Scalable strategy produces high-quality black phosphorus nanoribbons for electronics

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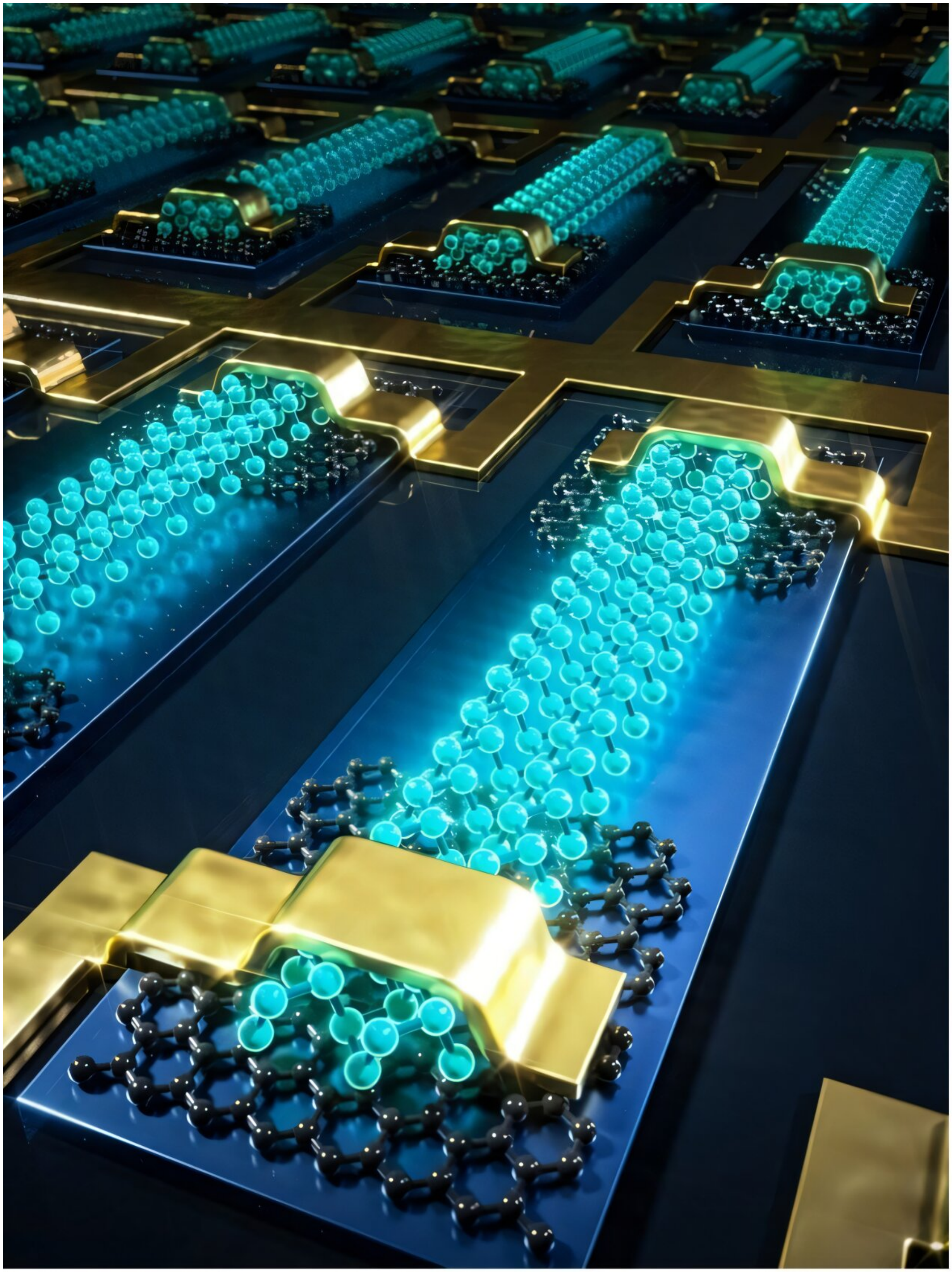

3D scientific illustration of an integrated circuit based on graphene-contacted black phosphorus nanoribbon field-effect transistors. Credit: Changxin Chen Group, School of Integrated Circuits, Shanghai Jiao Tong University.

Black phosphorus nanoribbons (BPNRs), thin and narrow ribbon-like strips of black phosphorus, are known to exhibit highly advantageous electronic properties, including a tunable bandgap. This essentially means that the energy difference between the region where electrons are bound together (i.e., valence band) and that where electrons move freely (i.e., conduction band) can be easily controlled by adjusting the width of the nanoribbons.

A tunable bandgap is essential for the development of transistors, the components that control the flow of electrical current through electronic devices.

While several past studies have highlighted the promise of BPNRs for the development of electronics, strategies that could enable their reliable fabrication on a large scale are still lacking.

Researchers at Shanghai Jiao Tong University and other institutes recently introduced a new scalable strategy for the realization of high-quality BPNRs that are consistent in size, have well-defined edges and exhibit minimal defects.

Their proposed approach, outlined in a paper published in *Nature Materials*, relies on a technique designed to peel apart layered materials leveraging ultrasonic sound waves in liquids.

"Our research group has long been devoted to identifying ideal channel materials to enable high-performance field-effect transistors with reduced size and power consumption," Professor Changxin Chen, who led the research, told Phys.org.

"BPNRs offer advantages as channel materials over other candidates such as carbon nanotubes, graphene nanoribbons and two-dimensional (2D) black phosphorus (BP). For example, BPNRs are entirely semiconducting, unlike carbon nanotubes, which can be semiconducting or metallic.

"Additionally, BPNRs exhibit a superior trade-off between mobility and bandgap than graphene nanoribbons. BPNRs also avoid the need to prepare large-area, few-layer 2D BP, providing sizable and widely tunable bandgaps."

For some time, Chen and his colleagues have been trying to devise a scalable strategy to realize high-quality and narrow BPNRs that have smooth edges and well-defined orientations. The fabrication strategy introduced in their recent paper is based on a newly introduced sonochemical exfoliation technique.

"We first used a short-way transport reaction to synthesize bulk BP crystals with a slightly enlarged lattice parameter along the armchair direction," explained Chen.

"This stress allows the crystal to unzip preferentially along the crystal plane perpendicular to the armchair direction rather than other planes. Then, we applied suitable ultrasonic conditions to unzip bulk BP crystals, thereby yielding one-dimensional (1D) high-quality BPNRs."

With their newly devised strategy, the researchers created nanoribbons with a width centered at 32 nm that can be as narrow as 1.5 nm; the narrowest among the BPNRs reported to date. Remarkably, their fabrication method exhibited a yield of up to 95%.

Moreover, the narrow width and zigzag edges of the resulting BPNRs gave rise to a large bandgap, while their nearly atomically smooth edges suppressed carrier scattering and led to high mobility.

"We achieved high-quality, narrow BPNRs with nearly atomically smooth edges and well-defined edge orientation at high yield through the sonochemical exfoliation of the synthesized bulk BP crystals with a slightly enlarged lattice parameter along the armchair direction," said Chen.

"With the prepared BPNRs, the field-effect transistor performance with an on/off ratio of 1.7×10^6 and mobility of 1,506 $cm^2 V^{-1} s^{-1}$, representing the highest comprehensive performance among the FETs based on BPNRs or 2D BP reported so far."

As part of their study, Chen and his colleagues showed that the BPNRs they created could also serve as near-infrared photodetectors. In fact, the narrow structures exhibited a responsivity of 11.2 A/W and specific detectivity of 1.1×10^{11} cm $Hz^{1/2} W^{-1}$, outperforming most existing near-infrared detectors based on 1D nanomaterials, 2D nanomaterials and other hybrid structures.

In the future, the new fabrication approach devised by this research team could be improved further and deployed in real-world settings, enabling the large-scale production of high-quality BPNRs. This could in turn pave the way for the development of compact electronic and optoelectronic devices that are significantly smaller than those available today.

"As part of our future research, we will develop controlled strategies to produce high-quality BPNRs with unidirectional alignment and uniform widths," added Chen.

"Such strategies are crucial for overcoming current challenges in scalability and structural variability for BPNRs and will ultimately enable BPNRs to be reliably integrated into large-scale integrated circuits."

More information: Teng Zhang et al, High-quality narrow black phosphorus nanoribbons with nearly atomically smooth edges and well-defined edge orientation, *Nature Materials* (2025). DOI: 10.1038/s41563-025-02314-7.

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