CHALCOGENIDE-BASED 2D MATERIALS

Intrinsic nanoscale patterning

A method to realize regular patterns with nanometre precision during the synthesis of PtSe$_2$ and CuSe monolayers has been developed.

Joseph W. Lyding

Two dimensional (2D) materials show great promise for applications in electronics, chemical sensing and catalysis. While graphene, a single sheet of carbon atoms, has been the most studied 2D material, the transition metal dichalcogenides (TMDs) and the transition metal monochalcogenides (TMMs) are now receiving major focus worldwide. TMDs are layered structures with the formula MX$_2$, in which a layer consists of a sheet of metal atoms (M) bonded to two adjacent sheets of chalcogen atoms (X = S, Se or Te). TMMs generally form as a flat or buckled single atomic layer with both constituent atoms in the same layer. Monolayer TMD and TMM systems have desirable properties that are not exhibited in multilayer or bulk crystals. Synthesis efforts have now led to the production of several examples of near-defect-free 2D materials. As such, they can be thought of in much the same manner as silicon wafers — blank slates to be modified for technological applications. Conventional silicon technology takes a top-down approach to these modifications, employing advanced techniques such as extreme ultraviolet lithography to achieve nanoscale patterning precision. Now, as reported in *Nature Materials*, Hong-Jun Gao and co-workers have demonstrated natural bottom-up processes that pattern PtSe$_2$ and CuSe monolayers with nanoscale precision.

For the PtSe$_2$ case, the process starts with ‘selenization’, a selenium treatment process that produces a monolayer of PtSe$_2$ on the platinum(111) crystal surface. In previous work, Gao and colleagues showed that selenization of a platinum(111) surface results in a single crystal PtSe$_2$ monolayer. Now, either by post-growth annealing or by establishing a Se deficiency during growth, Se vacancies form that self-organize into triangular boundaries tiling the surface in sub-5-nm domains that alternate between the semiconducting 1T phase and the metallic 1H phase. In the 1T phase the top layer of Se atoms in the PtSe$_2$ structure is rotated 60 degrees relative to the bottom layer, while in the 1H phase the Se atoms in the top layer are directly above those in the bottom layer. Without Se vacancies the entire surface is in the semiconducting 1T phase. The edge-on interfaces between the 1H and 1T domains potentially represent ideal metal–semiconductor junctions for device applications. Furthermore, in a process analogous to doping in conventional semiconductors, it may be possible to render the 1T semiconducting regions either electron rich (n-type) or deficient (p-type).

Gao and co-workers have observed that pentacene molecules adsorb onto the CuSe surface, as verified by scanning tunnelling microscopy images adapted from ref. 2, Macmillan Publishers Ltd.

**Figure 1** | Bottom-up patterning of chalcogenide-based monolayers. a. During the exposure to a flux of Se atoms (blue spheres), a continuous monolayer of 1T-PtSe$_2$ is formed on the Pt(111) surface (middle). Desorption through annealing or changes in the impinging Se flux lead to the formation of triangular domains of 1T and 1H phases (right). b. Patterns of nanopores created on CuSe monolayers on a Cu(111) substrate. c. Fe clusters preferentially absorbed in the nanopores. Scanning tunnelling microscopy images adapted from ref. 2, Macmillan Publishers Ltd.
future high-performance nanoelectronic devices. Moreover, the atomically controlled arrangements of Fe atoms in the CuSe voids suggest precision chemical catalyst applications, and the voids themselves suggest molecular precision filtration applications. However, challenges do remain. For example, many applications will require transferring the PtSe₂ and CuSe layers from their growth substrates to desired target substrates such as silicon wafers for electronic applications or microfluidic substrates for filtration applications. Fortuitously, such a transfer process would also enable an expensive Pt(111) substrate to be used many times over. Also, PtSe₂ and CuSe are but two examples of the scores of mono- and dichalcogenide systems known to exist. It will be interesting to see the methodology reported here extended to other metal surfaces, with treatment process that utilize sulfur, selenium or tellurium. The generalization to a very broad class of chalcogenide-based 2D materials will create further opportunities for fabricating nanoscale devices and chemical processing systems using the intrinsic nanoscale patterning processes demonstrated by Gao and colleagues.

Joseph W. Lyding is at the University of Illinois, Department of Electrical and Computer Engineering and Beckman Institute, Urbana, Illinois 61801, USA. e-mail: lyding@illinois.edu

References

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