A Nano-scale Quantum Dot Photodetector by Self-Assembly

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ABSTRACT

Modern CMOS transistors will not scale well in the next decade due to leakage currents, sources of variation, and platform requirements. To keep the cost per transistor decreasing, and to realize the feasibility of ultra-high density integrated circuits, low power techniques and efficiency optimization are being explored to counter these problems. Parallel to the development of electronic VLSI, using photons as a means of carrying information has been an appealing approach, due to the high speed and broad bandwidth of light, and the elimination of on-chip parasitic and electro-magnetic interference as its electronic counterpart. This paper focuses on photonic integrated circuits to solve the high-density problem, and presents a design for a nano-scale QD optical transducer (QDOT) that will function as a near-field photodetector and that can easily interface into a self-assembled QD integrated circuit (QDIC). The optical transducer consists of a QD between two metal electrodes. The tunneling current between the metal electrodes is mediated by the QD and can be gated by changing the optical signal intensity impinging on the QD. The device can be fabricated via self-assembly using QDs. In this method, a chemistry linker such as DNA or APTES is covalently bound to pre-defined zones on a substrate. The global location of these zones is defined via electron-beam lithography (EBL). Numerical simulations are discussed and ideal characteristics of the device are presented.

Keywords: Quantum dot, photonic integrated circuit, nano-scale photodetector

I. INTRODUCTION

The computing and communications industry continues to strive towards higher speed, higher bandwidth, higher density, smaller device size, and lower power devices. Realizing these goals and simultaneously keeping the cost per transistor decreasing is becoming more of a challenge every day. Several issues with current VLSI technology are expected to delay and possibly prevent the realization of these goals. In particular, traditional problems like on-chip parasitics, heat dissipation, and low-power requirements will increase with device density and electromagnetic coupling at high frequencies will play a more prominent role as the drive for higher bandwidth continues [1]. As device size continues to shrink, new problems like source-to-drain leakage currents and random dopant fluctuations will play an increasing role [1,2]. Finally, traditional fabrication techniques like diffusion and ion implantation, lithography and etching are approaching the fundamental limitations of their capabilities.

Some temporary solutions to these problems that are currently being researched include low-power techniques like body-biasing, stacking, and other forms of efficiency optimization. Novel fabrication techniques have been proposed and implemented such as micro-contact printing [3,4] and nano-imprint lithography [5]. Long-term solutions have thus far focused on new device structures that incorporate novel physical phenomena. For example, using electron or photon spin to represent logic states [6], quantum mechanical tunneling as the basis for carrier transport [7], and photon entanglement as the basis for secure communication networks [8] are all being actively researched. New fabrication techniques like DNA or protein self-assembly [9,10] and AFM Dip-Pen lithography are being used to assemble nano-scale devices.

The emerging field of nano-photonics offers the possibility of large bandwidth, high-speed, and high-density photonic integrated circuits for use in future all-optical computing and communications [11]. One critical component of nano-photonic integrated circuits will be nano-scale, super-sensitive single-photon detection and emission devices that require low-power. The unique opto-electronic properties of quantum dots (QDs) have been utilized in conjunction with traditional devices like field-effect transistors (FETs) to create single-photon detectors

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[12-20] by embedding QDs in the active region of these devices through epitaxial growth. These devices operate at low temperatures (< 77K) to reduce dark current effects and have low quantum efficiencies (< 10%) due to photon absorption by surrounding media. Furthermore, these devices are all micron-scale devices or larger and are subject to the same fabrication and scaling issues as traditional devices as they approach the nano-scale regime. Using single QDs as stand-alone devices has been preliminarily explored during studies of electron transport of single nanocrystals [21-23] and molecules [24]. These studies have largely focused on the electrical and optical properties of individual QDs and have not demonstrated single-photon detection ability or more generally the device's utility as a nano-scale optoelectronic component. Finally, there has been research on using single QDs as single-photon detectors by utilizing a device called a single-electron-transistor (SET) [25]. An SET is composed of a single QD sandwiched between electrodes and is highly sensitive to the surrounding electrostatic environment. An SET capacitively coupled to a QD can sense the change in electric charge on the QD as the QD absorbs a photon of radiation and ejects an electron. This type of detection, however, has only been demonstrated for very low temperatures (~70mK) and for SETs formed on the surface of much larger (>1 μm^2) heterostructures.

In order to address the challenges imposed by Moore's law on the VLSI world, quantum dots have recently been proposed as the building blocks of sub-diffraction limit waveguides, part of a larger effort towards a quantum dot integrated circuit (QDIC) [9].In this paper, we propose a new device design for a nano-scale quantum dot photodetector, a critical component of a future QDIC. The design is similar to the single nanocrystal device [21] and consists of a Si/SiO_2 substrate and a single or collection of QDs that have been positioned at specific locations on the substrate via a DNA or APTES-directed self-assembly process. The working principle of the device is based on electron tunneling between the QD and electrode, and can be gated by input optical intensity. We can use the optical gate to function as a near-field photodetector, and by utilizing the optical gain of QDs, the device can function as an optical transistor. The proposed QDOT is depicted in Figure 1.

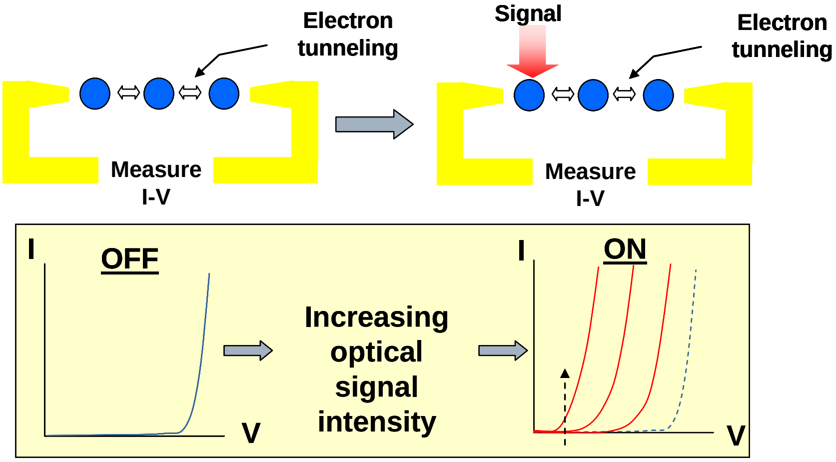


Figure 1. Predicted I-V characteristics of a QDOT with and without optical pumping

Resonant electron tunneling between QDs, or nano-crystals, happens as the inter-dot distance decreases or under applied bias that is strong enough [7,26]. Electrons occupying higher energy levels in the conduction band have higher tunneling rates than electrons occupying lower energy levels. The tunneling is therefore enhanced by photo-generated electrons that occupy higher energy levels. Thus, by optimizing the inter-dot distance such that tunneling does not occur without incident light, but is substantially enhanced by the photo-generated electrons, a transistor-like current (I)-voltage (V) characteristic as shown in the middle of Figure 1, should be obtained. The highly quantized energy levels in QDs (close to delta functions) results in a sensitive increase in the number of electrons occupying higher energy levels under photon excitation, and single photon detection for quantum computing is achievable [18]. The device demonstrated in [18] is a micron-scale device with many QDs sandwiched in one of the epitaxial layers. The QD photodetector proposed here is a nano-scale device that builds on individual QDs. The fabrication process is also compatible with the overall DNA-directed self-assembly fabrication of the QDIC. This nano-scale device will serve as a highly-sensitive photodetector for a future quantum dot integrated circuit (QDIC). It can also function as an optical transistor with electrical signal output, by utilizing the intensity of the optical signal as a control gate. Therefore it serves as a natural interface for seamless integration between future QDIC's and the current VLSI world. Its nanometer scale, fabrication compatibility with other QDIC components, high sensitivity and the prospect of single-photon detection are the chief advantages of the proposed QDOT, compared to other conventional integrated optical detection schemes such as photoconductors, PIN photodiodes, MSM photodetectors, and avalanche photodetectors. In section II of this paper, we outline a theoretical model for charge transport in the QDOT and simulate the I-V characterisitics. In section III, we use the results of the simulation to characterize figures of merit of the QDOT. In section IV, we describe how a QDOT might be fabricated, and in section V we conclude with a summary and description of future work.

II. TRANSPORT MODELING AND SIMULATION

The purpose of the model is to study the I-V characteristics of the QDOT under varying applied biases and optical pump powers, in order to optimize the sensitivity, power consumption, and other important factors. To understand how a QDOT will theoretically operate, it is useful to compare the QDOT to a standard MOSFET. Figure 2 shows the similarities and differences between a QDOT and MOSFET.

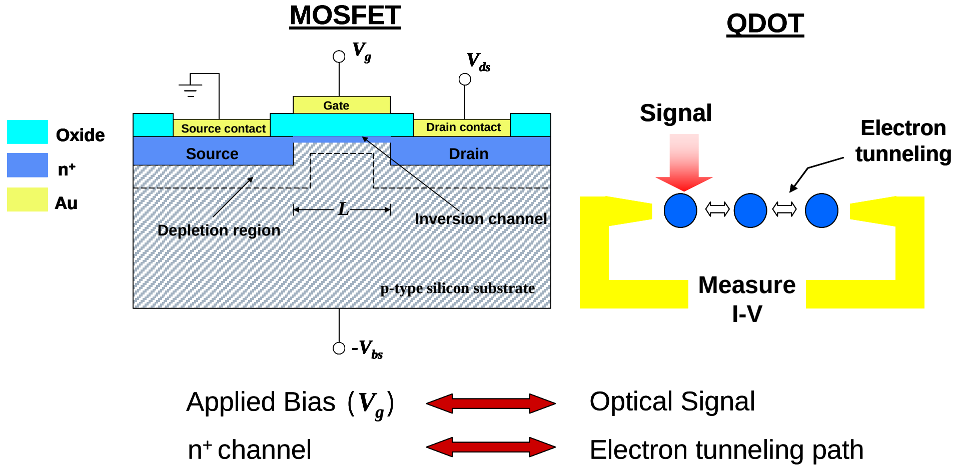


Figure 2. Model of a MOSFET and QDOT. Figures of merit are analogous but distinct

Here, the optical pump power in a QDOT is analogous to the applied gate voltage in a MOSFET. In a standard transistor, depletion processes in the substrate give rise to a conduction channel, but in a QDOT, the conduction channel is simply the path through which electrons tunnel. Quantum dots can be treated for modeling purposes as artificial atoms; i.e., the conduction band density of states is a discreet value, because electrons are confined in all three dimensions. Such a system is often referred to as a zero-dimensional system. In order to introduce a high population of free carriers, i.e., electrons in the conduction band, some type of population inversion must occur. This is easily achieved by optically pumping the system of QD's with light of energy higher than the band-gap of the QD material. Figure 1 shows the predicted I-V characteristics of the QDOT without pumping and with pumping. As shown in the figure, only under very high biases will the QDOT exhibit conduction. This is due to the lack of free carriers mentioned before. Optical pumping, however, lowers the threshold voltage of the QD's, effectively acting as an on/off switch.

II.A. First-Order modeling and simulation of the QDOT

Here, a simple model for electron transport in electronically coupled QDs is presented. Figure 3 shows a more detailed conceptual picture of this device.

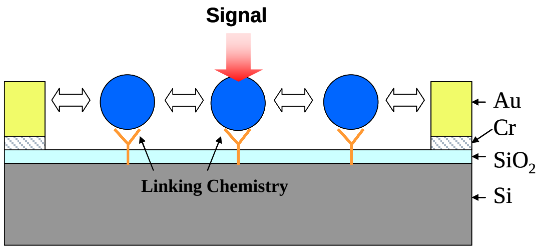


Figure 3. Quantum dots anchored to a Si/SiO_2 substrate between Au electrodes.

The total current through the device is given by summing the product of the carrier concentration at each energy level n_i with the tunneling rate at each energy level Γ_i

$$I = \sum_{1}^{n} n_i \Gamma_i \tag{1}$$

where Γ_i is given in [27] to be

$$\Gamma_i = \frac{\Delta E_i}{2\hbar} \tag{2}$$

Here, ΔE_i is the energy-level splitting due to electron wave-function coupling between QDs. There is also an associated energy-level broadening due to coupling between the electrode and QD that is not considered in this model. The carrier concentration n_i is given by

$$n_i = \int_{E_1-\delta}^{E_2+\delta} f(E) \cdot N(E) dE \tag{3}$$

where *f(E)* is the Fermi-Dirac function and *N(E)* the density-of-state function. The limits of integration are set by the discreet energy level E_i +/- δ where δ represents the finite line-width of each energy level due to thermal broadening. *N(E)* is given by

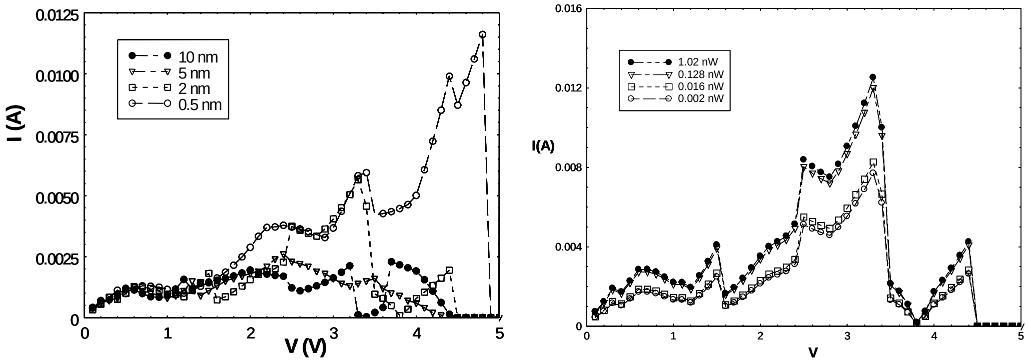
$$N(E) = g(E) \cdot \frac{\hbar / \tau_{in}}{(E - E_i)^2 + \left(\hbar / \tau_{in}\right)^2} \tag{4}$$

where $g(E)$ is the discrete density-of-states for a QD and τ_{in} is the intraband relaxation time. The energy level splitting ΔE_i of the QD-coupled system can be found by describing the system with an appropriate Hamiltonian and solving the discretized Schrödinger equation. Here, we choose an effective mass Hamiltonian to describe coupled CdSe/ZnS QDs with a spacing of 2 nm. We calculated the energy splitting for the first quantized energy level in a coupled two-QD system, and converted the result to tunneling rate. Following the approach of Ref.[9], we find the quasi-fermi levels in the conduction and heavy-hole valence band as a function on optical pump power using the following relations:

$$N = \frac{P_{pump}}{\hbar \omega_p} \Delta t \alpha(\omega_p) L_z = \sum_{lmn} \frac{2}{\left[1 + \exp\left(\frac{E_{clmn} - E_{fc}}{kT}\right)\right]}, \tag{5}$$

$$P = \frac{P_{pump}}{\hbar\omega_p}\Delta t\alpha(\omega_p)L_z = \sum_{lmn}\frac{2}{\left[1+\exp\left(\frac{E_{fv}-E_{hlmn}}{kT}\right)\right]}, \tag{6}$$

Here, $\alpha(\omega_p)$ is the linear absorption coefficient at optical pump frequency ω_p, Δt is the pulse duration, P_{pump} is the optical power, $E_{c(v)lmn}$ is the allowed quantized electron (hole) energy, and L_z the lateral dimension of the quantum box. An I-V curve can be calculated for each of these Fermi levels. The current versus voltage for various inter-dot spacing is shown in Figure 4(a). The current reduces as the spacing increases, as expected. Figure 4(b) shows current versus bias across both QDs for a fixed inter-dot spacing and various optical pump powers. The plateaus are due to the resonant tunneling when the quantized energy levels in the two QDs align with each other. The line-width broadening was not considered in the simulation yet, which would make the resonant feature less visible. As expected, the current increases with increasing optical power. This preliminary formulation serves as a "first-order" model, because it does not consider coupling to the electrodes, nor does it consider the effect of the chemistry linker molecules from electrode to QD.



(a)

(b)

Figure 4. Simulated I-V characteristics of a 1-D array of electronically coupled QDs (a) without optical power and (b) with optical power

These results suggest the possibility of very sensitive optical measurements, because there is clearly a measurable difference in peak current between 0.002 and 0.016 nW of pump power. This difference is on the order of 1 mA, which corresponds to a difference in power of 0.014 nW. The energy of a single photon at a wavelength of 455 nm is approx. 4.37E-19 Joules. Given a time step of 20 ns pulse duration, this would correspond to a power of approximately 0.02 nW. So, we need to be able to sense a difference of pump powers that differ on the order of 0.02 nW. Since these simulations suggest that we can differentiate on the order of 0.014 nW (0.016-0.002), single photon detection may be a possibility.

III. FIGURES OF MERIT

We can characterize the photodetector performance using standard figures of merit for photodetectors, such as quantum efficiency η, responsivity R, and noise effective power (NEP). The quantum efficiency η, and responsivity R are given in [28] to be

$$\eta = (I_p/q)/(P_{opt}/h\nu) \tag{7}$$

and

$$R = \frac{I_p}{P_{opt}} = \frac{\eta q}{h\nu} = \frac{\eta \lambda(\mu m)}{1.24} \qquad (8)$$

where I_p is the photogenerated current, P_{opt} is the incident optical power, q the electronic charge, and $h\nu$ the photon energy. The noise effective power NEP corresponds to the incident rms optical power required to produce a signal-to-noise ratio of 1 in a 1-Hz bandwidth [28] and is given by

$$NEP = \sqrt{2}(h\nu/\eta)\left(I_{eq}/q\right)^{1/2} \qquad (9)$$

where

$$I_{eq} = I_B + I_D + 2kT/qR_{eq} \qquad (10)$$

where I_B is the background radiation current, I_D is the dark current due to thermal generation of electron-hole pairs, and R_{eq} is the equivalent resistance of any measurement circuit used in the detection process which will contribute additional thermal noise to the system.

For the simulation results shown in Figure 4 (a) and (b), we can calculate an estimate of the quantum efficiency η, and responsivity R. For this calculation, we assume a pump light of wavelength λ = 455 nm. From the simulations, P_{opt} is 0.016 nW per quantum dot, which is roughly 512 μW over the entire device. We take the maximum current Figure 4 (b) as the difference between the current at 0.016 nW/QD pump power and the current at 0 nW/QD of pump power (Figure 4(a)) to be ~ 0.15 mA. This yields a quantum efficiency of

$$\eta \approx 0.80 = 80\% \qquad (11)$$

and responsivity R of

$$R \approx 0.29 \qquad (12)$$

for an applied bias of ~ 3 V. To calculate the NEP, we must first characterize the experimental setup to find the equivalent resistance and hence the contribution of the system to thermal noise.

IV. PROPOSED FABRICATION

In order to achieve maximum conduction through the QD photodetector, the separation between electrode and QD must be as small as possible to reduce the path resistance. Self-assembly using DNA or APTES as a chemistry linker can be combined with a novel technique for creating single nanometer-sized gaps between electrodes, called a break-junction technique. As first demonstrated in [29] and subsequently in [30-33], EBL and shadow-evaporation can be used to define electrode regions of varying thickness on a SiO_2 substrate. EBL on PMMA/P(MMA-MAA) bi-layer resist can be used to create a resist bridge suspended above a SiO_2 substrate. A Cr adhesion layer and Au layer at +/- 15 degree angles with respect to the normal can be evaporated so that successive angle evaporation results in overlap to form the center electrode region. Finally, a thick layer of Cr/Au can be evaporated straight down through the resist bridge to ensure bonding between the nano-junction region and the larger Au pads, also defined by EBL.

When the electrode is subjected to a large current density, a phenomenon known as electromigration occurs. Electromigration refers to the motion of atoms in the electrode and is caused by a direct force and momentum transfer from conduction electrons to lattice defects. The direct force is proportional to the electric field strength at the charged lattice defect, while the momentum transfer is proportional to the local current density. The resistance of the electrode can be carefully measured as more current is supplied. A large increase in the resistance (several orders of magnitude) will be observed when the central area of the electrodes breaks, presumably because the Au layer is thin (< 10 nm) in this region. This results in a gap in the electrode between 1 - 10 nm. We can then use solution-phase deposition to deposit QDs, whose outer shell has been functionalized with a self-assembled monolayer of 1,6-hexanedithiol, to the electrodes. The linear dithiol molecules will bind to the Au electrodes and will act as a tunneling barrier between electrode and QD. The effects of the dithiol molecules on the conduction properties of the QD photodetector will have to be incorporated into the theoretical simulations [34]. Figure 5 shows a conceptual picture of what the QDOT will look like after this fabrication method. This method is compatible with the fabrication of a larger quantum dot integrated circuit (QDIC), consisting of several different devices made out of quantum dots. Self-assembly provides the ability to mass fabricate such circuits and the surface functionality of QDs allows for compatibility with widely varying substrates (e.g. Si/SiO_2, organic, biological, etc).

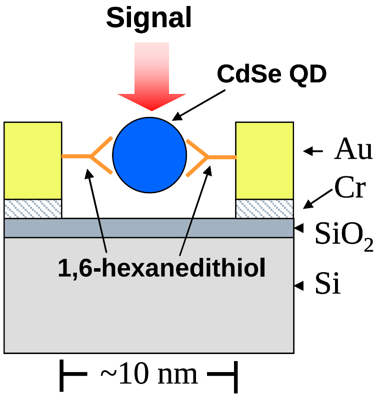


Figure 5. Post-fabrication conceptual picture of QDOT

V. CONCLUSION

We propose a new nano-scale quantum dot photodetector (QDOT) for high-speed computing and communication applications. A preliminary theoretical model that illustrates the basic qualitative characteristics of charge transport under optical pumping in the QDOT is presented. We also discuss aspects of fabricating a QDOT and show how the proposed self-assembly process is compatible with a large-scale effort to fabricate a QDIC. Future work will include the development of a more complete theoretical model, the study of electron coupling between QDs and photon pumping on QDs, and optimization of the device behavior. We will also continue to optimize the device fabrication.

The proposed QDOT provides the first step for the development of an ultra-high density quantum dot integrated circuit (QDIC). As electronic logic gates process signals in an electrical circuit, our photon-based QDOT may do the same, with higher speed and integration density that best capitalize on photons as information carriers, and low-power operation of the QD devices.

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