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Introduction to Nanotechnology Term Paper

Single Electron Devices

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Abstract

Single Electron Devices (SED) are devices that control the movement and positions of a single or a small number of electrons. The field of Single Electron Devices is also referred to as Single Electronics. SEDs have many prospective applications in both the digital and analog domains of electronics along with some possible applications in standards. Specifically, SEDs have the potential to take over for silicon transistors in processor chips and other integrated circuits in trying to keep up with Moore's Law; they also provide new means of memory and data storage. One of the main interests in SED is the scaling down electronic devices, even possibly down to a fundamental size limit.

The basic concepts behind SEDs will be discussed, along with applications in the analog and digital domains, standards, and issues with fabrication and mass production.

Introduction

The basic concept behind single electronics is to be able to add or subtract a single or small number of electrons from a system. To accomplish this, a small electroneutral conductor, a conductor with exactly m protons and m electrons in its crystalline structure, has an electron added to it by an external force which makes the system no longer electroneutral (Fig. 1A). The small conductor is typically referred to as an island and characteristically ranges in size from 5 to 100 nm at their smallest dimension, when the island is very small it can be considered a quantum dot. The island with the electron added to it now exerts a small electric field (Fig. 1B).

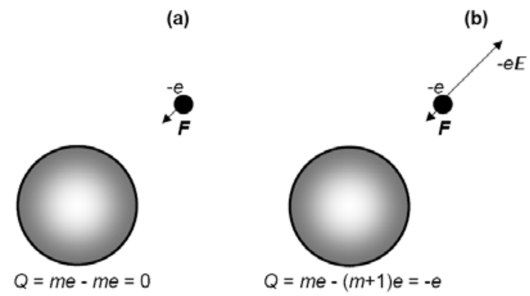

Figure 1: Basic Operation of a Single Electron Device

A field created by the charge of an electron may be very small on our scale, but the charge is inversely proportional to the size of the island, for example, the charge -q, where q is equal to 1.602×10^{-19} Coulombs, on an island with a diameter of 10 nm can create an electric field as large as 140 kV/cm in a vacuum.

The strength of single electron effects is better measured by their charging energy than by their electric field. This charging energy is the square of the charge divided by the capacitance of the island. In order for single electron effects to be observed, the charging energy (E_C) needs to be greater than the energy related to temperature fluctuations or more specifically $E_C \geq k_B T$. The electron addition energy (E_A) and the quantum kinetic energy (E_K) are also some important variables in determining single electron effects and are linearly related to the charging energy by:

$$E_A = E_C + E_K$$

The electron addition energy also needs to be greater than the energy related to temperature fluctuations but about ten times greater $E_A \geq 10 k_B T$ in order to observe single electron effects.

Single Electron Devices take advantage of the Coulomb Blockade effect which states that electrons cannot tunnel if the bias voltage is smaller than the threshold voltage, Vth = e/C, and the Coulomb Staircase effect which states that the external charge of the system increases as a step wise function of e (ΔQe = e) at low temperatures. As the temperature gets higher, the stepwise function smears to a more linear function (Fig. 2).

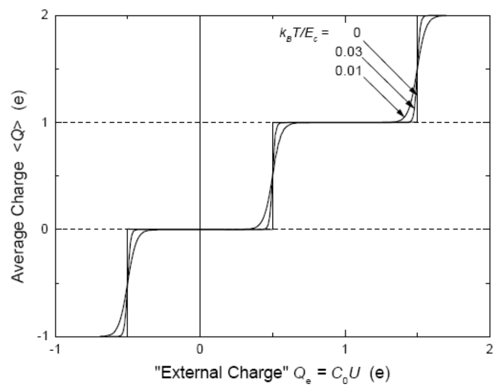

Figure 2: Coulomb Staircase

The field of single electronics has an "orthodox theory" that makes some assumptions in order to simplify calculations; these assumptions are to ignore any energy quantization internal to the islands from any electrons, treat tunneling time as negligible as it is very small compared to other related time scales, and to assume cotunneling (simultaneous tunneling events) is nonexistent. The first of these assumptions is only valid if the kinetic energy of the added electron is much smaller than the energy from thermal fluctuations. The second assumption is generally for all single electron devices and the third assumption is only valid if all of the barriers combined have a large resistance.

Some basic devices that can be made as single electron devices are Single-Electron Transistors (SET), single-electron boxes, single-electron traps, single-electron turnstiles, single-electron pumps, SET oscillators, superconducting systems. The most important of which is the SET because it is very similar in operation to a MOSFET.

Single-Electron Transistor

Bulk properties of semiconductors begin to disappear as the semiconductors get smaller. Semiconductor properties are essential to the workings of transistors, diodes, and many other electronic devices. The disappearance of these bulk properties shows that a fundamental size limit of traditional semiconductor will be reached. The limit of Moore's Law will also be reached; Single Electron Transistors (SETs) may be an avenue of hope.

A single electron transistor is similar in construction to a MOSFET (Fig. 3a), however, it only allows a discrete number of electrons to pass through, letting only specific energies to pass (Fig. 3b).

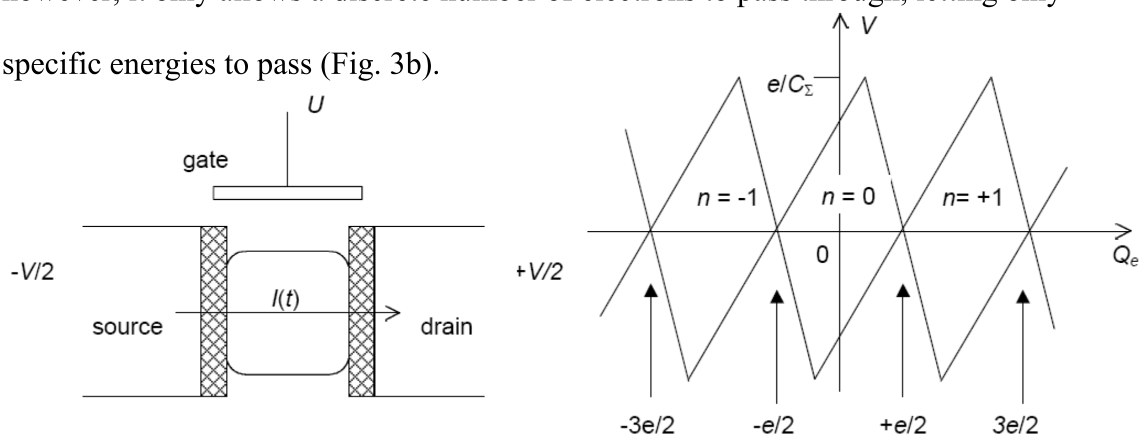

Figure 3: Single Electron Box

Single Electron Box

A single electron box consists of an island separated from electrodes by a barrier and a capacitance (Fig. 4a). Its function is to allow the addition or subtraction of single electron, the count of electrons changes the external charge of the system (Fig. 4b) in discrete units. The single electron box is more of a research utility and does not really have any practical applications. This is because it cannot be used for information storage because the number of electrons is a unique function of the applied voltage and it cannot carry DC current so the charge cannot be measured except by extremely sensitive

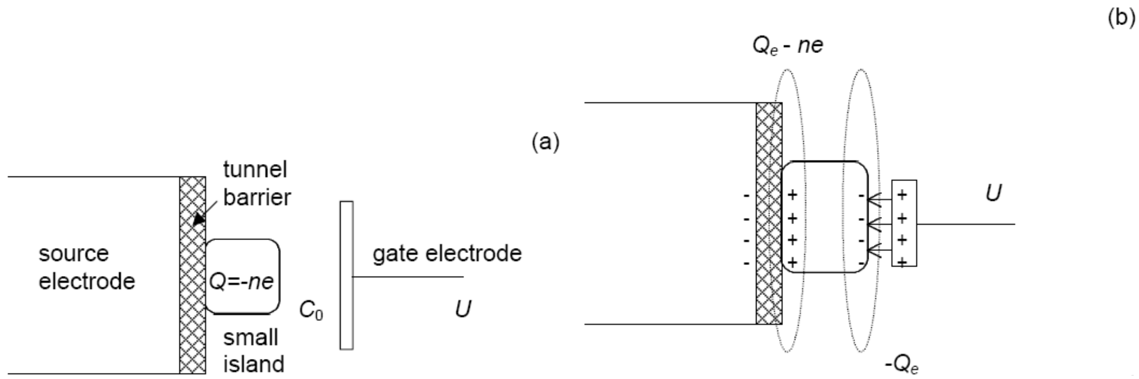

Figure 4: Single Electron Box

Single Electron Turnstile

A single electron turnstile traps an electron in its center as the gate voltage increases past a certain threshold level and holds it their until the gate voltage decrease past a certain threshold level. With a bias voltage of zero the center island accepts an electron from either the source or the drain randomly. By introducing a bias voltage, the electron can be selected from either the source or drain depending on direction of bias.

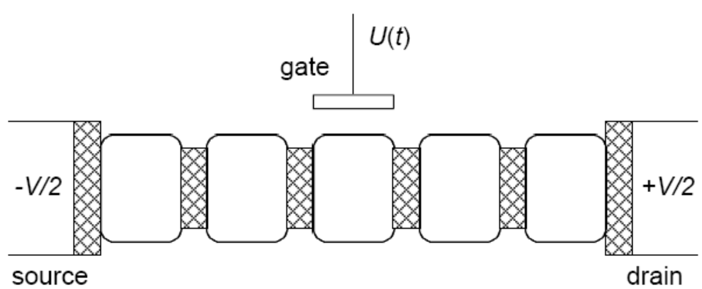

Figure 5: Single Electron Turnstile

Single Electron Pump

Similar to the turnstile, a single electron pump moves and electron to the specified gate and traps it there, pumping it to the next island with signal to the next gate. Using the system in this way, the system no longer needs a bias voltage across the two electrodes Direction of flow is now controlled by the sequence of pulses as seen in Fig. 6b.

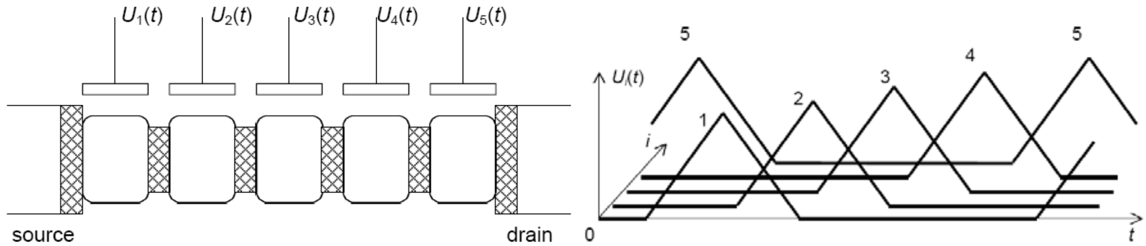

Figure 6: Single Electron Pump

SET Oscillator

When current is injected into the single electron transistor oscillator, the charge of the system oscillates at a frequency that is proportional to the current divided by the charge of the electron. SET oscillations only occur when

$$Vth>e/2C,$$

and is wiped out when

$$I>0.1e/RC.$$

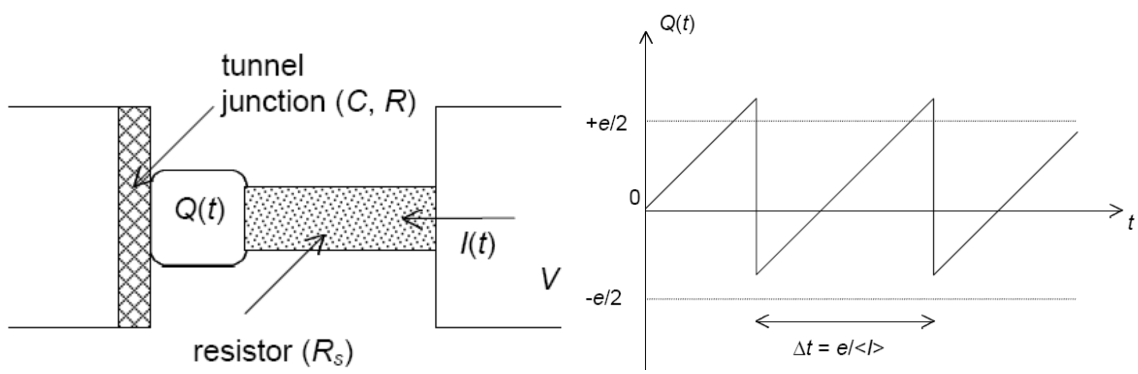

Figure 7: Single Electron Oscillator

Analog

Some analog applications for SEDs would help in the fields of chemistry and physics, such as supersensitive electrometry and single-electron spectroscopy. They could help make some constants for reference measurements, for instance, DC current standards, temperature standards, and resistance standards. Finally, they could also be useful as measurement devices themselves; experiments have been made using SED to detect of infrared radiation.

Digital

SED are not only for the analog domain, many possible uses are being explored in the digital domain, such as, logic gates, using voltage states or charge states. More actively, research is being poured into using SEDs for memory and storage, some examples of which are background-charge-insensitive memory, NOVORAM, and electrostatic data storage.

Conclusion

Promising strides have been made towards many applications, but there are many issues still facing large scale fabrication of these devices. Many tries at fabrication of single electron devices currently use multi-wall nano tubes (MWNT) because they are easier to manufacture, however, MWNTs do not have the properties they need in order to make functional devices that will work at room temperature. Single wall nano tubes (SWNT) potentially have the properties necessary to make many devices feasible, although, SWNT are more difficult to manufacture on a large scale. Once some other more fundamental nanotechnology fabrication methods and techniques are improved, better single electron devices will then be able to be manufactured.

Currently, SETs are speculated to consume about 10^{-7} W per transistor. Which may be very small, however, to theoretically pack in more than 10^{11} transistors per square centimeter, the total power consumption will be on the order of kilowatts. Taking that into consideration, there are serious questions as to whether single electron transistors could take over for MOSFETs in integrated circuits and processor chips.

Perhaps using the discrete energy levels of SETs could lead to a revolutionary new logic processing instead of using only 1's and 0's, and possibly using 0's, 1's, 2's, 3's, etc. While they may not be able to scale down more efficiently than transistors, using a new logic system they could possibly process more efficiently using the same space.

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