AC 2009-1859: A NANOTECHNOLOGY RESEARCH AND EDUCATION EFFORT AT SUNY-ONEONTA

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Dr. Monisha Kamala Mahanta is an associate professor in the Department of Physics and Astronomy at the State University of New York College at Oneonta which offers a baccalaureate degree in Physics with emphasis on undergraduate research and a three two engineering cooperative program. Dr. Mahanta has been pursuing research in the fields of Quantum Information Processing(QIP) and Nanotechnology for several years. The QIP research was carried out at the US Air Force Research Laboratory, Rome, NY through several summer fellowships and a two year (2004-2006)Senior Research Fellowship awarded by the National Academy of the Sciences. The research involved the study of light profiles with orbital angular momentum, called a donut beam, which can be used as a quantum tool for processing information as well as for nanowire manipulation. The characterization data were published through presentation at International conferences of IEEE and QCMC in Singapore and Japan as well as at Rochester, NY. Dr. Mahanta continues to investigate the use of the donut beam for nanowire characterization and manipulation in the next phase of her research.

A Nanotechnology Research and Education Effort at SUNY-Oneonta

Abstract

The SUNY College at Oneonta collaborated in the DOE/ NYNBIT (New York Nano-Bio-molecular Information Technology) Incubator project[10], initiated by a group of New York universities, funded by the U.S. Department of Energy and administered by the SUNY Institute of Technology at Utica, NY in the years 2006-2008, with a two-prong proposal for a feasibility study in the areas of Quantum-Dot Cellular Automata (QCA) and Nano-wire technology. The availability of equipment such as thermal evaporation units, a spin-coater and a furnace at SUNY-Oneonta, access to an Atomic Force Microscope (AFM) at the New York University and, the purchase of some optical equipment on the grant for LG beams have made this feasibility study a successful venture that leads to future possibilities worth pursuing. An educational outcome of this project has been undergraduate student research[8] and contribution to a DOE/NYNBIT summer camp organized by SUNY Institute of Technology on the foundations of nanotechnology for selected high school seniors and teachers[10].

Introduction

Limits of shrinking devices

The serious limitations experienced in the miniaturization of devices with the current-switch paradigm of turning the current "on" and "off" giving binary digits 0 and 1 include the inability to turn the current on and off cleanly, needing longer time to charge the interconnect lines between devices, presence of large statistical current fluctuations caused by charge quantization, occurrence of considerable energy dissipation.

At the macroscopic level of large dimension devices, charges are considered to flow in a continuous manner making the flow of current analogous to fluid flow so that the laws of fluid mechanics can be applied to the motion of charges. In miniaturized structures, however, charges can no longer be treated as a continuous fluid and need to be quantized into finite and small numbers that follow the laws of quantum mechanics. For such structures a noticeable fluctuation in voltage is observed due to the tunneling or similar effect of a quantum of charge moving from one conductor to another causing a change of energy and potential. The reduction in the capacitance with the shrinking size in the relationship between charge, voltage and capacitance $\Delta Q = C\Delta V$ is at the root of this sensitivity since at a capacitance of 10^{-17}F or less, ΔV is likely to be larger than the thermal voltage for a single electron moving from one side to the other[1]. Such effects cause degradation in the performance of CMOS technology ultimately limiting the device densities attainable with transistors. These limits have led to the growing importance of developing alternative bottom up approaches such as nano-technology which allows scaling at the limits of molecular dimensions. QCA and nano-wires are two such approaches and our interest in these two areas has been guided by the PI's prior experience in the field of Quantum Information Technology using Laguerre Gaussian beams of laser light acquired during her senior fellowship from the US National Academy of the Sciences.

Thus, QCA and nano-wires are two significant developments in the field of nano-science and technology with great potential for miniature technology based on a bottom-up process rather than the top-down process that governs practical applications till now. The process of miniaturization to the nano-level is, however, fraught with as much difficulty as it offers promises due to the fact that as we shrink to small dimensions, fundamental limits are faced in device behavior. Classical dynamics reaches its limits and quantum mechanics starts to play a role and physical effects resembling optical behavior such as quantization of motion, diffraction and interference effects, tunneling modify the performance of devices.

Quantum-Dot Cellular Automata (QCA)

The QCA approach to nano-scale electronics for encoding information involves Coulomb interactions and tunneling between metal dots that operate at cryogenic temperatures or molecular cells that operate at room temperatures. QCA cells have no current flowing between the cells. Metal dot QCA devices such as logic gates, clocked shift registers have been demonstrated to have power gain; however, the disadvantage is the need of cryogenic temperatures. QCA molecules with redox centers, on the other hand, offer the advantage of working at room temperature.

The literature review shows a fair amount of research done in both metal-dot and molecular cell QCA. An idealized QCA cell is like a box with dots or charge containers at its four corners[2], and two extra mobile electrons in that confinement can orient themselves in those dots creating charge configurations in a polarized cell which can be interpreted as a binary “0” and a binary “1”. Thus the binary information of “0” and “1” is stored in the bistable charge configuration of the cell instead of the on-off states of a current switch since there is no current flowing from cell to cell. The dots or charge containers in the cell can be created by a) electrostatically formed quantum dots in a semiconductor, or, b) small metallic islands connected by tunnel junctions, or, c) redox centers in a molecule. The electrons can have quantum tunneling between the dots; however, they are not allowed to tunnel between cells. The cells are connected by Coulomb electrostatic forces only, thereby making it possible to configure binary circuits.

As reported in ref 2, the Notre Dame group (Orlov et al) demonstrated in 1997 the first metal dot QCA cell using aluminum islands as the dots coupled by aluminum oxide tunnel junctions. The procedure used for the formation of these dots and junctions involved e-beam lithography and two angled metal evaporations with an intervening oxidation step. The tunnel junctions were realized by overlapping two metal layers.

Lent et al[2] have reported the use of metal dot cells as prototypes for molecular QCA cells. The shadow evaporation technique they used kept the capacitance at a relatively high value and enabled experimentation at 70mK temperature, yet to reach the room temperature performance of molecular devices.

QCA research using metal dots has reported results such as the demonstration of the first functioning QCA cell, signal transmission down a QCA line, construction of a QCA logic gate, clocked QCA switching, power gain. The QCA feasibility research proposed by SUNY-Oneonta was encouraged by the success of this line of research and the availability of some of the equipment necessary for the work.

In contrast to metal dots cells, single molecule QCA cells generate much larger Coulomb energies due to their small size making room temperature operation possible and have low power requirements and heat dissipation making high density molecular logic circuits and memory feasible. A single molecule implementation of a QCA cell requires a molecule in which charge is localized on specific sites and can tunnel between these sites. These molecules have their redox center playing the role of dots or charge containers and the tunneling paths are provided by bridging ligands. The Aviram molecule composed of two allyl groups separated by an alkane/butyl bridge illustrates the basic features of molecular QCA as reported by Lent et al. The literature review brought us to the conclusion that although our first QCA effort has been at the metal island level, that approach would ultimately have to be abandoned in favor of a single molecule approach due to the room temperature advantage. However, it is to be noted that the next phase of our research is likely to concentrate more on nanowire research due to the availability of facilities.

Nano-wires

Nanowires are quasi-one-dimensional structures of nano-scale diameter and micron length rationally assembled on atoms or other nanosize building blocks, with unique quantum properties and the potential to be integrated into electronic and opto-electronic devices at the nanoscale. One-dimensional structures are the smallest dimension structures that can be used for efficient transport of electrons and optical excitations which make these critical to the function and integration of nanoscale devices. The emphasis on nanowires as a foundation for the bottom-up paradigm is driven by the realization that nanowires can function both as active devices and interconnects simultaneously which is critical in any integrated nanosystem.

Semiconductor nanowires represent one of the best defined and best controlled class of nanoscale building blocks and can be synthesized rationally and predictably in single crystal form with all of their key parameters such as chemical composition, geometric dimensions, doping etc. controlled during their growth. A wide range of device concepts and integration strategies have been enabled by these novel structures due to the fact that it is possible to combine them in ways beyond the scope of conventional electronics.

Nanowire applications include individual nanowire-based biological sensors, crossed p-n junction light-emitting diodes, integrated nanowire logic devices.

Nanowires of various compound semiconductors such as ZnO, GaN, In_2O_3, Si_3N_4, Ga_2O_3, and MgO have been synthesized successfully. However we have been interested in ZnO because of the advantages it offers[3]. It is a semiconductor with a wide and direct band-gap of 3.37eV at room temperature and a large exciton binding energy (60 meV), which is much greater than the thermal energy at room temperature, and has a high piezoelectric constant. Also it is considered to be bio-safe and bio-compatible. These characteristics make this material highly valuable for fabricating mechanical devices such as acoustic transducers, sensors and actuators, for application in opto-electronics, biomedical science and other areas.

We are interested in the optical, electrical and thermal characterization of nano-wires and decided to prepare for future experimentation on ZnO. Accordingly we reviewed the literature for fabrication and characterization techniques and found fabrication techniques such as sputter deposition, template assisted growth, chemical vapor deposition growth using vapor-liquid-solid (VLS) for nanowire synthesis in the literature. The thermal evaporation units and the furnace available at SUNY-Oneonta are anticipated to be useful for this kind of experimentation on nanowires.

Optical manipulation

An additional interest in the feasibility study was the optical manipulation of nanowires using Laguerre Gaussian profiles which carry orbital angular momentum[4]. The PI has experience in the field of Laguerre Gaussian beams[5] shown below and would like to apply those for nanowire characterization and manipulation.

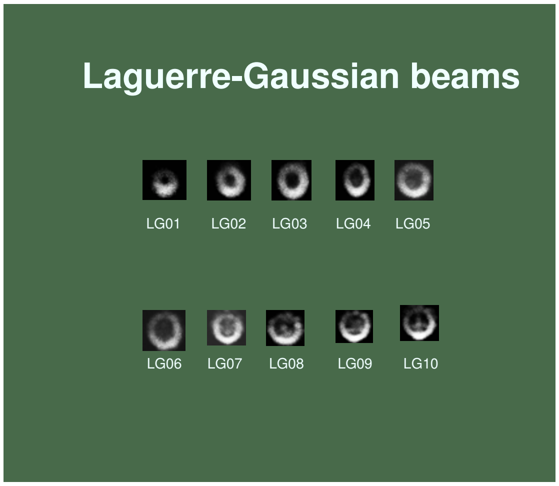


Fig. 1. LG beam profiles created by the PI in an earlier research[5]

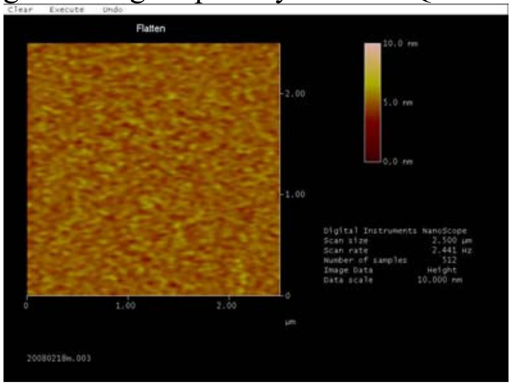
Reference 6 reports the rotation of a semiconductor nanowire with the helical Laguerre-Gaussian profiles of light. Also reported in the reference is the assembly of a rhombus from semiconductor nanowires using optical traps. This has encouraged us to plan to investigate the potential of our LG profiles for similar manipulation of nanowires.

The Oneonta effort

The availability of a thin film lab equipped with a couple of thermal evaporation units and a spin-coater at SUNY-Oneonta led to the anticipation that a feasibility study into one or both of these areas (QCA and Nanowires) of nano-science and technology would be worthwhile and might lead to some useful experimentation. Initially QCA was thought to have better prospects than the nanowire research. However, the situation seemed to develop more favorably toward the latter. Therefore the research progressed accordingly.

As written in the proposal, the QCA effort aimed at reaching the molecular level ultimately because of its temperature and size related benefits; however, due to the complexity of the process and lack of equipment, the first attempt had to be made at the relatively simple level of very thin coatings of pure metal with the idea of depositing islands which could be observed under an Atomic Force Microscope (AFM), the search for which was itself a part of the proposed feasibility research since Oneonta does not have the AFM. Several attempts to establish contact with the nano-technology center at Albany, NY were unsuccessful and that almost brought the QCA effort to a halt which forced SUNY-Oneonta's efforts to be directed toward nanowires. In that process, however, a window opened with the kind offer from the New York university collaborators of NYNBIT to allow the PI of this project to use their AFM to observe the thin films made at the SUNY-Oneonta lab. Some of those data are submitted in this report in Figures 2, 3, and 4. The data on ordinary thin films of copper and gold on silicon substrates were found to be encouraging for both QCA and nanowires since a quantitative measurement of the hills and valleys of the coatings at the nano level was made possible for the project by the AFM as shown in the figures below.

The next phase would be to design strategies for developing a variety of coatings of better quality and more suitable for QCA studies and use in a variety of environments for nanowire experimentation which would then lead to some characterization experiments. It is to be noted that with metal coatings, QCA work would need cryogenic temperatures (about 100K) which is likely to be difficult; however molecular QCA might be more approachable due to its ambient temperature possibilities. The spin coater is anticipated to be useful for this purpose. It has not been possible, however, to test it in this feasibility study owing to the lack of a fume hood, much needed for health safety, in the thin film laboratory. Once the appropriate coatings are made for QCA work, experiments can be designed on Coulomb force effects, electrical conductivity, quantum tunneling effect to shed light on how to analyze the charge transfer phenomena for information processing at the nano-level. However, it must be noted that due to better preparation, the nanowire research is likely to be given a higher priority than the QCA research.



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Digital Instruments NanoScope
Scan size              2.500 µm
Scan rate              2.441 Hz
Number of samples       512
Image Data            Height
Data scale          10.000 nm
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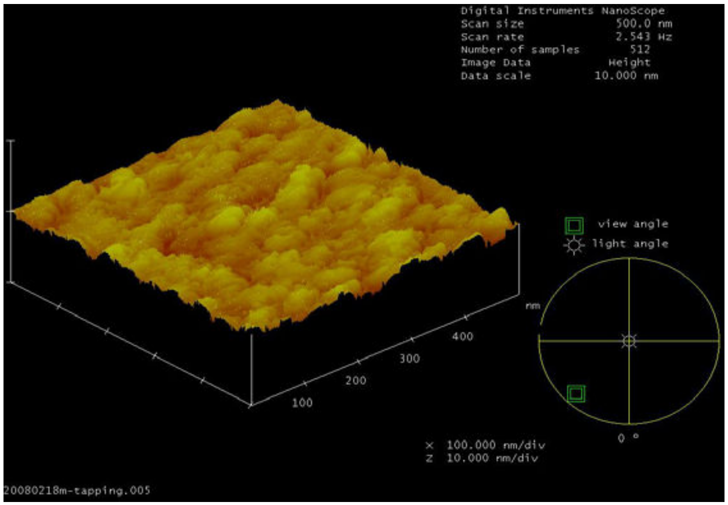
Fig 2. AFM data: A color coded view of the hills and valleys of the coating. The darker spots correspond to 0-5nm and the brighter spots correspond to 5-10nm as shown on the scale on the side.

Ref 7 shows an array of ZnO wires at different resolutions. The 2 micron view appears to have the same graininess as the 2.5 micron view of our simple thin coating data shown in fig. 2 above. This lends feasibility to our line of thought. We are planning to generate in the next phase of our research, data on nanowires similar to those in ref 7.



Digital Instruments NanoScope
Scan size 500.0 nm
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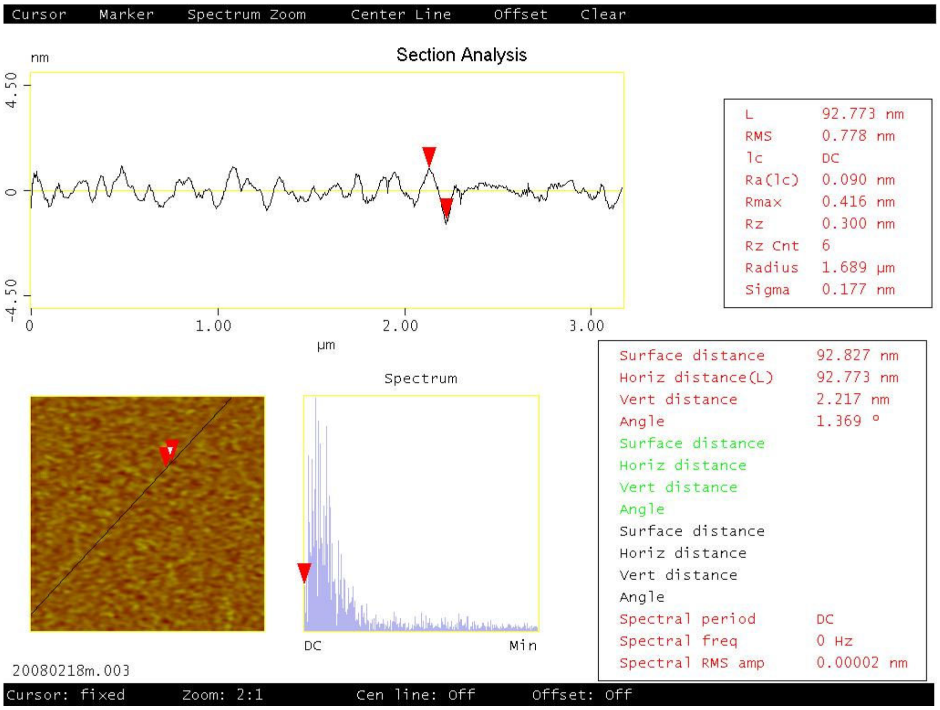
Number of samples 512
Image Data Height
Data scale 10.000 nm

Fig 3. AFM data: An angular view of the roughness of the coating



L 92.773 nm
RMS 0.778 nm
lc DC
Ra(lc) 0.090 nm
Rmax 0.416 nm
Rz 0.300 nm
Rz Cnt 6
Radius 1.689 µm
Sigma 0.177 nm

Surface distance 92.827 nm
Horiz distance(L) 92.773 nm
Vert distance 2.217 nm
Angle 1.369 °
Surface distance
Horiz distance
Vert distance
Angle
Surface distance
Horiz distance
Vert distance
Angle
Spectral period DC
Spectral freq 0 Hz
Spectral RMS amp 0.00002 nm

Cursor: fixed Zoom: 2:1 Cen line: Off Offset: Off

Fig 4. AFM data: Analysis of a small section on the thin coating.

The feasibility study on nano-wires has benefited from the availability of the AFM at NYU, a furnace in the Department of Chemistry and Bio-chemistry of SUNY-Oneonta and the prior experience of the PI in the field of Laguerre-Gaussian (LG) beams with orbital angular momentum built into it. An exhaustive survey of the literature has shed light on the experimental approach for nanowire fabrication using materials such as ZnO, gold-coated silicon substrates etc. A successful fabrication of nanowires at the Oneonta labs will be well served in observation and measurement by the AFM available at NYU, although an effort is currently under way to acquire an AFM at SUNY-Oneonta. The feasibility study has made it possible to envision the use of the LG beams for studying the mechanical and optical properties of nanowires. The grant has enabled the enhancement of the lab at Oneonta for this purpose, thereby pushing the nano-science and technology effort at SUNY-Oneonta beyond the limits proposed for the feasibility study.

Additional accomplishments of the project

1. SUNY-Oneonta desires of its undergraduate students to get involved in faculty research which is also a goal of the NYNBIT Incubator. This research was able to accomplish that by using a part of the grant for educational and training purposes

A student was recruited to help with the literature review and the initial planning of the research. The student presented his work titled "Synthesis of Nano-Structures: A Feasibility Study" at the XXVI Annual Rochester Symposium for Physics Students, SPS Zone 2 Regional Meeting held at Rochester University on April 21, 2007[8].

2. The thin film lab at SUNY-Oneonta was used in the summer of 2007 to introduce the practical thin-film aspect of nano-technology to two summer camps of promising high school students hosted by SUNYIT, Utica, NY. The fabrication of thin films and the furnace to be used for nano-wire fabrication were demonstrated following a Power Point presentation of some of the fundamentals and applications of nano-wire technology.

3. A local industry has expressed interest in collaborating with SUNY-Oneonta in the nanowire research. The focus of this research is likely to be on medical application of the nanowire technology. The focus will however have to be narrowed further to areas with the greatest relevance. One possibility is the Optical Nerve system, the literature on which is being reviewed.

Student's Conference presentations and Publications from this research project

Corey Lemley (Supervisor M. K. Mahanta): "Synthesis of Nano-Structures: A Feasibility Study" presented at the XXVI Annual Rochester Symposium for Physics Students, SPS Zone 2 Regional Meeting held at Rochester University on April 21, 2007, published in the proceedings of abstracts of the conference.

Conclusion

In conclusion, this feasibility study has been a successful venture on the part of SUNY College at Oneonta leading to future possibilities worth pursuing. The next phase of the research has been geared toward the fabrication of ZnO and Si_3N_4 nanowires and their characterization using Laguerre Gaussian beams of light. Further equipment will be necessary for that phase; however, we are hoping to break new grounds and generate interesting data.

Acknowledgements

This project was conducted with a grant (Project # 1059010) from the US Department of Energy grant as part of the collaboration on the NYNBIT project (Grant # DE – FG02-06ER64281) administered by the SUNY Institute of Technology, Utica, NY. The author thankfully acknowledges the support.

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