Heated Motorized Stage for Nanoscale Thin Film Deposition

ME 450 Report

TEAM 19

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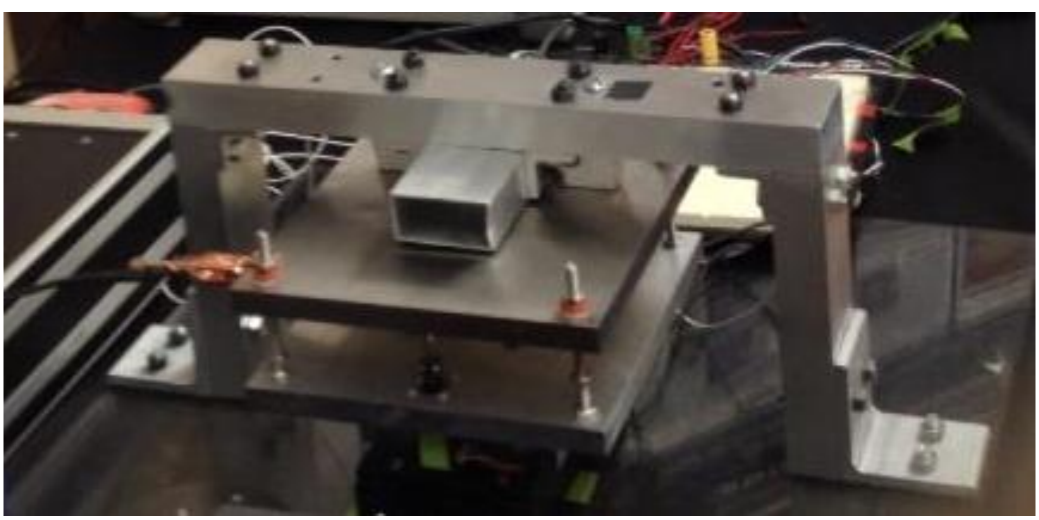

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A. Executive Summary

Thin film deposition is a technology of applying a very thin film of material onto a substrate surface to be coated, or onto a previously deposited coating to form layers. As a modified Atomic Layer Deposition method, Spatial ALD grows as a promising technique that improves the efficiency of the process by separating the half-reactions spatially instead of through the use of purge steps in convectional ALD. Dasgupta Research Group is interested to study about the effect of deposition conditions such as gap size, gap alignment and substrate temperature on the characteristics of thin film coating. Therefore, Professor Dasgupta requested for the design and manufacture of a heated motorized substrate stage as a part of the Spatial Atomic Layer Deposition system. The motorized stage has six major specifications: x-axis linear motions to achieve the deposition rate of 0.1 nm/sec; uniform heating of the substrate from ambient temperature up to maximum temperature of 200 °C; precise 20-50 μm gap size control between the substrate and the depositor; gap alignment to ensure parallelism between the substrate and the stage; 5μm flatness tolerances of the stage; securing of the substrate throughout the process.

Based on the engineering specifications and budget constraints, the team used Pugh Chart to assist the concept selection process. The concept, with the use of three stepper motors and gap measurements sensors to control the gap size and gap alignment, was chosen because of reasonable costs involved and its precise close-loop feedback control system used to achieve the project goals. The final design includes seven key components: Invar as heated plate to reduce the effect of thermal expansion, capacitive sensors to measure the gap size; vacuum chuck to secure the substrate; polyimide heater to heat the stage uniformly; stepper motors to perform tilt and vertical (z-axis) height adjustments; horizontal linear stage to oscillate the stage in x-axis during deposition; set screws to secure the heated stage in place. In order to achieve low flatness tolerances, the team selected grinding and milling as two major manufacturing methods for the Invar plate and the aluminum plate. The low flatness tolerances of the final product proved that the selected manufacturing methods were suitable for the applications. Through persuasive design concept and persistent negotiation with the vendor, the team successfully kept the budget under USD 10,000 and acquired all the component with the cost of USD 7969.06.

Overall, the final design achieved all the required specifications except uniform heating due to the delay in the arrival of the parts. Through validations and engineering analysis performed, the final design proved to be a promising solution for Dasgupta Research Group's SALD study. Nonetheless, based on the performance of the prototype, the team recommended the use of the three sensors instead of two for better gap size control results, recalibration of the sensors to improve the accuracy of the sensors result, use of thicker screw sizes to better support the heated plate, and use of several thermocouples for precise temperature measurements. The design can be further improved with a more advanced user interface for the control system, a more precise sensor mounting method, and additions of markings on the heated plate for repeatable wafer placement.

B. Problem Descriptions and Background

B.1 Background

Thin film deposition is a technology of applying a very thin film of material onto a substrate surface to be coated, or onto a previously deposited coating to form layers. Developed primarily for the silicon integrated circuit industry, thin film deposition has become a general technology used in various areas of application for designing and constructing complex structures, layer by layer. Nowadays, thin film deposition manufacturing processes are widely utilized in semiconductor industry and solar energy conversion applications [1].

One of the most widely researched film deposition methods is atomic layer deposition (ALD) which is a thin film growth technique capable of the conformal coating of ultra-high-aspect-ratio structures with sub-nanometer precision films. As shown in Figure A, the atomic monolayers are formed through two time-sequenced self-limiting surface reactions, each one being separated by purge steps. It has been shown that the material loading and particle size can be controlled by simply varying the number of ALD cycles. [2] ALD can be used to deposit various types of materials such as compound semiconductors, high-κ dielectrics and metallic nitrides used in the metal gates of MOSFETs. [3] Especially due to its sub-nanometer precision film deposition capability, ALD has become a widely used technique in semiconductor industry to form metal/high-k (high permittivity) gate oxide stacks for field effect transistors, capacitors for dynamic random access memory (DRAM) devices, as well as in the thin film magnetic head industry to form gap dielectrics, where the control of ultra-thin films is essential and the conformity requirements are high. [4] For instance, Intel Corporation has reported using ALD to deposit high-k gate dielectric for its 45 nm Complementary metal–oxide–semiconductor (CMOS) technology. [5] Also, there have been many approaches regarding its utilization in solar energy conversion applications such as lithium batteries, photovoltaics and photoelectrochemical cells.

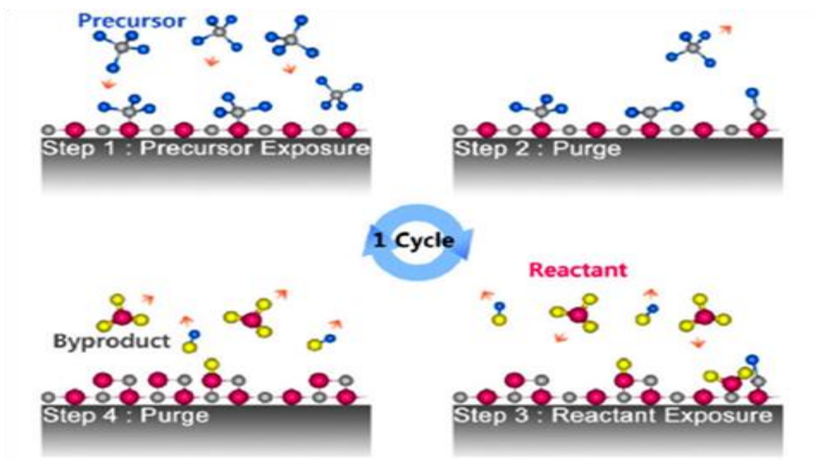


Figure B.1: Schematic illustration of a complete atomic layer deposition (ALD) cycle including 4 steps- precursor dose, purge, reactant dose and purge), separated into individual half-reactions and purge cycles, on the Substrate [6]

Though ALD allows the nanoengineering of surfaces with precise nanoscale control, there are several major drawbacks regarding ALD, which are its low deposition rate and limited chamber size, making ALD less attractive for commercial and industrial applications that require high throughput processing and large scale chemical deposition. An approach to overcome these drawbacks is SALD, which is a modified ALD method where the half-reactions are separated spatially instead of through the use of purge steps. As illustrated in Figure B, the different precursors are supplied constantly in between inert gas regions. Films are then grown by alternatively exposing the substrate from one precursor region to the other going across the inert gas regions. In this way, the oscillation of the substrate (or of the gases injector) from one precursor zone to the second one, going across the inert gas regions, reproduces the classical conventional ALD scheme which is that the first metal precursor reacts with the surface forming a monolayer while any unreacted precursor is swept away and purged in the inert region; then the second precursor reacts with the previous monolayer forming a layer of material; finally the sample returns to the first precursor region again going across the inert region where any by-products and excess precursor are purged. This allows for higher deposition rate and higher throughput ALD. [7]

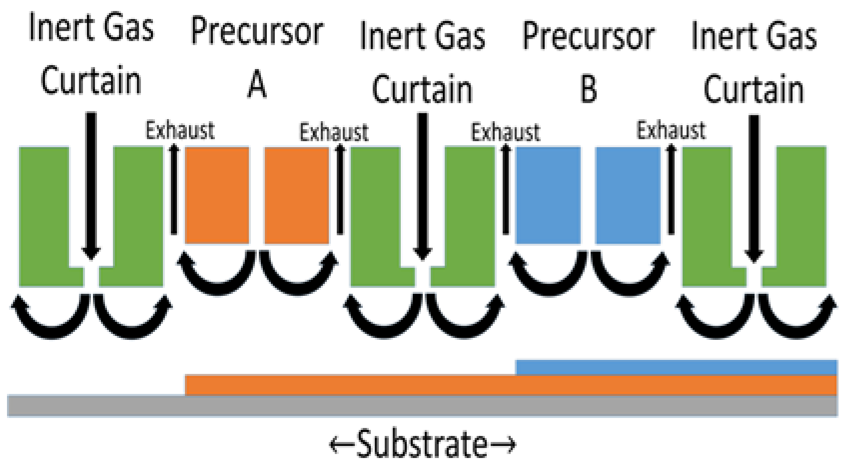


Figure B.2: Schematic illustration of a complete spatial atomic layer deposition (SALD) reactor concept, where the precursor half-reaction zones are separated by inert gas curtains. By moving the substrate horizontally underneath the injector, the two half-reactions will take place sequentially to form an ALD monolayer. The close proximity between the depositor and the substrate combined with the inert gas flows gives an excellent separation between the precursors [8]

B.2 Motivation

SALD is becoming more popular and shows great promises in overcoming the limitations found in conventional ALD. However, it is a relatively new technique, and requires further research and development for optimization. Dasgupta Research Group is currently designing its own SALD reactor to evaluate the effect of deposition conditions on the growth properties of SALD. Thus, Professor Dasgupta requested that the team design and build a heated motorized substrate stage as a part of the SALD system which is capable of controlling and altering gap space and gap alignment between the substrate and the depositor and temperature of the substrate in order to study how these factors affect the homogenous coating of nanoparticles.

B.3 Problem Descriptions

Dasgupta Research Group is currently designing its own SALD station to conduct a research which studies the effect of deposition conditions on the characteristics of thin film coating. The group’s current design concept fulfill the requirements but does not have a tilt adjustment system. Therefore, the gap alignment between the substrate and the depositor is not adjustable. Professor Dasgupta requested that the team design and build a heated motorized substrate stage as a part of the SALD system that is capable of controlling and adjusting gap space, gap alignment, and temperature of the substrate. There have been previous SALD stations built by companies and research groups that are capable to perform heating and oscillating movement of substrate. However, none of the machines have the capability to fulfill all the requirements stated by the sponsor which include substrate holding system, substrate heating system and precise adjustment of gap space and gap alignment of the substrate with respect to the depositor.

B.4 Key Challenges

After the interview with the sponsor, the team found several possible key challenges regarding the completion of the project as listed below:

B.4.a Budget

Find an option that satisfies both the engineering specifications and available budget provided by the sponsor. The team will have to compare and select a feasible option from different ideas such as purchasing products and partly building a customized system.

B.4.b Material selection

Components such as substrate stage are required to be uniformly heated up to 200 ℃ and maintain acceptable tolerances for flatness. Thus, the team will have to find suitable materials that not only have sufficiently low coefficient of thermal expansion but also reasonable thermal conductivity and machinability.

B.4.c Modeling and computational analysis

Finite element analysis is planned to be used to study the mechanical stability and heat transfer along the substrate to predict heat transfer along the substrate and possible alterations in tolerances of flatness due to thermal expansions on the heated component because the system requires microscale precision.

B.4.d Safety

It is very essential that the system is safe for users, so the team will have to consider safety mechanism that prevents any thermal, electrical and chemical hazards.

B.5 Literature Review

The team did research on other SALD station in existence right now for the reference and also to form a benchmark for the design. Examples of these designs are shown and discussed in more detail below.

B.5.a Eastman Kodak

Eastman Kodak is a company based in the United States, their main focus of using SALD is for thin film transistors using Aluminum oxide and Zinc oxide deposition. In their design for SALD (Figure C, pg. 6), the substrate is placed on top of the depositor head and supported by the flow of gases which are pumped through the gas slots. Deposition occurs when the substrate oscillates back and forth over the gas flows. The proximity between the substrate and the coating head is determined by the pressure of the gas flow.

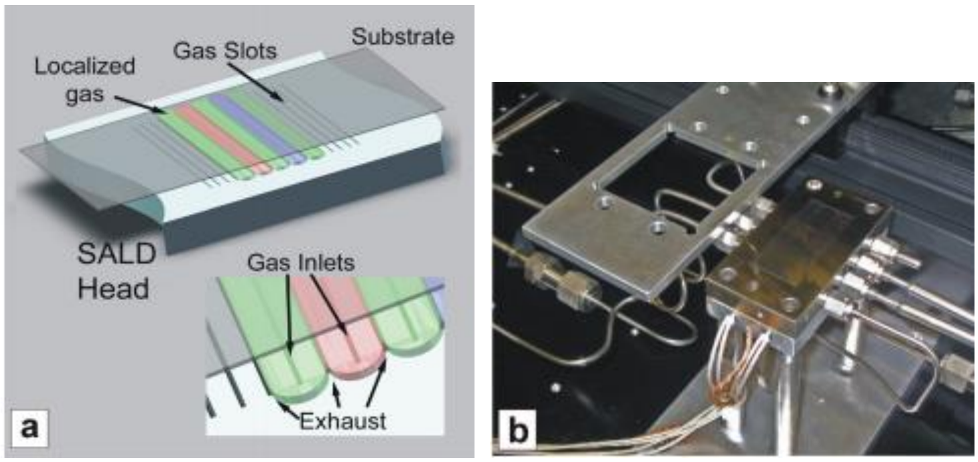


Figure B.3: Schematics (a) and actual machine (b) of Eastman Kodak SALD station

Since the system uses pressure of gas flow to support the substrate, the substrate is maintained in close proximity to the depositor without the need for extremely high tolerance mechanical fixtures. This allows the substrate to have a higher translation speed across the reactor which will result in a higher deposition rate. However, this design concept does not suit the purpose of this project. Although it has a high deposition rate, it is not the major requirement for the design. Whereas the gap size is very important because it is the manipulated variable for the research. Therefore, one of the disadvantages of this design from Eastman Kodak is the inaccurate gap sizing which just sufficient for good deposition. [9]

B.5.b TNO

This design was created by TNO which is a company based in Netherlands. The main application for TNO using SALD is the surface passivation layers on crystalline silicon solar cells. They started their rotary proof of principle reactor in 2009. As shown in Figure D, the half reaction zones are incorporated in a round reactor head surrounded by exhaust zones. The reactor head is mounted on top of a rotary substrate table. The whole reactor is built in a convection oven. The round reactor is stationary with the substrate table rotating under it for deposition.

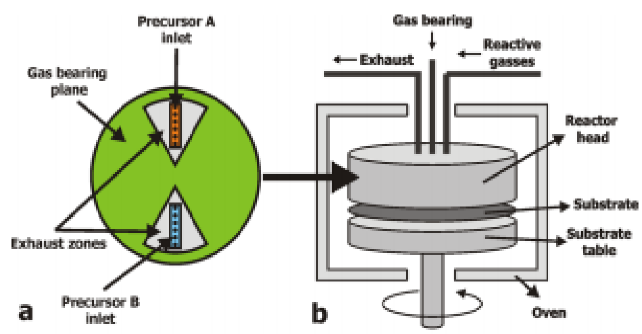


Figure B.4: Schematics of the SALD station by TNO.

Their machine was able to achieve a high rotating speed of 600 rpm and a deposition rate of 0.12 nm/cycle which is a high value for an industrial scale. Again, speed is not the team's main focus in the design and the speed of wafer passing through the reactions zones varies radially. Although in theory, the growth per cycle in ALD is independent of rotation speed, the exposure time of the substrate to the precursor have to be sufficient for saturation in order to achieve a homogenous deposition layer. Other than that, this design is limited to the geometry of the substrate it can hold. Since it is the substrate table is round, substrates used are only limited to round wafers of 150 or 200mm or semi squared substrates. Lastly, the team are unable to very its gap between the substrate and the depositor. [10]

Overall, after researches on other SALD stations and the interview with Professor Dasgupta, the team are able to sort out and determine the user requirements of the project.

C. User Requirement and Engineering Specification

The meeting with Professor Neil Dasgupta, the main sponsor of the project, gave the team a clear idea on the requirements that need to be addressed. Table 1 (pg. 7) shows the summarized list of user requirements explicitly described by the project sponsor, the priority level and engineering specification for each user requirement. The team gained understanding on the relative priority of the user requirements through the interview session and sorted the user requirements into three different categories, which are high, medium and low; high represents requirements that must be satisfied in the solution; medium and low represent requirements that are not the main focus of the project, but would be an added plus if able to be satisfied. Under Professor Dasgupta's suggestions, the team have divided the project requirements into four main areas; mechanical design of the heated plates & finite element analysis, heat transfer analysis, electronic control and external requirements.

Table C.1: Summarized list of user requirements for specific areas of the heated motorized stage along with their respective priority level and engineering specification

Requirements (order of priority)	Engineering Specifications	Priority**
Consistent parallel alignment	Gap difference along the stage measured by 2D gap sensor: < 10 μm	★
Flat Surface	Tolerance of surface machining: ±1 μm	★
Gap Control	Minimum gap size: 20 - 50 μm Resolution of z-axis linear motion: 10 μm	★
Uniform heating of the stage	Temperature gradient: < 5 ^{o}C/cm	★
Required Deposition Rate of 0.1nm/sec	Velocity: 30 cm/sec	★
Ability to secure the substrate firmly	Force exerted: < 40 N (for standard silicon wafers)	O
Ability to work under a wide range of temperature	Operating temperature: Ambient - 200 ^{o}C	O
Components should withstand high temperature	% difference between maximum operating temperature and measured component temperature > 10 %	O
Cleanliness	Cleanroom standards: ISO 9	O
Safety	Teflon coating: withstand up to 327 ^{o}C	O
Ability to hold various types of substrates	Able to hold 3 different material type (various with size)	X

** (★: high O: medium X: low)

C.1 Mechanical Design of the Heated plates and Finite Element Analysis
The heated plate holds an extremely important role in this project. Its main function is to hold the substrate, move it rapidly during the deposition process, and able to hold various types of substrates.

C.1.a A very flat heated plate surface (★)
Similarly, flatness of the heated plate is the key to ensure a uniform deposition surface on the substrates. The heated plate needs to have a very flat surface relative to the depositor. In order words, the team need to control the parallelism between heated plate and the depositor as high as possible with ±1 μm surface machining tolerance. After talking to several companies which specialized in making isolation platform like NewPort, this is definitely a good target value for the project.

C.1.b Deposition rate of 0.1nm/sec (★)
According to Professor Dasgupta, the substrates needs to move at the desired velocity in order to achieve the deposition rate of 0.1nm/sec. The team have performed the calculation based on the assumptions given by Professor: a) the deposition takes place 1 Å per cycle. b) 4 cycles per oscillations. c) size of depositor is approximately 150mm, i.e. the substrate need to pass through 150mm to complete one oscillation. Using Eq. 1, the team determined that the heated plate together with the substrate need to move around 60mm/s. After reviewing the related catalog online from company like Zaber, this value is a reasonable target value that enables the team to reach the ideal speed while not losing its resolution.

C.1.c Able to secure the substrates firmly throughout the process (o)
As required, heated plate needs to be able to secure the substrates firmly while moving the substrate rapidly especially during the depositions. In other context, the holders is required to hold the substrate, keep it at a certain temperature and release it quickly without damaging the substrate or causing contamination. Throughout the process, it should not exert force larger than its tensile strength and should not interrupt the movements of the substrates. [11] For now, the team will use the commonly-used silicon wafer as the standard. Thus, the target value is a chucking system that applied force is not larger than 40 N. [12] and the pressure is between range of 200 mbar and 800 mbar. [11] According to Professor Dasgupta, vacuum chuck, electrostatic and mechanical clips are the three most common methods to secure the substrates in the industry. [13] Electrostatic chucks might not serve as a good option for the team because of its poor thermal control and also possible particle entrapment in the chuck. On the other hand, vacuum chuck has proved to be a promising method and has been greatly used in the related field. [14]. For mechanical clips, although it serves as a less costly option, it might need extra care when selecting the right material to work with especially no unnecessary heat loss is desired throughout the process.

C.1.d Able to hold various types of substrates (X)
The substrates holder should be able to hold various kind of substrates. It will greatly enhance its functionality if it is able to hold substrates varies in geometry, size, texture and ductility. Thus, the team need a chucking system that is flexible with the inputs and able to hold various kind of substrates equally well. Thus, the target engineering specification is to be able to hold 3 different substrates material, like glass, silicon wafer, and plastic, with various size. If the heated plate is able to secure 3 different substrates material, the heated plate is considered to have the ability to holder various substrate types and thus the requirement is fulfilled.

C.2 Heat Transfer Analysis

Since SALD process required heating of the substrate up to 200 ^oC, all components needed to have wide working temperature range and withstand the high operating temperature for long period of time. Meanwhile, the heated plate needed to be heated uniformly during the process.

C.2.a Able to work under a wide range of temperature (O)

As requested by the sponsor, the motorized stage should be able to be operated at a wide range of temperature, specifically from room temperature to 200 ^oC. The main reason for this is to study the effect of temperature on the spatial atomic layer deposition. By providing options to the user to calibrate the temperature level ideal to specific chemical reaction for effective film layer deposition, [15] the temperature range where growth is saturated depends on the specific ALD process or also referred to as the 'ALD temperature window' can be determine. That way, uniform and saturated monolayer of film could be formed. Besides that, the ability of the stage to be calibrated into a range of temperature increases its potential to accommodate film layer deposition for various chemical reactions, instead of being specific to only a single chemical process.

C.2.b Uniform heating of the stage (★)

It is important to ensure a uniform heating throughout the stage. The heating chuck has to be able to heat up the surface of the stage involved in the deposition process through conduction. In engineering words, the temperature gradient along the surface should ideally be zero. This means the everywhere along the surface of the stage has the same temperature value. Realistically, this is impossible. Therefore, the team specified a benchmark for the temperature gradient along the surface of the stage to be 0.5 $^oC/cm$. Uniform heating of the stage facilitates even deposition of the film layer along the stage. Besides that, the stage would undergo even linear thermal expansion when exposed to uniform heating, and thus able to retain the desired flat surface throughout the deposition process. In order to achieve uniform heating, a planar-like heating mechanism that is able to cover the entire surface of the stage will be used to simultaneously heat up the entire surface of the stage. The option the team are currently considering to use as the heater is [16] Watlow's silicon rubber heater, which could be designed to the exact shape and size needed.

C.2.c Manufactured components are able to withstand operating temperature (O)

Besides the stage, there are several other main components involved in the building of the whole system. Since the stage will be heated up to a maximum of 200 ^oC, it is crucial to make sure that the other components are also able to withstand the same maximum temperature. Therefore, materials with an ideally low coefficient of thermal expansion (CTE) will be selected to manufacture parts under thermal exposure. [17] CTE is the change in dimension (linear, area, or volume) of a material in response to a change in temperature. The reason for this is to prevent unwanted expansion of the parts, which will affect alignment of the stage. The stage has to be aligned and parallel to the gas manifold throughout the entire deposition process to be able to deposit uniform and even nanofilms.

C.3 Electronic Controls

Feedback control system is critical in ensuring the parallel alignment and precise gap control between the depositor and the substrate.

C.3.a Parallel alignment (★)

The substrate need to be able to work with perfect parallel alignment with the depositor especially during the deposition process. This is extremely crucial because failure to do so will cause non-uniform deposition and produce undesired substrates. In order words, the heated plate and the depositor as well as the ground should maintain constant parallel alignment between each other.

In order to achieve this, the heated plates need to function under the conditions that the distance between the substrate and the depositor is always 90 degree. Same goes to the heated plates and the depositor with the ground plate. To fulfill this requirement, the team set the target gap difference along the stage as measured by a 2D gap sensor should be less than 10 μm. This is a reasonable target value, measurable at the same time not losing the high resolution required by this project.

C.3.b Precise gap control (★)
The motorized stage is required to have a good gap control between substrate and depositor. Distance between substrate and the depositor need to be small in order for a good atomic deposition to take place. Besides, serving as a research prototype, Professor requested the team to have the gap control to be within range of 20 to 50 μm. This enables Professor and his group to conduct related experiments in figuring out the effect of gap distance on the spatial atomic layer deposition process. The team also set the z-axis linear motion to have at least 10 μm to have a more precise gap control. This target value, again, is backed with research backed on the available solution in the market like micrometer head and high-precision z-axis linear actuator.

C.4 External Requirements
Other than user requirements, there are external requirements that need to be fulfilled for high quality product and user experience.

C.4.a Cleanliness (O)
The overall cleanliness of the system should be maintained at all times. A clean outer casing to surround the stage and its other components could be built to prevent any contamination from the external environment. Besides that, materials used to manufacture the system are potentially at risk of chemical corrosion, due to the constant exposure to chemical gases. Corrosion of any part of the system would cause unwanted contamination to the deposited film. [18] So, to prevent corrosion from occurring, either the material or the chemical environment must be adjusted. In the project, specific reactant gases have already been fixed and therefore, the team look to adjust exposed material with protective coating, resistant to chemical reactions. Besides that, the system will be installed in a laboratory of the Dasgupta's Research Group. ISO cleanroom standards will be used to classify the room air condition in the laboratory. [19] ISO cleanroom describes the classification of clean rooms exclusively in terms of the concentration of airborne particles. The laboratory environment will be represented by ISO class 9, which represents standard room air condition.

C.4.b Safety (O)
The safety of the project will always be the main priority. It is of utmost importance to ensure that the design fulfills safety regulations and could operate safely without causing any harm to users. As mentioned by Professor Neil Dasgupta, there are three major safety aspects that needs to be considered; which are thermal, electrical and chemical hazards. The system will potentially be heated up to 200 ^oC. Excessive heating could cause undesirable effect to the system. The material used to manufacture the stage should be able to resist expansion upon thermal contact. This is crucial to maintain the flatness of the stage for uniform deposition. [20] Various binary iron-nickel alloys such as Invar with CTE of $1.2 \times 10^{-6} K^{-1}$ is a great option to be considered. However, minor components such as wiring, micrometer, etc. which are sensitive to heat, could be damaged by the overexposure to heat. Burnt components such

as exposed wires due to the melting of non-heat resistant insulator will potentially induce electrical threats to any users, which could result in electric shock, electrocution or even fire. Therefore, all the components that are under thermal contact are to be properly insulated using Teflon coating. The high melting point of Teflon at 327 ^{o}C helps to protect heat-sensitive components from being damaged. Besides that, the temperature of the system could be regulated by having a proper cooling system such as air flow or heat conductive shelves [21]. By installing air flow at areas where heat is undesirable, ideal operating temperature will be able to be maintained. The specified benchmark to prevent the overheating of components is to have the measured component temperature to be below 10% of the maximum operating temperature of that particular component.

D. Concept Generation

Concept generation was carried out after the project goal and problems were defined through sponsor interviews, and user requirements and engineering specifications were identified. As a preliminary step of the concept generation, function structure development was done through systematic methods. Finally, team members used concept generation techniques to generate concepts that satisfy the user requirements and engineering specifications.

D.1 Function Structure Development

In order to generate concepts, a thorough analysis on device functions was necessary. Function structure development on the heated motorized stage was carried out in a systematic way, including brainstorming, functional decomposition and morphological matrix. Each stage of the development was determined based on the user requirements and engineering specifications that were previously identified by a stakeholder.

D.1.a Brainstorming

As an initial step of function structure development, the team created a mind map, as shown in Figure D.1. It included the main project goal and following user requirements that need to be fulfilled. After the user requirements were specified in the mind map, further brainstorming was done for each user requirement by creating branched out functions that find solutions to the requirements.

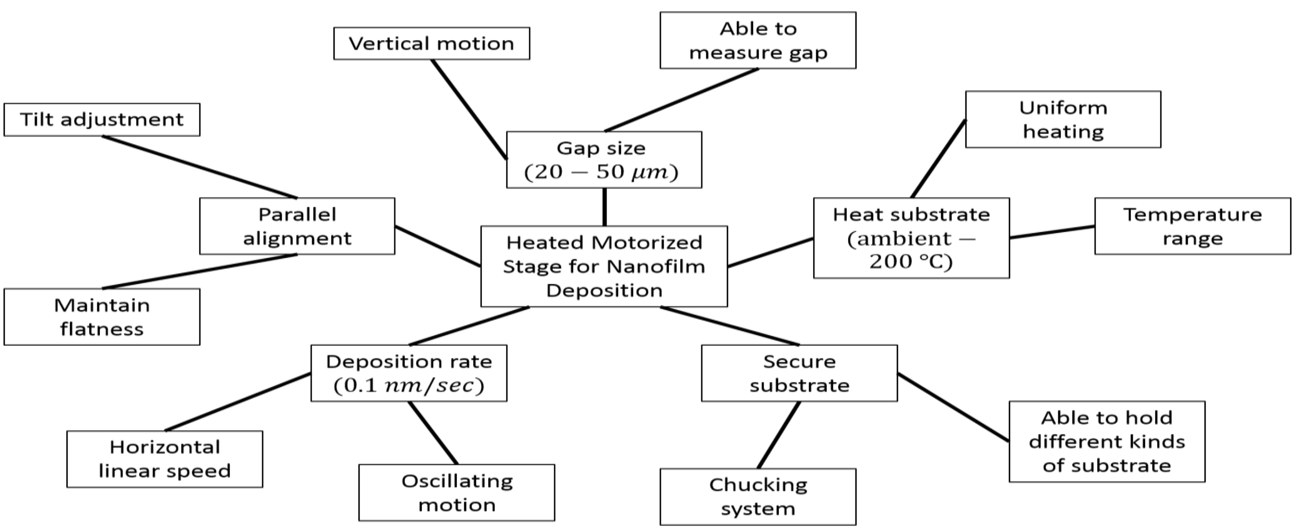


Figure D.1: Mind map that brainstorms the project goal, user requirements and functions that fulfill the requirements.

D.1.b Functional Decomposition

After major functions were identified and discussed by creating the mind map, functional decomposition was used to break down complex problems into simpler functions. In order to simplify the problem, a function tree (Figure D.2) was developed to address the problem as several primary functions such as to control gap size, to maintain parallel alignment, to heat substrate, etc. Then, further functional decomposition was performed to identify sub-functions.

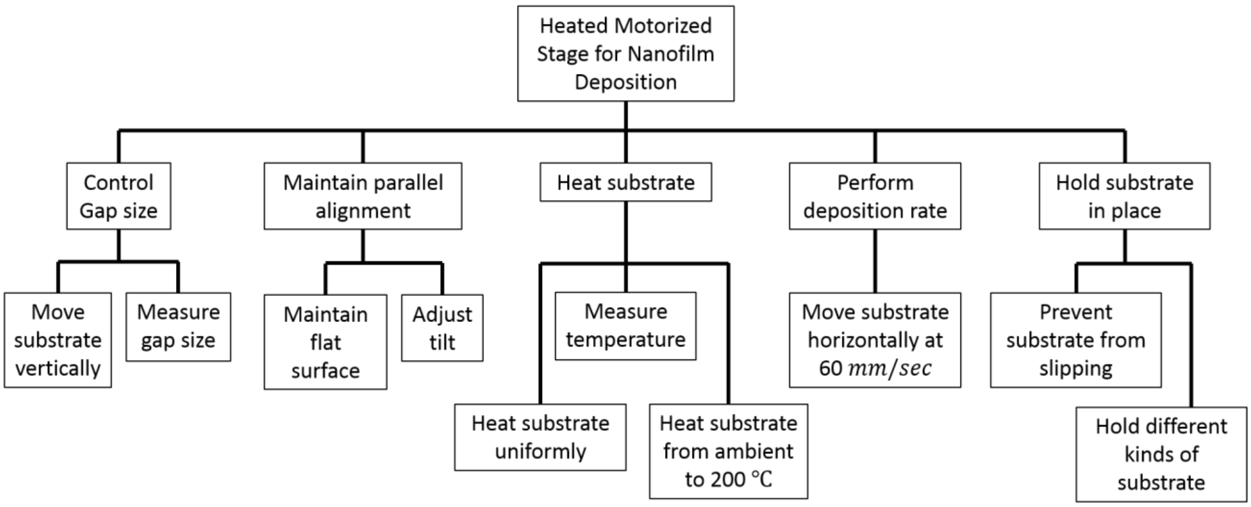


Figure D.2: Function tree includes the project goal, primary functions and corresponding sub-functions.

D.1.c Function Structure Diagram

Functional decomposition that was defined as a function tree was transformed into a function structure diagram (Figure D.3). Based on the main functions and sub-functions defined in the function tree, a block diagram was designed to demonstrate and study the logical flow of energy, material, and information as the product performs the function for which it was designed. In the design, energy included mechanical, electrical and thermal energies, material included various kinds of substrate, and information signals took forms of mechanical, electrical and software. The function structure diagram helped in understanding the interrelationships among the sub-functions. As an example, when horizontal oscillating movement of the substrate was considered, substrate slides along the surface of the heated plate due to inertia had to be taken into account. This indicates that the horizontal substrate movement was indeed related to the substrate holding mechanism. In addition, gap control, another essential sub-function, is determined by various other sub-functions such as substrate heating which might cause non-uniform thermal expansion, vertical linear motion of substrate stage and tilt adjustment mechanism. Knowing the inter-relationships among the sub-functions, the team combined and modified some of these features and integrate them into a concept as a whole.

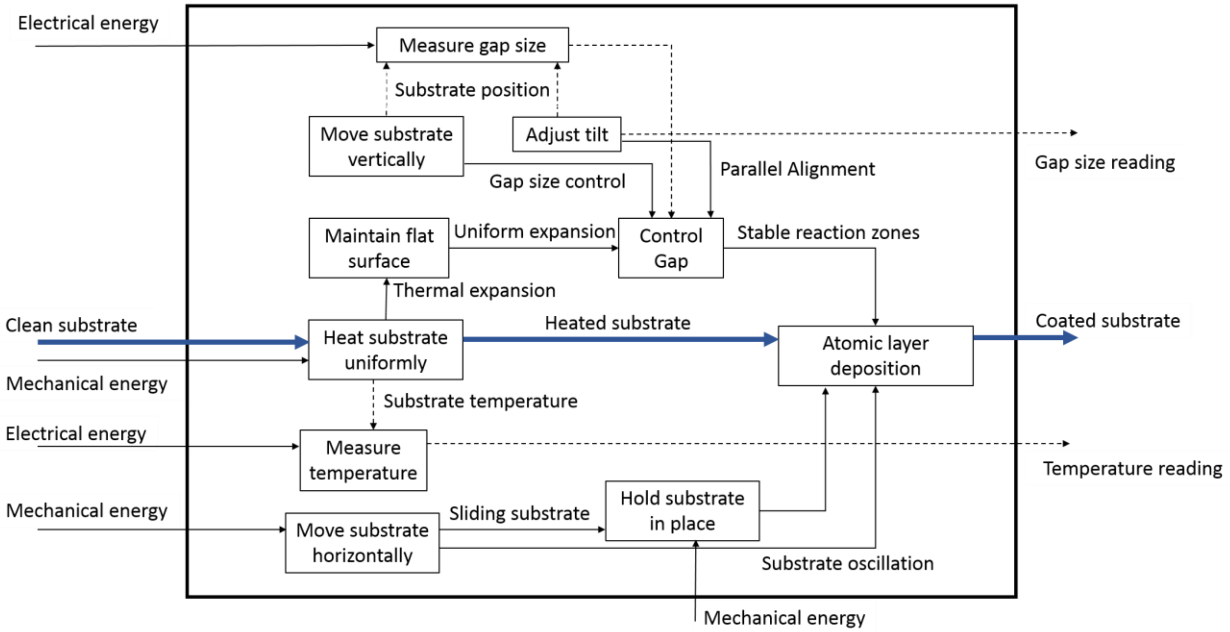


Figure D.3: Function structure diagram demonstrates the flow of energy, material and information within the Spatial ALD system. A large box with bold outlines represents the entire system, and small text boxes indicate sub-functions that need be included in the concepts. The diagram shows the interrelationships among the sub-functions.

D.2 Morphological Matrix

As the last step of concept generation, the morphological matrix was created. Morphological matrix is a tool that provides a systematic way to generate creative solutions in design. Using the functional decomposition results, sub-functions were listed on the leftmost column of the matrix. Then, sketches and texts were filled out across the horizontal rows to describe the means for fulfilling that function. After various possible solutions for each sub-function were found, the table was examined to combine the partial solutions to form full solutions.

Table D.4: Morphological matrix shows sub-functions that need be fulfilled and possible solutions for each sub-function. The cells colored blue indicates one possible full solution to the problem.

A	Vertical Motion	Pulley	Hydraulic	Linear Stage	Motor	Slots
B	Gap Measurement	Digital Microscope	Laser Sensor	Capacitor Sensor	Caliper	Taper Gauge
C	Tilt Adjustment	Machine	Stepper Motor	Magnets	Pressurized Gas	Spring
D	Horizontal Oscillating Motion	Tread	Newton Billiard Balls	Rotational	Linear Stage	Magnet Levitation
E	measure temperature	Infrared	Thermometer	Thermocouple	Laser	Feedback Sensor
F	heat from ambient to 200 deg C	Solar Radiation	Convection	Conduction	Induction	Infrared
G	Uniform Heating	Thin Plate	Insulating Case	Jacket Heater	Flexible Heaters	Fluid Heating
H	Secure Substrate	Mechanical	Vacuum	Electrostatic	Groove	Threaded

D.3 Concept Generation Results

After the function structure was developed, twenty concepts were generated to find solutions to the defined problems. Various types of concepts were created by combining functions to form a total solution. The team used the SCAMPER (Substitute, Combine, Adapt, Modify, Put to another use, Eliminate and Reverse) method to generate useful and innovative concepts.

The team substituted a conventional linear motorized stage and a tilt adjustment stage with stepper motors and set screws to save cost. Secondly, the team combined the tilt adjustment and height adjustment mechanisms into one system using the stepper motors and set screws, so that the team could save cost from spending two separate parts for each mechanism. Additionally, the team also modified the shape of the circular groove and heated plate to be a rectangular shape in order to enhance the machinability of the parts. Lastly, since the team were provided with a vacuum line at Dasgupta Research Lab, the team used this vacuum channel as the vacuum chucking system for the substrate.

D.3.a Concept 1

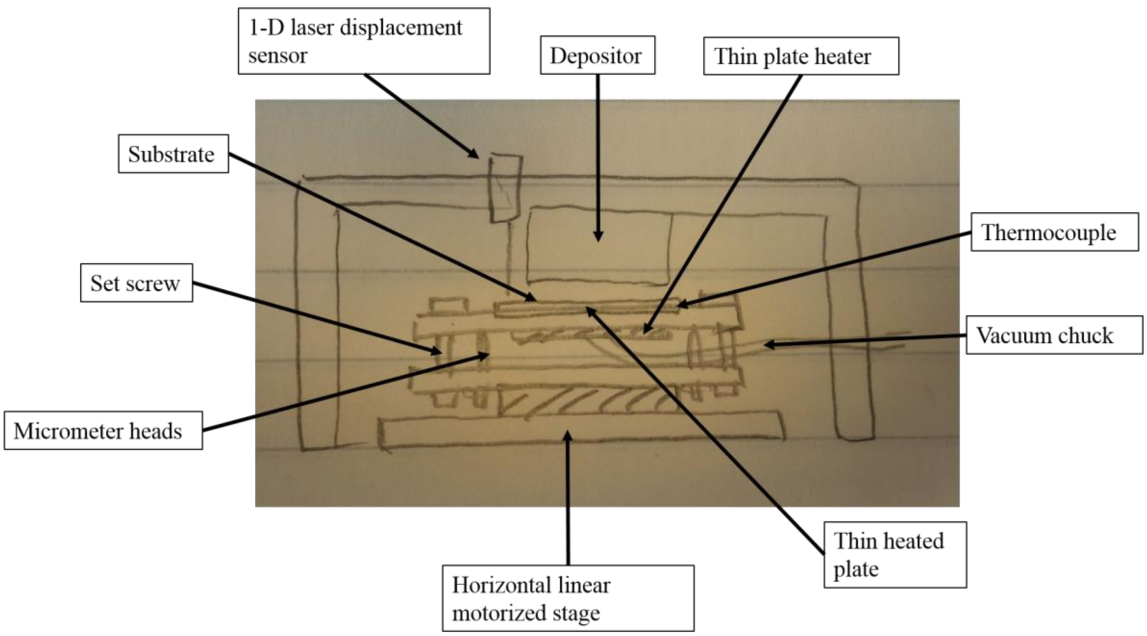


Figure D.5: Generated concept 1 which includes labelled parts that satisfy sub-functions identified from the functional decomposition process

This concept uses a vacuum chucking system to hold the substrate in place on top of a heated plate which is heated by a thin plate heater placed at the bottom of the heated plate. The vertical motion is actuated by the three micrometer heads which also perform tilt adjustment of the substrate to maintain parallelism with respect to the depositor, and four set screws are used to secure the position of the plates. These vertical linear motion and tilt adjustment stages are mounted on a linear motorized stage and oscillate horizontally. The system is equipped with a thermocouple and 1-D laser displacement sensor for temperature and gap size measurement. The primary advantages of this concept are the high precision vertical and horizontal motion controlled by the micrometers, laser displacement sensors and linear actuator. However, the use of manual equipment such as micrometers could introduce systematic and human errors to the measured readings.

D.3.b Concept 2

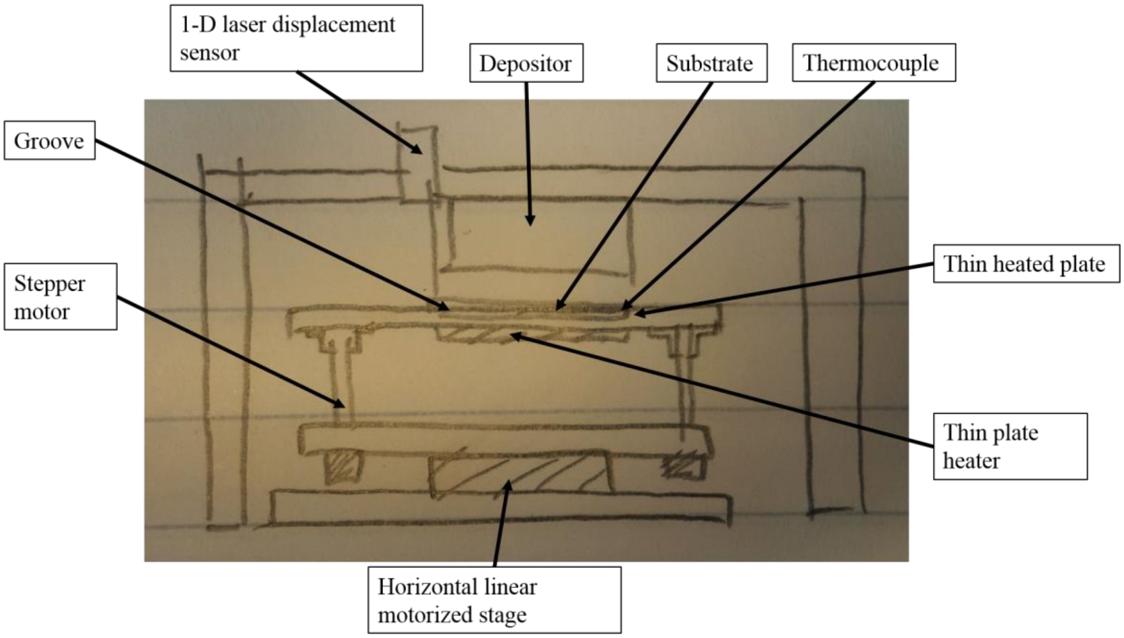


Figure D.6: Generated concept 2 which includes labelled parts that satisfy sub-functions identified from the functional decomposition process

This concept uses a groove to place and hold the substrate in place on top of a heated plate which is heated by a thin plate heater located at the bottom of the heated plate. The vertical motion is actuated by the three stepper motors which also perform tilt adjustment of the substrate to maintain parallelism with respect to the depositor. These vertical linear motion and tilt adjustment stages are mounted on a linear motorized stage, and the system and oscillate horizontally. The system is equipped with a thermocouple and 1-D laser displacement sensor for temperature and gap size measurement. One of the main advantages of the concept is the use of stepper motor for vertical axis motion, which provides high resolution motion control.

D.3.c Concept 14

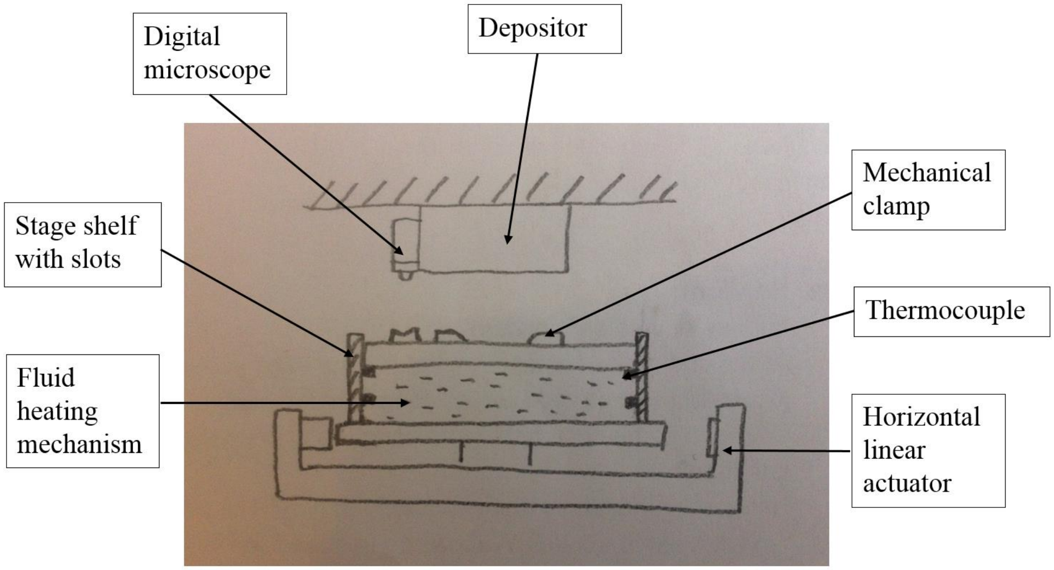


Figure D.7: Generated concept 14 which includes labelled parts that satisfy sub-functions identified from the functional decomposition process

This concept uses a simple mechanical clamp to secure the substrate to the stage, in order to prevent the substrate from moving during horizontal and vertical motion. To aid vertical motion for gap control, a "stage-shelf" with slots at different height levels is used. The stage can be easily moved to different height levels and fixed on the respective slots. Then, a digital microscope will function to measure the gap between the depositor and stage to ensure precise gap control. On the other hand, a linear actuator is used to facilitate horizontal motion. For heating, fluid is flowed through a channel beneath the stage, which then conducts heat through the stage to provide energy for the deposition process. One of the main advantages of this concept is that the height level could be easily adjusted, but the large resolution of the vertical motion is a potential drawback.

D.3.d Concept 9

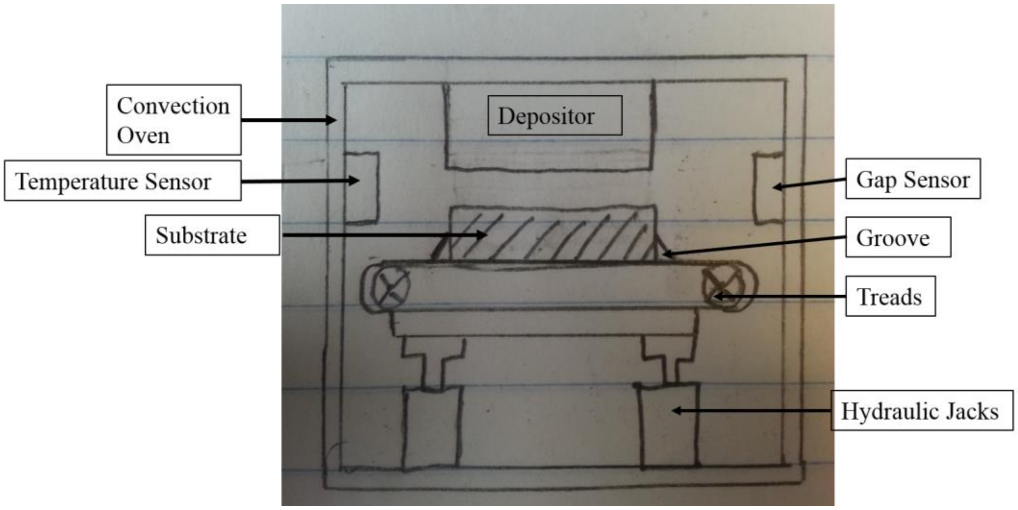


Figure D.8: Generated concept 9 which includes labelled parts that satisfy sub-functions identified from the functional decomposition process

This concept uses grooves to hold the substrate in place on top of a moving conveyor stage. Under the conveyor stage, 4 hydraulic jacks are place to adjust the tilt angle of the stage to align it to the depositor. The whole system is placed inside a convection oven to for heating and equipped with a temperature sensor and 2D gap sensor. The main advantage of this concept is its ability to provide uniform heat to the system. However, this may cause unwanted overheating on other minor components that have low operating temperature.

D.3.e Concept 12

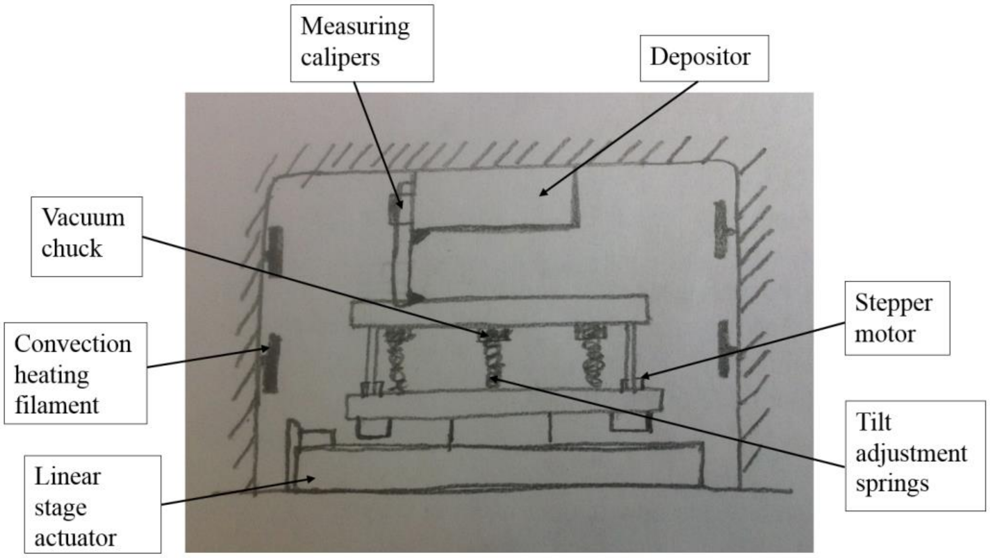


Figure D.9: Generated concept 12 which includes labelled parts that satisfy sub-functions identified from the functional decomposition process

This concept is similar to the convective oven concepts. Using several convection heating filaments can ensure uniform heating of the substrate. Besides, this concept also uses the tilt adjustment springs to ensure the parallelism between the heated plate and the depositor. Besides, using the linear stage actuator, the stage can undergo a precise and fast oscillation motion. The stepper motor and measuring calipers, on the other hand, are used for z-axis motion control, allowing the user to measure and hence control the gap size. Lastly, to secure the substrate to the stage, vacuum chuck is used to exert certain pressure on the substrate and hold it in place. The primary advantage of this concept is the comprehensive vertical axis control using springs, weights and stepper motor. However, the use of the measuring calipers to monitor gap size is not ideal to measure nanoscale gaps.

E. Concept Selection

After the 20 concepts were generated, a scoring system was developed to assess the ability of each concept to meet the project’s engineering specifications. The engineering specifications developed from the user requirements with the stakeholders in the beginning of the project were used in this scoring system and weights were applied to these engineering specifications according to their importance. These engineering specifications and their associated weights are documented in the QFD which is located in Appendix B. Using the previous motorized stage design as the benchmark, a Pugh chart was created and the concepts could be generated and narrowed down to five concepts from 20 concepts.

The chosen five concepts are listed and described above. In order to choose the best concept out of the five, external requirements were introduced into the scoring system to further assess the feasibility of these concepts. The external requirements added are the machinability, safety, durability and estimated cost of the concept. The Pugh chart with the external requirements included was created and shown below.

Table E.1: Pugh chart of the five chosen concepts which includes weighted engineering specifications and scores of each concept

Concept Selection Legend	
Better	+
Same	S
Worse	-

Key Criteria	Rating	Benchmark	Concept 1	Concept 2	Concept 9	Concept 12	Concept 14
Consistent parallel alignment (Gap difference along the stage measured < 10 µm)	10		+	+	+	S	S
Precise vertical linear motion (resolution: 10	8		S	S	+	+	+
Precise horizontal linear oscillating motion (resolution: 0.5 mm)	6		+	+	+	+	S
Uniform substrate heating (temperature gradient: 0.5 K/cm)	3		S	S	S	S	S
Flat surface tolerances (tolerance of surface machining: ±5 µm)	6		S	S	S	S	S
Minimum gap size (gap size: 20 - 50 µm)	9		+	+	+	+	S
Ability to secure substrate (force exerted: <30 N (for standard silicon wafers)	5		+	+	+	S	+
Function under a wide range of temp (ambient - 200 °C)	7		S	S	S	S	S
Ability to hold substrate with different	2		+	+	-	-	-
Deposition rate of 0.1 nm/sec	5		S	S	S	+	+
Machinability	5		-	-	S	S	S
Durability	5		+	+	S	-	-
Safety	5		S	S	S	S	S
Price (available budget: < $10,000)	8		S	-	-	-	+
Sum of Positives			6	6	5	4	4
Sum of Negatives			1	2	2	3	2
Sum of Sames			7	6	7	7	8
Weighted Sum of Positives			37	42	38	28	26
Weighted Sum of Negatives			5	13	10	15	7
TOTALS			**32**	**29**	**28**	**13**	**19**

After carefully assessing each criteria, a design was singled out from the rest and that became the final design. This design is concept design 1 (Figure D5, page 18). This concept uses stepper motors for tilt adjustment and vertical linear motion and set screws are used to bolt down the stage after any tilt adjustments. A linear motion stage is used for horizontal motion and a sensor to measure the gap size between the substrate and the depositor. The stage is also equipped with a groove and a vacuum chucking system to hold the substrates in place and a thin film heating system right under the stage.

The top five concepts were able to meet most of the user requirements given by the stakeholders. One of the advantages of the chosen concept that makes it more suitable than the other five is mostly due to its ability to function at a more precise manner particularly in the gap size and gap alignment requirement as well as its motion in the vertical and horizontal plane. Although Concept 2 has around the same level of functionality as Concept 1, the cost of it is above the budget given to the team causing it to be ruled out. However, Concept 1 do come with some disadvantages. One of the disadvantages is the manufacturability of the concept where it needs to be precise and flat, the usage of an outside source to accomplish this is required.

F. Final Concept Description

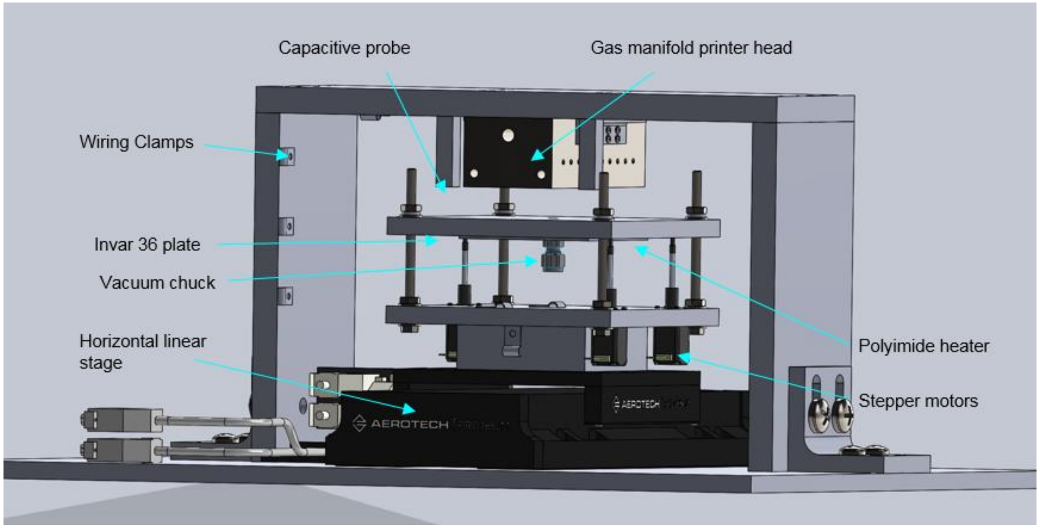


Figure F.1: CAD illustration of the chosen current concept incorporated the latest updates in the design which includes labelled parts that satisfy sub-functions identified from the functional decomposition process

There are 7 key features in the latest concept: substrate securing mechanism, substrate heating system, vertical linear motion, tilt adjustment, position securing mechanism, horizontal linear motion, and gap measurement system. The primary advantages of this concept were the high precision vertical and horizontal motion controlled by the stepper motors, capacitive sensors and linear translational stage.

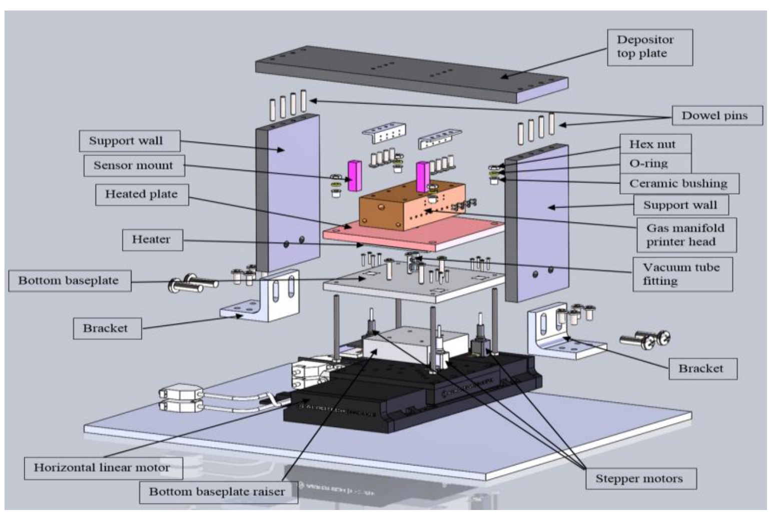


Figure F.2: Exploded view of the overall assembly. It involves the detailed illustration of all the parts and components used in the assembly.

F.1.Vacuum chucking System

It uses a vacuum chucking system to hold the substrate in place on top of a heated plate which is made out of Invar 36 and is heated by Watlow Electric’s Polyimide heater attached at the bottom of the heated plate with thermally conductive adhesive. NPT fittings and Teflon tubing were used to channel the vacuum from the source to the plate.

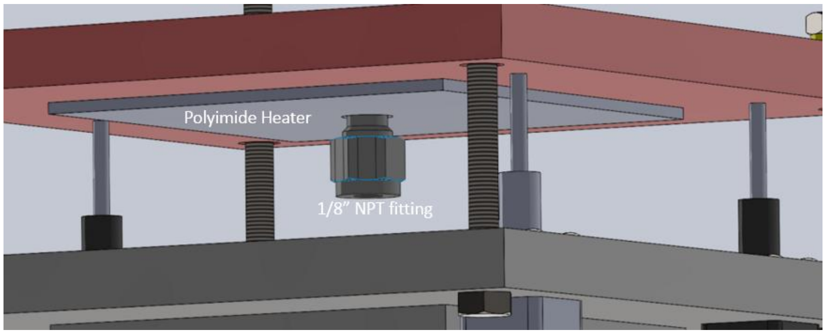


Figure F.3: Close-up of the vacuum chuck and heater connections.

F.2. Vertical Linear Motion and Tilt Adjustment

The vertical motion is actuated by the three stepper motors with resolution of 1.5 µm. The stepper motors were also used to perform tilt adjustment of the substrate to maintain parallelism of the substrate with respect to the depositor.

F.3. Set Screws Securing Mechanism

There are four set screws with O-rings to provide downward forces onto the heated plate that acts as a clamping mechanism to maintain the adjusted position. The O-rings were isolated from the stage using the ceramic shoulder bushing. The shoulder bushing also insulated the set screws to prevent thermal expansion of the set screws.

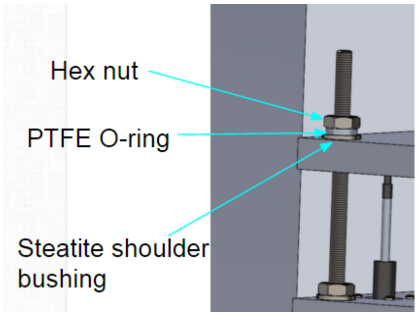


Figure F.5: Illustration of the position securing mechanism that involves the Hex nut, ¼" Stainless Steel Screw, PTFE O-ring and Steatite shoulder bushing.

F.4. Horizontal Linear Motion

The stepper motors and the heated plate were mounted on a linear motorized stage and oscillate horizontally. The linear motion was performed by using horizontal linear stage from Aerotech Inc..

F.5. Polyimide Heater

The uniform heating of the stage was ensured using polyimide heater and several thermocouples installed along the stage. The polyimide heater was flexible and thus was cover the entire stage easily. Thermocouples were installed along the stage to monitor the temperature gradient of the stage.

F.6. Gap Size Control
Two capacitive sensors probes with 0.1 µm resolution were used to monitor the gap size between the depositor and the substrate. The gap measurements were then processed in Matlab and commands were sent to the stepper motors through Arduino to achieve the desired gap size.

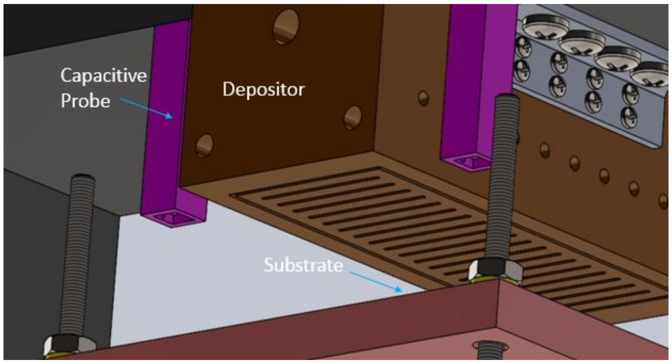


Figure F.3: Close-up view of the depositors and substrate. It demonstrates the gap measurement process between the depositor and the heated plate.

F.7. Wiring Management
Wire clamps were used to manage the wire and prevent the tangling of the wires during motion. Additionally, a wire carrier was used to carry wires from the stepper motors and the capacitive sensors.

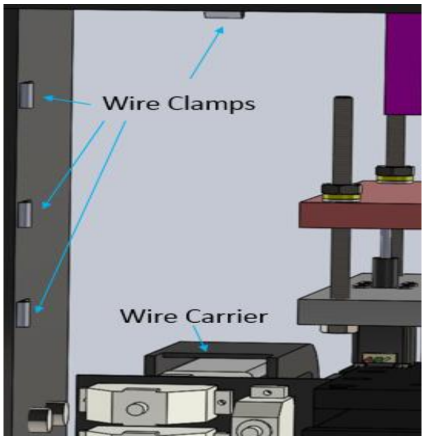


Figure F.6: Illustration of the wiring management in the design. Wire clamps and wire carrier are used to prevent tangling of the wires during the dynamic motion.

G. Key Design Drivers and Challenges

G.1. Key Design Drivers

Table F.1: Key design drivers that motivate the design specifications of the project are illustrated.

Priority	Design Drivers	Description	Importance
1	Gap control and tilt adjustment	Stage must have the ability to move along the Z-axis to control gap size, while being able to tilt at a correct angle to ensure parallel alignment between the stage and depositor.	Improper alignment between the stage and depositor will cause both surfaces to collide during horizontal motion of the stage. Inability to maintain gap size at a desired value will prevent from studying the effect of gap size on Spatial ALD results.
2	Uniform substrate heating	The heated plate should be uniformly heated to a specific temperature between ambient to $200\ °C$.	Without uniform heating, deposition will not occur at a uniform and ideal rate. In ability to maintain constant temperature will prevent from studying the effect of temperature on Spatial ALD results.
3	Chucking system	The prototype should have a mechanism which holds the substrate in place during the deposition process.	Substrate needs to stay in place during the accelerating and decelerating motion of the stage. Moving substrate will affect the repeatability of Spatial ALD results.
4	Horizontal linear motion	The stage should be able to perform oscillating motion in horizontal axis during deposition process at a desired speed.	The ability to control the motion of the stage at a desired speed will help determine the rate of deposition.

There were four main design drivers including, gap control, uniform substrate heating, substrate chucking system and horizontal linear motion. Based on the design specifications, the engineering fundamentals were identified.

First, gap control was a crucial aspect that needed to be fulfilled. The stage had to be able to move along the vertical axis in order to adjust to the desired gap distance between the substrate and depositor. This ability to adjust the stage to variable height in manipulating gap size helped future research studies on the effects of gap size on Spatial ALD results. Besides that, the stage had to perform tilt adjustment at a correct plane angle to ensure parallel alignment between both the stage and depositor. It was important that parallel alignment was maintained throughout the deposition process to prevent unwanted collision of the01 depositor and the heated plate. In order to achieve these requirements, a three-point-micrometer mechanisms and laser displacement sensor were required.

Secondly, uniform heating of the substrate was another important design driver of the design process. Every chemical reaction takes place at a specific temperature range. Therefore, the substrate had to be able to be heated to a desired temperature between ambient to $200\ °C$. Temperature adjustability of the substrate would help study the effect of temperature on Spatial ALD results. In addition, the specified temperature for the deposition process should be maintained during the deposition process, because constant temperature would result in uniform deposition.

The substrate chucking system was another key design driver in the project. The stage needed an appropriate mechanism to hold and secure the substrate in place during the deposition process, which involved horizontal linear motion. The reason for this was to prevent the substrate from sliding or rotating as the stage accelerated or decelerated. Moving substrate could lead to non-uniform deposition. Vacuum chuck was selected to fulfill the substrate securing.

Lastly, the horizontal linear motion of the system was required, because the substrate should be able to oscillate forth and back during the deposition process at a desired speed. The ability of the linear actuator to control the motion of the stage at a desired speed would enable control of deposition rate. Therefore, the system required a high end linear actuator to control the horizontal motion.

G.2. Engineering Analysis on Gap Control

It was important to be able to monitor the gap size effectively. One main motivation of the project was to study the effect of gap size on Spatial ALD results. Therefore, the team needed to perform engineering analysis to study precise gap size control. Theoretical modelling was utilized as the mode of analysis. Based on the analysis, physical requirements of the components, such as the stepper motors, sensors and the heated plate could be determined. There were three aspects the team considered analyzing; load and stress applied on the stepper motors both during static and in motion and sensors specifications.

Firstly, the static load applied on the stepper motors was determined. The stepper motors are the only supporting mechanism that would hold the heated plate. In order to perform this analysis, the mass of the heated plate had to be calculated. Since Invar 36 was used (refer engineering analysis for uniform heating mechanism) as a material for the heated plate, its density was obtained to calculate the total downward force due to weight using Eq. 1, where ρ = density of the materials, V = the volume of the components and g = the acceleration due to gravity. By calculating the force due to weight, load exerted on each of the three stepper motors supporting the stage could be determined. Figure G.2.1 shows the components of the analysis. The maximum static load upon each stepper motors was calculated to be 3.24N, using Eq. 2.

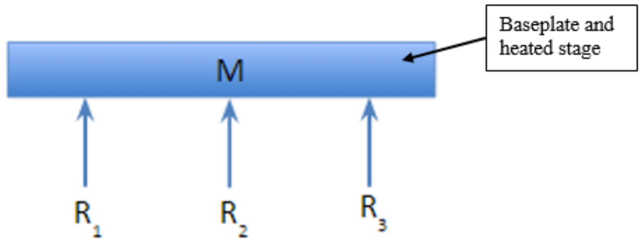


Figure G.2.1: Free body diagram for static load analysis on stepper motors with M representing the total mass of the heated plate and R1, R2 and R3 representing the reaction forces from the stepper motors.

$$W = \rho V g \quad \text{(Eq. 1)}$$
$$R_1 = R_2 = R_3 = W/3 \quad \text{(Eq. 2)}$$

where M = mass of the heated plate and R1, R2, R3 = reaction forces from the stepper motors.

After that, the load exerted on the stepper motors at motion (during deposition process) was calculated. During the deposition process, the stage would oscillate back and forth horizontally. This motion would cause the stage to shift from its desired position. Therefore, a locking mechanism composed of nuts and compressive silicon o-rings was introduced at the four ends of the heated plate, to impose a downwards force on the heated plate against the stepper motors, creating friction to hold the heated plate in place. The assumption made for this analysis was that the normal force from the motors on the heated plate are only dependent on the amount of force exerted by the springs and the weight of the stage. The relationship is shown in Eq. 3, with F_s = spring force, M = weight of the stage, and F_m = force on the motor. After trial and error, the team calculated that when the force of the locking mechanism exerted was 14N, the upward thrust of the motor was 23.7N, using the result from Eq. 2. This result showed that the total frictional force on the heated plate was greater than inertial force causing the heated plate to shift, as shown in Eq. 3. With these values, the resulting total load applied on the stepper motors was calculated to be 23.7 N, by summing up both the forces from the locking mechanism and weight of the heated plate, using Eq. 4. To prevent any unwanted failure modes, the team decided to define a safety factor of 2 for the maximum load capacity of the stepper motors. Eq. 5 was used to determine the appropriate motor load capacity with safety factor of 2, with S.F. = safety factor, F_m = total load applied upon the three stepper motors.

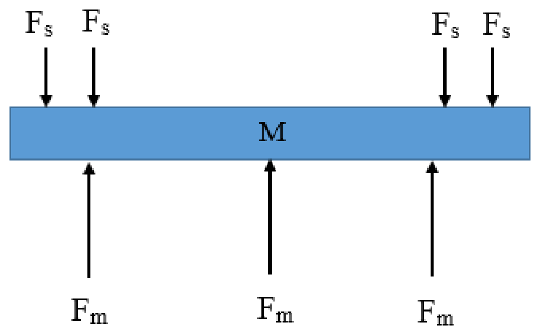


Figure G.2.2: Free body diagram for dynamic load analysis on the heated plate with M representing the total mass of the heated plate and F_s and F_m representing the spring forces and reaction forces from the stepper motors respectively.

$$F_s + M = F_m \qquad \text{(Eq. 3)}$$

$$\mu_s . F_s + \mu_s . F_s = F \qquad \text{(Eq. 4)}$$

$$\text{Maximum load capacity of each stepper motor} = S.F.(F_m)/3 \qquad \text{(Eq. 5)}$$

where F_s = spring force, M = weight of the stage, and F_m = force on the motor.

Lastly, an appropriate set of sensors had to be used to ensure precise gap control. Analysis on sensor specifications was done to determine suitable sensors for the project. The resolution of the sensors was an important specification because without sufficient resolution, the system would not be able to reliably make the required adjustment. On the other hand, sensors with great resolution specification, far beyond the needed criteria for the system would impose burden on the budget. It was decided by the project sponsor, Professor Neil Dasgupta, that the stage could be adjusted from a gap of 20 to 50 microns from the depositor. To achieve this gap control range, sensors with at least one micron resolution would provide the stage the ability to be adjusted to at least 100 step heights within the 100 microns range. Besides that, the bandwidth of the sensor was as important as the resolution. It indicates the ability of the sensor to respond at different frequencies. Since the measured target, the heated plate, would be oscillating horizontally at 60 mm/sec, it was essential to select sensors with appropriate bandwidth characteristic. The team worked closely with engineers from Capacitec to select the best sensors suitable for the project.

G.3. Engineering Analysis on Uniform Substrate Heating

Maintaining uniform substrate heating was crucial in ensuring the success of the project. In order to achieve this, heat transfer analysis was carried out and theoretical modeling was chosen as the major mode of the analysis. It provided better understanding of the heat transfer mechanism in the system and determined the constraints or requirements for the materials properties. In general, there were three key components in the heat transfer analysis: thermal expansion of the heated plate, thermal conductivity of the heated plate and the heat loss to the environment.

First of all, the thermal expansion of heated plate was calculated. Using Eq. 6, the minimum coefficient of thermal expansion for substrate stage and heated plate were determined. The assumptions were made based on the engineering specifications and the dimensions of the final design. The assumptions included the maximum allowable expansion of the material was 10 µm, the thickness of the heated plate was 0.1", the thickness of the substrate stage was 0.5", the ambient temperature,T_1 and final temperature, T_2 were 21°**C** and 200°**C** respectively.

$$\Delta L = \alpha L_o \Delta T \qquad \text{(Eq. 6)}$$

where ΔL = change in length, α = coefficient of thermal expansion, L_o = initial thickness of the heated plate, and ΔT = change in temperature of the plates.

From the calculation, the maximum thermal expansion coefficient of the heated plate material was 21.99 x 10^{-6} K^{-1} and that for the substrate stage was 4.40 x 10^{-6} K^{-1}. Material with higher coefficient of thermal expansion would result in expansion of more than 10 µm which was undesired. Thus, as long as the selected material for heated plate and substrate stage had the coefficient of thermal expansion below these values, it was safe to conclude that the thermal expansion effect on the uniform substrate heating was negligible.

Next, to determine the thermal conductivity of the heated plate, Eq. 7 and Eq. 8 were used. It was assumed that the system was in parallel slab, the ambient temperature was 21 °C, the final temperature was 200 °C and applied watt densities from Ultramic (the heating filaments provided by the sponsor, Watlow Electric) was between 600 - 750 W/in^2. Therefore, the minimum thermal conductivity coefficient for heated plate with dimension of 1" x 4" x 4" was 13.2 - 16.5 W/mK.

$$Q_c = (T_2 - T_1)/R_{1-2} \qquad \text{(Eq. 7)}$$

$$R = L/Ak \qquad \text{(Eq. 8)}$$

where T_1 = ambient temperature, T_2 = final temperature, R_{1-2} = thermal resistance; L = thickness of the heated plate, A = area of the heated plate and k = thermal conductivity coefficient.

Knowing the minimum thermal conductivity coefficient and the maximum thermal coefficient, the team could select the best candidate for heated plate and substrate stage. Through careful comparison, Invar

36, with thermal expansion coefficient of 1.72 x 10^{-6} K^{-1} and thermal conductivity of 13 W/mK, stood out as the most promising candidate for heated plate.

G.4. Engineering analysis on Clamping/Chucking System

During the concept selection process for the clamping or chucking system, the team decided to opt out of mechanical clamping mechanism and chose to utilize a vacuum chucking system for the final design. This was because the team did not want any extra features present on top of the surface of the substrate. This would not only cause the added features to obstruct the path of the deposition process, it would prevent some parts of the substrate surface from getting exposed to the reaction gases.

The vacuum chucking system on the other hand will not encounter these problems as it was able to hold the substrate in place from the bottom of the substrate. Besides that, it has the ability to hold substrates of various shapes and sizes. Instead of purchasing a vacuum chucking system, the team decided to build one by drilling a hole through the center of the substrate stage and run a vacuum channel through it.

In order to prove that the designed chucking system would work, the team decided that an empirical testing on the system is the most appropriate because it was fast and most credible in proving the functionality of the concept. The objective was to determine how much force is needed to move the substrate while under vacuum suction and to ensure it will not break under the vacuum pressure. Since a 100mm diameter silicon wafer would be the first substrate to be tested by Dasgupta Research Group with the prototype, a silicon wafer was used to prove the functionality of the vacuum chucking system. The experimental setup and the force gauge used was a Model HF-200 digital force gauge shown in Figure G.4.1 and Figure G.4.2.

The empirical test was conducted in the research lab of Dasgupta Research Group. A 1/16 inch aluminum plate was machined to scale to the substrate stage with a 0.25 inch hole in the center. The empirical test was conducted according to a written procedure which can be found in Appendix H.

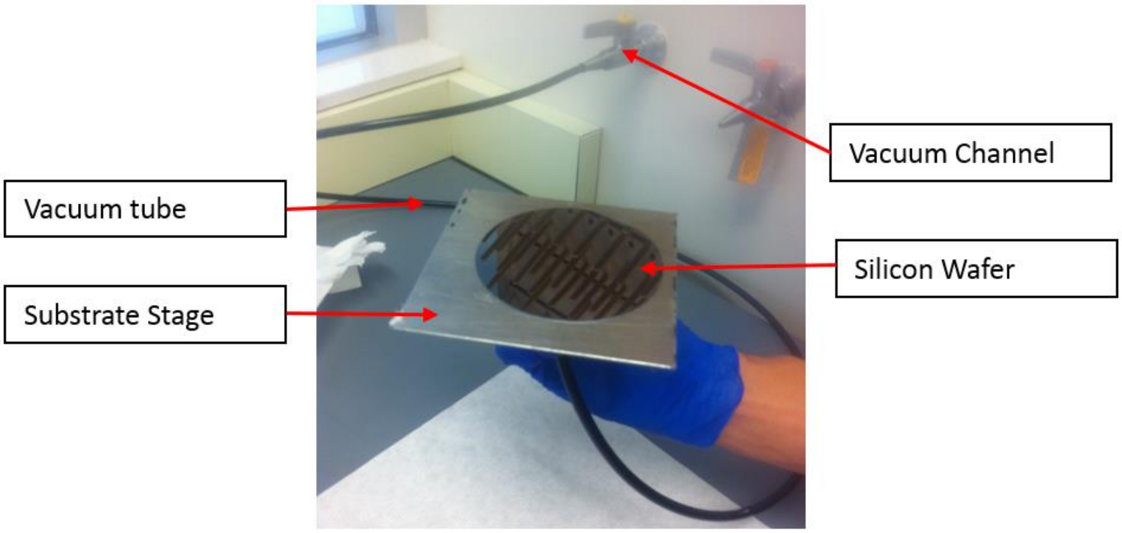


Figure G.4.1: experimental setup of the empirical testing

Figure G.4.2: Picture of Model HF-200 Digital Force Gauge used in the empirical testing of vacuum chucking system

The force exerted on the substrate during the deposition process due to inertia was calculated using Newton's 2nd law, F=ma, where m is the mass of the substrate = 0.040kg, a = acceleration of the substrate = 3 x 9.8m/s^2 = 29.4m/s^2, and force applied from inertia = F = 1.176N.

Table G.4.1: Results of the empirical testing for the vacuum chucking system shows the consistency of the three experiments conducted.

Test Number	1	2	3
Force (N)	2.5	2.4	2.6

The force needed to move the substrate away from its initial position was an average of 2.5N, which was nearly twice as large as the inertial force. Therefore, the team was able to conclude that the vacuum chucking system provided a sufficient amount of force to hold the substrate in place and did not break the wafer during the deposition process. The team decided to keep the dimensions of the design unchanged because of the satisfactory results it had provided. This fulfilled the chucking system design driver. With this major design driver fulfilled, further testing would need to be done in the future on different substrates of different materials and rigidity.

G.5. Engineering Analysis on Horizontal Linear Motion

In order to verify that the chosen linear stage, PRO-165LM-0150 by Aerotech satisfies the user requirements, engineering analysis was performed. Because each unit of horizontal linear translational stage is costly, there was difficulty in performing tests with the actual linear stages. Thus, various kinds of theoretical engineering analysis was conducted instead of an empirical testing. Theoretical modeling included the horizontal motion speed and acceleration required for the application and error in pitch and roll rotations during the motion.

One of the significant user requirements Professor Dasgupta mentioned during the sponsor interview was that the SALD system must be able to perform the deposition rate of 0.1 nm/sec. In order to find a suitable linear stage for this application, the team calculated the minimum speed and acceleration of linear motion based on the deposition rate, geometrical parameters and characteristics of ALD.

Using the given values as listed in **Table G.5.1**, the team converted the deposition rate to the linear motion speed using **Equation 9**.

Table G.5.1: The table summarizes the given information on the deposition rate and specifications of the linear stage.

Required deposition rate	0.1 nm/sec
Total length of the gas depositor	0.127 m
Thickness of Al2O3 atomic monolayer	1 Å/cycle
Number of ALD cycles during one oscillation	4 cycles

To fulfill the required deposition rate, 0.4 nm Al2O3 should be deposited in 4 sec. Knowing that one oscillation along the depositor is consisted of four ALD cycles, the team found out that 0.4 nm of Al2O3 layers would be formed. Thus, the team concluded that the substrate must be able to travel one oscillation in approximately 4 sec. The total length of the gas depositor is 0.127 m, so the speed required is 0.03175 m/sec.

In order to achieve, the required speed within a range of 0.011 m, the team used Eq. 9, Eq. 10 and Eq. 11 to calculate the minimum acceleration required for the linear stage: [23]

$$a_{stage} = 3g = 29.42\,m/s^2 \quad \text{(Eq. 9)}$$

$$v_{required} = 0.03175\ m/s = v_0 + a_{stage}t = 0 + 29.42\,m/s^2 \times t \quad \text{(Eq. 10)}$$

$$t = 0.001079\ \text{sec}$$
$$x = \frac{1}{2}a_{stage}t^2 + v_0t + x_0 = \frac{1}{2}(29.42\ \text{m/s}^2)(0.001079\ \text{sec})^2 + 0 + 0 \quad \text{(Eq.11)}$$
$$= 0.00001713\ \text{m} < 0.011\ \text{m}$$

where, a_{stage} is the acceleration of the linear translational stage provided in the spec sheet of PRO-165LM-0150 by Aerotech, $v_{required}$ is the required velocity, v_0 is the initial velocity, t is the time of acceleration, and x_0 is the initial position of the stage. Based on the calculation, the team concluded that the acceleration of the stage is sufficient to move the stage as required.

In addition to satisfying the deposition rate with an appropriate speed and acceleration in linear motion, it was essential to calculate the possible error from linear motion along the rail of the linear stage, PRO-165LM-0150 by Aerotech. By considering the calculated error as shown in Figure G.5.2, it could be confirmed that the given information on the pitch tolerances and roll tolerances, shown in Table G.5.1, was sufficiently low to satisfy consistent parallel alignment.

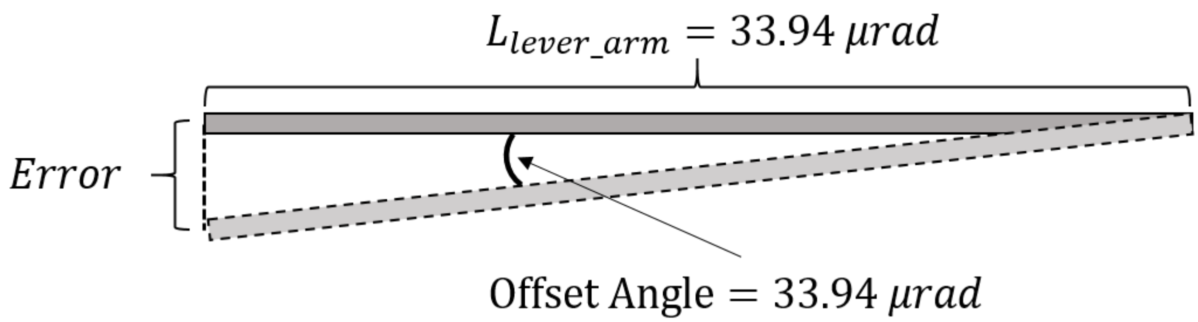


Figure G.5.1: A schematic representation of the error caused by pitch and roll rotations of the stage as it slides along the rail of the linear stage

Table: G.5.2: The error due to the pitch and roll tolerances are summarized, and shows that the error is low enough to maintain the flatness tolerances for parallel adjustment.

Model: PRO-165LM-0150 by Aerotech	**Tolerances**	**Error due to 3.5 inch lever arm**
Pitch	33.94 μrad	3.017 μm
Roll	33.94 μrad	3.017 μm

Based on the dimensions of the heated plate, the team found out that the length of the lever arm was 3.017 μm. Using Eq. 12, the team found out that the largest error caused by the pitch and roll tolerances was calculated. [23]

$$Err = Tolerance_{pitch\_roll} \times L_{lever\_arm} \quad \text{(Eq. 12)}$$
$$Err = 33.94 \times 10^{-6} \times 0.0889\ \text{m} = 3.01726 \times 10^{-6}\text{m} = 3.017\ \mu\text{m}$$

where Err is the error due to the pitch and roll rotations, $Tolerance_{pitch\_roll}$ are the pitch and roll tolerances and L_{lever_arm} is the length of the lever arm.

Based on the calculated error, the team could confirm that the error caused by the pitch and roll rotations are within the error limit defined as the engineering specification for consistent parallel alignment.

G.6. Finite Element Analysis

In order to ensure that the theoretical calculations performed on the thermal and static loading analysis hold true, further computer-aided analysis was carried out. Finite element analysis on the heat transfer and deflection was performed using Solidworks Simulation.

G.6.1. Heat Transfer along Top Surface of Heated Invar 36 Plate

In order to ensure that the silicon wafer placed on top of the heated plate was uniformly heated at $200\ ^\circ\mathrm{C}$, heat transfer analysis was conducted on the system. Assuming that the Polyimide heater remained its constant temperature at $200\ ^\circ\mathrm{C}$, the team performed finite element analysis, including thermal conduction of materials with thermal conductivity coefficients of $15\ \mathrm{W/m \cdot K}$ for Invar 36 and $1.3\ \mathrm{W/m \cdot K}$ for silicon, thermal convection coefficient of $10\ \mathrm{W/m^2 \cdot K}$ for natural air convection, and surface to surface radiation considering ambient temperature and emissivity coefficient of 0.93 for silicon wafer. As shown in Figure G.6.1., it could be concluded that the temperature of the silicon wafer would be maintained at $200\ ^\circ\mathrm{C}$.

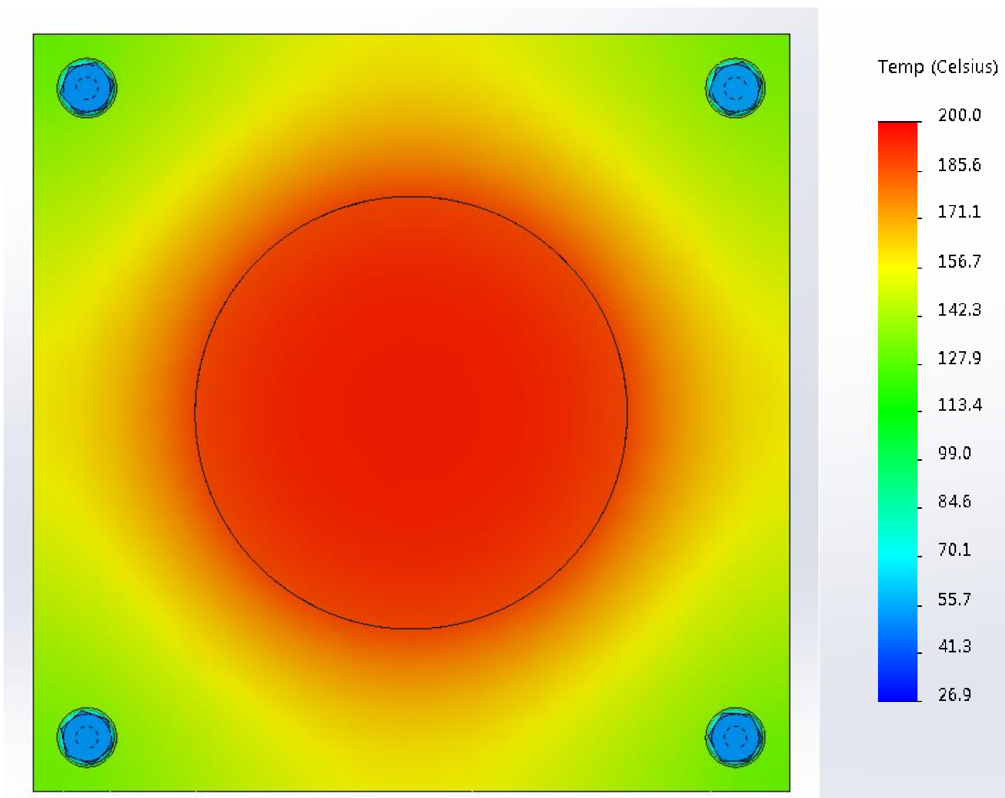


Figure G.6.1.: The schematic representation of the finite element analysis on heat transfer along the top surface of the heated Invar 36 plate

G.6.2. Heat Transfer on Screws and Stepper Motor Spindles

For the stepper motor spindles, it was essential to ensure that the spindles did not get heated up to temperature that is above the operating temperature of the motor body. If excessive heat was transferred from the spindle to the motor body, there could be possibility of motor failure. Using the material properties of stainless steel 303 and silicon, including the thermal conductivity coefficients of $16.3\ \mathrm{W/m \cdot K}$ and $149\ \mathrm{W/m \cdot K}$, respectively, thermal convection coefficient of $10\ \mathrm{W/m^2 \cdot K}$ for natural air convection, and surface to surface radiation considering ambient temperature and emissivity coefficient of 0.54 for stainless steel 303. As shown in Figure G.6.2., it could be confirmed that the temperature of the stepper motor spindle decreases, and the temperature at the bottom of the spindle would be 61.3 ℃, which was lower than 140 ℃, the operating temperature of the stepper motor.

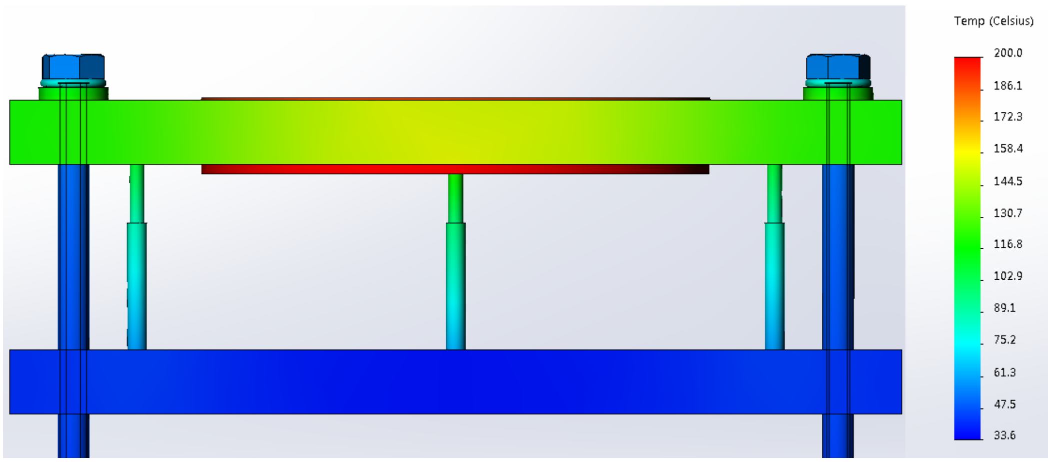


Figure G.6.2.: The schematic representation of the finite element analysis on heat transfer on the stainless steel 303 stepper motor spindles

G.6.3. Deflection on Motor Spindle Due to Load at Different Angles

Even though the maximum loading capacity of the motor, 45 N, provided by the vendor was sufficient to support the normal stress caused by the weight of the heated plate, there could be possible failure of the motor spindle when the force due to weight was at an angle instead of being normal to the horizontal x- and y- plane. Therefore, failure analysis of the motor spindle was carried out, using the mechanical properties of stainless steel 303, including, yield strength of 621 MPa, Young's Modulus of 193 GPa, and Poisson's Ratio of 0.25. Force due to weight of the heated plate distributed among the three spindles with the magnitude of 15 N applied at 5 degrees of offset from the vertical axis. The angle of 5 degrees was chosen as an extreme case where the tilt of the heated plate became 5 degrees with respect to the horizontal x- and y- plane. As shown in Figure G.6.3., it could be concluded that the motor spindle neither failed nor buckled. The results also showed that the amount of deflection in x-direction, but the deflection did not affect the flatness and parallel alignment of the SALD system, because gap size measurement would be done after the deflection occurred.

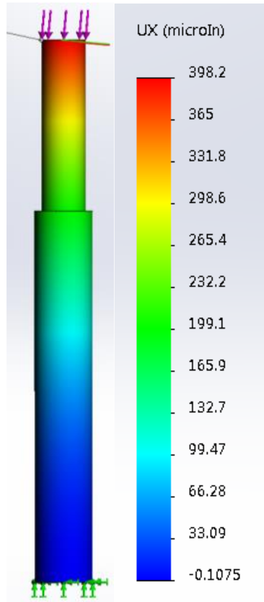


Figure G.6.3.: The schematic representation of the finite element analysis on deflection of the stainless steel 303 stepper motor spindle due to weight of the heated plate applied to the top of the spindle at an angle of 5 degrees

G.6.4. Deflection of Heated Invar 36 Plate

The deflection of the heated Invar plate was one of the most critical factor in determining the flatness tolerance of the silicon substrate. Because there were three point loads from the three motor spindles that act against the weight of the heated plate, analysis on possible deflection of the plate due to moment was necessary. For the finite element analysis, identical geometries for the plate, motor spindle, and location of the three motor spindles were identified, and the density of $8.055\ \mathrm{g/cm^3}$ was used as the mechanical property of Invar. As shown in Figure G.6.4., it could be concluded that the deflection at the center of the heated plate was observed carefully, because the 4 in diameter silicon wafer will be placed at the center portion of the heated plate. The difference in height at the center portion was $\pm\ 0.16\ \mu\mathrm{m}$ which was quite negligible compared to the flatness tolerance of $\pm\ 10\ \mu\mathrm{m}$ which was identified as one of the engineering specifications.

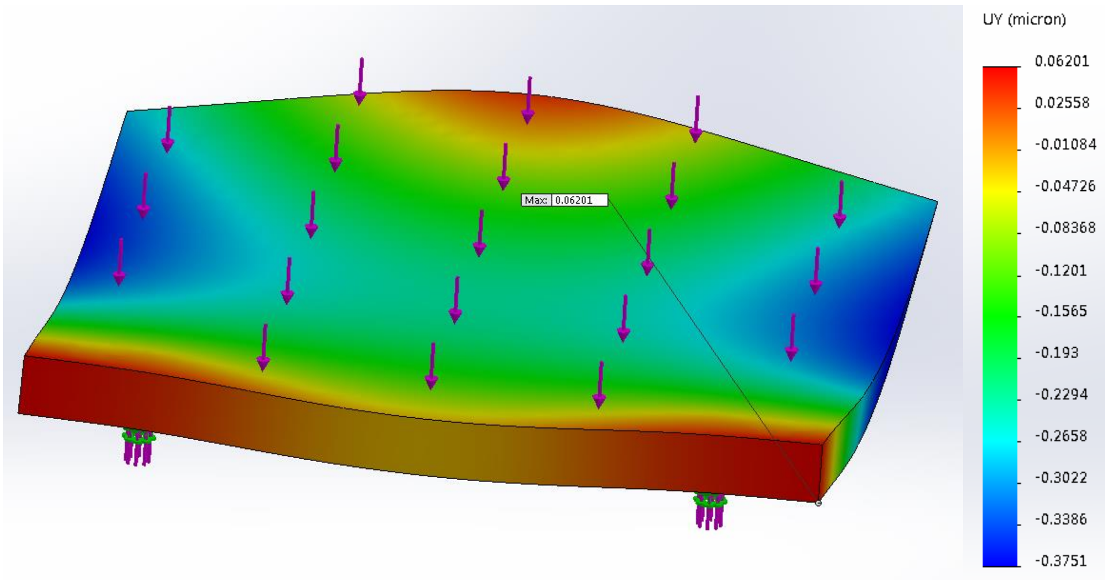


Figure G.6.4.: The schematic representation of the finite element analysis on deflection of the heated Invar 36 plate as a result of moment caused by the distributed downward force due the weight of the plate itself and the reacting upward force from the three stepper motor spindles.

G.7. FMEA / Risk Analysis

Table G.7.1: FMEA Table, where data and analysis on the failure modes effects were tabulated

Item	Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s)/ Mechanism(s) of Failure	Occurrence	Current Design Controls	Detection	RPN	Recommended Action
Heated plate	Heats up the substrate	Non-uniform heat points on the heated plate surface	Uneven heating of the substrate	7	Wrong placement of heater causing the heat transfer to be non-uniform across the stage	2	Test by measuring temperature	1	14	Choose suitable heating plate
	Secures the substrate in place, parallel to the depositor	Bending of the surface due to thermal expansion	Misalignment between substrate and depositor (not parallel)	7	Uneven surface machining	2	Choose a material with low coefficient of thermal expansion	4	56	Choose material with low coefficient of thermal expansion

Bottom plate	Holds the stepper motors (mounts) and all the components above (heated plate, stage)	Cracks and breaks	Material is not strong enough to withstand load	4	Fatigue	2	Perform strength calculation	2	16	Choose material that is durable
Stepper motor	Adjusts the vertical height of the stage (tilt control)	Step losses	Errors in output heights, causing misalignment of stage with depositor	7	Back driving and pay load increase with time	2	Test and validate method	6	84	Research on motor specifications
	Holds the stage in position	Wearing of the spindle tip	Errors in output heights, causing misalignment of stage with depositor	5	Repeated loading and unloading	2	Non-rotating spindle to reduce point friction	3	30	Choose suitable tip and spindle characteristics
Horizontal linear actuator	Controls the horizontal motion of the system	Overheated motor	Mechanical and electrical components failure	8	Extended use of actuator	1	Cooling system	4	32	Research on motor specifications
Bread board	Holds the linear actuator in position	Potential deformation of breadboard due to creep	Uneven surface of breadboard, leading to misalignment of installed stage	3	Fatigue	3	Perform stress calculation. Compare with material properties	1	9	Simulation on breadboard material
Vacuum tubing	Channels and evacuates air/gases	Worn and tangled tube	Pressure leakage	1	Fatigue and creep	1	Choose a material resistant to	1	1	Choose durable

	from the heated plate						wearing. Remove excessive lengths of tube			tubing material
Screws and Silicone rubber O-rings	Connects the heated plate and stage	Fatigue, screw fracture	Heated plate will collapse or misalignment	3	fatigue and creep	3	Perform stress calculation	3	27	Research insulating methods
	Secures the position of the stage after tilt and height adjustment	Fatigue, screw fracture, heated springs	Unable to compress the springs to lock the heated plate in place	3		2	Perform stress calculation	5	30	Research insulating methods
Capacitive sensor	Monitors the gap between the depositor and stage		Unable to provide accurate measurement	3	Dirty and wet environment	2	Test and validate method	5	30	Research sensor specifications
Thermocouple	Monitors the temperature of the substrate	Detached thermocouple	Inability to monitor temperature accurately	6	Loose connection	2	Test and validate method	5	60	Research thermocouple specifications

Based on the FMEA table, the team was able to identify what kind of failure in the design is most likely to occur. With the heated plate heated to a temperature of 200 ^{o}C, many sub-components of the system like the stepper motors and set screws have the possibility of getting heated as well. This will cause the possibility of thermal expansion in these sub components and will therefore results in non-uniform deposition and thermal stress. Over time, thermal stresses will cause fatigue and failure of these components. Maximum operating temperature of the stepper motors becomes an issue as well since they are in close proximity with the heated plate.

To reduce the risk of thermal stress and overheating components, the team used steatite shoulder bushings and silicone rubber O-rings to insulate the set screws from getting heated up and the O-rings to compensate the thermal expansion. Round cap screws were used to have a point contact between the stepper motor spindle and heated plate. This minimized the heat transfer potential between the components.

Table G.7.2: Illustration of the risk associated with each hazard

Hazard	Hazard Situations	Likelihood	Consequence	Overall Risk	Approach	Status of Approach/Timeline
Burns	The users could be burnt when exposed to the high temperature heated plate or depositors as a result of carelessness or in the event of accidents.	4	4	16	Mitigate and Research: Add insulation on the stage.	Engineering analysis performed on heated stage.
Electrical Shock	When using the device, the user could be shocked due to the exceeded current, broken wires or parts, or water exposures.	3	5	15	Research: Perform circuit analysis and make sure the wiring and the components used are water resistant.	Will be included in the next stage of engineering analysis.
Cut	The user could be cut due to the broken substrates.	4	2	8	Watch: In the future, some sensors might incorporate into the stage to detect the broken substrates and alert the users accordingly.	-
Finger Sprain	For users with big hands, they could get finger sprain when tightening the set screws.	2	3	6	Research and Watch: Perform empirical tests and build computer simulations to make sure the users can easily tighten or untighten the	Obtaining the part and getting ready to build the prototype.

					screws under normal circumstances. In the future or if time allows, some reminder/safety labels will be used.	
Hand injuries	In the event of the stage collapses due to overload or fatigue when the user is tightening the set screws, the user could experience hand injuries	3	4	12	Research: Conduct fatigue analysis to make sure the stage can withstand the loads for a long period of time.	Will be included in the next stage of engineering analysis.
Suffocating chemical gases	During the deposition, the user might experience suffocation from the chemical vapors.	3	4	12	Watch: Still unsure about the deposition process.	-
Body parts stuck in the machine components	The user might have their body parts caught in the suction of the vacuum.	2	4	8	Watch: The possibility of this hazard can be greatly reduce by installing the design in the fume hood instead. With that, the user will not interact with the motorized stage directly.	-

Based on the risk analysis, the hazards that possess the highest overall risk was the burn injuries. The heating process involved in the design reaches as high as 200 °C. Hence, the user might experience burns as a result of carelessness or in the event of accidental contacts with the heated plate or depositors. The likelihood of this hazard to occur is high and the consequence of this hazard varies depending on the level of exposure to the high temperature components. To further reduce the possibility of this hazard happening, engineering analysis regarding the heat transfer in the substrate stage is conducted.

In general, to reduce the risks associated with the design, it is advisable to install the design in fume hood. With this measure, the users will reduce the interactions with the design during the heating process and therefore greatly decreases the hazard possibility. Thereby, the overall risk associated with the design is at an acceptable levels as long as the design is installed in the fume hood for the safety measure.

G.8. Challenges

While some of the challenges mentioned in Design Review 2, which includes the parallelism difficulty and the budget constraints, remain as something the team strive to work better on, there are some new challenges emerged as the project progresses.

One of the major newly emerged challenges is the determination of the springs with the appropriate spring constant. As the team improvised the mock-up with the latest locking mechanism using springs, it was a challenge for the team to determine the appropriate springs to ensure that the springs exert the right amount of force on the substrate stage and will not cause instability in the system. Through thorough engineering analysis and close examinations on the engineering specifications, the team eventually overcame the challenge by using O-rings instead of the springs.

There are several issues that is unknown to the team and require further analysis on. First, the difference of expansion rate for heated plate and the heating filament might cause undesired effects. Heated plate, which is made of Invar (1.72 -2.1 cm/cm℃), and the heating filament, which mainly made of Aluminium Nitride (4.5 cm/cm℃), have different coefficient of expansion. This will lead to different expansion rate and even accumulate shear stress on the rather brittle heating filament. Therefore, the team need to acquire more information for the polyimide Heater and perform empirical tests as well as theoretical analysis regarding this issue. These issues are important and require the team to look further into to make sure the final design is capable of achieving the desired goals.

In an effort of addressing the problem proposed by the sponsors under the budget limits, the design is updated and improvised. However, there are still some major expected issues. First of all, with the change from micrometer heads to stepper motors, the team might encounter challenges when writing codes for the stepper motors. With the lack of strong background in the mechatronic field, it might cost the team a lot of time and effort in writing the required codes to achieve the task. The same also applies to the sensors application. Therefore, the team needs to obtain the parts as soon as possible and familiarize with them. The team can approach the company and request some helps from the companies.

Furthermore, the gap control system using the stepper motor might induce some problems in the next design and manufacturing stage. One of the major concerns in using stepper motor is step losses. Although the gap control system involves a closed loop control system, step losses might lead to constant calibration and adjustment which is undesired. Fortunately, the cost of the stepper motor is considerably affordable. This provides the room for the team to perform tests on the stepper motor before finalizing the design.

Among all, maintaining the parallelism between the depositor and the substrates is considered the most challenging aspect in the design. It is critical to ensure that the depositor and the substrates are parallel to each other. Failure to achieve this might result in non-uniform deposition and unwanted machine failure due to collision. To tackle the parallel alignment issue, the design uses a three-point-micrometer head mechanism and a high precision laser displacement sensor. However, the micrometer head and laser sensor contribute to a certain degree of measurement error. Furthermore, these micrometer heads are adjusted manually to achieve the desired heights based on the laser sensor readings. Thus, this design aspect requires high precision and accurate components with proper tools handling to hit the desired parallel alignment requirement.

Due to the budget constraints of the project, it is very difficult to keep the cost low while being able to achieve all the requirements of the projects. This project requires high resolution and precision in controlling the stage, horizontal and vertical motion, and therefore, it is expensive to acquire the motors and sensors that are able to meet the required specifications accordingly. To ensure a high quality outcome of the project, it is crucial to consider the trade-offs between obtaining the required high precision and resolution components and cost.

Based on the final design concepts, there are several expected major problems. Firstly, utilizing stepper motors and set screws as the tilt adjustment and vertical-axis motion mechanisms may be a challenge because the team has no previous experience in building this mechanism. Thus, unexpected manufacturing and assembly issues could potentially occur. To solve this problem, the team sought assistance from Leo Tse, a PhD candidate from Barton Research Group in University of Michigan, to provide the team with technical assistance and advices regarding vertical axis motion and tilt adjustments. He will serve as a valuable asset to the team based on his previous experience in building a similar mechanism for his project.

Furthermore, the team may encounter problems implementing a feedback control system to monitor the heating of the substrate due to unfamiliarity in this particular field. This could result in ineffective heating of the substrate, leading to an inability to provide uniform heat to the stage. Therefore, the team will be receiving technical advices regarding heating mechanisms from one of the project’s sponsor, Watlow Electric Manufacturing Company. The engineers from Watlow Co. will be providing appropriate solutions for proper and uniform heating of the stage, besides building a suitable feedback control system to monitor the heating process.

The last major problem could be the machining of the flat surface for the stage and heated plate. The flat surface is critical to ensure uniform deposition of the nanofilm layers. However, the fine surface machining are costly and difficult to achieve with the equipment currently available in the machine shop. The team will consult the machine shop coordinator and outsource to various fine machining companies around Ann Arbor to find the best way to manufacture the necessary flat surface stage.

G.9. Validation

Verification is necessary to make sure the design can achieve the engineering specifications of the project. The team verified three key design drivers, including uniform heating, flat surface, and securing the substrate, by conducting virtual or physical tests to ensure the result met the corresponding engineering specifications. For the remaining design drivers, the team will start performing the corresponding physical tests to verify the feasibility of the components once the parts arrive. Below include the detailed discussions of the recommended verification methods. The further descriptions of the verification methods, that could be done once all the components are arrived, are described in Appendix I.

G.9.1. Gap Alignment and Gap Size Control

First and foremost, the design was required to maintain consistent parallel alignment. The engineering specifications for this key design driver is that the gap difference along the stage needs to be less than 10 microns. To verify this engineering specification, the team performed motor performance testing.

In order to ensure precise control of the parallel alignment and gap size, it was essential to determine the resolution of vertical motion. Since the vertical motion of the heated plate was solely dependent on the resolution of the stepper motors, the step resolution of the motor's linear motion had to be calculated. Because the motor spindle is expected to move with a fine resolution of 1.5 $\mu m/step$, the spindle linear motion was measured using a digital microscope (Infinity 2-2). The digital microscope enabled a close-up picture to be digitally captured to a PC, and this digital image of the linear motor spindle motion could be measured following the recommended ASTM E-399 procedure. First, using the PC monitor image resolution of 1280 x 1024, an image of a ruler with known scales (resolution: $200\ \mu m$) was captured and utilized to establish the scaling factor. By measuring the number of pixels using a computer software, *Paint*, a scaling factor (units of $14.29\ \mu m$ per pixel) was established by a calibration process. The number of pixels on the digital image could then be converted into the range of motion in μm. After 100 steps and 1000 steps, the motor spindle was calculated to have moved $144\ \mu m$, and $1447\ \mu m$, respectively. It could be concluded that the motor testing showed repeatable step resolution of the stepper motors. Thus, the team could ensure that precise control of the parallel alignment and gap size could be fulfilled with the stepper motors.

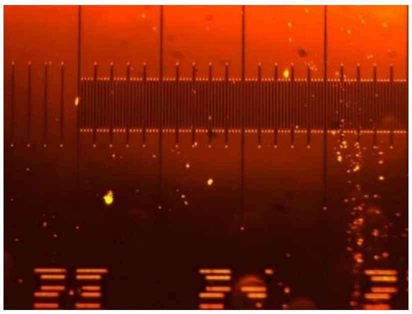


Figure G.9.1: A digital image of a ruler which was used to establish a scaling factor of $14.4\ \mu m$ per pixel (20 pixels for $200\ \mu m$)

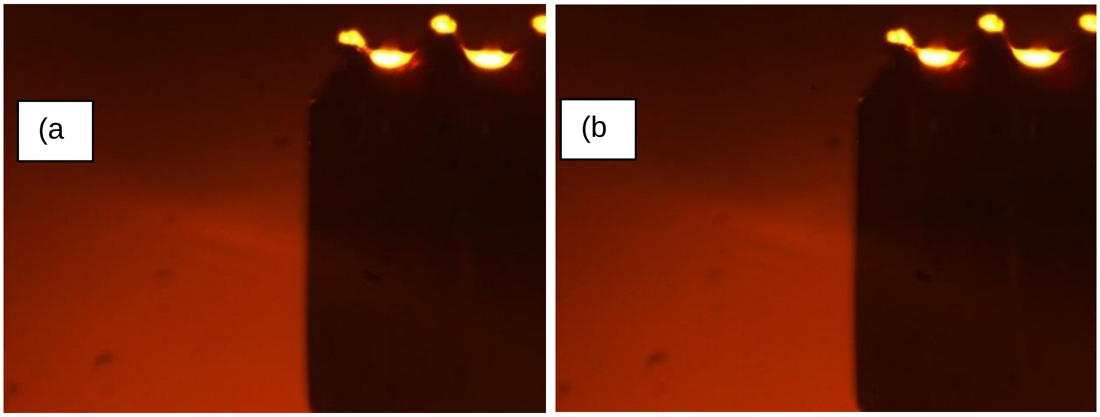


Figure G.9.2: Two digital images which show (a) starting and (b) end position of the motor spindle set to move 100 steps which is equivalent to 10 pixels ($x_1 = 914,\ x_2 = 904$).

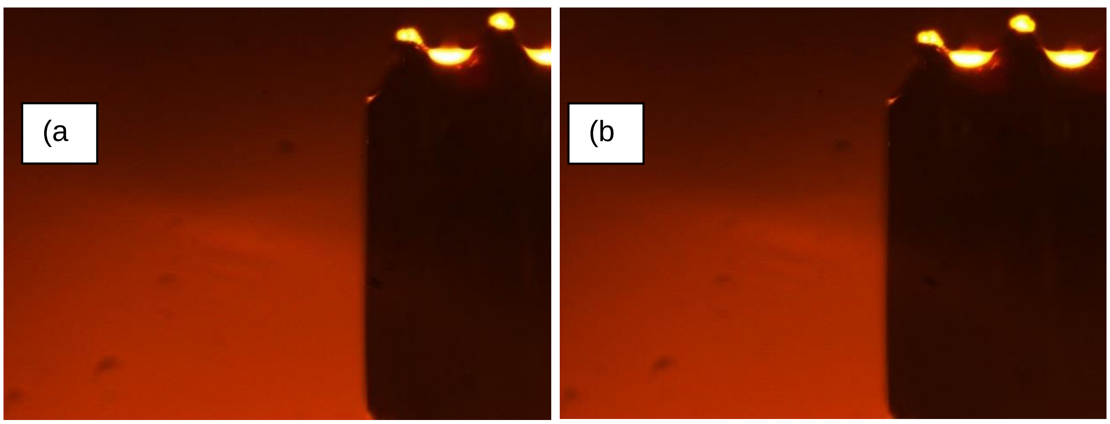


Figure G.9.3: Two digital images which show (a) starting and (b) end position of the motor spindle set to move 1000 steps which is equivalent to 101 pixels ($x_1 = 1076,\ x_2 = 975$).

G.9.2. Flat Surface

The thickness of the Invar 36 plate was measured at 8 different points on the plate. The measured maximum thickness was 0.013033 m and minimum thickness was 0.013025 m. By calculating the difference between the two measured values, it was concluded that the thickness tolerance achieved after surface grinding was 8 μm.

The deflection of the heated Invar 36 plate was one of the most critical factor in determining the flatness tolerance of the silicon substrate. Because there are three point loads from the three motor spindles that act against the weight of the heated plate, analysis on possible deflection of the plate was necessary. Thus, a finite element analysis was conducted using ANSYS to study the possible deflection of the Invar 36 plate. For the analysis, identical geometries of the plate, motor spindles, and location of the three motor spindles were identified, and density of $8.055\ \mathrm{g/cm^3}$, Young's Modulus of 141 GPa and the yield strength of 276 MPa were used as the mechanical properties of Invar 36. As shown in Figure XX, it could be concluded that the maximum deflection along the surface of the heated plate was $\pm\ 0.4371\ \mu\mathrm{m}$

which was quite negligible compared to the flatness tolerance of $\pm$ 10 μm which was identified as one of the engineering specifications.

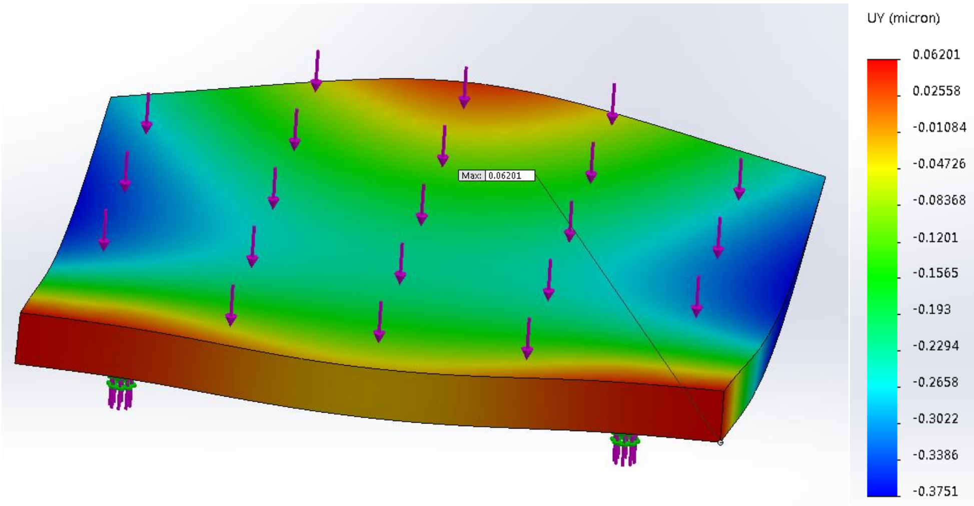


Figure G.9.4: The schematic representation of the finite element analysis on deflection of the heated Invar 36 plate as a result of moment caused by the distributed downward force due the weight of the plate itself and the reacting upward force from the three stepper motor spindles.

G.9.3 Uniform Heating

In order to ensure that the silicon wafer placed on top of the heated plate is uniformly heated at 200 °C, heat transfer analysis was conducted on the system. Assuming that the Polyimide heater remains its constant temperature at 205 °C. The finite element analysis was performed using thermal conduction of materials with thermal conductivity coefficients of 15 $\mathrm{W/m \cdot K}$ for Invar 36 and 1.3 $\mathrm{W/m \cdot K}$ for silicon, thermal convection coefficient of 5 $\mathrm{W/m^2 \cdot K}$ for natural air convection, and surface to surface radiation considering ambient temperature and emissivity coefficient of 0.8 for components. As shown in Figure XX, it could be concluded that the temperature of the silicon wafer would be maintained at 200 °C.

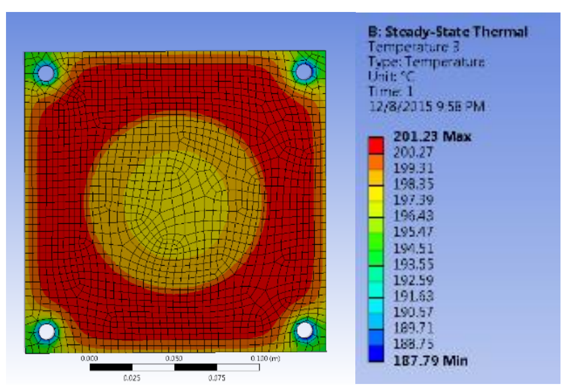


Figure G.9.5: Schematic representation of the surface temperature map of the top surface of the heated Invar 36 plate created using ANSYS

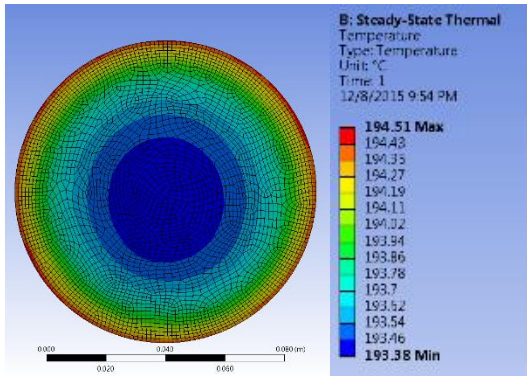


Figure G.9.6: Schematic representation of the surface temperature map of the top surface of the heated silicon substrate using ANSYS

G.9.4 Substrate Securing Mechanism

In order to validate that the vacuum chucking system, an empirical testing was performed. The maximum force required to move the substrate was determined. The testing was also utilized to ensure that the substrate did not break due to the downward force caused by vacuum suction. A 100 mm diameter silicon wafer was used during the testing because it was likely to be the most frequently used substrate. The digital force gauge was used to measure the shear force needed to move the substrate that was secured in place by the vacuum chucking system. The force from the force gauge was applied at an angle of 45° from the x-axis. After obtaining the force value of 19 N, the reaction force was calculated using Equation XX, $Horizontal\ Reaction\ Force, F_h = 19 \times \sin(45°) = 13.44\ N$. Thus, the maximum shear force required to move the secured silicon wafer was determined to be $13.44\ N$. The experimental setup and the force gauge used was a Model HF-200 digital force gauge are demonstrated in Figure XX and Figure G.9.7.

Figure G.9.7: Picture of Model HF-200 Digital Force Gauge used in the empirical testing of vacuum chucking system

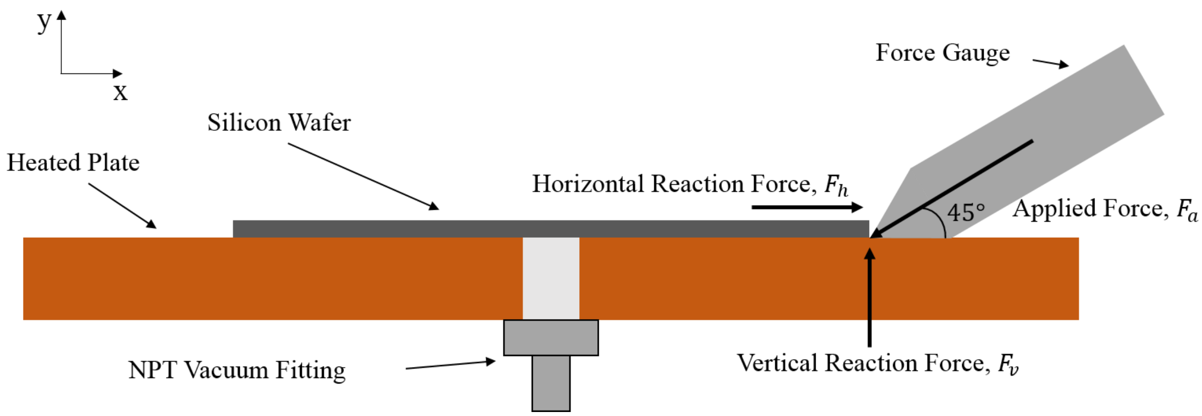


Figure G.9.8: Free body diagram of the empirical testing on vacuum chucking system\

G.9.5. Deposition Rate

Another significant user requirements defined by the sponsor was to fulfill deposition rate of 1 nm/sec. Based on numerical calculations using Eq. 9, 10 and 11, it was concluded that the heated plate had to oscillate in a horizontal axis at a speed greater than 31.75 cm/sec. Because the main purpose of the Spatial ALD system is to be able to deposit atomic monolayers on the substrate at a desired deposition rate, the speed of the horizontal motion became one of the priority design drivers. However, it was inappropriate to directly relate the linear motion speed to the deposition rate, because the deposition characteristics of Spatial ALD were still not well defined. For example, there were other factors such as shearing of reactant gas zones at the contacting surface of the substrate and thermal gradient which would form along the substrate at different positions and high speed which could prevent the system to achieve the desired deposition rate.

After Aerotech's PRO165LM-200 was determined as the horizontal linear stage, it was necessary to validate that the linear motion speed actually fulfills the desired deposition rate. However, since the depositor was not scheduled to be designed and functioning yet, the process of conducting empirical experiments through actual atomic layer deposition was not feasible. The team will be able to test the validity by performing Spatial ALD once the depositor is capable of creating two reactant gas zones separated by inert gas curtains.

If the experiment is conducted, the team will record the duration of deposition. After the deposition is over, the thickness of atomic monolayers deposited on the sample will need to be analyzed. In order to measure nano-scale thickness of the monolayers, X-ray reflectivity (XRR) will be used. XRR is one of the most reliable techniques to determine film thickness and surface/interface roughness with no special sample preparation. It can be used to determine measure film thickness from several to 1000 nm. Thus the multilayer thin film ALD samples can be characterized by determining the thickness, roughness and density of the film using XRR data.

H. Discussion/ Design Critique

Based on the performance of the final design, the team evaluated the strength and weakness of the design. A further reflection on the future improvements for the design was made. The team also provided several recommendations on both system-level and detailed-level to further increase the functionality of the design.

H.1. Strength and Weakness of the Design

After the team built a working prototype and performed validation tests, the team was able to evaluate the strengths and weakness of the design. The strengths and weakness were evaluated based on the fulfillment of the user requirements.

User Requirements	Strength	Weakness	Potential Improvement
Consistent Parallel Alignment and Gap Control	1) The system was able to precisely align the stage within 10 μm according to the measurements of the sensors. 2) The system was able to adjust the gap size with high precision and accuracy.	1) Significant amount of human error involved in the mounting of the sensors. Sensors need to be mounted parallel to each other. 2) Significant amount of time is consumed for the gap alignment process to take place.	Use a different power supply to power the stepper motors to perform faster
Flat Surface	The surface's flatness was sufficient to show the proof of concept < 10μm	The flatness requires a higher level of machining in order to achieve a flatness of < 5μm	Used a different machining method other than surface grinding
Uniform Heating	Virtual analysis proves that uniform heating is achievable with the heating system Watlow is providing.	Requires validation in the future	N/A
Secure substrate firmly	The vacuum chucking system was able to hold the substrate in position during operation	Difficult to position the center of the substrate on top of the vacuum opening	Have markings/ grooves on the stage to indicate optimal placement of substrate

H.2. Future Modifications

Based on the performance of the prototype, the team suggested several future modifications to further improve the current design. Below includes the details descriptions of each suggestion.

First of all, the team suggested an improved, more precise sensor mounting method. In the current prototype, the sensors were mounted using adhesive and double-sided tape. This might affect the alignment of the sensors and the depositor, resulting in less accurate measurements. Therefore, it is strongly advised to have the sensors mounted carefully using better adhesive with the consult of engineers from Capacitec company. Besides, to ensure the depositor is aligned with the sensors, it is critical to manufacture the depositor and the sensors mounting case with higher precisions, 5 μm. This can further improve the alignment between the depositor and the sensors.

Additionally, the design can be further improved with a more robust control system with better user interfaces. The algorithms and sensors data were currently processed in Matlab under the command from the user. A separate, Aerotech-owned software/interface was used to control the linear stage. To simplify the procedures, it is suggested to develop a more involved feedback control system, allowing the user to control both the linear stage and the tilt adjustment mechanism with a single interface. In order to complete the feedback control system, it is advised to consult Aerotech engineers to obtain more information for the data acquisition from the linear stage. A modified user interface can be performed using MatLab GUIDE or LabView with window that includes the list of the commands available to control Arduino and the linear stage as well as textbox or drop down menu to allow the user input the command.

Furthermore, the team suggested the purchase of ceramic shoulder bushings with larger inner diameter or use of other insulation methods. From the attempts made to grind or sand the shoulder bushing to a larger inner diameter, the team concluded that it is extremely hard to machine ceramic shoulder bushing. Therefore, it is strongly suggested to purchase ceramic shoulder bushing with the inner diameters, 0.3”. Besides that to improve the design, it is advised to include markings on the heated stage for repeatable wafer placement. This could be done by machining small circle markings with various dimensions on the heated plate.

Lastly, to better improve the uniform heating of the stage, the heater could be designed through several stages of analysis. In the first pass, it is encouraged to design the heater based on the Finite Element Analysis (FEA) on the Invar plate by assuming that that heater is heating the stage uniformly at 200 ℃. From the FEA result, the engineers from Watlow will determine the number of heating zones required for uniform heating and manufacture the heater for the testing purpose. If it does not perform the heating uniformly. The second stage of the heater design should be carried out. In the second pass of heater design, the heater will be designed based on the FEA results on the heater with the assumption that the Invar is heated to 200 ℃ and determining the required power density to supply to each heating zones. Close cooperation with Watlow engineers are strongly encouraged to guarantee the heater designed with the desired specifications.

H.3. Recommendations

To further improve the functionality of the design, the team provided several recommendations in both system and detailed levels.

H.3.1. System-Level Recommendations

Recommendations for the overall system were made. Below includes the details descriptions of each suggestion.

1. Number of iterations
   One cycle of the current control system involves roll axes control at home position, then another roll axes control at the end of the stage, and lastly pitch axes control at the end of the stage. This helped to align the heated plate to the depositor. However, due to mechanical limitations, the heated plate would not be perfectly parallel to the depositor. A certain degree of angle error would be introduced. To resolve this issue, the aforementioned cycle could be repeated several times to reduce the magnitude of angle error. The Matlab codes involved could be placed in a loop cycle to be repeated at defined number of times.

2. Addition of an extra sensor
   Currently, two capacitive sensors were used to measure the gap between the heated plate and the depositor. These sensors were initially installed directly above the two tips of the stepper motors. This location was defined as the home position. Within the control system, the stage would then be moved in order to align the third stepper motor x-location with the two sensors. Therefore, the gap at three stepper motor tips could not be actively determined at every instance. To resolve this issue, a third sensor could be introduced and installed directly above the third stepper motor tip. This could help to actively determine the gap size at three locations of the stage at every instance, instead of two.

3. Addition of thermocouple
   To ensure uniform heating of the stage, thermocouples would be introduced along the heated plate. Engineers from Walow recommended the team to bore holes on the heated plate to install these thermocouples. These additional holes on the heated plate would subsequently increase the number of heat sinks, and therefore reducing the ability of the heater to uniformly heat the plate. To resolve this issue, more heat transfer analysis were needed to be done to determine these locations of cold zones.

H.3.2. Detailed-Level Recommendations

Some detailed level recommendations were also made to improve the design. Below includes the details descriptions of each suggestion.

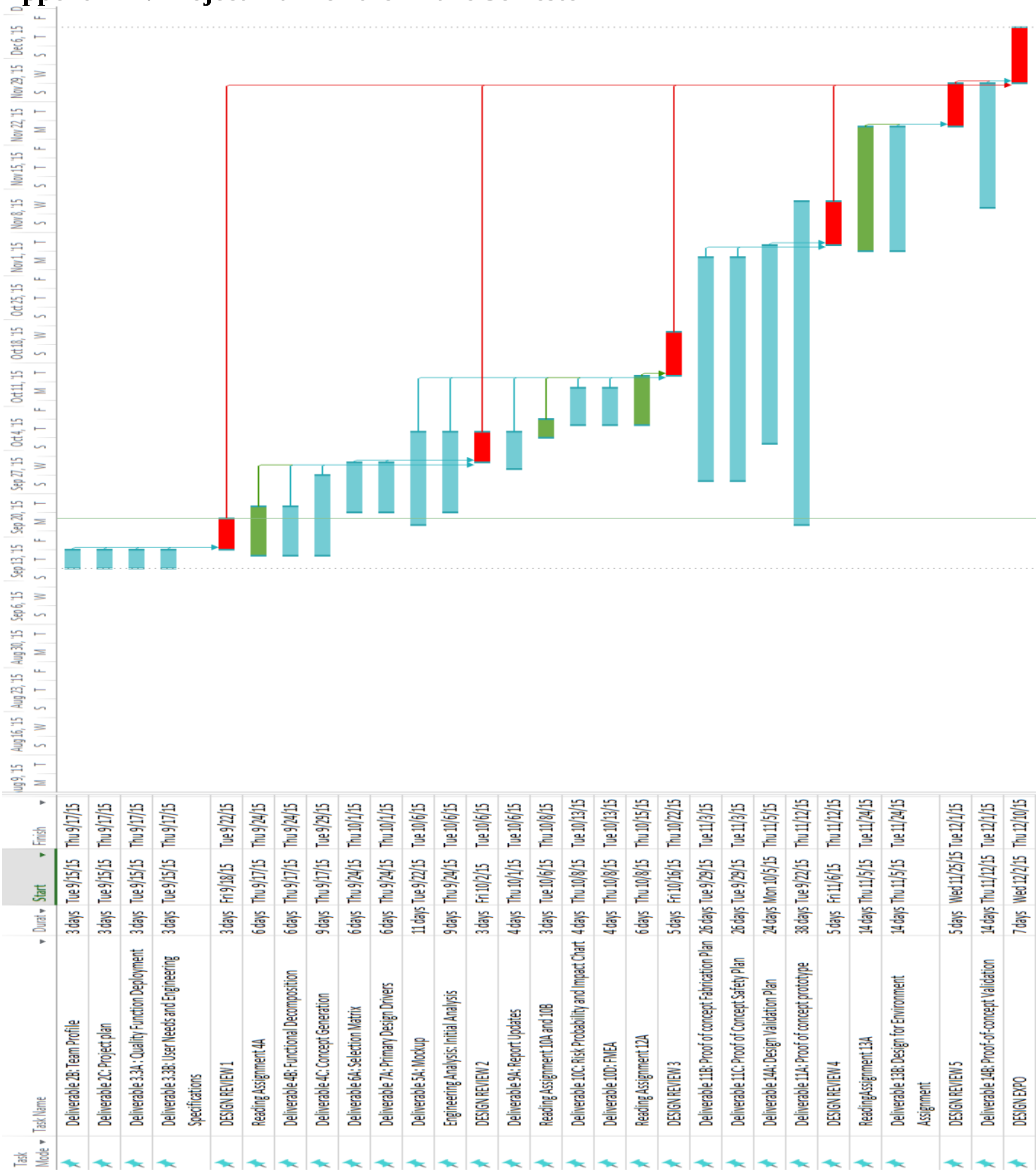
1. Sensors recalibration
   Currently, the capacitive sensors were only able to detect gap range up to 250 micrometers. Therefore, tilt adjustments of the heated plate could only be done within the mentioned gap range. This limited the adjustability of the stage. To improve this, the sensors could be calibrated to a higher sensing range. The maximum sensing range that could be possibly calibrated with the sensors was one millimeter. Besides that, the sensors were to be tested to determine the accuracy of their readings. A high precision micrometer could be used to calibrate the readings of the sensors. The reading from the micrometer could be used to compare with the readings from the sensors to identify their degree of accuracy.

2. Power supply for each motor
   Power supply with similar volt-amp values should be provided to each stepper motor. Currently, two stepper motors were supplied with the same power sources. This reduced the speed of the motors. Therefore, providing similar volt-amp values to each motor would help to maintain the stepper motors at similar vertical speed. By doing so, each stepper motors would be supplied with the same power to drive their respective spindles.

3. Thicker screw size
   To better support the linear stage and enhance stability of the system, it is recommended to use a thicker screw size for set screw securing mechanisms. Currently, 10-32 screws were used. The team suggested the use of ¼” screws to substitute these screws in providing better balance and ensuring longer life spans of the set screws mechanisms.

APPENDIX

Appendix A: Project Plan for the Entire Semester



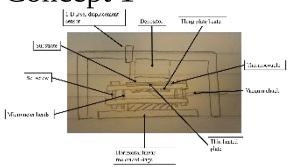
Task Mode	Task Name	Duration	Start	Finish
	Deliverable 2B: Team Profile	3 days	Tue 9/15/15	Thu 9/17/15
	Deliverable 2C: Project plan	3 days	Tue 9/15/15	Thu 9/17/15
	Deliverable 3.3A : Quality Function Deployment	3 days	Tue 9/15/15	Thu 9/17/15
	Deliverable 3.3B: User Needs and Engineering Specifications	3 days	Tue 9/15/15	Thu 9/17/15
	DESIGN REVIEW 1	3 days	Fri 9/18/15	Tue 9/22/15
	Reading Assignment 4A	6 days	Thu 9/17/15	Thu 9/24/15
	Deliverable 4B: Functional Decomposition	6 days	Thu 9/17/15	Thu 9/24/15
	Deliverable 4C: Concept Generation	9 days	Thu 9/17/15	Tue 9/29/15
	Deliverable 6A: Selection Matrix	6 days	Thu 9/24/15	Thu 10/1/15
	Deliverable 7A: Primary Design Drivers	6 days	Thu 9/24/15	Thu 10/1/15
	Deliverable 5A: Mockup	11 days	Tue 9/22/15	Tue 10/6/15
	Engineering Analysis: Initial Analysis	9 days	Thu 9/24/15	Tue 10/6/15
	DESIGN REVIEW 2	3 days	Fri 10/2/15	Tue 10/6/15
	Deliverable 9A: Report Updates	4 days	Thu 10/1/15	Tue 10/6/15
	Reading Assignment 10A and 10B	3 days	Tue 10/6/15	Thu 10/8/15
	Deliverable 10C: Risk Probability and Impact Chart	4 days	Thu 10/8/15	Tue 10/13/15
	Deliverable 10D: FMEA	4 days	Thu 10/8/15	Tue 10/13/15
	Reading Assignment 12A	6 days	Thu 10/8/15	Thu 10/15/15
	DESIGN REVIEW 3	5 days	Fri 10/16/15	Thu 10/22/15
	Deliverable 11B: Proof of concept Fabrication Plan	26 days	Tue 9/29/15	Tue 11/3/15
	Deliverable 11C: Proof of Concept Safety Plan	26 days	Tue 9/29/15	Tue 11/3/15
	Deliverable 14A: Design Validation Plan	24 days	Mon 10/5/15	Thu 11/5/15
	Deliverable 11A: Proof of concept prototype	38 days	Tue 9/22/15	Thu 11/12/15
	DESIGN REVIEW 4	5 days	Fri 11/6/15	Thu 11/12/15
	ReadingAssignment 13A	14 days	Thu 11/5/15	Tue 11/24/15
	Deliverable 13B: Design for Environment Assignment	14 days	Thu 11/5/15	Tue 11/24/15
	DESIGN REVIEW 5	5 days	Wed 11/25/15	Tue 12/1/15
	Deliverable 14B: Proof-of-concept Validation	14 days	Thu 11/12/15	Tue 12/1/15
	DESIGN EXPO	7 days	Wed 12/2/15	Thu 12/10/15

Appendix B: QFD Chart

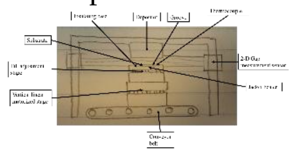
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)																				
				Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Range of motion in x and z axis (+)	Minimum controlled gap (-)	Amount temperature gradient along the substrate (-)	Coefficient of Thermal Expansion (-)	Coefficient of Thermal Conduction (+)	Normal loading capacity (+)	Attraction force on the substrate (+,-)	Speed of linear motion (+)	Resolution of displacement measurement (+)	Settling time of temperature PID control (-)	Flatness Tolerance (-)	Yield strength of materials (+)	Pitch and roll tolerance (-)	Amount of contaminants (-)	Chucking compatibility (+)	High resolution tilt adjustment (+)	Amount of electronic hazards (-)	Resolution of motion in x axis (-)	Resolution of motion in z axis (-)	Steady State Error of temperature control (-)
1	9	8.9	10.0	Uniform Atomic Layer Deposition	O	Θ	Θ	O	Θ	▲	O	O	Θ	O	Θ	▲	O	Θ	O	Θ	▲	Θ	Θ	Θ
2	9	8.0	9.0	Maintain at desired gap between substrate and printerjet	Θ	Θ	O	Θ	O	▲	O	O	Θ	▲	Θ	▲	Θ	O	O	Θ	▲	▲	Θ	O
3	9	6.3	7.0	Uniform Heating	▲	▲	Θ	▲	Θ	▲	▲	▲	▲	Θ	O	▲	▲	▲	O	▲	▲	▲	▲	Θ
4	9	6.3	7.0	Able to hold wafer in place during motion	▲	▲	▲	▲	▲	▲	Θ	O	▲	▲	O	▲	▲	O	Θ	▲	▲	▲	▲	▲
5	9	7.1	8.0	The components need to withstand high temperature	▲	▲	O	Θ	O	▲	▲	▲	O	O	O	▲	▲	▲	▲	▲	Θ	O	O	▲
6	9	8.0	9.0	Substrate need to oscillate in x-axis	Θ	O	▲	▲	▲	O	O	Θ	O	▲	▲	▲	▲	▲	O	O	O	Θ	▲	▲
7	9	4.5	5.0	Safe to use	▲	▲	O	▲	▲	Θ	O	O	▲	▲	▲	Θ	▲	O	O	▲	Θ	▲	▲	O
8	9	5.4	6.0	Stable Mechatronic System	Θ	Θ	O	▲	O	Θ	Θ	O	▲	Θ	▲	Θ	O	▲	O	O	O	Θ	O	O
9	9	6.3	7.0	No contamination	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	O	▲	▲	Θ	▲	▲	▲	▲	▲	▲
10	9	4.5	5.0	Modular Design	O	Θ	O	O	▲	O	O	Θ	O	O	O	Θ	O	▲	Θ	O	▲	▲	O	▲
11	9	4.5	5.0	Size of the entire system must be within 4 ft x 4 ft	Θ	O	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
12	9	7.1	8.0	Flat surface	▲	▲	Θ	Θ	O	▲	O	▲	▲	▲	Θ	▲	▲	Θ	▲	▲	▲	▲	▲	▲
13	9	6.3	7.0	Able to heat and keep substrate at desired temperature	▲	▲	Θ	Θ	Θ	▲	▲	▲	▲	Θ	▲	▲	▲	▲	▲	▲	▲	▲	▲	Θ
14	9	5.4	6.0	Safe wiring system	O	O	O	▲	▲	▲	▲	O	O	▲	▲	▲	▲	▲	▲	▲	Θ	▲	▲	▲
15	9	3.6	4.0	Able to work with different substrates in geometry and types	▲	▲	▲	O	▲	▲	Θ	▲	▲	▲	▲	▲	▲	▲	Θ	▲	▲	▲	▲	▲
16	9	8.0	9.0	Keep the substrate and printerjet aligned	O	Θ	Θ	Θ	O	▲	O	O	Θ	▲	Θ	▲	Θ	Θ	O	Θ	▲	O	Θ	O
				Target or Limit Value																				
				Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	5	10	7	5	5	5	7	6	8	8	8	5	8	4	8	5	6	6	9	4
				Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
				Weight / Importance	360.7	414.3	462.5	426.8	342.9	203.6	319.6	292.9	350.0	283.9	417.9	214.3	266.1	380.4	312.5	335.7	262.5	308.9	333.9	323.2
				Relative Weight	5.5	6.3	7.0	6.5	5.2	3.1	4.8	4.4	5.3	4.3	6.3	3.2	4.0	5.8	4.7	5.1	4.0	4.7	5.0	4.9

Appendix C: Generated Concepts

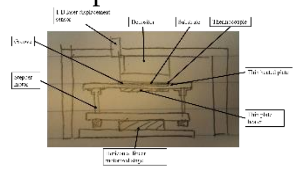
Concept 1



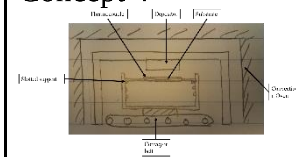
Concept 2



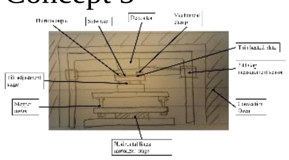
Concept 3



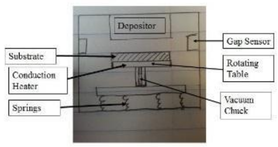
Concept 4



Concept 5



Concept 6



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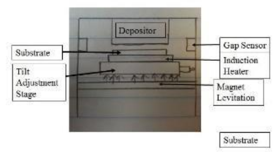

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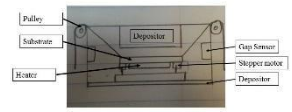

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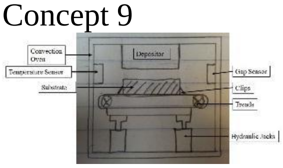
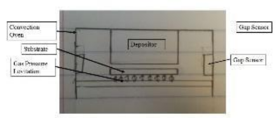


Concept 10



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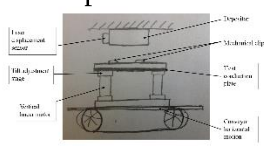
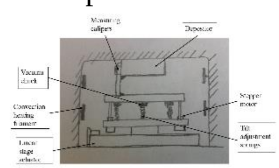


Concept 12



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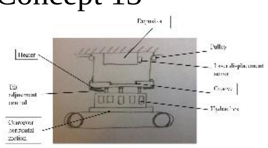
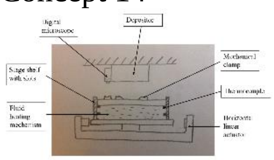
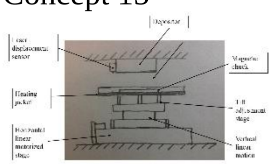


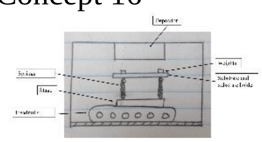
Concept 14



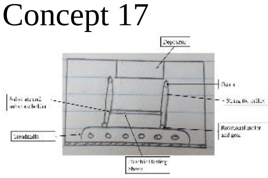
Concept 15



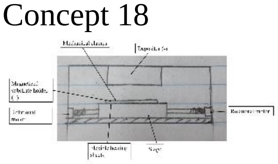
Concept 16



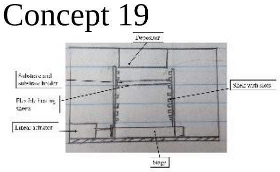
Concept 17



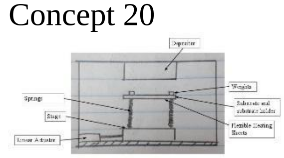
Concept 18



Concept 19



Concept 20



Appendix D: Pugh Chart

Concept Selection Legend

Better	+
Same	S
Worse	-

Key Criteria	Importance Rating	Benchmark Option	Concept 1*	Concept 2*	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7	Concept 8	Concept 9*	Concept 10	Concept 11	Concept 12*	Concept 13	Concept 14*	Concept 15	Concept 16	Concept 17	Concept 18	Concept 19	Concept 20
Consistent parallel alignment (Gap difference along the stage measured < 10 µm)	10		+	+	-	-	-	+	S	-	+	-	S	S	+	+	+	+	S	+	-	S
Precise vertical linear motion (resolution: 10 µm)	8		S	S	+	+	+	-	+	+	S	S	+	S	S	-	S	S	S	S	S	S
Precise horizontal linear oscillating motion (resolution: 0.5 mm)	6		+	+	+	+	-	+	S	+	S	-	-	+	S	+	-	-	S	S	S	S
Uniform substrate heating (temperature gradient: 0.5 K/cm)	3		S	S	S	S	S	S	+	S	S	+	S	S	-	+	-	-	+	S	S	-
Flat surface tolerances (tolerance of surface machining: ±1 µm)	6		S	S	-	S	S	S	-	S	S	S	S	S	S	S	S	S	S	S	S	+
Minimum gap size (gap size: 20 - 50 µm)	9		+	+	+	+	-	S	S	+	+	-	+	S	+	S	S	S	S	S	+	S
Ability to secure substrate (force exerted: <30 N (for standard silicon wafers)	5		+	+	+	-	+	S	S	-	+	S	-	+	+	S	S	S	+	-	S	+
Function under a wide range of temp (ambient - 200 °C)	7		S	S	S	-	S	S	+	-	S	-	-	S	-	S	S	S	S	S	-	S
Ability to hold substrate with different geometry	2		+	+	-	-	-	S	-	+	S	-	+	+	S	+	S	S	-	-	-	S
Deposition rate of 0.1 nm/sec	5		S	S	-	+	+	S	S	S	S	S	S	S	-	S	S	S	S	+	S	S
Sum of Positives			5	5	4	4	3	2	3	4	3	3	3	3	3	4	2	2	2	2	1	2
Sum of Negatives			0	0	4	4	4	1	1	1	0	1	1	0	3	1	1	1	1	2	2	1
Sum of Sames			5	5	2	2	3	7	7	7	8	7	7	7	4	6	7	7	7	6	6	7
Weighted Sum of Positives			32	32	28	28	18	16	18	11	23	15	15	21	24	21	10	10	8	15	9	11
Weighted Sum of Negatives			0	0	23	24	27	8	8	4	0	20	6	0	15	8	9	9	2	7	19	3
TOTALS			32	32	5	4	-9	8	10	7	23	-5	9	21	9	13	1	3	6	8	-10	8

Appendix E: Initial Mock-up Design

To better visualize the final design concept and ensure the feasibility of the design, a design mock-up was created based on the final design concept. The material used in the mock up included 4 wood rods, 3 black solid plastic rod, foam and cardboards.

A.E.1. Features

The mock-up consistd of 6 main components: the depositor, the substrate, stage with groove, stepper motors as tilt adjustment mechanisms, linear actuator and the heating system.

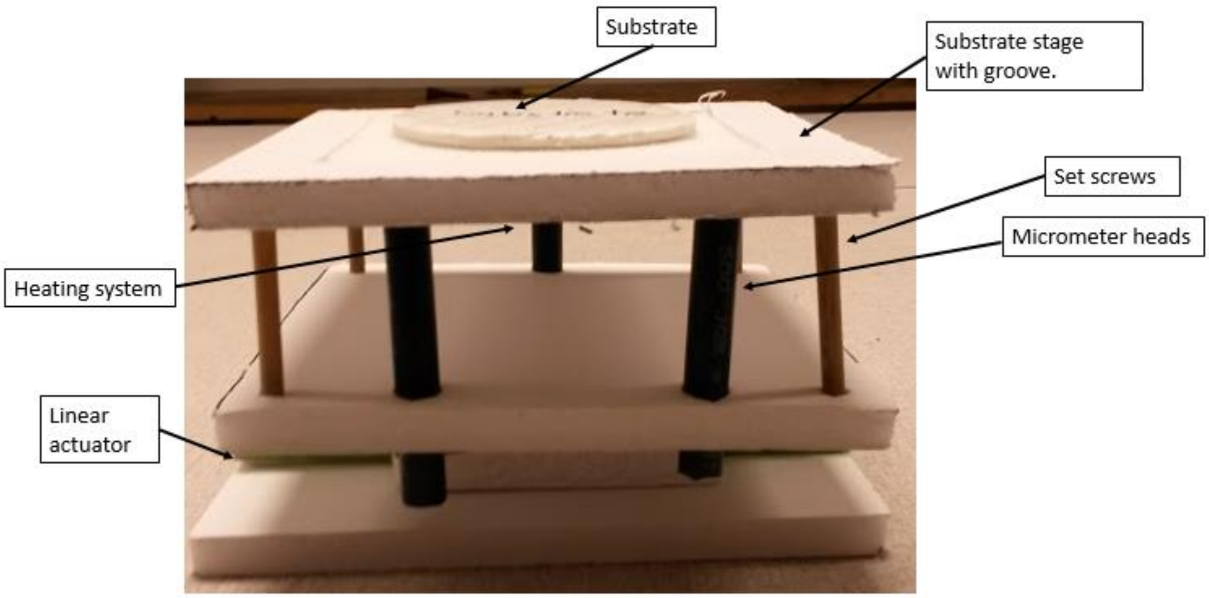


Figure A.E.1: The mock up consisted of several components. The major components included: substrate stage with groove, set screws (4 wood rods), stepper motors (black solid plastic rod), linear actuator and the heating system.

The mock-up was built closely to the final design concepts based on the relative dimensions and size required by the sponsor, Professor Dasgupta. The 'stepper motors' built using black solid plastic rod was adjustable, mimicking the real functions of stepper motors in the real design, i.e. adjusting the tilt and height of the stage.

Moreover the stage was built on top of the linear actuator which was covered with tape at the sides to reduce frictions and to allow horizontal motion of the stage as an effort to simulate the motion of the actual linear actuator.

In conclusion, the mock-up was built very similarly with the final design concepts, illustrating all the features in it. This provided the team a better picture of the functionality of the design and useful insights on the potential problems or issues to consider in the next steps of the project.

A.E.2. Key Insights gained from the mock up.

Through the construction of the mock up, team gained several insights and developed a better understanding on the design.

Firstly, it helped the team to be aware of potential design and manufacturing issues that could rise when the actual prototype were to be built. Some of the features of the design that could be a manufacturing challenge were the groove, the mounts of the sensors and stepper motors. The construction of the mock-up's stage to full scale dimensions helped the team in gaining a better idea on the set screws sizes suitable for t design, the maximum length of the stepper motors' spindle needed and the machining of the stage required to achieve target flatness. Additionally, the building process of the mock-up provided useful hints on possible methods of securing the stage to the linear actuator and the installation the suitable pipe fittings for the vacuum chuck system.

Besides that, by building the simple mock-up, the team was able to better understand the sequence of assembling the components together. This helped in visualizing the interaction between the components when the system was functioning. Thus, it increased the team's awareness on the effects of the different processes, such as heating, displacement sensing and gap alignment adjustment on the deposition of the thin film nano layers.

Appendix F: Written Procedure

1. Wear safety glasses and nitrile gloves during the testing procedure.
2. Clean the surface of the substrate stage with a clean fabric before placing the silicon wafer on top.
3. Connect a suitable sized tube from the pipe fitting of the substrate stage to the vacuum channel provided in the lab.
4. Hold the substrate stage in an upright position.
5. Place the silicon wafer using a specialized forceps.
6. Turn on the vacuum channel.
7. Prepare the force gauge and exert a force onto the wafer on the side.
8. Once the wafer moves away from its initial position, record the force value used.
9. Repeat step 8 for 2 more times.

Appendix G: Manufacturing Plans and Drawings

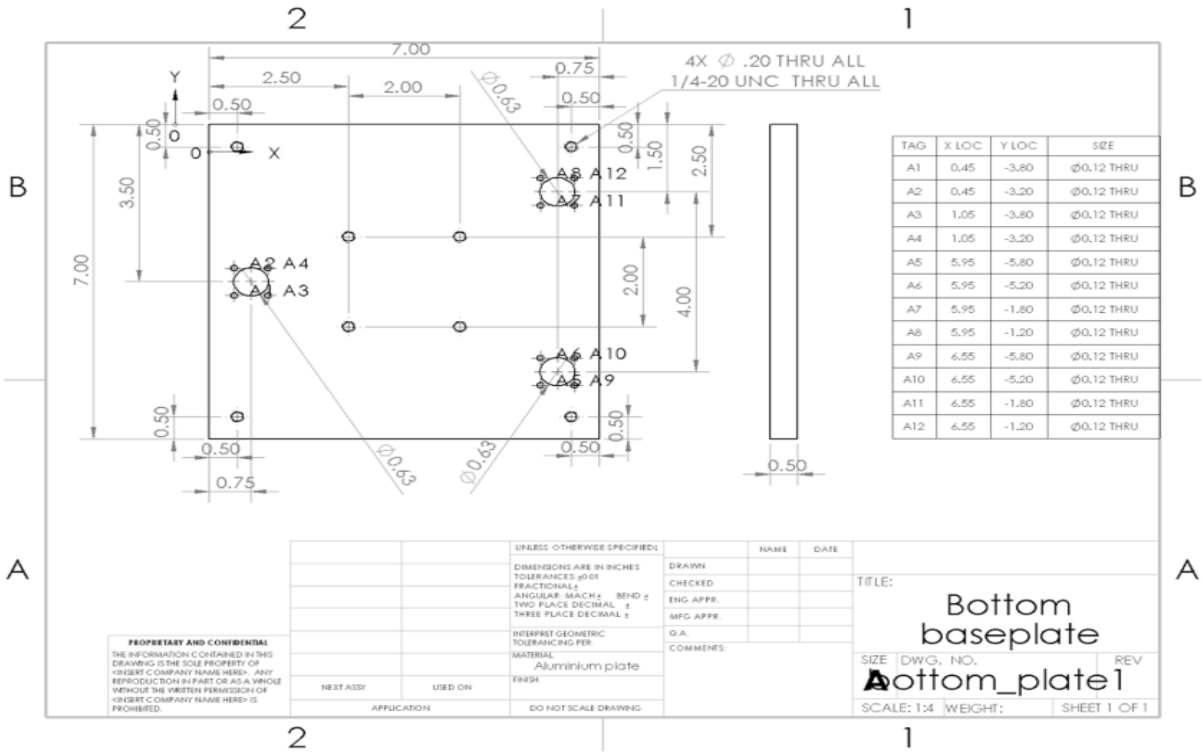
Machining Plan Analysis

Table A.G.1.: Descriptions of the manufacturing methods and its corresponding advantages as well as the disadvantages of the methods.

Manufacturing Methods	Advantage	Disadvantage
Waterjet	Versatile, precise	Messy, Noisy
End Milling	Precise	Time consuming, expertise
Band saw	Quick, non-versatile	Inaccurate
Laser Cutting	Versatile, precise, clean	Expensive
Shearing	Quick	Inaccurate

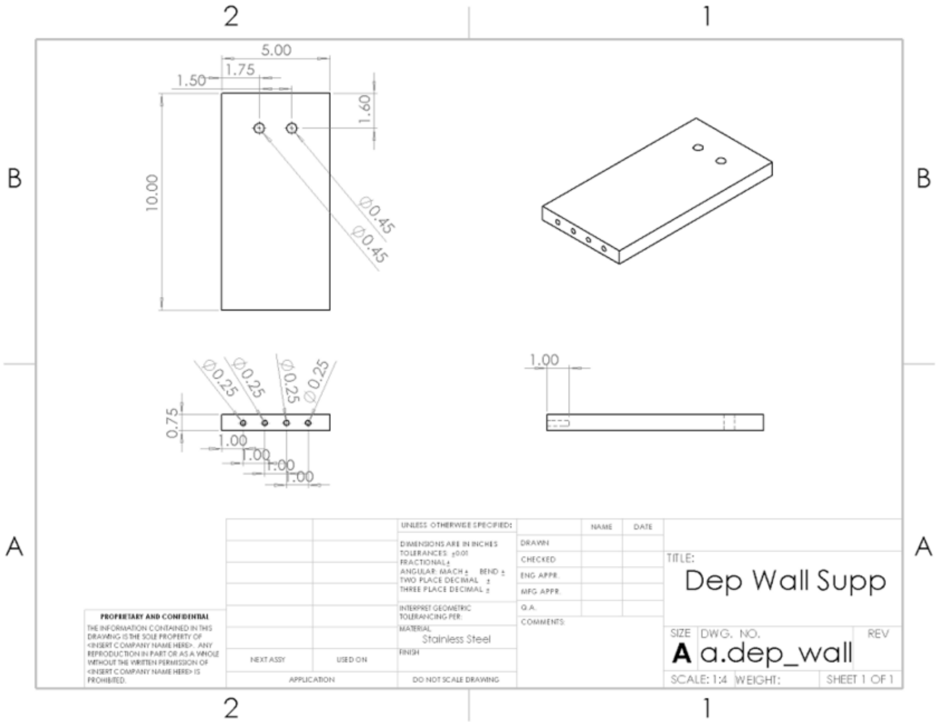
Since flatness is very crucial for the design, the materials for the main components of the prototype were machined to be as flat as possible. The bottom plate and bottom support block were purchased with polished surface. The team decided to use the milling machine provided by the university to drill the holes and end mill the parts to size since it has high precision. The Invar plate was not purchased to be surface polished, therefore the team outsourced the Invar plate to be surface ground at Wolverine Grinding Inc. Surface grinding was able to achieve a flatness of $< 10\mu m$. The rest of the materials were found in the University's Machine shop to fabricate a replica depositor to show in the Design Expo. The team still used the milling machine because high precision is required for the mounting of the sensor on the replica depositor. Below consists the manufacturing plans and drawings for all the machined parts.

Bottom Plate



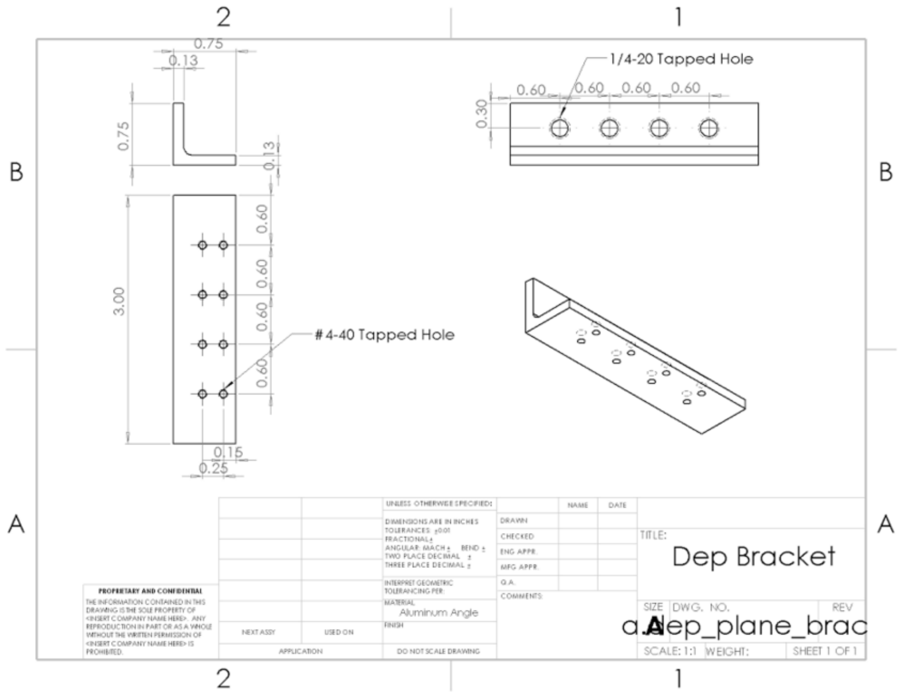
BOTTOM PLATE					
Raw Material Stock: aluminum 12" x 12" x 0.375"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Measure and mark the dimensions needed to cut on material with extra 1/8"		Square	Sharpie and scribe	
2	Cut the material according to markings	Horizontal bandsaw		File	
3	Hold part vertically in vise and face mill the top edge	Mill	vise	collet, 2" endmill	1000
4	Turn the plate 180 degrees and face mill the other side	Mill	vise	collet, 2" endmill	1000
5	Place the part flat on parallels and face the two other edges	Mill	vise, parallels	collet, 2" endmill	1000
6	Use edgefinder to locate the lengthwise edge of the plate	Mill	vise	drill chuck, edgefinder, collet, parallels	900
7	Remove edgefinder. Install drill chuck and center drill	Mill	vise	drill chuck, center drill	
8	Center drill the holes and drill eight 1/4"-20 holes using size 7	Mill	vise	Size 7 drill bit	1600
9	Center drill the holes and drill twelve size 31 holes	Mill	vise	Size 31 drill bit	1200
10	Center drill the holes and drill three 41/64" holes	Mill	vise	41/64 drill bit	350
11	Remove part from vise. Break all edges by hand.			File	
12	Tap drill the holes to 1/4" - 20 screw size			1/4" 20 tap drill	

Support Wall



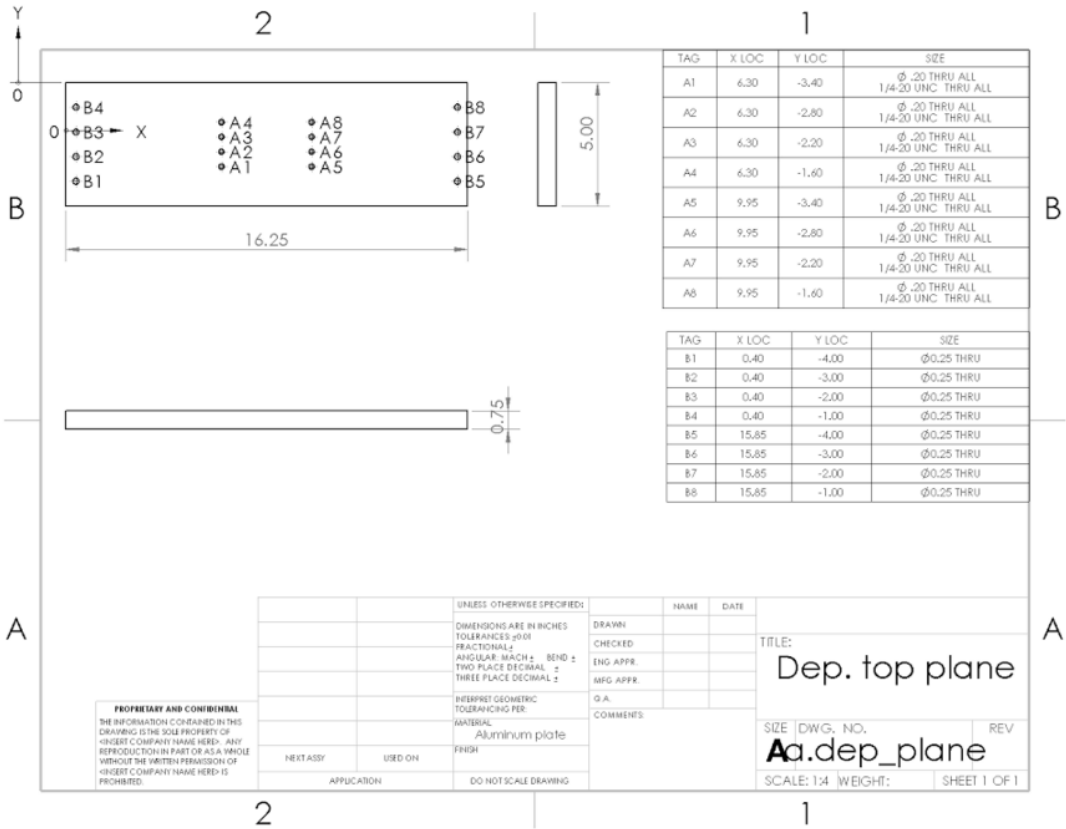
DEPOSITOR WALL					
Raw Material Stock: Stainless Steel plate 5" x 24" x 0.75"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Measure and mark the dimensions needed to cut on material with extra 1/8"		Square	Sharpie and scribe	75-100 FPM
2	Cut the material according to markings	Horizontal bandsaw		File	
3	Hold part vertically in vise and face mill the top edge	Mill	vise	collet, 1" endmill	320 RPM
4	Turn the plate 180 degrees and face mill the other side	Mill	vise	collet, 1" endmill	320 RPM
5	Place the part flat on parallels and face the two other edges	Mill	vise, parallels	collet, 1" endmill	320 RPM
6	Use edgefinder to locate the datum on the X and Y axis	Mill	vise, parallels	drill chuck, edgefinder	1000 RPM
7	Center drill the holes and drill 2 through holes using 29/64" drill bits	Mill	vise, parallels	29/64" drill bit	400 or less
8	Place the part on its shorter edge with the holes on the vise				
9	Use edgefinder to locate the datum on the X and Y axis	Mill	vise, parallels	drill chuck, edgefinder	1000 RPM
10	Center drill the holes and drill four 1/4" blind holes using 1/4" drill bits	Mill	vise, parallels	1/4" drill bit	750 or less
11	Remove part from vise. Break all edges by hand.			File	

Depositor Bracket



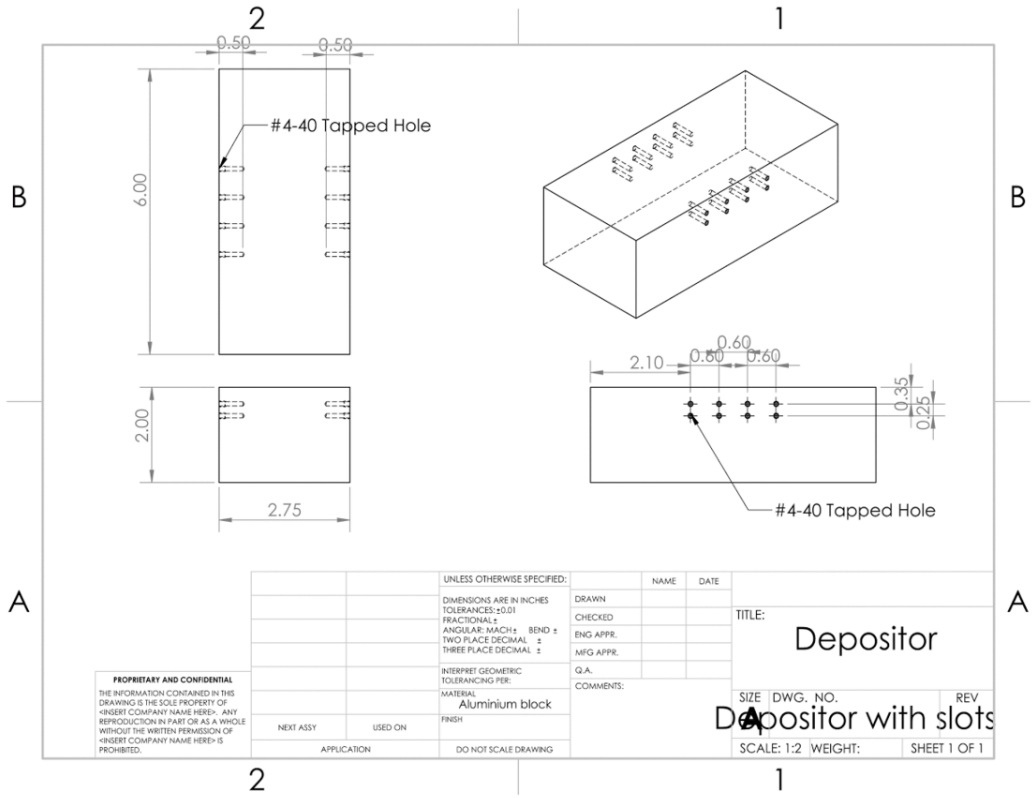
DEPOSITOR BRACKET					
Raw Material Stock: Stainless Steel plate 5" x 24" x 0.75"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Measure and mark the dimensions needed to cut on material with extra 1/8"		Square	Sharpie and scribe	75-100 FPM
2	Cut the material according to markings	Horizontal bandsaw		File	
3	Hold part vertically in vise and face mill the top edge	Mill	vise	collet, 1" endmill	320 RPM
4	Turn the plate 180 degrees and face mill the other side	Mill	vise	collet, 1" endmill	320 RPM
5	Place the part flat on parallels and face the two other edges	Mill	vise, parallels	collet, 1" endmill	320 RPM
6	Use edgefinder to locate the datum on the X and Y axis	Mill	vise, parallels	drill chuck, edgefinder	1000 RPM
7	Center drill the holes and drill 2 through holes using 29/64" drill bits	Mill	vise, parallels	29/64" drill bit	400 or less
8	Place the part on its shorter edge with the holes on the vise				
9	Use edgefinder to locate the datum on the X and Y axis	Mill	vise, parallels	drill chuck, edgefinder	1000 RPM
10	Center drill the holes and drill four 1/4" blind holes using 1/4" drill bits	Mill	vise, parallels	1/4" drill bit	750 or less
11	Remove part from vise. Break all edges by hand.			File	

Depositor Top Plate



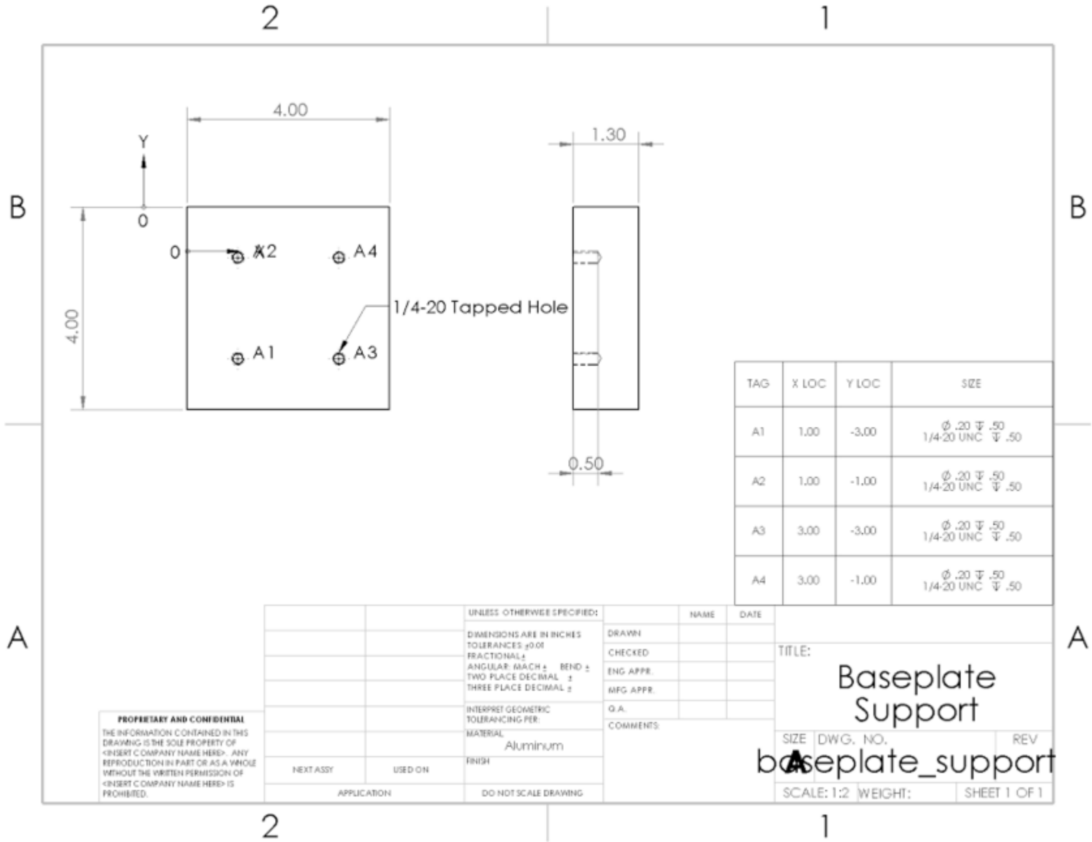
DEPOSITOR TOP SUPPORT					
Raw Material Stock: Stainless Steel plate 5" x 24" x 0.75"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Measure and mark the dimensions needed to cut on material with extra 1/8"		Square	Sharpie and scribe	75-100 fps
2	Cut the material according to markings	Horizontal bandsaw		File	
3	Hold part vertically in vise and face mill the top edge	Mill	vise	collet, 1" endmill	320 RPM
4	Turn the plate 180 degrees and face mill the other side	Mill	vise	collet, 1" endmill	320 RPM
5	Place the part flat on parallels and face the two other edges	Mill	vise, parallels	collet, 1" endmill	320 RPM
6	Use edgefinder to locate the datum on the X and Y axis	Mill	vise, parallels	drill chuck, edgefinder	1000 RPM
7	Remove edgefinder. Install drill chuck and center drill	Mill	vise, parallels	drill chuck, center drill	
8	Center drill the holes and drill 8 1/4"-20 holes using size 7 drill bit	Mill	vise	Size 7 drill bit	less than 750
9	Center drill the holes and drill eight 0.25" thru holes using 1/4" drill bit	Mill	vise	drill chuck, center drill, 1/4" drill bit	less than 750
10	Remove part from vise. Break all edges by hand.			File	
11	Tap drill the holes to 1/4" - 20 screw size			1/4" 20 tap drill	

Depositor



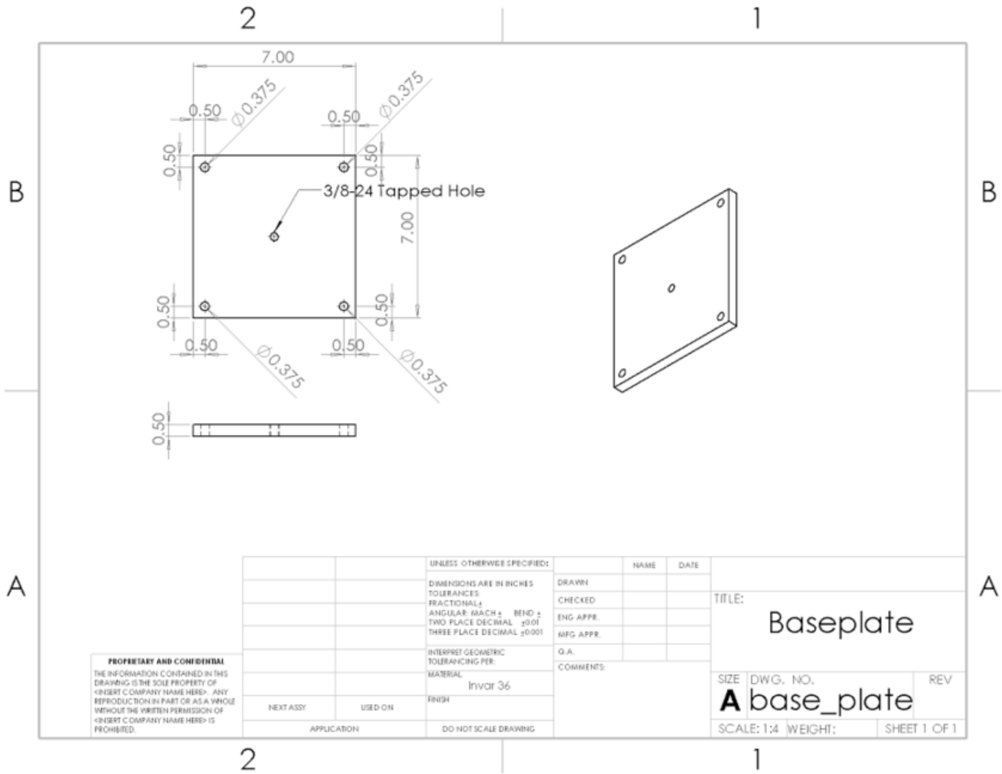
DEPOSITOR					
Raw Material Stock: aluminum Block 3" x 3" x 12"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Measure and mark the dimensions needed to cut on material with extra 1/8"		Square	Sharpie and scribe	
2	Cut the material according to markings	Horizontal bandsaw		File	200 FPM
3	Hold part vertically in vise and face mill the top edge	Mill	vise	collet, 1" endmill	400 or less
4	Turn the plate 180 degrees and face mill the other side	Mill	vise	collet, 1" endmill	400 or less
5	Place the part flat on parallels and face the two other edges	Mill	vise, parallels	collet, 1" endmill	400 or less
6	Use edgefinder to locate the lengthwise edge of the plate	Mill	vise	drill chuck, edgefinder, parallels	1000
7	Remove edgefinder. Install drill chuck and center drill	Mill	vise	drill chuck, center drill	
8	Drill blind holes with depth of 1/2" using size 43 drill bits	Mill	vise	Size 43 drill bit, drill chuck	
9	Flip the part to its opposite side	Mill	vise		
10	Use edgefinder to locate the lengthwise edge of the plate	Mill	vise	drill chuck, edgefinder, parallels	1000
11	Remove edgefinder. Install drill chuck and center drill	Mill	vise	drill chuck, center drill	
12	Drill blind holes with depth of 1/2" using size 43 drill bits	Mill	vise		
13	Remove part from vise. Break all edges by hand.			File	
14	Tap the size 43 holes to #4-40 screw size			#4 - 40 tap drill	

Bottom plate Support



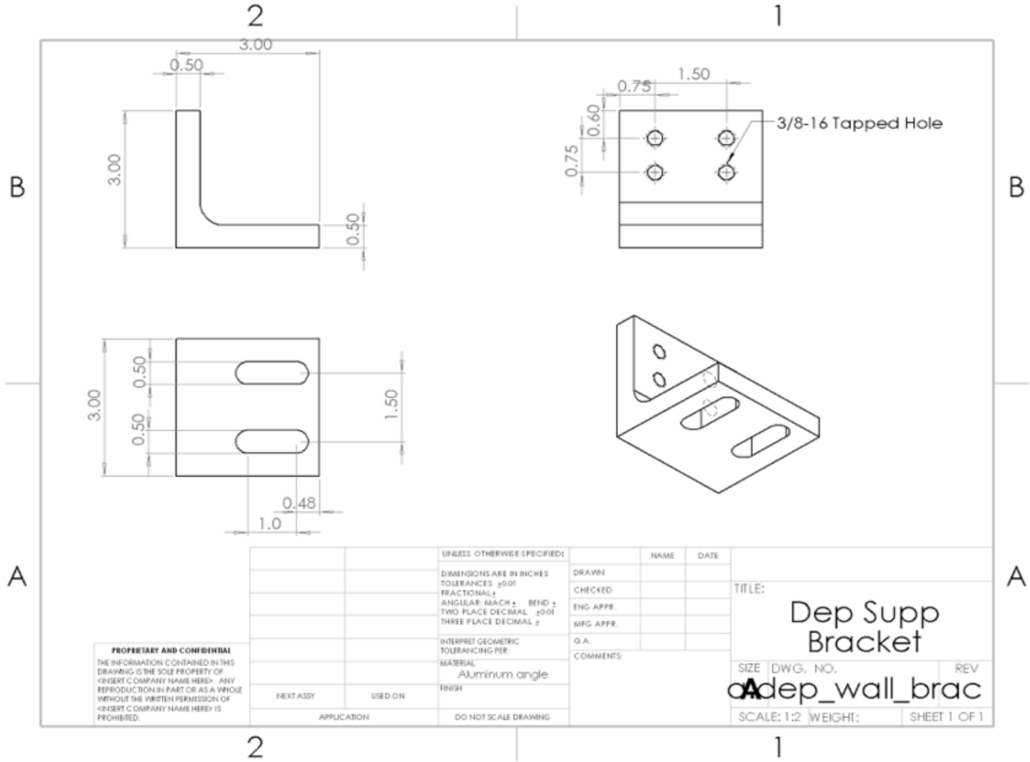
BASEPLATE SUPPORT					
Raw Material Stock: aluminum plate 3" x 3" x 12"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Measure and mark the dimensions needed to cut on material with extra 1/8"		Square	Sharpie and scribe	200 FPM
2	Cut the material according to markings	Horizontal bandsaw		File	
3	Hold part vertically in vise and face mill the top edge	Mill	vise	collet, 1" endmill	400 or less
4	Turn the plate 180 degrees and face mill the other side	Mill	vise	collet, 1" endmill	400 or less
5	Place the part flat on parallels and face the two other edges	Mill	vise, parallels	collet, 1" endmill	400 or less
6	Use edgefinder to locate the datum on the X and Y axis	Mill	vise, parallels	drill chuck, edgefinder	1000 RPM
7	Remove edgefinder. Install drill chuck and center drill	Mill	vise, parallels	drill chuck, center drill	
8	Center drill the holes and drill four 1/4"-20 blind holes with depth of 1/2" using size 7 drill bit	Mill	vise	Size 7 drill bit	1200
10	Remove part from vise. Break all edges by hand.			File	
11	Tap drill the holes to 1/4" - 20 screw size			1/4" 20 tap drill	

Base Plate/Heated Plate



BASE PLATE					
Raw Material Stock: aluminum plate 12" x 12" x 0.375"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Measure and mark the dimensions needed to cut on material with extra 1/8"		Square	Sharpie and scribe	
2	Cut the material according to markings	Horizontal bandsaw		File	200 FPM
3	Hold part vertically in vise and face mill the top edge	Mill	vise	collet, 0.75" endmill	500
4	Turn the plate 180 degrees and face mill the other side	Mill	vise	collet, 0.75" endmill	500
5	Place the part flat on parallels and face the two other edges	Mill	vise, parallels	collet, 0.75" endmill	500
6	Use edgefinder to locate the lengthwise edge of the plate	Mill	vise	drill chuck, edgefinder, collet, parallels	1000
7	Move edgefinder down 0.1". Edgefinder should have datum line for Y.	Mill	vise	edgefinder, collet, parallels	1000
8	Use edgefinder to locate the lengthwise edge of the plate	Mill	vise	edgefinder, collet, parallels	1000
9	Remove edgefinder. Install drill chuck and center drill	Mill	vise	drill chuck, center drill	
10	Center drill and drill the four holes near the edge of the plate using size 11/32 drill bit	Mill	vise	drill chuck, center drill, 11/32" drill bit	1600
11	Locate the center point, center drill and drill the center holes using Q drill bit	Mill	vise	drill chuck, center drill, Q drill bit	
12	Remove part from vise. Break all edges by hand.			File, deburring tool	

Depositor Supporting Bracket



SLOT BRACKET					
Raw Material Stock: Equal right angle bar 0.75" x 0.75" x 12"					
Step #	**Process Description**	**Machine**	**Fixtures**	**Tool(s)**	**Speed (RPM)**
1	Measure and mark the dimensions needed to cut on material with extra 1/8"		Square	Sharpie and scribe	
2	Cut the material according to markings	Vertical bandsaw		File	200 FPM
3	Place the part with the side getting drilled on the top and face the two size edges to desired dimensions	Mill	vise, parallels	collet, 1" endmill	400 or less
4	Use edgefinder to locate the datum on the X and Y axis for one face of the angled bar	Mill	vise, parallels	drill chuck, edgefinder	1000
5	Remove edgefinder. Install drill chuck and center drill	Mill	vise, parallels	drill chuck, center drill	
6	Center drill the holes and drill four through holes using 5/16" drill bits	Mill	vise, parallels	5/16" drill bit	900
7	Flip the part on its other face		vise, parallels		
8	Use edgefinder to locate the datum on the X and Y axis for the other face of the angled bar		vise, parallels	drill chuck, edgefinder	1000
9	Use 1/2" diameter end mill to drill a thru hole and move an 1.0" to create a slot	Mill	vise, parallels	1/2" end mill	800 or less
10	Remove part from vise. Break all edges by hand.			File	
11	Tap drill the 5/16" holes to 3/8-16 screw size			3/8-16 tap drill	

Appendix H: Bill of Materials

	No.	Part Description	Part Number	Supplier	Cost per part (USD)	Quantity	Price (USD)
Stepper Motors	1	Hybrid captive stepper motor	E21K4U-2.33-900	Ametek	$105.67	3	$317.01
	2	EasyDriver - Stepper Motor Driver	A3967 Microstepping Drive	Sparkfun	$14.95	3	$44.85
	3	Arduino Uno Microcontroller	ARDUINO UNO REV3	Arduino	$32.15	1	$32.15
	4	AC to DC Power Supply Dual Output 5 Volt 12 Volt 15 Amp 10 Amp 130.9w	RD-125A	MEAN WELL	$32.95	1	$32.95
Sensors	5	Button Probe; 205oC temperature rating	HPB-75A-E-L3-5-B-D	Capacitec	$460.00	2	$920.00
	6	4004-P115-OBNC Equipment Rack	40041070	Capacitec	$488.25	1	$488.25
	7	4100-C Clock Driver Card	4100C277	Capacitec	$140.00	1	$140.00
	8	Amplifier Card, 232Hz-3dB frequency response, +/-2.0% f.s. linearity (better than 0.1% with Bargrafx®)	4100-S-BNC	Capacitec	$393.75	1	$393.75
	9	A/D & USB digital Interface (LabView Compatible); 48ks/S	4100-DAQ	Capacitec	$525.00	1	$525.00
	10	Blank Filler Plate	4100-B	Capacitec	$8.75	1	$8.75
	11	Capacitec Bargrafx® Standard Software	2 low-pass filters	Capacitec	$0.00	1	$0.00
Motorized Linear	12	Pro165 linear motor stage set with absolute encoders and 200 mm travel	PRO165LM-200-PRO165LM	Aerotech	$4,322.50	2	$8,645.00
	13	Ensemble MP Series multi-axis PWM digital controller, 10A peak, 5A continuous, 10-80VDC input, with Ethernet interface.	ENSEMBLEMP10	Aerotech	$0.00	2	$0.00
	14	Software Document, configure, and test components as a system.	INTEGRATION - TEST AS !	Aerotech	$0.00	2	$0.00
	15	Feedback cable, 5.0 meters long	C18391-50	Aerotech	$0.00	2	$0.00
	16	Motor power cable, 5.0 meters long	C19360-50	Aerotech	$0.00	2	$0.00
	17	4.5m (14.7 ft) Ethernet cross over cable	ENET-XOVER-45	Aerotech	$0.00	2	$0.00
Materials	18	Invar 36 plate, 8" x 8" x 0.5"	N/A	Ed Fagan Inc.	$400	1	$400
	19	Aluminum plate, 7" x 7" x 0.5"	9057K37	McMasterr	$100.89	1	$100.89
	20	Aluminum plate, 4" x 4" x 1.3"	9057K448	McMasterr	$123.79	1	$123.79
Vacuum Chuck	21	1/8" NPT M x 1/4" Tube Connector	SS-CT12AS12AS12-48	Swagelock	$6.90	2	$13.80
	22	Teflon tape	n/a	Dasgupta Lab	$0	2	$0
	23	PTFE tube, 1/4" diameter	n/a	Dasgupta Lab	$0	1	$0
Position Locking	24	PTFE O-rings 3.520" OD, 3.100" ID, 0.210" Width (2 ea.)	9559K282	McMasterr	$9.87	3	$29.61
	25	Type 316 Stainless Steel Cap Screws, 1/4"-20, length: 4.5"—Head: Wd. 7/16", Ht. 5/32" (5 ea.)	93190A562	McMasterr	$2.54	4	$10.16
	26	SS 1/4"-20 Nuts	n/a	X50 Assembly Room	$0	8	$0
	27	SS 0.3" Washer	n/a	X50 Assembly Room	$0	8	$0
	28	Steatite Ceramic Shoulder Bushings	AS-1039	LSP Ceramics	$0	4	$0
	29	M3 x 0.5 Cap Nuts, SS 316 for stepper motor spindle tips, (25 ea.)	95514A101	McMasterr	$7.12	1	$7.12
	30	M2 x 0.4 Screws for stepper motor mounting, 316 SS, (50 ea.)	91290A047	X50 Assembly Room	$9.56	1	$9.56
	31	Black Insulator for 2-7/16" Length, Alligator Clip	7236K182	McMasterr	$0.70	2	$1.40
	32	Metric 316 Stainless Steel Pan Head Phillips Machine Screw, M2 Size, 20MM Length, .4MM Pitch, Packs of 100	90116A027	McMasterr	$12.00	1	$12.00
	33	Metric 316 Stainless Steel Pan Head Phillips Machine Screw, M4 Size, 40MM Length, .7MM Pitch, Packs of 50	90116A233	McMasterr	$12.40	1	$12.40
	34	Alligator Clip, Heavy Duty with Crimp Connection, 2-7/16" L, Copper	7236K61	McMasterr	$1.64	2	$3.28
	35	Aluminum Female Threaded Round Standoff, 1/4" OD, 1/2" Length, 10-32 Screw Size	93330A468	McMasterr	$0.38	10	$3.80
	36	18-8 Stainless Steel Pan Head Phillips Machine Screw, 10-32 Thread, 4-1/2" Length, Packs of 10	91772A854	McMasterr	$5.36	1	$5.36
	37	Type 18-8 Stainless Steel Hex Nut, 10-32 Thread Size, 3/8" Wide, 1/8" High, Packs of 100	91841A195	McMasterr	$3.98	1	$3.98
	38	Ultra-Compressible O-Ring, High-Temperature Silicone, Dash Number 202, Packs of 25	1173N202	McMasterr	$7.03	1	$7.03
Heating System	39	Polyimide heater 7" x 7"	n/a	Watlow Electric	$0	1	$0
	40	Thermocouple	n/a	Watlow Electric	$0	3	$0
	41	Control Box	n/a	Watlow Electric	$0	1	$0
	42	Cables and Wires	n/a	Watlow Electric	$0	1	$0
	43	Insulative Adhesive (for heater and cap sensors)	n/a	Watlow Electric	$0	1	$0
						Total	$12,291.89

Appendix I: Validation Protocol

This section provides further descriptions of the empirical tests to validate the engineering specifications once all the components, including depositor (manufactured to tight tolerances), heater, and thermocouples, are installed into the current prototype.

A.I.1 Parallel Alignment

Engineering Specifications: The gap difference along the stage needs to be less than 10 microns

Components needed to test: Heated motorized stage with the linear stage, depositor and capacitive sensors casing (if capacitive sensors are used)

Equipment: Slip gauge or two capacitive sensors with <10 microns resolution

Procedure:

1. Misalign the heated stage and perform tilt adjustments based on the feedback from capacitive sensors.
2. After the tilt adjustments, secure the heated stage using nuts.
3. Use the capacitive sensors or slip gauge to measure the gap distance between the depositors and the heated stage along the x-axis. (take at least 10 points)
4. Record the measurements and calculate the difference of the gap measurements.
5. After 30 minutes, measure the gap distance again.
6. Record the measurements and calculate the gap difference.
7. It is recommended to repeat step 5 and 6 for at least 3 times to ensure the consistent parallel alignments of the stage over a long period of time.
8. Repeat Steps 1 to 8 for two times.

Note: The process described above involves the use of capacitive sensors to measure the gap distance. In the case which slip gauge is used, the same procedures applied except the user do not need to calculate the gap differences (in Step 4 and 6). Slip gauge is used to verify if two objects is separated by a certain distance and do not provide the misalignment information.

Result / Data Analysis:

1. If the gap difference is less than 10 microns for all 5 sets of measurements, it is safe to say that the stage is in consistent parallel alignment.
2. If the gap difference after a specific time exceeds the 10 microns requirements, the stage is said to maintain parallel alignment for only a certain time period. The stage is hence recommended to recalibrate after that period of time using the closed loop feedback tilt adjustment.
3. If the gap difference is more than 10 microns at the first set of measurements, the stage is failed to achieve this engineering specification. Modifications of the design is required.

A.I.2. Surface Flatness

Engineering Specifications: Tolerance of surface machining of 1 micron.

Components: Heated Plate (Invar 36)

Equipment: Micrometer with an accuracy of 0.0001" and a resolution of 0.0001" or 0.00005".

Procedure:

1. Use the micrometer to measure the thickness of the plate at 8 different points around the plate.
2. Record the values of the measured thickness.
3. Calculate the Mean value of the measurements.
4. Calculate the variance and standard deviation of the measurements using the mean value obtained above
5. If standard deviation is less or equal to 0.0001", the flatness is within the required tolerance.

Data Analysis Method:

1. If the surface machining tolerance is less than or equal to 1 microns, it is safe to say that the heated plate reach the engineering specification.
2. If the surface machining tolerance is more than 1 microns, further surface grinding and polishing will be done.

Result:

1. The surface machining tolerance is 2.5 microns; therefore, further surface grinding will be done and chemical polishing will be used to minimize surface roughness.

A.I.3. Gap size control

Engineering Specifications: Gap size between 20 to 50 microns

Components needed to test: Heated motorized stage with the linear stage, depositor and capacitive sensors casing (if capacitive sensors are used)

Equipment: Slip gauge or two capacitive sensors with <10 microns resolution

Procedure:

1. Set up the heated stage and mount the capacitive sensors onto the designated casing.
2. Move the heated stage to 100 microns distance from the depositors.
3. Use the capacitive sensors to measure the gap distance between the depositors and the heated stage.
4. Take at least 10 measurements and record the measurements.
5. Repeat Step 2 - 4 for 20, 30, 40, 50, and 75 microns distance.

Note: The process described above involves the use of capacitive sensors to measure the gap distance. In the case which slip gauge is used, the same procedures applied. Slip gauge is used to verify if two objects is separated by a certain distance and do not provide the misalignment information.

Result / Data Analysis:

1. If the stage is able to reach gap size control between 20 to 50 microns, the engineering requirement is achieved.
2. If not, determine the range of the gap size control for the stage using the current feedback control system. Improve the design by using a more refined control system or a higher resolution stepper motors to perform the tilt and height adjustment.

A.I.4. Uniform Heating

Engineering Specifications: Temperature gradient less than 0.5 K/cm

Components needed to test: Heated motorized stage with the linear stage and heating filaments

Equipment: Thermometers or thermocouples

Procedure:

1. Set up the stage and attach the heating filaments onto the heated plate.
2. Heat the heated plate until 200 °C.
3. Use thermometers or thermocouples to measure the temperature at least 10 different points along the stage.
4. Record all the measurements and calculate the temperature gradient along the heated plate.

Result / Data Analysis:

1. If the temperature gradient along the heated plate is less than 0.5K/cm, it is safe to say that the plate is being heated uniformly.
2. If the temperature gradient exceeds the 0.5K/cm requirements, it is recommended to improve the design by using a better heating system.

A.I.5. Optimum Deposition Rate

Engineering Specifications: Deposition rate should be 0.1 nm/s

Components needed to test: linear stage and depositor

Equipment: X-ray Reflectivity (XRR) station and ALD thin film sample

Procedure:

1. Place a silicon wafer at the center of the heated plate.
2. Turn on the Polyimide heater and heat the stage up to a controlled temperature of 150 ℃.
3. Perform parallel alignment of the heated plate and move the heated plate up to the desired gap size.
4. Enable the mass flow controllers and set the desired mass flow rates of TMA (Trimethylaluminium), nitrogen and water.
5. Enable the horizontal linear stage
6. Record the duration of the atomic layer deposition.
7. After the deposition is finished, measure the thickness of the deposited aluminum oxide by running X-ray reflectivity (XRR) on the thin film sample.
8. Calculate the deposition rate by dividing the measured thickness value by the duration of deposition process.
9. Compare the calculated deposition rate with the goal deposition rate specified by the sponsor.

Result / Data Analysis:

1. If the deposition rate is greater than 0.1 nm/s, then the linear stage speed is satisfactory.
2. If the deposition rate is less than 0.1 nm/s, then the linear stage speed has to be increased.

A.I.6. Secure substrate

Engineering Specifications: Substrates secured during operating conditions

Components needed to test: Silicon wafer, vacuum fitting

Equipment: Force gauge

Procedure:
1. Wear safety glasses and nitrile gloves during the testing procedure.
2. Clean the surface of the substrate stage with a clean fabric before placing the silicon wafer on top.
3. Connect a suitable sized tube from the pipe fitting of the substrate stage to the vacuum channel provided in the lab.
4. Hold the substrate stage in an upright position.
5. Place the silicon wafer using a specialized forceps.
6. Turn on the vacuum channel.
7. Prepare the force gauge and exert a force onto the wafer on the side.
8. Once the wafer moves away from its initial position, record the force value used.
9. Repeat step 8 for 2 more times.
10. Calculate the average force value needed to shift the wafer.

Result / Data Analysis:
1. If the amount of force needed to move the wafer is greater than the inertial force of the wafer, it is safe to say that the wafer would not move during horizontal motion.
2. If the wafer shifts, it is recommended to use a vacuum pump with higher pressure value.

Appendix J: Matlab Code

```
%%%% serial communication between Matlab and Arduino UNO
% define computer port
comport = 'COM4';
baudrate = 9600;
arduino = serial(comport, 'BaudRate', baudrate);
fopen(arduino);

% user input to move stage up to sensors detectable range
servalue= input('move the heated stage up to 200 micron range:');
% clear old sensors data
delete('reading.txt');
% delay time to allow new sensors data to be saved
pause(2);

% read new sensors data
[date, time, sensorA, sensorB, t, t, t, t, t, t, t, t, t, t, t, t, t, t] = textread('reading.txt','%s %s %f %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f', 1);
ABdiff = sensorA - sensorB % can be pos or neg
abs_ABdiff = abs(ABdiff) % magnitude of height

% runs loop until both sensors are within 200 microns from heated stage
while (sensorA > 200 || sensorB > 200)
   delete('reading.txt');
   pause(1);
   if (sensorA > 200)
      a = 1;   % steppor motor 1 moves up a step
      fprintf(arduino,a);
   end
   if (sensorB > 200)
      a = 3;   % steppor motor 2 moves up a step
      fprintf(arduino,a);
   end

% read new sensors data again to evaluate loop condition
  [date, time, sensorA, sensorB, t, t, t, t, t, t, t, t, t, t, t, t, t, t] = textread('reading.txt','%s %s %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f %f', 1);
end
```

```
% user input to begin first roll control at home position
servalue= input('first roll control, move the stage to home position:');
% define maximum height difference at two points on heated stage
goalvalue = 3; % 3 microns

% runs loop until goal value is achieved
while (abs_ABdiff > goalvalue)
   if (ABdiff > 0)
      a = 4;   % steppor motor 2 moves down a step
      fprintf(arduino,a);
   elseif (ABdiff < 0)
      a = 2;   % steppor motor 1 moves down a step
      fprintf(arduino,a);
   end

   % clear old sensors data
   delete('reading.txt');
   pause(1);

   %read new sensors data
   [date, time, sensorA, sensorB, t, t, t, t, t, t, t, t, t, t, t, t, t, t] = textread('reading.txt','%s %s %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f', 1);

   % evaluate sensors data for loop condition
   ABdiff = sensorA - sensorB
   abs_ABdiff = abs(ABdiff)
end

delete('reading.txt');

% user input to begin second roll control
servalue= input('second roll control:');
delete('reading.txt');
pause(5);
[date, time, sensorA, sensorB, t, t, t, t, t, t, t, t, t, t, t, t, t, t] = textread('reading.txt','%s %s %f %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f', 1);
ABdiff = sensorA - sensorB
abs_ABdiff = abs(ABdiff)
goalvalue = 3; % 3 microns
```

```
while (abs_ABdiff > goalvalue)
   if (ABdiff > 0)
      a = 4;   % steppor motor 2 moves down a step
      fprintf(arduino,a);
   elseif (ABdiff < 0)
      a = 2;   % steppor motor 1 moves down a step
      fprintf(arduino,a);
   end
   delete('reading.txt');
   pause(1);
   [date, time, sensorA, sensorB, t, t, t, t, t, t, t, t, t, t, t, t, t, t, t] = textread('reading.txt','%s %s %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f %f', 1);
   ABdiff = sensorA - sensorB
   abs_ABdiff = abs(ABdiff)
end
delete('reading.txt');
```

% user input to begin third roll control, at home position again

```
servalue= input('third roll control, move the stage to home position:');
delete('reading.txt');
pause(5);
[date, time, sensorA, sensorB, t, t, t, t, t, t, t, t, t, t, t, t, t, t, t] = textread('reading.txt','%s %s %f %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f', 1);
ABdiff = sensorA - sensorB
abs_ABdiff = abs(ABdiff)
goalvalue = 3; % 3 microns

while (abs_ABdiff > goalvalue)
   if (ABdiff > 0)
      a = 4;   % steppor motor 2 moves down a step
      fprintf(arduino,a);
   elseif (ABdiff < 0)
      a = 2;   % steppor motor 1 moves down a step
      fprintf(arduino,a);
   end
   delete('reading.txt');
   pause(1);
   [date, time, sensorA, sensorB, t, t, t, t, t, t, t, t, t, t, t, t, t, t, t] = textread('reading.txt','%s %s %f %f %f
%f %f %f %f %f %f %f %f %f %f %f %f %f %f', 1);
   ABdiff = sensorA - sensorB
```

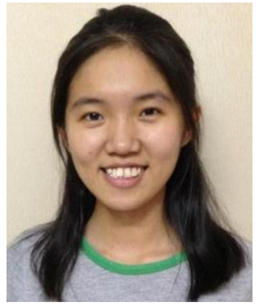
```
    abs_ABdiff = abs(ABdiff)
end
```

Appendix K: Arduino Code

```
int command;
int dir;
int count;
int microsteps = 1; //The steps/rev used in the stepper motors
int dirpin1 = 9;
int steppin1 = 8;
int dirpin2 = 11;
int steppin2 = 10;
int dirpin3 = 13;
int steppin3 = 12;
void setup() {
  Serial.begin(9600);
  pinMode(steppin1, OUTPUT);
  pinMode(dirpin1, OUTPUT);
  pinMode(steppin2, OUTPUT);
  pinMode(dirpin2, OUTPUT);
  pinMode(steppin3, OUTPUT);
  pinMode(dirpin3, OUTPUT);
  pinMode(13,OUTPUT);
  digitalWrite(13, LOW);
  digitalWrite(steppin1, LOW);
  digitalWrite(dirpin1, LOW); //LOW = Going Up; High = Going Down
  digitalWrite(steppin2, LOW);
  digitalWrite(dirpin2, LOW);
  digitalWrite(steppin3, LOW);
  digitalWrite(dirpin3, LOW); }
void loop() {
  if  (Serial.available()>0) {
    command = Serial.read();
    if (command == 1) {
      digitalWrite(dirpin1, LOW);
      delay(2);
      for (count = 0; count < microsteps; count++) {
        digitalWrite(steppin1, HIGH);
        delay(1);
        digitalWrite(steppin1, LOW);
        delay(1); }
       count = 0; }
    else if (command == 2) {
      digitalWrite(dirpin1, HIGH);
      delay(2);
      for (count = 0; count < microsteps; count++) {
        digitalWrite(steppin1, HIGH);
        delay(1);
        digitalWrite(steppin1, LOW);
```

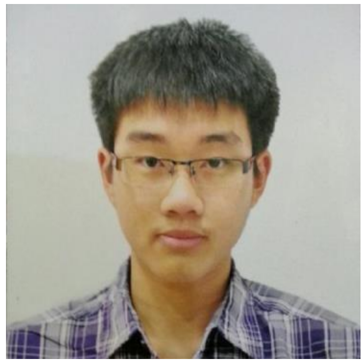
```
    delay(1); }
   count = 0;}
else if (command == 3) {
  digitalWrite(dirpin2, LOW);
  delay(2);
  for (count = 0; count < microsteps; count++) {
    digitalWrite(steppin2, HIGH);
    delay(1);
    digitalWrite(steppin2, LOW);
    delay(1); }
   count = 0; }
else if (command == 4) {
  digitalWrite(dirpin2, HIGH);
  delay(2);
  for (count = 0; count < microsteps; count++) {
    digitalWrite(steppin2, HIGH);
    delay(1);
    digitalWrite(steppin2, LOW);
    delay(1); }
   count = 0; }
else if (command == 5) {
  digitalWrite(dirpin3, LOW);
  delay(2);
  for (count = 0; count < microsteps; count++) {
    digitalWrite(steppin3, HIGH);
    delay(1);
    digitalWrite(steppin3, LOW);
    delay(1); }
   count = 0; }
else if (command == 6) {
  digitalWrite(dirpin3, HIGH);
  delay(2);
  for (count = 0; count < microsteps; count++) {
    digitalWrite(steppin3, HIGH);
    delay(1);
    digitalWrite(steppin3, LOW);
    delay(1); }
   count = 0;} } }
```

Appendix L: Authors



Leng Ying Khoo is a senior studying Mechanical Engineering with a minor in Astronomy and Astrophysics in the University of Michigan. To date, Leng Ying's primary areas of interest range from flight software to Auto-Cad simulation. In Summer 2015, she has participated in Summer Undergraduate Research Program(SURE) under the supervision of Professor Mark Moldwin from Department of Climate and Space Sciences and Engineering. Her research project is mainly focus on the development of indoor localization technology using extremely low frequency waves. Additionally, she also involve in Great Lakes Multidisciplinary Design Team with Professor Derek Posselt and Allison Steiner. She, as a part of Data Visualization team, is responsible of developing 3D models for Great Lakes atmosphere and exploring the possibility of 3D data visualization. Previously, she participated in Texas Annual International Cansat Competition 2014 as a flight software team member and joined University of Malaya research team in Malaysia to develop a low-cost inertial measurement unit (IMU). Lastly, Leng Ying will complete her Bachelor's degree in May 2016 and will like to pursue a Master's or doctoral degree in Space Engineering/Physics. Her role in the team is portfolio manager.

Hyunwoo Park is a senior studying Mechanical Engineering in the University of Michigan. He was born and raised in Seoul, South Korea, and spent his youth in Fishkill, New York. Hyunwoo Park's areas of academic interest are atomic layer deposition (ALD) and vapor-liquid-solid (VLS) silicon nanowire growth as means to advanced energy solutions. He became a research member of Dasgupta Research Group in Winter 2015. Participating in Research, Innovation, Service and Entrepreneurship Program, Hyunwoo designed and built a vapor-liquid-solid station for silicon nanowire fabrication, and studied the growth characteristics of silicon nanowires with Au as catalyst. Additionally, in Summer 2015, he participated in University of Michigan Energy Institute Fellowship Program under the supervision of Professor N. Dasgupta from Department of Mechanical Engineering. His research project includes finite element analysis and computational fluid dynamic modeling of the spatial atomic layer deposition (SALD) reactor. After completing his Bachelor's degree in December 2015, he plans to begin Master's degree in Mechanical Engineering, and aims to pursue his engineering career in semiconductor industry. He is an active member of Korean-American Science and Engineers Association (KSEA). His role in the team is sponsor contact.



Tze Chien is a senior studying Mechanical Engineering at the University of Michigan. He is from Malaysia, a tropical country located just above Singapore. He studied in Taylor's college back in Malaysia before transferring to Michigan as a sophomore. Tze Chien chose Mechanical Engineering because he wants to follow his father's footsteps. Upon graduation, he aims to practice engineering either in the automotive or energy industry. He is a member of the Michigan Triathlon Team. He loves to swim, bike and play video games. His role in the team is facilitator.

Kit Siang Tan is a senior undergraduate student in the Mechanical Engineering department in the University of Michigan Ann Arbor. He completed high school in Malaysia and received a scholarship from the Malaysian Public Service Department to pursue his Bachelor's Degree in Mechanical Engineering in the United States. He has been a part of the BLUElab's Biogas International Project, designing and manufacturing a biogas compressor system that can help reduce the amount of biomass used as fuel, improve air quality and respiratory health, and empower local farmers in Mexico City to continue their use of sustainable energy. Upon graduation this coming May 2016, he aims to practice engineering in either automotive or energy industry. He loves playing badminton, and is a team member of the University of Michigan Collegiate Star League Dota2 team. His role in the team is safety officer and treasurer.

Appendix M: Bibliography

[1] Seshan, K. (2012). Handbook of thin film deposition ([3rd ed.). S.l.: William Andrew.
[2] Neil P. Dasgupta, Chong Liu, Sean Andrews, Fritz B. Prinz, and Peidong Yang, J. Am. Chem. Soc. 2013, 135, 12932-12935.
[3] Introduction to Semiconductor Manufacturing Technology, Second Edition by Hong Xiao, 2012, DOI: 10.1117/3.924283, eISBN: 9780819490933, Print ISBN13: 9780819490926.
[4] F. Lee, S. Marcus, E. Shero, G. Wilk, J. Swerts, J. W. Maes, T. Blomberg, A. Delabie, M. Gros-Jean, and E. Deloffre, 2007 IEEE/SEMI Advanced Semiconductor Manufacturing, 2007, p. 359.
[5] Edition: Volume 16, Issue 5, Publisher: The Electrochemical Society, Pennington, New Jersey, USA, Editor: S. Kar, D. Landheer, M. Houssa, D. Misra, S. Van Elshocht, H. Iwai, ISBN: 978-1-56677-651-6
[6] Kim, H., Lee, H., & Maeng, W. (n.d.). Applications of atomic layer deposition to nanofabrication and emerging nanodevices. Thin Solid Films, 2563-2580.
[7] Poodt, P., Cameron, D., Dickey, E., George, S., Kuznetsov, V., Parsons, G., . . . Vermeer, A. (n.d.). Spatial atomic layer deposition: A route towards further industrialization of atomic layer deposition. Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films J. Vac. Sci. Technol. A, 010802-010802.
[8] Udovsky, Joseph, Hemant P. Mungekar, Michael S. Cox, and Zheng Yuan. Apparatus For Spatial Atomic Layer Deposition With Recirculation And Methods Of Use. Patent US2014127404A1. 8 May 2014. Print.
[9] Paul Poodt, David C. Cameron et.al, Journal of Vacuum Science & Technology A 30, 010802 (2012); doi: 10.1116/1.3670745.
[10] Poodt, Paul, Adriaan Lankhorst, Fred Roozeboom, and Diederik Maas. "High-Speed Spatial Atomic-Layer Deposition of Aluminum Oxide Layers for Solar Cell Passivation." Print.
[11] Muller, R., Ziemann, M., & Berlin Glass KGaA Herbert Kubatz GmbH & Co. (2014). Perfect Chucks: Clamping Force and Flatness. -, -(-).
[12] Coletti, G., Van der Borg, N., De Iuliis, S., Tool, C., & Geerligs, L. (2006). MECHANICAL STRENGTH OF SILICON WAFERS DEPENDING ON WAFER THICKNESS AND SURFACE TREATMENT. 21st European Photovoltaic Solar Energy Conference and Exhibition, -(-). doi:-
[13] Kano, Shoji, Yamanura Waichi, US Patent 2007/0274021 (29 November 2007).
[14] Holding Small, Thin Parts for Effective Machining on a CNC Router. (2010, April 30). Retrieved September 23, 2015.
[15] Johnson Richard, Adam Hultqvist, and Stacey Bent. "Introduction." A Brief Review of Atomic Layer Deposition: From Fundamentals to Applications 17, no. 5 (2014): 337.
[16] Silicon Rubber Heaters. (n.d.). Retrieved September 23, 2015, from https://www.watlow.com/downloads/en/specsheets/colsrh0311.pdf.
[17] Hornyak, Gabor L. "Nanocomposites and Fibers: Thermal Properties." In Fundamentals of Nanotechnology, 428. Boca Raton: CRC Press, 2009.
[18] Thaler, B., & Bratt, P. (Eds.). (2009, December 1). Atomic Layer Deposition. Retrieved September 23, 2015.
[19] ISO 14644 Clean Room Standards. (n.d.). Retrieved September 23, 2015, from http://www.particle.com/technical-library/faqs/iso-14644-clean-room-standards.
[20] "Thermal Expansion." In ASM Ready Reference: Thermal Properties of Metals, 10. 06702G ed. Hitchin Hertfordshire SG4 0SX, United Kingdom: American Technical Publishers.

[21] Turner, Norman L., John M. White, and David Berkstresser. Methods of Heating and Cooling Large Area Substrates and Apparatus Therefor. Applied Materials, Inc, assignee. Patent 5,607,009. 4 Mar. 1997. Print.
[22] Hibbeler, R. (2010). Engineering mechanics (12th ed.). Upper Saddle River, NJ: Prentice Hall.
[23] Hover, F. (2820). Maneuvering Performance of Autonomous Underwater Vehicles. Ft. Belvoir: Defense Technical Information Center.
[24] Kaviany, M. (2011). Essentials of heat transfer: Principles, materials, and applications. Cambridge: Cambridge University Press.