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Integration of Nanotechnology in a STEM Based High School Curriculum Through the Investigation of Wetting Properties of Nano-imprinted and Silanized Surfaces

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Integration of Nanotechnology in a STEM Based High School Curriculum Through the Investigation of Wetting Properties of Nano-imprinted and Silanized Surfaces

by

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Dedication

This work is dedicated to my life partner Mohammed Sadiq Ali for providing me with the support and confidence that allowed me to complete this master's program. I am also thankful to my family for their encouragement to do my best throughout this program. I want to thank my mother Leticia Regalado for being an exceptional role model and for teaching me by example. I also want to give special thanks to my father Colonel Robert Negley for being one of my main inspirations through his discipline, love for teaching and by being an exemplary father.

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Abstract

Integration of Nanotechnology in a STEM Based High School Curriculum Through the Investigation of Wetting Properties of Nano-Imprinted and Silanized Surfaces

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The University of Texas at Austin, 2014

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Nanotechnology is an emerging field of engineering. Awareness needs to be fostered in the K-12 education system in order to sustain its expansion. As a current Algebra 1 teacher, I participated in the NASCENT research program to further my education in nanotechnology and find ways to integrate this content and practices in my Science Technology Engineering and Math (STEM) based Algebra 1 curriculum. During the research, I learned about surface tension of solids and liquids and its effects on materials' wetting properties. After completing the research program, I created a 2-week long project where students will replicate my experiences during this research. The purpose of this report is to investigate the need for the integration of nanotechnology in STEM classes and find ways to turn my research experience into real-world learning opportunities for my students.

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Chapter 1: Introduction

Nanoscale science, engineering and technology, commonly known as nanotechnology, encompass the study and exploitation of physical, biological and chemical processes and materials in which at least one dimension is at or below 100nm[1]. It is a broad multi-disciplinary field currently seen as the solution or a better solution to several societal grand challenges such as cancer treatment, clean and inexpensive energy, advanced electronics and self-healing materials. For these and many other promising applications, nanotechnology is seen as the answer to the betterment of our society and economy. Given that nanotechnology is still in its very early stages, awareness of this topic is very low among the community at large. Organizations like the National Science Foundation (NSF) are currently supporting programs like the National Nanotechnology Initiative (NNI) and Nanosystems Engineering Research Centers (ERCs)[2] to invest efforts towards the education of nanotechnology among the community. Thus far, outreach programs have been put in place to educate undergraduate students, K-12 students and the general community about nanotechnology.

As the focus for my report, I will dedicate my efforts towards investigating outreach programs that support secondary teachers and students in order to integrate nanotechnology in their science and mathematics curriculums. With this information, I will then create resources that can be used in a high school mathematics classroom that will allow the integration of nanotechnology concepts in the mathematics curriculum. As a way to pursue this goal, I will work with the NASCENT Center to convert lab experiences to resources and lessons that can be implemented in the mathematics

[1] One nanometer is one billionth of one meter or approximately four times the diameter of a hydrogen atom, see Nano.gov for more detailed discussion.
[2] The Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies (NASCENT) Center hosted by UT Austin is an example of a Nanosystems ERC funded by NSF.

classroom. During the lab experience, my plan is to investigate effective teaching materials and come up with best practices that can be implemented in the classroom as a way for students to gain a strong understanding of nanotechnology.

The instruction model that I will be using to write and deliver these lessons will follow Project Based Learning (PBL) instruction. In the PBL instruction model, the content is delivered to the students through engaging and authentic projects that require students to develop and apply collaboration, research, creativity, work ethic, oral communication, and technology skills. In the PBL learning community, teachers align curriculum and state mandated skills to the process and product that the students must complete during the cycle of a project. Another key aspect of PBL is that these projects are based on relevant real world current events and challenges that we face in today's society. In addition, I also intend to merge Science, Technology, Engineering and Mathematics in these lessons. As another crucial player in the instruction model that I am planning to follow, STEM curricula in the high school classroom are intended to teach students the problem solving systems in engineering through the integration of mathematics, science and technology in a seamless manner. Through the proper integration of STEM, the thinking process and problem solving ability of an engineer can be fostered in those of a high school student. Given that nanotechnology is viewed as the possible solution to many grand challenges in engineering, "the infrastructure for nanotechnology education should include educational models and curricula that will institutionalize and interdisciplinary education, thus exposing students to the connections between disciplines and their relationship to nanotechnology at all levels" (Foley and Hersam 467)[3].

As an advocate for the reforming movement of education but more importantly, as an advocate for the professional growth of teachers, my expectation for the

[3] 3 This document follows Modern Language Association (MLA) formatting.

development of these lessons is that other teachers can use their content as a resource that can assist them in writing and implementing their own STEM projects under the PBL scope that educates high school students about the mathematics and science involved with nanotechnology.

Chapter 2: Literature Review

2.1 What is Nanotechnology?

Investigation and exploitation of physical and chemical processes and properties at the nanoscale has become an important new direction for research. At these scales, physical and chemical properties of materials can be substantially different from their bulk macro-scale properties. For example, bulk gold appears yellow in color but its nanosized particles appear red. At this size, electrons in gold are not free to move like they do in their bulk size. Thus, nanosized particles react different in the presence of light. The growth of research in nanotechnology is grounded on the goal to harness the properties at the nanoscale. Learning about these properties is leading to the engineering and fabrication of structures to create new properties and functions or improve existing functionality. As an example, metal oxide nanoparticles show antimicrobial activity, which is due to their large surface area ensuring a broad range of reactions with bio-organics present on the cell surface. The high-throughput manufacturing of functional devices incorporating these nanoscale properties is termed nanomanufacturing. Top-down nanofabrication consists of "reducing large pieces of materials all the way down to the nanoscale. [T]his approach requires larger amounts of materials and can lead to waste if excess material is discarded. The bottom-up approach to nanomanufacturing creates products by building them up from atomic- and molecular-scale components, which can be time consuming" ("Nanotechnology and You"). The semiconductor industry serves as a useful benchmark where several representative nanofabrication-related processes have been developed and advanced. Some of these processes include:

- Chemical vapor deposition is a process in which chemicals react to produce very pure, high-performance films

- Molecular beam epitaxy is one method for depositing highly controlled thin films
- Atomic layer epitaxy is a process for depositing one-atom-thick layers on a surface
- Dip pen lithography is a process in which the tip of an atomic force microscope is “dipped” into a chemical fluid and then used to “write” on a surface, like an old fashioned ink pen onto paper
- Roll-to-roll processing is a high-volume process to produce nanoscale devices on a roll of ultrathin plastic or metal
- Self-assembly describes the process in which a group of components come together to form an ordered structure without outside direction.

The engineering and manipulation of materials at the nanoscale level is possible through these manufacturing processes. Through these processes, nanotechnology will lead to the elaboration of stronger, lighter, more durable, water repellent, and higher electricity conductivity materials. These will be the characteristics needed for the production of faster and energy efficient computers, high efficient and low cost batteries and solar cells in the auto industry.

2.2 Applications of Nanotechnology

The reason why nanotechnology is claimed as a major scientific development is due to its multiple applications that range from various disciplines. These applications include healthcare, telecommunication, agriculture, computer technology and car engineering, just to name a few. There is a vast range of nanotechnology products that exist on the current market consisting of faster computer processors, higher density memory devices, baseball bats, lighter auto parts, stain and water resistant clothing and even cosmetics. As a more specific example, nanomaterial-based biosensors possess the advantage of enhanced sensitivity and greater specificity in detection of “DNA, RNA, proteins, glucose, pesticides and other small molecules from clinical samples, food industrial samples, as well as environmental monitoring” (Zhang 1034). These major developments have the potential to improve production of drug delivery systems, gene therapy, tissue engineering and other medical treatments.

The elaboration of individual molecules as functional electronic devices was an idea originated in the 1970s (Joachim 541). Nowadays, thanks to recent advances in nanotechnology, stretchable transistors from carbon nanotubes contain properties that are key to the manufacturing of elastic electronics. The solutions and improvements that nanotechnology offers to current engineering and health challenges are multiple but further research and development need to be done before a lot of these applications become a reality.

2.3 Government Approach to Nanotechnology

The First National Nanotechnology Initiative (NNI) was launched in the U.S. in the year 2000 under Bill Clinton’s 2nd term as President with a budget of $464 million approved by Congress. Since then, “the NNI has enjoyed strong, bipartisan support from the executive branch, the House of Representatives and the Senate” (Sargent 2). Today, more than 60 countries have followed in the footsteps of the U.S. and have established their own nanotechnology initiatives. Despite the boom in nanotechnology in other countries, the U.S. is still a leader in research and development in this field. With the intention to sustain its global competitiveness in technological leadership and commercialization of nanotechnology, “in 2003, Congress enacted the 21st Century Nanotechnology Research and Development Act (P.L 108 – 153)” (Sargent 3). This act gave way to the formation of the National Nanotechnology Coordination Office that awards grants for various nanotechnology research facilities. This office also established a research program to identify ethical, legal, environmental and other societal concerns in nanotechnology.

2.4 Nanotechnology & Secondary Education

The job of an educator is to prepare students to perform successfully in their future careers, jobs, and other everyday decision-making challenges. Many children desire to be doctors, lawyers, veterinarians and even the next president of the United States of America when they grow up. With the vast changes in technology, “we are currently preparing students for jobs that don’t yet exist … using technologies that haven’t yet been invented … in order to solve problems we don’t even know are problems yet” (Richard Riley, Secretary of Education under Clinton). “Emphasizing that a robust nanoscale science and engineering infrastructure depends on greater progress in education and public outreach, Dr. Mihail C. Roco, Senior Advisor at the National Science Foundation, stressed the importance of early education to prepare American students for future careers in nanoscale science, engineering and technology” (“K-12 …”). Nanotechnology is a broad term added to an ever-increasing technology-reliant society. This, in turn, requires creating a technology savvy public capable of maintaining and applying technology and, even more importantly, able to criticize and judge the way new technologies are introduced in order to assure benefit to the whole society, and prevent abuse and irresponsible use of new technologies. “Further, decision makers need an expanded educational background for them to make optimal choices concerning nanotechnology” (Stinnett 551). Current and future policy makers will establish regulations and approve or disapprove budget spending on nanotechnology research and development, while the public will grant votes to the politicians they trust to be knowledgeable in the matter. The high school students of today are the decision makers of tomorrow. Currently, public knowledge of nanotechnology, its risks and benefits are not known nor have they been completely researched. Therefore, public acceptance or rejection of nanotechnology research and development can be easily manipulated if the public lacks essential knowledge in the matter. “The promise of nanotechnology is challenging today’s young professionals with complexity, interconnectivity and ambiguity. The depth and scope of knowledge required to make decisions is staggering” (Stinnett 551).

Focusing on improving social aspects of nanotechnology research and development, in 2004, the National Science Foundation (NSF) established networks aligned with national goals and outreach programs to target high school and undergraduate nanotechnology education. As an example, the NSF-funded Materials World Modules (MWM) has developed interdisciplinary modules that range from ceramics, biosensors, smart sensors, polymers, food packaging and sports materials. As part of nanotechnology integration into these modules, two new modules have been included for middle and high school STEM classes. Currently, over 35,000 students in school at the national level are using these modules. As a way to provide support for teachers, the MWM also provides a virtual community for teachers to collaborate and get support from other teachers and mentors. In addition, the National Nanotechnology Initiative along with eighty participant agencies in the establishment have developed 85 multidisciplinary research and education centers focused on nanotechnology. “The resources provided by these Nano Centers and Universities are designed as outreach to inform the public along with teachers and students” (Feather 123).

The University of Wisconsin-Madison Materials Research Science and Engineering Center, Materials World Modules at Northwestern University, and the National Center for Learning and Teaching Nanoscale Science and Engineering, also at Northwestern University, and Ohio State University Center for Affordable Nanoengineering of Polymeric Biomedical Devices are just a few of the many academic institutions that are taking the lead in a K-12 outreach program. As part of this program, these institutions are facilitating workshops for teachers that will help them develop and implement multidisciplinary lessons in their classrooms that integrate nanotechnology content. Some of the materials consist of online modules, design-based lessons, hands-on and inquiry-based activities. The content of the lessons and professional development for teachers include molecular modeling, atomic force microscope (AFM) modeling, understanding measurement, and modeling photolithography. Several research centers from various universities such as the University of Wisconsin offer units of activities that include labs suitable for the middle and high school classrooms along with several video lab demonstrations.

Working toward the same common goal, the National Nanotechnology Infrastructure Network (NNIN) supported by the National Science Foundation developed a children's magazine called 'Nanooze'. This is a kid-focused online and printed magazine that is distributed in classrooms, museums and other nanotechnology exhibitions and workshops where kids learn about the aspects of nanotechnology. In this publication, the NNIN educates kids about new advancements on nanotechnology and presents the information in a way in which is fun and easy for kids to understand. Each publication describes ways in which the world of nanotechnology is relevant to their lives and provides information about engineers and experts that work in the field of nanotechnology.

Efforts to educate future generations of college students and the work force similar to the ones cited above are being put in place by many other universities, research centers and organizations. Despite this growing initiative, there is still a lot of work to be done so that nanotechnology can take part in the K-12 education and for minority groups to become involved with the technology that has the potential to cause a change at a global scale.

2.5 Is the K-12 Education System Ready to Integrate Nanotechnology?

In October of 2005, the National Science Foundation gathered members of the Nanoscale Science and Engineering Education (NSEE) for a two-day workshop to evaluate outreach programs implemented in 7^{th} - 12^{th} grade science courses. Other participants of the NSEE workshop included project leaders, material developers, museum designers, and NSF program directors. During day 2 of this workshop, "more discussion time was devoted to challenges than successes. It was noted that the general public and students, in particular, lack fundamental background knowledge upon which to build an understanding of nanoscale phenomena" ("K-12 …" 4). As evidence to the concerns voiced during this workshop, research funded by the National Center for Learning and Teaching in Nanoscale Science and Engineering from the NSF highlights that strong comprehension of size and scale are needed as the foundation to build on basic understanding of nanotechnology. "Conceptually, size and scale are fundamental. They constitute a cognitive framework that helps us make sense of scientific and everyday phenomena. Scale is an important 'common theme' that can link student understandings across topics, disciplines, and grade levels" (American Association for the Advancement of Science [AAAS], 1993, Ch. 11). This research demonstrates that most people do not have a strong understanding of the size and scale, and that students struggle to perform calculations and manipulation of small numbers. Before making space for nanotechnology in the K-12 curriculum, there is a need to close the gap that already exists in the size and scale standards.

As a way to provide solutions, it was concluded that in order to see results in these efforts, there is a need for engaging instructional resources that support learning goals, content-rich professional development for teachers, meaningful integration of technology, and sharing of best practices across teachers, student and researchers.

A research document by Kelly Hutchinson, investigated the interest and motivation that 7^{th} - 12^{th} grade students have in nanoscience related topics. This research concluded that the interest of students in nanoscience was dependent on the application that these topics have in the student's own personal interests, the way it relates to their everyday life, and the hands-on activities experienced in the classroom. In addition, the student's interests in this topic were also related to gender, school context and grade. For example, within the parameters of this research, it was found that middle school students were more interested in science than high school students.

The lesson to be learned from these research results, as well as from the concerns of those who have invested and implemented resources towards the creation of an outreach program that can ensure understanding rather than awareness of nanoscience, is that there is a "need for effective materials that are based on best practices and have been subject to rigorous evaluation" ("K-12 …" 10). There is no doubt that the integration of nanotechnology in the K-12 classroom is a national and worldwide priority. It is essential that standards for K-12 education be developed so that teachers and students have an overview of the various topics that exist within nanotechnology. It is also imperative that best practices are developed and evaluated when teaching current mathematics and science content that support nanotechnology content such as size, scale, and the scientific methodology.

Chapter 3: Background Research

Cohesive forces between molecules inside a liquid are balanced with adjacent ones. Those on the surface of a liquid are unbalanced and as an effect, they exhibit strong attractive forces upon the solid where the liquid rests. These unbalanced intermolecular forces at the surface of a liquid cause surface tension. Thus, the surface tension of a liquid along with external forces such as gravity are responsible for the shape of the drop of a liquid when it comes in contact with a solid (Figure 1). This property can be visualized through the behavior of a drop of liquid on a solid because surface tension, along with gravitation force, is responsible for the shape of the liquid. When a drop of liquid comes in contact with a surface, three different surface tension interfaces can be found. These interfaces are surface-vapor, surface-liquid, and liquid-vapor. These three interfaces stop at the contact line where they come to equilibrium to minimize their surface energy (Figure 1). The contact angle (CA) is formed where a liquid/vapor interface meets a solid surface.

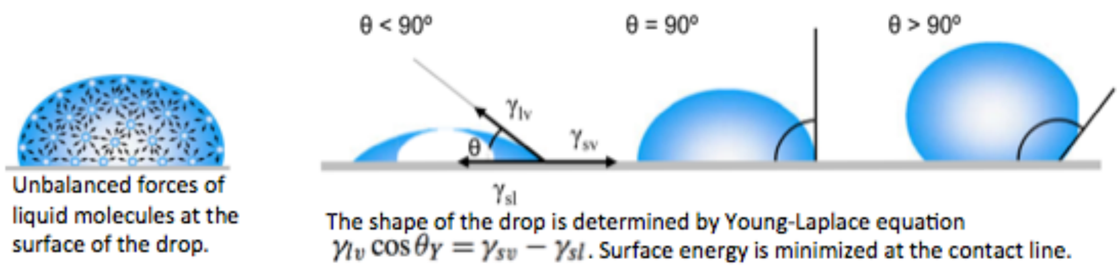


Figure 1: Surface tension and Young-Leplace contact angle. (Yuan and Lee 4-5)

If the liquid-vapor surface tension is smaller than the solid-vapor surface tension, the liquid-solid interface will increase in order to minimize energy. This will cause the contact angle between the surface and the liquid to decrease. If the contact angle of the liquid is less than 30 degrees, it is then said that the surface is hydrophilic, which means that the liquid will wet the surface. However, this does not necessarily mean that the water will easily drain from the surface. If the contact angle is less than ~10 degrees, the surface is then said to be superhydrophilic.

On the other hand, if the liquid-vapor surface tension is greater, then the liquid-solid interface will decrease its energy, resulting in a high contact angle between the surface and the liquid drop. If this contact angle for water is greater than 90 degrees, the surface is then hydrophobic, which means that the liquid will not wet the surface. Surfaces that display contact angles greater than ~120 degrees are identified as superhydrophobic. Surface tension values for liquids can be measured through lab procedures but the solid surface tension cannot be directly measured.

To obtain the surface tension value for a solid, the Zisman method can be used. This is based on Zisman's experimental findings that a liquid spreads freely on a surface if its surface tension is less than or equal to the surface tension of the solid where the liquid is dispensed. Further, critical surface tension occurs when the surface tension value of a liquid is equal to the surface tension value of a solid. At the critical surface tension values, the liquid will completely wet the solid surface, which will cause the contact angle to approach zero degrees. To obtain the critical surface tension value, the Zisman plot shows values for the surface tension of different liquids that are plotted against the cosine of their contact angle. With enough values, a line of best fit is used to extrapolate the surface tension value when the $\cos(\theta) = 1$, meaning the CA=0. It is at this point when an approximate value for the surface tension of a solid can be found. In addition, the Zisman plot can be used on flat surfaces when reliable measures of CA for various liquids with different surface tensions are used.

To attain hydrophobic properties, chemical treatments of a surface can be used to change its surface tension, which can result in hydrophobic properties. The theoretical maximum contact angle is 120 degrees on a chemically treated surface.

“Thus, the only way for realizing ultra-hydrophobicity surfaces indeed consists in designing textured (hydrophobic) surfaces”(Yuan and Lee 1**)** .

The introduction of roughness to the surface leads to the general behavior $\cos(\theta) = r \cos(\theta^*)$, where θ is the contact angle on the blank (flat) surface, θ^* is the contact angle on the rough surface and r is the roughness factor, by definition larger than unity (Quéré 76). The qualitative implication of this equation is that roughness enhances the wetting / dewetting properties observed on the flat surface, i.e. if the CA was less than 90 on the flat surface, the introduction of roughness will make the CA even lower. On the other hand, if the CA on the flat surface is higher than 90, introduction of roughness increases the CA to higher value than originally observed on the flat surface. At his point we will stress that in reality the quantitative interpretation predicting,

$\cos(\theta)/\cos \theta^* = r$ (constant).

This is not necessarily valid, as we shall see below.

Further, to measure the impact that a textured or imprinted surface imposes on contact angles, the KAO comparison method is used. This treatment was first carried by the Japanese KAO Corporation (Quéré 80). In the KAO experiment, the cosine of the apparent angle ($\cos\theta^*$), which refers to the CA taken on the textured surface, was plotted against the cosine of the CA taken on a flat surface ($\cos\theta$) of the same chemical composition. This comparison was done with the use of several liquids with different surface tensions. From the experiment conducted by the KAO Corporation, two different regimes can be observed, one on the hydrophobic side and the other on the hydrophilic side (Figure 2).

On the hydrophobic side, on the x-axis, $\cos(\theta)$ reached only up to -0.3, which corresponds to a contact angle of 110 degrees. However, when observing the y-axis, the cos(θ*) values were close to -1, which means that their contact angles reached values close to 170 degrees. These findings were particularly important because chemically treated surfaces are only able to reach values up to 120 degrees. On the hydrophobic state, the roughness enhances hydrophobicity. The wetting behavior proposed by Cassie and Baxter assumes that hydrophobic rough textures enhance hydrophobicity by trapping the air between the open films on a textured surface. (Martines et al. 2098). Thus, the Cassie-Baxter model is used to explain wetting behavior of the superhydrophobic textured surfaces. Thus, a new treatment to make surfaces superhydrophobic was shown to work with the KAO comparison method. On the hydrophilic side, when cos(θ) is greater than 0, cos(θ*) increases linearly with cos(θ). At this hydrophilic level, Wenzel's model of wetting shows how the liquid follows the textured patterns on the surface but does not travel beyond the liquid drop. (Figure 3) However, after the contact angle reaches a critical value, the cos(θ*) values become closer to 1, which means that the contact angle approaches 0 degrees. The behavior in this regime of data points displays a different behavior from Wenzel's contact angle. This difference refers to the expansion of the liquid into the textured films beyond the drop. This new behavior is known as hemi-wicking and is a result of superhydrophilic properties.

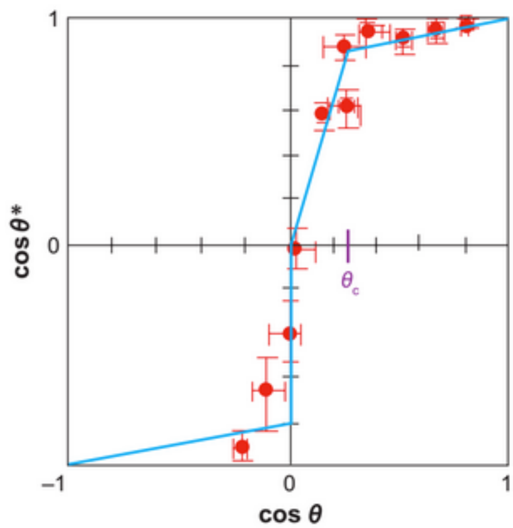


Figure 2: Cosine of the apparent contact angle θ* on a textured surface as a function of Young contact angle measured on a flat surface with the same chemical composition. (Quéré, 77)

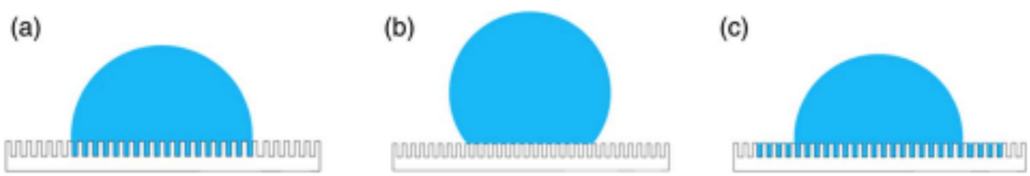


Figure 3: Wetting behaviors. A) Wenzel contact angle (b) Cassie-Baxter wetting and (c) hemi-wicking. (Vereecke et al. N3097)

Along with the chemical changes of a surface, physical changes with the introduction of roughness can change the surface tension of a solid and thus, change its wetting properties.

Chapter 4: Methods

The goals that guided the research were to practice the treatment of surfaces physically and chemically and to obtain results about surface wetting properties. The treatments to the surface investigated were physical surface modification techniques by imprinting anisotropic patterns, and chemical surface modification techniques through silanization. Silanization is a chemical change of a surface by covering it thoroughly with organofunctional alkoxysilane molecules. Mineral components like glass and metal oxide surfaces can all be silanized because they contain hydroxyl groups that attack and displace the alkoxy groups on the silane, which forms a covalent Si-O-Si bond. When silanes are applied to glass, they decrease the adsorption of polar compounds and minimize the triggering of lymphocytes, platelets, or other cells that can occur when untreated glass vessels are used.

As part of physical modification, nano-imprint lithography was used to create anisotropic imprints of approximately 50 nanometers. Contact angles of liquid on non-treated and treated surfaces were tested.

4.1 Materials

The materials used for this research were chemicals, substrates, a goniometer, and Microsoft Excel and ToupView software.

1) Chemicals:

- Surface cleaners
- Isopropanol
- Sulfuric acid
- Distilled water
- Silane solution
- Hexane
- Toluene

2) Substrates - used to practice imprint lithography and silanization treatment

- Microscope slides (only silanized, these were not imprinted)
- Imprinted glass wafers:

- WF – 3
- WF – 4
- WF – 5
- G2
- G3

3) Goniometer – system used to dispense drops of liquid through a needle in a controlled manner on various surfaces while a camera lens magnifies the view of this event. The goniometer connected to the camera and the software ToupView.

4) Software used to capture, measure and analyze data:
Microsoft Excel - use to document the contact angle measurements, and plot the values to create scatterplots.
ToupView - was used to capture images of the contact between the liquid and the surfaces tested.

5) Contact angle liquids – these liquids were chosen based on their surface tension values and their low-toxicity levels, and are listed in the table below (Table 1).

Liquids	**Surface Tension (dyne/cm)**
Fomblin	2
Methyl isobutyl ketone (MIBK	24
Hexadecane	27.5
Diethyl adipate	30
Benzyl alcohol	39
Dimethyl sulfoxide (DMSO)	44
Glycerol	64
Water	72

Table 1: Liquids used and their surface tension values.

4.2 Preparation of Materials:

All procedures were conducted inside a class 100 cleanroom. A cleanroom is an environment used for manufacturing or to conduct scientific research where pollutants and contaminants levels are low. In this type of cleanroom, the environment contains less than 100 particles (0.5 microns or smaller) per cubic foot of air.

4.2.1 Physical Treatment of Wafers Using Nano Imprint Lithography

To pattern the glass wafers, they go through the process of nano-imprint lithography. The first step in this process is to deposit a liquid photoresist material over the silicon dioxide wafer. A template is then use to mold an imprint pattern onto the photoresist. During this process, the wafer is exposed to UV light that solidifies the photoresist. The template is removed from the photoresist and at this point plasma etching is introduced to remove residual layers of photoresist. Next, the wafer goes through a second etching process where the pattern goes beyond the photoresist and is transferred onto the glass. To remove any photoresist layers on the glass, the wafers are placed in an acid bath. Figure 4 shows a schematic of the process. The imprinted pattern is only done at the center of the wafers; thus, each wafer has a blank non-imprinted area.

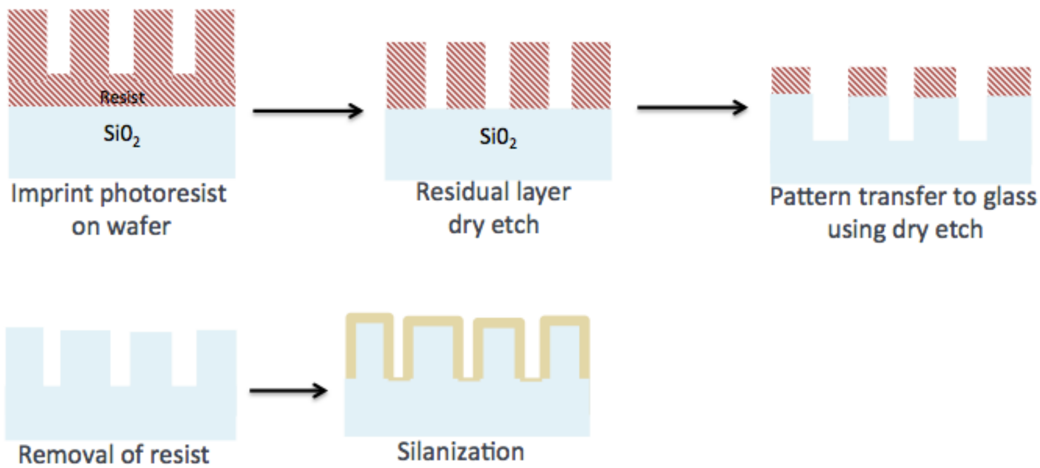


Figure 4: Schematic of the imprint lithography process.

The set of wafers WF-3, WF-4 and WF-5 were etched for 6, 30 and 10 minutes respectively using a predetermined etching recipe. The set of G2 and G3 were etched for 10 and 5 minutes respectively using a different predetermined etching recipe. Figure 5 shows scanning electron microscope (SEM) pictures that show anisotropic print on the wafer.

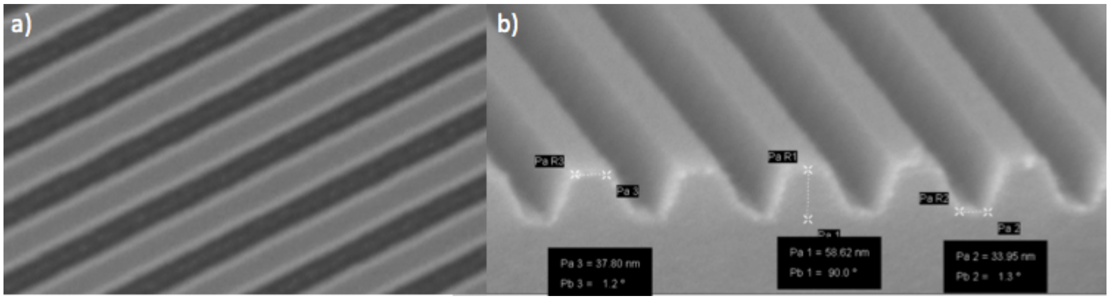


Figure 5: SEM images of anisotropic imprint. a) Shows top view of imprint. b) Cross-section view showing dimensions of ~58.62 nm height and top width of ~37.80 nm.

4.2.2 Chemical Treatment Using Silanization

To silanize the microscope slides, three slides were halfway dipped in silane solution in a closed container for 5 seconds, 30 seconds and 60 seconds respectively. Another two microscope slides were halfway dipped in a solution of silane and hexane, one for 60 seconds and the other one for 120 seconds.

Imprinted wafers WF-4, WF-5, G2 and G3 were split into two parts, A and B. Vapor phase silanization was performed for wafers WF-3, WF-4A, WF–5A, G2A and G3A. Wafers WF-4B, WF-5B, G2B and G3B were not silanized to serve as control samples. For the process of vapor phase silanization, a silane solution with hexane was placed in a closed container for 120 seconds. After this, the wafers were placed with the imprint facing down inside the container on a platform that suspends the wafer by holding it from three small areas. Each wafer was left in the enclosed container with the solution for 120 seconds. Once the wafers were removed from this container, they were washed with isopropanol and then dried with an air gun.

4.3 Contact Angle Measurement Procedure

Once the surfaces were prepared through the imprint, silanization and cleaning process, they were ready for their wetting properties to be investigated through their contact angle measurements. To capture and measure the contact angle a goniometer was used to place the surfaces on a leveled platform. The goniometer uses a camera lens that is connected to the computer and ToupView software was used to measure the contact angle. Measuring the contact angle requires taking the measurements when the drop is advancing and when the drop is receding. An advancing contact angle occurs when the drop intakes more liquid from the needle without increasing the area where the drop rests on the surface. On the other hand, a receding contact angle is taken when liquid is removed from the drop; the measurement is taken when the area where the drop rests on the surface decreases (Figure 6). Since we cannot take contact angle measurements while the drop is in motion, ToupView software was use to snap pictures of advancing and receding contact angles.

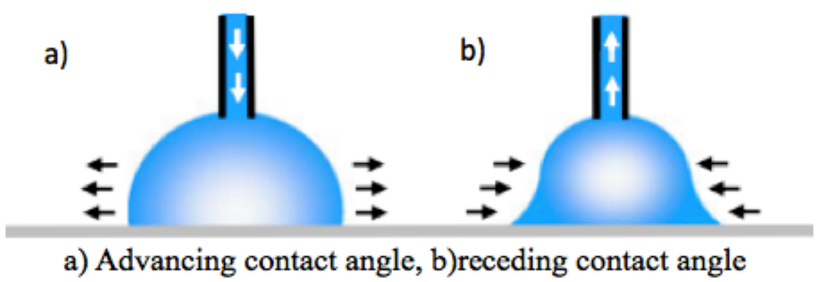
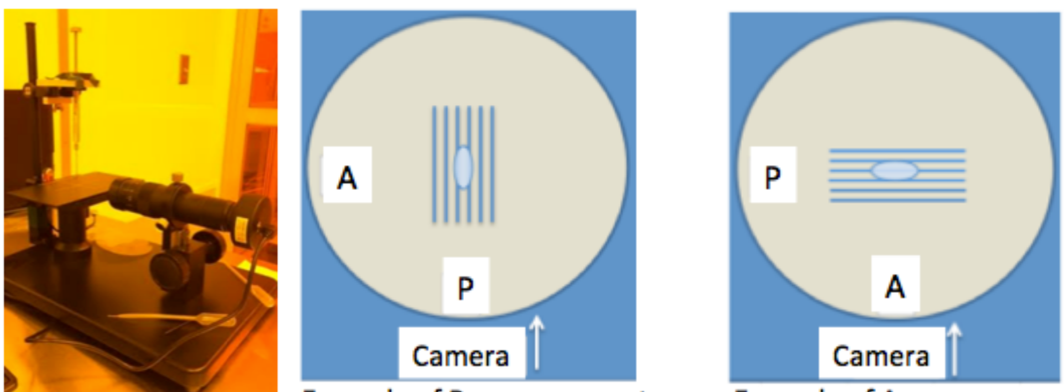


Figure 6: Advancing and receding contact angles. (Yuan et al. 6)

Since the pattern we used for our imprinted samples was different across the X vs. Y axes, measurements had to be taken with respect to the orientation of the patterns. An 'A' orientation contact angle measurement refers to the position of the wafer when the camera lens was perpendicular to the imprinted lines on the wafer. A 'P' orientation contact angle measurement refers to the position of the wafer when the camera lens was parallel to the imprinted lines of the wafer (Figure 7). Contact angle measurements were taken on imprinted areas at A and P orientations and at blank (with no imprinted patterns) areas on the wafers that were silanized (WF-3A, WF-4A and WF-5A), as well as on the wafers that were not silanized (WF-3B, WF-4B and WF-5B). To obtain a diverse representative sample, contact angle was measured on different areas of the wafers and measured across orientations A, P and blank (flat non-imprinted) areas. These measurements were taken using water as our primary surface-liquid interface; however, other liquids were also tested in order to investigate correlations for the Zisman plot for wafer G2-A at different orientations.



Goniometer Example of P measurement Example of A measurement

Figure 7: Goniometer and examples of A and P orientation measurements. Experimental results obtained using goniometer made in the NASCENT Lab. A and P measurements were taken using this goniometer.

Chapter 5: Results and Discussion

5.1 Effects of Nano-Imprint Lithography on Contact Angle

Table 2 below displays advancing and receding contact angle measurements made on A and P orientations of the imprinted and blank areas on the wafers. For this procedure, the goal was to find the physical treatment of a surface to produce hydrophobicity. Since we are only comparing the effects of the imprinted patterns on contact angle, the surfaces of these wafers were not silanized by the time the CA measurements were taken. The difference between the wafers is the amount of etching time that each wafer underwent during the imprint lithography process. From Table 1, imprinted wafer WF-5 shows meaningful results by displaying higher CA compared to wafers WF-3 and WF-4. Using the blank area as the controlled sample, Table 1 shows that there is an effect on the CA of the imprinted area compared to the blank area on WF-5. The difference between advancing contact angle on WF-5 blank area compared to imprinted area is 20 degrees. In addition, it can be observed that the CA values are greater on the P orientation when compared to the values obtained at the A orientation. The wafers that had the least CA effect were WF-3, G2 and G3. The CA increased by approximately two to four degrees on wafers G2 and G3, and eight degrees on the P orientation. In the case of wafers WF-4, the CA turned out to be larger in the blank area than on the imprinted area. Exposed glass wafers are very sensitive to contaminants and that can explain the high contact angle obtained for some of the samples. In addition, angles smaller than ~10 degrees are hard to measure objectively.

Wafer	Etching Time	Height (nm)	Width (nm)	Contact Angle (degrees) (adv / rec) Not Silanized		
				A	P	Blank Area
Imprinted wafer 4	30 mins	157.2	90.97	9 / 4	12/ 11	25 / 9
Imprinted Wafer 5	10 mins	N/A	N/A	40 / 11	53/ 11	33 / 8
Imprinted Wafer 3	6 min	63.62	56.73	3 /	8 /	~ 0
G2	10 min	100.6	63.4	7 / 8	11 / 10	9 / 7
G3	5 min	50.82	56.22	10 / 15	10 / 11	8 / 12

Table 2: Dimensions and contact angles for non-silanized wafers.

5.2 Finding the Best Silanization Process

Before silanizing the imprinted wafers, the best silanization method to produce hydrophobicity was tested on microscope slides. From the three slides that were dipped in silane, it was found that a time of 120 seconds produced higher CA values. When the solvent hexane was introduced into the silane, the CA increased. The slides were intentionally dipped only halfway inside the silane-hexane solution so that the non-dipped portion served as our control sample. After comparing CA values on the dipped and non-dipped portions of the slides, it was found that the CA was higher on the non-dipped portion of the slides. This suggested that vapor phase silanization took place. To check our hypothesis, vapor phase silanization was done on slide #A1 for a period of 120 seconds (Table 3).

Sample	Silanization Time	Silane solution	Contact Angle (adv / rec)	
			Dipped	Not dipped
Slide # 3	5 sec	Silane only	48 / 20	82 / 55
Slide #1	30 sec	Silane only	59 /	92 /
Slide #4	60 sec	Silane only	66 / 43	98 / 90
Slide # 11	60 sec	Silane & Hexane	73 / 52	98 / 83
Slide #A1	120 sec	Silane & Hexane	n/a (vapor)	102 / 93

Table 3: Contact angle of microscope slides silanized under various conditions.

5.3 Effects of Silanization and Imprinted Patterns on Contact Angle

To investigate the effects of the imprint on CA, measurements were taken on non-silanized wafers for A and P directionality and on blank areas. For this procedure, the effects of imprinted and silanized wafers on CA were measured and analyzed.

Table 4 displays CA of five different wafers that were etched for different times. The different etching timings and conditions lead to different geometric dimensions on the anisotropic patterns for each wafer. In the table, height and width refer to the height and width dimensions in nanometers of the imprinted patterns. Keeping consistent with CA measurements taken on the non-silanized wafers, CA taken at orientation P also shows higher CA values when compared to values obtained at the A orientation. From the table, WF-3 and G2 reached the highest CA values. The values that reached 150 degrees display CA values of a super hydrophobic surface.

Wafer	Etching Time	Height (nm)	Width (nm)	Contact Angle (degrees) (adv / rec) Silanized		
				A	P	Blank Area
Imprinted wafer 4	30 mins	157.2	90.97	121 / 101	128/ 89	106 / 90
Imprinted Wafer 5	10 mins	N/A	N/A	118 / 69	140 / 58	107 / 84
Imprinted Wafer 3	6 min	63.62	56.73	105 / 80	151 /	96 / 92
G2	10 min	100.6	63.4	130 / 111	150 / 95	106 / 86
G3	5 min	50.82	56.22	113 / 84	120 / 76	104 / 83

Table 4: Dimensions and contact angles for silanized wafers.

5.4 Contact Angles and Hemi-wicking of Wafers G2 and G3

The procedures to measure the water CA on these samples were the same as the ones followed for wafers WF-3, WF-4 and WF-5. For this set of wafers, silanized G2 wafer at P orientation demonstrated one of the highest CA. Similar to WF-3, G2 reached CA values of approximately 150 degrees (Table 5). However, since WF-3 and G2 were etched under different conditions, their etching times could not be directly compared. Thus, the similarity on their CA can be further explained with the geometry of each imprinted pattern.

In addition to testing water contact angles, G2 and G3 were the only samples on which multiple liquids were tested. For example, hexadecane was dispensed on silanized and non-silanized wafers G2 and G3, and showed hemi-wicking behavior. However, hemi-wicking appeared to be more aggressive on both silanized and non-silanized wafer G2A and G2B when compared to G3A and G3B. The hemi-wicking behavior indicates that when the liquid is dispensed on the wafer, the liquid propagates from the drop into the texture of the imprinted patterns of a solid. The opposite case occurs when air is trapped between the liquid and the textured features of a surface. Wafers G2A, G2B, G3A and G3B demonstrated hemi-wicking behavior for hexadecane, DMSO, MIBK, and Benzyl alcohol. Another important observation is that the hemi-wicking effect was not seen when water was dispensed on either of the wafers. Fomblin was also used to check for wetting properties but this chemical compound showed no hemi-wicking on the wafers despite its very low surface tension. The reason may be associated with the much higher viscosity of fomblin. Another liquid used was diethyl adipate. It was hard to check for hemi-wicking on this liquid because it easily spreads on the surface with low CA values.

5.5 Zisman Plot

CA measurements were taken on the silanized wafer G2A at orientations A and P, and on blank areas using water, hexadecane, DMSO, glycerol and benzyl alcohol. The purpose of collecting these contact angles was to plot these values on the Zisman plot and estimate surface tension values of the wafer.

To obtain the values needed to make the Zisman plot, the surface tensions of the liquids were placed on the x-axis and the cosines of the contact angles were placed on the y-axis. A plot was made for the CA obtained at the blank area (Figure 8), at orientation A (Figure 9) and at orientation P (Figure 10).

For the Zisman plot with contact angles for blank (not imprinted) areas and orientations A and P, linear regression was performed. To estimate the surface tension of the blank surface, the line of best fit was used to extrapolate the surface tension value at which the $\cos(\theta) = 1$. This is done because when $\cos(\theta) = 1$, the contact angle is 0 which implies that the liquid is able to spread freely on the surface. This behavior is an indication that the surface tension of the liquid is lower or equal to the surface tension of the solid upon which it is spreading. This point is known as the critical surface tension.

The surface tension value estimated for G2A at the blank area was approximately 14.6 dynes/cm.

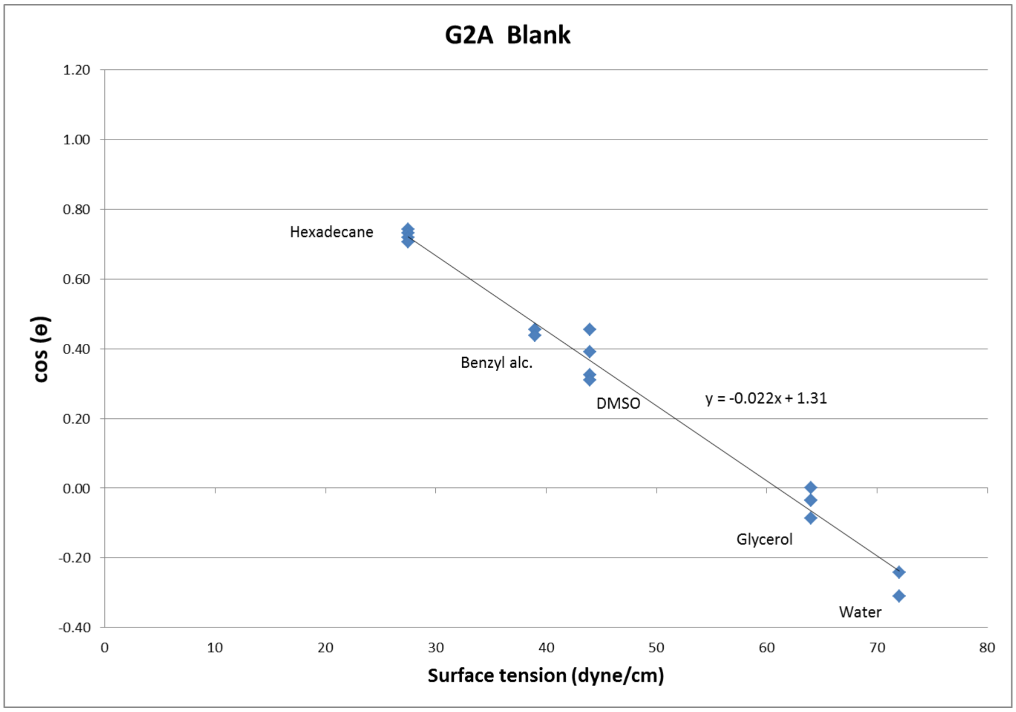


Figure 8: Scatterplot that models the cosine of the contact angle and surface tension of the liquids that were tested on wafer G2A's blank area.

For the patterned area in both orientations A and P (Figs. 9 and 10 respectively), the behavior in not so simple anymore. It can be noticed that the qualitative effect of the roughness induced by imprinting where wetting / dewetting behavior is more extreme in both orientations.

Figure 9 shows results for G2A at orientation A. There is no straightforward linear trend. We see a cluster indicating high wetting (cos(θ) close to 1) for hexadecane, benzyl alcohol and DMSO and another cluster indicating dewetting (cos(θ) <0) for glycerol and water.

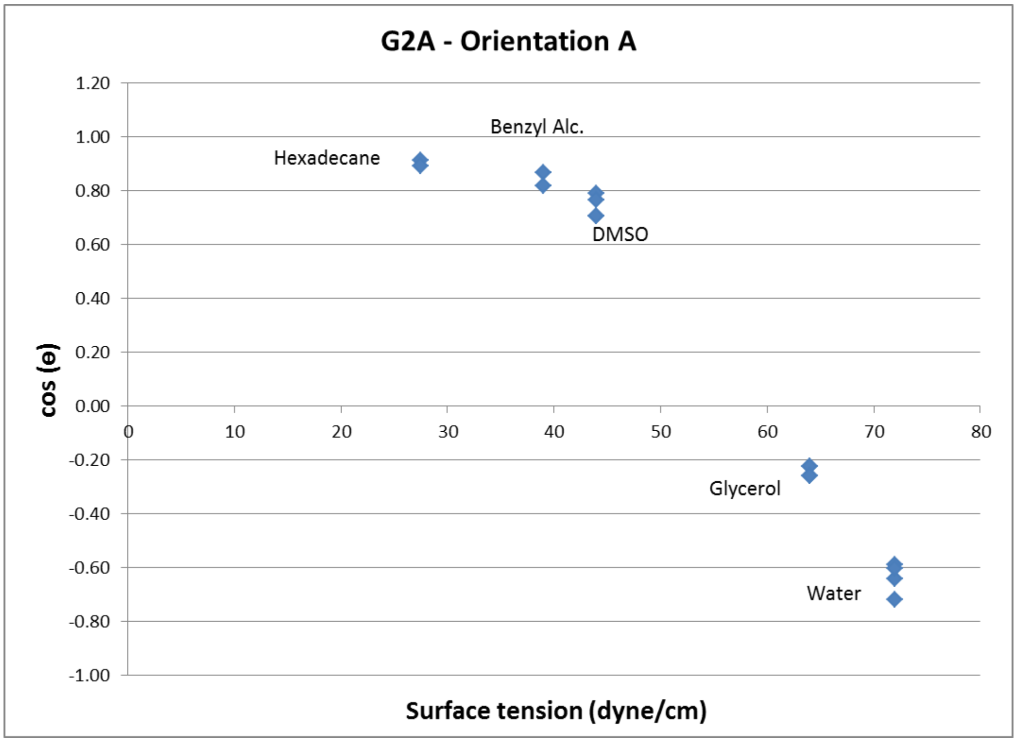


Figure 9: Scatterplot that models the cosine of contact angles and surface tension of various liquids tested on wafer G2A at orientation A.

Figure 10 shows more extreme behavior where we have two data clusters. One cluster indicates high wetting by hexadecane, benzyl alcohol and DMSO, and a second cluster shows high dewetting by glycerol and water. In each cluster, the contact angle is very similar despite the considerable differences in surface tensions of the liquids.

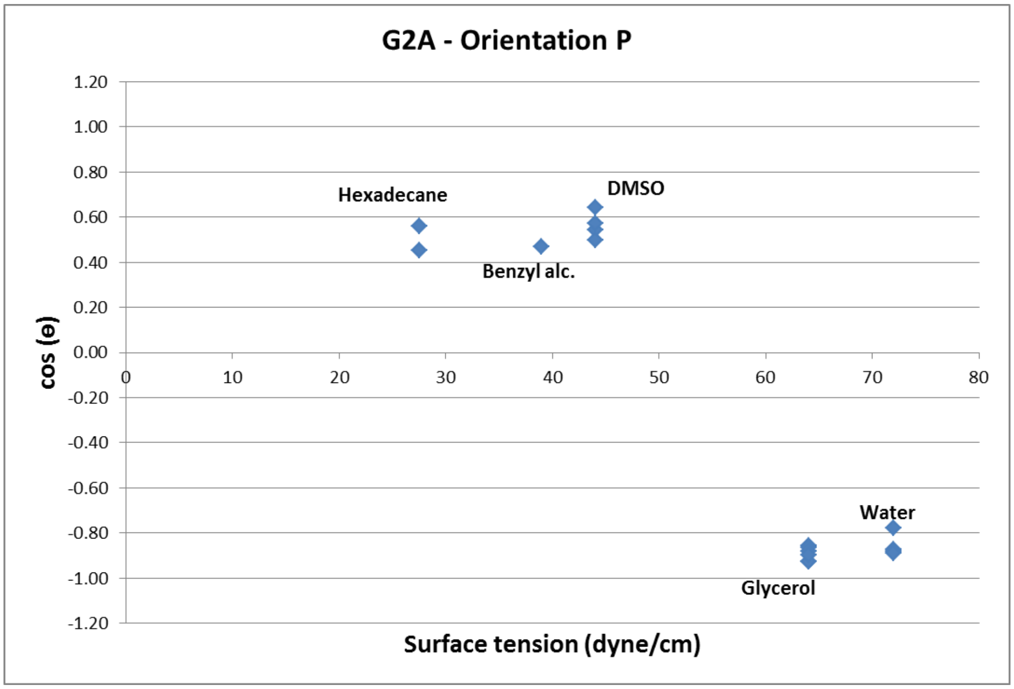


Figure 10: Scatterplot that models the cosine of contact angles and surface tension of various liquids tested on wafer G2A at orientation P.

5.6 The KAO Treatment

Using the same comparison method that the KAO Corporation used, the cosine of the apparent contact angle θ* on the imprinted surface was plotted against the cosine of the angle taken on a blank surface of the same chemical composition. In Figure 11, the apparent contact angle refers to the angles measured at the P orientation. In Figure 12, the apparent contact angle refers to the angles measured at orientation A. In both graphs, clustered data points can be seen at regimes when cos(θ) is negative and when cos(θ) is positive.

Figure 11 for orientation P already shows that cos (ɵ) /cos (ɵ*), discussed in chapter 3 above, is not constant. The cluster for water and glycerol corresponds to the Cassie-Baxter model where the liquid is on top of the imprint and does not penetrate into it, while the second cluster corresponds to the hemi-wicking regime where the liquid not only penetrates through the imprints but continues further (see figure 3 and right inset in figure 11).

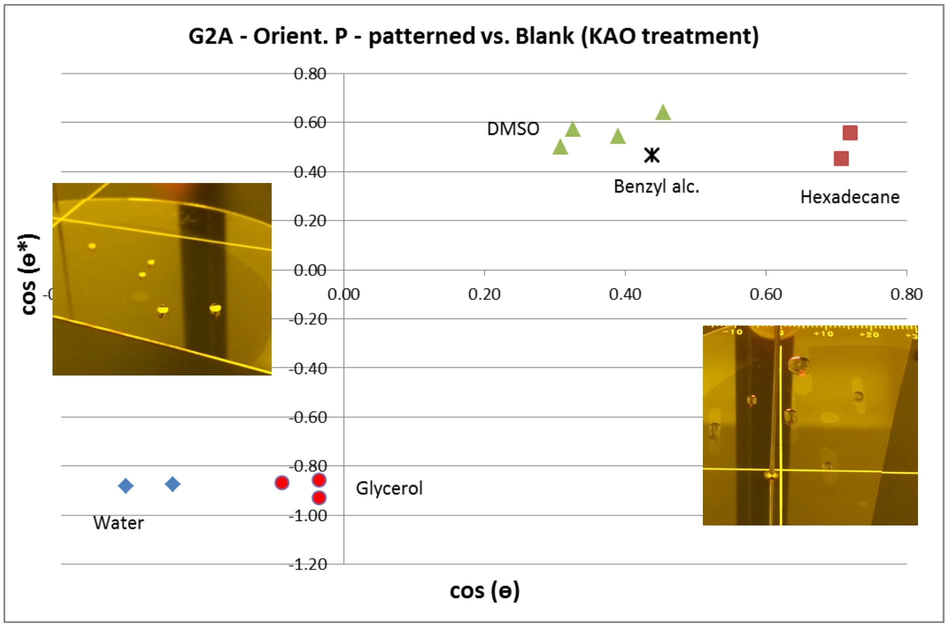


Figure 11: KAO comparison for apparent contact angle at P orientation vs. blank surface. Insets show water drops (left) and hemi wicking hexadecane drops (right).

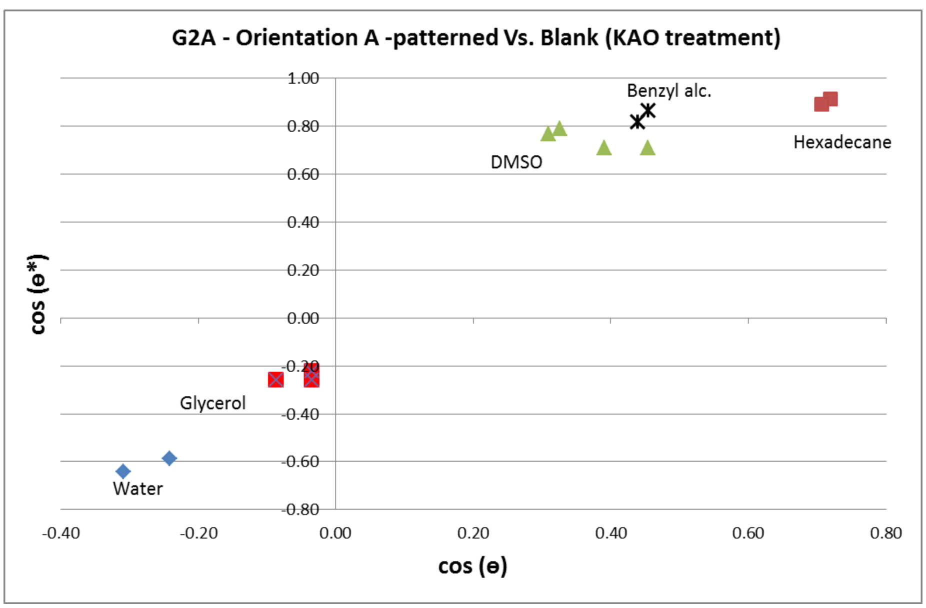


Figure 12: KAO comparison for apparent contact angle at orientation A vs. blank surface.

Figure 12 shows the KAO treatment for orientation A. Again we have a data cluster of the same liquids showing hemi wicking as seen for orientation P. Note that cos (ɵ*) in the A orientation for these liquids is considerably higher compared to orientation P. This is due to the contribution of wicking along the lines, as it is easier for the drop to spread on a surface composed of its own material.

The second data cluster for water and glycerol is not as well defined. It appears as if the glycerol data corresponds to the third possible regime of Cassie-Baxter (Fig. 3a) where there is partial penetration into the imprinted texture.

Overall, when comparing CA on silanized and non-silanized wafers, CA values taken at orientation P were higher than those taken at orientation A (Table 5 & Figure 13).

Wafer	Etching Time	Height (nm)	Width (nm)	Contact Angle (degrees) (adv / rec) Silanized			Contact Angle (degrees) (adv / rec) Not Silanized		
				A	P	Blank Area	A	P	Blank Area
Imprinted wafer 4	30 mins	157.2	90.97	121 / 101	128/ 89	106 / 90	9 / 4	12/ 11	25 / 9
Imprinted Wafer 5	10 mins	N/A	N/A	118 / 69	140 / 58	107 / 84	40 / 11	53/ 11	33 / 8
Imprinted Wafer 3	6 min	63.62	56.73	105 / 80	151 /	96 / 92	3 /	8 /	~ 0
G2	10 min	100.6	63.4	130 / 111	150 / 95	106 / 86	7 / 8	11 / 10	9 / 7
G3	5 min	50.82	56.22	113 / 84	120 / 76	104 / 83	10 / 15	10 / 11	8 / 12

Table 5: Dimension and water contact angles for silanized and non-silanized for wafers WF-3, WF-4, WF-5, G2 and G3.

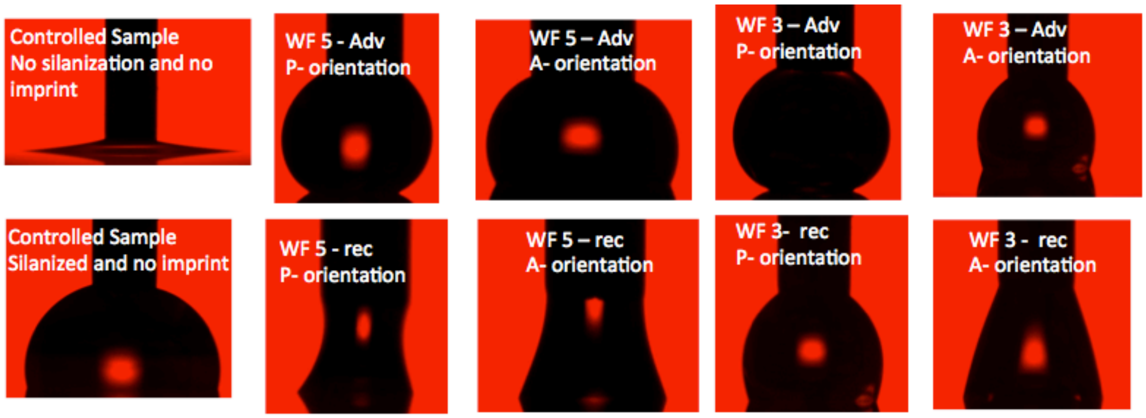


Figure 13: ToupView of water contact angle images.

This phenomenon can be explained due to the flow resistance that the anisotropic imprinted patterns impose on the liquid. For example, it can be seen from Figure 14 that the liquid flows in the direction of the patterned lines but it demonstrates resistance to flow in the parallel direction of the lines. More in detail, when the drop is dispensed at the P direction, it has some difficulty to expand and thus, creates high CA values. On the other hand, when a drop is dispensed on the A direction, the drop can easily travel along the imprinted pattern resulting in lower CA values. Another way to describe it is that along orientation A, the drop front sees 50% (silanized) glass top and 50% trenches already filled with its own material. It is, of course, easy for water to spread on water; thus, spreading is enhanced. On the other hand, at the P orientation, the drop front expands on alternating compositions of glass and trenches, which is less homogenous than the previous case.

Figure 14: Flow and resistance of water drop on anisotropic imprinted pattern.

Hydrophobic silanized surfaces became superhydrophobic when roughness was introduced. From wafer WF-4 it seems that 30 minutes might have been a long etching process time that produced denser lines. Given that all of the wafers underwent the same silanization process, it can be concluded that the difference in CA is attributed to the dimensions of the imprinted patterns. After looking at the SEM pictures (Figure 15), wafer WF-3 shows uniform patterns much like the shape of a trapezoid. Also, the height is larger on wafer G2 than on WF-3. On the other hand, G2 demonstrated less defined patters and round edges (Figure 16). Further, SEM images from WF-4 (Figure 17) show a narrow space between the patterns, a high height value and less smooth area when compared to wafer WF-3. More research is needed to assess the effect of depth and pitch on the CA.

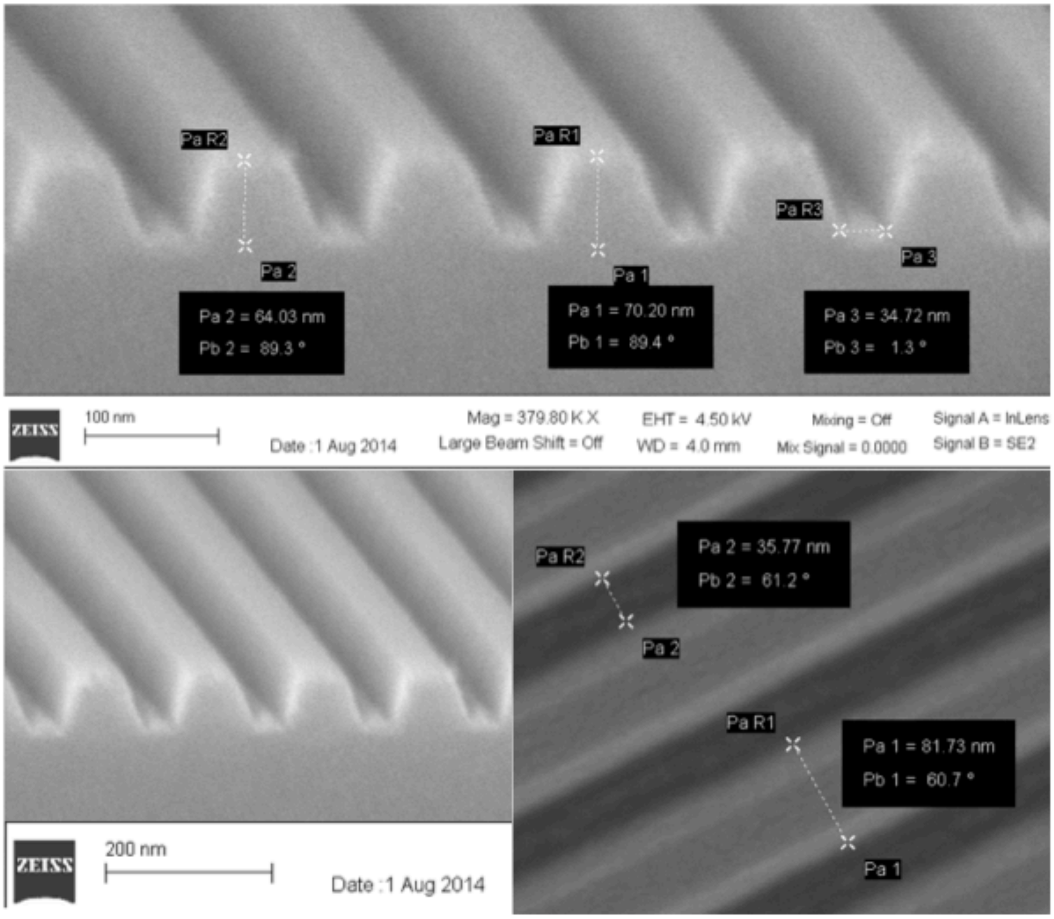


Figure 15: SEM images for wafer WF-3: a) cross section with dimensions, b) larger area cross-section of the imprint and c) top down view shows widths on imprint.

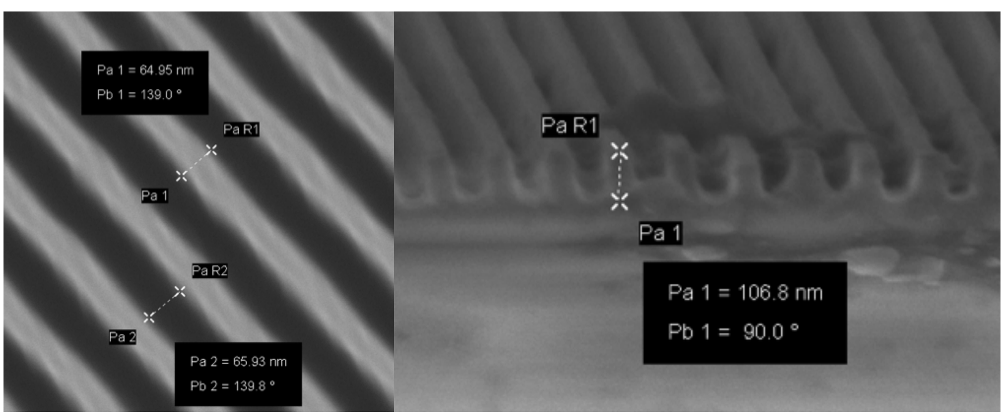


Figure 16: SEM images for wafer G2: a) top down view shows with dimensions, b) Cross-section view shows imprinted pattern with less uniform shape. The aspect ratio is about two.

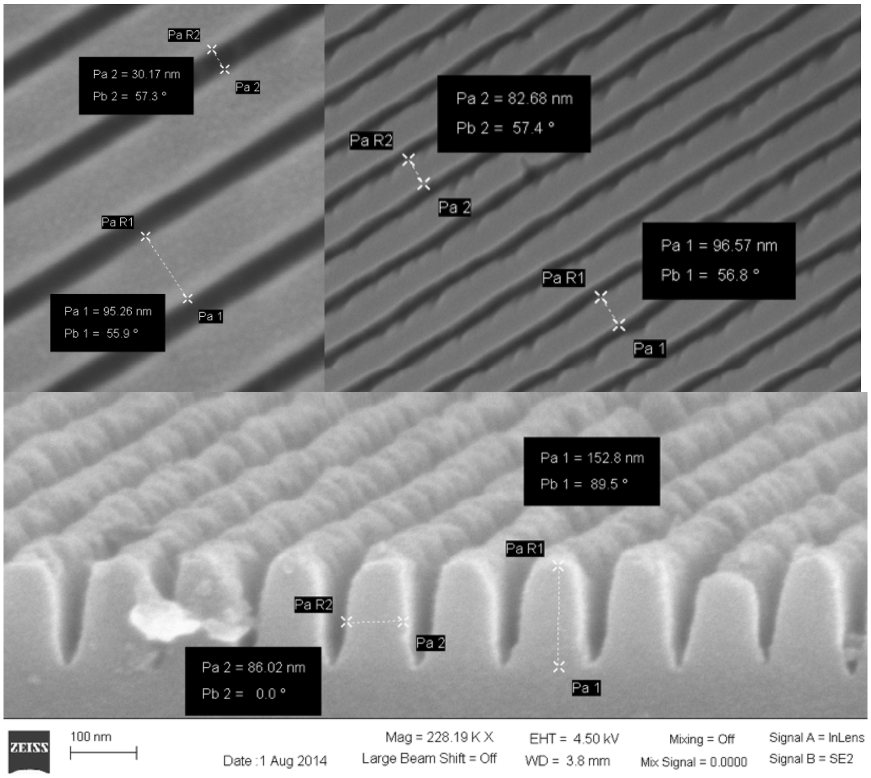


Figure 17: SEM image for wafer WF-4: a) Top down view shows large width but small distance between each line pattern. b) Top down view shows nonuniformities on the imprinted lines. c) Cross-section view shows round edges and tall imprints of 152.8 nm.

5.7 Sources of Error

To measure the contact angle, a picture needed to be taken while dispensing an advancing drop and another one when making a receding drop. The ideal collection of this data needs to happen under sturdy and static position of the needle. While collecting data, there were instances where the needle slightly moved while dispensing drops on a surface. As a result, some of the pictures taken did not always show symmetrical advancing and/or receding drops. In addition, some of these pictures had some shadowing effects at the edge of the drop that made it difficult to obtain a more precise contact angle. Slight hand movements while the mouse was measuring the contact angle caused the contact angle to change. Lastly, contamination of the surfaces and the needle during data collections might have occurred, which might have been responsible for error in contact angle measurements. To avoid these error scenarios, several measurements were taken at different places of the wafers and careful handling of wafers was followed to avoid contamination. In addition, hemi-wicking behavior and low surface tension of liquids made it difficult to obtain strong CA measurements.

Chapter 6: Conclusions and Future Research

Anisotropically patterned samples on glass were produced at the scale of ~60nm with various depths and pitches. A vapor phase silanization procedure was developed to change the surface properties of glass and used it to silanize our samples and compare them with non-silanized samples. Water and other liquids were tested on the samples to evaluate their behavior. Wetting properties were different across the lines vs. parallel to the lines. Silanization induced superhydrophobicity to the samples (water CA >~120). Additional liquids were tested to create a Zisman plot on the silanized blank non-imprinted surfaces and compared the behavior with imprinted samples in both possible orientations parallel to the lines and along the lines. The KAO analysis was conducted and the three wetting regimes according to Wenzel and Cassie-Baxter models were identified.

For future research goals, other liquids with different surface tension values can be tested and then plotted on the Zisman plot. During this research, CA values were obtained for various liquids but they were not tested on all of the wafers. In the future, it will be valuable to test other liquids or mixtures of liquids on wafers with strong hydrophobicity. In this research, the etching time was the variable used to compare the imprinted patterns on the wafers. Therefore, obtaining a more concrete value to evaluate the imprint, such as aspect ratio, can provide a clear way to compare imprints on wafers and their effects on CA values.

Chapter 7: Application to Practice (The Project)

Working with NASCENT gave me the chance to experience an actual research process that followed an experimental design procedure. During this experience, I went through the steps of forming research questions, stating a hypothesis, making a plan on how to treat the samples, identifying the data to collect and how, interpreting and analyzing data to form conclusions and to identify sources of error, and stating future work to be completed on the research topic.

These experiences served as an inspiration to develop learning experiences for my students that will replicate much of the work I completed during the summer. As a teacher, I often find myself explaining to students what it is like to work in the STEM field or what it is like to be a scientist. However, much of what I have explained to them comes from my own observations rather than primary sources. Now that I have completed the research with NASCENT, I will be able to talk to my students about the STEM fields based on the knowledge I gained from my own personal experiences while completing the research.

7.1 Driving Questions and Summary

The driving question for the project is *how can we learn about properties of hydrophobic materials and use this knowledge to evaluate and justify the durability of hydrophobic products currently found on the market?* During this project, students will work in groups of three and learn about the surface tension of liquid solutions at different temperatures. They will investigate these changes by planning and executing their own experimental designs. To complete this project, students will have to research the practices needed to run a lab experiment. Students will also collaborate with other groups during ‘critical friends’ sessions where they will obtain and give feedback to each other on their experimental design process. Groups will then be expected to make improvements based on the feedback they gain. After running the experiments, the students will model their data using algebraic models such as tables, graphs, equations and verbal descriptions. To document their work, students will also write a research paper that highlights all of their work and findings throughout the experiment. While completing the experiment, students will also complete guided research that will help them understand the relationship between surface tension and wettability of a surface. To apply their understanding of results gathered during experimental design students will then test hydrophobic materials that are sold in the market against the solutions used in their lab experiment. Students will justify if a liquid solution will wet a surface using its surface tension by using the data collected during the lab. This data will then be used to predict and explain why some liquid solutions will wet materials while others will not. Also, in order to expose students to information about the STEM work industry, they will investigate careers and companies that deal with the type of work put forth in this project. In addition, students will propose a new product for the market, or enhance a current one, with hydrophobic properties or behavior. On top of documenting their work, observations and conclusions for their research paper, students will lastly be required to present this information to their peers in the classroom and guest experts from the field.

7.2 Entry Event

To introduce the project in an engaging manner, I will start with a short presentation that exhibits nature's living organisms, which demonstrate hydrophobic properties. This presentation will explain how each eye of a mosquito provides them with anti-fogging properties that allow them to see under high humidity conditions. As a second example, I will explain to the students how the surface of a lotus leaf repels water and uses this process as a self-cleaning mechanism. As a second component to the entry event, I will show students a video prepared by NeverWet, LLC (Lancaster, PA), which explains that surface tension is the key factor in creating hydrophobic materials ("Surface Energy Explained"). As the video continues, it also shows two parts of a sheet of cardboard, of which one side is treated with a NeverWet product. The NeverWet product makes the surface become hydrophobic such that when test liquids are being poured onto the cardboard, it does not get wet.

In order to keep students engaged in the project, I also intend to bring hydrophobic materials such as magic sand, (which does not become wet even when submerged in water), hydrophobic fabric, and several samples of the lotus leaf. The goal is to have students wet these materials so that they are able to understand how their hydrophobic properties prevent them from wetting. As the next activity, I will have students write a journal entry where they will provide three products that they commonly use which will benefit from hydrophobic properties. They will also provide an explanation about how these properties will make their product better. The goal with the journal entry is to prompt students to start thinking about the real world application of this project and how it is relevant to their life experiences.

7.3 Experimental Design and Research Paper

This project is designed for an Algebra 1 classroom consisting of 9th graders. From my experiences, students at this level have not had much or any experience conducting research or writing research papers. As far as their Algebra 1 skills go, students come into the class with a limited amount of knowledge about variables, and little to no knowledge about how to make and use algebraic representations. At this level, students need help interpreting data and using it to make decisions and/or conclusions. Therefore, this project will require students to complete guided research that will teach them about the components needed for an Experimental Design (ED). I will guide this research by providing them with a diagram template that students can fill out while completing online research. The diagram includes a place for students to answer questions that will help them build their understanding on what each component in the ED process is and its purpose. For each phase of the ED process, students will answer the following questions:

a) What information goes on each phase of the experimental design?
b) Why is it important?
c) How is this information presented?
d) Does the information have to be presented in an organized manner?

After investigating what an experimental design is and its different components, students will then be ready to begin planning the process they will need to follow in order to conduct their experiment. Students will then present their proposed experimental design to other groups. The purpose of this activity is to prompt students to think critically about possible positive and negative outcomes of the experimental design being discussed and to provide advice accordingly. More than helping them understand the experimental design itself, the students will also learn how to collaborate with one another and begin to cultivate a collaborative learning community in the classroom. While students complete their experiments, they will also be required to document the work done in their notebooks. Since this might be their first research paper, students will be given prompts to complete the abstract, introduction, methods, results, discussion and conclusion components of the research paper. These prompts will serve as a guide to help students understand and complete each one of these components. Lastly, students will make use of example research papers provided to them as references that will act as guiding models for their own research paper.

7.4 Activities and Workshops

To support the development of Algebra 1 content during this project, students will be given different workshops from which they will learn new content material. In addition to the workshops, students will complete several activities through which they will practice this knowledge. To learn about algebraic representations, students will complete a foldable that displays the different ways to model data. This foldable will also display how independent and dependent variables are organized on each algebraic model. As a workshop to teach students about the independent, dependent and controlled variables, they will complete a diagram that describes key components of each variable as well as differences that set them apart. Activities that will be used for students to practice these skills will require students to create different algebraic models from a data set. After creating algebraic models, students will also be asked to identify these variables. A major Algebra 1 skill that students will learn and apply during this project is to construct a line of best fit from a given data set. From the trend line, students will need to extrapolate data that can be used to make predictions and decisions. As a way to foster critical thinking skills in students, they will be asked to explain the advantages and limitations of using the trend line.

7.5 Student Deliverables

To assess the transfer and application of STEM content knowledge, students will be asked to submit different deliverables throughout the project. The first product students will submit will be their experimental design. This document will include the revisions made based on feedback they gathered from other groups during the 'critical friends' session. As a way to assess collaboration, each group will be required to complete a reflection that explains how the 'critical friends' session helped them improve their experimental design. To assess research and engineering content, students will be asked to submit a document that contains the information gained during online research. This online research will include information about surface tension, hydrophobic materials on the market and relevant engineering careers. To help students complete the major research paper, they will be required to submit them in different parts. This will help deconstruct a major end of the project assignment into smaller tasks, which will need to be put together, revised and submitted at the end of the project. As part of the final presentations, students will prepare slides that include major parts of the experimental design and significant components of their research paper. As a final assignment, students will submit their product proposals in which they will provide ideas for a new product that has hydrophobic properties or an existing product that uses hydrophobicity for its enhancement.

7.6 Education Standards

The following are Texas Essential Knowledge and Skills (TEKS) and International Technology and Engineering Educators Association (ITEEA) standards covered in this project.

Algebra 1 TEKS:

A.1A: Describe independent and dependent quantities in functional relationships
A.1B: Gather and record data and use data sets to determine functional relationships between quantities
A.1D: Represent relationships among quantities using concrete models, tables, graphs, diagrams, verbal descriptions, equations, and inequalities.
A.1E: Interpret and make decisions, predictions, and critical judgments from functional relationships.

ITEEA Standard

The Nature of Technology:
Standard 3. Students will develop an understanding of the relationships among technologies and the connections between technology and other fields of study.

Technology and Society:
Standard 6. Students will develop an understanding of the role of society in the development and use of technology.

Abilities for a technological world:
Standard 13. Students will develop abilities to assess the impact of products and systems.

7.7 Engineering Applications

The field of materials engineering is in constant development with the creation of new materials or improvements of existing ones. These materials open doors to the formation of new technologies in all other fields of engineering. With the new advancements in nanotechnology, properties of materials themselves are under research. For example, NeverWet, LLC is a company that specializes in the treatment of surfaces that makes them water repellent. Other companies are structurally changing the surfaces of materials at the nanoscale to induce hydrophobic properties. Currently, hydrophobic materials are being developed to make anti-icing, anti-corrosion, anti-wetting and self-cleaning products. Thanks to the development of hydrophobic treatments, materials engineering has led to the development of products for construction workers such as waterproof work boots and gloves. In the field of medicine, materials have been designed to be non-wettable and self-cleaning to eliminate contamination. Understanding the relationships between a material's properties, structure, processing and performance makes the job of a materials engineer key in development of materials for the improvement and advancement of society.

7.8 Next Steps

My next step is the implementation of this project in my Algebra 1 classes. I am planning on teaching this two-week project towards the end of the first trimester of the school year. Modifications will be made during and after teaching the project. In order to make an impact in the STEM teaching field, I will be posting the revised version of this project on the teachengineering.org website. My goal is to provide reliable resources for STEM projects for other teachers to use.

As a way to bring nanotechnology content in STEM projects, I will continue to collaborate with all the great individuals in the NASCENT program. Future plans include the participation of NASCENT faculty, staff and graduate students in the student presentations part of the project. Along with their collaboration and the knowledge I have gained about nanotechnology, I will continue to find content that can be integrated into the high school mathematics classrooms. Furthermore, it is important to note that this integration of nanotechnology does not require the teacher to re-invent the wheel in their teaching practices. Much of the knowledge needed in the nanotechnology field begins with what is already being taught in our K-12 classrooms. Behavior of chemicals, taking measurements on data gathered, and decision-making based on its analysis are content skills where aspects of nanotechnology education can be successfully integrated.

Chapter 8: Applications to Practice (The MASEE Program)

I applied to the UTeach Summer Master's program because I was working at a STEM school and yet, I knew little about what that meant in terms of theory and much less in terms of practice. Given that one of the letters in STEM stands for Mathematics, which is the subject I teach, I did not know about how STEM education was supposed to be reflected in the day-to-day activities of my classroom and lesson planning. When reflecting on this, I knew I needed to take action in order to do my job right and integrate STEM in my classroom. Once I was fortunate enough to be accepted in this program and took the first few classes, I realized that I was working in an environment that was completely out of my comfort zone. My K-12 and most of my undergraduate classes followed the traditional school setup, which is based on lectures, homework, quizzes and tests; however, the UTeach*Engineering* classes followed a challenged based learning environment where collaboration, research, technology integration and problem solving skills were part of my day-to-day experiences. For example, some projects required us to design an earthquake resistant building under a set budget that had to meet the customer's needs. Another challenge that I had to complete was designing a car with strong aerodynamic qualities while maximizing its passenger and cargo capacity. These and many other engineering challenges that integrated mathematics, science, engineering and technology were completed with the collaboration of several other group members. Different from my existing experiences before UTeach*Engineering*, the collaboration during these projects followed engineering collaboration protocols. In other words, the work done as a group helped everyone enhance their understanding and resulted in the creation of a better-produced product. Prior to this, I viewed collaboration as a 'divide and conquer' approach that allowed groups to complete the work faster.

By working through real world engineering challenges, this Master's program educated me about engineering grand challenges, achievements and the work that needs to be done and/or improved in various fields of engineering. This awareness is now what enables me to continue to research current engineering challenges that can be integrated in my mathematics classroom. The classroom experiences, as well as the research documents that had to be read and discussed in class, have motivated me to seek out more learning opportunities. For example, while not being an engineer, I am constantly trying to learn about new advances in engineering as a way to stay current in this area. In addition, while writing lessons and projects for my students, I try to put myself in the position of an engineer to follow the design process mentally. These actions have allowed me to bring engineering practices into my classroom.

8.1 Developing Engineering Awareness

Before coming into this program, I did not feel prepared to talk to my students about engineering, what engineers do, and far less, I did not have the tools necessary to integrate engineering in my mathematics lessons. Most professional developments I have attended follow a 'sit and get' format that is often not very effective. However, rather than explaining what engineering was all about, the UTeach*Engineering* classes made us work through several challenges that reflected the work that engineers do. Having gone through these experiences, I have not only developed awareness about engineering but I have also gained a deeper knowledge about several engineering practices. This growing knowledge has and will always continue to provide me with the tools necessary to write and teach real-world challenges to my students while teaching the mathematics content.

Although some of what I have learned did not happen during the classes, what I learned provided me with a strong foundation that has allowed me to continue to learn many other important aspects of engineering on my own. For example, I have researched and found several engineering lessons from websites such as teachengineering.org and sciencebuddies.org, and have been able to transform them to integrate them into my classroom. The self-reliance that this program has given me to integrate engineering in my classes is significantly positive. Before starting this program, I did not feel confident to teach many of those lessons, much less being able to transform them to integrate them in my lessons. Nowadays, I am not only able to transform existing lessons but I have also been able to write my own original lessons. For example, for my Geometry students, I wrote a project that required them to re-design a bicycle that would accommodate the needs of their customer audience. While working through this project, students had to follow the engineering design process as they produced a prototype along with collaborating within their groups and other groups to ensure all of the customer's needs were met.

My goal for completing this program is to teach students about the engineering design process while working to advance my engineering knowledge into different disciplines. So far, I have taught lessons in my classrooms that have covered electrical and civil engineering content as well as a reverse engineering/re-design challenge. For future lessons, I am working towards writing projects that integrate biomedical and mechanical engineering.

The classes that I took during this program did not provide me with all that there is to know about engineering, understandably because that would be an impossible task for a field that is in rapid growth. However, I do strongly believe that this program has given me the foundation needed to personally master the necessary knowledge that will allow me to bring real-world engineering integration into my classroom. I am constantly learning about other STEM outreach programs, as well as STEM related topics through science related TV shows, articles and podcasts. By doing so, I am constantly trying to find lesson or project ideas for my students. Similar to the UTeach*Engineering* classes, I believe that teaching engineering practices through modeling and engaging activities results in a far better learning environment for the students.

8.2 Developing Engineering Habits of Mind

Fostering engineering habits to mind is not a practice that can be learned without providing the appropriate experiences. Working through several engineering challenges provided the set up I needed to begin developing these habits of mind. As an engineer, one needs to implement system thinking and observe a system as a whole and in its parts. As a teacher, in order to design engineering lessons to integrate in my classroom, I have to make sure that I am following the mandated state standards for my students. In addition, as a STEM teacher I also have to make sure that my students are able to learn and understand content knowledge by applying it to solve real-world engineering challenges. Designing and writing lessons, assessments and scaffolding activities that will support the learning goals for students requires me to think of the planning process as the bigger system. Within this system, each classroom activity and assessment is a smaller part of the system that must support the others in order to create lessons and projects that will result in student achievement. Thus, just like an engineer observes systems as a whole and its parts, in order to understand and obtain feedback from a system, as a teacher, I need to understand the learning goals for my students and understand how each component of the lesson can provide me feedback to monitor the effect of these components on student learning.

For teachers, our main goal is to target the learning goals of the students, and for students, their goal is to find the best design of a solution or product. To help my students understand the overall problem of a project, I am constantly helping them focus on the overall driving question of their project. In addition, the daily agendas for my classroom are worded in a way that demonstrates how the daily activities are helping them scaffold the design for their solution or product. Before beginning to work towards a solution, it is necessary to begin with the system's understanding and quantification. Understanding a system requires modeling of the inputs and outputs, using research and data analysis techniques. As a teacher, in order to understand and quantify learning goals of students, I use the backwards design process of a lesson, which helps me target student needs. During this process, I use student data such as previous test scores and homework grades as a way to understand what the real students' needs are. For students, I try to foster understanding of the problem presented by requiring them to gather information through research and data analysis. For example, during one of their projects, students were required to investigate and identify ways to reduce electricity consumption at home. In order for them to do this, they had to complete research about what electricity was, how it is supplied to their houses, and why is it important to save energy. As a next step, students collected and modeled data about power consumption of different household electronics. Doing so allowed them to fully understand the project they were working on. Designing lessons that successfully integrate content and real world applications that engage a student's interests is not an easy thing to do. Creativity has been one of the most challenging steps during lesson planning, project designing and writing. I am constantly making observations of the things I learn about engineering and am always thinking of different ways in which I can make them a part of my classroom.

Students are highly creative, but the traditional classroom setup does not always allow for the development of their creativity. However, when working through projects, I have found that students have little to no trouble being creative. Thus far, fostering creativity in my students has only required me to monitor and facilitate the process. As a teacher, it is my job to make sure that this process does not take longer than needed and that their ideas take into account the criteria and constraints imposed by the customer. Coming up with a solution restricted by different parameters requires innovation and creativity in order to apply different design approaches and concept generation techniques. As a way to ensure that the chosen solution is the best solution, engineers have to verify if the solution has truly met the requirements based on constraints established by the customer.

In terms of designing, writing and teaching the lesson, I verify the content understanding of my students through formative assessments. With this information, I either modify or create better learning opportunities for the students. To teach students how to verify their own work, I provide them with a rubric that lays out expectations and criteria for their work and solution in a progressive manner. For example, the rubric describes what emerging, intermediate and advanced levels of student work looks like. Through the course of these projects, I provide the students with opportunities to verify the progress and quality of their work by completing rubric checks during team meetings.

Communication of the understanding of the system as well as the development process of a solution must be demonstrated through clear and careful documentation in order to allow understanding, verification, feedback and replication of the engineering design process employed. Therefore, it is important for engineers to keep careful and detailed documentation of every taken step, observation made, data collected and any conclusions they derive. As part of the documentation process that I always complete when designing a lesson is that I fill out a lesson planning form that allows me to document and communicate my work during the stages of lesson planning, teaching of the lesson or project, and my analysis after having taught the lesson or project. As far as facilitating communication for students, I required them to keep an interactive notebook where they document their work through journal entries, sketches and group reflections. From my experiences, students do seem to struggle with writing the appropriate details of their work, reflection and conclusions; however, I have been able to help them improve on this skill by modeling the process by keeping my own personal design notebook and by providing them with constant feedback on their work.

Since two brains are more effective than one, engineers need to collaborate with others, not necessarily to divide and conquer, but to enhance each other's understanding, which will lead to a better solution and/or product.

As a teacher, I must also keep in mind that the lessons and projects I write on my own might not be academically strong unless I collaborate with other mathematics, science, humanities and engineering teachers. Being a STEM teacher requires me to have a strong knowledge of science and engineering. Having a background in mathematics and lacking much of the engineering and science knowledge, I am constantly collaborating with the science and engineering teachers at my campus. While collaborating with them, they provide me feedback on the positive and negative aspects of my lessons and projects, as well as provide advice on next steps that I can take in order to improve my lessons and projects. Currently, I am also working on making arrangements that will allow me to collaborate with undergraduate and graduate engineering students to design more engineering projects for my classroom.

Working at a school where the curriculum is taught by following a project based instruction model, where content is learned through the completion of projects, collaboration is a must instead of just an option. Students come into our school with the understanding that they will work with different teammates in every one of their classes for the entire school year. Even though this is something that they are not often very happy with, as they work through the projects, they are able to understand through experience the effectiveness and necessity of working in teams. Students not only understand that teamwork makes sense but they also learn the ability to truly collaborate. For instance, I provide students with protocols that must be followed to reinforce collaboration during the brainstorming process that gives everyone an equal voice. While working through the project, students collaborate by providing feedback to each other on the work completed by each group member. Furthermore, I also require students to complete collaboration evaluations where they discuss and reflect on ways in which the contribution of each group member enhances their own understanding. This has emphasized the importance of working in groups and also helped me find ways to support my students in becoming better collaborators.

A lot of the work and achievements completed by engineers has only been possible due to the use of appropriate tools and techniques. These tools and techniques provide a way for them to work smarter and more efficiently, which in turn allows them to complete tasks with the use of technology. Some of these tools and techniques include project and group management, computer software and technology tools, and relevant application of mathematics and science knowledge to help them work towards finding the best design of a product and/or solution. Having used various forms of technology during the UTeach*Engineering* classes has shifted my understanding of technology integration in the classroom. For example, I used to think of technology as a logistical solution to the classroom and a tool to get things done quicker. From my experience in this program, technology integration should allow students to collect data that they cannot get on their own and to complete concept modeling and research that support inquiry as a learning tool. Thanks to this program, I have developed project management tools such as calendars, rubrics, group contracts and tasks logs that I, along with the students, use while working through lessons and projects. In addition to that, I have also learned how to use technology tools such as Geometer's Sketchpad, MATLAB, LabVIEW and the TI-Nspire calculator's mobile application.

Implanting and nurturing engineering habits of mind is also not a linear process. Different skills are developed at different paces and stages during one or several projects. As a teacher, it is my responsibility to ensure that these habits of mind are not learned through theory but through practice. I make sure that I provide appropriate opportunities for my students to foster these habits of mind that I personally have adopted for most problem solving situations I am involved in. Now I strongly believe that these habits are actually best practices that one must apply when making important decisions and solving problem situations they face in their daily lives.

8.3 Developing an Understanding of the Engineering Design Process

When working on an engineering lesson or project, most students are highly interested because they think of engineering as their chance to build something. However, the amount of work that needs to be completed before the prototyping stage begins does discourage some students. Like the students, I also used to think that engineering was mostly about building, taking things apart and working with tools. Now that I have gone through the courses and the summer research of this program, I have been able to follow the engineering design process in a high school setting and in the actual research field. During my research experience, I was able to learn about how the goals of the research are often driven by developments in industry. In the case of manufacturing of semiconductors at the nanoscale, the need for its development was Moore's law. This law states that the number of transistors found in an integrated circuit doubles approximately every two years. Thus, in order to keep up with this law's expectations, a lot of engineering research in nanomanufacturing systems for mobile technologies is taking place.

Although challenging, I felt extremely fortunate to have taken part in the engineering research. Through this research, I learned that the engineering design process (EDP) is neither linear nor a process with a defined solution. This research showed that concept generation might require the development of new technologies and tools. To describe incorporated systems and to generate concepts to embody a solution is often a feedback loop process where researcher(s) may have switch between different stages of the EDP depending on the data they have gathered. Further, I was able to see how several research ideas had to be completed as part of a bigger design process. Different from my experiences with UTeach*Engineering* classes, the EDP that this research followed integrated experimental design. For example, rather than building or designing something, the research also has the purpose to test one or several hypotheses and answer questions rather than just building or designing. To follow the steps of the EDP, there is often a set of questions and procedures that need to be completed as a bridge to the next stage; however, a lot of these questions and procedures are not often defined during engineering research. In the case of UTeach*Engineering*, the EDP was presented with several scaffolding activities that facilitated this process for high school students. On the other hand, the EDP that this engineering research follows often lacks concrete procedures to be followed. Much of the research being done is often fairly new to a point where only limited reference materials and other foundational research actually exist. Having gone through the EDP in the UTeach*Engineering* classes and this engineering research experience has allowed me to witness its application in the classroom and at the professional level.

8.4 Developing Knowledge for and of Engineering Teaching

The engineering education classes gave me the opportunity to explore the theory and the work that has been done in the STEM field. Much of the information gained during classes, such as Curriculum History and Development, Knowing and Learning, and Systemic Reform in mathematics and science education, helped me learn about best practices that support effective STEM learning environments for the students. Thanks to this program, I also learned about existing issues in the STEM education field, such as inequality issues, poor teacher preparation and lack of support from authority figures in education in the success of STEM education. To sum it all up, I learned about what has been done, current movements, initiatives and practices, and what we can take from it to make decisions about what is left to do. As a result, the engineering classes have helped me write and teach lessons and projects in my classroom that are rich in STEM content. Similarly, the education classes have given me information about the pedagogical approaches that need to be taken into account to create a STEM learning environment in the classroom.

As an effort to put in practice what was learned during the program, I have written and taught two STEM projects each in my Geometry and Algebra 1 classrooms. In Geometry, my students completed a re-design project of a bicycle that followed the engineering design process and a project about sensor placement on bridges. For the Algebra 1 class, my 9^{th} graders completed a project on energy and a project that analyzed levers found in machines.

Recently, I was given the opportunity to write a curriculum that blended mathematics and engineering for a non-profit organization, BreakThrough Austin. This 14-day curriculum was written for a STEM summer school program that has a diverse and low-income student population. The STEM curriculum followed a project based type of instruction where students were required to re-design a product, complete research about different fields of engineering and build mechanically powered cars, as well as building mini-robots using motors and batteries.

Since practice is also a learning opportunity, the STEM lessons I have written and taught have helped me build systems to follow when writing STEM lessons and projects. Thus, I will not only continue to write more STEM lessons but I will also write more authentic and meaningful ones. For example, completing this engineering research experience has exposed me to the professional level of work that engineers adhere to. Hence, I will be able to bring this knowledge into the classroom and use it to provide my students with learning opportunities that can mirror the work of true professional engineers in the field.

It is important to highlight that developing knowledge for teaching engineering should not only be focused on the content of the lesson. Viewing our students as our biggest customers, it needs to be understood that creating a learning environment that accommodates the cultural backgrounds of students, and their interests and ages, are essential to the success of students in STEM classes. Therefore, I plan to continue to stay current on the research and practice of the different pedagogical approaches that makes a STEM class successful and engaging for all students.

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