Applications of Quantum Dots in Digital Logic

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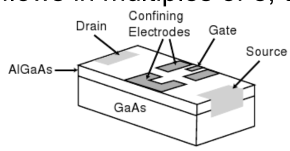
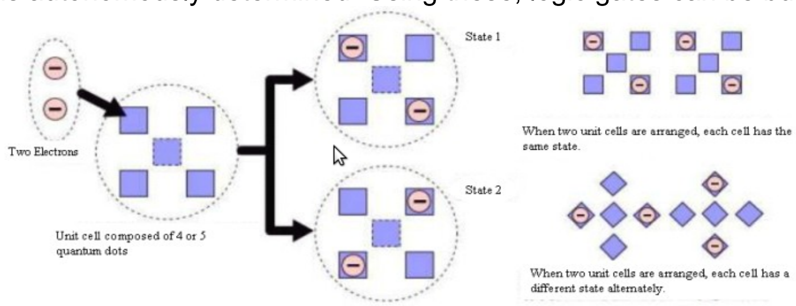
Introduction: A quantum dot is a semiconductor whose excitons are confined in all three spatial dimensions. As a result, they have properties that are between those of bulk semiconductors, and those of discrete molecules. Also, due to confinement in all 3 dimensions, they also differ from Quantum Wires and Quantum Wells in certain properties. The ability to tune the size of quantum dots is advantageous for many applications. For instance, larger quantum dots have a greater spectrum-shift towards red compared to smaller dots, and exhibit less pronounced quantum properties. Conversely, the smaller particles allow one to take advantage of more subtle quantum effects. Hence quantum dots find applications in various fields like Biology, Optics, Quantum Computing and Digital Electronics. Let us look at some of these applications in the field of Digital Electronics.

Single electron transistor: A Single Electron Transistor is a device based on the Coulomb-blockade effect. It uses controlled electron tunneling to amplify current. An SET is made from two tunnel junctions that share a common electrode. A tunnel junction consists of two pieces of metal separated by a very thin (~1 nm) insulator. The only way for electrons in one of the metal electrodes to travel to the other electrode is to tunnel through the insulator. Since tunneling is a discrete process, the electric charge that flows through the tunnel junction flows in multiples of e, the charge of a single electron.



Single Electron Transistors have been built using Quantum Dots (1). The room temperature operation of a single-electron quantum-dot transistor switch has been demonstrated where the dot is placed inside the channel to switch the current. The device is a basically a MOSFET, but its channel consists of a silicon dot connected to two narrow wires through two constrictions. During the process of fabrication, several Quantum Dots may be formed inside the channel, the smallest dot determines the behaviour of the device. The smallest dot has the highest charging energy, hence the highest threshold. It is the last one to be turned on, so that it dominates the behavior of the entire transport. The entire assembly thus acts as a transistor switch.

Logic Gates and Quantum Computers Using Quantum Dots: As Moore's law (the number of transistors that can be placed inexpensively on an integrated circuit doubles every two years) approaches its limits due to the Quantum effects as transistors get smaller, newer technologies must be developed to counter it. One of the areas in which such a breakthrough is being made is the area of **Quantum Computing**, which begins with designing of logic gates using Quantum Dots.
In an oversimplified model(3), a cell that consists of four or five quantum dots arranged in a square pattern is considered. When two electrons are injected into a dot, the electrons repel each other because of their negative electric charge (Coulomb repulsion) and occupy dots in corners opposite to each other (antipodal dots). When two unit cells, each comprised of four or five quantum dots, are arranged adjacent to each other, electrons move among the dots in each unit cell and the state of each dot in the two cells is autonomously determined. Using these, logic gates can be built.



Some recently published papers(2) have demonstrated a simple quantum logic gate with a single qubit and a coupled dynamic system of two linked qubits.

A team of engineers and physicists from Stanford University and the University of California - Santa Barbara reported on the formation of a simple "logic gate" based on a single quantum dot. Their device was constructed of an Indium Arsenide quantum dot nested in a small hole in a Gallium Arsenide photonic crystal. This set up allowed photons to be trapped by the photonic crystal as they interacted with the quantum dot. Their device allowed two photons to interact within this dot and hole combination. A pair of beams, named "signal" and "control," could be fired into the cavity and, depending on the difference between the two beams, a distinct beam of photons would emerge. The system was designed so that, if a photon of only the "signal" beam hit the cavity, it would emerge unchanged. If the "control" beam was present, then the amount of time the photons spent in the cavity would change and the photons emitted would have a measurable phase shift. Hence the assembly acts somewhat like a logic circuit (AB'+A'B). Different logic components can be made using similar methods.

Another study, carried out at the Institute of Quantum Electronics at (ETH)–Zürich and the University of Cambridge, describes a setup that uses a pair of quantum dots to achieve a phase shift gate. Here, the researchers exploit what is known as conditional quantum dynamics, where the state of one quantum systems controls the results of measurements performed on a second. Their experimental device was based on a stack of quantum dots embedded in a semiconducting material. They demonstrated that the state of one dot could be controlled by the presence or absence of optical excitation in an adjacent quantum dot. The interaction between the two dots relies on quantum tunneling and was shown to be tunable by changing the voltage difference across the entire stack. This optically-controlled phase gate can be used in a potential quantum computer. The logic is not strictly digital, but in fact involves Qubits.

A Qubit is a unit of quantum information. It is the quantum analogue of the classical bit. It is described by a state vector in a two-level quantum-mechanical system, which is formally equivalent to a two-dimensional vector space over the complex numbers. A qubit has some similarities to a classical bit, but is overall very different. Like a bit, a qubit can have two possible values—normally a 0 or a 1. The difference is that whereas a bit must be either 0 or 1, a qubit can be 0, 1, or a superposition of both. Quantum Dots can be used for the physical representation of Quibits. A singly charged quantum dot pair is used. Charge present on one of the dots represents a '0' and charge on the other dot represents a '1'. Alternatively, a single Quantum Dot can be used to represent a Qubit, in which case the spin of the Quantum Dot becomes the carrier of information. An up spin represents a '1' and a down spin represents a '0'.

A note on Quantum Computers and Algorithms: If Quantum Computers are built using logic gates built out of Quantum Dots, theoretically, the order of complexity of several algorithms changes due to the change in the hardware. For example, factorization of numbers, which is proved to be unsolvable in less than exponential time in conventional computers, becomes a polynomial time operation. If this happens, all encryption techniques of the world will become useless, since most of them assume factorization to be a difficult operation to perform.

Quantum Dot Display: Another application of Quantum Dots, which is not strictly Digital Electronics, but is still important all the same is in Quantum Dot Displays, which may serve as an alternative to conventional LEDs. This display technology differs from cathode ray tube units, liquid crystal displays, but it is similar to organic light-emitting diode (OLED) displays, in that light is supplied on demand, which enables new, more efficient displays, which enables mobile devices with longer battery lives. Surface-emitting, spin-polarized light-emitting diodes with a Mn-doped InAs dilute magnetic quantum dot spin-injector and contact region have been fabricated and characterized(4). However these do not yet work for room temperature. Sub Zero temperatures (<180K) are required. If successfully implemented at room temperature, these can act as a replacement to conventional LEDs.

References:

1. Silicon single-electron quantum-dot transistor switch operating at room temperature.
2. New quantum dot logic gates a step towards quantum computers
3. Do you know what quantum dots are?
4. Spin-Polarized Light-Emitting Diodes with Mn-Doped InAs Quantum Dot Nanomagnets as a Spin Aligner