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'Egg carton' quantum dot array could lead to ultralow power devices

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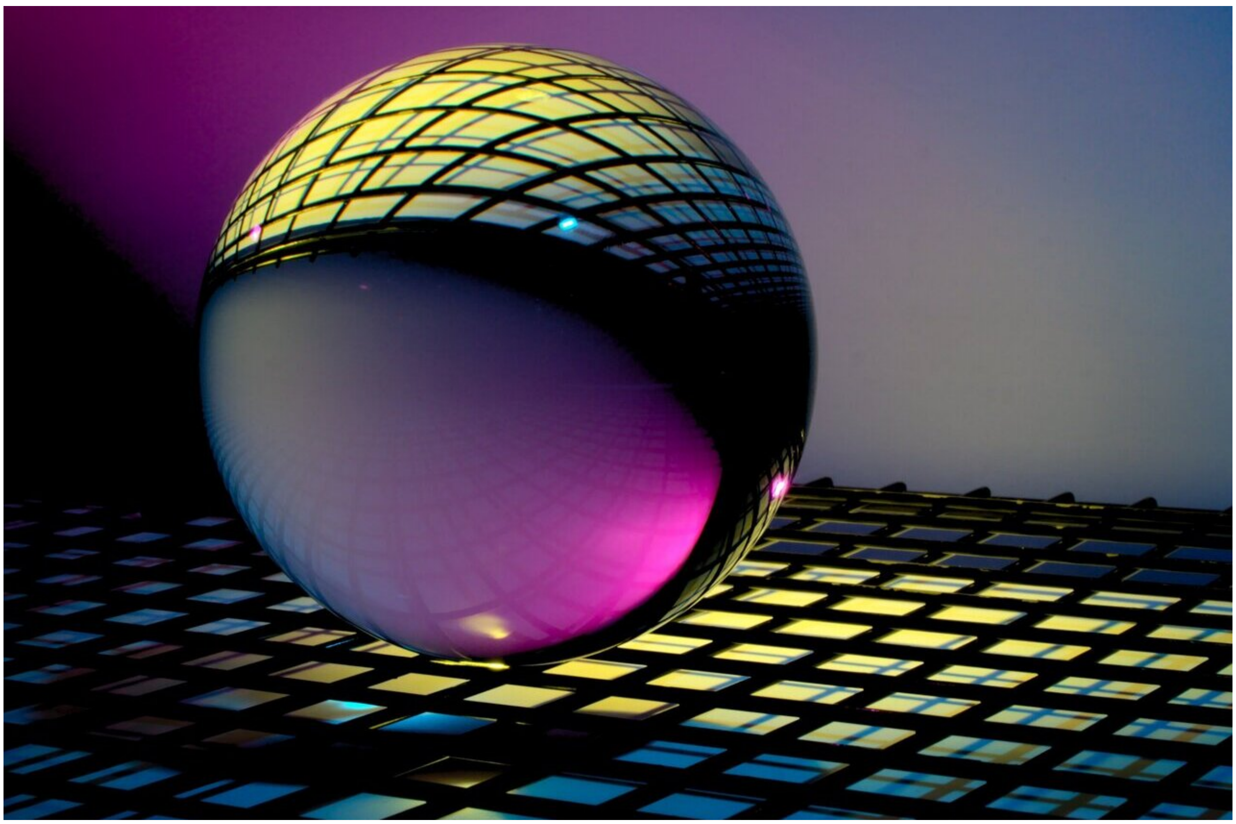

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A new path toward sending and receiving information with single photons of light has been discovered by an international team of researchers led by the University of Michigan.

Their experiment demonstrated the possibility of using an effect known as nonlinearity to modify and detect extremely weak light signals, taking advantage of distinct changes to a quantum system to advance next generation computing.

Today, as silicon-electronics-based information technology becomes increasingly throttled by heating and energy consumption, nonlinear optics is under intense investigation as a potential solution. The quantum egg carton captures and releases photons, supporting 'excited' quantum states while it possesses the extra energy. As the energy in the system rises, it takes a bigger jump in energy to get to that next excited state—that's the nonlinearity.

"Researchers have wondered whether detectable nonlinear effects can be sustained at extremely low power levels—down to individual photons. This would bring us to the fundamental lower limit of power consumption in information processing," said Hui Deng, professor of physics and senior author of the paper in *Nature*.

"We demonstrated a new type of hybrid state to bring us to that regime, linking light and matter through an array of quantum dots," she added.

The physicists and engineers used a new kind of semiconductor to create quantum dots arranged like an egg carton. Quantum dots are essentially tiny structures that can isolate and confine individual quantum particles, such as electrons and other, stranger things. These dots are the pockets in the egg carton. In this case, they confine excitons, quasi-particles made up of an electron and a 'hole.' A hole appears when an electron in a semiconductor is kicked into a higher energy band, leaving a positive charge behind in its usual spot. If the hole shadows the electron in its parallel energy band, the two are considered as a single entity, an exciton
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In conventional devices—with little to no nonlinearity—the excitons roam freely and scarcely meet with each other. These materials can contain many identical excitons at the same time without researchers noticing any change to the material properties.

However, if the exciton is confined to a quantum dot, it becomes impossible to put in a second identical exciton in the same pocket. You'll need an exciton with a higher energy if you want to get another one in there, which means you'll need a higher energy photon to make it. This is known as quantum blockade, and it's the cause of the nonlinearity.

But typical quantum dots are only a few atoms across—they aren't on a usable scale. As a solution, Deng's team created an array of quantum dots that contribute to the nonlinearity all at once.

The team produced this egg carton energy landscape with two flakes of semiconductor, which are considered two-dimensional materials because they are made of a single molecular layer, just a few atoms thick. 2-D semiconductors have quantum properties that are very different from larger chunks. One flake was tungsten disulfide and the other was molybdenum diselenide. Laid with an angle of about 56.5 degrees between their atomic lattices, the two intertwined electronic structures created a larger electronic lattice, with pockets about 10 atoms across.

In order for the array of quantum dots inside the 2-D semiconductor to be controlled as a group with light, the team built a resonator by making one mirror at the bottom, laying the semiconductor on top of it, and then depositing a second mirror on top of the semiconductor.

"You need to control the thickness very tightly so that the semiconductor is at the maximum of the optical field," said Zhang Long, a postdoctoral research fellow in the Deng lab and first author on the paper.

With the quantum egg carton embedded in the mirrored "cavity" that enabled red laser light to resonate, the team observed the formation of another quantum state, called a polariton. Polaritons are a hybrid of the excitons and the light in the cavity. This confirmed all the quantum dots interact with light in concert. In this system, Deng's team showed that putting a few excitons into the carton led to a measurable change of the polariton's energy—demonstrating nonlinearity and showing that quantum blockade was occurring.

"Engineers can use that nonlinearity to discern energy deposited into the system, potentially down to that of a single photon, which makes the system promising as an ultra-low energy switch," Deng said.

Switches are among the devices needed to achieve ultralow power computing, and they can be built into more complex gates.

"Professor Deng's research describes how polariton nonlinearities can be tailored to consume less energy," said Michael Gerhold, program manager at the Army Research Office, an element of the U.S. Army Combat Capabilities Development Command's Army Research Laboratory. "Control of polaritons is aimed at future integrated photonics used for ultra-low energy computing and information processing that could be used for neuromorphic processing for vision systems, natural language processing or autonomous robots."

The quantum blockade also means a similar system could possibly be used for qubits, the building blocks for quantum information processing. One forward path is figuring out how to address each quantum dot in the array as an individual qubit. Another way would be to achieve polariton blockade, similar to the exciton blockade seen here. In this version, the array of excitons, resonating in time with the light wave, would be the qubit.

Used in these ways, the new 2-D semiconductors have potential for bringing quantum devices up to room temperature, rather than the extreme cold of liquid nitrogen or liquid helium.

"We are coming to the end of Moore's Law," said Steve Forrest, the Peter A. Franken Distinguished University Professor of Electrical Engineering and co-author of the paper, referring to the trend of the density of transistors on a chip doubling every two years. "Two dimensional materials have many exciting electronic and optical properties that may, in fact, lead us to that land beyond silicon."

More information: Long Zhang et al. Van der Waals heterostructure polaritons with moiré-induced nonlinearity, *Nature* (2021). DOI: 10.1038/s41586-021-03228-5

Provided by University of Michigan

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