ATOMIC FORCE MICROSOPY ON SEMICONDUCTOR QUANTUM-DOT STRUCTURES FOR USE WITH QUANTUM INFORMATION PROCESSING

Stanton P. Harwood
University of Oklahoma, Norman

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We explore the foundation of an exciting new world by presenting a broad overview of quantum computing and the physics involved with it. We also survey the research being done in Prof. Jiang's Lab with the application of quantum dots as qubits. We then examine the importance and use of Atomic Force Microscopy with quantum dot structures when applied to quantum computing as well the data gathered by such methods.

I. Introduction

Imagine a world where even the most sophisticated encryptions known to man are deciphered in a short amount of time. Where incredibly large databases, once considered too massive to wrestle with, can be unanalyzed with ease. A world where we no longer fuss with attempting to try to calculate quantum mechanical problems or situations, but instead just simulate it on a computer. A world where the most complex schedule of events can be investigated and optimized. This may just be our world after the application of the quantum computer.

II. Background

Before we can dive into the use and application of an Atomic Force Microscope (AFM), we must first see the bigger picture. With the apparent trend of Moore's Law – which today states that the data density of integrated circuits doubles about every 18 months – holding fast, it is inevitable that as circuits get smaller we will reach a limit. Eventually integrated circuits will get so small they will cross over from being appropriately governed by classical mechanics to quantum mechanics. Not only is this inevitable, but if Moore's Law holds up, it will happen in the next couple of decades.

This realization has birthed the latest great research endeavor in computation, namely quantum computation. Since the advent of the digital computer in the 1940's[1], every step forward has simply been an innovative way to speed up or make smaller the same digital processes that existed in the original super computer. The physics has not changed. Until now.

A. Quantum Computation

To grasp the idea of quantum processing, first we review the classical computer, or digital computer. A digital computer uses a string of ones or zeros to carry out an operation. These ones and zeros are actually representations of high/low voltages, or power on/off, or true/false signals, etc. [2]. This operation can only be carried out on one set of numbers at a time. Thus, the whole process is in series, all the time. The building block of a classical computer is the bit (which can exist as a 0 or a 1). It is this process of implementing codes of zeros and ones that has been improved over the past several decades. We do it faster and take up less space while doing it.

Quantum computation, on the other hand, is any computation that utilizes quantum mechanical phenomena, such as quantum superposition and quantum entanglement [3]. Its building blocks are quantum bit, or *qubits.* The significance of the qubit is it can exist as a 0, 1, *or superposition of 0's and 1's.* We shall go into more details on each of these momentarily. A quantum computer promises to be immensely powerful because it can be in multiple states at once and can thus act on all its possible states simultaneously. Therefore, a quantum computer could perform a multitude of operations in parallel, in just a single step. [4]

First, what are the advantages of a quantum computer? Until the invention of Shor's Algorithm, quantum computers and their application were restricted to primarily academic curiosity [5]. Shor's discovery drastically revamped the relevance of quantum computation. Shor's algorithm, which utilizes quantum mechanics, is able to quickly factor very large numbers, which implies that encrypted information can be decoded. Many encryptions employed today to protect important information, such as back accounts, use the multiplication of large prime numbers. It would take even the fastest computer in existence billions of years to decode some of these codes [6]. However, a quantum computer could factor and decipher such codes in about a year. That means information that was once considered encrypted and safe, no longer is. These encryptions reach everywhere from private and public accounts, to government security, to secure communications.

Quantum computers also have application with NP-Complete Systems. The typical example of such a system is the traveling salesmen, which proposes the following: if you are given a list of cities to visit and the times it takes to get from city to city, what is the quickest way to visit every city? [7] This is actually a much more difficult problem than it looks, and cannot be solved by today's classical computers. In addition to this, quantum computers can be used to analyze large databases once considered far too massive to study, model sophisticated situations, and even simulate quantum mechanics itself.

B. Quantum Superposition and Entanglement

Quantum superposition is simply the application of the superposition principle to quantum mechanics.[8] Instead of adding the amplitude of the waves, we add the amplitude of the wavefunctions. These wavefunctions possess multiple values for different quantities of the wavefunction. Quantum entanglement is the phenomenon in which two quantum states, for example the spin of two electrons, become intimately related such that though they may be separated spatially, even by great distances, they still "talk to one another," and instantaneously. [9] Together, these two phenomena are the complex driving force behind the wonder that may someday be a quantum computer.

C. Quantum Bits, Decoherence, and Quantum Dots

We must briefly touch a few more topics before our discussion on Atomic Force Microscopy and its use on quantum dot structures. Specifically, what are these quantum dot structures? The quantum dot structures to be characterized function as quantum bits. As previously mentioned, qubits are the building blocks of a quantum computer. Since quantum computation is still in its infancy, there has not yet been determined the best way to physically construct these qubits. Some of the known approaches currently being researched include:

- Nuclear Magnetic Resonance (NMR) Quantum Computation
- Ion Trap Quantum Computation
- Neutral Atom Quantum Computation
- Cavity Quantum Electro-Dynamic (QED) Computation
- Optical Quantum Computation
- Superconducting Quantum Computation
- "Unique" qubits (e.g., electrons on liquid helium, spectral hole burning, etc.) Quantum Computation
- Solid-State (Spin Based and Quantum-Dot-Based) Quantum Computation

Of course, some of these have initially proved more successful than others, but few to none have been ruled out indefinitely. [10] It is beyond the scope of this paper to include a description of each, save to mention two important facets of the above list. One, Dr. Jiang's research is concerned with Solid-State (spin based and quantum-dot-based) Quantum Computation. And two, as of right now, there are many different methods to constructing a quantum computer.

When deciding which approach to use, one of the key aspects of the qubit is its ability to hold its superposition of states. For quantum mechanics to continue to govern the system, the system must not be "disturbed." Any disturbance, such as an atom colliding with an atom or a random photon entering the system, will technically count as a measurement. [4] By the definition of quantum mechanics, once a measurement is made on a quantum mechanical system, the superposition of the states collapse into a single state – the system goes from quantum to classical – and your measured value is that collapsed state. This process is referred to as *decoherence*. For quantum computation to work, this must be avoided. So, in essence, the qubits of the quantum computer must be totally separated from any outside influence, yet at the same time we must be able to read and analyze the system to perform the appropriate operations on the system. Tricky, at best.

The present solution to this problem lies in the time it takes a system to decohere (T_1) vs. the time it takes to perform an operation on a system (T_2). If $T_2 < T_1$, or better yet $T_2 << T_1$, then there is hope. Fortunately, this is the case. Recent research has shown that in certain quantum mechanical systems, the time it takes for a system to decohere (T_1) is much greater than the time it takes to perform an operation on the system (T_2). Which means, though the system will lose its incredibly key superposition of states because you disturbed it, it will do it slow enough that you can do it (an op[eration) hundreds of thousands of times (rough estimate) before the information is lost.

Finally, it is of certain relevance to again mention the method analyzed in this paper and elaborate on its structure. Through the approach of Solid-State Electron Spin Semiconductor Quantum Dot manipulation, researchers, include Dr. Jiang's Lab, hope to achieve quantum computation. A quantum dot is basically a small device with a small number of electrons; so few electrons that the addition or subtraction of one makes a significant impact.

By taking advantage of different band energies in different materials, you can "trap" electrons in a plane. Confining electrons in 2 dimensions in such a manner is often referred to as a quantum well (Fig. 1).

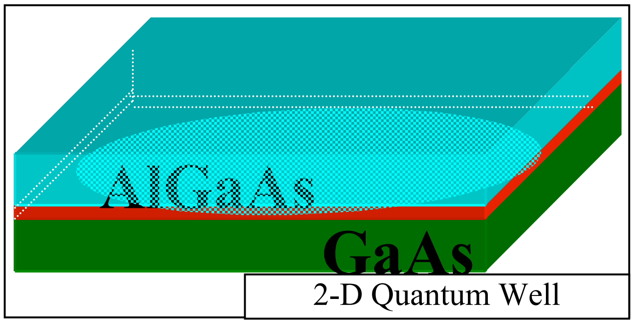


Fig. 1

Using physical structure, electric potentials, and other methods, you can further confine electrons into a single dimension; namely, a quantum wire (Fig. 2).

Fig. 2

Once more, you can confine electrons further still into 0-dimensional space. Like the period at the end of this sentence, only much, much smaller. This 0-D quantum confinement is what is referred to as a quantum dot.

As one can see, the quantum computer is not just the next step in computation, but it is instead a whole new world. A world full of potential and unseen possibilities. For this world to ever exist, though, one must be able to control these qubits. However, achieving such conditions and control is and will be very demanding and very difficult to accomplish. [11] Thus we come to our current topic: using an AFM to study semiconductor quantum dots – with hopes of learning how to better control them – for application in quantum computation.

III. Atomic Force Microscope

The Atomic Force Microscope, a device used to measure materials on an atomic level, will prove to be very useful in research involving quantum dots. Its simple design lends it too many applications. Using a very sharp tip (1nm-10nm radius of curvature) on the end of a cantilever, an AFM is able scan small surfaces and gather a great deal of information about a sample (See Figure 3 [12]).

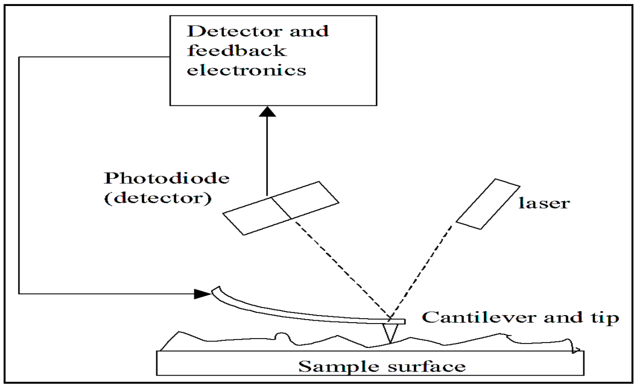


Fig. 3

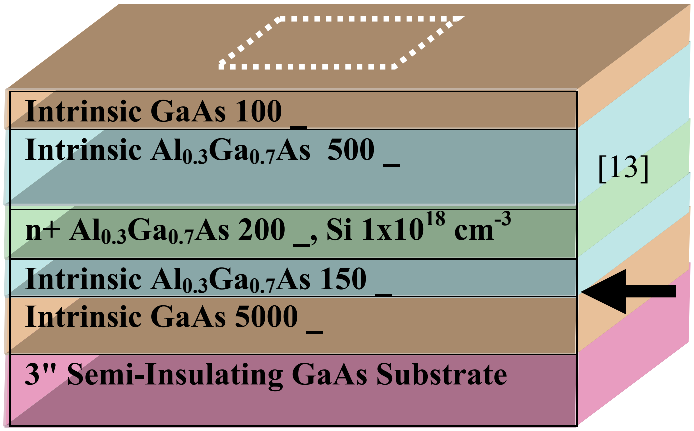
As shown above, a laser is directed onto the back of the cantilever such that when the cantilever changes position with the surface of the sample, the laser is deflected. This deflection is read by a photodiode detector and used to create a three dimensional image of the surface. One of the advantages of an AFM is it can gather this information from a non-conducting surface, unlike a Scanning Tunneling Microscope (STM).

Most pertinent to research with quantum dots, though, is the AFM's ability to gather this accurate topographical information as well as possibly electrostatic information about these quantum dot structures.

IV. The Double Semiconductor Quantum Dot

The remainder of this paper will cover the workings a double quantum dot. Research is already underway to construct qubits using semiconductor quantum dots. The first step in this process is controlling a pair of qubits. To do this, we can confine a pool of electrons to a small space using physical dimensions as well as electric potentials, as previously mentioned.

We (Dr. Jiang's Lab) have chosen to construct the double quantum dot structure on a sample fabricated in the manner laid out in Figure 4. By fabricating the sample as shown, we are able trap a pool of electrons between two layers of the sample. Specifically, directly below the intrinsic $Al_{0.3}Ga_{0.7}As$ layer and directly above the intrinsic GaAs layer, as shown by the arrow. This plane of electrons is referred to as a 2-Dimensional Electron Gas (2DEG). [14] Once the sample is complete, we use photolithography, thermal evaporation, and E-Beam writing to create on the surface the structure shown in Figure 5, 6, and 7.



[13]

Fig. 4

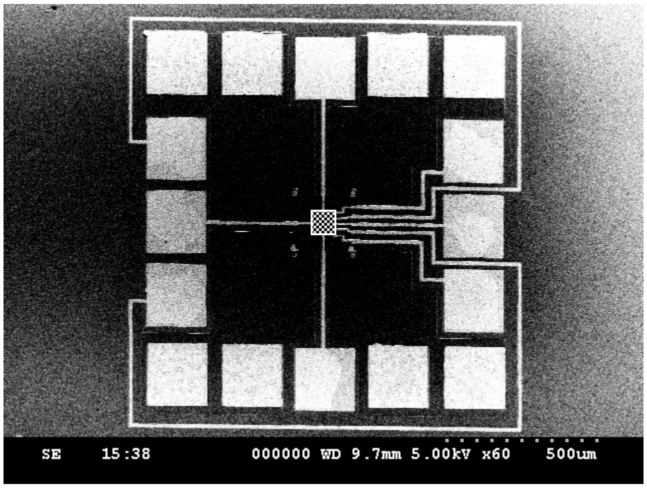
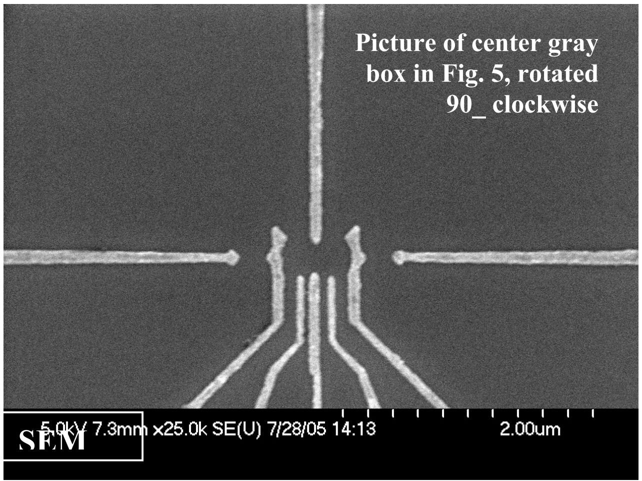


Fig. 5



Picture of center gray box in Fig. 5, rotated 90_ clockwise

Fig. 6

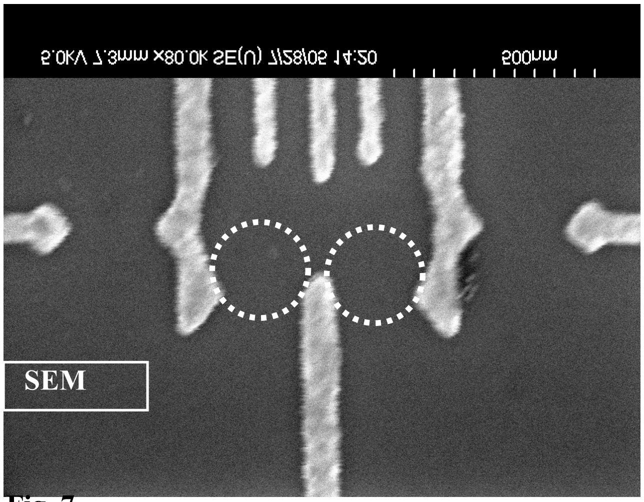


Fig. 7

his structure is created on the surface of the sample. (Observe the dotted parallelogram in Fig. 4) This structure is typically composed of gold. As previously stated, using electrical voltages, we confine two separate small pools of electrons to the two circular dotted regions, in the same plane as the 2DEG (Fig. 7 and Fig. 8).

More specifically, to create this confinement, we use the two plunger leads to "plunge" out the excess electrons. With these leads we can plunge ell electric charge out of the area, or we can leave one (as desired) or more electrons in the region. Using the two quantum point contacts leads we can measure the current that flows (white arrows) with great accuracy. By measuring this current we can know how many electrons are in the dot. Finally, the two leads in the center function to control the coupling between the quantum dots. By adjusting this voltage we can control how much the quantum dots interact with each other. (Refer to Figure 8)

It is important to mention that we have not done this successfully, yet. But, this is indeed the goal. As one may have noticed, electric potential plays a nontrivial role in all of this. To have precise control over the voltage applied through each lead, it is necessary to have accurate information about the physical depth and/or height of each lead. This is where Atomic Force Microscopy plays its vital role.

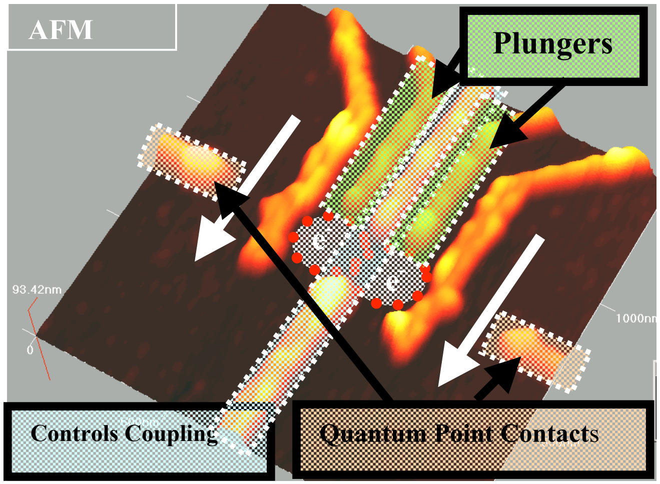


Fig. 8

Through Atomic Force Microscopy we have the ability to accurately measure how much gold has been deposited on our sample. With this information we will be able to calculate and precisely know the amount of voltage to apply in accordance with the size of our leads. As stated, being able to control the electric potential is key and knowing how much material is present for the potential to exist on will make it possible for us to control this voltage. It is this detailed information that will aid our efforts to produce the fine control of the applied voltages that will help make it possible to control the qubits that are the backbone to the quantum computer.

As an example, the following two images (Figures 9 and 10) are simple topographical 3-D images taken with the AFM. The images clearly show the structure that was deposited as well as the heights.

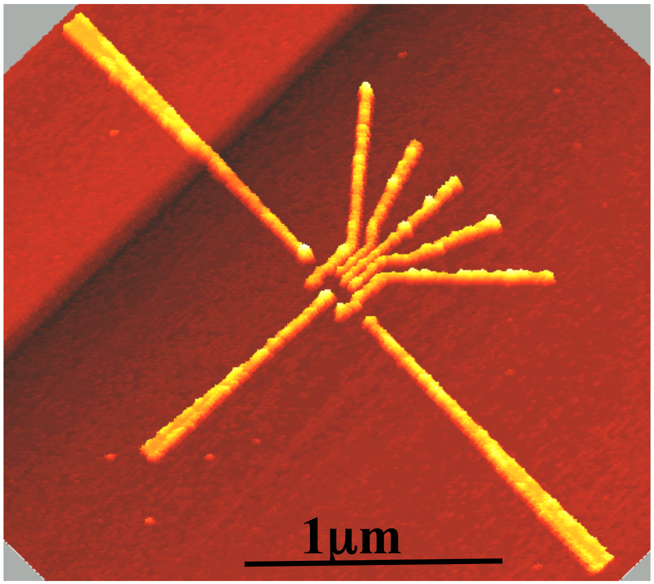


Fig. 9

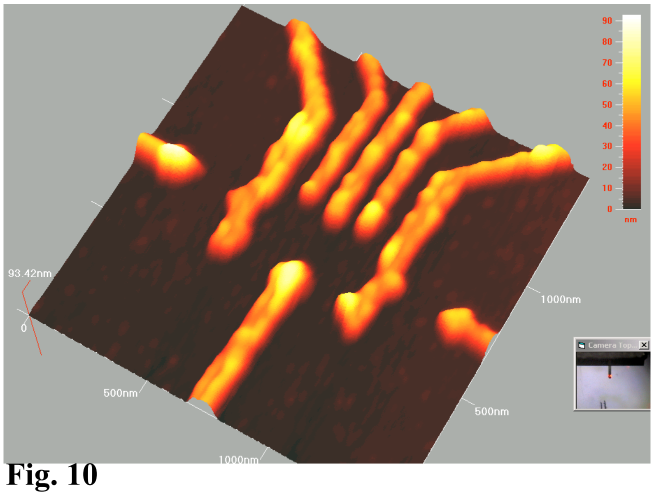
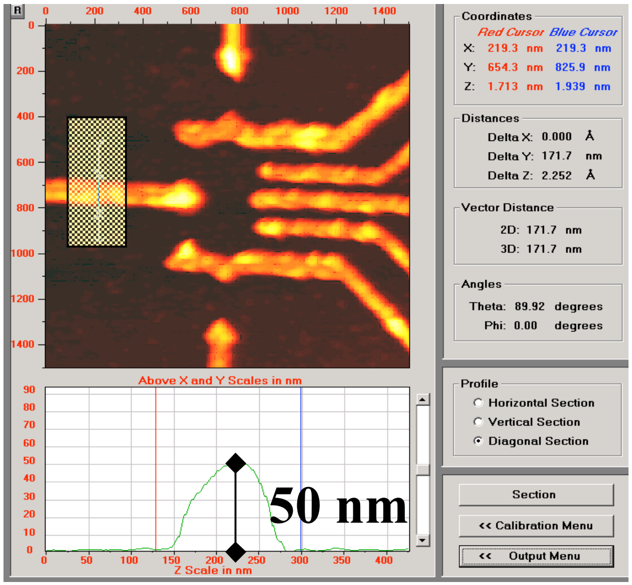


Fig. 10

Using our AFM we are able to measure the gold deposition on the surface of the sample with great accuracy. Each lead was expected to be roughly 50 nm in height. As the AFM scans the image, it records each separate scan line, as well as much more data.. This proves very useful. In the following three images (Figures 11, 12, and 13), we can see cross sections of each of the leads.



Coordinates

	Red Cursor	Blue Cursor
X:	219.3 nm	219.3 nm
Y:	654.3 nm	825.9 nm
Z:	1.713 nm	1.939 nm

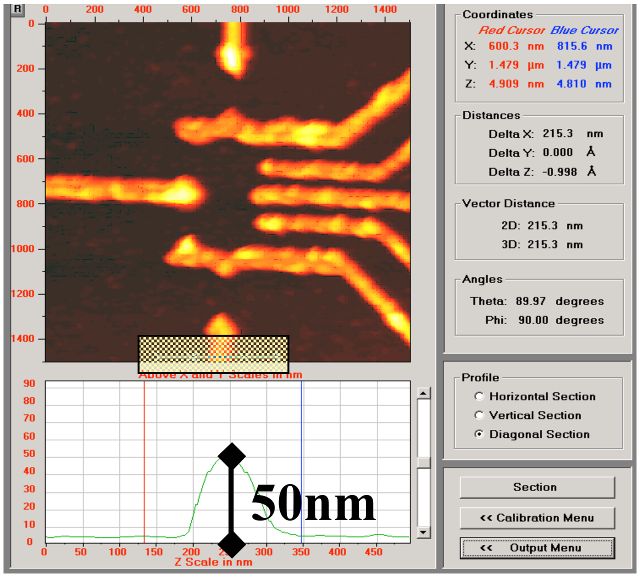
Distances
Delta X: 0.000 Å
Delta Y: 171.7 nm
Delta Z: 2.252 Å

Vector Distance
2D: 171.7 nm
3D: 171.7 nm

Angles
Theta: 89.92 degrees
Phi: 0.00 degrees

Profile
○ Horizontal Section
○ Vertical Section
● Diagonal Section

Fig. 11



Coordinates

	Red Cursor	Blue Cursor
X:	600.3 nm	815.6 nm
Y:	1.479 µm	1.479 µm
Z:	4.909 nm	4.810 nm

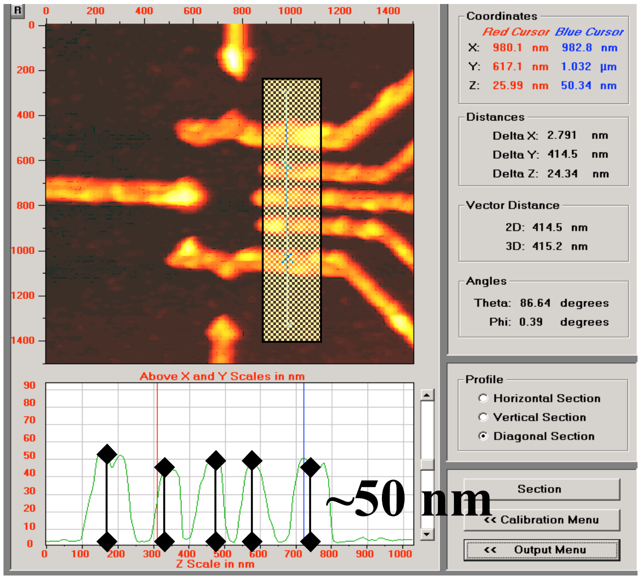
Distances
Delta X: 215.3 nm
Delta Y: 0.000 Å
Delta Z: -0.998 Å

Vector Distance
2D: 215.3 nm
3D: 215.3 nm

Angles
Theta: 89.97 degrees
Phi: 90.00 degrees

Profile
○ Horizontal Section
○ Vertical Section
● Diagonal Section

Fig. 12



Coordinates

	Red Cursor	Blue Cursor
X:	980.1 nm	982.8 nm
Y:	617.1 nm	1.032 µm
Z:	25.99 nm	50.34 nm

Distances
Delta X: 2.791 nm
Delta Y: 414.5 nm
Delta Z: 24.34 nm

Vector Distance
2D: 414.5 nm
3D: 415.2 nm

Angles
Theta: 86.64 degrees
Phi: 0.39 degrees

Profile
○ Horizontal Section
○ Vertical Section
● Diagonal Section

Fig. 13

By examining the cross-section of each lead we are able to accurately test and confirm the depth and width of each lead. For each lead, the height was right at 50 nm. For the plungers, can see that the width is about 100 nm. For the quantum point contact, we can see that the width is right abut the same, 100 nm. And for the leads that control the coupling, we can see that for the one on the right, the width is the same as the plunger and the quantum point contacts, 100 nm. But for the lead coming from the left, the width is slightly larger, about 125 nm. The AFM is accurate to within about 5% of the measurement. So in each of these measurements, the accuracy is to within about 2 to 5 nm. SO this is an incredibly sensitive and precise machine.

We can clearly see the benefit of an AFM. While a Scanning Probe Microscope, or Tunneling Electron Microscope will give us resolute images on atomic scales, they fail to give us any data in the 3rd dimension. Here, the AFM provides exactly that which is lacking.

V. Conclusion

As clearly seen, Atomic Force Microscopy proves immensely useful to semiconductor quantum dot characterization. Quantum computation rests solely on our ability to understand and control qubits. Just as a digital computer cannot function without properly functioning bits, neither can a quantum computer function at all if we cannot exploit and control the wonder that is a quantum bit. Our AFM has shown that it will be helpful in helping understand how electric potentials will govern these qubits. By having accurate and precise information about the surface of our samples, we will be able to better control the voltages used to harness the qubits. The data gathered by our AFM about XinChang Zhang's Double Semiconductor Au on GaAs Quantum Dot showed us that the measured Au deposition height was equal to the expected value. Thus, our AFM successfully furthered our goal of characterizing semi-conductor quantum dots for use with quantum computation

The future of quantum computation looks bright. There is much work left to be done and the field is still in its infancy. Nonetheless, the exciting discoveries, applications, results, and unknown possibilities that await continue to pour fire on the flame of quantum computational research.

VI. Acknowledgments

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