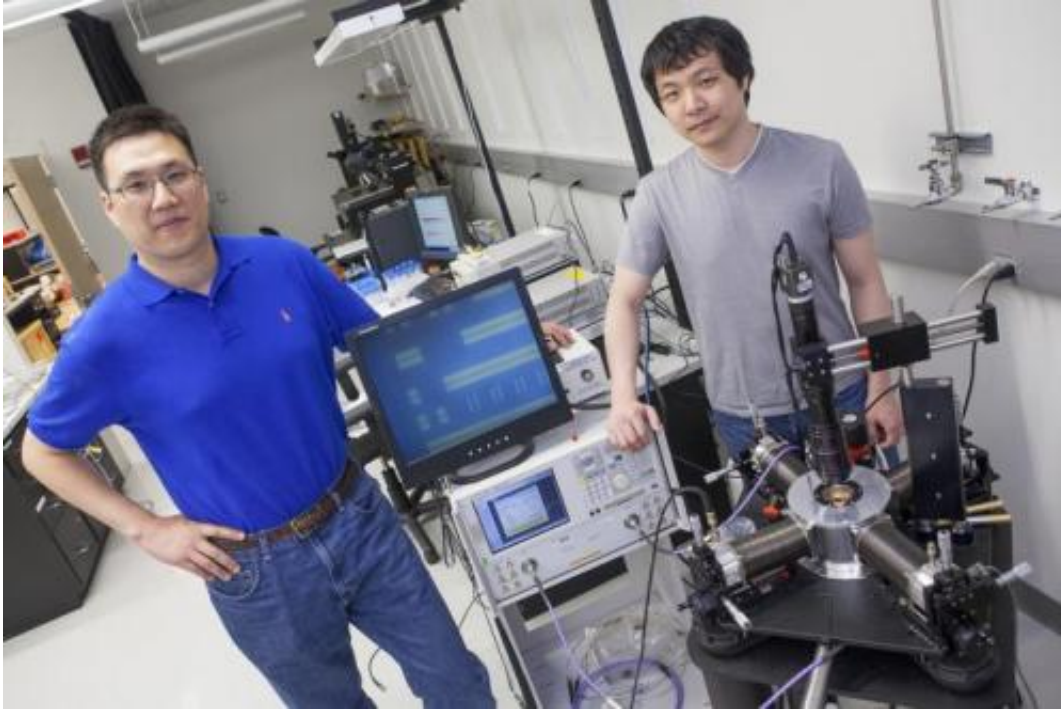


Measuring the mass of 'massless' electrons

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This image shows professor Donhee Ham and his student Hosang Yoon are in the laboratory at the Harvard School of Engineering and Applied Sciences. Credit: Eliza Grinnell, Harvard SEAS.

(Phys.org)—Individual electrons in graphene are massless, but when they move together, it's a different story. Graphene, a one-atom-thick carbon sheet, has taken the world of physics by storm—in part, because its electrons behave as massless particles. Yet these electrons seem to have dual personalities. Phenomena observed in the field of graphene plasmonics suggest that when the electrons move collectively, they must

exhibit mass.

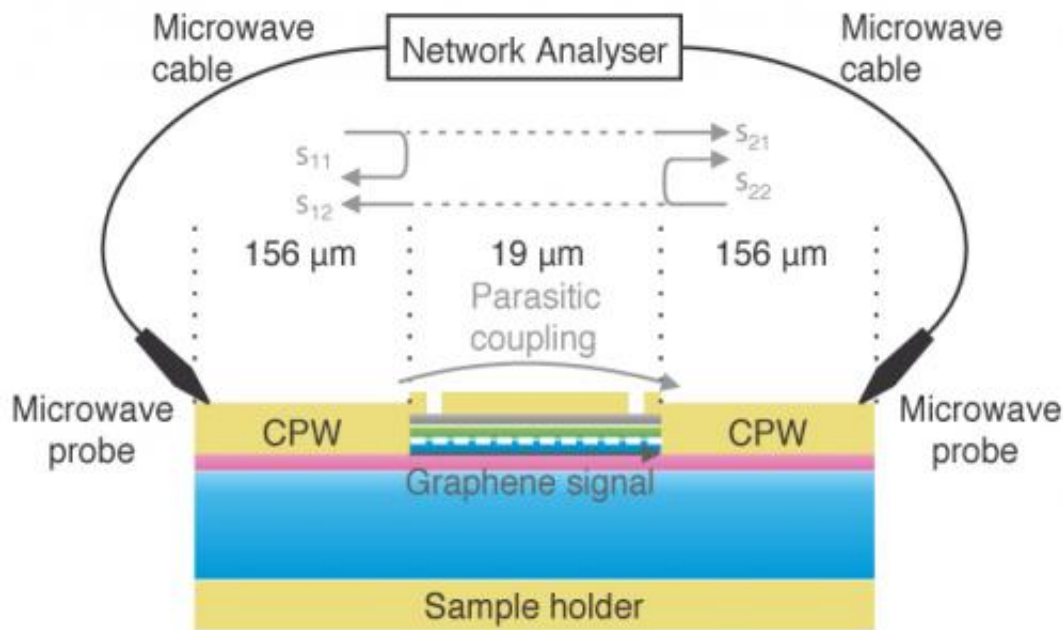
After two years of effort, researchers led by Donhee Ham, Gordon McKay Professor of Electrical Engineering and Applied Physics at the Harvard School of Engineering and Applied Sciences (SEAS), and his student Hosang Yoon, Ph.D.'14, have successfully measured the collective mass of 'massless' [electrons](#) in motion in graphene.

By shedding light on the fundamental kinetic properties of electrons in graphene, this research may also provide a basis for the creation of miniaturized circuits with tiny, graphene-based components.

The results of Ham and Yoon's complex measurements, performed in collaboration with other experts at Columbia University and the National Institute for Materials Science in Japan, have been published online in *Nature Nanotechnology*.

"Graphene is a unique material because, effectively, individual graphene electrons act as though they have no mass. What that means is that the individual electrons always move at a constant velocity," explains Ham. "But suppose we apply a force, like an electric field. The velocity of the individual electrons still remains constant, but collectively, they accelerate and their total energy increases—just like entities with mass. It's quite interesting."

Without this mass, the field of graphene plasmonics cannot work, so Ham's team knew it had to be there—but until now, no one had accurately measured it.



A schematic of the experimental setup is shown. Ham and Yoon measured the change in phase of a microwave signal sent through the graphene. Credit: Hosang Yoon, Harvard SEAS.

"One of the greatest contributions of this work is that it is actually an extremely difficult measurement," says Ham.

As Newton's second law dictates, a force applied to a mass must generate acceleration. Yoon and Ham knew that if they could apply an electric field to a graphene sample and measure the electrons' resulting collective acceleration, they could then use that data to calculate the collective mass.

But the graphene samples used in past experiments were replete with imperfections and impurities—places where a carbon atom was missing or had been replaced by something different. In those past experiments, electrons would accelerate but very quickly scatter as they collided with the impurities and imperfections.

"The scattering time was so short in those studies that you could never see the acceleration directly," says Ham.

To overcome the scattering problem, several smart changes were necessary.

First, Ham and Yoon joined forces with Philip Kim, a physics professor at Columbia who will join the Harvard faculty on July 1 as Professor of Physics and of Applied Physics. A Harvard graduate (Ph.D. '99), Kim is well known for his pioneering fundamental studies of graphene and his expertise in fabricating high-quality graphene samples. The team was now able to reduce the number of impurities and imperfections by sandwiching the graphene between layers of hexagonal boron nitride, an insulating material with a similar atomic structure. By also collaborating with James Hone, a professor of mechanical engineering at Columbia, they designed a better way to connect electrical signal lines to the sandwiched graphene. And Yoon and Ham applied an [electric field](#) at a microwave frequency, which allows for the direct measurement of the electrons' collective acceleration in the form of a phase delay in the current.

"By doing all this, we translated the situation from completely impossible to being at the verge of either seeing the acceleration or not," says Ham. "However, the difficulty was still very daunting, and Hosang [Yoon] made it all possible by performing very fine and subtle microwave engineering and measurements—a formidable piece of experimentation."

"To me, it was a victorious moment that finally justified a long-term effort, going through multiple trials and errors," says Yoon, lead author of the paper in *Nature Nanotechnology*. "Until then, I wasn't even sure if the experiment would really be possible, so it was like a 'through darkness comes light' moment."

Collective mass is a key aspect of explaining plasmonic behaviors in graphene. By demonstrating that graphene electrons exhibit a collective mass and by measuring its value accurately, Yoon says, "We think it will help people to understand and design more sophisticated plasmonic devices with graphene."

The team's experiments also revealed that, in graphene, kinetic inductance (the electrical manifestation of collective mass) is several orders of magnitude larger than another, far more commonly exploited property called magnetic inductance. This is important in the push toward smaller and smaller electronic circuitry—the main theme of modern integrated circuits—because it means the same level of inductance can be achieved in a far smaller area. Furthermore, Ham and Yoon say that this miniature graphene-based kinetic inductor could enable the creation of a solid-state voltage-controlled inductor, complementary to the widely used voltage-controlled capacitor. It could be used to substantially increase the frequency tuning range of electronic circuits, which is an important function in communication applications.

For now, the challenge remains to improve the quality of [graphene](#) samples so that the detrimental effects of electron scattering can be further reduced.

More information: *Nature Nanotechnology*,
www.nature.com/nnano/journal/v.../nnano.2014.112.html

Provided by Harvard University

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