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Doubling-down on borophene electronics

A double-layer borophene — a boron analogue of the double-layer graphene — has been synthesized, expanding the phase space and potential applications of two-dimensional boron.

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The discovery of graphene, an atomic-thick carbon layer that can be exfoliated off a bulk graphite[2], has demonstrated various surprising properties and inspired a fervent quest for other new quasi-two-dimensional materials. Many analogues have been discovered, including borophene, silicene, germanene, stanene, phosphorene, arsenene, antimonene, and bismuthine – one-atom-thick sheets of B, Si, Ge, Sn, P, As, Sb and Bi.[3-8] Borophene is a prototype for synthetic two-dimensional (2D) material which does not have bulk layered counterparts. The growth of borophene often requires the interfacial coupling with the metal substrate to stabilize its 2D form. Despite realizing rich polymorphs, the synthesized borophene is currently limited to only single atomic layer. Now writing in *Nature Materials*, Xiaolong Liu and colleagues report the synthesis of double-layer (DL) borophene, which offers another degree of freedom to tune borophene structures and physical properties for electronic applications.[1].

Being confined down to atomic thickness, the electronic spectrum of graphene has some unusual features; viewed along a high-symmetry direction, the energy bands cross at a

single point (today called Dirac crossing). Away from this point, the bands split and disperse, with the energy decreasing (increasing) linearly with the quasi-momentum. Close to the Dirac point, low-energy electronic excitations in graphene bear analogy to Majorana fermions, hypothetical relativistic elementary particles that are their own antiparticles. Thus, graphene has emerged as a convenient material platform to study fundamental physics. It incited a great interest in topological aspects of electron bands, and of possible usage of exotic (non-Abelian) quasiparticles in quantum computing. Graphene also shows a lot of promise for other industrial applications, for example in strain sensors, piezoelectric energy harvesting, steel coating, welding, and lubrication. The rise of graphene has stimulated researchers to explore many other 2D materials.

Initially envisioned by theorists, borophene was synthesized in 2015. [4] Borophene is akin to graphene, except that most hexagons host an extra boron atom in the center; alternatively, one can view this as a triangular boron lattice with some atoms missing. These vacancies can be arranged in many ways, and hence (unlike graphene) borophene can assume various structures, depending on the substrate, the facet orientation, and the growth conditions.[5-8] Besides this remarkable polymorphism, borophene features extraordinary mechanical and electronic properties, including topologically nontrivial electron bands, and (in certain heterostructures) might even host high-temperature superconductivity.[9]

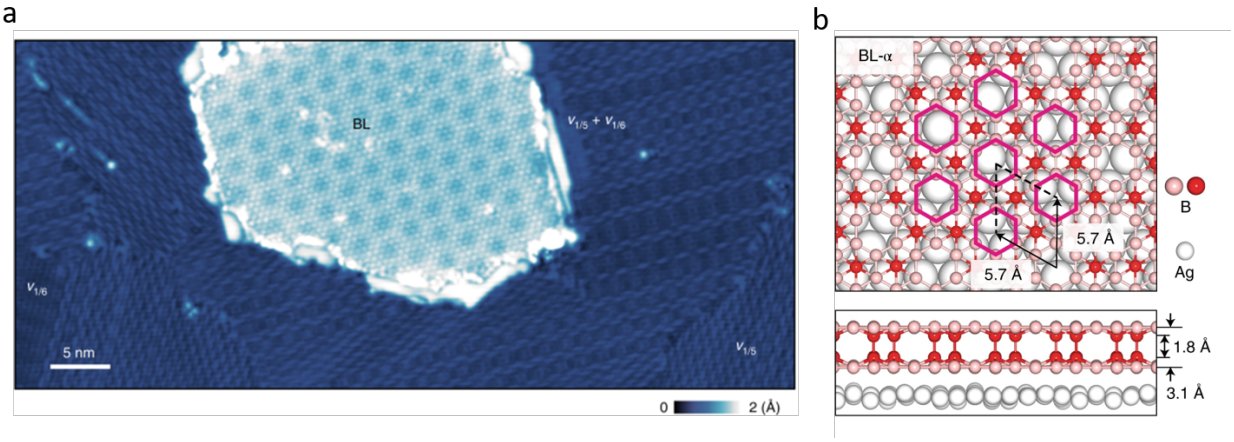
As borophene has been picking up the pace, the graphene research appeared to be slowing down. But then, in 2017, it was re-galvanized by the discovery of superconductivity in twisted-double-layer graphene (TDLG). Theorists conjectured that if two layers of graphene were stacked so that their high-symmetry axes are twisted at a particular “magic” angle, the bilayer would feature a flat electron band and superconductivity. Experiments vindicated this prediction.[10] TDLG is formed by dropping one graphene layer on top of

another, at a controlled angle. If the twist angle is 1.9 degrees, TDLG becomes superconducting below about 1 K.[10] This quickly became a topic of intense research, spread to TDLs of other van der Waals materials, and was dubbed “twistronics”.

However, borophene did not catch the fire of this second graphene revolution so far. Borophene has been synthesized at relatively high temperatures, and the growth found to be largely self-limiting to a single atomic layer (1L). Since mechanical exfoliation of borophene is not feasible, stacking has remained out of reach so far. While one would expect that a thicker layer may be grown at a lower substrate temperature, it was not clear *a priori* whether this would result in a DL borophene or in boron icosahedra such as form in bulk samples. Liu *and colleagues* have now settled this question by showing that DL borophene is stable theoretically and demonstrating its formation experimentally (as shown in Fig. 1).[1]

By combining scanning tunneling microscopy (STM) and atomic-force microscopy (AFM) with *ab-initio* simulations, Liu and coworkers have elucidated the crystal structure of DL borophene, which has two α-phase layers covalently bonded together (Fig. 1b). Field-emission resonance spectroscopy reveals high local work function suggesting the charge transfer from the substrate to the first and the second layer. Like in all similar studies of borophene and other “X-enes”, the inferred atomic structure should be taken with a grain of salt. While there is a good agreement between the simulated and the measured STM images, and the proposed structural model is plausible, the structure might not be unique.

This brings us to the speculations about the future. Further detailed characterization, by STM, atomic-resolution AFM, low-energy electron diffraction, transmission electron microscopy, and ARPES (hopefully revealing Dirac cones), would be useful to provide more information on DL borophene structure. The DL borophene was currently grown on Ag(111), leaving open the exploration of other substrates such as aluminum, gold, copper, iridium, etc.,[5-8] which may enable the formation of different crystal structures as well



as larger flakes of DL borophene, facilitating further fundamental and practical studies. Another apparent idea is to try adsorbing and/or intercalating dopants into the DL borophene. A more exigent task is to master borophene lift-off, ideally under vacuum or in an inert-gas atmosphere (since borophene oxidizes in air). That would open the path to manufacturing TDL borophene, and – given the remarkable polymorphism of borophene and the richness of ensuant band structures — probably trigger another avalanche of studies. But, ultimately, the longevity of borophene – 1ML, DL, TDL, etc., –- will depend on whether it finds applications, electronics or otherwise, in the real world.

Figure 1 Structure of BL borophene. a, Synthesized BL borophene island with a six-fold symmetric moiré superlattice surrounded by intermixed SL $\nu_{1/6}$ and $\nu_{1/5}$ borophene. b, Top and side views of the atomic structure of BL-α borophene relaxed on Ag(111), showing two covalently bonded single borophene layers. Figures adapted from Ref. 1, Springer Nature, Ltd.

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