'Mind the gap' between atomically thin materials

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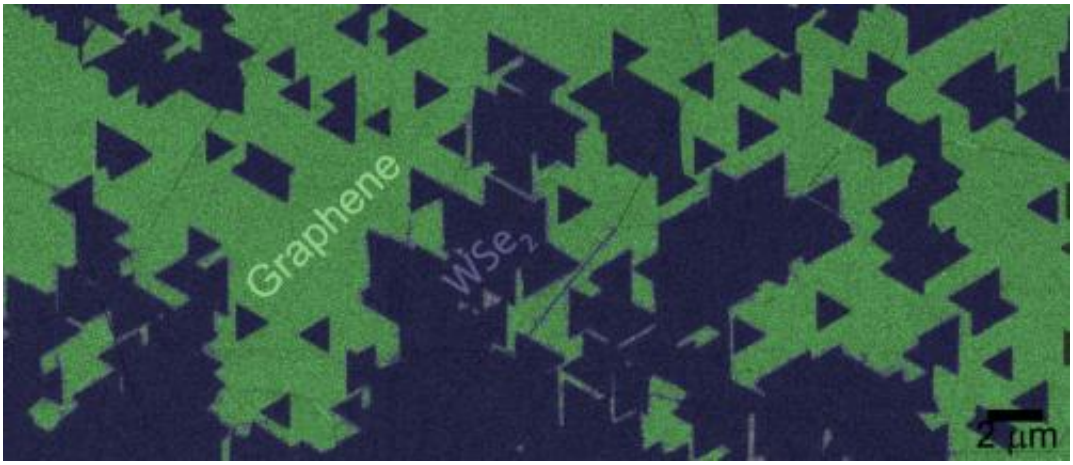

Colorized TEM image of tungsten disulfide triangles (black) growing on graphene substrate (green). Credit: Pennsylvania State University

In subway stations around London, the warning to "Mind the Gap" helps commuters keep from stepping into empty space as they leave the train. When it comes to engineering single-layer atomic structures, minding the gap will help researchers create artificial electronic materials one atomic layer at a time.

The gap is a miniscule vacuum that can only be seen under a high-power transmission electron microscope. The gap, researchers in Penn State's Center for 2-Dimensional and Layered Materials (2DLM) believe, is an energy barrier that keeps electrons from easily crossing from one layer

of material to the next.

"It's a natural insulating layer Mother Nature built into these artificially created materials," said Joshua Robinson, assistant professor of materials science and engineering and associate director of the 2DLM Center. "We're still trying to understand how electrons move vertically through these layered materials, and we thought it should take a lot less energy. Thanks to a combination of theory and experiment, we now know we have to account for this gap when we design new materials."

For the first time, the Penn State researchers grew a single atomic layer of tungsten diselenide on a one- atom-thick substrate of graphene with pristine interfaces between the two layers. When they tried to put a voltage from the top tungsten diselenide (WSe_2) layer down to the graphene layer, they encountered a surprising amount of resistance. About half of the resistance was caused by the gap, which introduced a large barrier, about 1 electron volt (1eV), to the electrons trying to move between layers. This energy barrier could prove useful in designing next generation electronic devices, such as vertical tunneling field effect transistors, Robinson said.

The interest in these van der Waals materials arose with the discovery of methods to make single layer graphite by using Scotch tape to mechanically cleave a one-atom-thick layer of carbon called graphene from bulk graphite. The van der Waals force that binds layers of graphite together is weak enough to allow stripping of the single atomic layer. The Penn State researchers use a different, more scalable method, called chemical vapor deposition, to deposit a single layer of crystalline WSe_2 on top of a few layers of epitaxial graphene that is grown from silicon carbide. Although graphene research exploded in the last decade, there are many van der Waal solids that can be combined to create entirely new artificial materials with unimaginable properties.

In a paper published online this month in *Nano Letters*, the Penn State team and colleagues from UT Dallas, the Naval Research Laboratory, Sandia National Lab, and labs in Taiwan and Saudi Arabia, discovered that the tungsten diselenide layer grew in perfectly aligned triangular islands 1-3 microns in size that slowly coalesced into a single crystal up to 1 centimeter square. Robinson believes it will be possible to grow these crystals to industrially useful wafer-scale sizes, although will require a larger furnace than he currently has in his lab.

"One of the really interesting things about this gap," Robinson said, "is that it allows us to grow aligned layers despite the fact that the atoms in the graphene are not lined up with the atoms in the tungsten diselenide. In fact there is a 23 percent lattice mismatch, which is huge. Mother Nature really relaxed the rules when it comes to these big differences in atom spacing."

The lead author on the *Nano Letters* paper is Yu-Chuan Lin, a graduate student in Robinson's lab. Other Penn State coauthors were Ram Krishna Ghosh, a post-doctoral fellow in electrical engineering (EE) who used computer modeling to help the team understand the energy barrier, Jie Li, post-doctoral fellow in EE, Theresa S. Mayer and Suman Datta, professors in EE and Robinson, who along with Lain-Jong Li of the Institute of Atomic and Molecular Sciences, Taiwan, was corresponding author. In a rare bit of serendipity, Jeremy Robinson, a researcher in the Naval Research Laboratory and Joshua Robinson's brother, was also co-author on the paper. Robert Wallace and his students from The University of Texas at Dallas provided TEM images.

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