



News and opinions

Graphene origami at the tip of a microscope

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Graphene sheets can be folded into atomically precise nanostructures with unique properties using the tip of a scanning tunneling microscope (STM), according to researchers from China and the USA [Chen et al., *Science* **365** (2019) 1036, <https://doi.org/10.1126/science.aax7864>].

“Two-dimensional (2D) atomic layer crystals like graphene can be considered as the thinnest ‘papers’ at the atomic scale and utilized as building blocks for creating novel devices with fascinating functional physical properties by employing the basic concept of conventional paper folding,” explains Hong-Jun Gao of the Institute of Physics and University of Chinese Academy of Sciences in Beijing, who worked with colleagues at Vanderbilt University and the University of Maryland, College Park.

Graphene-based nanostructures can be constructed by a variety of chemical, electrochemical, mechanical and other approaches, but creating sub-10 nm features with quantum functionalities has remained a challenge. STM, with its nanoscale manipulation capabilities, is a promising means of realizing such structures.

“We combined these two together to realize atomic scale origami and create new structural platforms with novel properties and potential application in future quantum devices,” says Gao.

On a highly ordered pyrolytic graphite substrate the researchers grew graphene nanoislands, which they repeatedly folded and unfolded using an STM tip. To create a fold, the tip is placed close to the edge of an island by reducing the tunneling resistance in the STM junction. When the tip is moved, it lifts and drags the edge of the island along with until it stops and places the graphene sheet at the desired location.

By changing the direction of the fold, just like in conventional origami, the researchers fabricated bilayer structures with different twisting angles up to 60°. The resulting tubular structures resemble carbon nanotubes or by folding graphene islands with well-defined edges, intramolecular junctions can be created (Fig. 1).

“The graphene origami nanostructures are three-dimensional in topography and relatively complex compared with other basic

graphene nanostructures, combining the one-dimensional characteristics of their edges with the two-dimensional characteristics of the stacked parts,” explains Gao.

Unlike other fabrication techniques, the process can be reversed completely to recreate the original flat graphene island. Moreover, the folding and unfolding can be repeated over and over again without introducing damage or structural defects into the graphene.

“The atomic configurations of graphene origami nanostructures can be precisely controlled through STM manipulations,” points out Gao. “Custom-designed origami nanostructures can be created by intentionally modifying the atomic structures (such as bicrystal graphene island) prior to STM manipulation, making graphene origami nanostructures truly useful for creating new structural platforms for various studies.”

Jiafang Li of Beijing Institute of Technology believes that there are two significant aspects to the work.

“First, it enables the twisting of bilayer graphene with nearly arbitrary angles, which may generate new physics like the emerging superconductivity of bilayer graphene with a magic twist angle. Second, it may make possible the multilayer stacking of graphene or other monolayer two-dimensional materials with atomic precision,” he points out.

The use of STM to perform atomically precise and direction-controllable folding of graphene could enable the creation of unprecedented heterostructures and devices.

“These origami graphene nanostructures could have uniquely engineered electronic properties and exotic boundaries, which would be very challenging to fabricate by other materials engineering approaches. It could speed up the discovery of new materials with versatile geometries,” he says.

This type of tiny graphene structures opens the way to new and unusual quantum phenomena that could ultimately facilitate the design and fabrication of quantum machines or molecular-scale electronic devices. The team now plans to explore these questions in graphene and other two-dimensional materials such as BN and MoS₂.

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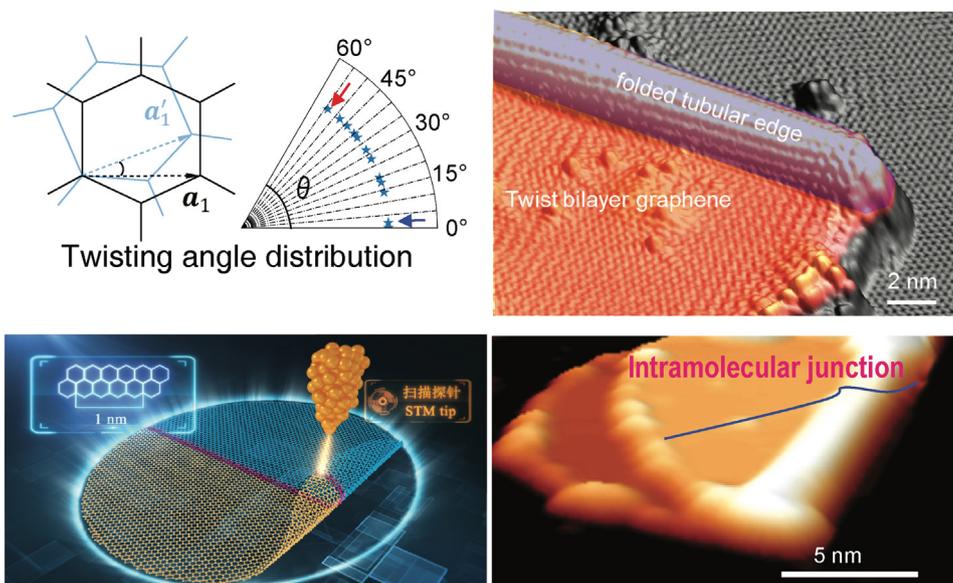


Fig. 1. (Top left) Schematic of 2D bilayer graphene nanostructure with twist angle produced by folding. The angle is defined by the folding direction. (Top right) Three-dimensional STM topography of a typical graphene origami nanostructure. (Bottom right) Folded over graphene island creating an intramolecular junction. (Bottom left) Graphene folding technique using the tip of an STM.

“We are trying to create complex new nanostructures by custom-designed folding of atomic layer materials, which will allow us to explore and test some predicted new physics and device concepts that are otherwise not feasible,” Gao told *Nano Today*.

Using origami to create novel properties that are different from two-dimensional materials is currently attracting a good deal of attention recently but most attempts to date have been limited in terms of the length scale, points out Amir A. Zadpoor, Antoni van Leeuwenhoek Distinguished Professor and professor of biomaterials and tissue biomechanics at Delft University of Technology (TUDelft).

“The methodology reported here pushes the boundaries of those attempts much further by achieving atomically precise origami structures,” says Zadpoor. “Moreover, the study shows that very interesting properties could be achieved by simply folding a two-dimensional material such as graphene. A host of other applications and two-dimensional materials could be manipulated in similar ways to achieve exotic properties.”