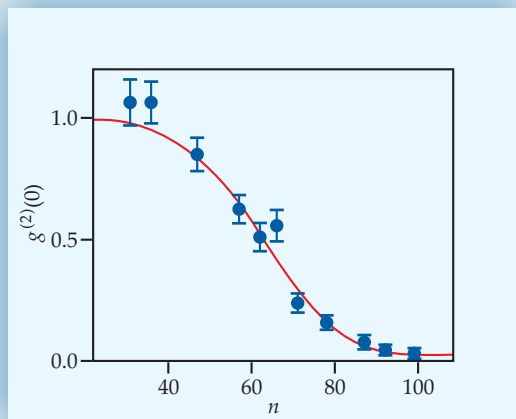


Figure 2. As the principal quantum number n of the Rydberg state is increased, multiphoton events become rarer. The second-order intensity correlation function, $g^{(2)}(0)$, measures the probability that two photons are produced at the same time, relative to a conventional source's Poisson distribution. (Adapted from ref. 1.)



interactions could reach from one end of the gas to the other. As it turned out, the 15- μm trap was not quite small enough to entirely prevent two atoms from being excited to Rydberg states simultaneously. But when two Rydberg excitations are present in the gas, they can interact, disrupt the phase coherence, and prevent either excitation from producing a photon that emerges in the desired direction.

Two-photon suppression

To illustrate the power of the Rydberg interactions, Dudin and Kuzmich repeated the experiment with the Rydberg-excitation laser tuned to different wavelengths, chosen to excite the atoms to states with different n . Figure 2 shows the results. For n less than 40, the valence-electron wavefunctions are too small to influence distant atoms, and $g^{(2)}(0)$ is no better than for a conventional source. But for n near 100, Rydberg interactions are much stronger, and two-photon events are suppressed by a factor of 25.

For any $n \geq 70$, the probability of detecting even a single photon in a given repetition was just 2–3%. “That may sound small,” says Kuzmich, “but it’s also better than the other single-photon sources that have been explored for quantum applications.”

Because of background counts in the detectors, even a perfect single-photon source will yield a nonzero measured value of $g^{(2)}(0)$. Dudin and Kuzmich calculate that their detector background rate gives a lower bound for $g^{(2)}(0)$ of 0.025, compared with 0.040, the best value they measured. The researchers are working on increasing the probability of single-photon events, which would lower $g^{(2)}(0)$ further, even with the same detector background rate.

Beyond its usefulness as a single-photon source, Dudin and Kuzmich’s setup may find use in implementing photon–photon quantum gates. Photons are excellent carriers of quantum information, but their reluctance to interact with each other limits their applicability in processing that information. But if a photon could be stored as a Rydberg excitation, made to interact with other Rydberg excitations, and retrieved as a photon, that could overcome the difficulty.

Johanna Miller

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Graphene photodetectors get gain

By spraying quantum dots onto a graphene flake in a circuit, researchers have produced a phototransistor a billion times more sensitive than any prior graphene-based device.

Graphene makes for a nearly ideal photodetector: It absorbs light over a broad range of wavelengths—from the UV to the far-IR—and then ballistically conducts the

photoexcited electrons, even at room temperature. But as a single monolayer of atoms, graphene can only absorb 2.3% of incident light.

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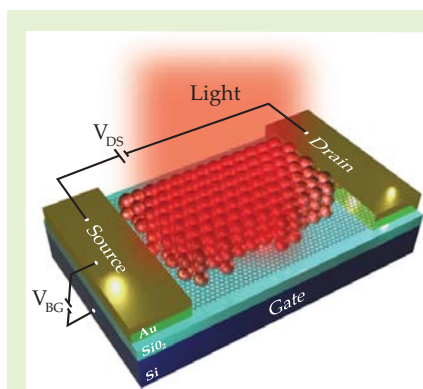
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and colleagues demonstrated an ultrafast graphene photodetector three years ago,¹ his group and others have been developing strategies to ameliorate the limited absorption. One can, for instance, place graphene in an optical cavity to repeatedly pass 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.

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

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.)

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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.