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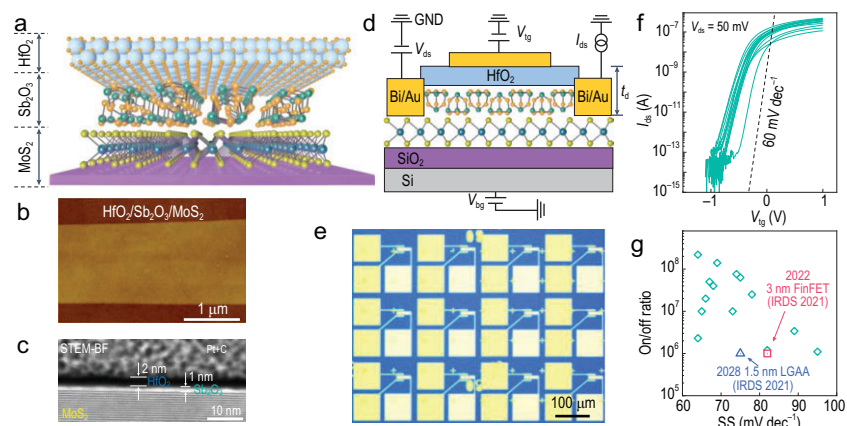
## MATERIALS SCIENCE

## Two-dimensional semiconductors integrated with hybrid dielectrics for post-Moore electronics

Wei Zhai<sup>1</sup>, Yao Yao<sup>1</sup>, Zijian Li<sup>1</sup>, Li Zhai<sup>1,2</sup> and Hua Zhang<sup>1,2,3,\*</sup>

As the basic building blocks of modern electronics, field-effect transistors (FETs) use gate electrodes to control the conductivity of channel materials through the electrical polarization of dielectrics [1]. The performance of FETs relies not only on the channel materials and their contacts with the electrodes, but also on the dielectrics and their interfaces with the channel materials [1,2]. According to Moore's law, FETs composed of conventional bulk semiconductors are approaching their physical limits and new semiconducting materials are thereby highly demanded. Recently, 2D semiconductors have shown great potential as promising channel materials to replace conventional bulk semiconductors for next-generation FETs due to their atomically thin thickness and dangling-bond-free characteristics [2]. To date, great efforts have been made in the design and preparation of 2D semiconductor-based FETs with desirable performance. However, it remains challenging to fabricate dielectrics with high-quality interfaces in 2D semiconductor-based FETs using processes that are compatible with the complementary metal-oxide-semiconductor (CMOS) technology [1].

Recently, the Zhai research group reported a versatile method to prepare high-quality dielectrics on 2D semiconductors with sub-1-nm equivalent oxide thickness (EOT) [3]. Specifically, a thermally evaporated inorganic molecular crystal,  $\text{Sb}_2\text{O}_3$ , was innovatively introduced as the buffer layer between the 2D semiconducting  $\text{MoS}_2$  and the



**Figure 1.** FETs fabricated with  $\text{MoS}_2$  and hybrid  $\text{HfO}_2/\text{Sb}_2\text{O}_3$  dielectric layer. (a) Schematic diagram of the fabricated  $\text{HfO}_2/\text{Sb}_2\text{O}_3$  hybrid dielectric layer on  $\text{MoS}_2$ . (b) Atomic force microscope image of  $\text{HfO}_2/\text{Sb}_2\text{O}_3$  on  $\text{MoS}_2$ . (c) Bright-field cross-sectional scanning transmission electron microscopy image of  $\text{HfO}_2/\text{Sb}_2\text{O}_3$  on  $\text{MoS}_2$ . (d) Schematic illustration of the FET structure with the hybrid  $\text{HfO}_2/\text{Sb}_2\text{O}_3$  layer as the gate dielectric. (e) Optical image of FET arrays fabricated with a  $\text{MoS}_2$  monolayer and a  $\text{HfO}_2/\text{Sb}_2\text{O}_3$  hybrid dielectric layer. (f) Transfer characteristic curves of FET arrays fabricated with a  $\text{MoS}_2$  monolayer and a  $\text{HfO}_2/\text{Sb}_2\text{O}_3$  hybrid dielectric layer. (g) The statistics of SS values and on/off ratios of FET arrays. Reprinted with permission from [3].



ultra-thin atomic-layer-deposited high- $\kappa$   $\text{HfO}_2$  layer (Fig. 1a–d).  $\text{Sb}_2\text{O}_3$  can form a high-quality interface with  $\text{MoS}_2$  due to its cage-like molecular structure without dangling bonds [4]. Moreover, the hydrophilicity of  $\text{Sb}_2\text{O}_3$  facilitates the precursor adsorption during atomic layer deposition of  $\text{HfO}_2$ , resulting in the uniform deposition of the high- $\kappa$   $\text{HfO}_2$  dielectric layer. The hybrid dielectric layer composed of  $\text{Sb}_2\text{O}_3$  and high- $\kappa$   $\text{HfO}_2$  has a high-quality interface with  $\text{MoS}_2$  and an excellent dielectric property with a high gate capacitance of  $3.2\text{--}3.5\ \mu\text{F}/\text{cm}^2$ . The performance of FET arrays (Fig. 1e) fabricated with the  $\text{MoS}_2$  monolayer and the hybrid  $\text{HfO}_2/\text{Sb}_2\text{O}_3$  dielectric layer

proves that their approach has good reproducibility and device uniformity. The fabricated top-gated FETs exhibit an average subthreshold swing (SS) value of  $73\ \text{mV}/\text{dec}$  and an on/off ratio of  $5 \times 10^7$  (Fig. 1f and g), which are comparable to the state-of-the-art Si-based transistors. Especially, this approach is compatible with CMOS technology, holding great promise for industrial applications in post-Moore electronics.

The research work [3] demonstrates the key role of the dielectric design in boosting the performance of 2D semiconductor-based FETs for post-Moore electronics. More functional 2D semiconductor-based devices fabricated

with various hybrid dielectrics are anticipated. In addition to the dielectric layer, the contact between the channel material and the electrode also plays a critical role in determining the performance of FETs. Recently, phase engineering of nanomaterials (PEN) [5] has been used as an effective strategy to reduce contact resistances and improve the performance of FETs [6]. We believe that the combination of dielectric engineering and PEN paves the way toward practical applications of 2D semiconductor-based FETs in post-Moore electronics.

**Conflict of interest statement.** None declared.

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