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Enhancement of Fabrication Procedures by Modularization

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BY MODULARIZATION

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by

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THESIS

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Abstract

Fabrication of semiconductor technology grows in importance every year, from metal-oxide-semiconductor (MOS) technology to fabricating integrated circuits (ICs) used in everyday life. These ICs are implemented into computers, phones, and vehicles for complex functions and safety features. Another semiconductor technology is microelectromechanical systems (MEMS), located in actuators and sensors on multiple systems. In academia, it is inherently essential for students to learn the theory of such devices and have exposure to the fabrication process of the technology in question. The importance of theory and practice in fabrication is skyrocketing due to the global chip shortage, making workforce development vital for the nation's economic security. However, process drift is a common issue in fabrication facilities, affecting the throughput of MOS and MEMS devices in university cleanrooms.

In this research, theoretical models, and technology computer-aided design (TCAD) simulations are used to analyze the relationship between input parameters and changes on the semiconductor. By modularizing the complementary metal-oxide-semiconductor (CMOS) process used at UTEP's cleanroom, it was possible to analyze each step in the fabrication process as an independent system or module. Before experimenting inside the cleanroom, some insight was gathered by simulating the oxidation of a semiconductor under different parameters. Some parameters were assumed in the simulation for an initial estimate. In the cleanroom, these parameters could be better observed when setting up the experiments to oxidize multiple silicon samples. Afterwards, these parameters were updated in the simulation so that a better prediction could be made through before executing the next experiments. This method proved useful for documenting the module and monitoring any process drift in the future. If this method of calibration is applied to the rest of the modules, it is possible to create a well ordered fabrication

process that will enable easy and early identification of process drift within the fabrication life of MOS and MEMS devices.

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Chapter 1: Background

1.1 Semiconductor Fabrication Facilities in Industry

Semiconductor fabrication continues growing due to electronics being present everywhere. For example, Metal-Oxide-Semiconductor (MOS) technology is used for integrated circuits (IC), which are used in increasing number of devices in our everyday lives. Complex systems, such as vehicles, are increasingly using more ICs in their designs for safer and more reliable use. Furthermore, Micro-Electromechanical System (MEMS) technology are used as tire pressure sensors and crash detection actuators in automobiles. Complementary to semiconductor fabrication facilities, Technology Computer-Aided Design (TCAD) is specialized software that can accurately simulate various fabrication processes used to manufacture electronic devices. TCAD can be used to obtain a deeper understanding of fabrication processes as well as design new device technologies.

The recent global scarcity of semiconductor chips has called attention to the importance of onshore semiconductor manufacturing. The scarcity of chips has highlighted the threat to national and economic security of having primarily offshore supply chain. To address global IC demand and address national security, a larger national workforce is needed. The demand for electrical engineers has suddenly made knowledge of device fabrication a much more marketable and desirable skill. Academia must play a vital role in dramatically expanding the national workforce.

1.2 Semiconductor Fabrication Facilities in Academia

In an educational setting, semiconductor fabrication facilities are crucial to train the next generation of engineers on basic processing techniques used to manufacture semiconductor devices. Moreover, the fabrication facilities are also used to develop novel devices. Semiconductor fabrication facilities are powerful hands-on laboratories for students to learn how to fabricate devices as well as to perform research [1]. This teaches students how to handle equipment, materials, and learn essential device fabrication techniques. As such, they are multi-user facilities with the mission of training new cohorts of students every semester. To accomplish their mission, facility managers have the tasks of maintaining equipment, materials, processes in a reliable and safe environment that is easily accessible to many novice users as well as experienced users.

A long and interrelated series of steps is usually required to fabricate semiconductor devices. This makes fabrication a complicated process that requires knowledge of the cause and effect within and between many of the steps. One way to study the cause/effect relationships within the steps is to cast them into a processing–structure–properties relationship observed in nature as shown in Figure 1 (a). In this relationship, processing describes the application of thermodynamic, physical, and chemical forces that cause permanent structural changes in a material at the atomic level. One example is the exposure of silicon to thermal energy and molecular oxygen to cause the conversion of silicon to silicon-dioxide. The purpose of processing is to achieve a structure containing a desired microstructure and morphology. The structure should change only when the forces are applied and should remain stable when the forces are removed. In other words, processing causes a material to obtain a certain structure. Similarly, the structure of a material gives rise to its electrical, mechanical, and optical properties. For example, the atomic microstructure of silicon dioxide causes it to have a high electrical resistivity. In summary, forces during processing cause structural changes, and the resulting structure gives rise to properties.

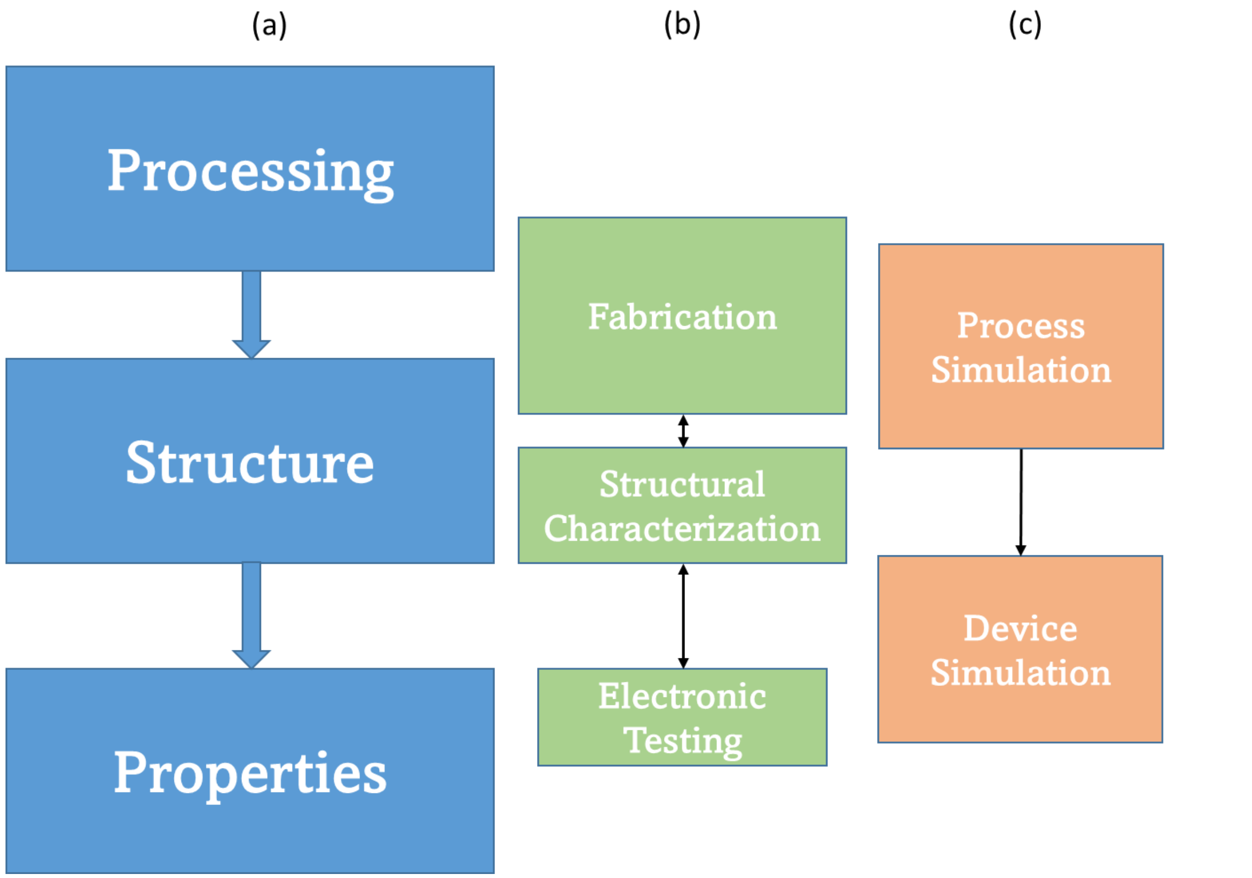


Figure 1. General operation of fabrication process and relations with real fabrication and simulation

In practice, the relationships between processing, structure and properties can be studied through experimentation as shown in Figure 1 (b). Experimentation involves fabrication and measurement of various parameters and properties. Structures are fabricated under controlled conditions and the fabrication conditions, structure, and properties are measured. For example, to study oxidation of silicon it is important to measure the processing conditions (such as temperature and oxidant flow rate), the structure of the silicon-dioxide (such as thickness and density), and its properties (such as resistivity and refractive index). The measured data is then analyzed to study the relationships between processing, structure, and properties.

Theoretical or empirical models can be developed by systematically studying the relationships between processing, structure, and properties. Modeling and simulation are particularly useful because they help predict the outcomes of experimentation using mathematical formulas. This can reduce the cost of developing a technology by first simulating the outcome of processing steps. Simulation is also highly useful to infer processing conditions that cannot be readily measured. This reduces the time and cost of developing a processing technology. Modeling can be divided into two aspects as shown in Figure 1 (c) to simulate the relationship between processing/structure and structure/properties.

Since models are incomplete descriptions of nature, it is important to understand their limits and verify their accuracy. Verification can be accomplished by comparing experimental data from fabrication to results obtained from simulation. Often, the models are applicable over only a limited range of the parameter values. Moreover, empirical fitting parameters may be needed to more accurately fit simulation results to experimental data. However, once adequate verification is achieved, simulation can be used to infer experimental conditions that are difficult to measure or even detect due to experimental measurement errors. For example, TCAD can be used to accurately predict the outcome of a complicated fabrication process.

1.3 Fabrication Facility Management Issues

While fabrication facilities are extremely useful for workforce training, there are a number of issues that make them difficult to manage. A common issue is the lack of process control, also known as process drift. Drift means that multiple factors have affected the fabrication process due to unintentional changes in the processing conditions. The causes of process drift include contamination in the fabrication facilities, degradation of materials, equipment wear, and human error [2]. Another issue is the long and interrelated series of steps required to fabricate an electronic device. This makes the fabrication process complex and difficult to analyze and improve over time. For example, the threshold voltage of a MOSFET transistor depends on several factors that occur at several points in the fabrication process, such as the substrate doping and the oxide thickness. The combination of process drift and complexity makes management of a fabrication facility an exceedingly difficult challenge. Therefore, an approach that can address drift and complexity may dramatically reduce the difficulty of managing the facilities.

1.4 MODULARIZATION IN FABRICATION FACILITIES

The concept of modularization is to simplify a large complicated system by dividing it into smaller independent modules. To modularize a system, it is necessary to find natural divisions within the system. A large complicated system is then divided into smaller independent modules with each module performing a specific function. Because the modules are independent, they can be modified or improved without affecting the other modules [3]. A benefit of a modular design is that a whole new system can be created by combining several modules in a different manner [5]. Another advantage is that it simplifies the management of large systems.

Fortunately, fabrication processes which usually consist of a long series of interrelated steps can be naturally divided into a small set of essential processing techniques. The essential processing techniques consist of wet chemical processing, mask making, lithography, thermal processing, thin films, etching, testing, packaging, and planarization. A whole fabrication process can be developed by combining the essential processing techniques. By dividing and grouping the steps in the overall process, a semiconductor fabrication facility becomes much more manageable. Thus, modularization of the process and operations in a fabrication facility may address the management issues presented in the previous section.

1.5 Contribution of this Thesis

There are many ways in which an information system of a nanofabrication facility can be organized. Managing the fabrication at UTEP has become a difficult task due to the interrelated procedures in developing semiconductor devices. The process may become manageable by modularizing through decoupling into smaller steps. Different nanofabrication facilities were analyzed to develop a modular architecture, including Georgia Tech's [6] and UC Berkeley's [7]. Berkeley's architecture has divided the facilities into machines, methods, and outcomes. In this thesis, Berkeley's architecture was modified to fit UTEP's facilities by modularizing in a similar structure, with an additional module encompassing modeling of methods and their outcomes. Measurement of processing conditions, structure, and properties of standard (baseline) processes is essential to monitor for process drift. Through documenting the modules, a connection between experimental and simulation modules is possible with the correct data analysis. Finally, it was specified to create exemplar modules to demonstrate elements of the framework.

Chapter 2: Modular Architecture

2.1 UC Berkeley's Modular Architecture

In the previous chapter, it was mentioned that finding the natural divisions in the nanofabrication facilities was essential to modularize a facility's management system. Moreover, the set of essential processing techniques provide natural divisions for the modularization. However, the main objective of an academic multi-user facility from a facility management perspective is to provide equipment, materials, and standard operating procedures and not to develop semiconductor technology. The development of semiconductor technology is the responsibility of principal investigators. In other words, the main function of a facility is to support the operation of equipment and handling of materials so that novice and experienced users can learn and develop technology in a safe environment. Therefore, the main divisions for a facility management system should be associated with this function.

The modularization of UC Berkeley's facility management system reflects this function as shown in Figure 2 where the main modules are associated with the operation of the equipment, basic processes, and monitoring trends in process outcomes. The main modules are indicated by the orange rectangles in Figure 2 and are called: "Equipment Manual", "Process Manual", and "Process Specifications". The "Equipment Manual" module contains information about the equipment available in the facility. The "Process Manual" module contains information about how to use equipment in combination with materials to process basic structures. Finally, the "Process Specifications" module contains historical data and plots trends to indicate the performance of a piece of equipment and process over time. For example, the structural and electronic characteristics of silicon-dioxide layers created with an oxidation furnace in combination with a specific recipe are plotted to monitor the performance of the furnace and materials overtime. This information is contained in a spreadsheet located in the Process_Specifications/Thermal_Processing subdirectory.

However, the essential processing techniques are also used as divisions but one-level down in the hierarchy as shown by the blue rectangles in Figure 2. The natural divisions of the essential processing techniques are consistently employed under the three main modules. However, it is important to point out that the three main modules and the Processing Techniques modules do not contain any information per se. They are just used for organizing the information like a directory/subdirectory filing system. Instead, the actual information is contained in documents at the lowest (third) level of the architecture as shown in Figure 2. For example, information about an oxidation furnace will reside in a document in the Equipment_Manual/Thermal_Processing directory.

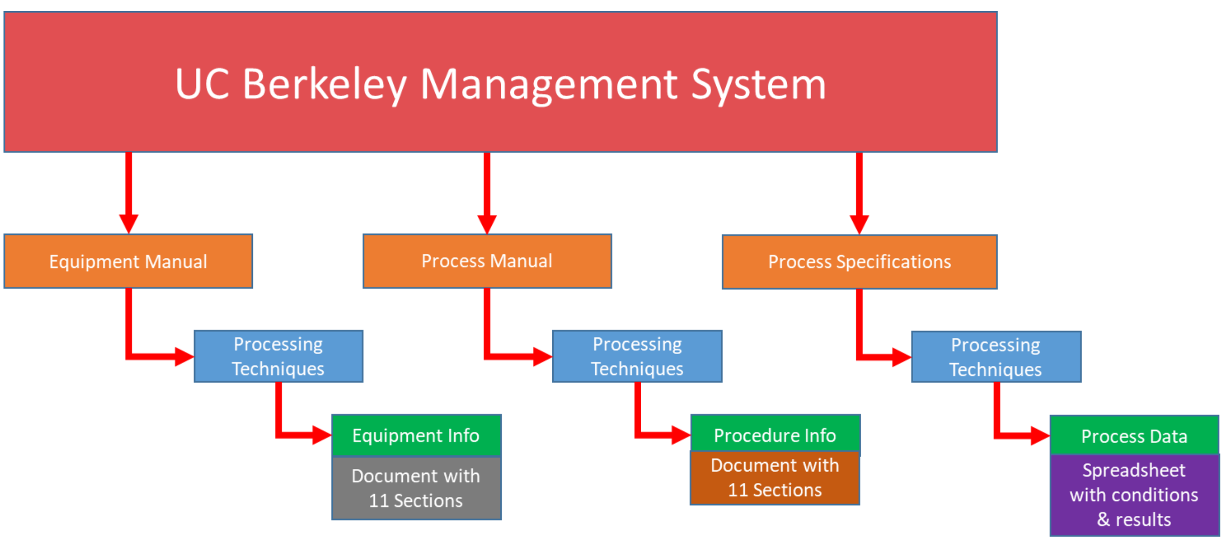


Figure 2. UC Berkeley's modular architecture of nanofabrication facility.

There are ten subdirectories within the Processing Techniques module as shown in Figure 3. The first subdirectory is for general information and the remaining nine are grouped according to the essential processing techniques. The "General" subdirectory holds information on how to become a user, safety rules, manual templates, etc. While this module is not a processing technique, it is useful for guiding members and the providing facility management information. The other nine subdirectories are processing techniques in which equipment, processes, and data may be categorized. Therefore, consistent use of these ten subdirectories simplifies organizing and finding the appropriate information.

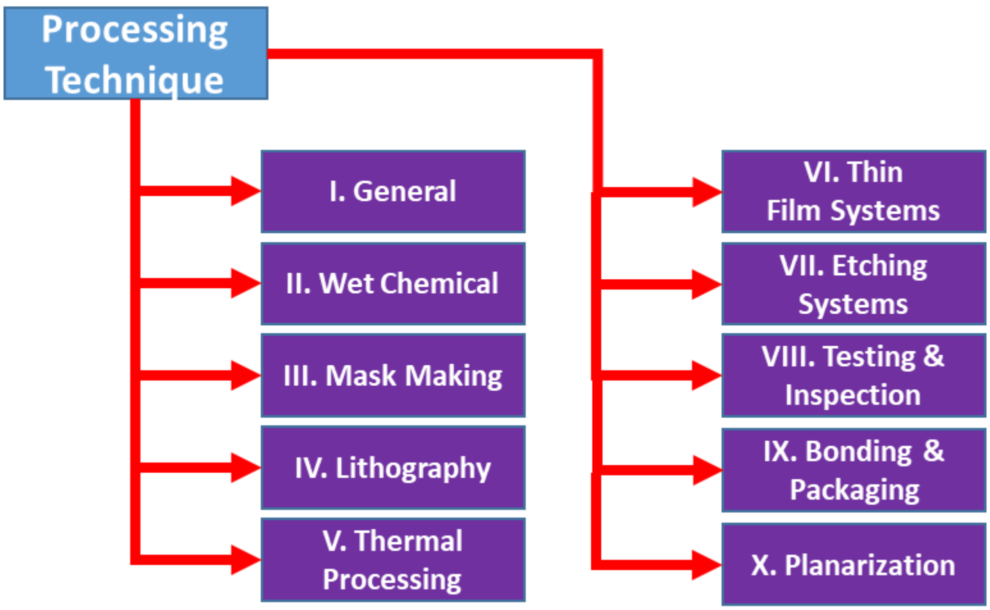


Figure 3. Division of processing techniques.

As mentioned above, actual information is contained in documents within their appropriate category at the lowest (third) level of the architecture as shown in Figure 2. The information under the Equipment Manual and Process Manual modules is contained in Word documents. In contrast, the information under the Process Specifications module is contained in Excel spreadsheets.

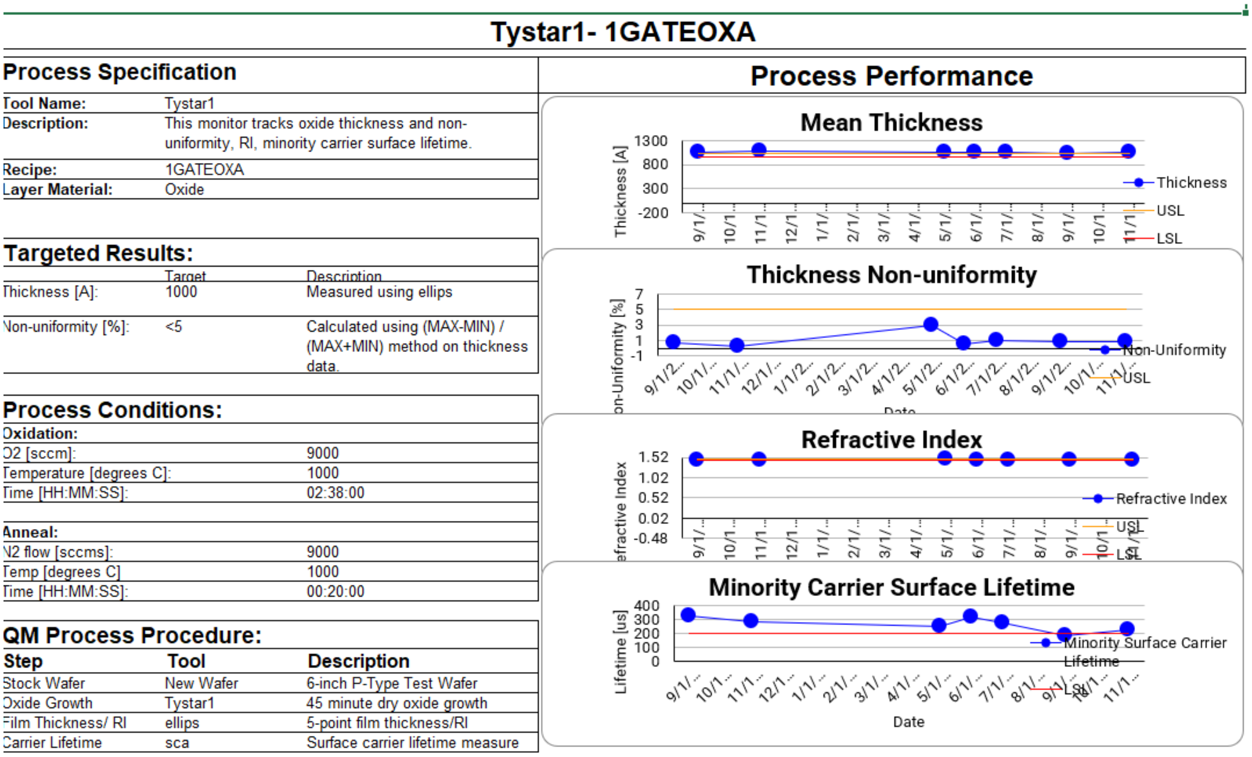
The information in the Word documents follow a standard format where all the sections are consistently numbered and named the same. There are eleven standard sections as shown in Figure 4. Organizing all the Word documents in this consistent way facilitates finding relevant information. This is similar to how information in Safety Data Sheets is organized into standard sections to find relevant information quickly.

Another major benefit of using a standard format is that it simplifies the creation of new Word documents. This is accomplished through the use of pre-formatted template documents. The template documents contain the standard sections and instructions how to create new Word documents. This recursion of providing templates and instructions of how the create new documents is a powerful feature that makes the facility management system amenable to improvement and expansion over time.

	Equipment Info	Procedure Info
1	Equipment Purpose	Process Summary
2	Material Controls & Compatibility	Material Controls & Compatibility
3	Training Procedure & Applicable Documents	Training Procedure & Applicable Documents
4	Definitions & Process Terminology	Definitions & Process Terminology
5	Safety	Safety
6	Process Data	Process Data
7	Available Processes	Process Explanation
8	Equipment Operation	Process Procedure
9	Troubleshooting	Troubleshooting
10	Study Guide	Figures & Schematics
11	Appendices, Figures & Schematics	Appendices

Figure 4. Berkeley's equipment manual vs process manual comparison

The purpose of the "Process Specifications" module is to monitor the performance of each piece of equipment and process over time. To do this effectively, Excel workbooks are used to document process conditions, enter outcomes, and graph the results over time. The Excel workbook contain 4 spreadsheets. The main spreadsheet summarizes process information and presents graphs indicating the performance of the process as a function time. An example of the main spreadsheet is shown in Figure 5 which is from the workbook published by UC Berkeley's NanoLab for a gate oxidation process using their Tystar1 furnace. The left side of the spreadsheet conditions the process conditions and other valuable information. The graphs are especially useful to detect drift by monitoring for variation in the trend.


Tystar1- 1GATEOXA

Process Specification

Tool Name:	Tystar1
Description:	This monitor tracks oxide thickness and non-uniformity, RI, minority carrier surface lifetime.
Recipe:	1GATEOXA
Layer Material:	Oxide

Targeted Results:

	Target	Description
Thickness [A]:	1000	Measured using ellips
Non-uniformity [%]:	<5	Calculated using (MAX-MIN) / (MAX+MIN) method on thickness data.

Process Conditions:

Oxidation:	
O2 [sccm]:	9000
Temperature [degrees C]:	1000
Time [HH:MM:SS]:	02:38:00
Anneal:	
N2 flow [sccms]:	9000
Temp [degrees C]	1000
Time [HH:MM:SS]:	00:20:00

QM Process Procedure:

Step	Tool	Description
Stock Wafer	New Wafer	6-inch P-Type Test Wafer
Oxide Growth	Tystar1	45 minute dry oxide growth
Film Thickness/ RI	ellips	5-point film thickness/RI
Carrier Lifetime	sca	Surface carrier lifetime measure

Figure 5. Process specifications main spreadsheet

The other 3 spreadsheets are used to enter data, calculate statistics, and generate the graphs. The spreadsheet used to enter data is shown in Figure 6. Furthermore, the day the sample was made, and the user are written into the spreadsheet as this may be used for insight. For example, a new user may be prone to causing drift due to user error. Analyses of the data is performed in another spreadsheet as shown on Figure 7. Some statistical analysis that may aid in detecting drift include uniformity or standard deviation.

			6in Growth Thickness					
Wafer ID	Operator	Date	T	C	F	L	R	Mean
NOV 2021	eejanda1	11/2/2021	1060	1060	1063	1070	1052	1061
SEP 2021	eejanda1	9/2/2021	1046	1045	1045	1055	1038	1045.8
JUL 2021	eejanda1	7/28/2021	1064	1050	1048	1063	1042	1053.4
JUN 2021	eejanda1	6/24/2021	1057	1057	1059	1060	1047	1056
MAY 2021	eejanda1	5/21/2021	1042	1054	1105	1061	1045	1061.4
NOV 2020	jmccurdy	11/3/2020	1079	1080	1081	1077	1077	1078.8
SEP 2020	jmccurdy	9/17/2020	1066	1062	1070	1068	1055	1064.2
AUG 2020	jmccurdy	8/7/2020	1060	1058	1060	1076	1051	1061
AUG 2020	jmccurdy	8/5/2020	1216	1213	1213	1222	1205	1213.8
AUG 2020	jmccurdy	8/3/2020	1219	1216	1217	1228	1205	1217
JUL 2020	jmccurdy	7/17/2020	290	289	283	291	295	289.6
FEB 2020	c_lung	2/7/2020	270	271	271	270	272	270.8

Figure 6. Process specifications measurements spreadsheet

Run Information			Thickness Calculation				
Wafer ID	Operator	Date	Mean Growth Thickness	SD	MAX	MIN	Non-Uniformity [%]
NOV 2021	eejanda1	11/2/2021	1061	6.480740698	1070	1052	0.848256362
SEP 2021	eejanda1	9/2/2021	1045.8	6.058052492	1055	1038	0.812231247
JUL 2021	eejanda1	7/28/2021	1053.4	9.68504001	1064	1042	1.044634378
JUN 2021	eejanda1	6/24/2021	1056	5.196152423	1060	1047	0.616990982
MAY 2021	eejanda1	5/21/2021	1061.4	25.50098037	1105	1042	2.934326968
NOV 2020	jmccurdy	11/3/2020	1078.8	1.788854382	1081	1077	0.185356812
SEP 2020	jmccurdy	9/17/2020	1064.2	5.93295879	1070	1055	0.705882353
AUG 2020	jmccurdy	8/7/2020	1061	9.16515139	1076	1051	1.175364363
AUG 2020	jmccurdy	8/5/2020	1213.8	6.140032573	1222	1205	0.700453234
AUG 2020	jmccurdy	8/3/2020	1217	8.215838363	1228	1205	0.945334977
JUL 2020	jmccurdy	7/17/2020	289.6	4.335896678	295	283	2.076124567
FEB 2020	c_lung	2/7/2020	270.8	0.836660027	272	270	0.36900369

Figure 7. Process specifications equations spreadsheet

2.2 UTEP's Modular Architecture

The architecture developed for UTEP was based on UC Berkeley's with a significant difference being the addition of a high-level module called "Simulation Software Manuals". There were also minor modifications to the naming of the modules to better convey the purpose and contents of each module. Figure 8 shows UTEP's architecture with the new names and additional major module called "Simulation Software Manuals." This section describes the purpose, framework, and contents of the overall architecture and of each module. The purpose of the processing techniques for this architecture will be described in this section. Also, the templates for the different manuals in the architecture will be covered.

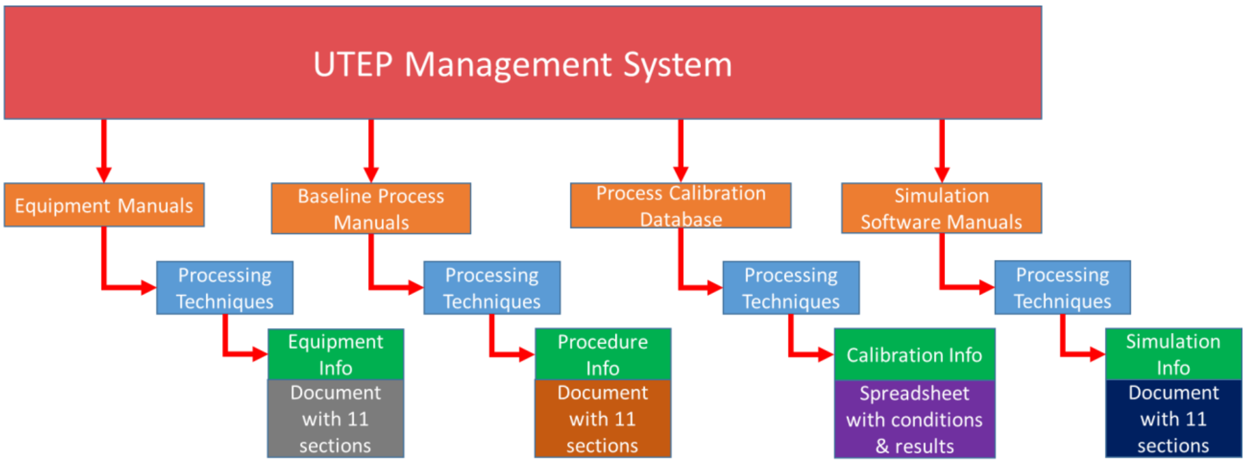


Figure 8. UTEP's modular architecture of nanofabrication facility.

Each major module is consistently divided into the same 10 categories shown in Figure 3. The categories consist of a general section and 9 processing techniques. The consistent use of the same 10 categories under each major module gives the architecture a very uniform structure that is very helpful for staff and experienced users to manage the information and evolve the management system. However, the repeated use of the same category names may be confusing for new users due to the ease of losing track in which subdirectory one is located. Nevertheless, the benefits outweigh the disadvantages.

The "general" sections have a special significance. As mentioned in a previous section, information is stored in "manuals" which are Word documents or Excel Workbooks at the lowest level of the management system. For example, the management system contains Word documents that describe the equipment and standard procedures in the lab. It also contains Excel workbooks that graph the outcomes of standard procedures over time. However, the equipment in use and the standard procedures are likely to change over time, which will require new manuals or at least modification of an existing manual. For example, when an obsolete instrument is replaced by a new one, a new manual will be required for the new instrument. In the case of UTEP, the management system is new and many of the manuals still need to be created for the various equipment and procedures. This is where the importance of the "general" sections of the management system comes into play. The "general" sections contain information of how to make and modify manuals. This information is contained in the form of formatted template files that can be filled in with the appropriate information for each instrument or procedure. The template files for the UTEP management system are described below.

The information from the nanofabrication facility needs an easy method to document all aspects. The efficient method to write all information pertaining to the facility would be through manual templates. The equipment manual template is based on Berkeley's equipment manual due to it conveying information effectively. The baseline process manual template was designed to match the sections of the equipment manual template for the purpose of having a standard method of writing manuals. Lastly, the process calibration database will have the same spreadsheet sections as Berkeley's, the only difference will be the data from UTEP's samples. Through comparing both Figure 9 and Figure 10 it is noticeable that most of the sections should have similar names and contents. There are differences in the templates that are worth analyzing to avoid confusion when creating manuals. Further analyzing the similarities and differences of the templates will help avoid confusion as users gain experience.

The manual templates have eleven sections, some of which may vary depending on the purpose of the manual. The first section of both manuals should briefly describe the purpose of the equipment and baseline process. Section five is extremely important since it covers safety measures users must take when handling the equipment and materials. The procedure steps will be in section eight for both manuals as a standard. All equipment manuals will be able to link to all its available baseline processes in section seven, in contrast the baseline process will cover theory in this section. Both manuals have section ten as a study guide, the equipment manual will link to all information about the equipment and its procedures. Meanwhile, the baseline process manual will instead link to safety datasheets (SDS) of the materials which will be in use. A complete version of both the equipment manual and baseline process manual templates are found in Appendix 1. Equipment Manual Template and Appendix 2. Baseline Process Manual Template respectively.

1. ***Equipment Purpose*** – The processing techniques which the machine can run.
2. ***Material Controls & Compatibility*** – Materials that harm the machine will be here.
3. ***Training Procedure & Applicable Documents*** - All the steps required to become a user of the machine will be here.
4. ***Definitions & Process Terminology*** - Any terminology applicable to the equipment.
5. ***Safety*** - Any precautions needed for safe use of the equipment.
6. ***Process Calibration Data*** – Links to process calibration databases pertaining to equipment.
7. ***Available Processes, Gases, Materials. Process Notes*** – Links to the baseline process documents.
8. ***Equipment Operation*** - A step-by-step description on how to operate the equipment.
9. ***Troubleshooting Guidelines*** - Any fixes to errors which any user can handle will be in this section.
10. ***Study Guide*** - Documents which will aid in understanding the use of the equipment and in training.
11. ***Appendices, Figures & Schematics*** - Any other information which pertains to the machine.

Figure 9. Sections of the equipment manual template

1. ***Process Summary*** - The goals of the baseline process.
2. ***Material Controls & Compatibility*** – Materials used in the process.
3. ***Training Procedure & Applicable Documents*** - The equipment manual may be linked here for training purposes.
4. ***Definitions & Process Terminology*** - Any terminology applicable to the process.
5. ***Safety*** - Any precautions needed to safely handle the materials.
6. ***Process Calibration Data*** - Links to process calibration databases pertaining to equipment.
7. ***Process Explanation*** - A brief explanation of the process and the theory behind it.
8. ***Process Procedure*** – Required conditions to meet the goals of the baseline process and additional steps not included in equipment manual.
9. ***Troubleshooting Guidelines*** - Any fixes found for common errors in the process will be found in this section.
10. ***Study Guide*** - Any documents that may need to be studied before running a process, such as safety datasheets (SDS).
11. ***Appendices, Figures &Schematics*** - Any other figures which are applicable to the baseline process.

Figure 10. Sections of baseline process manual template

Simulation software was essential in developing the calibration files for the baseline processes in the cleanroom. The main simulation software used was Synopsys TCAD which can create designs for semiconductor devices through simulating the processing of such devices. Furthermore, this software has capabilities to test the simulated sample for its electrical properties. Documenting the use of simulation was instrumental for UTEP's nanofabrication facility.

The simulation software manual template was designed using the previous templates as a basis. For this reason, the manual is also made up of similar eleven sections shown in Figure 11. Similar to the other templates, section one focuses on the purpose, section five on safety, and section eight holds the steps to execute the simulation. The full version of the template is found on Appendix 4. Simulation Software Manual Template. For a user to use this manual effectively, it is assumed that they understand the syntax used for Synopsys TCAD. Under the "Simulation Software Manuals/General" subdirectory a document with basic syntax and use of the software will be found.

1. ***Code Purpose*** - The goals on the simulation.

2. ***Compatibility*** - All simulation tools that are compatible with this process.

3. ***Training Procedure & Applicable Documents*** - All documents which help access software.

4. ***Definitions & Process Terminology*** – Any terminology applicable to this simulation.

5. ***Computer Security*** - This section will include basic computer security tips.

6. ***Process Calibration Data*** – Links to process calibration database.

7. ***Available Processes, Gases, Materials. Process Notes*** – Links to baseline processes applicable to simulation.

8. ***Code Sample*** - An example of the code for simulation.

9. ***Troubleshooting Guidelines*** - Typical bug fixes and tips will be found here.

10. ***Study Guide*** - Recommended files that the user must study.

11. ***Appendices, Figures & Schematics*** - The output data and other images.

Figure 11. Summary of simulation software manual template

Chapter 3: Method to Develop Baseline Processes

3.1 Model for Calibration

Baseline process documents provide standard recipes which members can use to create samples with pre-determined properties. The importance of these samples is in their use to monitor drift to keep the facility running within specified limits. However, a method to create baseline processes was necessary since UTEP's architecture is in its early lifetime.

A flow chart can be an effective general way to describe how to develop baseline processes. A flow chart is general and can work with a wide variety of processes. Figure 12 shows a block diagram of the method that consists of several steps. The method starts with first stating the purpose and goals of the procedure. An example would be to create and document a standard oxidation process. The next step is to determine suitable processing conditions to create a sample but taking into consideration any physical or logical constraints. For example, the process conditions to oxidize silicon wafers but within limitations of the equipment and time to ensure efficient and safe operation. Simulation can play a significant role in determining suitable processing conditions before performing the physical experiment. For example, conditions are used in simulation to infer the characteristics of a structure. Some of the conditions may be assumed initially, which will be updated if the results from the simulation are not desirable. Simulation is repeated until desirable results are obtained. The conditions developed from simulation are then used in an experimental procedure to create a sample which should match the simulation results. Next, characterization of sample is used to verify that the desired results, such as oxide thickness, match the simulation before writing this data onto a baseline process manual and a spreadsheet. When developing a baseline process manual, a calibration database workbook should also be created.

After creating a manual, a sample can be manufactured with the conditions written. The expected properties of the sample are now known, so measurements are done for comparison of previous data in the calibration database workbook. Process drift is present once the data stops matching the measurements from previous dates. When this happens, the method loops back to the choosing conditions for recalibrating the baseline process. Some insight that the recalibration process may give is information on how often equipment needs to be maintained.

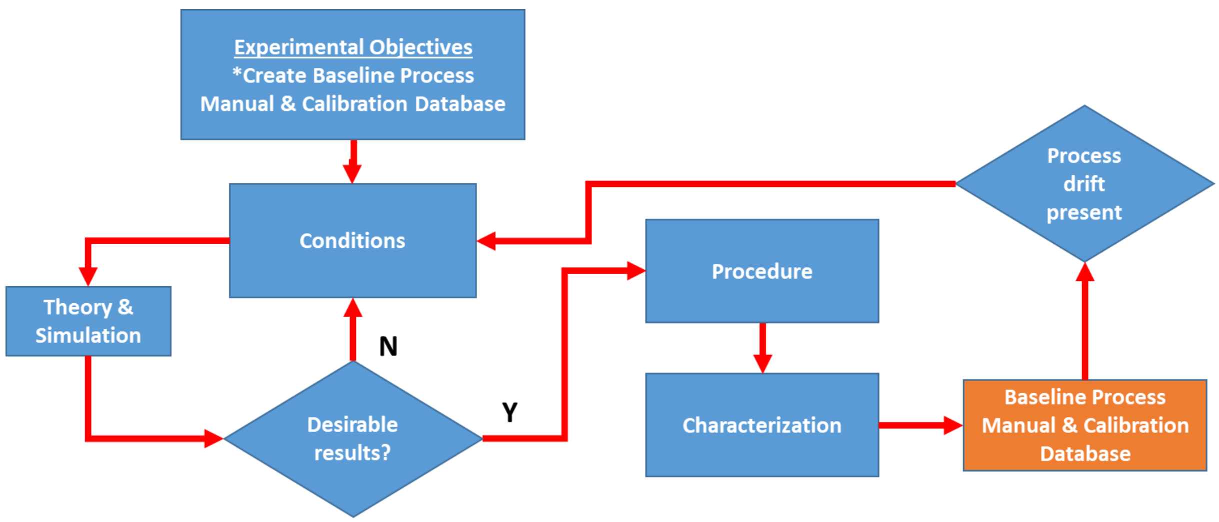


Figure 12. Method to develop baseline process manual and calibration database

3.2 Synopsys TCAD in Process Development

Simulation was used to aid real experiments in the nanofabrication facility due to its ability to model a real-world procedure. Theoretical models include equations which approximate the behavior or changes in the system in question. Theoretical models are used in TCAD which may provide graphical and visual data of the system simulated. This data is essential to calibrate the process conditions given the results of an experiment. Some of the conditions may be unknown, so assumptions are made to get an initial output from the simulation. Through experimentation it is possible to get insight on these assumed conditions, which is done in the method to develop baseline processes back in Figure 12. This set of steps create a relationship between real-world experiments and TCAD to approximate any changes to a module. Furthermore, process drift can now be easily monitored and identified through observing new data, leading to calibration of the baseline process. Using TCAD software can save time and resources since fabrication can become expensive due to materials and time [8].

In general, a Synopsys follows a process flow in which a recipe is set up to create a structure which will be analyzed for its properties later by using multiple tools. The tools used in this TCAD software include Sprocess, Svisual, and Sdevice. Both Sprocess and Sdevice use command files as their input to run a simulation. Figure 13 shows the flow of the simulation process where an ideal process control where no drift is present is assumed. The Sprocess command file will define the process which will be executed and takes the conditions desired by the user. The output becomes a structure file which Svisual can open for a 2D and 3D images of the device. The structure file can be electrically simulated in Sdevice by writing a different command file. In this new file the probing points of the device are specified to gather current-voltage (IV) data.

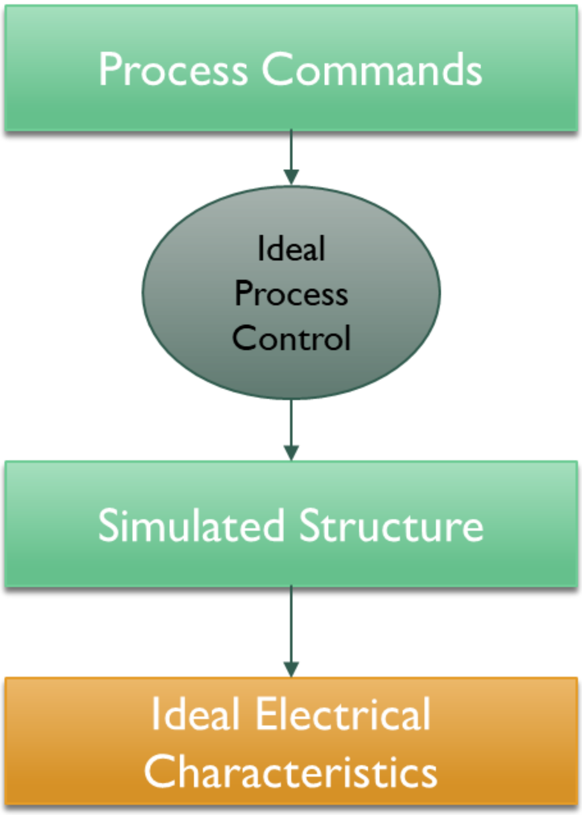


Figure 13. Flow of Synopsys TCAD simulation

Chapter 4: Development and Calibration of Oxidation Processes

Dry and wet oxidation processes were developed and calibrated by comparing real data to predicted results from simulation. The simulations were performed using an analytical Deal-Grove model and the Synopsys TCAD environment. The real experiments were performed in UTEP's nanofabrication facility.

4.1 Oxidation Simulation

The oxidation process was simulated using the Sprocess tool within the Synopsys TCAD environment and an analytical Deal-Grove model. The Sprocess tool is capable of simulating many processes used for semiconductor fabrication. Sprocess reads commands from a text file that specify the processes and their conditions and executes them line-by-line in chronological order. Generally, the command file begins with specifying the initial conditions of the substrate such as size, dopant and concentration. The commands that follow then specify the processing to be performed on the substrate in sequential order.

Sprocess uses the Massoud-modified Deal-Grove model to simulate the oxide growth which takes into account the fast oxidation rate at thin oxide thicknesses that the Deal-Grove fails to model [12]. Sprocess simulates oxidation as a thermal process under a user-defined atmosphere. The ambient is defined in the code via the partial pressure of gases in the atmosphere. The diffusion of the oxide is controlled by the temperature of the ambient and time exposed. In the Sprocess code, variables are used by enclosing the name of the variable with "@", for example "@myTemp@." In Figure 14 the code for dry oxidation written in Sprocess is provided showing the commands in sequential order. The first command defines the substrate material (silicon) and size. The boron concentration is written with the "init" command. The dry oxidation is done at an ambient of only oxygen under a pressure of 1 atm. The parameters for oxygen are set up with the “gas_flow” command, where more than one gas may be added as a mixture if required. The “diffuse” command will use the defined ambient at the specified temperature and variable time for the oxidation reaction to take place.

```
region Silicon xlo=top xhi=bottom ylo=left yhi=right
init concentration=5e15 field=Boron
gas_flow name=DryOx partial.pressure= {O2=1}
diffuse temperature=1050 time=@time@ gas_flow=WetOx
```

Figure 14. Synopsys TCAD Sprocess code for oxidation

In Figure 15 the red graph is the continuous Deal-Grove model while the blue triangular points represent the simulated oxidation in Sprocess. The two models are in general agreement, however, notice that Sprocess predicts slightly thicker oxides compared to the Deal-Grove model. This is due to the Sprocess using the Massoud modification of the Deal-Grove model to account for faster oxidation at thin oxides.

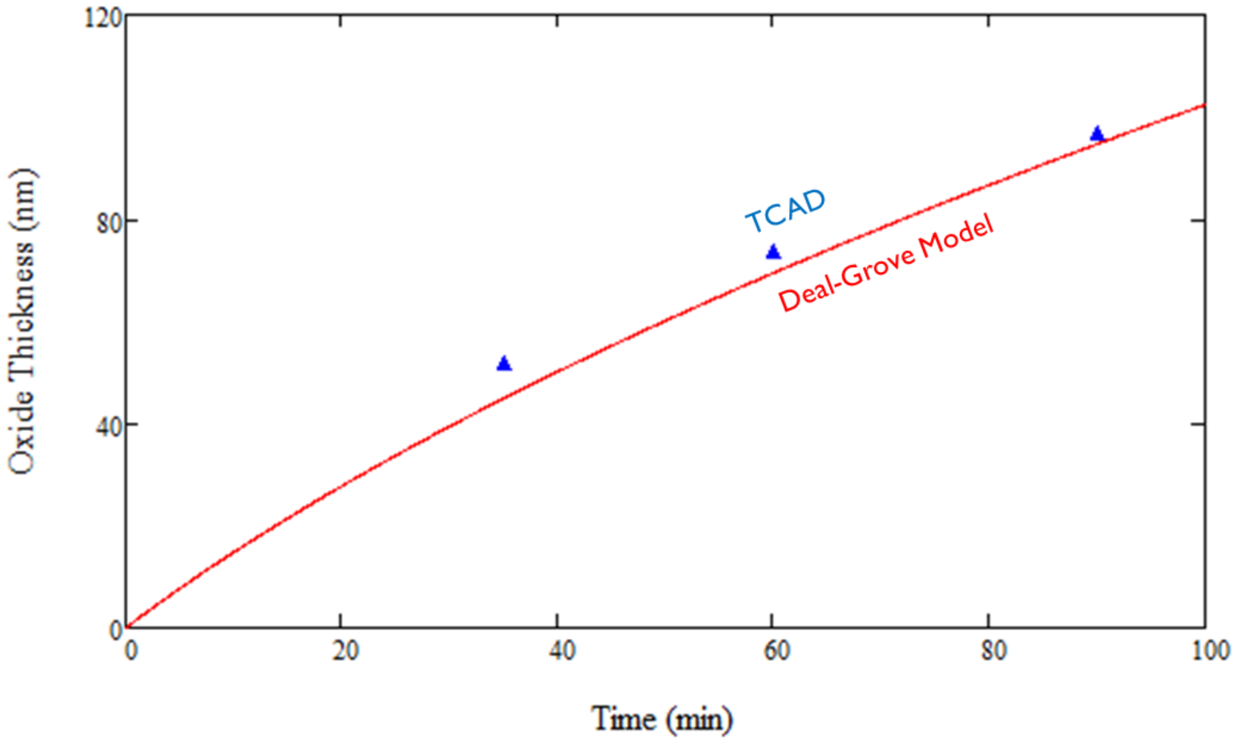


Figure 15. Dry Oxidation, Deal-Grove vs. Synopsys TCAD

Figure 16 shows a colorized cross-sectional image of the wafer after oxidation created by the Sprocess code. A uniform oxide layer can be observed on the surface of the substrate in maroon. The dopant is shown to have diffused during the oxidation process; the gradient shows how near the surface this concentration is lower than the initial $5x10^{15}$ cm^{-3} due to segregation of boron at the oxide/silicon interface.

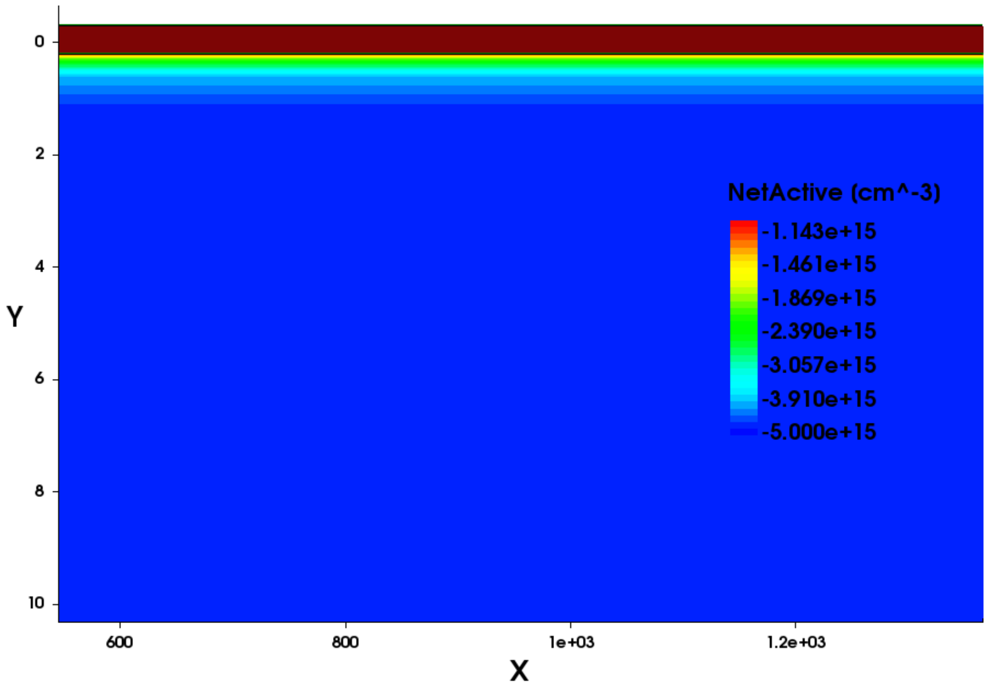


Figure 16. Wet Oxidation Step in Synopsys TCAD

4.2 Development of Dry Oxidation Process

A baseline process for dry oxidation is described in this section. Real silicon wafers were oxidized and the thickness and uniformity of the resulting oxide layers were compared to simulation results. The processing conditions include the flow rates of oxygen and nitrogen, the temperature of the furnace, and the time of oxidation. The real and simulated oxide thicknesses are shown in Figure 17 as a function of time (35, 60, and 90 min.), at two different temperatures (1050 and 1070°C) and at an oxygen flow rate of 6.2 L/min. The red triangles are at 1050°C while the blue diamonds are at the higher temperature of 1070°C. The real and simulated data points are represented by the solid and hallow shapes, respectively. The continuous curves were used as a comparison to the Deal-Grove model. These experiments tested the accuracy at which simulation and theory can approximate the average film thickness for UTEP's baseline processes. Notice that the simulated Sprocess results matched the real data very accurately.

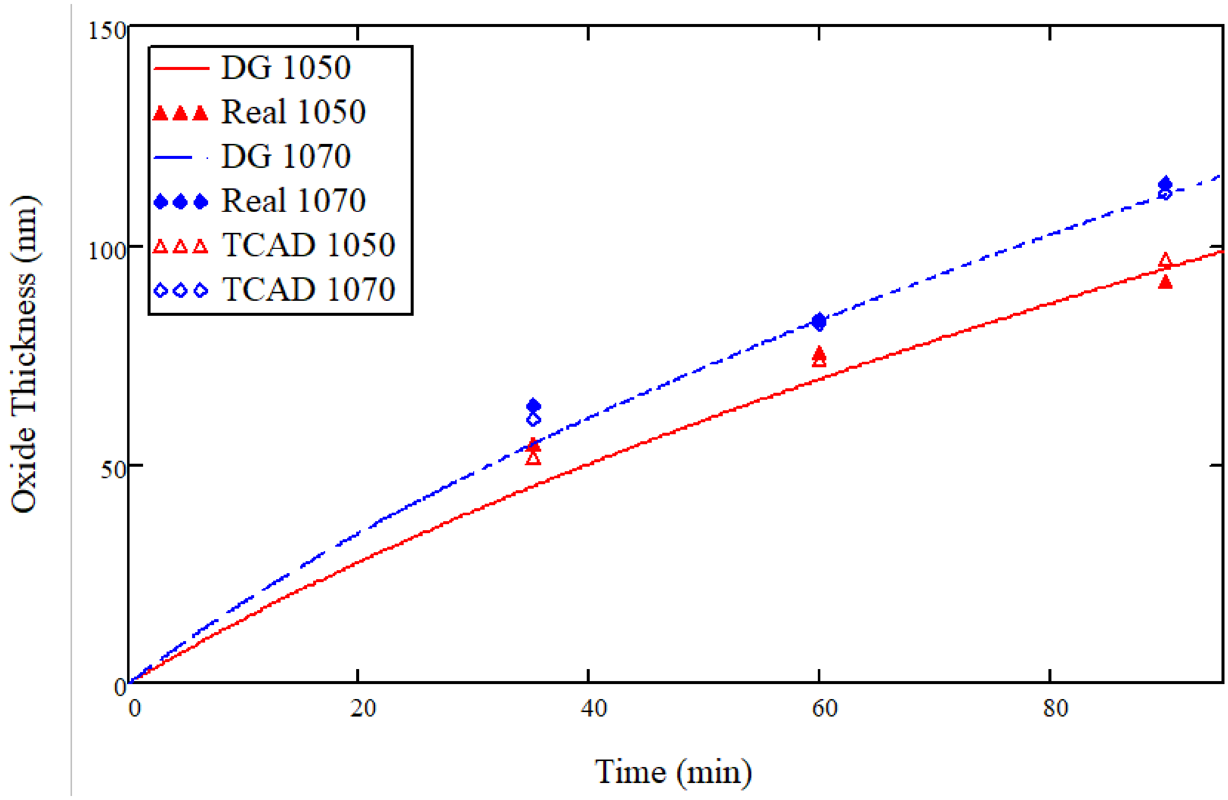


Figure 17. Dry oxidation, thickness vs. time. Two different temperatures are used with 1050℃ in red and 1070℃ in blue.

The uniformity of the oxide layer thickness was also studied as a function of oxygen flow rate. However, in order to study uniformity, it was necessary to measure and determine the gas flow rates. A linear relationship between the ball pin position of the oxygen flow tube and flowrate is established by using the datasheet of the Aalborg Rotameter [13]. The graph in Figure 18 portrays this linear relationship, which was used to measure oxygen flowrate.

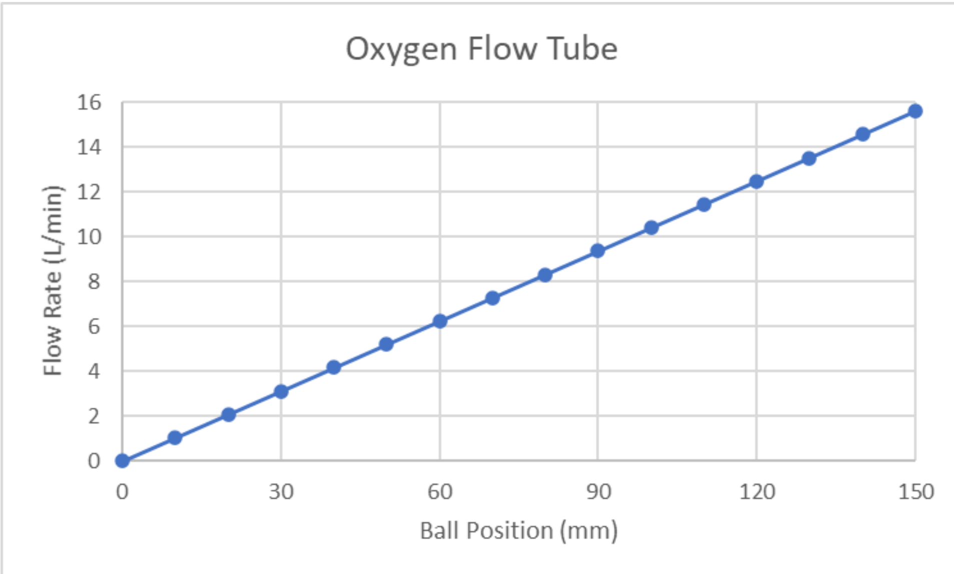


Figure 18. Oxygen Flow Rate vs Ball Position

Once accurate measurement of the oxygen flow rate was established, the uniformity of the oxide layer thickness was studied as a function of oxygen flow rate. The non-uniformity measurement verifies the consistency of the oxide film across the silicon wafer. This parameter is calculated with the formula $NU = \left(\frac{Max-Min}{Max+Min}\right) \times 100\%$, where "Max" is the thickest point of the sample and "Min" the thinnest. It is typical for highly non-uniform films to have a skewed average film thickness. Figure 19 shows the effects of oxygen flow rate on the non-uniformity of the sample. As the flow rate increases, the film becomes more uniform which is correlated to more oxidant species being present.

One of the objectives of this study was to determine parameters that resulted in non-uniformity below 5% as shown by the orange line in Figure 19. The lowest flow rate tested had a non-uniformity is above the limit of 5%. In contrast, the flow rates of 6.2 and 12.5 L/min were both below the 5% limit. The oxygen consumption rate is also indicated in Figure 19. Given the only marginal improvement in non-uniformity but 2.5 times higher consumption rate of the 12.5 L/min rate, the 6.2 L/min flow rate was selected as a baseline value for future oxidations.

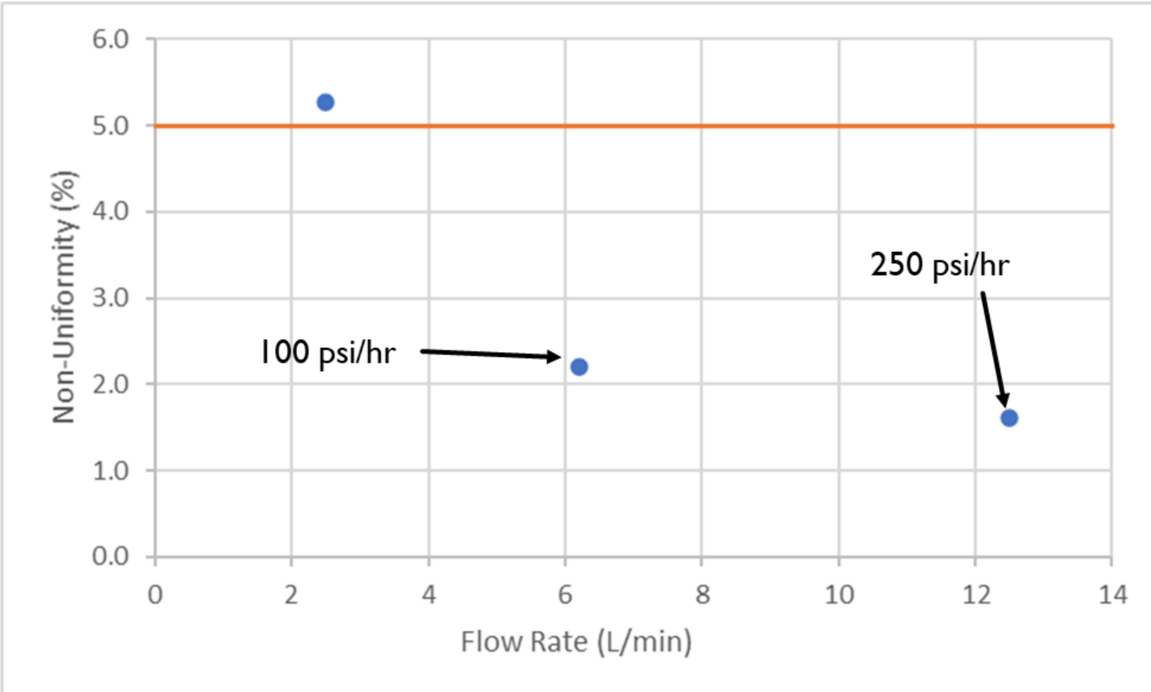


Figure 19. Non-Uniformity vs. Oxygen Flow Rate. These data points were gathered from dry oxidation experiments

4.3 Development of Wet Oxidation Process

Generally, the dry oxidation process has a low oxidation rate, which would consume time when attempting to grow a field oxide. To grow an oxide at a faster rate a wet oxidation procedure may be used. Typical applications of this oxide include hard masking and field oxide. The density is different for this type of oxide, which causes problems with the current on gate oxides. For this layer to grow quickly and uniformly, it is necessary to have sufficient flow of water vapor through the furnace tube.

Generating steam may be done through a variety of equipment which vary in sophistication and control by the user. Some methods to generate steam include a pyrogenic system [14] which ensures only water molecules flow through the furnace by superheating some hydrogen gas with oxygen gas. The reaction for water is done by the time the molecules make it into the furnace, which decreases the chances of precipitation on the walls of the tube. By keeping a low pressure inside the oxidation tube, it is possible to keep the water vapor from condensing. Another method uses an external torch for rapid water vaporization as a means to generate enough steam for oxidation. This machine introduces liquid deionized water (DI) into a high temperature quartz tube, usually around 600°C for fast evaporation. Moreover, to introduce the water vapor into the tube, a carrier gas is flowed to transport the water molecules. This allows the water vapor to enter the oxidation furnace without precipitating since temperature remains high through its entire travel time towards the substrate. Both methods explained aim for high steam generation for the wet oxidation process, while attempting to keep water in gas form as long as possible.

At UTEP's nanofabrication facility, steam generation is done through a heating mantle and bubbler. The bubbler, in Figure 20, is filled with DI water then placed on the heating mantle to begin the evaporation process. This bubbler has an opening to allow the carrier gas to flow into the flask. The opening on the right side of the schematic flows the steam and carrier gas into the oxidation furnace quartz tube. The flow of water vapor inside the tube is expected to be constant to avoid bad oxidation samples.

The sample can show a gradient coloring on its surface if the steam flow is not enough. A gradient coloring is a sign of a poor film since the thickness is changing over the surface. Oxygen is used as a carrier gas with the same flow rate as the baseline dry oxidations, 6.2 L/min. The oxidant species is kept constant by using oxygen as a carrier gas. The only parameter which needed to be found for the baseline wet oxidation was the heating mantle's temperature for an appropriate steam generation.

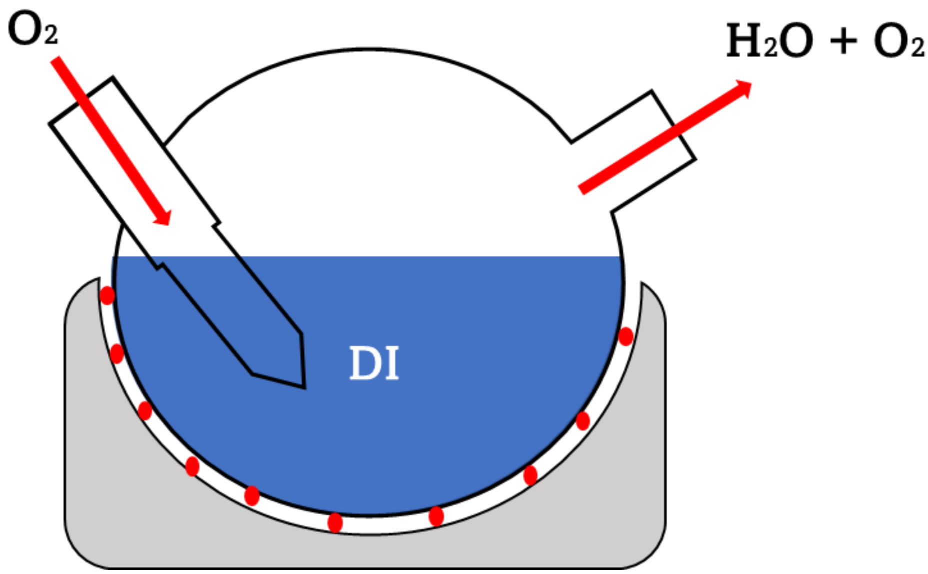


Figure 20. Bubbler and heating mantle schematic

All the methods to generate steam needed a high temperature to appropriately control the flow of water vapor, which is no different for the bubbler. The temperature of the heating mantle is controlled through a power knob which shows the total percent power used, rather than the temperature output. A thermocouple is placed on the heating mantle while the DI water is heating up to make measurements simple. Through experimenting at different bubbler temperatures, the data on Figure 21 was plotted. A low temperature created a highly non-uniform oxide, mainly due to a lack of steam generation. The temperature of the bubbler would range between 85-90℃ throughout the oxidation run while the heating mantle was at 90% power. This temperature range yields an oxide within the threshold set for the baseline wet oxidations.

The baseline processes for wet oxidation were designed to use the same oxidation temperatures and times as the dry oxidation. The data points were plotted in a similar manner to the dry oxidation, comparing simulated data points with the real experiments, which can be appreciated in Figure 22. The graphed experimental and TCAD points matched closely to each other, which is useful for calibration purposes. Moreover, the black square in the graph shows the effects of a lower bubbler temperature, which has an undesirable oxide thickness for the purposes of field oxides. Lastly, the experimental matched the Deal-Grove model nicely, which will be a good metric for calibration.

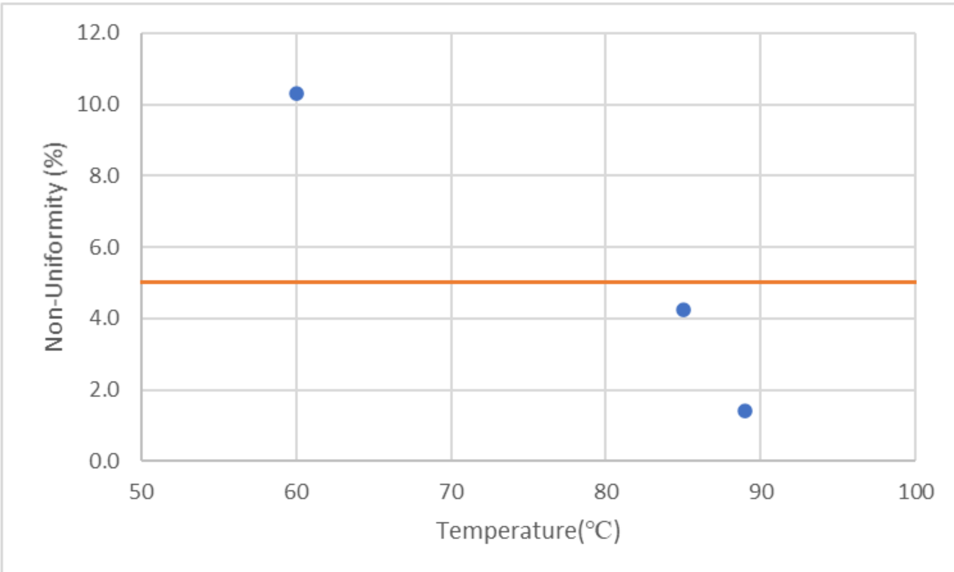


Figure 21. Non-Uniformity vs. Bubbler Temperature.

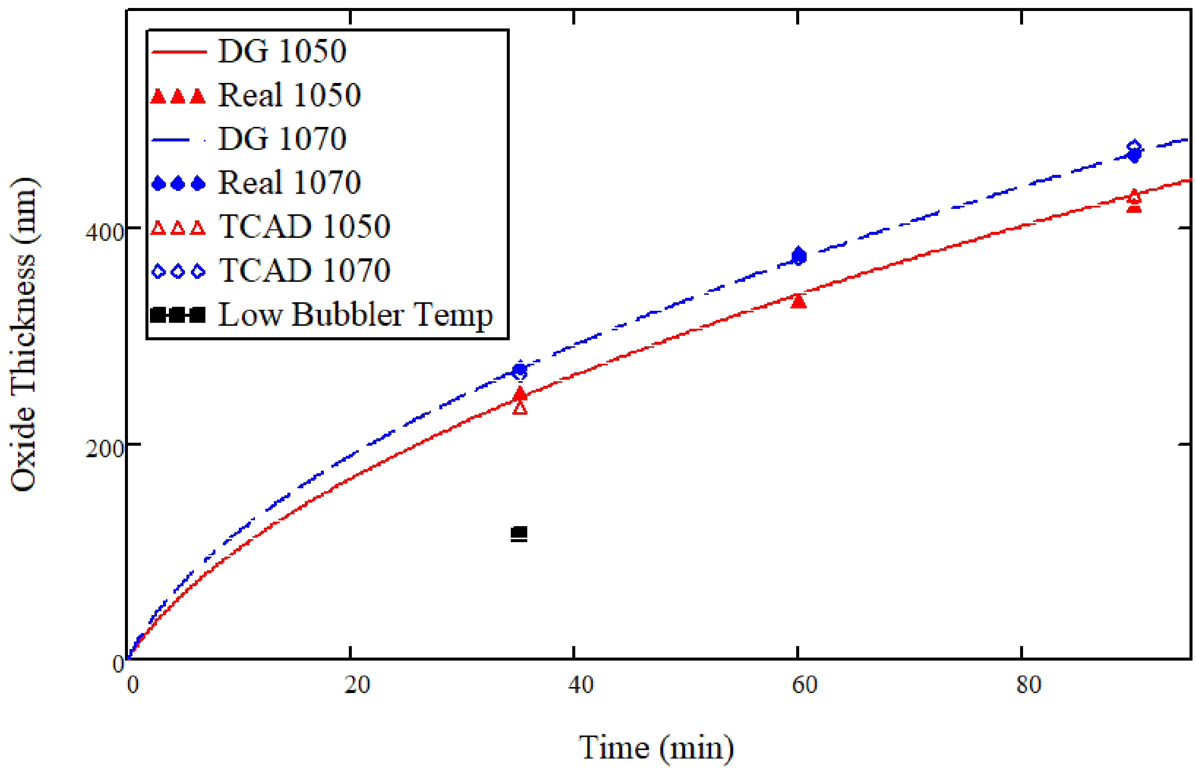


Figure 22. Wet Oxidation, Thickness vs. Time. Two different temperatures are used with 1050℃ in red and 1070℃ in blue. The black point shows a lower bubbler temperature

Chapter 5: Exemplar Manuals on Oxidation

Through following the methods to develop baseline processes and calibration databases, multiple manuals were created to archive this information. This new information will continue to be used at the nanofabrication facility at UTEP to develop multiple samples and devices. Moreover, simulation of oxidation was used heavily, which lead to writing a manual pertaining to this procedure. Continuously using the oxidation furnace led to the creation of its own manual, mainly due to insight gained through its constant use. Lastly, the baseline process manual for a wet oxidation and its respective calibration database were written.

5.1 Dry Oxidation Simulation Manual

Dry Oxidation Synopsys Code

(synopsys dryox)

1.0 Code Purpose

1.1 This Synopsys sprocess code simulates the environment in the cleanroom for dry oxidation.

1.2 This assumes the total oxygen pressure is 1atm, the temperature and time can be changed.

2.0 Compatibility

3.0 Training Procedure & Applicable Documents

3.1 Every UTEP ECE student has access to this software through the E-319 computer lab.

3.2 Read the **Synopsys General manuals** to learn the environment, syntax, and get remote connection.

4.0 Definitions & Process Terminology

4.1 **Gate Oxidation**: A special dry oxidation (O_2) process that produces high quality silicon oxide film (well controlled thickness, and process).

4.2 **Dry/Wet Oxidation**: A high temperature oxidation (dry O_2 or steam) process that oxidizes the underlying silicon to forms SiO_2. Dry oxidation uses oxygen for better process control. Wet oxidation uses both DI water and oxygen for a fast reaction rate.

4.3 **TCAD:** Technology computer-aided design. Synopsys is a TCAD simulation software for semiconductor devices.

5.0 Computer Security

5.1 TBD

6.0 Process Calibration Data

6.1 Link to Process Calibration Data

7.0 Available Processes, Gases, Materials. Process Notes

7.1 TBD

8.0 Code Sample

8.1 Dry Oxidation

```
line x location= 0 spacing= 10 tag=Top
line x location= 30 spacing=10 tag=Bottom

line y location= 0 spacing= 250 tag=Left
line y location= 500 spacing= 250
line y location= 2000 spacing= 250 tag=Right

region Silicon xlo=Top xhi=Bottom ylo=Left yhi=Right

init concentration=5e15 field=Boron

#Gas flow definition
gas_flow name=DryOx partial.pressure= {O2= 1}

#Oxidation process
diffuse temperature= @Temperature@ time= @time@ gas_flow=DryOx

# Extract oxide thickness
set oxidelayer [lindex [layers y=500 Oxide] 1]
puts "DOE: tox [format %.4f [expr [lindex $oxidelayer 1] - [lindex $oxidelayer 0]]]"

#Etching done to take a snapshot
mask name=Ox segments= {0 5 1995 2000} negative
etch material= {Oxide} rate= {.6} time=1 type=anisotropic mask=Ox

struct tdr=dryoxT@Temp@t@time@
```

9.0 Troubleshooting Guidelines

9.1 TBA.

10.0 Study Guide

10.1 Synopsys Manuals

11.0 Appendices, Figures & Schematics

11.1 Dry Oxidation Graph

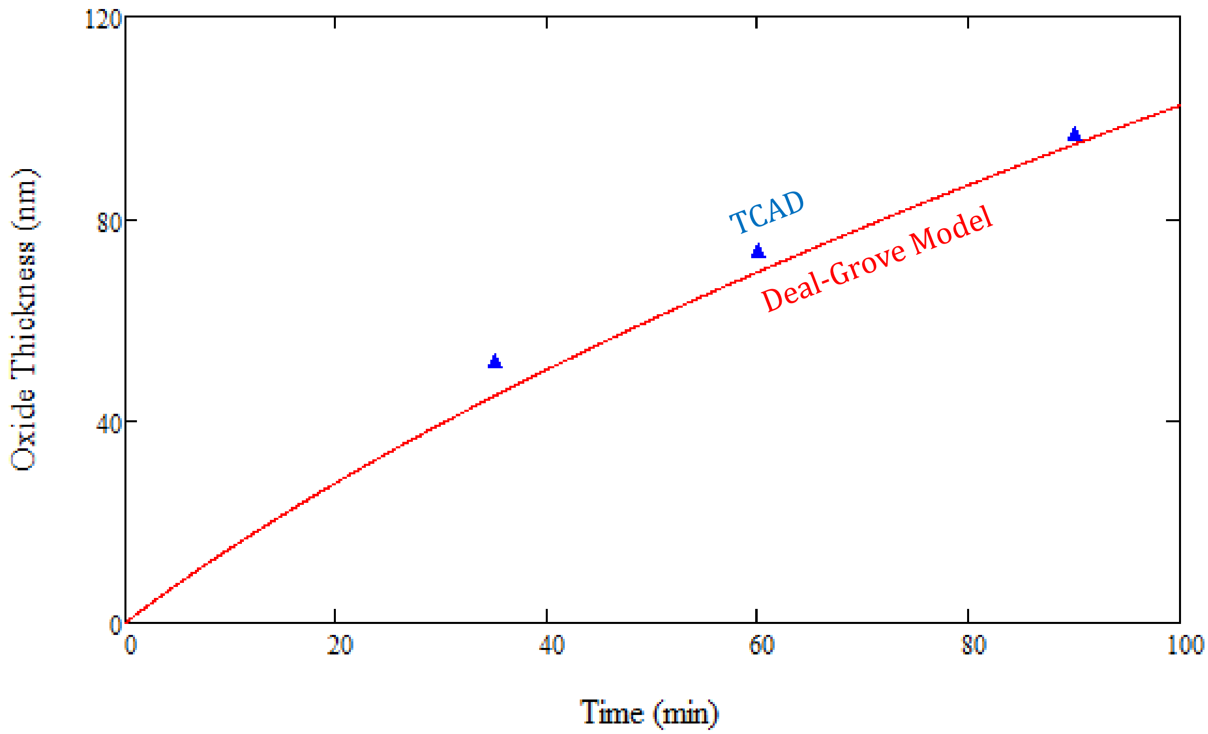


Figure 23. Oxide Thickness vs Time at 1050C. TCAD and Deal-Grove Model are plotted together to show similarities.

11.2 Workbench Screenshot

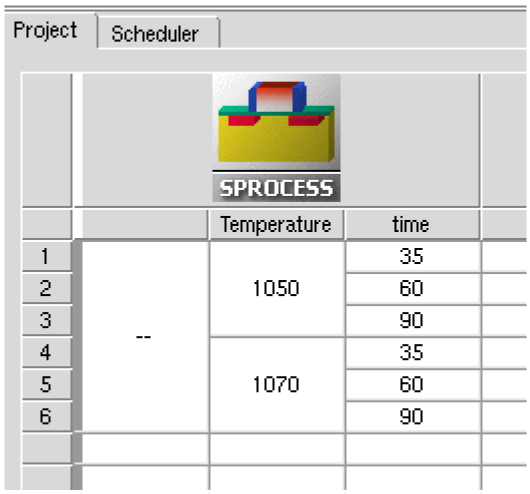


Figure 24. Synopsys workbench with variables

5.2 Thermco MB-80 Equipment Manual

Thermco MB-80

(thermco XX)

1.0 <u>Equipment Purpose</u>

1.1 The Thermco MB-80 is an oxidation furnace which can handle wet and dry oxidation for 3" wafers.

1.2 This furnace works at 1atm and can handle **<u>temperatures up to 1100°C.</u>**

2.0 <u>Material Controls & Compatibility</u>

2.1 No photoresist allowed in the furnace.

3.0 <u>Training Procedure & Applicable Documents</u>

3.1 Must read the manual for Thermco MB-80.

3.2 Shadow a user with experience working with Thermco MB-80

3.2.1 Time needed to shadow TBA.

3.3 Test – Must show a super user the ability to operate Thermco MB-80

4.0 <u>Definitions & Process Terminology</u>

4.1 **Gate Oxidation**: A special dry oxidation (O_2) process that produces high quality silicon oxide film (well controlled thickness, and process).

4.2 **Dry/Wet Oxidation**: A high temperature oxidation (dry O_2 or steam) process that oxidizes the underlying silicon to forms SiO_2. Dry oxidation uses oxygen for better process control. Wet oxidation uses both DI water and oxygen for a fast reaction rate.

4.3 **Annealing**: A high temperature process that uses nitrogen to keep wafers in an inert atmosphere.

4.4 **Furnace Flat Zone**: An area inside the furnace with least temperature variation across it (best place to process wafers).

5.0 ***Safety***

5.1 **Electric Shock Hazard:** Thermco furnaces utilize **high electric power** (high current) to generate heat. Do not open the side panels or touch the high-power electrical parts in the furnace cabinet.

5.2 **Burn Hazard**: Rod, boats and wafers coming out of the furnace are very hot. Wear high-temperature gloves when loading/unloading wafers. Proceed with caution. Avoid touching any furnace quartz ware to prevent burning your hands, as well as contaminating the furnace. No flammable chemical, especially organic solvents are allowed at the load station.

5.3 **Boiling Water Hazard**: The bubbler will boil DI water and must be handled with care using mitts. Avoid placing face directly in front of an opening when removing caps from bubbler.

6.0 ***Process Calibration Data***

6.1 Link to Process Calibration Data

7.0 ***Available Processes, Gases, Materials. Process Notes***

7.1 Baseline Processes

7.1.1 Thermco Dry Oxidation – 50nm

7.1.2 Thermco Dry Oxidation – 75nm

7.1.3 Thermco Dry Oxidation – 90nm

7.1.4 Thermco Wet Oxidation – 250nm

7.1.5 Thermco Wet Oxidation – 330nm

7.1.6 Thermco Wet Oxidation – 420nm

7.2 Available Gases

7.2.1 **Nitrogen (N_2):** Used to purge out room air and keep the process tube in an inert/clean atmosphere.

7.2.2 **Oxygen (O_2):** Used for dry/wet oxidation process.

7.2.3 **DI Water Vapor (H_2OVAP):** Used for wet oxidation.

8.0 ***Equipment Operation***

8.1 Dry Oxidation Procedure

8.1.1 Furnace Preparation

1. Ensure that there is enough O_2 pressure in the oxygen tank and N_2 in the nitrogen tank for the duration of the oxidation run. At an oxygen flowrate of **6.2 L/min** it is expected to use up **100 psi/hr.**
2. **IMPORTANT: Ensure there is enough distilled water in the chiller.**

3. **IMPORTANT: Turn on the furnace chiller**.
4. Set oxygen and nitrogen to the **desired flow rates.**
5. Stabilize the middle furnace to the **desired temperature** with N_2 flowing constantly.
6. After the furnace has had ample time to stabilize, open the oxygen valve and allow the oxygen to flow.
7. Close the nitrogen valve.

8.1.2 Procedure

1. Don the high temperature protective gloves.
2. Load the wafers into the oxidation boat.
3. Load “dummy” wafers at both ends of the boat.
4. Place the boat of wafers in the open end of the lower furnace with the polished side facing forward for 5 minutes. Note that the temperature at the opening of the tube is approximately 400 °C.
5. Slowly push the boat into the flat zone of the furnace tube. This “push” should take about 5 minutes.
6. Start marking time and oxidize the wafers for the **desired time**.
7. After the appropriate length of time has elapsed close the oxygen valve.
8. Open the nitrogen valve.
9. Set middle temperature to 0℃.
10. Turn off the heaters of the furnace.
11. Slowly pull the boat towards the opening. This removal should take about 5 minutes. Leave the boat at the open end of the furnace tube and allow the wafers to stabilize for about 5 minutes. Note that the temperature at the opening of the tube is approximately 400 °C.
12. Remove the boat from the open end of the furnace tube and allow to cool for at least 10 minutes.
13. Turn off gases.
14. Once the furnace temperature is below 450℃, turn off the furnace.
15. Turn off the furnace chiller

8.2 Wet Oxidation Procedure

8.2.1 Furnace Preparation

1. Ensure that there is enough O_2 pressure in the oxygen tank for the duration of the oxidation run. (Reference Flow rate, psi consumed/time)
2. **IMPORTANT: Ensure there is enough distilled water in the chiller.**
3. **IMPORTANT: Turn on the furnace chiller**.
4. Set oxygen to the **desired flow rates.**
5. Stabilize the middle furnace to the **desired temperature**
6. Give the furnace ample time to stabilize.

8.2.2 Bubbler Preparation

1. Add 750mL of DI water to the bubbler flask.

2. Turn on heating mantle.

3. Use thermocouple to keep track of the temperature of the bubbler.

4. Set the heating mantle dial for good water vapor generation, 90% mark is recommended.

5. Once the bubbling begins, near the 90°C range, open the oxygen valve so water vapor can flow into the furnace.

8.2.3 Procedure

1. Don the high temperature protective gloves.
2. Load the wafers into the oxidation boat.
3. Load "dummy" wafers at both ends of the boat.
4. Place the boat of wafers in the open end of the lower furnace with the polished side facing forward for 5 minutes. Note that the temperature at the opening of the tube is approximately 400 °C.
5. Slowly push the boat into the flat zone of the furnace tube. This "push" should take about 5 minutes.
6. Start marking time and oxidize the wafers for the **desired time**.
    a) Note: ***After 60 minutes of oxidizing, you should refill the flask with pre-heated DI.***
        i. ***Turn off the heating mantle 5-10 minutes before you want to refill***
        ii. ***Close the oxygen when you are ready to refill with pre-heated DI.***
        iii. ***Make sure the bubble is seated before turning on the heating mantle.***
        iv. ***Open oxygen and continue taking time.***
7. After the appropriate length of time has elapsed close the oxygen valve.
8. Open the nitrogen valve.
9. Set middle temperature to 0℃.
10. Turn off the heaters of the furnace.
11. Turn off the heating mantle.
12. Slowly pull the boat towards the opening. This removal should take about 5 minutes. Leave the boat at the open end of the furnace tube and allow the wafers to stabilize for about 5 minutes. Note that the temperature at the opening of the tube is approximately 400 °C.
13. Remove the boat from the open end of the furnace tube and allow to cool for at least 10 minutes.
14. Turn off gases.
15. Once the furnace temperature is below 450℃, turn off the furnace.
16. Turn off the furnace chiller.
17. Empty out the bubbler flask.

9.0 Troubleshooting Guidelines

9.1 TBA.

10.0 Study Guide

10.1 TBA.

11.0 Appendices, Figures & Schematics

11.1 Dry Oxidation Graphs

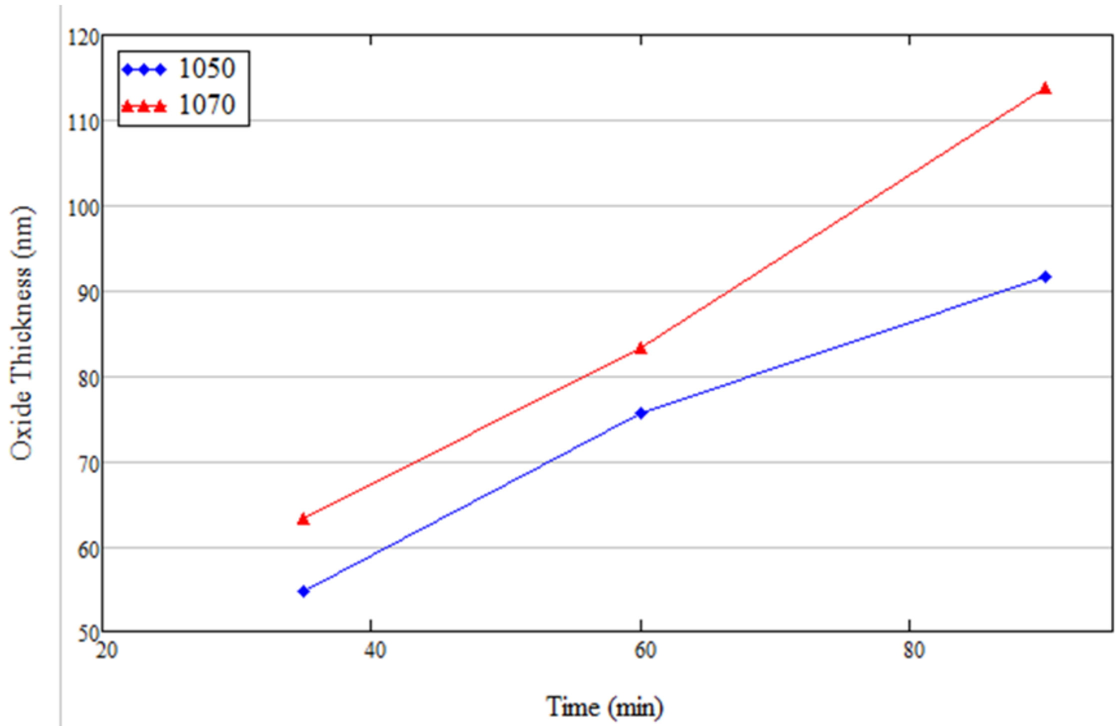


Figure 25. Oxide Thickness vs Time of Dry Oxidation at 1050C and 1070C

11.2 Wet Oxidation Graphs

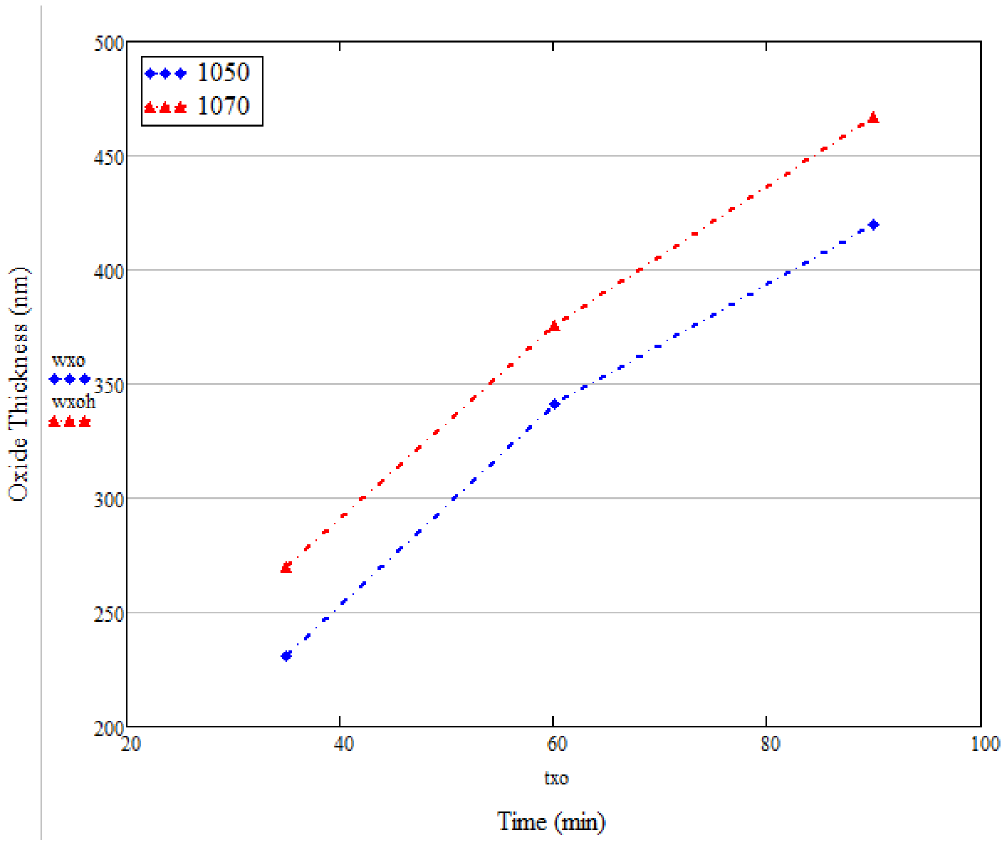


Figure 26. Oxide Thickness vs Time of Wet Oxidation at 1050C and 1070C

11.3 Flowmeter Maximum Flowrate

11.4 Recommended Gas Flow Rates

Gas	Ball Position (mm)	Flow Rate (L/min)
Oxygen	60	6.2
Nitrogen	60	6.7

TABLE 8 - 150mm FLOW TUBES, GAS FLOW CAPACITIES OF ROUTINE GASES												
FLOW TUBE MAXIMUM FLOW RATES												
FLOW TUBE NUMBER	ARGON [smL/min]	[scfh]	CARBON DIOXIDE [smL/min]	[scfh]	HELIUM [smL/min]	[scfh]	HYDROGEN [smL/min]	[scfh]	NITROGEN [smL/min]	[scfh]	OXYGEN [smL/min]	[scfh]
034-39-GL	7266	15.39	7304	15.47	19040	40.33	29795	63.12	8695	18.42	8091	17.14
034-39-SA	9373	19.85	9406	19.92	24810	52.56	39101	82.84	11270	23.87	10535	22.31
034-39-ST	13977	29.61	13728	29.08	39280	83.22	58968	124.9	16794	35.58	15610	33.07
034-39-CA	19580	41.48	19296	40.88	54965	116.4	84023	178.0	23444	49.66	22000	46.61
034-39-TA	20938	44.36	20543	43.52	60207	127.5	89109	188.7	25084	53.14	23500	49.78

Figure 27. Flowmeter Flowrate at 150mm Point for Nitrogen and Oxygen

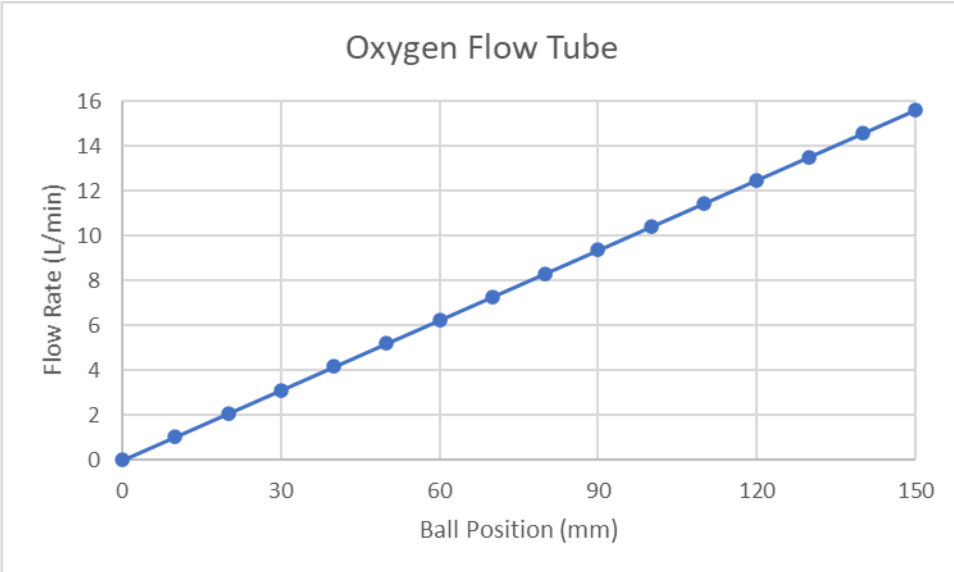


Figure 28. Oxygen Flow Rate vs Ball Position

11.4.1 Non-Uniformity at Different Flow Rates. A flow rate with below 5% non-uniformity is optimal.

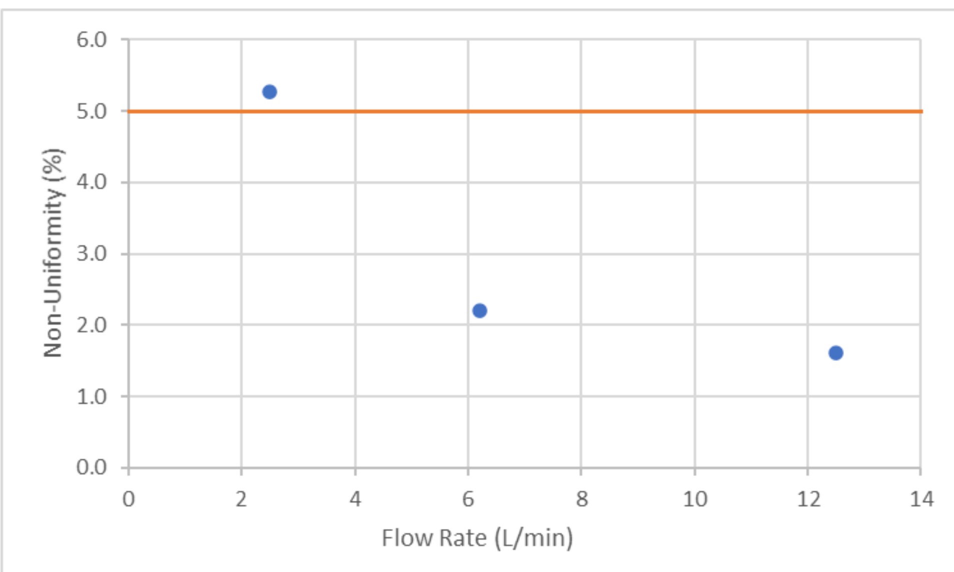


Figure 29. Non-Uniformity vs Oxygen Flow Rate

11.4.2 Non-Uniformity at Different Bubbler Temperatures. A bubbler temperature with below 5% non-uniformity is optimal.

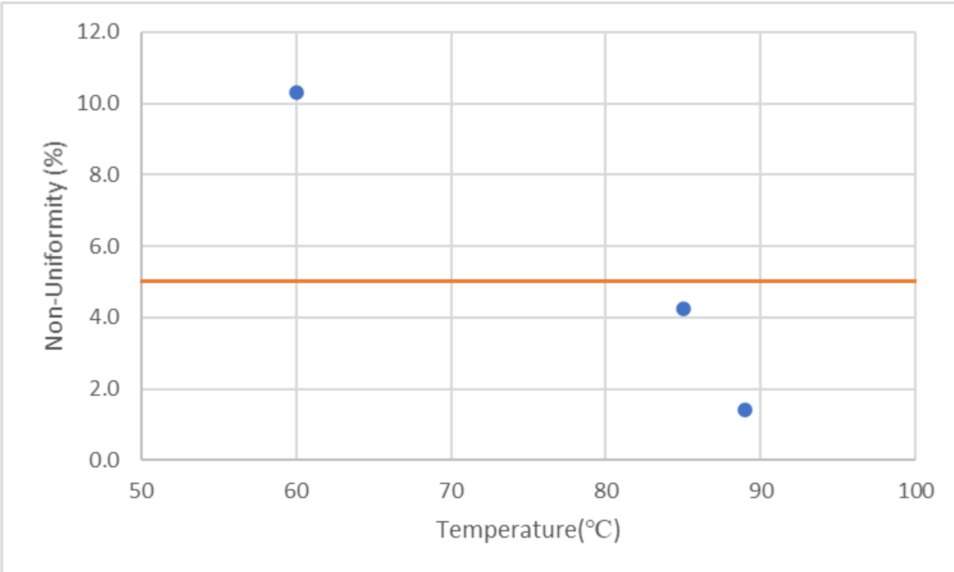


Figure 30. Non-Uniformity vs Bubbler Temperature

11.5 Pictures of Equipment

Figure 31. Thermco MB-80

Figure 32. Bubbler

5.3 Wet Oxidation – 330nm Baseline Process

Thermco Wet Oxidation – 330nm

(WetOx330)

1.0 Process Summary

1.1 This manual covers the steps for the 330nm wet oxide baseline using the Thermco furnace.

2.0 Material Controls & Compatibility

2.1 This baseline process is to be used on clean 3" silicon wafers.

2.2 Wet oxidation is a faster oxidation process, usually used for field oxides.

3.0 Training Procedure & Applicable Documents

3.1 Thermco MB-80 Manual

4.0 Definitions & Process Terminology

4.1 **Gate Oxidation**: A special dry oxidation (O2) process that produces high quality silicon oxide film (well controlled thickness, and process).

4.2 **Dry/Wet Oxidation**: A high temperature oxidation (dry O2 or steam) process that oxidizes the underlying silicon to forms SiO2. Dry oxidation uses oxygen for better process control. Wet oxidation uses both DI water and oxygen for a fast reaction rate.

4.3 **Annealing**: A high temperature process that uses nitrogen to keep wafers in an inert atmosphere.

4.4 **Furnace Flat Zone**: An area inside the furnace with least temperature variation across it (best place to process wafers).

5.0 Safety

5.1 **Electric Shock Hazard:** Thermco furnaces utilize **high electric power** (high current) to generate heat. Do not open the side panels or touch the high-power electrical parts in the furnace cabinet.

5.2 **Burn Hazard**: Rod, boats and wafers coming out of the furnace are very hot. Wear high-temperature gloves when loading/unloading wafers. Proceed with caution. Avoid touching any furnace quartz ware to prevent burning your hands, as well as contaminating the furnace. No flammable chemical, especially organic solvents are allowed at the load station.

5.3 **Boiling Water Hazard**: The bubbler will boil DI water and must be handled with care using mitts. Avoid placing face directly in front of an opening when removing caps from bubbler.

6.0 Process Calibration Data

6.1 Link to Thermco Wet Oxidation – 330nm Data

7.0 Process Explanation

7.1 Wet oxidation is a fast process which will grow a lower-quality oxide. For wet oxidation, the oxide is grown in the following reaction:

$Si + 2H_2O \rightarrow SiO_2 + H_2$

A model for the oxidation reaction kinetics was proposed over twenty-five years ago and is known today as the Deal-Grove model of thermal oxidation. Calculations based on this model provide a good first-order approximation of the resulting oxide thickness especially for oxide thickness' greater than 300 angstroms. However, the Deal-Grove model is not well suited for oxide films thinner than 300 angstroms.

8.0 Process Procedure

8.1 Follow the **Wet Oxidation Procedure** in the Thermco MB-80 Equipment Manual

8.2 Use the following settings

Temperature (℃)	Time (min)	O_2 Flow Rate (L/min)	Flask Temperature (℃)
1050	60	6.2	90

9.0 Troubleshooting Guidelines

9.1 TBD

10.0 Study Guide

10.1 SDS for Oxygen Gas.

11.0 Appendices, Figures & Schematics

11.1 Oxidized Silicon Wafer Image

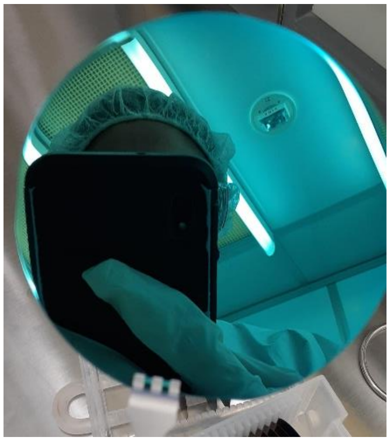


Figure 33. Oxidized Silicon Wafer with 330 nm SiO2

11.2 Calibration graph of flow tube

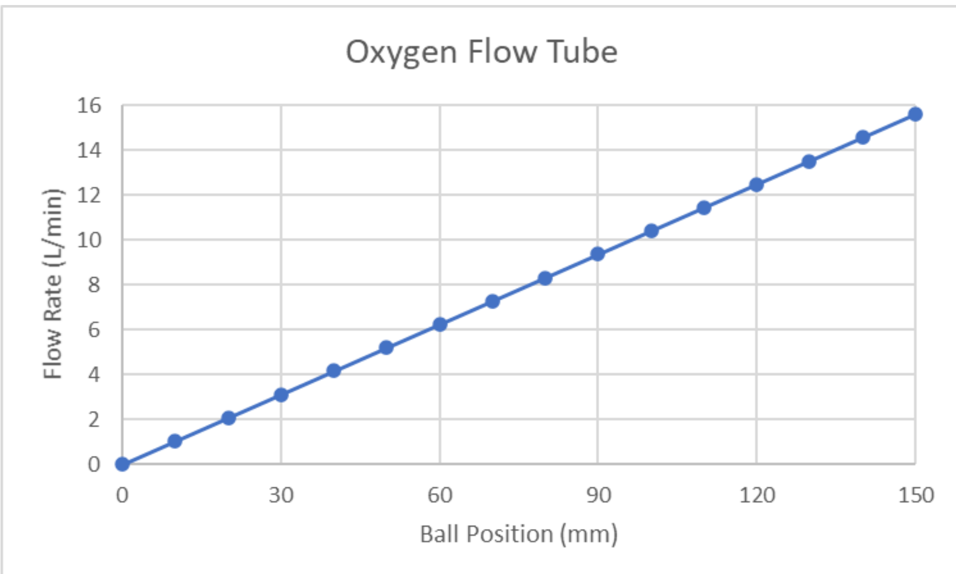


Figure 34. Oxygen Flow Rate vs Ball Position

11.3 Heating mantle calibration

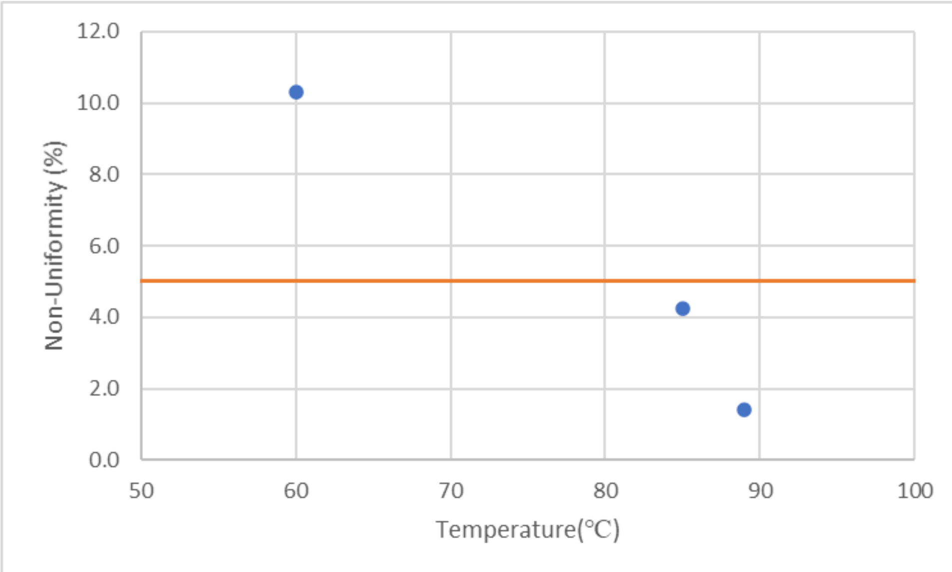


Figure 35. Non-Uniformity vs Bubbler Temperature

5.4 Wet Oxidation – 330nm Process Calibration Database

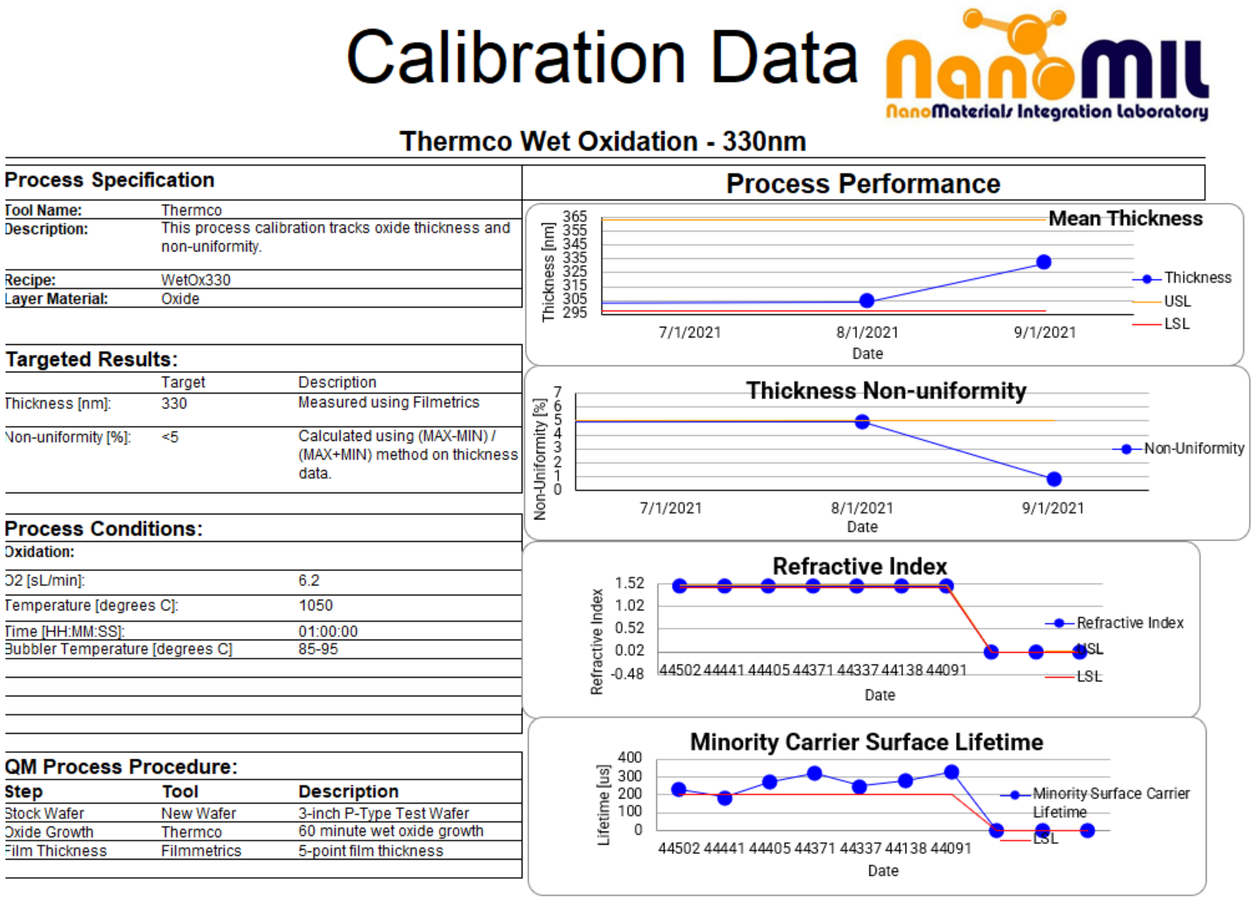


Figure 36. Process calibration database of wet oxidation for 330nm.

				3in Growth Thickness					
Wafer ID	Operator	Date		T	C	F	L	R	Mean
FakeTrial	asagredo	8/12/2021		300	305	290	320	305	304
Fall2021_18	asagredo	9/12/2021		328.7	331.8	331.3	334	332.9	331.74

Figure 37. Process calibration database measurements spreadsheet

Run Information			Thickness Calculation				
Wafer ID	Operator	Date	Mean Growth Thicknes	SD	MAX	MIN	Non-Uniformity [%]
FakeTrial	asagredo	8/12/2021	304	10.83974169	320	290	4.918032787
Fall2021_18	asagredo	9/12/2021	331.74	1.993238571	334	328.7	0.799758563

Figure 38. Process calibration database equations spreadsheet

Chapter 6: Conclusion

This work developed an architecture for UTEP's nanofabrication facility with modular design in mind. Through this modularization a simpler method of documenting the use of the facility was achieved by finding the logical divisions. The major modules include equipment, baseline processes, process calibration database, and simulation software. Each of these major modules were then modularized by the processing techniques which connected equipment with different recipes and simulation of processes. By keeping a similarly modular documentation within each module the manuals may be used in a flexible manner to develop complex devices. In this paper, multiple exemplar modules were designed encompassing all aspects of the cleanroom operation.

Each of the exemplar modules was developed independently to allow for future changes. Any editing may be done from identifying drift in a process or a new baseline being designed to have higher performance. This architecture may be used by future cohorts to continue modularization of the rest of the cleanroom operation. The nanofabrication facility has enough equipment to develop an extensive documentation system which will allow for the development of a multitude of technology.

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Appendices

Appendix 1. Equipment Manual Template

Chapter [#]

Tool Name

(toolname - location)

1.0 Equipment Purpose

1.1 The processing techniques which the machine can run will be written here along with some information on the settings.

2.0 Material Controls & Compatibility

2.1 Any materials that are not compatible with the equipment should be written in this section.

3.0 Training Procedure & Applicable Documents

3.1 All the steps required to become a user of the machine will be here. These might be shadowing, reviewing documents, and written tests.

4.0 Definitions & Process Terminology

4.1 Any terminology applicable to the equipment will be found here for the purpose of giving enough context to the reader.

5.0 Safety

5.1 Any precautions needed for safe use of the equipment will be here. This section focuses on the health of the user.

6.0 Process Calibration Data

6.1 All documents with calibration data from the baseline processes is found here.

7.0 Available Processes, Gases, Materials. Process Notes

7.1 All the baseline process documents can be found here so any user can try the recipe.

8.0 Equipment Operation

8.1 A step-by-step description on how to operate the equipment may be found here.

9.0 Troubleshooting Guidelines

9.1 Any fixes to errors which any user can handle will be in this section.

10.0 Study Guide

10.1 Documents which will aid in understanding the use of the equipment and in training will be placed here.

11.0 Appendices, Figures & Schematics

11.1 Any other information which pertains to the machine is found here.

APPENDIX 2. BASELINE PROCESS MANUAL TEMPLATE

Chapter [#]

Process Name

(recipe)

1.0 Process Summary

1.1 The goals of the baseline process is written in this section; i.e. chemicals used, thickness, etc.

2.0 Material Controls & Compatibility

2.1 Any information on the materials the process works on will be placed here; i.e. bare silicon, oxidized silicon, etc.

3.0 Training Procedure & Applicable Documents

3.1 The equipment manual may be linked here for training purposes and some SDS for chemicals used.

4.0 Definitions & Process Terminology

4.1 Any terminology applicable to the process will be found here for the purpose of giving enough context to the reader

5.0 Safety

5.1 Any precautions needed to safely handle the materials will be placed here.

6.0 Process Calibration Data

6.1 All documents with calibration data from the baseline processes is found here.

7.0 Process Explanation

7.1 A brief explanation of the process and the theory behind will be in this section.

8.0 Process Procedure

8.1 All the required settings to meet the goals of the baseline process and additional steps will be written in this section. It may be applicable to link the equipment manual.

9.0 Troubleshooting Guidelines

9.1 Any fixes found for common errors in the process may be found here.

10.0 Study Guide

10.1 Any documents that may need to be studied before running a process should be here. Generally, information about the materials which will be used should be here.

11.0 Appendices, Figures &Schematics

11.1 Any other figures which are applicable to the baseline process should be attached here.

APPENDIX 3. PROCESS CALIBRATION DATABASE TEMPLATE

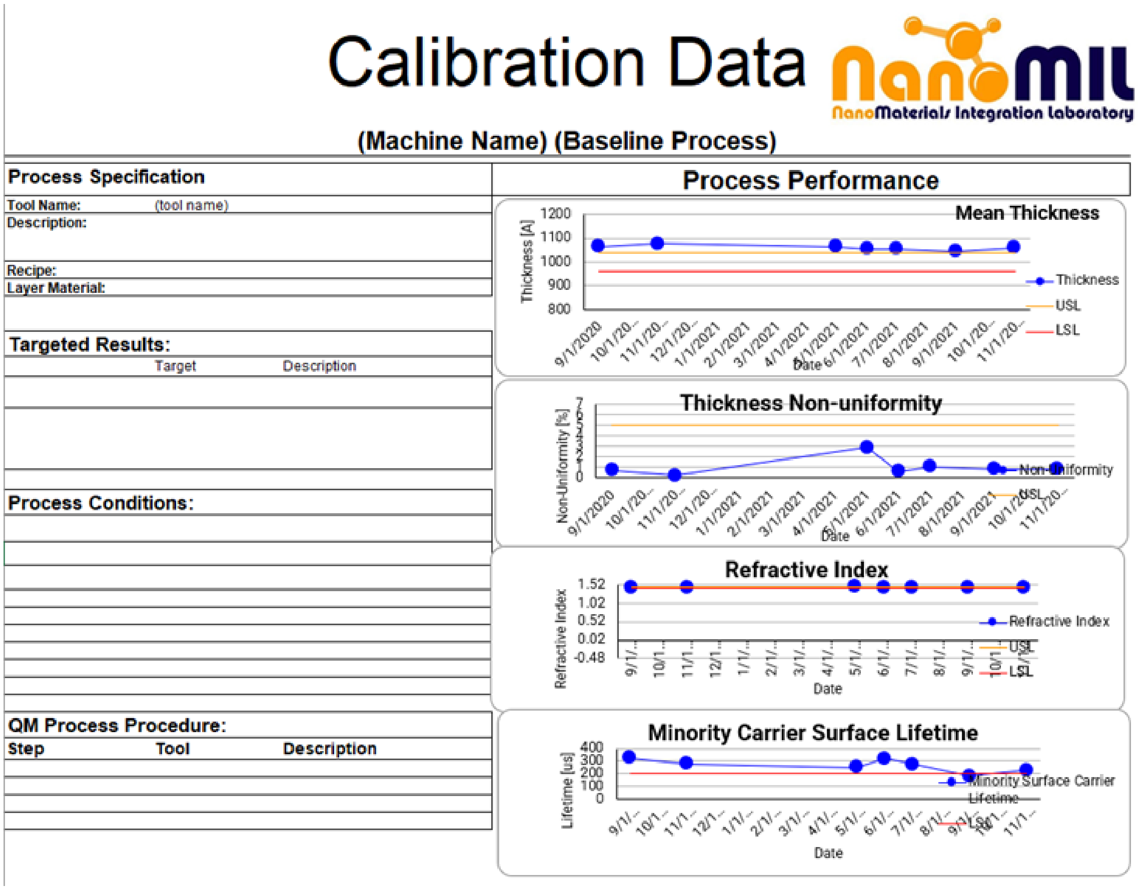

Figure 39. Calibration Data Spreadsheet Template

APPENDIX 4. SIMULATION SOFTWARE MANUAL TEMPLATE

Chapter [#]

Simulation Code

(simulation tool recipe)

1.0 <u>Code Purpose</u>

1.3 The goals on the simulation code are written here.

2.0 Compatibility

2.1 All tools that are compatible with this process are included here.

3.0 Training Procedure & Applicable Documents

3.1 All documents which help with a successful run of the simulation are linked in this section.

4.0 Definitions & Process Terminology

4.1 All terminology applicable to this simulation will be found here for the purpose of giving enough context to the reader.

5.0 Computer Security

5.1 This section will include basic computer security tips.

6.0 Process Calibration Data

6.1 The baseline calibration data will be linked here so the user can compare.

7.0 Available Processes, Gases, Materials. Process Notes

7.1 Any processes similar to the simulation code will be linked in this section.

8.0 Code Sample

8.1 An example of the code in written in this portion of the document, the assumption is made that the reader has already learned the syntax.

9.0 Troubleshooting Guidelines

9.1 Typical bug fixes and tips will be found here.

10.0 Study Guide

10.1 Recommended files that the user must study to understand the code are linked here.

11.0 Appendices, Figures & Schematics

11.1 The output data and other images which helps in the simulation will be attached here.

Vita

Andres Sagredo was born in El Paso, Texas and spent his childhood in the border city of Ciudad Juarez, Chihuahua. At twelve years-old he moved back to El Paso already showing interest in the fields of math and science. Andres found an interest in semiconductors in 2019 and began researching with Dr. Zubia. In this research, he was able to aid a graduate student in research of MEMS actuators both in simulation and inside the nanofabrication facility. Andres graduated from his Bachelor of Science in Electrical Engineering in spring of 2020 in the midst of a pandemic.

Despite being in an online setting, Andres continued his pursuit for a Master’s degree in Electrical Engineering focusing in semiconductor devices and their fabrication. To do this in an online setting, he had to learn simulation software which help in the design of such devices. Using this software, he was able to aid in enhancing the fabrication of semiconductor devices at UTEP by applying this newfound knowledge at the laboratory. Andres graduated from his Master of Science in Electrical Engineering in fall of 2021 after returning physically to the university.