The Thesis Committee for Andrew Ian Westfahl
Certifies that this is the approved version of the following thesis:

Design of Particle Mitigating Wafer Chucks for Yield Enhancement

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor:

S.V. Sreenivasan

Richard H. Crawford

Design of Particle Mitigating Wafer Chucks for Yield Enhancement

by

Andrew Ian Westfahl, B.S.M.E.

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

August 2014

Dedication

This work is dedicated to my parents, Kenny and LaDonna Westfahl, for their infinite support and guidance.

Acknowledgements

I would like to thank Dr. S.V. Sreenivasan for allowing me the opportunity to work on nanomanufacturing projects and introducing me to the field. I would also like to thank Sandia National Laboratories and the University of Texas for the continued quality education. I would like to acknowledge my fellow members of the High Throughput Precision Nanomanufacturing Lab and NASCENT for their insight and assistance in my research as well as Molecular Imprints Inc. for their contributions. Lastly, I would like to thank my friends and family for their support and encouragement.

Abstract

Design of Particle Mitigating Wafer Chucks for Yield Enhancement

Andrew Ian Westfahl, MSE

The University of Texas at Austin, 2014

Supervisor: S.V. Sreenivasan

As the semiconductor industry drives down the minimum feature size on wafers to increase performance and device density, the necessary site flatness of a standard 26 x 33 mm field becomes much more stringent. A significant unresolved cause for non-planarity is particle contamination at the interface of the wafer substrate and the wafer chuck. The result is an out of plane distortion that can affect a significant portion of the wafer resulting in device yield loss.

This research looks at two methods for mitigating the effects of particle contamination. The first method investigates using an in-situ cleaning approach in a wafer chuck to eliminate particles. This concept is called a Particle Eliminating Pin (PEP) chuck. The second method proposes enhancements to a wafer chuck design based on compliant mechanisms resulting in a chuck that is tolerant of particle contamination, referred to here as the enhanced compliant pin chuck (E-CPC).

The PEP chuck was explored relative to well-established methods for removing back-side particles and demonstrated it could eliminate an additional 18.5% of particles that could not be removed *via* the well-established methods. Additional potential effectiveness of a PEP chuck is also discussed based on future improvements. A scaled prototype of the proposed new design of the E-CPC was fabricated and tested as well. The prototype validated most of the proposed improvements but failed to maintain the mechanism's rotational requirement. With the understanding gained from this design and experimental research a future design of the E-CPC has been proposed in the future research section such that this new design can achieve all the proposed goals while still maintaining the required mechanism rotation.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

Since its implementation in the 1990s, step-and-scan reduction photolithography has been improving the speed, reliability, and cost effectiveness of semiconductor integrated circuits significantly by improving the resolution. With minimum feature sizes reaching sub-50nm, the resolution obtainable by photolithography is being pushed to its limits. Step-and-scan methods work by adjusting to focus on one field at a time and then exposing light through a patterned mask. The scan is done through a narrow slit such as an 8mm x 26mm sliver until the field is fully exposed (Okazaki, 2008). The standard field size for a photolithography pattern transfer is 26mm x 33mm. The process then steps to the next field. A crucial part of the photolithography pattern transfer is to have a highly flat substrate at each site to receive the pattern. The site flatness requirement for such a field will reach sub-20nm by 2017 as outlined by the ITRS Roadmap (ITRS, 2012). Challenges must be overcome to accomplish this level of planarity and still maintain high device yields.

The research work provided here serves as a supplement to ensuring the required site flatness can be achieved with acceptable yields by addressing the issues that arise from particle contamination. The remainder of this chapter further discusses the need for planarity, causes for non-planarity, and current approaches to resolving the detrimental effects of particles.

1.2 Need for Planarity

To keep up with demands for faster and denser integrated circuits, photolithography has largely relied on two methods for decreasing the minimum feature size of transistors. The first method implemented is reducing the wavelength of the laser used to expose the pattern on to the wafer. Today's standard is the 193nm ArF laser. This is an improvement on the 436nm lamps used in the 1980s; however, further reduction in exposure wavelength to 157nm has proven to be impractical. A reduction to extremely short x-ray wavelengths of 13nm is also being explored as Extreme Ultraviolet Lithography (EUVL) and is discussed later.

The second method to decrease minimum feature sizes is to increase the numerical aperture (NA), which is defined as a dimensionless number that characterizes the range of angles over which the optical system can accept or emit light. One approach to accomplish this currently is to perform lithography with the system immersed in water, which improves the NA from ≈1.0 to ≈1.4 (Bruning, 2007).

The two methods affect the minimum feature size as follows (Kemp et al., 2006):

$$R \approx \frac{k_1 \lambda}{NA}$$

Where

R is the resolution or minimum printable critical-dimension (feature size),

k_1 is a process dependent factor that varies from 0.3 to 1.0,

λ is the exposure wavelength, and

NA is the numerical aperture.

The reduction in the minimum printed dimension also affects the depth of focus (DOF). This effect is given by the formula:

$$DOF = \pm \frac{k_2 \lambda}{NA^2}$$

Where

DOF is the depth of focus,

k_2 is a process dependent factor of ~0.5.

From these equations, it is evident that the same factors that are used to improve resolution also limit the depth of focus. This is the main reason wafer planarity is important to photolithography since the entire surface of a wafer substrate must lay within a specific range of depth of focus for the print to be successful (Kemp et al., 2006).

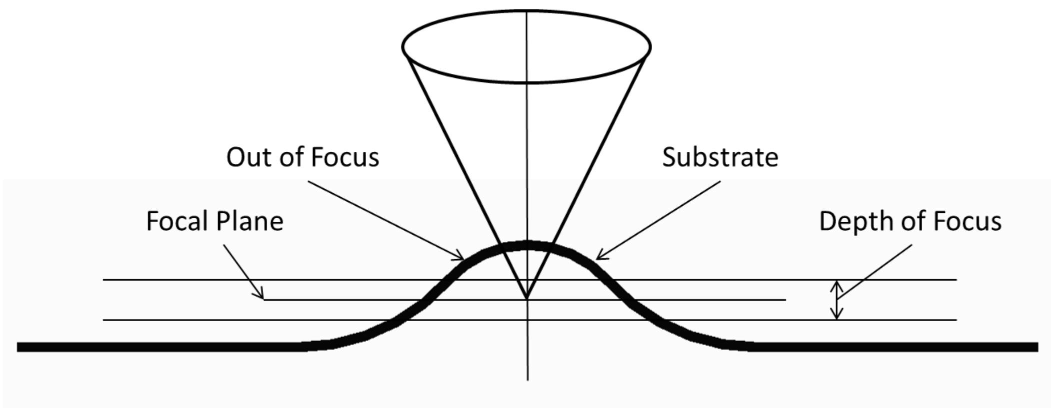

Figure 1-1: Illustration of Importance of Planarity

One next generation approach for higher resolution patterning is extreme ultraviolet lithography (EUVL). The exposure wavelength for this process is 13.5nm. Wafer planarity is a serious concern with EUVL due to the decreased DOF with short exposure wavelengths (Kemp et al., 2006). Wafer planarity also remains an important factor beyond photolithography. Alternative technologies such as imprint lithography, which uses direct or liquid contact to establish a uniform thin film that includes a molded pattern, may not rely on depth of focus from an optical perspective but still benefits from a planar wafer substrate to be successful.

1.3 Causes of Non-Planarity

Wafer non-planarity can come from several sources. These sources can be characterized into two types, intrinsic and extrinsic.

1.3.1 Intrinsic Sources

Intrinsic sources are those that come from the wafer substrate itself. Such non-planarity can be from warp, bow, and thickness variation. Common parameters used in industry are local thickness variation (LTV), total thickness variation (TTV) and site flatness least squares range (SFQR). The SFQR is observed as the most important parameter as it correlates to the thickness variation during one scan step. For a given wafer, the SFQR is the largest thickness variation found over one site. If the SFQR is beyond the acceptable tolerance then there could be pattern defects generated (Okazaki, 2008). SFQR requirements are typically <100nm over the 8mm x 26mm field but more stringent values of <25nm over a 26mm x 33mm field will likely be required in the next generation of 450mm wafers (ITRS, 2012). Table 1.1 lists typical values for wafer characteristics. These parameters can be optimized with cost by better wafer polishing. Since wafers are consumables, there will always be a balance between the careful polishing of wafers and the cost associated with the polishing.

Parameter	300mm Wafer	450mm Wafer
Diameter	300.00 ± 0.20 mm	450.00 ± 0.10 mm
Thickness	775 ± 20 μm	925 ± 20 μm
Total Thickness Variation, Max. (TTV)	10 μm	
Global Backside Indicated Reading (GBIR)	≤ 3 μm	
Warp, Max.	100 μm	≤ 50 μm
Flatness/SFQR **(26 mm x 8 mm site size)**	32 nm, 22 nm, or 16 nm (as determined by the resolution of minimum feature sizes)	

Table 1-1: Typical Wafer Parameters, Republished with permission from Semiconductor Equipment and Materials International, Inc. (SEMI) © 2014.

1.3.2 Extrinsic Sources

Extrinsic sources are all the causes of non-planarity external to the wafer substrate itself. These extrinsic sources generally come from two places, the wafer chuck and contamination from particles that could be found in between the chuck and the wafer.

The wafer chuck serves as a flat reference and a precision x-y-θ locator for the wafer substrate that is constrained by the chuck. This is usually done by pulling a vacuum between the wafer and the chuck. Typically, vacuum pressures vary from 80 to 90 kPa (Turner et al., 2013). Another common method uses electrostatic chucks to restrain the wafer to the chuck. The two important parameters for planarity from wafer chucks are chuck flatness (Stauch et al., 1994) and chucking force (Une et al., 2009). A high degree of chuck flatness can be attained by high-end lapping and polishing processes. Unlike wafers, chucks are part of the equipment and can process millions of wafers over their lifetime. This allows more expense and care to be put into making the chuck flat to the high degree necessary. Chucking force can be optimized based on the wafer substrate material and chuck design.

Particle contamination tends to be a more significant problem for creating non-planarity in wafers. Though wafer processing is done in clean rooms, there is always a small number of particles present. This is because even continually cleaning the environment by air filtration techniques is not sufficient as the processing of wafers generates particles (Firtion et al., 1980). Predicting when and where a particle will appear is impractical so more creative methods than mere air filtration are necessary to insure low defect processing resulting in high yields.

1.4 Detrimental Effects of Particles

Since the presence of particles is unavoidable, it is necessary to determine what the effect of a particle is on wafer non-planarity. Particles of many sizes are found in cleanroom environments. Minimum feature sizes of less than 50nm are common in modern lithography so the presence of a single particle of nearly any size can cause significant defects.

The immediate concern of a particle lodged between the wafer and chuck is the resulting out of plane distortion. Particle size, shape, composition, and concentration can contribute to the total resulting out of plane distortion. To simplify the characterization of the effect, the metric referred to as effective particle height is used. This is the height of the particle contaminant after it has been deformed due to the chucking force. The effective particle height could vary from its original dimensions as it could be crushed or embedded into the wafer or wafer chuck. The particle height is also directly correlated to the gap radius which is the metric used to evaluate the distance the particle's effect carries over the wafer. This relationship is defined by the following formula (Tejeda et al., 2002):

$$a = [\frac{16Eht^3}{3q(1-v^2)}]^{\frac{1}{4}}$$

Where

a is the gap radius,

E is the elastic modulus of the wafer,

h is the effective particle height,

t is the wafer thickness,

q is the chucking pressure, and

v is the Poisson's ratio of the wafer.

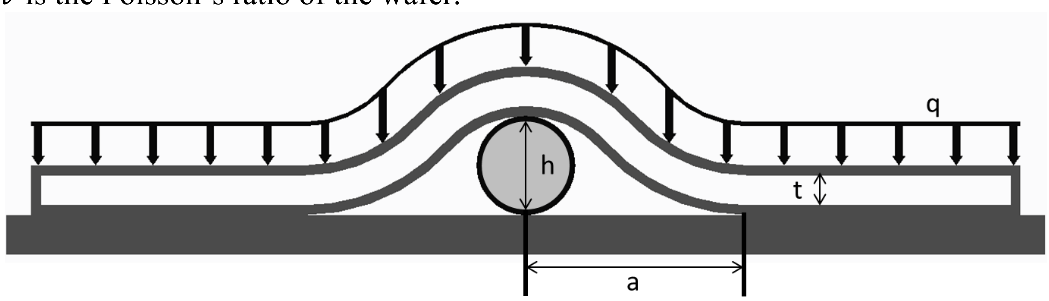

Figure 1-2: Particle effect

This allows us to determine how a particle's effective height affects the area that will result in some out of plane distortion. To better understand the relationship we assume the chucking pressure to be 80 kPa, the elastic modulus of a silicon wafer to be 130 GPa, the Poisson's ratio of the wafer to be 0.28, and the wafer thicknesses of 775µm for 300mm wafers (Turner et al., 2013) and 925µm for 450mm wafers. We can then plot particle height (nanometers) vs. gap radius (millimeters) as shown in Figure 1-3.

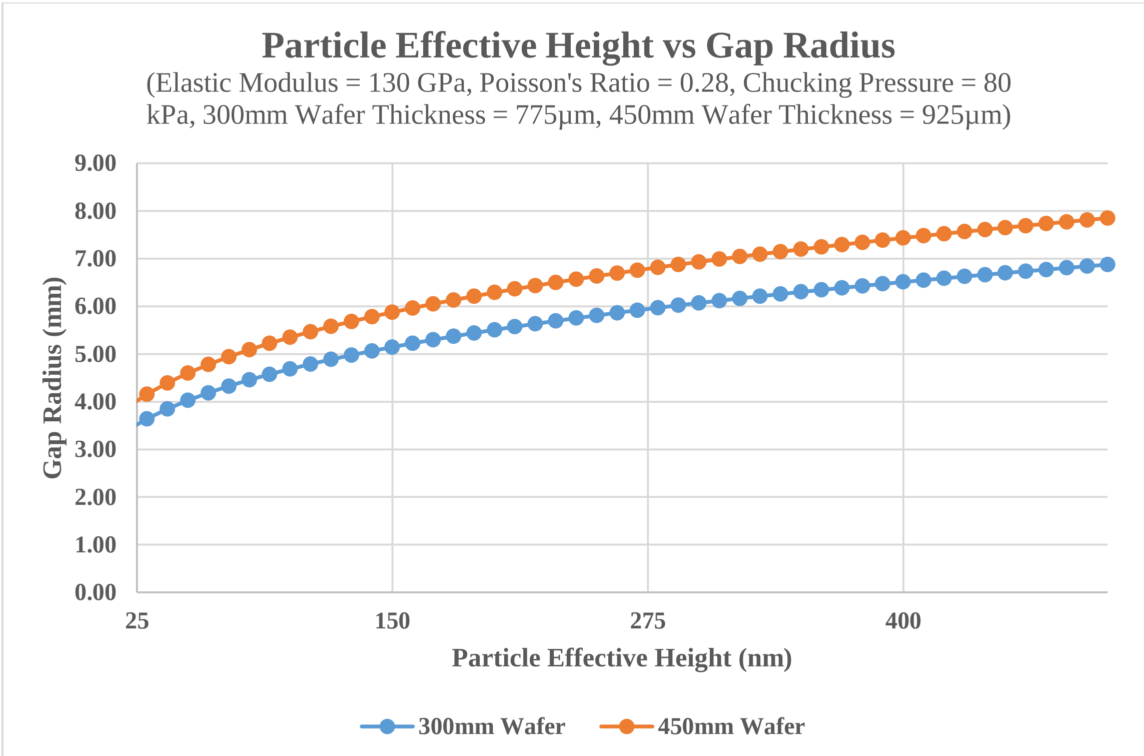

Figure 1-3: Particle Height vs Gap Radius

The plot shows that for a given submicron particle, a millimeter-scale gap radius is expected. This is a significant area of wafer real estate to be affected by a single particle. The plot also shows that the problem increases with thicker wafers. This means that processes will be more sensitive to particle contamination when making the leap from 300mm to 450mm diameter wafers.

1.5 Relevant Literature Review

To understand how to mitigate the effects of particles it is necessary to see what is already being done in the field of wafer chuck design. The purpose of the wafer chuck is to serve as a flat reference for the wafer. This removes some of the non-planar attributes of the wafer such as warp and bow. To achieve this, the wafer chuck itself needs to be extremely flat to the degree required by the particular process. For photolithography, the required chuck flatness is expected be 24nm for a single 26mm x 33mm site by the year 2015 (ITRS, 2012). The wafer chuck then provides a force, usually vacuum or electrostatic, to conform the wafer to the chuck. This must be done evenly so that the chucking force does not induce additional non-planarity. As discussed previously in the gap radius formula this chucking force also contributes to the area affected by particle contamination. This means that the particles must be mitigated in some way.

1.5.1 Conventional Wafer Chucks

The most common approach employed by industry today is to reduce the contact area between the wafer and the wafer chuck. The two types of chucks using this method are pin type and ring type chucks. A patent for the pin type chuck specifically mentions using limited area contact regions to reduce the probability of particles lodging between a wafer and wafer chuck (Firtion et al., 1980). Ring type chucks work in a similar fashion but instead of having independent pins, there are concentric rings that continue around the chuck. Each groove between the rings has its own source for a vacuum to conform the wafer to the chuck (Aoyama et al., 1994).

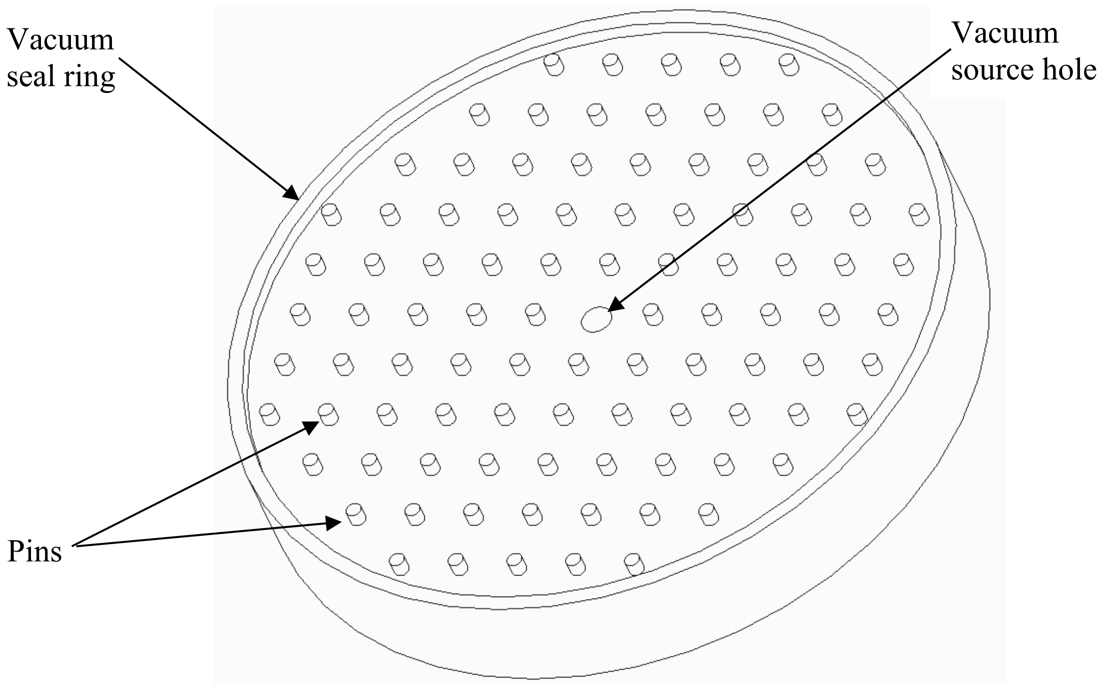

Figure 1-4: Pin type wafer chuck

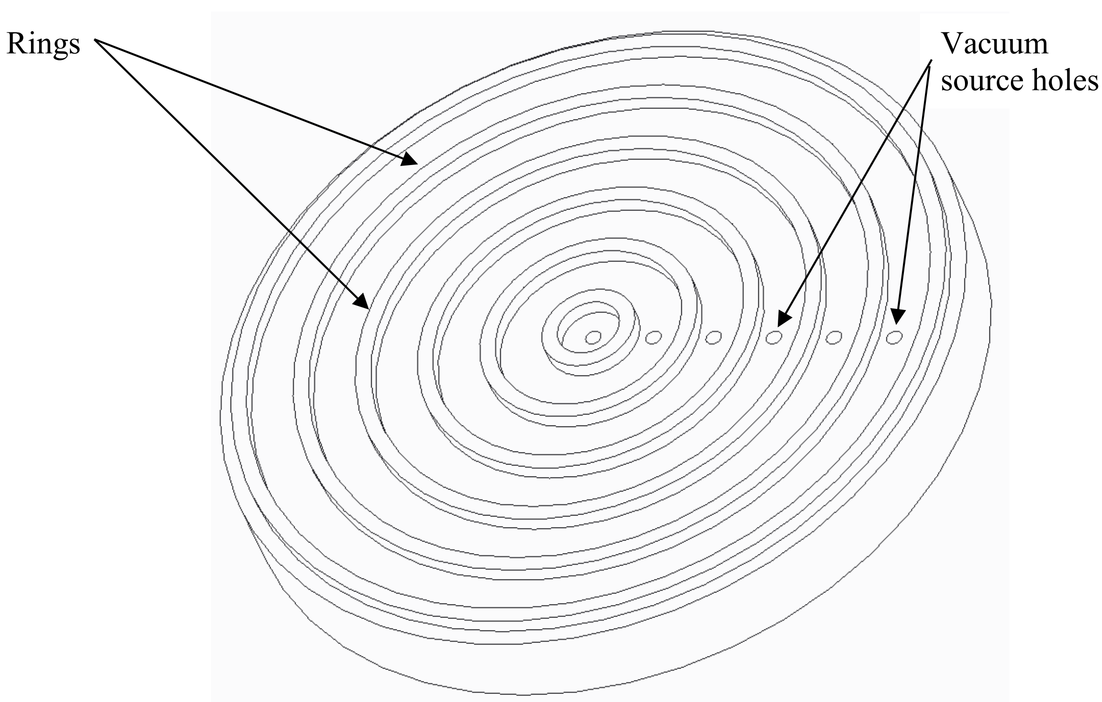

Figure 1-5: Ring type wafer chuck

The method of reducing contact area is not without flaws. The approach only reduces the probability that a particle will have an effect by requiring it to land on a pin or a ring. This does not directly address the particles that could appear at the interface of the wafer and wafer chuck. In addition, a thermal issue arises when the contact area between the wafer and wafer chuck is reduced. By reducing the contact area, the wafer becomes thermally isolated from the chuck. This is a concern because many lithography processes pour energy into the wafer causing localized thermal expansion. These distortions cause alignment issues as features on the wafer move with the distortions. To eliminate thermal expansion distortion the temperature of the wafer must be maintained nearly constant. To do this the heat from processing needs to be pulled from the wafer through the wafer chuck. Low thermal expansion and higher thermally conductive chuck materials as well as larger contact areas contribute to reduced distortion from thermal loads (Peschel et al., 2012). The distortions have been simulated to reduce by an order of magnitude when the wafer is thermally coupled with the wafer chuck (Gianoulakis et al., 2000).

1.5.2 Wafer Chuck Cleaning Method

Methods that are more sophisticated have been developed to reduce the effects of particles. One method is to use a wafer made of a cleaning material to soak up contaminant particles between process cycles. The cleaning wafer would be chucked to allow any particles to collect and stick to the wafer then removed from the chuck when the cleaning wafer is removed. This method works well to remove a majority of particles but still allows contamination to occur when the chucking of the wafer to be processed ensues. This method also has the potential to assist the contamination by transporting particles to the chuck (Yamauchi et al., 2003).

1.5.3 Compliant Mechanism Wafer Chuck

Another method evaluated at the University of Texas in 2004 by Pawan Kumar Nimmakayala looks at passively decreasing the effects of particles by having compliant mechanisms as the pins on the wafer chuck (Nimmakayala, 2004). The mechanisms used are called flexures. Flexures are an attractive mechanism to use because they have very low friction, predictable and repeatable motion, linear displacement at small deflections and little to no hysteresis when not overloaded (Smith, 2000). The chuck, called a Compliant Pin Chuck (CPC), utilizes flexures at the edges of the pin supports to allow for the pin to recess when there is a large force, such as those induced by particles. In an experiment, the CPC corrected ~60% of the out of plane distortion compared to non-accommodating chucks. This is a considerable amount and serves as a good benchmark for future similar work. The limitations of this chuck were mostly fabrication related. The chuck was fabricated using MEMS techniques and had to be constructed from three separate layers. The alignment of these layers is difficult to achieve. Any misalignment could drastically affect the performance of the chuck (Nimmakayala, 2004).

1.5.4 Actuated Wafer Chucks

Other chucks use a different approach when dealing with wafer planarity. Rather than passively mitigating the effects of particles, chucks have been developed to remove wafer non-planarity by actuating different regions of a chuck. This actuation can be done using piezoelectric mechanisms (Siddall, 1985) (Maltabes et al., 2001) or pneumatic systems (Cherala et al., 2013), among other methods. To accomplish this a high-resolution image of the surface topography of a chucked wafer is obtained and evaluated to check for regions of non-planarity. This information is then used to actuated individual regions of a chuck and manipulate the wafer to a more planar state. These methods are somewhat limited in their effectiveness because distortion due to particles is localized. A large number of actuators would be needed to have the high enough resolution to manipulate the effect of a single particle and nothing more. The issue with a large number of actuators is that the additional weight makes having quick, accurate stage motions difficult. Though larger regions of non-planarity can be addressed, small areas of effect are impractical to correct. Large area actuated wafer chucks have been demonstrated to be beneficial in such applications as imprint lithography in the efforts to prevent bubble formation (Cherala et al., 2013).

There has been extensive research on removing non-planarity in wafers due to particle contamination during lithography. However, with continuing reduction in minimum feature sizes, more research is needed to develop chucks that can more significantly address the problem of particle contamination.

1.6 Thesis Objectives

The research presented in this thesis will evaluate two approaches of mitigating the effects of particles caught at the interface between a wafer substrate and a wafer chuck. By lowering or eliminating particle effects, device manufacturing yield can be sustained, if not improved, even as minimum feature dimensions decrease.

To accomplish this goal an understanding of wafer chucks and their requirements is critical. This can then be applied to the design of new concepts. The designs must consider effectiveness, fabrication and feasibility. The designs must then be evaluated by metrics that relate to the yield of manufactured devices to determine the value added by this research. Two such designs are conceptualized and evaluated in this research.

Chapter 2: Design Requirements and Concepts

To develop new concepts to replace conventional chucks it is necessary to understand the function of a wafer chuck and document their requirements. Besides the functional requirements, there are also significant material requirements to be considered. Once the requirements are understood, we can evaluate the concepts for particle mitigation and then select the most attractive concepts.

2.1 Wafer Chuck Functional Requirements

The primary function of the wafer chuck is to force the wafer substrate to a planar state and to hold it in x-y-θ directions. The wafer chuck then has two requirements to accomplish wafer planarity:

The wafer chuck must serve as a flat reference for the wafer substrate.

The wafer chuck must provide a chucking force to compel the wafer to conform to the chuck in an evenly distributed manner.

There are some secondary functional requirements that the wafer chuck should include. The wafer chuck should be able to allow the motion of wafers reliably as a part of a stage system. This allows for proper location and orientation of the wafer. The chuck force ideally would be able to be toggled off to allow for the removal and addition of wafers. This can be done easily by turning on and off the chucking source, whether it is vacuum or electrostatic. Numerous other requirements such as durability, thermal properties and the ability to be polished are also very important. These are mostly determined by the material being used for the wafer chuck so those requirements are discussed in the next section.

2.2 Wafer Chuck Material Requirements

The material should have a good strength to weight ratio.

Since the chuck serves as the reference flat for the wafer, the chuck should remain rigid for all process scenarios. Thus, a high elastic modulus material is desired. The chuck should also be lightweight. This is important because the stage system including the chuck needs to move at relatively high accelerations considering nanometer position accuracy is need. Increased weight would make positioning the stage quickly, with high accuracy more difficult. During scanning of wafers, accelerations of $10m/s^2$ are common and accelerations up to $40m/s^2$ are used in some dual-stage scanners (Butler, 2011).

The material should have good abrasion resistance.

The chuck should be able to tolerate thousands of cycles of wafer processing without losing its flatness. To achieve this, the chuck should be resistant to the wear associated with the chucking of a wafer. Thus, the chuck material should have adequate hardness. Being resistant to wear will also prevent the production of particles that could contaminate the lithographic process.

The material should not attract particles.

Since particles have been demonstrated to cause wafer non-planarity, it is naturally desired to avoid particles from collecting on the chuck. Particles can become electrically charged and adhere to the chuck surface. This should be avoided if possible.

The material should be able to be polished.

Making the wafer chuck flat was mentioned as a primary functional requirement. To do this the chuck has to go through thorough and expensive grinding and polishing processes. Thus, ease of this polishing is important to reduce cost.

The material should have a low coefficient of thermal expansion or match that of the wafer substrate.

During the processing of wafers small, localized heat can be generated. This heat results in small expansions of the wafer. If the chuck and wafer have differing coefficients of thermal expansion then there could be small relative motions between the wafer and chuck. This is a problem because the chuck has position sensors on it for locating the wafer. If the wafer moves with respect to the chuck then there will be alignment errors during exposure.

The material should have good thermal conductivity.

Good thermal conductivity of the chuck material would also be desired. This allows the temperature of the chuck and wafer to be regulated to a tight tolerance by using water-cooling systems. If sufficient thermal conductivity is present, the heat generated could be pulled out of the wafer through the chuck.

It is apparent that the chuck material selection is a crucial part of the design process since there are many properties that have requirements to make a desirable chuck. Material selection is discussed further in the discussion of each concept selected.

2.3 Conceptual Designs

Conventional and novel wafer chucks that seek to mitigate the effects of particles can be classified into two types: passive and active wafer chucks. Passive chucks are defined as those that deal with detrimental effects of particles without any sensing involved. Active chucks involve the sensing then correction of particle effects. Passive chucks can be further categorized into reduced contact area chucks and compliant mechanism chucks while active chucks can be further classified as actuator wafer chucks and particle eliminating wafer chucks.

2.3.1 Reduced Contact Area Chucks

Reduced contact area chucks are conventionally used in industry. This concept relies on reducing the interface area between wafers and wafer chucks. The approach does not directly seek to mitigate the effects of particles but instead relies on probability to avoid particles appearing on the tops of pins or rings. The simplistic nature of this concept makes it reliable and easy to fabricate. Further development of this concept could involve new schemes for supporting the wafer with reduced contact area but the fundamental dependence on probability to avoid particles as well as the stable thermal requirements are reasons to reject further study of this method at this time.

2.3.2 Compliant Mechanism Chucks

Chucks utilizing some sort of compliant mechanism to tolerate particle contamination by deflecting in localized regions are also considered passive. As seen in the Compliant Pin Chuck (CPC), this can be done using mechanisms called flexures (Nimmakayala, 2004). The complex fabrication of chucks, like the CPC, makes implementation into industry difficult. However, with the recent momentum in the development of 3-D additive manufacturing processes, complex wafer chucks once thought unviable may be possible. The use of a 3-D additive manufacturing process would also allow for designs that not only are unfeasible but impossible to be made using traditional fabrication methods. This is because certain designs, specifically those that have complex self-contained features, cannot be made using the traditional machining tool because it cannot reach the areas on the part it needs to machine. The design would need to be broken up into sections, fabricated, then bonded together in order to use traditional methods. This concept is attractive for further development because of its freedom to utilize previously implausible designs that could prove to be very effective in mitigating particles.

2.3.3 Actuator Wafer Chucks

Chucks that use sensing schemes to evaluate the flatness of a chucked wafer and then deform in selected regions via actuators on the wafer chuck are considered actuator wafer chucks. As discussed previously with the piezoelectric and pneumatic actuated chucks, the issue comes from adding the weight associated with additional actuators. This concept would be attractive if a scheme could be developed that had a high resolution of deflectable regions but with a minimal number of actuators.

2.3.4 Particle Elimination Chucks

Chucks that can eliminate particles from the wafer and chuck interface would be valuable if it can be done simply and effectively. Possible methods for elimination could include using mechanical devices, magnetics, or pneumatics. Particles are typically eliminated through air filtration in the clean room environment or from pneumatics and cleaning liquids prior to wafer chucking. Rarely is a backside particle eliminated while a wafer is being chucked. Techniques have been developed to eliminate topside particles via liquid nitrogen (Menon, 1996). Particle elimination should be an attractive concept if a similar process could be developed for the backside of wafer during the chucking process. If the particle elimination could occur during the chucking process then there would be no time for more particles to collect and contaminate the lithographic process.

2.4 Concept Selection

From evaluating the concepts presented, the particle-eliminating concept and an enhanced compliant mechanism chuck are the most attractive. Both have been chosen to be evaluated and characterized for the scope of this research. The particle-eliminating chuck is an attractive concept due to its potential for effectiveness and simplicity as it could completely get rid of any negative effects by simply removing any particle. The enhanced compliant mechanism chuck concept is attractive due to the potential brought by allowing designs fabricated using additive manufacturing. The concept is also attractive because it is based on previous work that has been proven to significantly reduce particle effects using compliant mechanisms (Nimmakayala, 2004). The next two chapters discuss and evaluate each concept individually.

Chapter 3: Particle-Eliminating Pin Chuck Concept

3.1 Design

An optimal design for a particle eliminating chuck is one that minimizes complexity while maximizing effectiveness. By making the design simple, the chuck fabrication becomes more cost effective. The simplest way to eliminate particles at the interface of the chuck and wafer is to supply airflow to carry the particles away from the interface. As opposed to a magnetic or motion mechanism, a pneumatic design has no moving parts and does not significantly add weight or complexity. The design would only need to incorporate features to allow for the directing of airflow to the interface.

The design theorized in this research is a pin chuck that incorporates a pneumatic component comprised of a series of pins with holes at their surface to allow for airflow. These pins are equally spaced in a grid layout with regular pins in between. The particle eliminating pins then share a common plenum within the chuck to direct airflow from an external reservoir to the chuck-wafer interface. The plenum must be separate from the vacuum cavity that is also within the chuck to provide the required chucking force to restrain the wafer. The vacuum holes are then situated below the pins as with conventional chucks. This concept is called a particle-eliminating pin (PEP) chuck and is illustrated in the Figures 3-1 and 3-2.

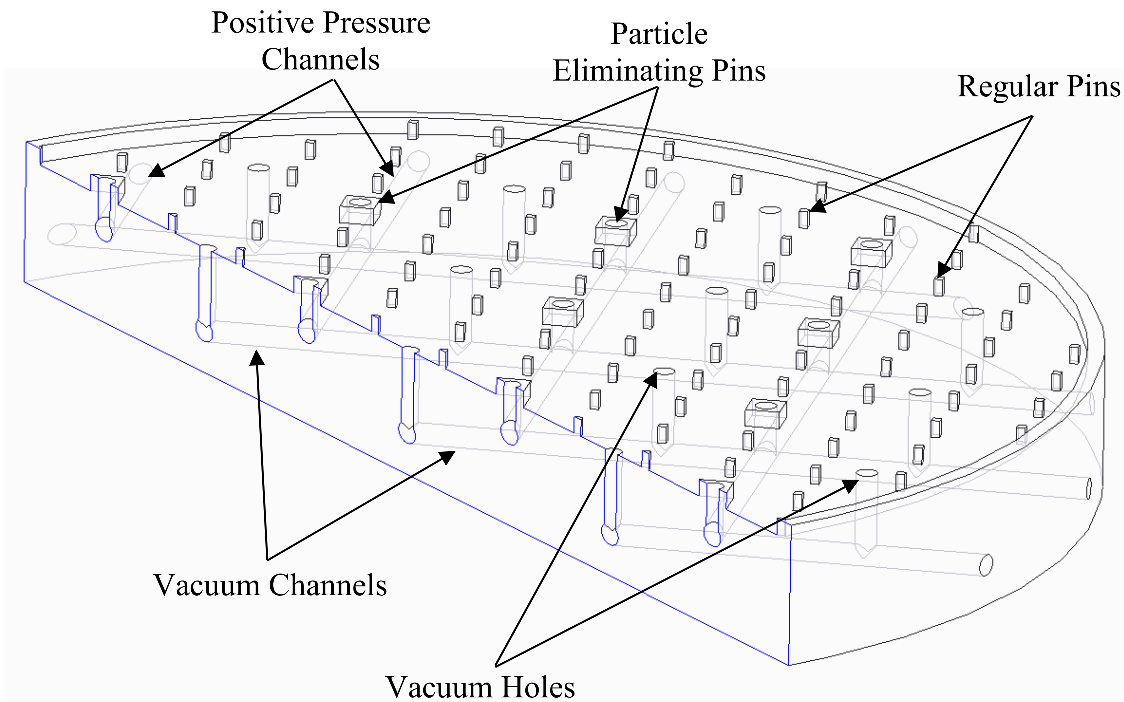

Figure 3-1: Particle-Eliminating Pin Chuck Cross-Section Illustration (hidden lines shown)

A wafer chuck that was developed by Molecular Imprints, Inc. for a different application encompassed the goals of the illustrated design. This chuck was graciously donated for the purpose of this research, which eliminated the need for fabrication of a chuck.

The original application for the chuck is outlined in the patent filing for the chuck. The chuck is described to be a part of a chucking system that is used "to facilitate separating a template from a solidified layer disposed on a substrate in an imprint lithography process" (Babbs et al., 2010). Even with the different intended use, the chuck design aligns very well with the requirements for this research.

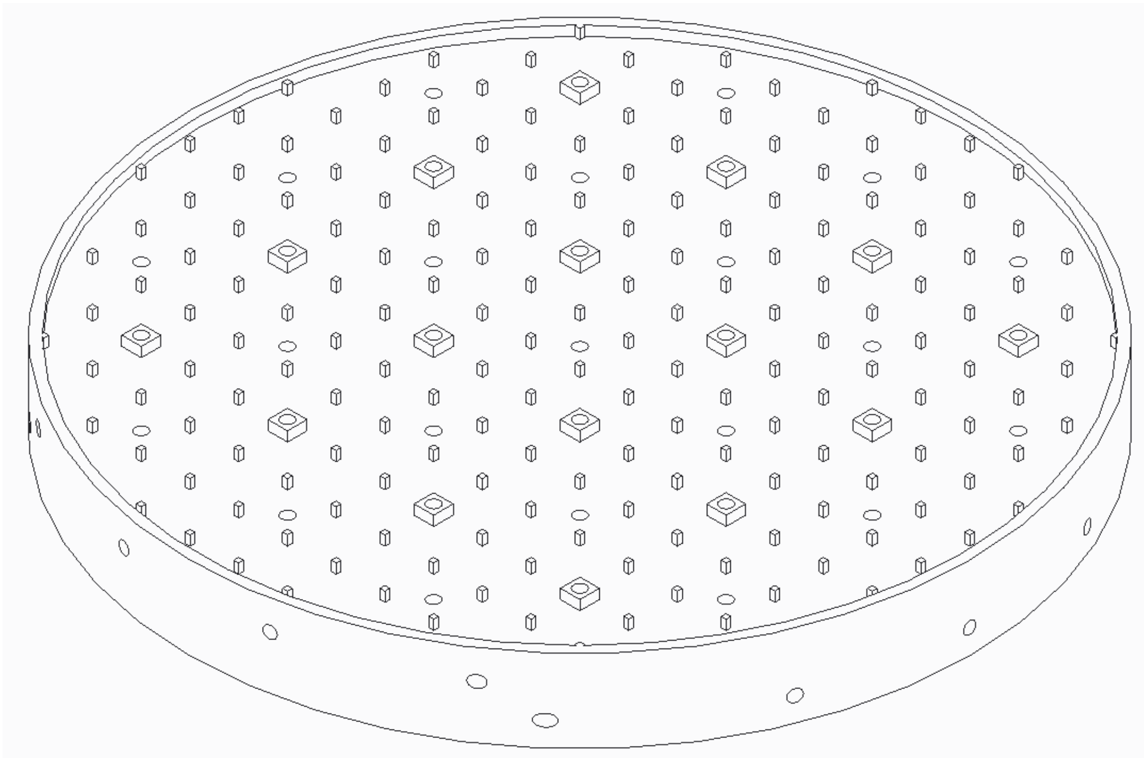

Figure 3-2: Particle-Eliminating Pin Chuck Simplified Illustration

3.2 METRICS FOR EVALUATION

The ultimate value of this research is to improve the yield of fabricated devices, however testing the PEP chuck's effectiveness by fabricating a large number of devices and determining yield improvement is neither feasible nor time efficient. Instead, one can evaluate the presence of particles and the ability for their effects to be removed which correlates to an improvement in yield. Therefore, the metric for evaluating the effectiveness of the PEP chuck is the presence of particles, sometimes called "hot spots", and its ability to remove those particles. The relationship between the effective particle height and the effectiveness of the PEP chuck is also worth analyzing to determine if the particle's effective height contributes to its ability to be removed.

Both the location of hot spots and their effective heights can be determined using a high precision 3D profilometer. Such a profilometer built by the Zygo Corporation was used in this research. The machine allows for nanometer scale z-direction detection over a circular field of view with a diameter of 100mm.

3.3 Experimental Procedure

For the collection of experimental results, the PEP chuck was mounted below the Zygo profilometer in a class 100 cleanroom. The chuck was then connected to a clean dry air source via pneumatic hoses. The hoses were then connected with a pressure gage and a regulator in series to allow for variable and documented positive pressures. Silicon wafers of 8" in diameter were then left exposed inside the clean room for several hours to allow for particles to settle on them. These wafers were then vacuum chucked on to the PEP chuck one at a time for evaluation of any particle contamination.

For each wafer, the surface topography was recorded with specific attention to particle-induced distortions. The wafer chuck vacuum pressure was then turned off and the wafer was shifted laterally while in contact with the wafer chuck. This is a common practice in industry to "knock off" any particles that happen to be at the top of the pins. The wafer was then re-chucked with vacuum at its original position to reevaluate the surface topography. If any of the particles that were present prior to the lateral shift remained then the chuck vacuum was once again removed and a positive pressure was activated through the particle eliminating pins. After this operation the chuck was once again vacuum chucked and reevaluated. If a particle remained after all of the prior procedures then it was declared persistent. Between each session of wafer evaluations, the wafers were cleaned using isopropanol and an air dryer. The PEP chuck was also cleaned between sessions using an adhesive tacky mat. An outline of the procedure is summarized in Table 3-1.

Step	Procedure
1	Wafer backside allowed to collect particles for several hours in a clean room
2	Wafer is vacuum chucked and surface topography is recorded
3	Wafer chuck vacuum removed and wafer is slid laterally
4	Wafer is vacuum chucked and surface topography is recorded
5	Wafer chuck vacuum removed and pneumatic particle eliminating system is initiated
6	Wafer is vacuum chucked and surface topography is recorded
7	Wafers and wafer chuck are cleaned in preparation for the next session of testing

Table 3-1: Outline of Experimental Procedure

3.4 RESULTS AND DISCUSSION

In all 16 wafers were evaluated for 100 assessments following the above procedure. Particles were detected on 62 of the assessments with an average of two particles per wafer. A majority of the particles were submicron in effective height. A sample of an observed particle event is shown in Figure 3-3 and the subsequent image of post-pneumatic particle elimination is shown in Figure 3-4.

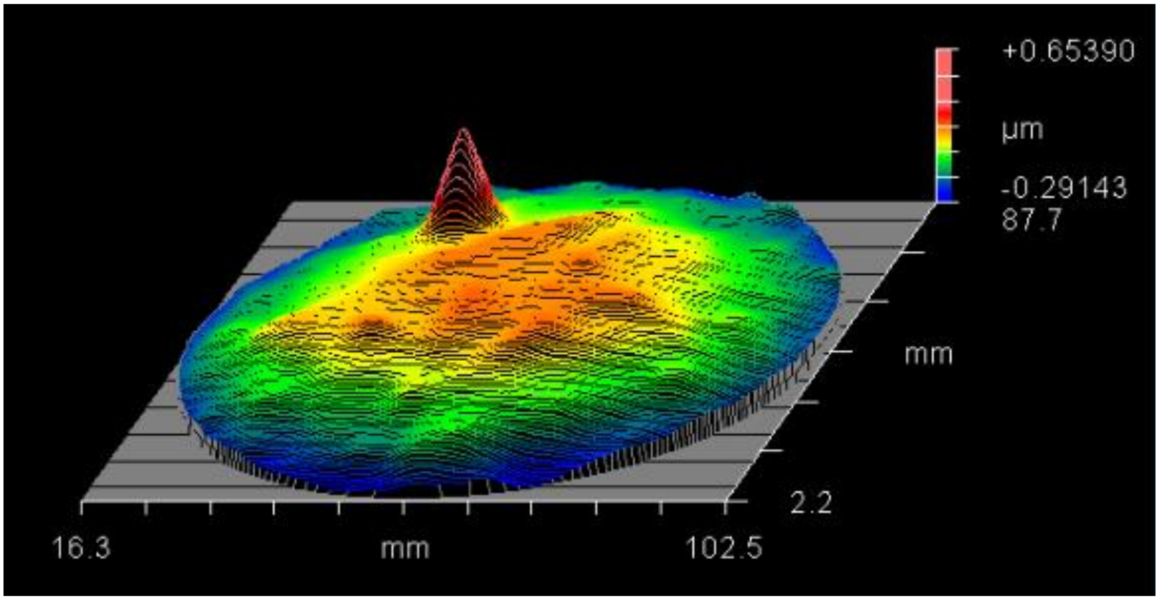

Figure 3-3: Surface topography post lateral slide (effective height 600 nm)

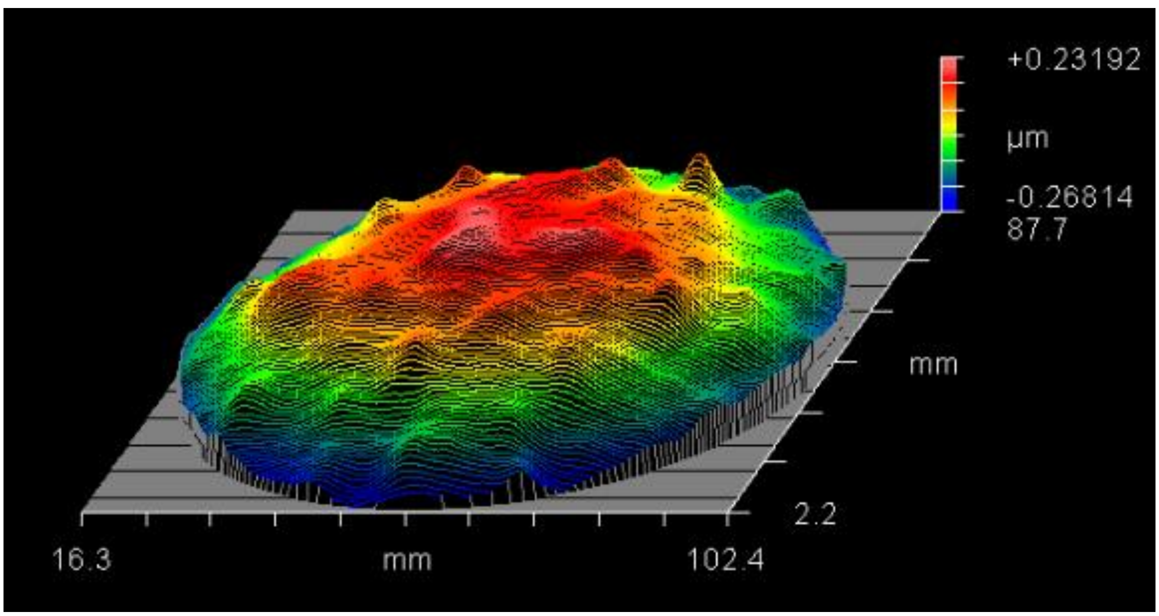

Figure 3-4: Surface topography after particle elimination

Of the particles observed during these experiments, 33.1% were persistent where neither the lateral slide nor the particle eliminating airflow removed the particles. Lateral shifting then removed 48.4% of the particles. The final 18.5% of particles were removed via the particle eliminating airflow after lateral shifting was attempted. Figure 3-5 shows the relationship between effective particle height and the ability for a particle to be removed.

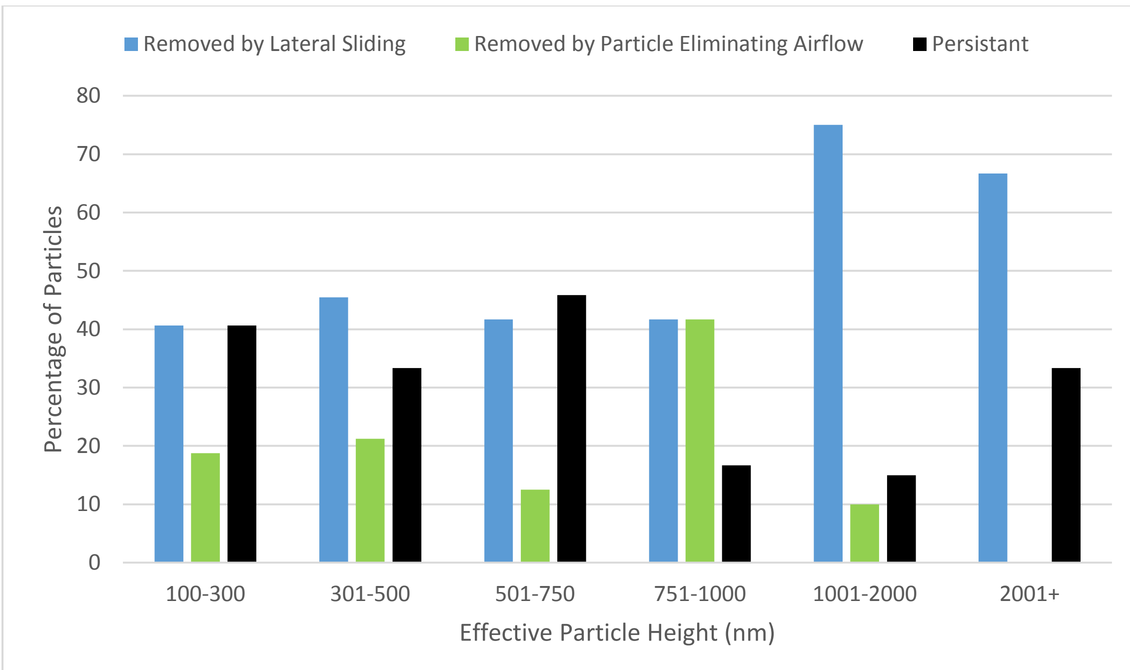

Figure 3-5: Effective Particle Height & Removal Method

As the figure shows, the lateral sliding eliminated almost all particles that were larger than one micron in effective height. The figure also shows that the particle eliminating airflow method supplements the removal at almost all particle sizes. An additional study of particle-contaminated wafers was done to evaluate the effectiveness of only using the particle eliminating airflow method. This research was performed by swapping the order of operation for the lateral shifting and the particle eliminating airflow. The study found more particles of a micron or larger and resulted with 16.4% of particles being persistent, 50.7% of particles removed via particle eliminating airflow, and the remaining 32.9% of particles removed via lateral shifting after particle eliminating airflow was attempted.

The conclusion of these studies is that the combination of the industry used method of lateral shifting and the proposed PEP chuck provided the best results in removing particles from the interface of a wafer and a wafer chuck. The effectiveness of PEP chucks can be increased by implementing improved designs. Suggestions for such improvements are discussed in the future work section of Chapter 5.

Chapter 4: Enhanced Compliant Pin Chuck Concept

4.1 Previous Designs

As discussed in Chapter 2, wafer chucks utilizing flexures to achieve a compliant pin design have been proven to reduce particle induced out of plane distortion. Reductions of around 60% in the out of plane distortion were demonstrated (Nimmakayala, 2004). Nimmakayala achieved this level of success by using a thorough design that utilized a few key elements. A figure adaptation of his design concept is shown in Figure 4-1.

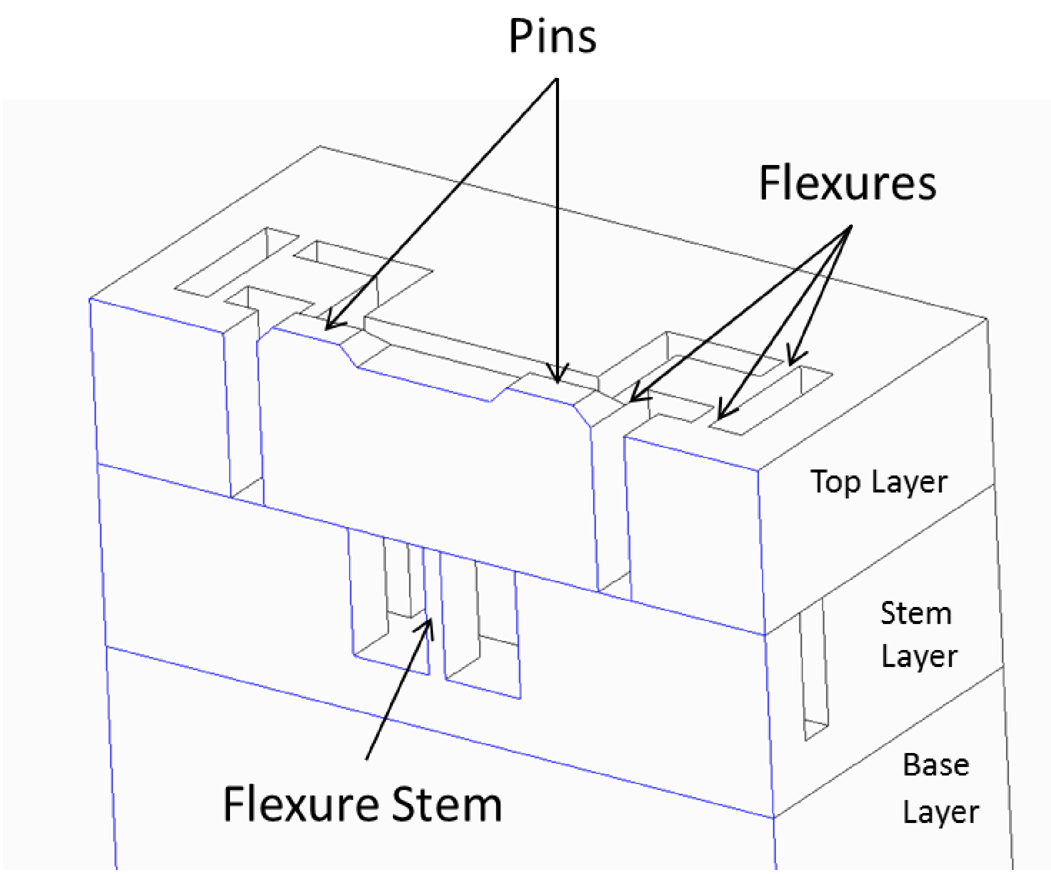

Figure 4-1: Cross Section of Compliant Pin Chuck Concept (Recreated from Nimmakayala, 2004)

These key design elements included two opposing pins that when both pins interface with the wafer, as is the case during chucking, the load is transferred through a primary stem resulting in little or no deflection. However, if the two pins are loaded asymmetrically then the pin seeing the larger load deflects resulting in a reduction in the overall out of plane distortion. Such an asymmetric load is present when a particle is atop one of the pins. The pins themselves each have a series of flexures that allow for compliance. The flexures act as rotary joints allowing for compliance about the flexures. They are also situated along a common plane, which is orthogonal to the direction of deflection. This allows the entire mechanism to rotate about the opposing pin. From a practical sense, this means that when one of the pins deflects due to the presence of a particle, the opposing pin does not raise up vertically and induce its own out of plane distortion. These important design elements need to be carried over into any potentially enhanced designs in order to maintain the same effectiveness without negative effects.

4.2 Proposed Enhancements

Though the compliant pin chuck design has proven to be effective, there are still some areas where improvements could be made. As discussed in Chapter 2, thermal conductivity is important in wafer chuck design. By having a large interface area between the wafer and wafer chuck, the temperature of the entire system can be regulated to eliminate localized thermal expansions that may result in defects. Increasing the compliant pin chuck's contact area to around 20% would go a long way to improving the system's overall ability to be thermally regulated. To achieve this, the compliant flexures must be designed more compactly to allow larger pins to be placed closer together.

Another area that can be enhanced is increasing the sensitivity of the compliant pins. If the flexures were designed smaller and thinner, they would be more compliant to the presence of particles resulting in a more effective reduction in out of plane distortion. The overall compliance should not exceed the amount required to remain rigid during normal chucking operations.

A third area of development is in the fabrication of the chuck. The compliant pin chuck was originally demonstrated by fabricating three layers separately then joining the layers together. This extra step requires alignment and bonding which introduces extra costs and the potential for errors in the mechanism. If these layers could be fabricated as one continuous, unified piece then the assembly step would be avoided.

To accomplish these goals a prototype design was developed with the intent to be fabricated using a selectively laser-sintered (SLS) method. By using SLS, a one piece design with smaller flexures and larger pins is possible. The sintering process uses a high powered laser that can translate in an x-y plane and bonds a bed of powder of the desired material together along the laser's trajectory. After the laser completes one layer of sintering, another layer of powder is rolled on top of the previous and the process is repeated. The process is done until a completed three dimensional object of sintered material is formed. The additive nature of the process allows for the manufacturing of geometries that are not possible with traditional machining.

By using SLS, the flexure thicknesses for the compliant elements of the design are not limited to the layer thickness of the raw chuck material. This means softer flexures can be fabricated without compromising the overall mechanical strength of the chuck. By having the three-dimensional freedom, it is also possible to pack more pins and flexures closer together. By improving the packing in conjunction with larger pins, a wafer and wafer chuck interface of 20% becomes feasible. SLS also eliminates the need for discrete layer fabrication since the entire chuck, including the pins, flexures, and base, can be fabricated in one build. A design that incorporates the capabilities of SLS for fabrication provides a concept that can meet all the requirements and proposed enhancements for a compliant pin chuck.

4.3 Prototype

To validate a conceptual flexure pin mechanism it is necessary to evaluate its compliant motion through fabrication and testing of the design. To achieve this, a prototype needs to be created that matches an implemental design as best as possible. The following section describes such a prototype.

4.3.1 Design

The design of the prototype follows closely to that of the original compliant pin chuck but implements the enhancements discussed previously. The pins themselves are designed such that when they are packed together into an array, the contact area is 20% that of the wafer backside area. While this improves thermal characteristics, it does so at the risk of increasing the likelihood of particles to land on a pin. This negative effect is mitigated by using notch type flexures that are much smaller, thus more compliant, than in original designs. A drawing of the prototype design is shown in Figure 4-2.

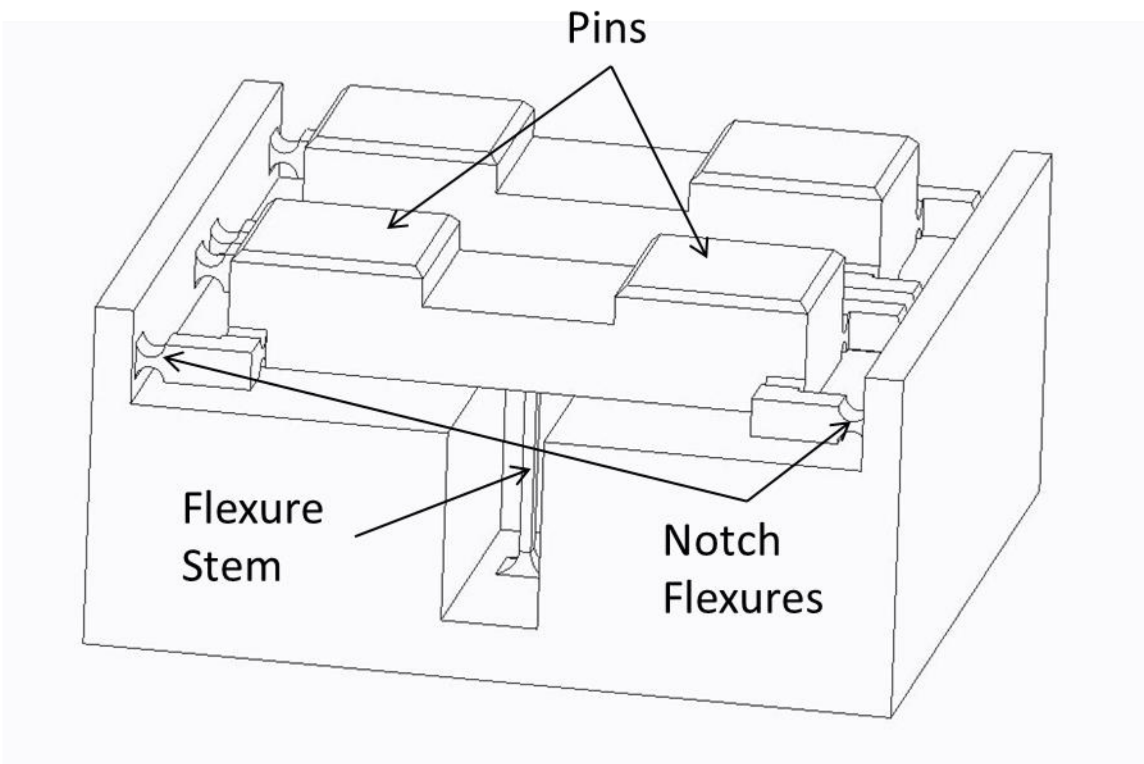

Figure 4-2: Design of Proposed Compliant Pin Chuck

4.3.2 Fabrication

Fabricating a prototype mechanism at the appropriate scale and material is very difficult with the current technology of SLS systems. Silicon carbide has been a preferred material for semiconductor wafer chucks in industry for a long time. This is due to its exceptional material properties such as its strength to weight ratio, abrasion resistance, and thermal properties. SLS has been demonstrated previously to fabricate complex silicon carbide piece parts (Stevinson et al., 2008). However, the process resolution is not currently developed enough to reach the requirements for the minimum feature size of the proposed design, which is 25μm. Research to improve resolution is currently in progress and has a lot of momentum and interest in several fields beyond that of the semiconductor industry. Another problem is the silicon carbide sintering process.

This is done today using indirect sintering which introduces some geometry errors during infiltration. These errors are due to overfilling which is caused by a material mismatch of the infiltrating silicon and the base silicon carbide (Stevinson et al., 2008). Ideally the future holds the development of direct sintering of silicon carbide at a resolution of at least 10µm. Since the technology is currently not mature enough for a prototype of this scale and material, a prototype was fabricated using a SLS material and process that has been developed and established for several years. This material was nylon. The SLS machines that utilized nylon are also intended for larger parts so the design was also scaled to 25x its intended dimensions.

In fabrication for an industrial use chuck the entire chuck would be fabricated at once rather than just one mechanism. There would be thousands of such mechanisms equally spaced to the form factor desired of the wafer chuck. One concern that needs to be considered during the fabrication of an implemented design for industry is the polishing step that all wafer chucks require. The polishing makes sure that all pins are relatively on the same plane such that when a wafer is chucked it is sufficiently flat. The polishing is done through a chemical-mechanical process. The mechanical part involves contact with the pins. A compliant deflection of the pins during polishing could reduce the effectiveness of the polishing process. Therefore, to correct for this the voids of the wafer chuck should be filled with a temporary material that can solidify and support the compliant pins during polishing. The material could be then evaporated or melted and removed after polishing.

4.4 Evaluation and Calculations

The proposed design can be evaluated analytically in comparison to the original compliant pin chuck. This can give the theoretical compliance of the design. The equations for doing so can be broken down into the following equations for angular flexure stiffness (Smith, 2000):

Leaf-type (beam) flexure:

$$k = \frac{2Ebt^3}{3L^2}$$

Notch-type flexure:

$$k = \frac{2Ebt^{\frac{5}{2}}}{9\pi r^{\frac{1}{2}}}$$

Where

k is the angular stiffness,

E is the modulus of the flexure material,

b is the depth of the flexure in the direction of motion,

t is the thickness of the flexure,

L is the length of the flexure and,

r is the radius of the circular notch.

The original compliant pin chuck used leaf-type flexures while the proposed design utilizes notch-type flexures. A table of the calculated values for pin stiffness of the compliant pin chuck and the proposed design is shown in Table 4-1.

Design	**Stiffness (N/θ)**	**Compliance (θ/N)**
Original CPC	3375.0	0.0002963
Proposed Design	1.3680	0.7310

Table 4-1: Independent Pin Stiffness Calculations for Each Design

These calculations assume silicon carbide as the chuck material and similarly sized flexure features. The main variation is the depth of the flexure that is much thinner in the proposed design. Also assumed is that each pin is independently supported for both designs. This is not true in reality and produces inaccuracies in the actual pin stiffness. An example would be that a pin is much stiffer in symmetrical loading due to the opposing pins coupling effect. These effects are ignored. Even with these inaccuracies, it is revealing to calculate the independent pin stiffness for each design to compare their approximate stiffness with the other. The results depict the proposed design to be much more compliant than the original CPC thus being much more sensitive to particles.

4.5 Evaluation of Prototype

Though the compliant stiffness of the prototype cannot be directly measured due to material and scale differences, the prototype can still be evaluated to ensure the mechanism works as designed. To do this an experimental setup was constructed to variably apply point loads to the prototype's pins and observe the compliance. A figure of the setup is shown in Figure 4-4. Utilizing a high resolution camera it is also possible to measure the deflections of the pins at different points along the top of the mechanism. Using this data we can determine the instantaneous axis of rotation for a given load. As discussed previously in Section 4.1, rotation about the opposing pin is desirable to ensure no additional out of plane distortion is incurred by the opposing pin.

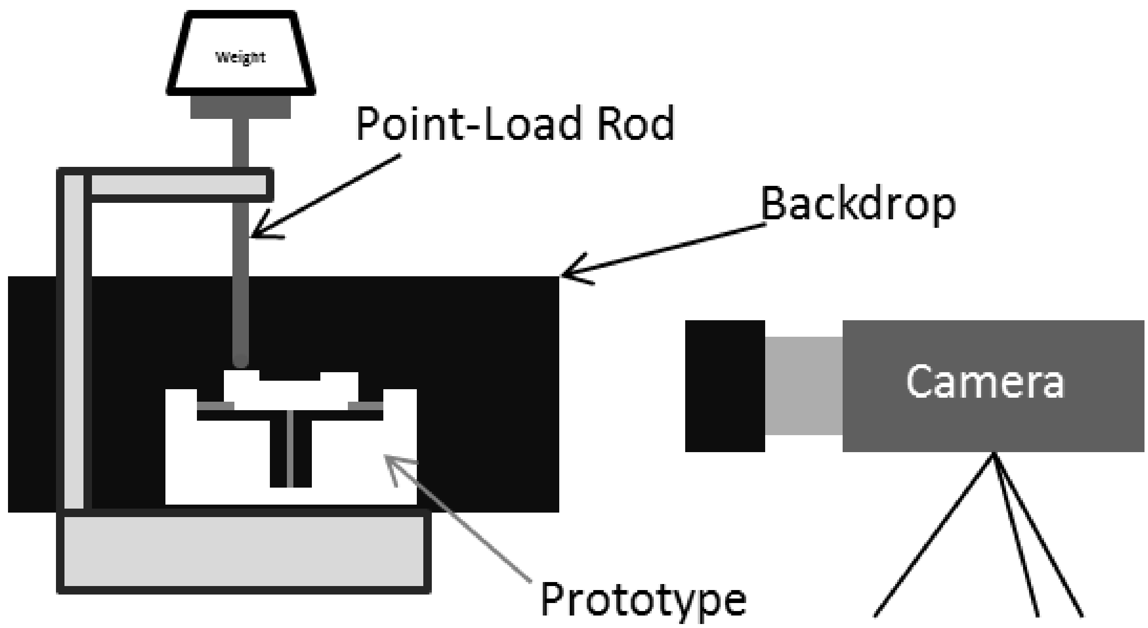

Figure 4-3: Illustration of Experimental Setup

In addition to checking the instantaneous axis of rotation, it is also necessary to ensure that the compliance of the mechanism is only present or at least significantly greater during the scenario of asymmetrical loading. This means that we should see large deflections when only one pin is loaded and not both. When the same load is distributed to both pins there should be significantly less deflections at these pins. In addition to the symmetric nature of loads during wafer chucking with no particles, the loads are typically smaller on the pins than when a particle is present. This is because the chucking pressure over the large area affected by a particle is transferred completely to the pin.

We can calculate the force on a pin caused by a particle, known as the crush force, by this simple formula (Tejeda et al., 2002).

$$k = \pi a^2 q$$

Where

k is the crush force,

a is the gap radius induced by the particle and,

q is the chucking pressure.

We can also calculate an estimation of the forces that a pin sees when only loaded by the wafer due to the chucking force. The formula for the force per pin is described in the following formula:

$$f = \frac{\pi r^2 q}{n}$$

Where

f is the force per pin,

r is the radius of the wafer chuck,

q is the chucking pressure, and

n is the number of pins on the wafer chuck.

These calculations also assume that all or most pins on the chuck are in contact with the wafer and the chucking pressure is uniformly distributed. We can then assume a chucking force of 80 kPa, a chuck radius of 100 mm, and ~32,000 pins (based on a pin pitch of 1mm and a contact area of 20%). With these assumptions we can calculate and estimate a force per pin value of 0.08 N. By using the same assumed values we can also calculate the force applied to a pin that has a particle that is introducing a 4mm gap radius (which corresponds to a particle with a ~100nm effective particle height). That force comes out to be 4 N. This shows that particles induce forces on pins nearly two orders of magnitude higher than pins with just the chucking force alone. This means the compliant mechanisms will be more accommodating to particles than to chuck pressure loading.

Also aiding the selectivity of compliance of particles versus compliance of wafer chucking is the symmetry of the forces. For non-particle scenarios, two pins sharing the same flexure stem will have equal forces that couple about the stem and produce no rotation. The load of the chucking force is transmitted through the stem into the chuck base. In a particle scenario not only is a larger force produced on only one of the pins but the gap radius produced causes the opposing pin to see little, if any, loading. This further magnifies the asymmetry of the load.

4.5.1 Scenario 1: Particle-Induced Compliance

The first scenario evaluated is that of particle compliance. A series of point loads were applied and compliance was recorded via a high-resolution camera. Images were evaluated using the ImageJ image processing software to determine compliant deflections observed. The ImageJ software was developed by the National Institutes of Health as a public domain, Java-based image processing software (URL: http://imagej.nih.gov/ij/). A graph of the force versus compliant deflection is shown in Figure 4-5.

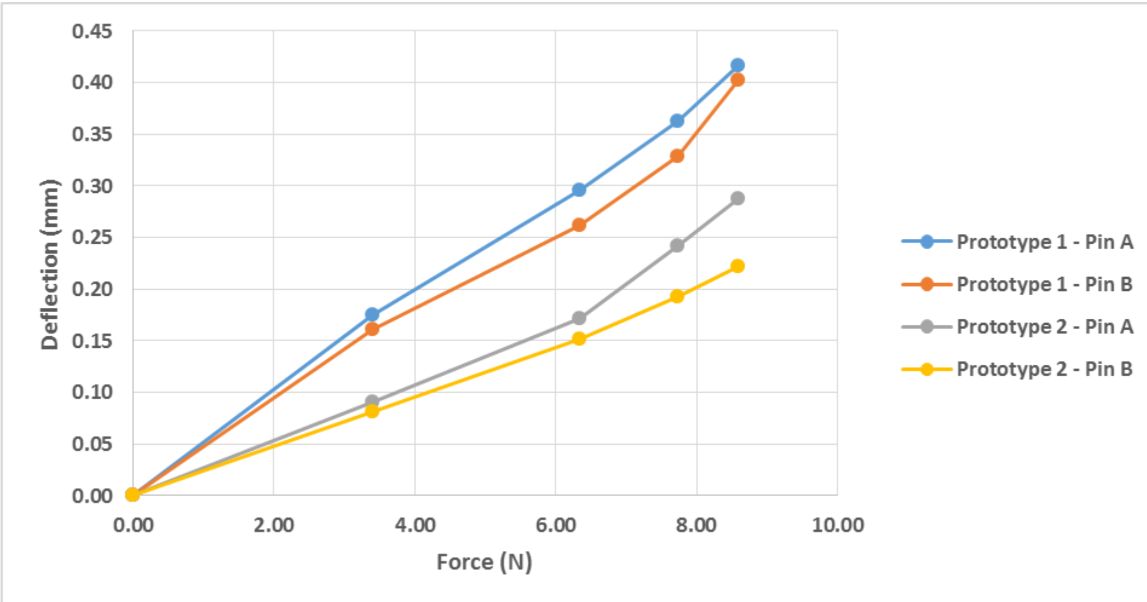

Figure 4-4: Point Load vs. Compliant Deflection of Prototype

These results show a good linear relationship between the load force and the resulting compliant deflection. The graph also shows good consistency between two pins on the same prototype but some differences between the two prototype parts built. This is most likely due to variations in the material properties of the sintered nylon.

An image showing the prototype unloaded is shown in Figure 4-6. An image showing the compliance of a loaded pin is shown in Figure 4-7. These images are further evaluated in Section 4.6.2 for the determination of the center of rotation.

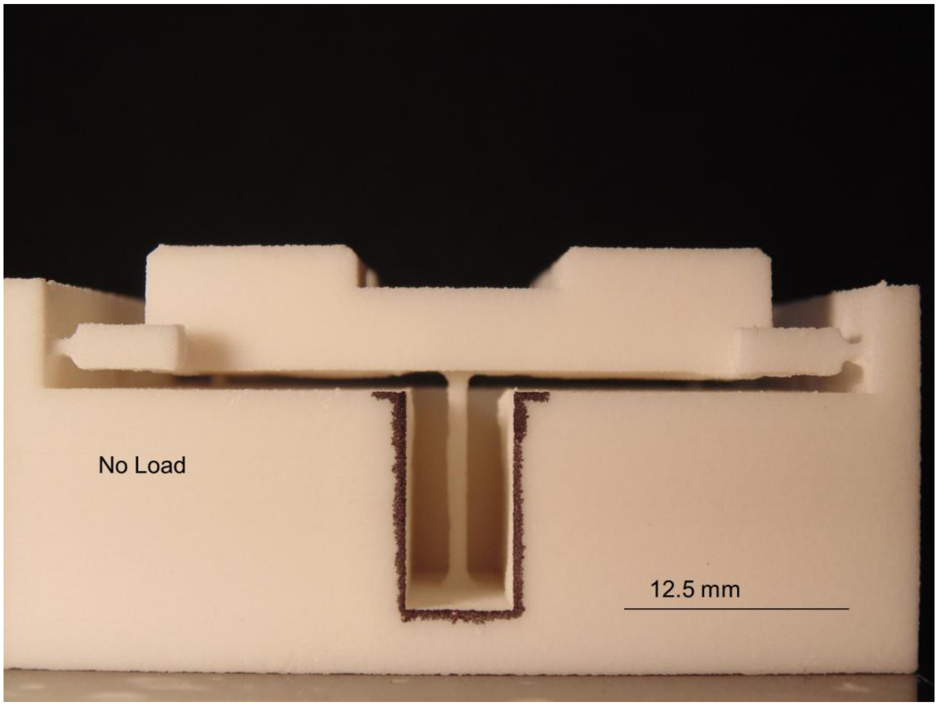

Figure 4-5: Image of Prototype (No Load)

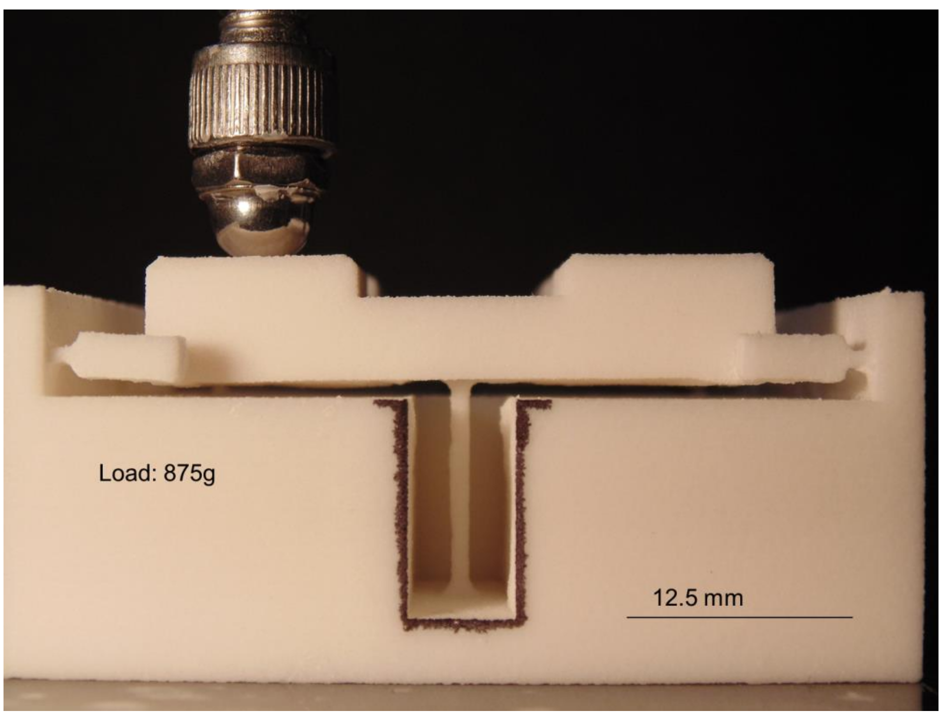

Figure 4-6: Image of Prototype Point Loaded

4.5.2 Scenario 2: Symmetrically Loaded Compliance

The additional scenario of a symmetrically loaded mechanism was also evaluated by using an intermediate part to distribute the force equally to two pins. Images of this scenario are shown in Figure 4-8 and Figure 4-9.

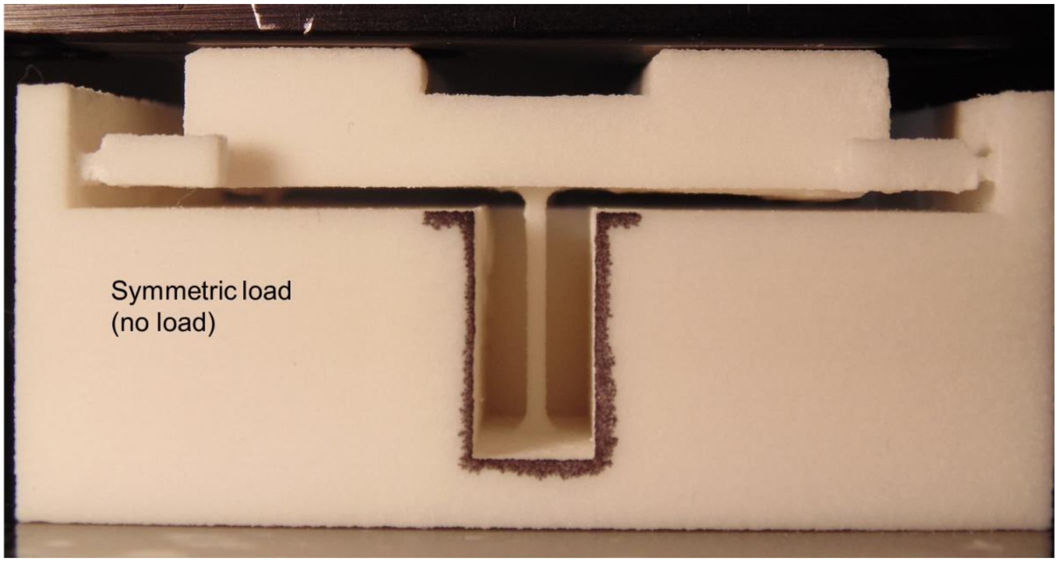

Figure 4-7: Image of Prototype Symmetrically Loaded (No Load)

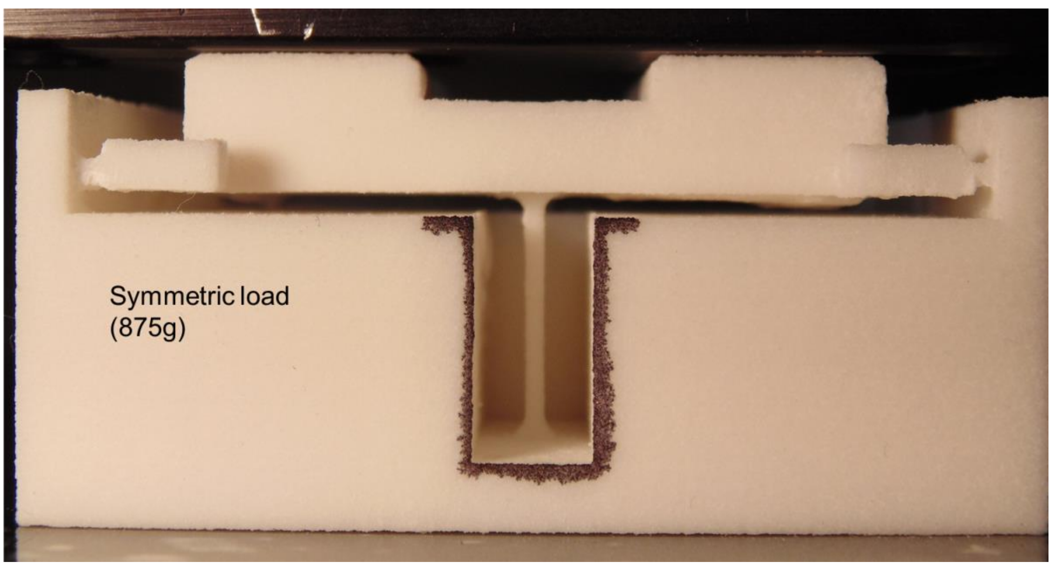

Figure 4-8: Image of Prototype Symmetrically Loaded (875g)

4.6 Discussion of Phenomena

This section discusses the evaluation of the prototype and the phenomena observed. This data and understanding is then used to suggest further improvements in Chapter 5.

4.6.1 Particle-Induced Compliance vs. Symmetrically Loaded Compliance

By investigating the two scenarios tested, the symmetrically loaded orientation was much stiffer than the asymmetrical point load. Negligible deflections of less than 10μm were observed under 875g of symmetric load. This is much lower than the 200-400μm deflections observed of the same load but only to one pin. This shows the design passes the requirement of having higher compliance for particle-induced loads versus symmetric wafer chucking induced loads.

4.6.2 Center of Rotation Evaluation

The second design requirement that needs to be maintained by the E-CPC is the location of the center of rotation for the compliant mechanism. By placing reference points along the joining structure of the pins and a constant landmark point on the base, we can track the motion of the body as a whole as the pin is loading differently. This motion can then be used to determine an approximate center of rotation. This evaluation indicates a center of rotation located in Figure 4-10.

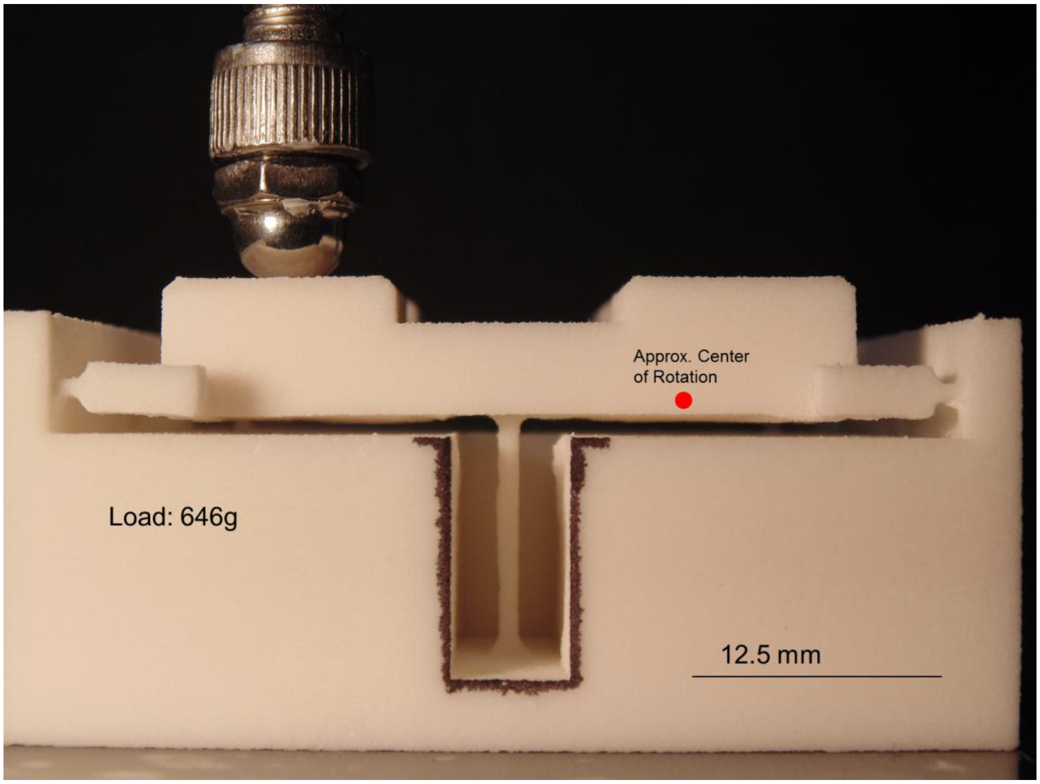

Figure 4-9: Approximated Center of Rotation

As the image shows, the center of rotation is not about the opposing pin but rather in between. A reassessment of the prototype design generates the reason for this behavior. Because the flexure members of the compliant mechanism are on a same plane orthogonal to the direction of deflection, the axis of rotation of the mechanism is free to occur anywhere on that plane.

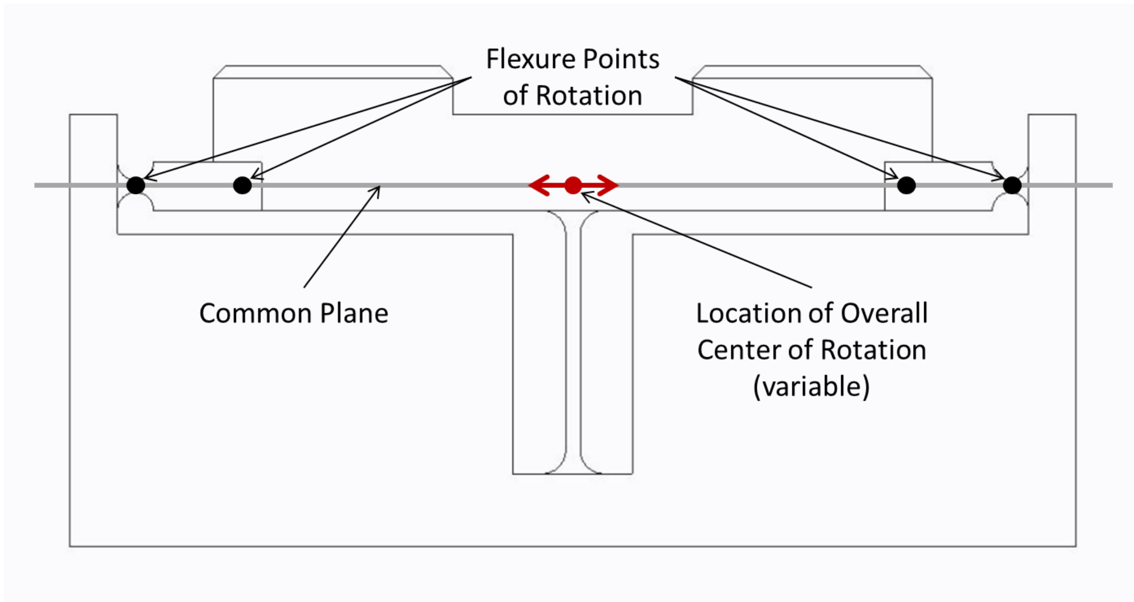

Figure 4-10: Illustration of Rotation Axis Variability

The exact location of the axis is determined by the combination of the compliant mechanisms involved. Stiffer components have more influence. The greater the influence the closer the center is to that component. The extremes of this help illustrate its effect. If no flexure stem existed in the current design then the axis of rotation would be about the flexure member of the opposing pin. On the other hand if the flexure stem was very large to the point where it is very rigid, then the center of rotation would be about the flexure stem. The intermediate scenario is the one that is observed with the prototype. Figure 4-12 further illustrates these scenarios.

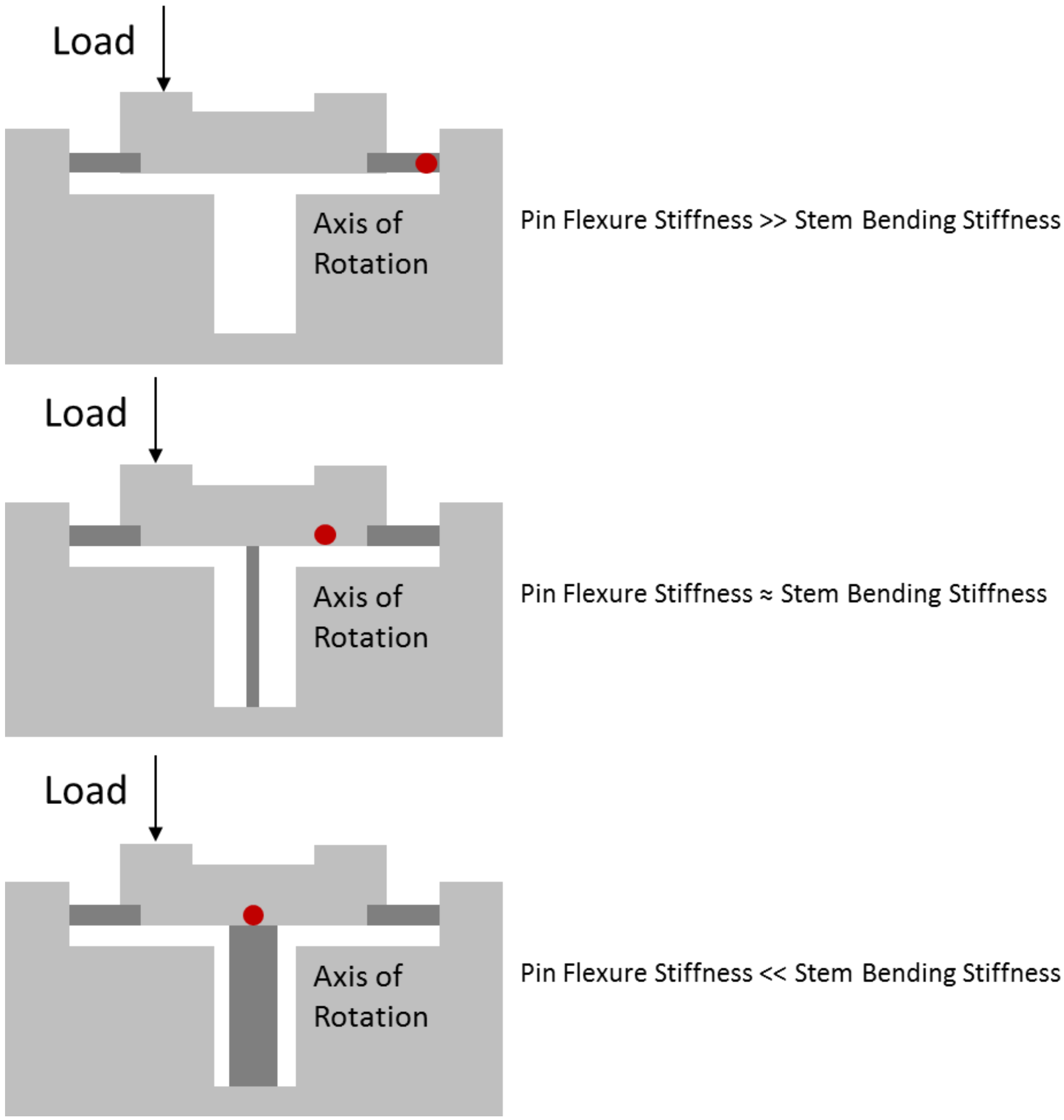

Figure 4-11: Stiffness Contribution to Location of Rotation Axis

This additional understanding shows that for the compliant pin chuck configuration to work, the flexures supporting each pin must collectively have a much higher bending stiffness than the flexure stem. This would effectively put the center of rotation at the opposing pin rather than somewhere in between.

From this evaluation it can be determined that the proposed design for an E-CPC in this research does not meet the requirement with regard to the center of rotation for the mechanism. By reducing the stiffness of the pin flexures to increase the sensitivity to particles the stiffness became much closer to that of the bending stiffness of the flexure stem resulting in a center of rotation that was shifted toward the stem. Suggestions for improving the compliant pin chuck sensitivity without compromising the center of rotation are discussed in the future work section of Chapter 5.

Chapter 5: Conclusions

5.1 Future Work

This section outlines how each of the concepts discussed in this thesis could be progressed towards improvements in effectiveness and eventual integration into a product deserving of industrial usage.

5.1.1 Particle-Eliminating Pin Chuck

The PEP chuck was demonstrated to be effective but it was not without flaws and has some areas that can be improved. On rare occasions, particles were relocated from one pin to another and still produced non-planarity. This could be prevented if the airflow was directed out and away from the edges of the chuck. To accomplish this, a multi-zone PEP chuck could be developed. By having multiple regions of the chuck that could be activated independently, one would have additional options to eliminate particles. Interior zones could be activated first then propagate outwards pushing any particles from the center regions to the edge and off the chuck. A multi-zone PEP chuck could also be used to target a specific area of the chuck where a particle is known to exist. The multi-zone chuck should be designed such that while a given region is activated for positive pressure, the other regions remain restrained with a vacuum. This would allow the wafer to be restrained even during particle elimination. It would also seal off particle-free areas from being contaminated by areas where particles exist. Such a design would be more complex both for fabrication and implementation. Care would need to be given to keep cost and chuck weight down.

Simpler improvements such as a design using a denser array of particle-eliminating pins and using higher air pressure for higher airflow velocity could be implemented fairly easily. One interesting idea worth investigating is using fluids other than simple dry air. Ionized air could be used to attract particles, pull them off the chuck surface, and carry them away. Certain liquids may also be effective at cleaning the chuck surface and wafer backside without introducing particles. More investigation would be necessary to evaluate the effectiveness of these concepts.

5.1.2 Enhanced Compliant Pin Chuck

From a design aspect, the proposed design for an E-CPC in this research was flawed with a center of rotation problem. With the understanding discussed in Chapter 4 the design could be corrected by stiffening the pin flexures and decreasing the flexure stem's bending stiffness. This would allow for the center of rotation to be shifted towards the opposing pin eliminating any unintentional rise of the pin.

The enhancements proposed for the compliant pin chuck in this research address the main areas of potential improvement. These areas are increased sensitivity and compliance to particle contamination, increased contact area to improve thermal conductivity of the chuck, and a unified design to eliminate assembly steps. The lack of a high resolution direct selective laser sintering method with the capability of fabricating silicon carbide with features of 25 μm in size is the largest obstacle for implementation. With the current momentum of three-dimensional freeform fabrication technology, it is reasonable to expect this capability to be developed in the near future. Once the technology is available, it can then be applied to the production of wafer chucks that are currently not feasible for fabrication.

5.2 CONCLUSIONS

Two wafer chuck concepts that mitigate the effects of particle contamination in photolithography were explored and evaluated in this research. Both methods showed promise for being effective in reducing the effects of particles at the interface of the wafer and wafer chuck. The particle-eliminating pin chuck that utilizes an in-situ method to deliver airflow was experimentally tested. The results showed an 18.5% increased effectiveness in clearing particles off of pins when used in conjunction with the conventional lateral sliding method. The proposed design for an E-CPC achieved its goals in increasing sensitivity to particles through softer flexures, an increased contact area through larger pins, and a one piece design through fabrication with selective laser sintering technology. However, the proposed design did not maintain the center of rotation requirements necessary for a compliant pin chuck. Both concepts would need to be matured but have the potential to be implemented into the semiconductor industry to help meet the future requirements of wafer site planarity and defectively. This would allow for maintaining or improving the yield of devices even as minimum feature sizes continue to decrease.

References

Aoyama, M., & Kimura, K. (1994). *Patent No. 5,324,012.* United States of America.

Babbs, D. A., Choi, B.-J., & Cherala, A. (2010). *Patent No. 7,798,801.* United States of America.

Bruning, J. H. (2007). Optical Lithography ... 40 years and holding. *Society of Photo-Optical Instrumentation Engineers*, 652004.

Butler, H. (2011, September 16). Position Control in Lithographic Equipment. *IEEE CONTROL SYSTEMS MAGAZINE*, pp. 28-47.

Cherala, A., Choi, B., Lu, X., & Sreenivasan, S. (2013). Active Wafer Shape Modulation Using a Multi-Actuator Chucking System. *ASPE Spring Topical Meeting – Precision Control for Advanced Manufacturing Systems*, (pp. 1-4). Cambridge, Massachusetts.

Firtion, V. A., Herriott, D. R., Poulsen, M. E., Rongved, L., & Saunders, T. E. (1980). *Patent No. US4213698.* United States of America.

Gianoulakis, S., Liddle, J., Stanton, S., & Gallatin, G. (2000). Thermal Distortion Predictions of a Silicon Wafer during Exposure in a SCALPEL Tool. *Microelectronic Engineering*, 357-360.

ITRS 2012 Update. (2014, February 6). Retrieved from The International Technology Roadmap for Semiconductors: http://public.itrs.net/Links/2012ITRS/Home2012.htm

Kemp, K., & Wurm, S. (2006). EUV lithography. *C. R. Physique 7*, 875-886.

Maltabes, J., Charles, A., & Mautz, K. (2001). *Patent No. 6,313,567.* United States of America.

Menon, V. B. (1996). *Patent No. 5,555,902.* United States of America.

Nimmakayala, P. K. (2004). Developement of a Compliant Pin Chuck for Minimizing the Effect of Backside Particles on Wafer Planarity. University of Texas at Austin.

Okazaki, M. (2008). Wafer flatness requirements for 45nm node (65 nm hp) lithography process. *IEEE/SEMI Advanced Semiconductor Manufacturing Conference* (pp. 356-358). Santa Clara, CA: IEEE.

Peschel, T., Kalkowski, G., & Eberhardt, R. (2012). Influence of thermal load on 450 mm Si-wafer IPD during lithographic patterning. *Alternative Lithographic Technologies IV.* Proc. SPIE 8323.

Siddall, G. J. (1985). *Patent No. 4,506,184.* United States of America.

Smith, S. T. (2000). *Flexures: elements of elastic mechanisms.* Boca Raton: CRC Press.

Stauch, H., Simon, K., Scheunemann, H.-U., Huber, H.-L., & Gabeli, F. (1993). Impact of Chuck Flatness on Wafer Distortion and Stepper Overlay. *SPIE*, 282-289.

Stevinson, B., Bourell, D., & Beaman, J. (2008). Over-infiltration mechanisms in selective laser sintered Si/SiC preforms. *Rapid Prototyping Journal*, 149-154.

Tejeda, R., Engelstad, R., Lovell, E., & Blaedel, K. (2002). Particle-induced distortion in extreme ultraviolet lithography reticles during exposure chucking. *Journal of Vacuum Science and Technology B*, 2840-2843.

Turner, K. T., Ramkhalawon, R., & Sinha, J. K. (2013). Role of wafer geometry in wafer chucking. *Micro/Nanolithography, MEMS and MOEMS*, 023007-1 to 023007-8.
Une, A., Ogasawara, N., Fukuda, T., Yoshise, M., & Xin, P. (2009). Influence of a lift hole-equipped pin chuck on wafer flatness. *Microelectronic Engineering*, 517-520.
Yamauchi, H., FASL, F. J., Shimajiri, M., Imaoka, K., & Takahashi, H. (2003). Removal of particles from wafer stage using wafer-formed cleaning material. *Semiconductor Manufacturing, 2003 IEEE International Symposium* (pp. 389-391). IEEE.

Vita

Andrew Ian Westfahl graduated in 2007 from Okeene Senior High School in Okeene, Oklahoma then continued his education by attending and graduating from Oklahoma State University in December of 2011 with a Bachelor of Science in Mechanical Engineering degree. He was then hired by Sandia National Laboratories as a part of the Masters Fellowship Program. Choosing to attend the University of Texas at Austin, he enrolled in the fall of 2012 pursuing a Master of Science degree in Mechanical Engineering.

E-mail address: drew.westfahl@gmail.com

This thesis was typed by the author.