



News and opinions

Nanoscale carving tunes graphene's bandgap

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Two-dimensional materials like graphene should be ideal candidates for bandgap engineering using surface patterning. However, it has proved more difficult than anticipated to generate quantum confinement to control the electronic properties of graphene using lithographic patterning because the process introduces contamination and damage. Now researchers from the Technical University of Denmark, Aalborg University, and National Institute for Materials Science in Tsukuba, Japan, have achieved lithographic patterning of graphene down to 10 nm [Jessen and Gammelgaard et al., *Nature Nanotechnology* (2019), <https://doi.org/10.1038/s41565-019-0376-3>].

“Carving out graphene on the nanoscale to change the band structure or to make narrow wires for nanoelectronics has been seen as a major goal in the field. It has however, turned out to be extremely difficult, without causing unacceptable damage to graphene,” explains Peter Bøggild, who led the effort. “We have shown that it can be done, even down to the 10 nm scale, without losing the properties [of graphene] that we wanted in the first place.”

The key to the team's ability to engineer the bandgap of graphene via lithographic patterning is their preparation of the material. First the researchers encapsulated the graphene in hexagonal boron nitride (hBN), which protects the graphene, particularly at its vulnerable edges. Next, a very dense pattern of holes is created in the structure using lithography (Fig. 1). Finally, a different etch is used to remove the graphene gently from the holes.

“The ability to control the etching depth with atomic precision is, we believe, one of the reasons [our approach] works so well,” says Bøggild.

Cleverly, the researchers created graphene samples with both pristine and nanostructured regions so that the electronic behavior of the two could be compared directly (Fig. 2). The team found that carrier mobility, which measures how easily electron waves travel through the device, is 2–3 orders of magnitude higher in the nanostructured graphene than usually achieved. This indicates that patterning the graphene did not produce damage, which reduces the carrier mobility because the electron waves are scattered by defects.

However, the researchers found something more surprising when they looked at the magnetoresistance. The pristine graphene showed behavior that you would expect from high quality material. The nanostructured graphene did not.

“The patterned graphene looks completely different, with clear indications of a bandgap and so-called Landau levels, which are curved rather than straight,” points out Bøggild. “In short, the

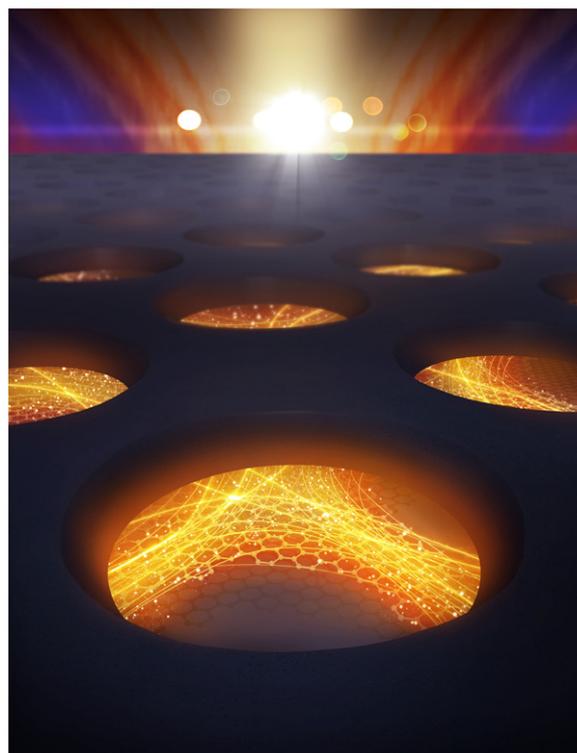


Fig. 1. Illustration of lithographically carved nanographene. Image credit: Carl Otto Moesgaard.

transport properties of nanopatterned graphene show a significant change in band structure.”

Moreover, the tell-tail signs of the ‘twist’ that arises when sheets of two-dimensional materials are overlain and rotated were detectable even after the lithographic patterning. This twist effect can have a remarkable influence on electronic properties and ‘twistronics’ is currently attracting a good deal of attention.

“[It is] striking that the ‘twistronic’ signatures survive the ultra-dense patterning,” Bøggild says. “It’s like chopping a tree into matchsticks and finding that the tiny pieces of wood are still alive afterwards.”

What exactly this means is not yet clear, say the researchers, but since twistronics can turn two graphene layers into a

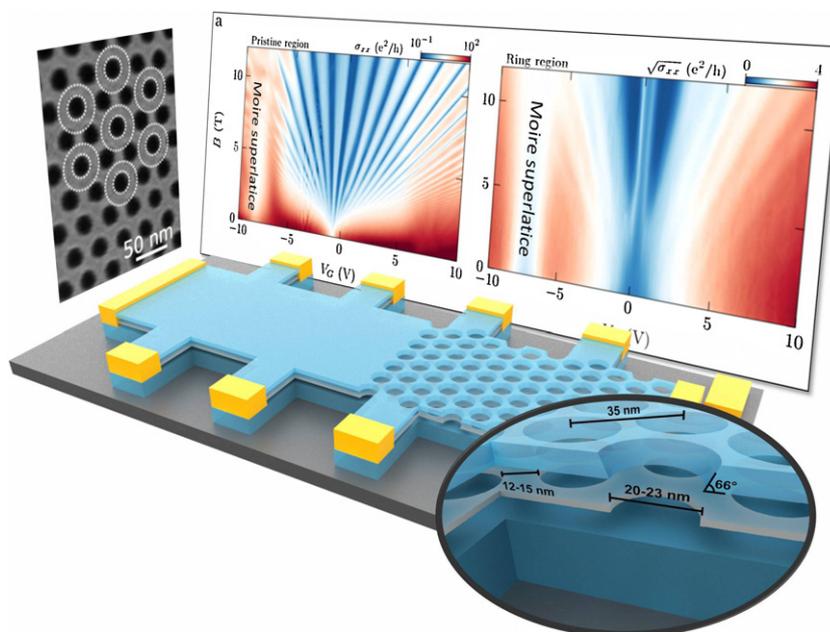


Fig. 2. Top left: Scanning electron microscope image of the van der Waals heterostructure after nanostructuring. Main image: Schematic of the device architecture of the Hall bar used for electrical measurements. The left-hand side is left pristine, while the other is shaped into a densely patterned superlattice. Top right: Comparison of magnetotransport in pristine and nanostructured graphene. [Image credit: Daniel Halkjær].

superconductor, it could be possible to fabricate nanocircuits with superconducting properties.

Bøggild hopes that other researchers will use their lithographic approach to explore the behavior of nanostructured graphene in more detail and use it to design electronic and optical devices.

“We picked a very simple pattern [to see if our approach works],” he adds. “Now we will expand the palette by making waveguides, holes with non-circular shapes, and other fun stuff to see how far we can push this.”

One of the most attractive properties of graphene is the ability to tune its properties by structure engineering, comments Cinzia Casiraghi of the University of Manchester.

“Experimentally, however, nobody has been able to see quantum confinement effects for nanostructured graphene on the scale of 10–15 nm,” she says. “This is due to the edges of the patterned graphene. Disorder at these edges ‘kills’ all effects coming from quantum confinement.”

To truly exploit quantum confinement effects in graphene nanostructures perfect atomic control of the edges is required, Casiraghi adds.

“This has been achieved for the first time by Bøggild et al. with a very simple method: encapsulating graphene between two crystals of hexagonal-boron nitride (h-BN). The structured graphene created in this way reproduces the theoretically expected

properties of perfect graphene nanostructures. This is a remarkable result because up to now it was believed that achieving perfectly structured graphene below 100 nm would only be possible using bottom-up approaches. The results demonstrate that lithography is a suitable technique to produce perfect structured graphene with the properties that we want.”

The results are a further demonstration, Casiraghi believes, that while graphene has outstanding properties, encapsulation with hBN is vital to allow scientists to observe and study those amazing electronic properties.

Christoph Stampfer of RWTH-Aachen University agrees that the work demonstrates an important improvement in the patterning of hBN-encapsulated graphene.

“What I find particularly encouraging is that they show by their well-controlled experiment that there is true hope that edge disorder can be substantially reduced such that designed size confinement in graphene might become possible one day,” he told Nano Today. “If this technology also works for nanoribbons it may allow the fabrication of graphene transistors. That would be fantastic!”

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