spoke of the project. There were many parts to the project, across a range of fields: design, mathematics, computation, and materials science. The breadth of the project brought together several laboratories including Raviv's laboratory at MIT, laboratories at Autodesk Inc., Stratasys Ltd., and Singapore University of Technology and Design. Skylar Tibbits at MIT's Self-Assembly Laboratory also contributed significantly. Their work anticipates developments in—and increasing use of—soft robotics, where this has many potential applications *in vivo*. A thermally activated stent, for example, could be printed and inserted into a collapsed artery where it would expand and open the artery on its own. The confluence of materials science, 3D printing technology, and computational engineering heralds a future in which these active, self-evolving structures find many invaluable uses.

**Antonio Cruz**

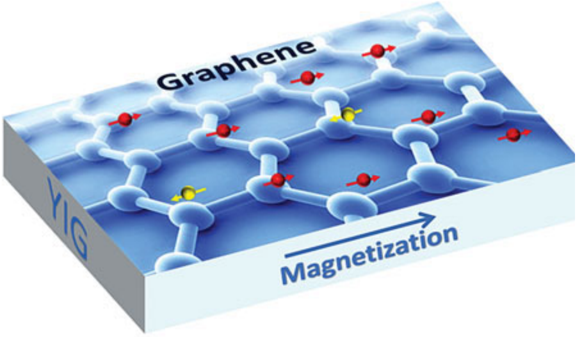
## Ferromagnetic thin film induces magnetism in graphene

Over the past decade, graphene has become one of the most intensely investigated materials. Graphene shows high electrical conductivity, and understanding the electrical properties of high-quality graphene under different conditions is a topic of great interest. In an article recently published in the January 7 issue of *Physical Review Letters* (DOI: 10.1103/PhysRevLett.114.016603), researchers at the University of California–Riverside have determined a way to induce ferromagnetism in graphene, opening a new path of investigation especially into its spintronics applications.

"Graphene has many interesting properties," said Jing Shi, professor of physics at the University of California–Riverside. "It's especially unusual compared to other conducting materials. And now it's even more unusual that we know what it exhibits with an anomalous Hall effect."

The ordinary Hall effect is equivalent to a magnetic field sensor, meaning that it can be used to measure the direction and strength of a magnetic field. A material that shows the anomalous Hall effect is sensitive to the direction of magnetization of a magnetic material. The idea behind the present work is that attaching a magnetic material to graphene can make graphene ferromagnetic, which can induce the anomalous Hall effect. By measuring shifts in the Hall effect, researchers can better understand the properties of a material or the interactions between two materials.

A standalone graphene sheet has been known to exhibit diamagnetism, said Shi. But such magnetism is not very useful for electronic device applications. Attempts to create magnetism in graphene by doping have not been very successful, and would also hurt graphene's excellent electrical transport properties. Shi and his group decided to attempt to induce magnetism by attaching a single layer of graphene to an yttrium iron garnet (YIG) thin film. This film is magnetic up to 550 K. An important aspect of the YIG thin film is that it is an insulator, so it would not divert electric current away and thus affect graphene's conductivity.



A single layer of graphene on top of a ferromagnetic yttrium iron garnet (YIG) thin film. Together, they create an anomalous Hall effect. Credit: Jing Shi.

A single layer of graphene was first fabricated on top of a traditional $SiO_2$ substrate. Hall effect measurements were taken at this point to create a baseline. One side of the graphene was spin-coated with poly(methyl methacrylate) (PMMA) that acted as a support during transfer. It was then soaked for two days in a 1 M NaOH solution to completely remove any traces of $SiO_2$. Once free of the $SiO_2$, the PMMA-coated graphene was placed on the YIG thin film as a new substrate for the graphene. Then acetone was used to wash away the PMMA, leaving just the graphene and YIG film behind.

Once the graphene was attached, Hall effect measurements were taken again. Since YIG is already magnetized in the film plane, it takes a perpendicular field to rotate the magnetization out of plane; the anomalous Hall effect occurs when such a rotation takes place. It was seen that the Hall effect was indeed present in the graphene, meaning that YIG had induced magnetization in the graphene sheet. The Hall effect senses the magnetization (or electron spin) direction in magnetized graphene that can represent non-volatile information.

"When you put graphene in contact with bulky materials with, say, stronger 'personalities,' it borrows the personality from them," said Antonio Castro Neto, Director of the Centre for Advanced 2D Materials and the Graphene Research Centre at the National University of Singapore. Neto has done similar work with graphene, bulking up the spin orbit interaction of the material by putting it into contact with tungsten disulfide. Three-dimensional materials like YIG and tungsten disulfide have many more atoms than the two-dimensional graphene sheets, he said. "Hence, these three-dimensional materials have billions of atoms more than graphene and, hence, they can 'bully' graphene around. Graphene has no option but to adapt," Neto said.

**Meg Marquardt**