Researchers use oxides to flip graphene conductivity

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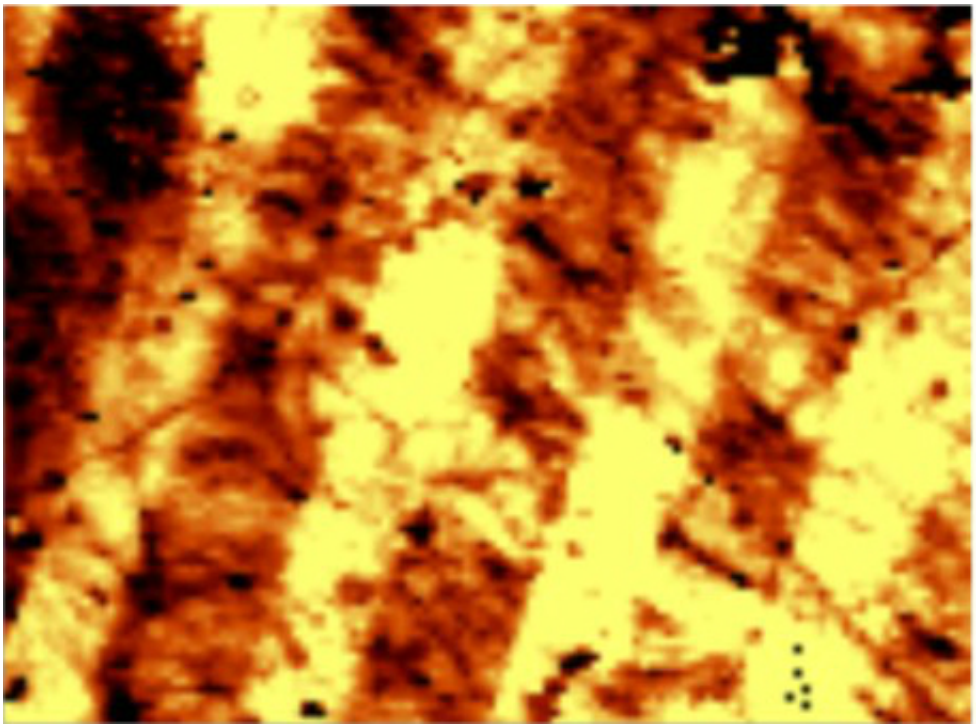

The researchers suspended graphene over periodically poled lithium niobate. The "stripes" indicate different polar regions.

Graphene, a one-atom thick lattice of carbon atoms, is often touted as a revolutionary material that will take the place of silicon at the heart of electronics. The unmatched speed at which it can move electrons, plus its essentially two-dimensional form factor, make it an attractive alternative, but several hurdles to its adoption remain.

A team of researchers from the University of Pennsylvania; University of California, Berkeley; and University of Illinois at Urbana-Champaign has made inroads in solving one such hurdle. By demonstrating a new way to change the amount of electrons that reside in a given region within a piece of graphene, they have a proof-of-principle in making the fundamental building blocks of semiconductor devices using the 2-D material.

Moreover, their method enables this value to be tuned through the application of an electric field, meaning graphene circuit elements made in this way could one day be dynamically "rewired" without physically altering the device.

The study was a collaboration between the groups of Andrew Rappe at Penn, Lane Martin at UC Berkeley and Moonsub Shim at Illinois.

It was published in the journal *Nature Communications*.

Silicon is used for making circuit elements because its charge-carrier density, the number of free electrons it contains, can be easily increased or decreased by adding chemical impurities. This "doping" process results in "p-type" and "n-type" semiconductors, silicon that has either more positive or more negative charge carriers.

The junctions between p- and n-type semiconductors are the building blocks of electronic devices. Put together in sequence, these p-n junctions form transistors, which can in turn be combined into integrated circuits, microchips and processors.

Chemically doping graphene to achieve p- and n-type version of the material is possible, but it means sacrificing some of its unique electrical properties. A similar effect is possible by applying local voltage changes to the material, but manufacturing and placing the necessary electrodes

negates the advantages graphene's form factor provides.

"We've come up with a non-destructive, reversible way of doping," Rappe said, "that doesn't involve any physical changes to the graphene."

The team's technique involves depositing a layer of graphene so it rests on, but doesn't bond to, a second material: lithium niobate. Lithium niobate is ferroelectric, meaning that it is polar, and its surfaces have either a positive or negative charge. Applying an electric field pulse can change the sign of the surface charges.

"That's an unstable situation," Rappe said, "in that the positively charged surface will want to accumulate negative charges and vice versa. To resolve that imbalance, you could have other ions come in and bond or have the oxide lose or gain electrons to cancel out those charges, but we've come up with a third way.

"Here we have graphene standing by, on the surface of the oxide but not binding to it. Now, if the oxide surface says, 'I wish I had more negative charge,' instead of the oxide gathering ions from the environment or gaining electrons, the graphene says 'I can hold the electrons for you, and they'll be right nearby.'"

Rappe suggested using lithium niobate, as it is already commonly used in optical engineering and has properties that would lend themselves to creating p-n junctions. The researchers took advantage of the fact that a certain type of the material, periodically poled lithium niobate, is manufactured so that it has "stripes" of polar regions that alternate between positive and negative.

"Because the lithium niobate domains can dictate the properties," Shim said, "different regions of graphene can take on different character depending on the nature of the domain underneath. That allows, as we

have demonstrated, a simple means of creating a p-n junction or even an array of p-n junctions on a single flake of graphene. Such an ability should facilitate advances in graphene that might be analogous to what p-n junctions and complementary circuitry has done for the current state-of-the-art semiconductor electronics.

"What's even more exciting are the enabling of optoelectronics using graphene and the possibility of waveguiding, lensing and periodically manipulating electrons confined in an atomically thin material."

Their experiments also involved adding a single gate to the device, which allowed for its overall carrier density to be further tuned by the application of different voltages.

By taking into account how the oxide balances out its surface charges on its own, or by binding ions from the aqueous solution, the researchers were able to show the relationship between the polarization of the oxide and the charge carrier density of the graphene suspended over it.

And because the oxide polarization can be easily altered, the type and extent of supported graphene doping can be altered along with it.

"You could come along with a tip that produces a certain electric field, and just by putting it near the oxide you could change its polarity," Martin said. "You write an 'up' domain or a 'down' domain in the region you want it, and the graphene's charge density would reflect that change. You could make the graphene over that region p-type or n-type, and, if you change your mind, you can erase it and start again."

This ability would represent an advantage over chemically doped semiconductors. Once the atomic impurities are mixed into the material to change its carrier density, they can't be removed. Future research will investigate the feasibility of designing dynamic semiconducting devices

with this technique.

"We can't currently do that, but that's the direction we want to take it," Rappe said, "There are some oxides that can be repolarized on the timescale of nanoseconds, so you could make some really dynamic changes if you needed to. This opens up a lot of possibilities."

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