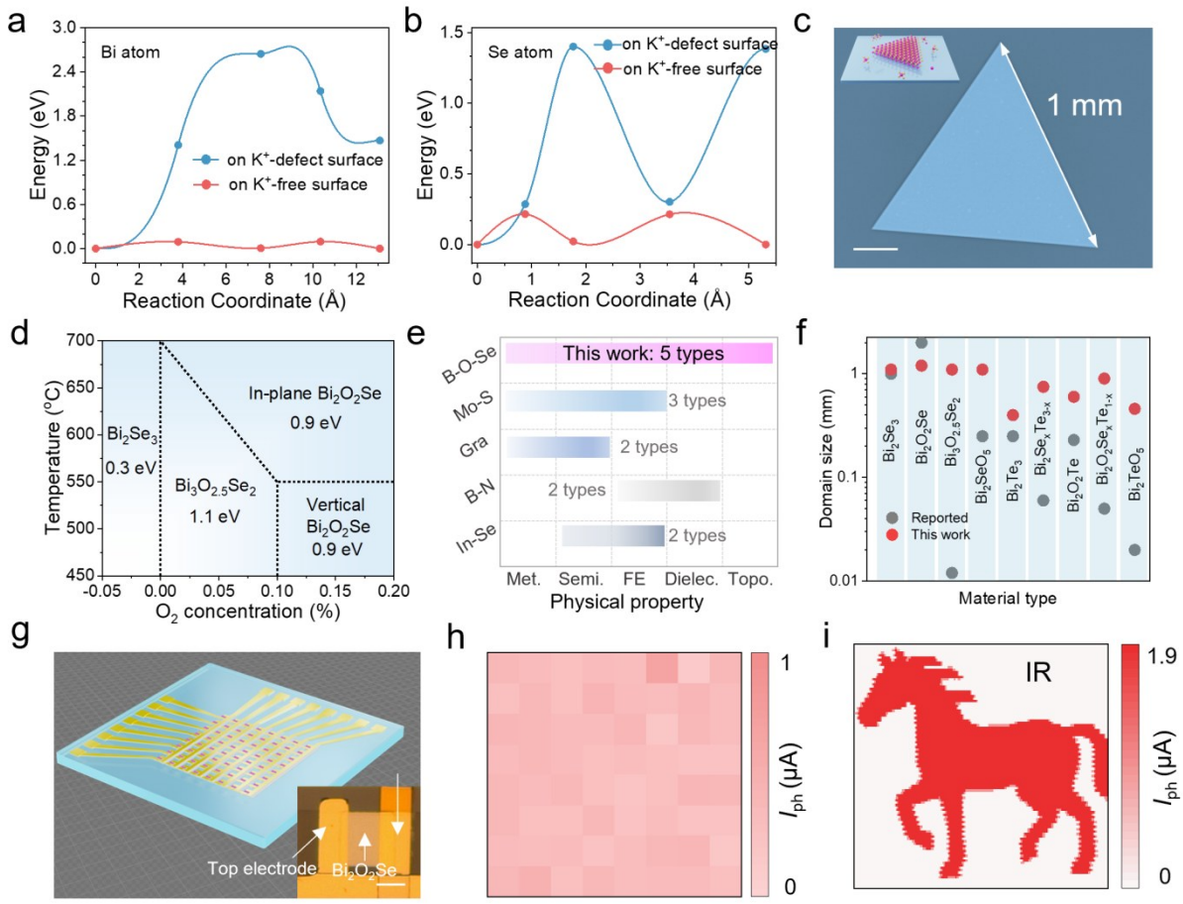

图 1 （a）铋原子在云母表面的扩散能垒；（b）硒原子在云母表面的扩散能垒；（c）毫米级 Bi_2Se_3 的光学显微图像（比例尺：200 μm），插图为对应的原子结构示意图；（d）通过温度和 O_2 浓度调控实现不同带隙 Bi 基化合物的可控合成设计图；（e）本工作合成的晶体与其他材料体系的物理性质对比（物理性质包括半导体（Semi.）、铁电（FE）、介电（Dielec.）、拓扑（Topo.）和金属（Met.）性行为）；（f）本工作合成的 Bi 基单晶尺寸与已报道值的对比；（g）8 × 8 Bi_2O_2Se 光电探测器阵列示意图。插图为单个像元的光学显微图像（比例尺：10 μm）；（h）1 550 nm 光照下光电流分布，展示均匀响应；（i）光电探测器在 1 550 nm 光照下的成像演示

Fig. 1 （a）Calculated diffusion energy barrier for a Bi atom on mica；（b）Calculated diffusion energy barrier for a Se atom on mica；（c）Optical micrographs of millimeter-sized Bi_2Se_3. Scale bar：200 μm. The insets show corresponding atomic structure diagram；（d）The controllable synthesis design of Bi-based compounds with different band gaps via temperature and O_2 concentration regulation；（e）Comparison of the physical properties of the synthesized crystals with those of other material families. Physical properties include semiconducting（Semi.），ferroelectric（FE），dielectric（Dielec.），topological（Topo.），and metallic（Met.）behaviours；（f）Size comparison of the bismuth-based single crystals synthesized in this work with previously reported values；（g）Schematic of an 8 × 8 Bi_2O_2Se photodetector array. Inset：optical micrograph of a single pixel（Scale bar：10 μm）；（h）Distribution of photocurrent under 1 550 nm illumination，demonstrating uniform response；（i）Imaging demonstrations using the photodetectors at 1 550 nm

References

[1] Tan C，Tang J，Gao X，et al. 2D bismuth oxyselenide semiconductor for future electronics[J]. Nature Reviews Electrical Engineering，2025，2(7)：494-513.

[2] Wu Q，Li Z，Han B，et al. Wafer-scale ultrathin and uniform van der Waals ferroelectric oxide[J]. Science，2026，391(6784)：eadz1655.

[3] Tan C，Yu M，Tang J，et al. 2D fin field-effect transistors integrated with epitaxial high-k gate oxide[J]. Nature，2023，616(7955)：66-72.

[4] Feng T，Li Y，Xue C，et al. Epitaxial integration of single-crystalline 2D Bi_2O_2Se semiconductor film on silicon[J]. Journal of the American Chemical Society，2026，148(6)：6324-6331.

[5] Wu J，Tan C，Tan Z，et al. Controlled synthesis of high-mobility atomically thin Bismuth oxyselenide crystals[J]. Nano Letters，2017，17(5)：3021-3026.

[6] Xue C，Tan C，Gao X，et al. Wafer-scale uniform epitaxy of transferable 2D single crystals for gate-all-around nanosheet field effect transistors[J]. Nature Communications，2025，16(1)：10587.

[7] Zhao T，Liu X，Ge X，et al. K+-free mica-assisted epitaxy of Bi-based chalcogenide and oxychalcogenide single-crystals[J]. Nature Communications，2026.

[8] Zhao T，Duan S，Dou W，et al. Edge-dominated epitaxy of topological insulator Bi_2Se_3 with ultrabroadband response[J]. ACS Na-

no, 2025, 19(28): 26055-26064.
[9] Chen Y, Wang Y, Wang Z, et al. Unipolar barrier photodetectors based on van der Waals heterostructures[J]. Nature Electronics, 2021, 4(5): 357-363.

铋基单晶的普适性合成策略

王伟军[1,2], 何颂贤[1,2,3,4]
(1. 香港城市大学 材料科学与工程系 香港特别行政区 香港 999077;
2. 香港城市大学 太赫兹及毫米波国家重点实验室, 香港特别行政区 香港 999077;
3. 九州大学 先导物质化学研究所, 日本 福冈 816-8580;
4. 香港城市大学深圳研究院, 广东 深圳 518057)

摘要: 本文报道了一种基于K^+去除云母表面的普适性外延策略,在单一低成本衬底上实现了九种毫米级铋基硫族及氧硫族化合物单晶的通用合成,并展示了其在高性能光电探测器及阵列成像中的应用潜力,为多功能二维材料体系的集成光电子学应用开辟了新途径。 **关键词:** 铋基硫族化合物;化学气相沉积;界面工程;毫米级单晶;光电探测器