A Brief Survey of the Field of Quantum Dots

Jeremy Hance

The purpose of this paper is to provide a high level introduction to the field of Quantum Dots. Four brief papers follow, each covering a single subfield of Quantum Dot research and application. On Thursday, May 15th, 2008, each author shall make a presentation of roughly ten minutes to the full body of our organization. After these presentations, all authors shall participate in a panel discussion defending and discussing their specific field of research. At the close of the evening, the full organization shall select one of the presenters upon which to bestow a research grant to continue their work.

In traditional semiconductors, excitons are only constrained by their distance. An exciton is the binding between an electron in its excited state and the imaginary “hole” of opposite charge left when the electron transitioned into its excited state. If further constraints are placed upon the exciton, the properties of the semiconductor can be changed. Constraining the excitons to two dimensions produces “Quantum Wells”, which are used in diode lasers, certain transistors, and infrared imaging. Further constraining the excitons to one dimension results in “Quantum Wires”, such as carbon nanotubes.

When the excitons are bound in all three dimensions, the resulting structure is the “Quantum Dot”. Quantum dots (also commonly referred to as “artificial atoms”) behave much like very large atoms. Electrons of an atom become excited, and move into higher but less stable levels, when energy is applied to the atom. Upon the electron’s return to the lower, but more stable state, the extra energy is emitted as electromagnetic radiation at a corresponding frequency. Quantum dots display the same behavior, where the emitted EM radiation is typically in the spectrum of visible light, and the frequency (color) is directly related to the size of the quantum dot, irrespective of the material used to construct the structure. Long wavelengths (low frequency/red) are produced from large quantum dots, and small quantum dots result in small wavelengths (high frequency/blue).

There are multiple methods used to produce Quantum Dots, but only two are currently considered as viable for commercial applications: “Colloidal Synthesis” and “Self-Assembly”. Self-Assembly is a process where a thin film of a semiconductor is grown on a material whose lattice structure differs slightly in size from the semiconductor. This size difference results in stresses on the growing film, and that stress is relieved by the formation of quantum dots at the points of stress. In Colloidal Synthesis, Quantum Dots are grown through traditional chemical processes.

Both manufacture methods have their benefits and drawbacks. Colloidal Synthesis is less expensive, and can be more easily scaled up to larger amounts of quantum dots. Most quantum dots used for research in biology and medicine are of the Colloidal Synthesis variety. However, currently, there is no known way to attach electronics to quantum dots grown through Colloidal Synthesis, so even though it is more expensive, and less productive, most quantum dots used in the various electronics fields are produced through Self-Assembly.

Several companies are currently producing quantum dots commercially, but not yet in the kinds of quantities required for large scale commercial applications. Quantum dots are being researched and used in many fields including: quantum computers, transistors, solar power, lighting, LEDs, LCDs, lasers, telecommunications, biology and medicine.

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Semiconductor Quantum Dot based Quantum Computer
Chun Ho Cheung

Comparing to other types of quantum computers, e.g. Ion-trap, Cavity QED, the experimental progress of solid state schemes, including semiconductor quantum dots based quantum computer, have been slow. However, due to the scalability of semiconductor fabrication which offers the potential of building large-scale quantum computer, there are many proposals for implementing quantum computer based on quantum dots. Broadly speaking, they can be categorized into charged-based and spin-based [1]. This document will provide a high-level overview of an example from each category.

An example of Charged-based quantum dot quantum computer

One of the charged-based quantum dot quantum computer [3] uses a double quantum-dot to represent a single qubit (Figure 1).

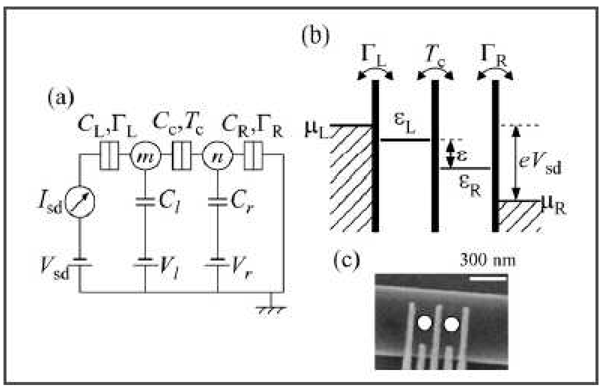

Figure 1 - Single qubit charge-based quantum dot gate

Initially, when the gate coupling T_c, controlled by changing the voltage at T_c, is low, the quantum dot pair is not in superposition state. The voltage between the quantum dot pair, V_{sd}, is used to initialize the qubit. When the gate coupling is changed such that ε, the electrochemical potential difference, is near zero and V_{sd} is zero, an excess electron in the quantum dot pair can occupy in superposition of the left dot and the right dot. The excess electron can't leave the quantum dot pair because Coulomb blockage prevents current from flowing. When T_c is changed back to the initial value, we can determine the quantum state by measure the current I_{sd}, – A current can be detected if and only if the electron exists on the right dot. Arbitrary unitary operators are performed by sending through the gate a rectangle pulse of variable width and a tipping pulse of variable peak voltage which overlaps with a rectangle pulse (Figure 2). To implement a two qubit control NOT gate, the single qubit can be arranged in the configuration in (Figure 3). Q_1 is the control gate and Q_2 is the target gate. Q_1 performs identity operator. The quantum state of Q_1 modify the gate coupling T_c of Q_2, such that Q_2 performs identity operator if the left dot of Q_1 is occupied and NOT operator if the right dot of Q_1 is occupied.

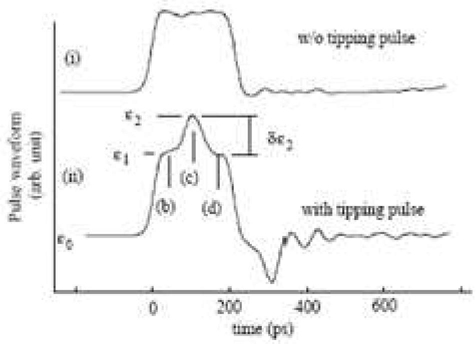

Figure 2 – Pulses for performing 4rbitrary unitary operators for a charged-based quantum dot computer

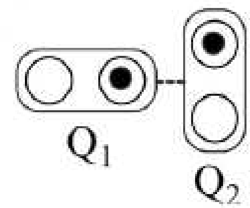

Figure 3 – 2-qubit charged based quantum dot control NOT gate

An example of Spin-based quantum dot quantum computer

One of the spin-based quantum dot quantum computer [4] uses the spin state of an electron in a quantum dot to represent a qubit.

The quantum state of electron in each quantum dot is initialized by a strong magnetic field, which can be produced by a current wire. Magnetic field of varying strength is used to implement the single-spin rotations for arbitrary single qubit unitary operators. The 2 qubit control NOT gate can be implemented by a few rotation operators on two nearby qubit and square-root of the 2-qubit swap operator. The 2-qubit swap operator is implemented based on the coupling due to Coulomb interaction and the Pauli exclusion principle. Measurement of qubit can be done using a switchable "spin-filter" tunnel barrier which allows either spin-up or spin-down electrons to tunnel, but not both, to another quantum dot, in which the present of electron triggers a voltage reading in an electrometer.

Discussions

Quantum dot quantum computers are mostly still in theoretical and small scale experimental stage. One main challenge is maintaining coherency of qubit from disturbance in the operating environment. Many of the proposals, including the ones above, require operating in very low temperature (less than 100mK). Disturbance can also come from surrounding neutrons and nearby gates [1].

References

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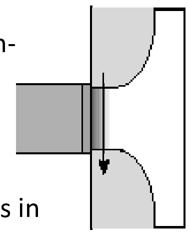
2. Michael A. Nielsen et al Quantum Computation and Quantum Information. *Cambridge*, 279-283(2001)
3. Toshimasa Fujisawa *et al* Time-dependent single-electron transport through quantum dots. *Rep. Prog. Phys.* **69** 759-796 (2006)
4. Guido Burkard *et al Fortschr.* Spintronics and Quantum Dots for Quantum Computing and Quantum Communication *Phys*. **48**, 965-986 (2000)

Single Electron Transistor

Amit Kumar Ghosh

Classical MOSFET:

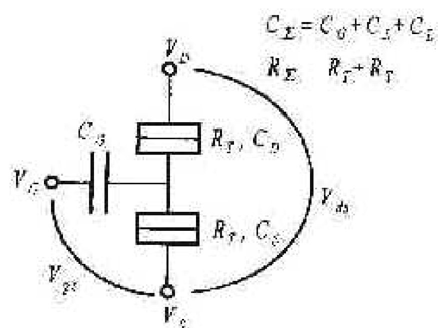


The functioning MOSFETs are is very simple. For n-channel MOS, source and drain are n-type semiconductors. And channel is not doped. Now if you apply a +ve voltage on gate electrons will be induced on the channel creating a continuous conducting path and the transistor will be switched on. This is completely classical and nothing quantum about it. But when transistor size becomes very small and say couple of atoms in size, quantum effect starts exhibiting.

Theory behind SET:

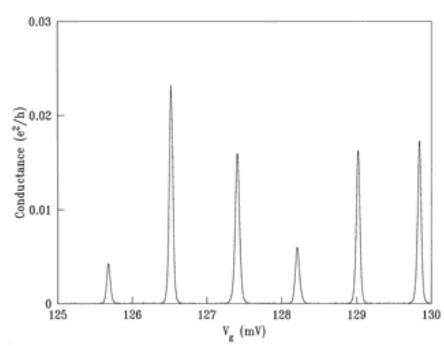
In such a small dimension the gate capacitance is so small that addition of a single electron can increase noticeable energy (i.e. $\frac{e^2}{2C}$). Now, a tunneling junction is formed when a very thin (few nm) insulator is sandwiched between 2 metals. Tunneling junctions exhibits a quantum effect where electron not having sufficient energy, can cross the junction by tunneling. Tunneling of electrons can cause voltage build up at the tunnel junction which can prohibit further tunneling. This phenomenon is called Coulomb blockade.

SET and its working principle:



If we connect 2 tunnel junctions with a conductor Coulomb island is formed in between. We can change the energy of Coulomb island by applying voltage to the gate terminal which connected to the island through insulator layer (i.e., capacitively coupled). And we get what is called a Single Electron Transistor. Why? That I am explaining below.

If we apply a voltage between drain and source of the SET, coulomb blockade will prevent current to flow. Now if we apply some voltage to gate so that a single electron will flow into the gate capacitor and that will increase the energy of the coulomb island by $\frac{e^2}{2C}$ which is sufficient to overcome Coulomb blockade, hence current will start flowing. But after some time again Coulomb blockade will appear and current will stop flowing. Again if we apply some more voltage and one more electron can flow again current will be able to flow. Hence conductance of the SET will vary periodically with the applied gate voltage.



Note that the Coulomb island is nothing but a Quantum Dot where electrons are confined in the 3D space by insulators. And Pauli's exclusion principle says that's in such system each electron should have different energy levels. Hence with increase of $\frac{e^2}{2C}$ energy the island can accommodate only finite amount of more electrons. This can give an alternate explanation of the behavior of SET.

Applications:

- High density Single electron Memory: With SET we can achieve a density of $1\frac{Gb}{cm^2}$
- High sensitive electrometers: With 1 electron flowing in the gate the current through the Coulomb island can be 10^9 e/sec. This sensitivity is many orders of magnitude higher than traditional electrometers.
- If a SET is attacked black body radiation, the photon-aided tunneling will affect the charge transfer of the system. The sensitivity of this equipment is about 100 times higher than the current best thermal radiation detector.

Drawbacks:

Main drawback of the SET as of now is fabrication difficulty, thermal stability, and connecting SET with outside environment.

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Application of Quantum Dot in Solar Power -- Roy Chiu

Quantum dot (also named as nanocrystal solar cell) is considered a very good candidate to become a viable solution for being used as photovoltaic cell to produce electricity at competitive cost.

Commercial production of solar cells that convert solar power to electricity was long available. However, the cost associated to making it is too expensive that it is still uneconomical to become a major source to produce electricity. Two major factors contribute to the highly cost are production processes and conversion-yield efficiency.

First generation of solar cell was made of silicon wafer. Since silicon is not sensitive to absorbing light, solar cell has to be made very thick. This requires a lot more materials to make. Improvement was made in the process in the second generation to produce much thinner film and reduce cost of material. However, the making of the solar cell with silicon depends on expensive high-vacuum processes. Also, the yield efficiency is still low. In today's solar cell technology, 20% is about the amount of efficiency it can yield.

Scientists are looking into a number of areas to improve the efficiency and reduce the amount of material of making solar cell. By studying of material at nano scale, more characteristics in materials are found, and that can be applied to making more efficient and cheaper solar cells.

Silicon is a popular material and is in high demand because of its semiconducting characteristic. This characteristic is critical in solar cell. Researcher has found that there are more materials that have semiconducting behavior and can yield better results than silicon.

Energy is absorbed when exciting electrons to higher energy levels. Energy is released when electrons drop from a higher energy level to a lower level. The difference between two energy levels is the bandgap. By constructing quantum dots that have bandgap energy closer to the spectrum of sunlight, more energy can be converted into electricity. Furthermore, quantum dots with multiple bandgaps within the sunlight spectrum waste less energy because more wavelengths can be absorbed by different bandgaps.

When formed in quantum dots, materials such as lead selenide is found to produce as many as 7 electrons from one high photon of sunlight. That is 7 times of conventional solar cell. It is believed that efficiency of solar cell can be improved to as much as 60%.

By applying manufacturing process of "spinning-coating" or printing, quantum dots can be uniformly applied onto a substrate at a very thin layer. The thin layer gives great flexibility in production and requires less material. Both reduce production cost dramatically.

Although there are many promising results in quantum dots, there are still a lot of obstacles to cross in technical level and manufacturing steps. Current technology of solar cell can generate electricity at about 3 times of the cost compared to other energy sources. In order to use solar cells as a true alternative for generating electricity, those obstacles have to be overcome.

Quantum Dot Applications in Biology and Medicine

Mark McCasey

Due to their high quantum yield and relative stability, quantum dots have practical applications wherever a controlled stream of photons is desired. In the field of biology and medicine two current practical examples of their application can be found in medical imaging and quantum dot lasers.

Medical Imaging

In modern biological analysis, it is common to use various dyes and markers to prepare cell specimens. These markers are complex molecules that are designed to attach themselves to a particular target cellular structure. The marker molecules also carry a component called a fluorophore. Fluorophores absorb energy of a specific wavelength and re-emit energy at a different wavelength. In other words, fluorophores will fluoresce (glow) when exposed to a particular wavelength of light. Fluoprophore-based markers provide researchers with the ability to "light-up" samples for better contrast, or to easily identify the location of targeted cellular structures that are difficult to resolve. These markers can also be used to track cellular movements, such as the rate at which a particular enzyme is penetrating the cellular wall.

Unfortunately, all dyes and markers share a common problem called photodestruction or photobleaching. Photobleaching occurs when a fluorophore permanently loses the ability to fluoresce due to photon-induced chemical damage and covalent modification. Depending upon the molecular structure of the fluorophore and the intensity of the exposure, noticeable photobleaching can occur within seconds. This makes tracking cellular behavior over extended periods of time difficult if not impossible to achieve.

Quantum dots go a long way toward solving the photobleaching problem. Because their excitons are constrained in three dimensions, a fluorophore constrained within a quantum dot does not readily interact with its environment even when in an excited state. This gives quantum dots a great degree of photostability, and thus vastly improved observable lifetimes compared to traditional organic markers. For example, quantum dots have been observed in the lymph nodes of mice for more than 4 months.[i] The longevity of quantum dots also opens up new imaging techniques. For example, a three-dimensional image can be constructed by acquiring many consecutive focal-plane images of a target. Without quantum dots, this process would be too photodestructive to achieve at high-resolution.

Another benefit of quantum dots is their high degree of quantum yield. This results in brighter fluorescence than with other marker types under identical conditions. Moreover, adequate fluorescence can be achieved with a lower intensity light source.

Quantum Dot Lasers

Much research has been conducted into the use of quantum dots as an active laser medium. There are numerous benefits to using quantum dots as a gain medium vs. traditional semiconductor materials.

Improvements in modulation bandwidth, lasing threshold, relative intensity noise, and temperature insensitivity have all been observed. Quantum dots can be engineered to operate at different wavelengths by varying dot size and composition. This allows quantum dot lasers to be fabricated to operate at wavelengths previously not possible using semiconductor laser technology.

In the field of medicine, the benefits of quantum dot lasers have been commercialized in the form of quantum dot laser scalpels. Quantum dots are also finding an application in the emerging field of optical coherence tomography (OCT). OCT is a technique for obtaining sub-surface images of translucent or opaque materials at a resolution equivalent to a low-power microscope. It is effectively 'optical ultrasound', imaging reflections from within tissue to provide cross-sectional images. In both laser scalpels and OCT systems, quantum dots provide finer emission control and greater temperature stability than previously achievable.

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