Valleytronics researchers fabricate novel 2D material enjoying long-life excitons

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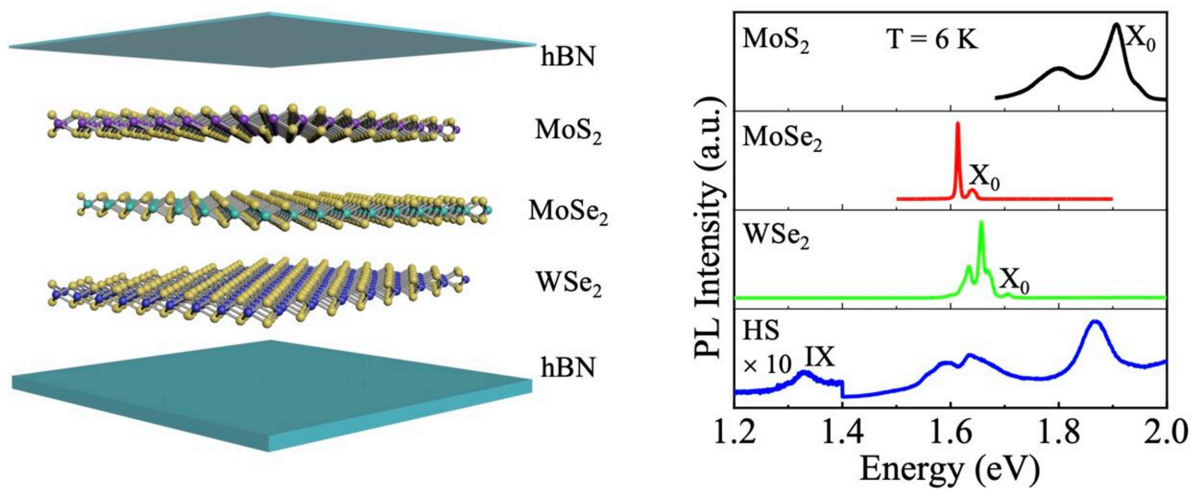

Valleytronics researchers have developed 2D material that significantly enhances the utility of exciting particles. Credit: Nano Research, Tsinghua University Press

The emerging field of valleytronics, which exploits the momentum preference of excited electrons, or excitons, in a variety of optoelectronic devices, is closely tied to the fabrication of novel 2D materials just atoms thick. This month, a group of valleytronics researchers from Central South University in Changsha, China, have developed one such 2D material that significantly enhances the utility of these exciting particles.

The details of its fabrication and an elucidation of its properties are described in the journal *Nano Research*.

In the realm of materials science, the term 2D materials refer to solids that are just one layer of atoms thick. These are of interest not just because they are very small but because new physical properties emerge when a material is thinned down to just this one atomic layer. Perhaps the most famous 2D material is graphene, a single layer of carbon atoms, which has some astonishing properties very different from other forms that carbon takes when it comes in bulk (or more formally, 'bulk crystal'), including being some 200 times stronger than steel.

But there are hundreds of other types of 2D materials, which again offer very different properties to their bulk crystal form. One such 2D material, transition-metal dichalcogenide, or TMD, is of particular interest in the world of optoelectronics, the science and technology of light-emitting and light-detecting devices. Underlying all optoelectronic devices is the photovoltaic effect, or the generation of electric current in a material when hit by a beam of light—such as in a photovoltaic cell in a solar panel, and its inverse form, the production of light from electrical signals.

Such technology depends upon materials that are semiconductors. To use the example of the PV cell again, when light hits a semiconductor, this energy is sufficient to excite electrons to jump a "band gap" up from the valence level of an atom to its conduction level—where these excited electrons, or more simply excitons, can now flow freely in an electric current. In effect, the light has been transformed through this special band gap property of semiconductors into electrical energy. This same band gap property is what allows transistors—made of semiconductor material such as silicon—to act as on/off switches used to store data in the form of ones and zeros, or "bits" in computers.

The 2D material graphene, a semi-metal, has no band gap. It's a conductor, not a semiconductor. Single layers ("monolayers") of TMD—made of a transition metal atom such as molybdenum or tungsten bonded to an atom from the same column on the periodic table as oxygen (the chalcogens), such as sulfur, selenium or tellurium—do however have a band gap. This makes TMDs very interesting for the fabrication of transistors and other optoelectronic devices.

Just as the monolayer of a material has different properties from the same material in bulk crystal form, 2D materials that are two or three layers (bilayer or trilayer) thick can have different properties again to the same material in monolayer form. And a multilayer 2D material composed of layers of two or more different materials is called a heterostructure, which will enjoy even more differences in its properties.

Strictly speaking, the term exciton refers to both the electron and the empty space or "hole" it leaves behind but to which it remains attracted and thus bound: an electron-hole pair. Because the electron has a negative charge, the electron hole can be said to have a positive charge. Combined, the electron-hole pair, or exciton, is an electrically neutral "quasiparticle."

Excitons in 2D materials also favor one of two states of momentum, depending on the polarization of light that has excited them. These favored momenta are often known as "valleys," as it takes a lot of energy to move an exciton up from one favored momentum state down into the other.

This on/off, binary nature of such exciton valleys potentially offers a novel way to store a bit and perform logic operations. The emerging field of "valleytronics," which investigates this phenomenon, has exploded in recent years due to the range of potential applications, including incredibly fast logic operations and, perhaps one day, small-sized room-temperature quantum computing.

Typically, excitons exist within a layer of 2D material—an intralayer exciton. But there also exists an exotic interlayer type of exciton, one that exists between two monolayers, with the electron and the hole located in different layers. These interlayer excitons themselves have various novel and tantalizing properties, including significantly longer lifetimes than their intralayer counterparts, expanding applications in long-life exciton devices.

Bilayers of TMDs have in recent years become especially attractive to optoelectronics researchers because they are particularly good at hosting these interlayer excitons.

But the Central South University researchers thought they could go one layer better.

"Most TMD exciton studies are obsessed with heterostructures composed of two different monolayer TMDs," said Yanping Liu, a physicist and engineer specializing in valleytronics and corresponding author of the paper. "But our interest was in designing a trilayer heterostructure with type-II band alignment."

Compared to bilayer TMD heterostructures with type-II band alignment, the trilayer type-II band alignment in principle offers a range of efficiency improvements, and the interlayer excitons should enjoy an even longer lifetime, boosting the application potential of TMDs in devices such as photodetectors, light-emitting diodes, lasers, and photovoltaics. But until now, the interlayer excitons had only been observed in bilayer TMD heterostructures.

The team were able to fabricate a trilayer TMD heterostructure (composed of molybdenum and sulfur, molybdenum and selenium, and tungsten and selenium), which they then observed using photoluminescence spectroscopy. They confirmed the presence of interlayer excitons and described various properties and requirements of the phenomenon.

Having fabricated the novel TMD heterostructure, confirmed the existence of the long-lived interlayer excitons, and extensively cataloged properties and requirements, the team now has to investigate more precisely the range of potential applications for their TMD in optoelectronic devices.

More information: Biao Wu et al, Observation of interlayer excitons in trilayer type-II transition metal dichalcogenide heterostructures, *Nano Research* (2022). DOI: 10.1007/s12274-022-4580-3

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