Quantum Computing via Single Charges in Self-Assembled Coupled Quantum Dots

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Abstract:

Quantum computers take advantage of the phenomenon known as quantum mechanics. The quantum bits, or 'qubits' that comprise these computers have the capability of existing in two states simultaneously, allowing them to provide more bit representation then the conventional transistor. As a result, quantum computers will be faster, contain more memory and possess superior encrypting capability than today's traditional computers.

The purpose of this research is to define the independent control of both the loading and tuning of charges in quantum dots using applied voltage as opposed to sample doping. The tunnel splitting of the coupled electronic states is in the terahertz regime but they are only split at specific applied electric fields. The quantum dot sample being used is comprised mainly of InAs and GaAs. That is, InAs layers deposited between GaAs layers, which are deposited on top of a AlGaAs sample.

Introduction:

Quantum dots are defined as anything that can contain and confine one or more electrons in all three dimensions. As a result, they are commonly referred to as "artificial atoms." One exciting characteristic of quantum dots is that they can actually be manipulated with respect to the number of these electrons. This phenomenon is known as loading and unloading, and can be accomplished utilizing an applied voltage in conjunction with light pulses to create the free electrons then fill the quantum dots. The sample is comprised of three materials (AlGaAs, InAs and GaAs, Figure 1) each having a different band gap energy. This band gap energy level is important because it specifies the level at which electrons are excited and "freed" within the material. The light pulse (from a laser diode) is tuned to a certain frequency or energy that when applied to the sample, will excite and generate electron/hole pairs in only one of the present materials. Once the free electrons are present within the sample, loading the quantum dots is only a matter of manipulating them. This is where the voltage differential comes into play. This applied voltage shifts the band gap diagram as shown in Figure 2. This shift then fills the quantum dots due to their tendency to flow to the level of lowest energy.

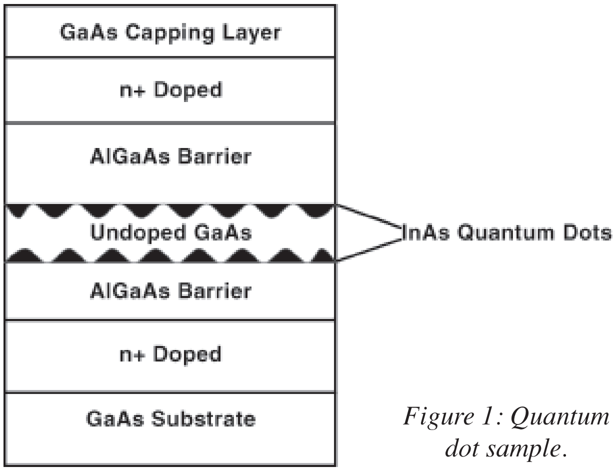

Figure 1: Quantum dot sample.

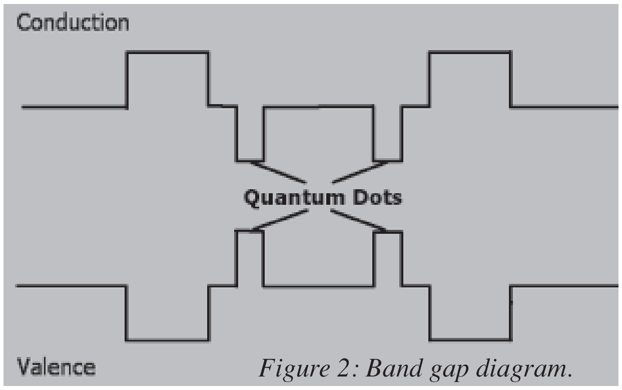

Figure 2: Band gap diagram.

The next area of concern is the tuning of coupled quantum dots. Tuning essentially involves the discrete control of two quantum dots constructed in a way that their band gap energy states are superimposed as far as the electrons are concerned. This provides the stability necessary to create the eventual quantum bit. The technique involved with tuning is a little more complex but it is important to note that the process of doping the sample is involved.

We now arrive at our present challenge. Both loading/unloading and tuning have been accomplished but we aim to do both simultaneously, without involving the complexities of doping, controlling them only with light pulses and applied voltages.

Procedure:

The investigation of coupled quantum dots involves many procedures done at different levels of experimentation. The different levels are single quantum dots and coupled quantum dots and the procedures can be classified as diagnostic, inquisitional then experimental. We begin performing diagnostic research at the single quantum dot stage (on single quantum dot layers). The tests include taking capacitance readings as a function of applied voltage (C-V) and current readings as a function of voltage (I-V). As implied, these tests serve the main purpose of validating our test sample. These tests allow us to determine whether or not our sample is constructed properly. By looking at the conductivity of the sample, we can tell if the sample, including the voltage leads, are positioned properly. If misplaced, the C-V curve will indicate the sample is acting more like a short or open circuit. Finally, the I-V curve reveals the proper range in which our experiments can be conducted.

Once sufficient data has been analyzed to confirm the sample's validity, we move to the more inquisitional tests. These include photoluminescence (PL) tests and sample responses as a function of temperature, voltage, light intensity, and period (to name a few). The purpose of these tests is to further define the behavior of our quantum dots. The PL test is set up to allow us to view the intensity signature as electrons and holes are created and recombine within the sample. The sample responses as a function of temperature, voltage and light intensity allow us to study and determine various characteristics of the sample. These include charge lifetime, unloading dependency and frequency reaction. Upon completion, the actual experimental procedure of loading and unloading the dots using voltage pulses is performed.

Results:

There are many charts, tables and graphs in which to show various characteristics and responses of our sample as a function of frequency, voltage, light intensity, temperature and so forth. Due to our restriction in space, we now discuss only a couple of our results taken in the experiment. First, we show a C-V plot of our sample in Figure 3. As stated earlier, this graphically represents the capacitance of the sample. In our construction, the sample acts like a small capacitor due to the fact that it is comprised of two metal plates (the voltage leads) with a dielectric contained between (the semiconductor material). Depending on the graphical output, we can determine the validity of our sample. If constructed incorrectly, the graph will show the response of a more open circuited object where there is no current charge. If the leads actually touch (also improper construction), the graph will show the response of a more short circuited object.

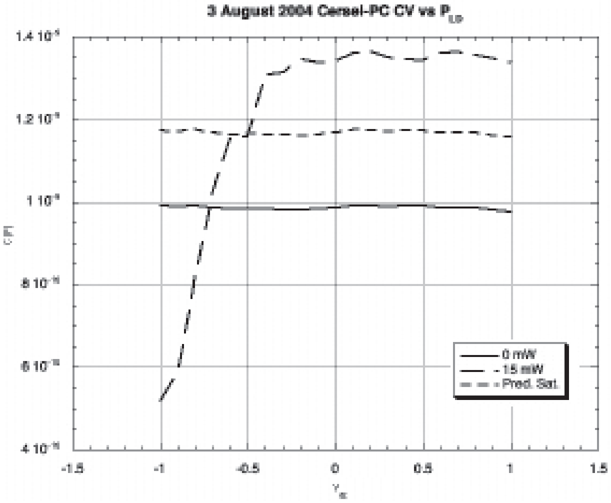

Figure 3: C-V plot.

The next set of data is loading and unloading pulse height as a function of period. From this plot in Figure 4, we calculate the line function whose inverse exponent component reveals the lifetime of our charge (the electrons) within the sample. This lifetime turned out to be roughly one second.

Future Work:

As stated earlier, this project involves more than one stage. To this point, we have embarked on researching the first stage (that of single quantum dot systems). Once sufficient leeway is made on single quantum dots, the next step is to research coupled, quantum dot systems. In this stage, many of the same tests and procedures will be carried out. In addition, determining the proper setup to accomplish independent loading/unloading and tuning using only light pulses and voltage biases will be studied.

Acknowledgements:

To begin, I would like to thank my mentor, Kohl Gill, for giving me the opportunity to study under his tutelage and (attempt to) contribute to his work in the wonderful field of physics. Then I would also liek to thank Mark Sherwin, the entire Sherwin quantum computing research group, UCSB, NNIN and NSF.

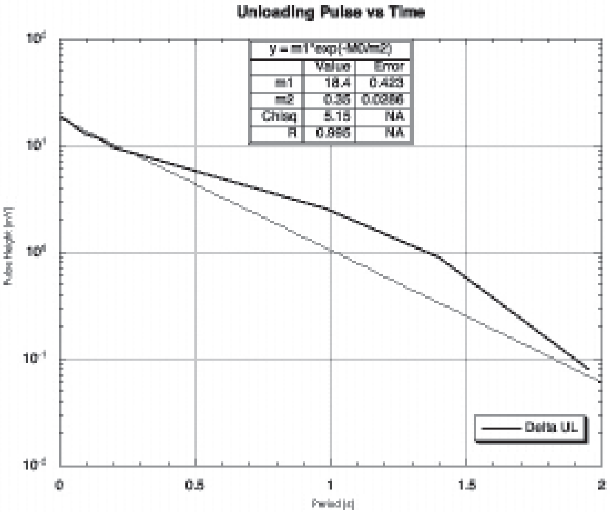

Figure 4: Pulse vs Period (time).