

seismometers, that needs information for groundwater management. Groundwater is critical to supporting agriculture and human communities in the Central Valley, the southwestern US, and the Great Plains above the Ogallala Aquifer, among other regions. Seismic hydrography can work in those regions, too, thanks to a technique called distributed acoustic sensing, which uses optical fibers, instead of dedicated seismometers, to measure seismic waves.

(See the Quick Study by Ethan Williams, *PHYSICS TODAY*, October 2022, page 70.)

The details of the analysis will need to be adjusted because seismometers measure ground movement, whereas optical fibers measure ground strain. “But fibers are everywhere, even where there are no seismometers,” says Ellsworth. “With seismometers, you might get one measurement every ten miles. Fibers give thousands of measurements

over the same distance. So the information content just explodes.”

Johanna Miller

References

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To make atomically thin metals, just squeeze

Metals aren’t naturally stable in 2D form. But when forced into thin sheets, they exhibit new and unusual properties that researchers are eager to explore.

Since sticky tape was used just over two decades ago to isolate a single layer of graphene, an entire field of research has emerged to find more 2D materials, which have the thickness of just one or a few atoms. (See the article by Andrey Geim and Allan MacDonald, *PHYSICS TODAY*, August 2007, page 35.) Materials with atomic-scale dimensions exhibit distinct and exotic properties because of quantum confinement effects. Graphene, for example, has exceptionally high electrical conductivity because its structure hosts mobile electrons that behave like massless particles. (See *PHYSICS TODAY*, December 2010, page 14.)

Graphene provided a natural route into the realm of 2D materials because its one-atom-thick sheets have strong internal bonds but connect to other graphene sheets through weaker van der Waals forces. Those features make graphene relatively easy to peel off from its bulk form, graphite. Development of other 2D van der Waals materials, such as the insulating boron nitride and the semiconducting molybdenum disulfide (MoS_2), has followed. (See the article by Pulickel Ajayan, Philip Kim, and Kautav Banerjee, *PHYSICS TODAY*, September 2016, page 38.) Theory is used to predict some of the exotic properties of new 2D material phases. Under certain conditions, for example, 2D bismuth is expected to be a topological insulator—a material that conducts charge along its surfaces or edges while its interior acts as an insulator.

But bismuth, like other ordinary metals, is not thermodynamically stable as atomically thin sheets, so finding a way to

make 2D materials out of it and other metals has not been straightforward. One approach to creating 2D metals has been to mix transition metals with carbon, nitrogen, or both—such mixtures make up a class of materials known as MXenes (pronounced Maxines, like the name; see *PHYSICS TODAY*, June 2023, page 12). Very small pieces of pure metal films, ranging from nanometers up to about $10\text{ }\mu\text{m}$ across, have been synthesized using various other approaches, such as chemical vapor deposition, molecular-beam epitaxy, hot pressing, and growth confined between other 2D materials.

Researchers have probed the material properties of those small pieces, but the samples are not large or uniform enough to be useful in engineered applications like microchips or qubits. Now, doctoral student Jiaojiao Zhao, his coadviser Luojun Du, lab director Guangyu Zhang, and their colleagues at the University of Chinese Academy of Sciences in Beijing and Songshan Lake Materials Laboratory in

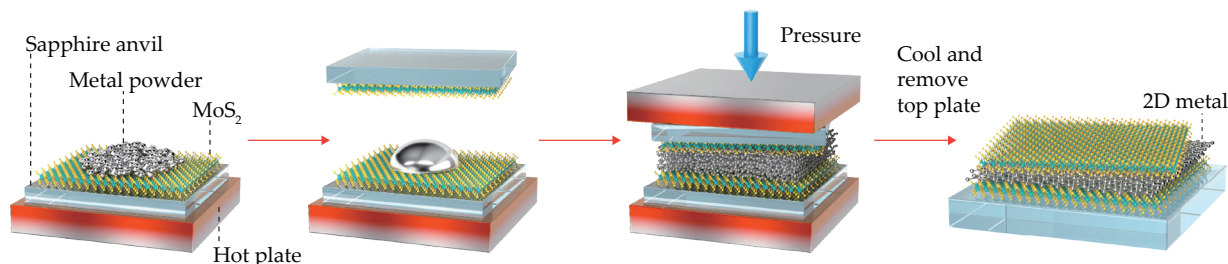


FIGURE 1. SQUEEZING A MOLTEN METAL between two sheets of molybdenum disulfide (MoS_2) produces sheets of metal just two atoms thick. The MoS_2 , a van der Waals material that is stable as atomically thin sheets, provides a near-perfectly flat surface on which a 2D metal can be formed. Being encapsulated by MoS_2 prevents the 2D metal from oxidizing but still allows access to the unique material properties that emerge because of quantum confinement effects that occur in atomic-scale materials. (Schematic adapted from ref. 1.)

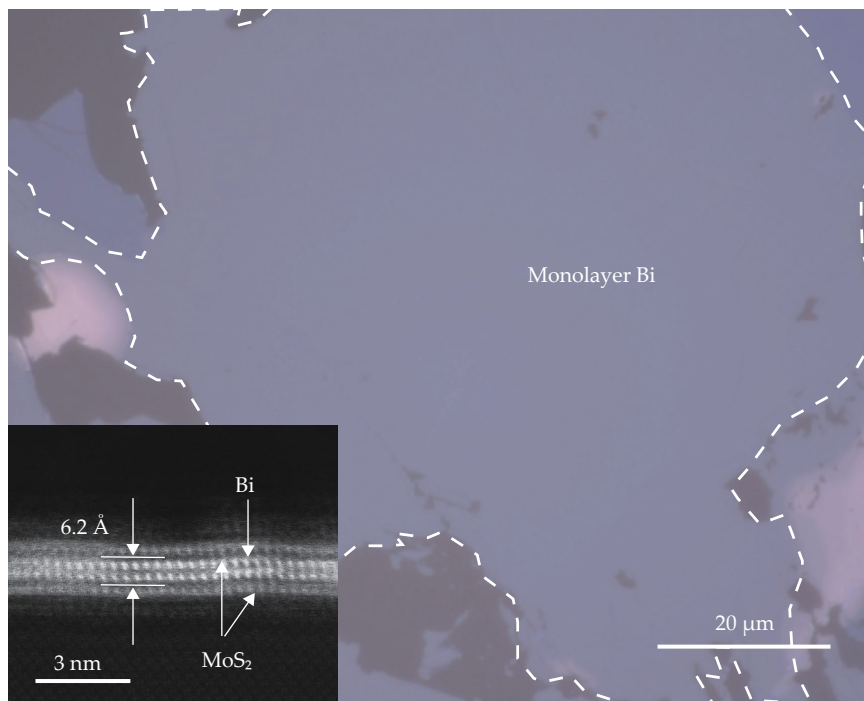


FIGURE 2. AN ATOMICALLY THIN SHEET OF BISMUTH is more than 100 μm across, an order of magnitude larger than 2D metals that have been created by other approaches. Imaging of the edge of one such sheet (bottom left inset) reveals a two-atom-thick monolayer of bismuth sandwiched between sheets of molybdenum disulfide (MoS_2). (Images adapted from ref. 1.)

Dongguan, China, have created atomically thin metal sheets that are orders of magnitude larger by squeezing them with a hydraulic press.¹ “We have developed a very simple technique to prepare 2D metal, using an atomically flat surface to squeeze elements, and it works well,” says Zhang, who led the research.

A form of flattery

The atomically flat surfaces used to squeeze the metals are sapphire anvils fully coated with single layers of MoS_2 and trimmed into 1 cm^2 squares (see figure 1). In recent years, Zhang’s lab had fabricated exceptionally large (circles more than 20 cm across) and uniform monolayer MoS_2 on sapphire crystals using chemical vapor deposition. Those MoS_2 sheets are useful in their own right, but they also provided the researchers with the tool needed to create atomically thin metals, something the lab had been working toward since 2015.

As shown in figure 1, the MoS_2 -coated sapphire anvils are heated to melt a metal powder, which is then gradually squeezed to up to 200 MPa, roughly double the pressure at the bottom of the Mariana Trench. While maintaining high

pressure, the researchers let the system slowly cool to room temperature. The MoS_2 -encapsulated metal, shown in figure 2, can then be easily peeled from the sapphire blocks with tweezers. “In some sense, what they have achieved is the flattest substrate ever realized,” says Javier Sanchez-Yamagishi of the University of California, Irvine. “Sapphire is already very flat, but you put this layer of MoS_2 on it, and it makes it even flatter.”

In addition to providing a flat surface to guide the pressed metals into a 2D form, the sheets of MoS_2 also protect the metal from air. If one sheet of MoS_2 is removed via reactive-ion etching, the metal quickly oxidizes and balls up. With the protection of the van der Waals material, though, the metal sheets are stable for at least a year.

Because the metals are not chemically bonded to the MoS_2 , their intrinsic electronic, optical, and magnetic properties can be probed—similar to the way that you can read what is written on a laminated piece of paper. But at room temperature, MoS_2 is a semiconductor. So to isolate the electronic properties of the confined metal, the researchers took measurements at cryogenic temperatures. At

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those low temperatures, MoS₂ acts as an insulator and doesn't contribute to the system's conductivity.

Zhao and colleagues used the squeezing technique to produce 2D sheets of bismuth, indium, tin, lead, and gallium. They focused their material characterization on 2D bismuth, which has been shown in previous studies (on smaller samples) to exhibit attractive properties, such as photoluminescence² and exceptional electronic transport.³ By connecting the 2D bismuth to electrodes, the researchers observed electronic properties that aren't seen in bulk metals. For example, the bismuth's conductivity could be altered by an applied electric field in a phenomenon known as the field effect—a useful quality for building transistors.

Just a phase

The bismuth film produced in Zhao and colleagues' study is, at its thinnest, two atoms thick. Those two atoms constitute a unit cell of the material's rectangular crystal phase, the phase produced in the study. But many other phases can exist. A hexagonal phase of bismuth is pre-

dicted to have topological insulating properties at room temperature. Tweaking the fabrication technique's conditions, such as the temperature or the angle between MoS₂ sheets, could allow the creation of more material phases in the future.

Sheets of bismuth with four or six layers of atoms were produced when the researchers adjusted the pressure applied to the anvils. The researchers have had success with every single-element material they have tried the technique on, and their future work will investigate mixtures. "The first thing to do is study. We have almost no knowledge of these structures, 2D metals. We should first look at their fundamental properties," says Zhang.

"It's a great technological advance that can be applied to more materials," says Princeton University's Sanfeng Wu, who also works on the engineering of novel 2D metals. "I see a bright path forward for 2D metals and for techniques based on them to engineer quantum devices."

By further refining the technique to produce extremely uniform surfaces to

work with, the researchers may be able to create even larger metal sheets. The immense squeezing pressures inevitably scratch the steel plates used to compress the sapphire anvils, for example, so they must be polished back to a perfectly flat surface after each experiment. Any blemish in the surface can lead to the anvils fracturing at high pressures. But those are straightforward technological challenges Zhang is confident his lab can overcome.

"It's not how people usually think about growing crystals—it's a creative approach," says Sanchez-Yamagishi. "It's very cheap and simple compared to the million-dollar ultrahigh-vacuum systems which are typically used for growing thin crystals. Now that they've shown that it works, I expect other people to try."

Laura Fattaruso

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