New type of semiconductor may advance low-energy electronics

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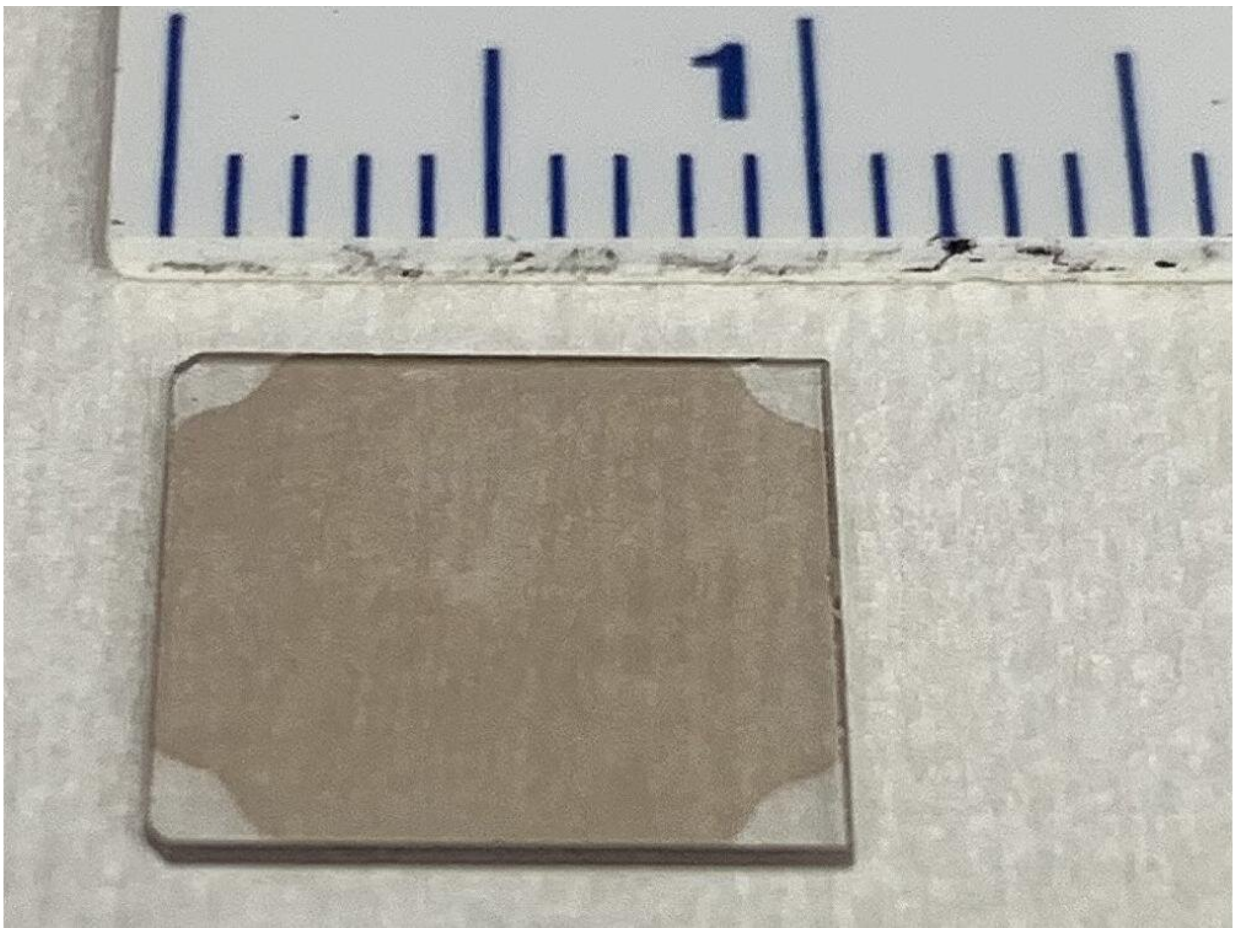

Nine layers of SnSe that were epitaxially grown on an a-plane sapphire substrate. Credit: Wouter Mortelmans/MIT

A research partnership between Penn State and the Massachusetts Institute of Technology (MIT) could enable an improved method to make a new type of semiconductor that is a few atoms thin and interacts with light in an unusual way. This new semiconductor could lead to new computing and communications technologies that use lower amounts of energy than current electronics.

The new type of semiconductor, tin selenide (SnSe), would be useful for developing a new type of electronics known as "photonics" that use particles of light, or photons, to store, manipulate and transmit information. Traditional electronics use electrons to do this, while photonics use photons. Tin selenide is a binary compound consisting of tin and selenium in a 1:1 ratio.

The material has a peculiar interaction with light that gives it great potential for use in electronics.

"It can be described as a material that has two different colors, meaning that depending on the orientation that you look at it, you will observe a different color," said Wouter Mortelmans, a postdoctoral associate in the Department of Materials Science and Engineering at MIT, and lead author of the study. "This peculiar optical property could be very useful to compute, store, or transmit information using light."

To make use of these orientation-dependent properties, it is very important that the fabrication of the material is done with atomic-precision control, said Mortelmans. The dependence of color on material orientation would enable faster and easier inspection of material quality.

"We need a reliable way to make the material, to manufacture devices to spec, without worrying about random, natural variations," said Rafael Jaramillo, Thomas Lord Associate Professor of Materials Science and Engineering at MIT and senior author of the study published in *ACS*

Nano.

The key to enabling such precision, defect-free material is a process which can be challenging for atomically thin semiconductors known as epitaxy.

"Epitaxy can be imagined as similar to building with Legos, where the material of interest is broken up into small individual unit cells of either triangular or rectangular Lego bricks," said Maria Hilse, assistant research professor, thin films-MBE, with the Penn State Materials Research Institute's 2D Crystal Consortium (2DCC). "The base is an ultra-clean host crystal substrate that allows for a certain shape of 'Lego' bricks to be put on it. We select this starting substrate plate, ideally, so that it fits perfectly with the crystal structure of the material we want to compose, i.e., our Lego bricks. In the case of SnSe, we would have a pool of rectangular-shaped Lego bricks that we want to assemble on a rectangular-shaped Lego base plate, which is an aluminum oxide (11-20) surface."

The study was enabled in part by a research relationship between Jaramillo and the 2DCC. The 2DCC is a national user facility supported by the National Science Foundation that is focused on advancing the synthesis of 2D layered chalcogenides for next-generation electronics and quantum technologies.

"Roughly half of the experimental work was performed at the 2DCC, with hands-on collaboration between Drs. Mortelmans and Hilse," Jaramillo said. "Working with the 2DCC greatly expanded the set of experimental capabilities that we could work with, making this project much more rigorous and convincing than it otherwise would have been. In particular, early discussions with Dr. Hilse and others there were important for motivating and de-risking the work."

Hilse's responsibilities with the 2DCC include the growth facility where part of the SnSe growth for the study was carried out.

"The 2DCC made it possible for Wouter to come to Penn State and get trained by me on the synthesis method here on site, which enabled him to perform the experiments he needed for this publication," Hilse said. "The unique capabilities of the 2DCC and my supervision and experience helped to accumulate the amount of data that the publication is built on."

The results outlined in the study of this partnership offer benefits for both researchers and the public. For researchers, said Mortelmans, it offers insights into the fabrication of 2D materials.

"We developed a new epitaxy process for a 2D material with atomic precision control, which gains new insight in how to fabricate high-quality 2D material," Mortelmans said. "The study of epitaxy processes of 2D materials is a relatively young field with room for optimizations. With the new insights obtained in this work, we hope to further contribute to the advancement of epitaxy processes of 2D materials."

In addition, the researchers developed an original structural characterization method to measure the quality of the epitaxially grown 2D material.

"This fast and easy structural characterization method applies to all materials that have orientational-dependent optical properties," Jaramillo said. "This method could significantly reduce the time and cost for the further development of such materials."

In turn, the kind of widespread photonic technology that their research could help enable would have multiple benefits for society. These range from reduced power consumption for large-scale electronics to low-cost environmental sensors for agriculture, air quality monitoring, public health and transportation, to computer vision and light-based sensing for improved safety systems in self-driving vehicles.

"Photonics has tremendous potential to reduce power consumption particularly at large data centers, which are a big and growing consumer of electrical power, and thereby are responsible for a sizable fraction of greenhouse gases emitted by electrical power generation," Jaramillo said. "Therefore, in a quantifiable way, future light-based computing can slow global warming."

Given the new fabrication process developed by the researchers is a first step to making information storage and transmission in SnSe using light possible, Mortelmans said it is very possible the MIT researchers will be back using the 2DCC facilities and expertise in the future.

"The 2DCC has outstanding facilities to fabricate 2D materials and measure the ultra-thin films after fabrication," Mortelmans said. "There is a lot of expertise available in many different important areas of 2D materials R&D. There are no concrete plans yet for future work at 2DCC, but connections are made and whenever there is a new opportunity for an interesting collaboration, these connections will be very useful."

More information: Wouter Mortelmans et al, Measuring and Then Eliminating Twin Domains in SnSe Thin Films Using Fast Optical Metrology and Molecular Beam Epitaxy, *ACS Nano* (2022). DOI: 10.1021/acsnano.2c02459

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