FABRICATION OF INAS SINGLE ELECTRON TRANSISTORS AND TERAHERTZ EXCITATION

J. Olitsky[1,2]*, K. Hirakawa*[2]*, K. Shibata*[2]*, Y. Zhang*[2]

1. Department of Physics, Carnegie Mellon University
2. NanoJapan: International Research Experience for Undergraduates
3. Institute of Industrial Science, University of Tokyo

The goal of this experiment is to study the effects of irradiating an indium arsenide single electron transistor with terahertz frequency photons. The single electron transistors (SETs) are constructed using self-assembled InAs quantum dots (QDs) approximately 50nm in diameter. Titanium-gold nanowires are laid on top of the substrate, and electron beam lithography is used to create a nanogap in the wire approximately 30nm across. The conductive substrate is used as the gate. An SET occurs when a QD lies beneath the nanogap, close enough to each side to allow for a good tunneling current. As the 50nm quantum dots are relatively large, the apparatus is cooled in liquid helium in order to reduce the energy of the ambient temperature below the difference in energy levels on the QD, producing quantized effects. While in liquid helium, the gate and source-drain voltages applied to the SET are swept to produce a Coulomb diamond pattern. Good samples display sharp, symmetric diamond patterns. A long-term goal is to study the behavior of the samples under THz stimulation. In order to focus THz radiation on the sample, a hemispherical silicon lens will be placed on the back of the substrate. In preliminary testing, fine positioning of the sample at the focal point resulted in greatly increased effects at lower power output. It is hoped that it will be possible to create polar current flow using THz radiation to precisely control the potential well of the quantum dot such that electrons of a particular spin are able to pass through and the opposite polarity is not.

Contact: Jacob Olitsky ~ jolitsky@andrew.cmu.edu

InAs Quantum Dot Single Electron Transistors

J. Olitsky[1,2], K. Shibata[2], K. Hirakawa[2], Y. Zhang[2], N. Nagai[2]

1. NanoJapan program, Rice University
2. Institute of Industrial Science, University of Tokyo

Summary

Single Electron Transistors (SETs) are one of many attempts to replace conventional silicon based transistors. SETs operate on discrete quantities of electrons. By controlling the potential well of gate, current through the SET can be blocked or allowed via Coulomb blockade. The purpose of this experiment is to investigate some properties of quantum dot (QD) based SETs, with a goal of later studying the effects of photon assisted tunneling by THz excitation of the SETs.

The SETs used in this experiment are constructed using self-assembled InAs QDs approximately 50nm in diameter. Titanium-gold nanowires are laid on top of the substrate, and electron beam lithography is used to create a nanogap in the wire approximately 30nm across. The GaAs substrate is used as the gate. An SET occurs when a QD lies beneath the nanogap, allowing electrons to tunnel on and off the QD. The apparatus is cooled in liquid helium in order to reduce the energy of the ambient temperature below the difference in energy levels on the QD, producing quantized effects. While in liquid helium, the gate and source-drain voltages applied to the SET are swept to produce a Coulomb diamond pattern. Good samples display sharp, symmetric diamond patterns. A long-term goal is to study the behavior of the samples under THz stimulation.

Fabrication: Substrate & QDs

Each SET consists of a single InAs QD, approximately 50nm in diameter, sitting beneath a nanogap (approx. 30nm) in a titanium-gold wire. The InAs QDs are self-assembled by deposition onto a GaAs substrate. A gate is separated from the rest of the SET by an insulating later of AlGaAs.

The nanogap is surrounded by a larger bow-tie structure that acts as an antenna to focus THz radiation on the SET. While stimulating the SET with THz radiation was beyond the scope of this research project, such testing is planned to be performed on working samples in coming months.

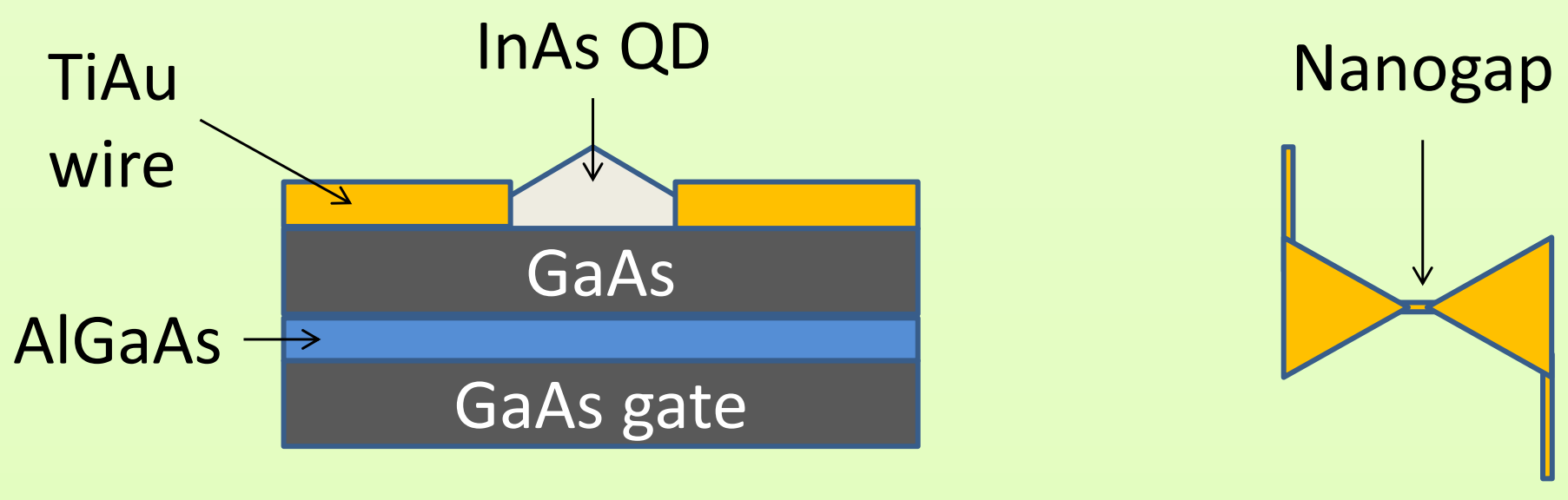

Figure 1. Side and top views of SET structures.
The left diagram shows the nanogap, QD, and substrate configuration used for the SET (not to scale). The whole substrate is about 500nm thick. Not pictured: a hemispherical Si lens on the bottom which will be used in the future to focus THz photons on the QD.
The diagram on the right shows the large bow-tie antenna structure, which is roughly 20µm across and surrounds the nanogap. This structure focuses THz radiation on the sample.

Fabrication: nanowires & gap

The nanowires used in the SET are placed by etching patterns into resist material using electron beam lithography (EBL), followed by depositing first titanium and then gold ions onto the surface of the substrate. Removing the resist leaves only the wires in etched-out areas. The nanogap is etched out by EBL. Finally, larger wires and contacts are placed on the substrate similarly to the smaller wires using photolithography.

Currently, the wires are placed unguided on the substrate, and SETs are successfully created when a QD happens to sit beneath a nanogap. The yield rate is approximately 1%. Research is currently underway by other groups to improve site-controlled deposition of InAs QDs, but that is beyond the scope of this research.

Quantum dot Behavior

The InAs quantum dot acts as an artificial atom. The quantum dot forms a potential well for electrons, with the differences between allowed energy states for the electrons depending on the size of the quantum dot. When immersed in liquid helium, electrons on the approximately 50nm diameter InAs quantum dots used in this experiment have gaps between energy states larger than the ambient thermal energy.

For typical operation, an electrical potential is created between the source and drain, and the gate voltage is used to manipulate the energy states of electrons on the QD, allowing or disallowing current to flow. Due to the small size of the QD, this effect takes place on the level of individual electrons, hence “single electron transistor”.

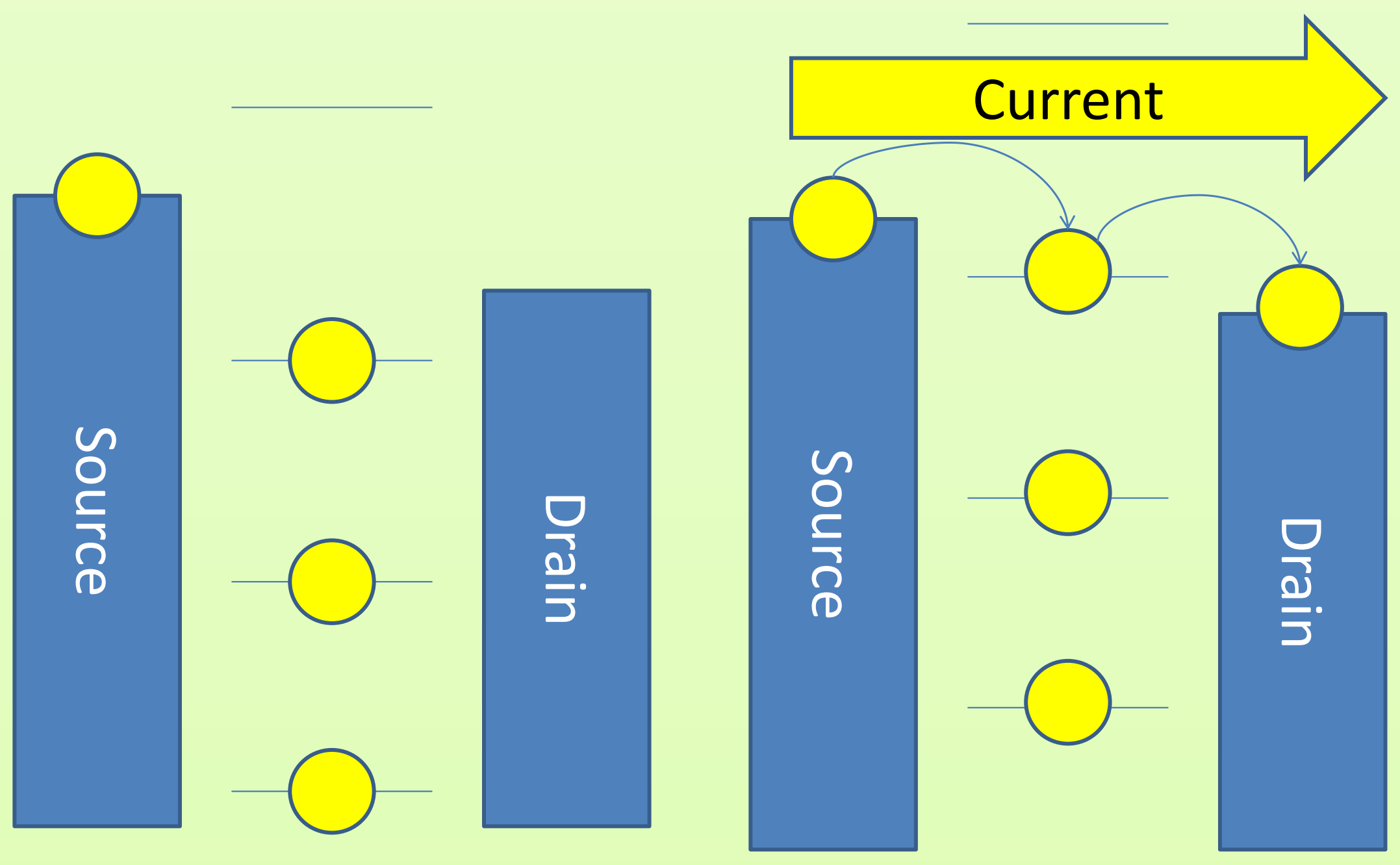

Figure 2. Energy diagrams showing QD behavior.
Lines represent energy states on the quantum dot, and circles represent electrons. On the left, there is no available state between the source and drain, so no current flows. On the right, an energy state between the source and drain energies allows electrons to “bounce” off of the quantum dot, and current flows.

SET Coulomb diamond

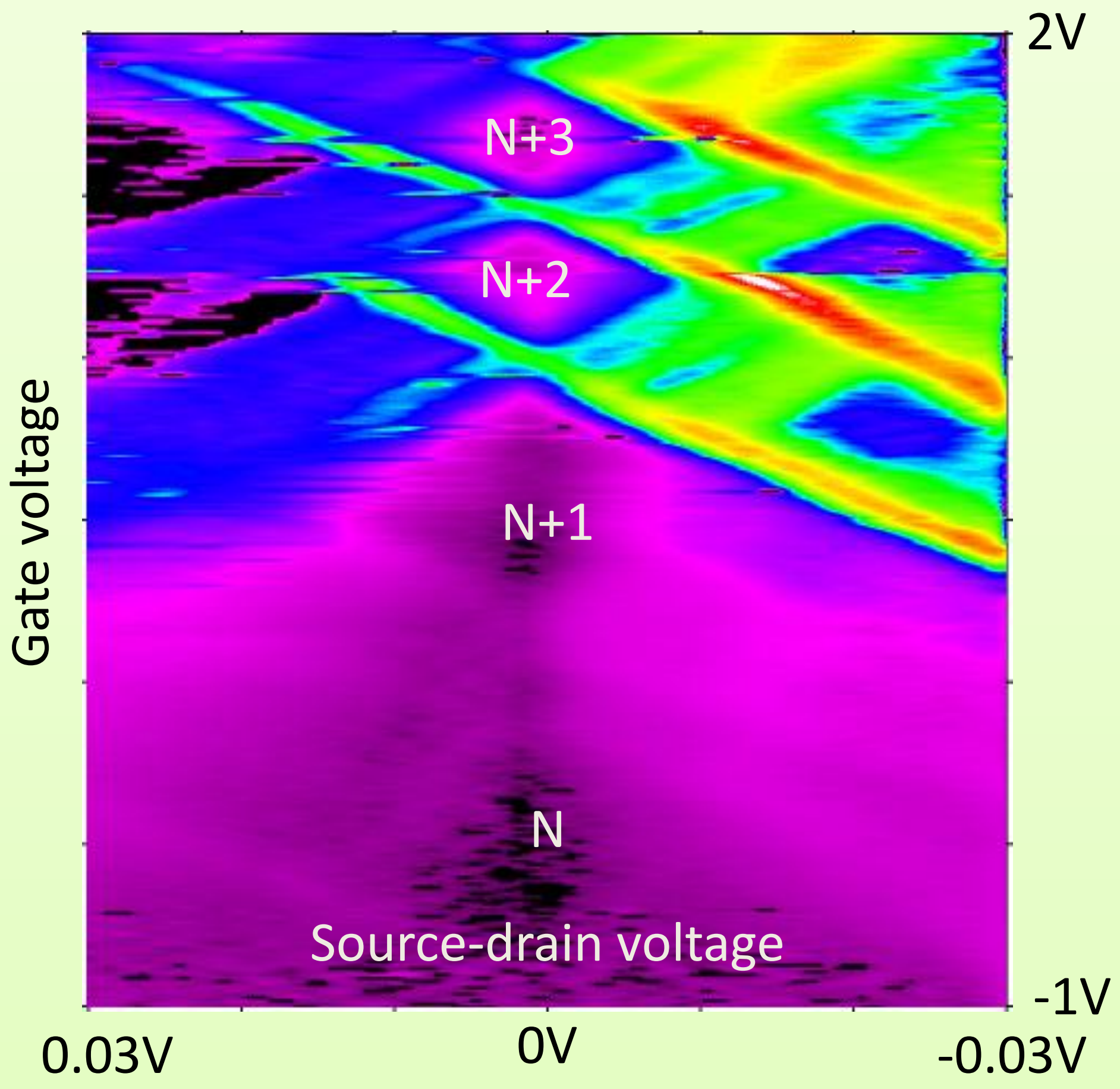

Figure 3. A Coulomb diamond diagram.
The pattern above is produced by sweeping the gate voltage and source-drain voltage of the SET. Black areas indicate no current, cool, dark areas indicate low current, and bright, warm areas indicate high current. Ideally, the pattern would be symmetrical with clear diamond patterns. Each diamond corresponds to a state with a specific number of excess electrons on the QD. With more ideal SETs, it is possible to determine exactly what number of electrons corresponds to each state.

Results

Unfortunately, I found no useable samples during this experiment, likely due to a combination of the relatively short research time period and low sample yield rate. However, working InAs based SETs have been found by other researchers, such as the one borrowed to produce the Coulomb diagram seen to the left.

Future Research

The longer-term goal of the research- outside the scope of this particular project- is to investigate the behavior of SETs under THz radiation. One expected effect- observed by preliminary experiments- is photon assisted tunneling (PAT), where THz frequency photons excites an electron on the QD into a higher energy state, whence the electron tunnels onto the drain, allowing a new electron to tunnel from the source to the QD. This has the effect of circumventing the Coulomb blockade and allowing current to flow when it is normally forbidden. It is also hoped that precision control of the source, gate, and drain voltages will allow for the creation of single-spin electron pumps, which would operate by taking advantage of degenerate states between spin up and spin down electrons, so that only one polarity has an available energy state to tunnel source to QD to drain.

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