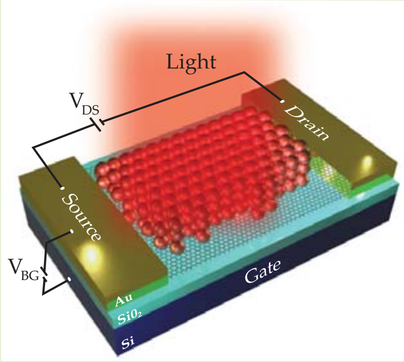
and colleagues demonstrated an ultrafast graphene photodetector three years ago,[1] his group and others have been developing strategies to ameliorate the limited absorption. One can, for instance, place graphene in an optical cavity to repeatedly pass light through it or position plasmonic nanostructures near electrodes on opposite sides of the graphene to dramatically amplify the local electric field.

Researchers led by Gerasimos Konstantatos and Frank Koppens at the Institute of Photonic Sciences in Barcelona, Spain, have now developed a fundamentally different approach. They used graphene as an ultrafast charge-transport channel but relegated the light absorption to a roughly 60-nm-thick film of colloidal quantum dots deposited on it.[2] Because the dots can be synthesized with a broad distribution of sizes (and thus bandgaps), they can absorb over a broad spectral range. More significantly, because graphene is sensitive to any electrostatic perturbation close to its surface, the quantum-dot layer acts like a gate that controls the amount of charge flowing through the graphene below it. The combination of the two materials in a circuit provides a gain mechanism that can generate multiple charge carriers for each incident photon.

As proof of concept, the researchers created an ultrahigh-gain phototransistor. To build the device, shown schematically in the figure, they started with a micron-sized flake of graphene peeled from graphite and deposited on silicon dioxide using the now-famous "Scotch tape" method (see PHYSICS TODAY, August 2010, page 15). They then sprayed the surface with lead sulfide quantum dots. Lead sulfide was chosen for its ability to absorb strongly in the visible and IR, and the dots were specially prepared with short ligand molecules that bind them to the graphene and efficiently transfer charge to it.

Photons incident on the PbS excite electron–hole pairs. Thanks to an inherent electric field at the graphene–PbS interface, those pairs immediately separate. The electrons migrate outward, only to become trapped for a few hundred milliseconds in shallow surface states, while the holes are swept into the graphene, where in nanoseconds they are conducted under an external field to the drain. Electrons trapped in the PbS dots induce the photogating effect, in which the presence of the electrons alters the graphene's resistance to current.



A hybrid graphene phototransistor. Gold electrodes are the source and drain on opposite sides of a graphene flake deposited on a silicon dioxide/silicon wafer and coated with light-absorbing quantum dots made of lead sulfide. Incident light generates electron–hole pairs in the dots. Holes are transferred to the graphene and quickly drift toward the drain under the influence of a voltage V_{DS}, while electrons remain trapped in the PbS. Capacitive coupling between the oppositely charged layers modulates the current, which is amplified by the continual replenishment of holes that flow through graphene during the milliseconds that electrons remain trapped. A back-gate voltage V_{BG} can be adjusted to tune graphene's charge density and maximize the circuit's light sensitivity. (Adapted from ref. 1.)

The phototransistor's central feature, its enormous photoconductive gain, can be understood as the ratio of two lifetimes: the electrons' long lifetime trapped in PbS and the holes' short lifetime in transit through graphene. The negatively charged quantum dots induce positive carriers in the graphene sheet through capacitive coupling. So under the influence of a bias voltage between the two electrodes, holes are pulled from the source to replace those lost to the drain during the milliseconds that a single electron is trapped. The current through the graphene leads to a measured gain of up to 10^8 holes per photon. That gain, equivalent to about 10^7 amps per watt of incident light, is a billion times greater than that of any other graphene-based photodetector.

As a result, signals as small as 10 attowatts are detectable. But such sensitivity comes at the price of slow switching frequencies. Whereas other graphene phototransistors modulate currents at more than 40 GHz (and may potentially exceed 500 GHz), the Barcelona group's device typically operates at frequencies under 100 Hz. A back-gate voltage, typically used to tune graphene's change in conductance as additional holes from PbS are transferred, can also act as an electronic shutter. A periodic pulse supplies an electric field that empties the electron traps in the PbS so that the photocurrent through graphene decays and effectively resets the transistor.

"We envision our device as complementary to other graphene-based phototransistors, not as a replacement," says Koppens. He and Konstantatos imagine that it will find a niche in such applications as visible- and IR-sensitive cameras that can capture images at video rates. Andrea Ferrari of the University of Cambridge regards the achievement as having broader significance. It's the first, he argues, of a wide variety of sensors that researchers are likely to engineer from the interaction between graphene and quantum dots.

Mark Wilson

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Artificial materials manipulate heat flow

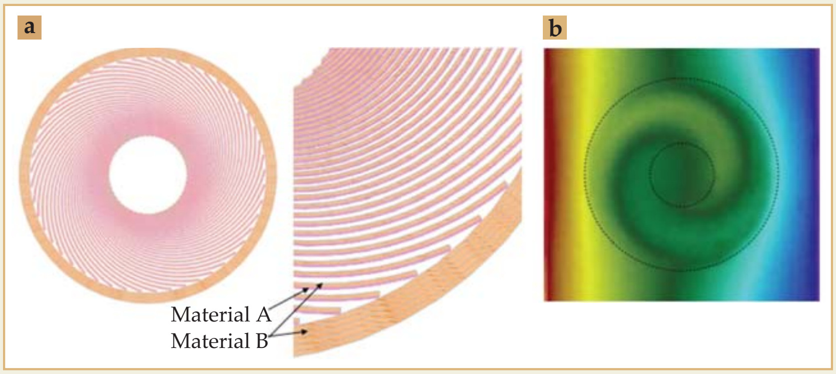
The layered composites conduct heat anisotropically, to counter-intuitive effect.

Heat flux is all around us—everywhere there's a temperature difference. It's intuitively easy to understand, at least at its most basic level: Heat flows from hot to cold and does so more readily through some materials than through others. But compared with the analogous flow of electric current, heat is much more difficult to control or put to good use. Better control of heat flux could help protect sensitive electronic components from temperature extremes, better harness solar thermal energy, or, more speculatively, create thermal analogues of electronic diodes and transistors.

Now Yuki Sato and his postdoc Supradeep Narayana, of the Rowland Institute at Harvard University, have used techniques from the field of metamaterials in order to manipulate heat flux.[1] Inspired by work on devices that "cloak" regions from electromagnetic waves (see PHYSICS TODAY, February 2007, page 19), acoustic waves, static fields, and other signals, they set themselves the challenge of designing a hollow, thick cylinder that, when embedded in a material with a uniform thermal gradient perpendicular to the cylinder axis, could drastically alter the heat flux inside the cylinder without disturbing the flux outside.

They quickly realized that no ordinary substance would do the trick. A hollow cylinder of a material with thermal conductivity much higher *or* much lower than the background material could lessen the thermal gradient inside, but at the expense of severely distorting it outside. "We started out by going back to basics," says Sato, "drawing up thought experiments to challenge our understanding of thermodynamics and to push the envelope a little and then trying to design physical systems to mimic them."

What they needed, the researchers found, was a material with anisotropic thermal conductivity. To make it, they stacked many alternating thin sheets of two ordinary materials, one a good thermal conductor and the other a good thermal insulator. Perpendicular to the planes of the sheets, their thermal resistances add in series; parallel to the planes, they add in parallel. With a suitable choice of the two materials—the product of their thermal conductivities must equal the square of the background material's conductivity—the stacked layers blend into the background material and induce almost no distortion in the surrounding thermal gradient.



A thermal inverter (a) made from layers of copper (material A, pink) and polyurethane (material B, orange) arranged in a spiral pattern. **(b)** When the inverter is embedded in an agar–water block that is subject to a thermal gradient, the gradient outside the cylinder is only slightly distorted. But the gradient inside the cylinder is reversed: The cylinder's inside edge is slightly warmer on the right than on the left. (Adapted from ref. 1.)

By arranging the layers in concentric circles, Narayana and Sato created a thermal shield that isolates the region inside from any measurable thermal gradient at all. Arranging the layers as radial spokes did the opposite: It enhanced the thermal gradient in the region inside the cylinder, a useful task in many energy applications.

But when they arranged the layers in a spiral pattern, as shown in panel a of the figure, they achieved perhaps the most counterintuitive effect of all: local inversion of the flux direction so that heat flows from right to left inside the cylinder in response to a left-to-right flux outside. Panel b shows the temperature map as imaged with an IR camera. Heat still flows from hot to cold (as it must), but the positions of the heat source and sink inside the cylinder are reversed.

Narayana and Sato are working on incorporating other materials engineering techniques into their toolbox for designing their thermal materials. They'd also like to explore the potential of materials with strongly temperature-dependent thermal conductivities.

Johanna Miller

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physics update

These items, with supplementary material, first appeared at http://www.physicstoday.org.

Spin correlation in top-quark pairs. Almost 200 times heavier than the proton, the top quark is by far the most massive of the six quark species that, together with their antiquarks, are the building blocks of the hadrons. But because it's so massive, a top quark (or its antiparticle) decays within 10^{-24} seconds of its creation—too fast to be affected by the processes that ordinarily clothe a quark in hadronic garb. So top–antitop pairs produced in CERN's Large Hadron Collider (LHC) provide a unique opportunity for studying the production and decay of quarks without the obscuring hadronic complications. Now the team that runs the LHC's gargantuan ATLAS detector has reported an analysis of correlation between the spin orientations of the top and antitop quarks in some 4000 identifiable top–antitop pairs produced in 10^{14} collisions between 3.5-TeV protons. The spin correlation is deduced from the directional correlations of high-energy decay leptons. The standard model (SM) of particle theory predicts that the top and antitop spins prefer to emerge with the same rather than opposite helicities (spin projections along the momentum direction). The team measured the correlation parameter A (same minus opposite fraction of all pairs) to be $(40 \pm 8)\%$, in reasonable agreement with the SM prediction. If, as some theories suggest, nonstandard Higgs bosons are involved in the production or decay processes, A could differ from the SM prediction. (G. Aad et al., ATLAS collaboration, *Phys. Rev. Lett.* **108**, 212001, 2012.) —BMS

Theory meets experiment in the blink of an eye. A healthy human eye has a thin, moist tear film that protects it, removes waste, and provides a smooth optical surface. The film—containing layers of lipids, water, and mucin—evaporates as the eye stays open and is replenished with a blink. Mathematical models typically show that the film warms between blinks. But precise noncontact laboratory