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Towards a global quantum network: Photoelectron trapping in double quantum dots

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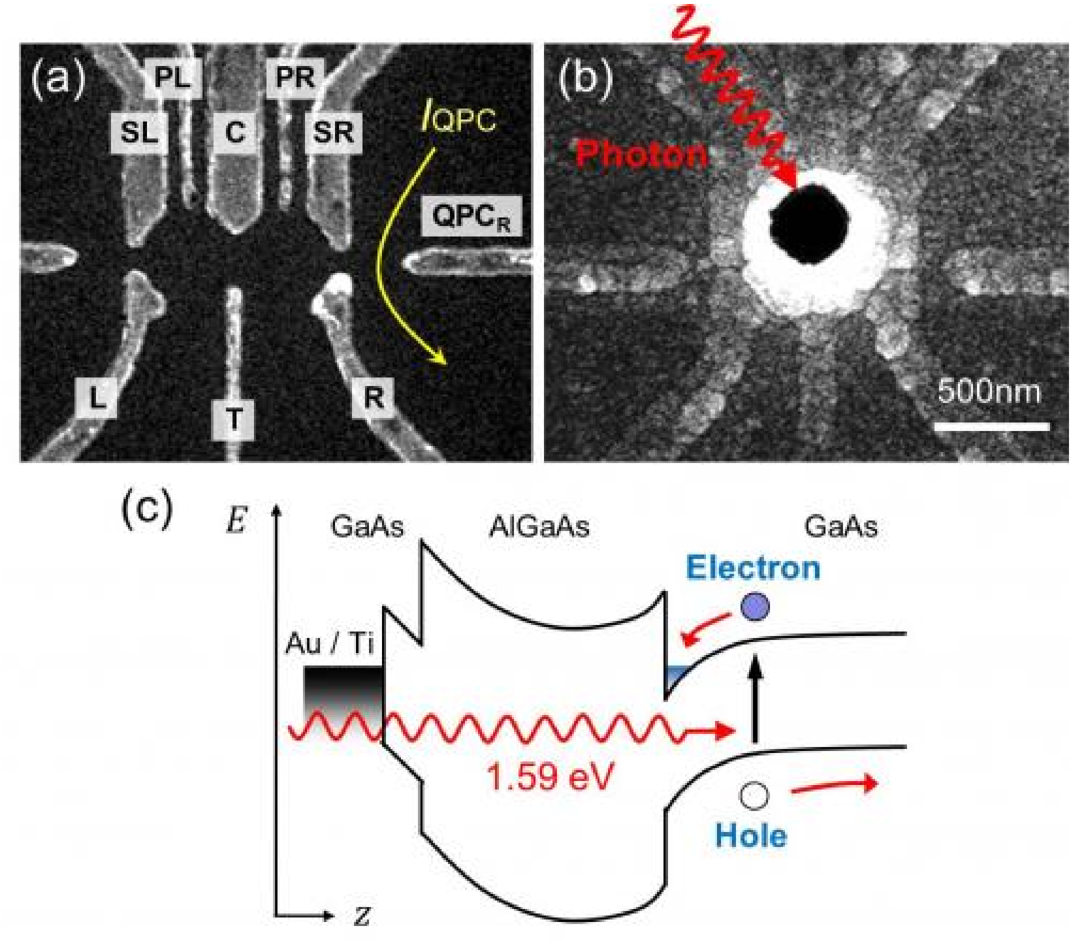

(color online). (a) A scanning electron micrograph of the typical lateral DQD device. The surface gates for dot formation have Tið10 nmÞ=Auð20 nmÞ metal thickness. A 60 nm thick Al2O3 insulating layer was formed on top of them by atomic layer deposition. (b) A Tið30 nmÞ=Auð220 nmÞ mask was fabricated on the surface above the DQD with an aperture of 400 nm diameter. (c) Band profile of the HEMT structure. The excitation laser energy is tuned just above the GaAs band gap. The excited electron-hole pair is separated due to the intrinsic electric field. Copyright © doi:10.1103/PhysRevLett.110.266803

(Phys.org) —While the journey from today's fledgling quantum computers to a global quantum information network may seem daunting, researchers are continually, and at an accelerating pace, making progress towards that goal. One key element essential to that progress is the transfer of quantum information between single photons and solid-state quanta – and the properties of semiconductor quantum dots (QDs) make them excellent candidates for photon-electron quantum coupling. One historical stumbling block has been that although quantum circuits require nondestructive transfer between separate dots, using single QDs usually fails due to destructive transfer in which photoelectrons are immediately lost upon measurement.

Recently, however, scientists at The University of Tokyo, Princeton University, Ruhr-Universität Bochum, and RIKEN found that nondestructive measurement is feasible using gallium arsenide double quantum dots (DQDs), thereby taking a significant step towards long distance entanglement distribution. Moreover, the importance of using a lateral dot is that these have a possibility to store and manipulate the photoelectrons – and while previous studies show detection of photocurrents or photoelectron signals, the scientists state that to their knowledge, none of them performed experiments demonstrating the possibility of further photoelectron storage or manipulation. Lastly, although the researchers have not yet demonstrated the spin manipulation of photoelectrons, their double dot structure shows repetitive tunneling of single photoelectrons, and so satisfies the photoelectron spin manipulation condition.

Researcher Takafumi Fujita discussed the research he, Prof. Seigo Tarucha, and their colleagues conducted with *Phys.org*. "The main challenge in demonstrating the trapping of single photons and interdot tunneling of the photogenerated electrons in a nondestructive manner using double quantum dots was to stabilize our quantum dot while performing single-shot single photon detection experiments," Fujita tells *Phys.org*. "Conventional lateral quantum dot devices can change their condition upon irradiation. We had to fine-tune and maintain the resonant interdot tunneling condition while performing irradiation experiments. The photon responses do not recover immediately so repetition of the irradiation sequence also had to be tuned to wait for photoconductivity to relax."

Regarding the use of resonant tunneling, Fujita explains, the idea of using a double dot was to use spin blockade, but the researchers also had to clearly distinguish photoelectron trapping signals from the noise. Rather than using a single-step signal – which can be difficult to distinguish in photon irradiation measurements – they decided to use iterative bi-stable charge tunneling signals in the double dot to clearly discriminate single photoelectron trapping events from noise. "With iterative bi-stable charge tunneling to determine the number of trapped photoelectrons," Fujita adds, "we had to wait in order to be certain that there were no other electrons left in the dot. However, we found that the resonant interdot tunneling would give us an immediate response of the last remaining electron." In addition, says Fujita, to infer photoelectron spin states, the scientists thought that they needed a large number of data samples – but once again, interdot resonance proved to be an advantage.

To successfully address these challenges, Fujita explains, the scientists relied on a small number of key insights and innovations. "A significant innovation was to introduce an additional infrared laser beam so that persistent photoconductivity would be erased. This was an innovative scheme because it made it possible to continuously experiment with photon irradiation single-shot single photon detection and obtain series of data." Another technique, he continues, was to form different kinds of charge sensors to improve the signals in DC measurements.

Several other interesting results were achieved in this study, one being that the researchers' approach offers a novel method to study the multielectron dynamics which are strongly affected by the Coulomb interaction in a multidot system. "Photoexcitation can create multiple electrons within the pulse duration, and the excited spins depend thoroughly upon the incident polarization," Fujita points out. "This allows initialization of multiple spins and multiple coupled dot experiments."

The demonstrated results can also be regarded as excited state spectroscopy, in that they correspond to a spin excitation over the ground state of the dot, which is an excited state. "Excited states reflect the configuration of the quantum dot which could be modified by tuning the gate voltages," Fujita notes. "Using our scheme we can investigate energy and spin correlations of excited states using photoelectrons through interdot interactions."

The paper also reports that fast initialization of the excited states can be realized by controlling the incident photon number, energy, and polarization. "Photon number could be tuned with the laser power, energy with the wavelength, and spin polarization with the photon polarization," Fujita explains. "The photon configurations are tuned in the optics and excitation could be realized fast within the laser pulse width. If we compare this with electrical initialization by tunneling from the leads, the initialization time is limited by the tunneling rate and exact spins are currently difficult to inject."

Using the resonant interdot tunneling in the DQDs, the researchers' technique would also open a way to high fidelity photon counting. "Our technique to keep the photoelectrons from escaping is an advantage for counting multiple photoelectrons," Fujita says. "We've shown that tunneling rates could be properly tuned in a desired range. This enables us to tune the tunneling of each electron number to a good tunneling rate so that every electron tunneling could be resolved and give us a higher fidelity."

Fujita also comments on the relationship between their findings and the no-cloning theorem, which he points out holds that quantum communication becomes perfectly safe – but on the other hand, there's also no way to amplify a quantum state to extend the communication length. This therefore restricts the length of quantum information transfer with a single photon. "Quantum repeaters would shorten each photon propagation," Fujita notes, "thus making it possible to connect between more distant places – and we've demonstrated a scheme that brings us closer to the realization of a quantum repeater."

More specifically, in the current study a quantum repeater is shown as a solution for extending the quantum communication length. "We think our demonstrated nondestructive single-shot single photon detection in lateral quantum dots is a good candidate for one of the ingredients of this repeater," Fujita tells Phys.org. "In the future it could realize determination and storage of the arrived photons to immediately create entanglement at its convenience to raise the entanglement creation rate. Further integration of quantum operations in our quantum dot would possibly move the establishment of information network forward, and thereby impact the establishment of a global quantum information network."

"We've demonstrated the detection of photoelectron spin configuration using two electron spin correlation, namely the spin blockade, so next we'll detect single photoelectron spin by correctly initializing the prepared spin." Fujita adds. "Our next step is to combine our photoelectron spin detection scheme with heavy hole excitations to verify angular momentum transfer,"

In terms their continued research, Fujita says that the researchers would like to verify the angular momentum transfer to the electron spins. "This requires selective excitation of electron hole spin states, so a wavelength-tunable single shot irradiation setup is needed. Another development," he continues, "would be to increase the photon absorption rate at a scale that would permit realizing sufficient entanglement between photons and electron spins." The scientists are also thinking of embedding Bragg reflectors inside the wafer.

Over the next decade, Fujita continues, their research would lead to the entanglement between distant solid state qubits by trapping entangled photon pairs. "After the verification of coherent angular momentum transfer, experiments on trapping entangled photon pairs will be demonstrated to verify the entanglement between photons and electron spins. The advantage of our lateral quantum dot is that 2-spin qubit operations could be done," Fujita concludes. "This will be then demonstrated in two trapped photons to create entanglement between distant entangled photon pairs."

More information: Nondestructive Real-Time Measurement of Charge and Spin Dynamics of Photoelectrons in a Double Quantum Dot, *Physical Review Letters* 110, 266803 (2013), doi:10.1103/PhysRevLett.110.266803

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