Active membrane masks for improved overlay performance in proximity lithography

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ABSTRACT

Membrane masks are thin (2 micron x 35 mm x 35 mm) structures that carry the master exposure patterns in proximity (X-ray) lithography. With the continuous drive to the printing of ever-finer features in microelectronics, the reduction of mask-wafer overlay positioning errors by passive rigid body positioning and passive stress control in the mask becomes impractical due to nano and sub-micron scale elastic deformations in the membrane mask. This paper describes the design, mechanics and performance of a system for actively stretching a membrane mask in-plane to control overlay distortion. The method uses thermoelectric heating/cooling elements placed on the mask perimeter. The thermoelectric elements cause controlled thermoelastic deformations in the supporting wafer, which in turn corrects distortions in the membrane mask. Silicon carbide masks are the focus of this study, but the method is believed to be applicable to other mask materials, such as diamond. Experimental and numerical results will be presented, as well as a discussion of the design issues and related design decisions.

Keywords: membrane mask, thermoelastic, overlay, proximity, X-ray

1. INTRODUCTION

Thin membrane masks are integral components of proximity (X-ray) lithography. Membranes are typically 1 to 2 µm thick with lateral dimensions as large as 50 x 50 mm^2. Stable high strength materials, such as diamond and silicon carbide, form the membrane base material. Radiation absorbing materials, such as gold or tantalum, are written on the membrane in intricate patterns for lithography masking. The composite membrane base with absorber mask structure must be able to sustain the mechanical loads of the operating environment. Following stepping and alignment, the mask must settle to a precise overlay configuration quickly, and must maintain shape during repeated exposures.

The traditional alignment approach is to fabricate the membrane mask out of a very stiff and stable material, and to then use precise rigid body alignment methods. The drive towards printing ever finer features forces consideration of flexible-body mechanics during stepping and alignment.

There are multiple sources of in-plane overlay errors, including mask manufacture, thermal stresses during exposure, and tool-to-tool registration errors that arise in the multi-step processing of wafers. Rigid body motion alignment is unable to correct for all in-plane distortions, in particular those with gradients that vary across the mask. Controlled in-plane stretching may be a means of correcting for in-plane distortions that defy rigid-body alignment corrections. A thermoelastic technique has been developed to stretch the mask in plane so as to provide additional degrees of freedom that allow for gradient control of mask in-plane geometry.

2. MEMBRANE MASK MECHANICS

The mechanics of thin membrane masks are characterized by relatively small displacements that typically keep the strains to well within the elastic limits. In this context, the mechanics of membrane masks follow that of most deformable solids where the external forces cause internal strains that induce internal stresses that balance the external

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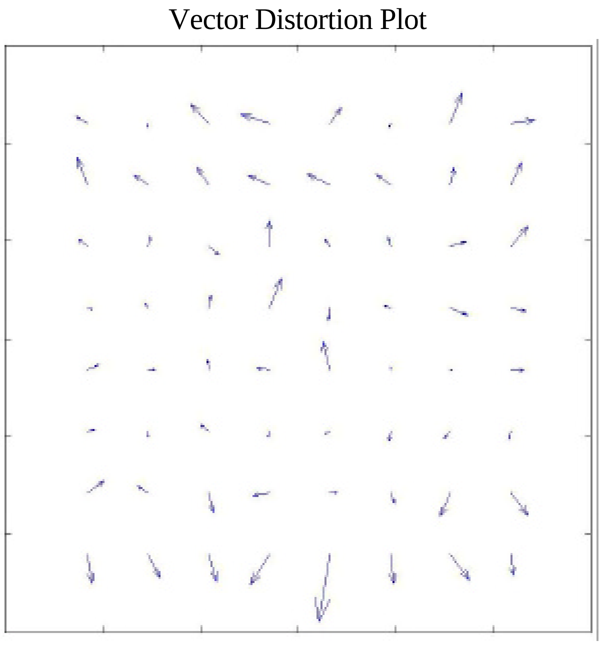
forces. The external forces on the membrane can be separated into those that act perpendicular to the membrane, i.e. out-of-plane forces, and those that are parallel to the membrane, i.e. in-plane forces. In-plane forces can include distortions due to processing, mask perimeter deformations, and gravity. Processing-induced in-plane stresses are of considerable concern with regard to the meeting of tight overlay tolerances. As a result, intensive steps are taken during the design and processing of membrane wafers so as to minimize the effects of in-plane stresses on overlay distortions. Nonetheless, these distortions arise and need to be corrected. Perimeter movements at the mask-wafer interface can also cause in-plane deformation. Controlled perimeter displacements as a means for correcting in-plane distortions are described.

Membranes are flat structures with span to thickness ratios on the order of 1,000 to 5,000. The composite mechanics of mask fine-scale absorber pattern structure with the base membrane may be very important in detail, but is assumed to form a structure that acts as a homogeneous isotropic continuum. The elastic mechanics of membranes can usually be split into out-of-plane and in-plane effects.

The in-plane linear elastic deformations in a thin membrane can generally be reduced to a two dimensional problem of plane stress elasticity[1]. That is, all forces, stresses and deformations act in a plane parallel to the top and bottom faces of the membrane, and in-plane deformations in the membrane are constant throughout its thickness. All numerical simulations that are described follow this assumption.

3. IN-PLANE OVERLAY ERRORS

In-plane overlay errors in masks can be characterized by measuring the actual location of a finite number of overlay-registration points on the membrane and comparing these measured positions to their intended positions. These overlay-registration points are typically evenly spaced in an x-y grid across the entire span of the mask membrane. Figure 1 illustrates a vector distortion plot of the overlay errors in a production mask membrane (provided by IBM).



X distortions:	Max= 0.020µm	Y distortions:	Max= 0.026µm
	Min= -0.024µm		Min= -0.057µm
	3 Std= 0.029µm		3 Std= 0.045µm

Figure 1: Vector Distortion Plot of Mask Overlay Error

Each vector represents the overlay error measured at each overlay-registration point. As these measurements were taken from a production mask, the magnitude of the overlay errors are representative of typical values using conventional passive mask error correction techniques. The current industry goals in X-ray lithography are to push the maximum X and Y overlay errors below the 10 nm threshold. Therefore, the aim of this research must be to accurately control membrane deformations, on the order of 10-20 nm, using thermoelastic actuation to correct such overlay errors.

4. IN-PLANE MASK DISTORTION CONTROL

Active control of in-plane deformation is a possible means for correcting uncontrolled distortions that give rise to overlay errors that cannot be corrected with rigid body alignment[2,3,4] There are several different techniques that can be used to effect a controlled in-plane distortion. These include mechanical or thermoelastic actuators applied to either the membrane, supporting wafer or supporting ring mount. After a careful consideration of the merits of the various possible design concepts, it was decided to attempt to control in-plane distortions by thermoelastically controlling the motion of the membrane support perimeter with thermoelectric techniques. Thermoelectric modules positioned on the membrane mask support wafer near to the perimeter of the membrane so as to impose a controlled temperature distribution throughout the wafer and mask. The localized temperature differences due to each thermal actuator causes a controlled thermoelastic deformation in the wafer, which if properly set, will correct distortions in the membrane mask. Bipolar thermoelectric controllers enables imposing temperatures above and below the ambient, which causes either expansion or contraction.

Appropriate temperatures for each thermal actuator can be determined using a linear control algorithm[2]. A change in temperature at any one of the thermal actuators will affect the position of every overlay-registration point uniquely. Therefore, by applying a one degree Kelvin temperature difference at each actuator and recording the respective x and y displacements of each overlay-registration point, an [M x N] temperature influence matrix, [A_{xy}], can be assembled with M actuators and N degrees of freedom to relate the effect of change in temperature of each actuator to the change in position of each overlay-registration point.

$$\left[A_{xy}\right]\left\{T\right\}=\left\{d_{xy}\right\} \tag{1}$$

This linear relationship is only valid for in-plane thermal strains that do not cause any inelastic deformations, buckling in the mask membrane, or other nonlinear effects.

In order to correct distortions in the mask, (1) can be used to determine the temperature applied to each actuator given the desired displacement of each overlay-registration point as dictated by the difference between measured and intended position. Solving for the applied temperatures, the influence matrix must be inverted such that

$$\left[A_{xy}\right]^{-1}\left\{d_{xy}\right\}=\left\{T\right\} \tag{2}$$

For non-square influence matrices, the Pseudo-Inverse or Moore-Penrose matrix may be used

$$\left[A_{xy}\right]^{\dagger}\left\{d_{xy}\right\}=\left\{T\right\} \tag{3}$$

where

$$\left[A_{xy}\right]^{\dagger}=\left(\left[A_{xy}\right]^{T}\left[A_{xy}\right]\right)^{-1}\left[A_{xy}\right]^{T} \qquad (4)$$

The thermoelectric controllers can then be set to maintain these temperature differences above or below ambient, as needed. The wafer and mask will undergo thermoelastic deformations and the overlay-registration points should move closer to their intended position. Depending on the performance of the control algorithm used, it may be necessary to re-measure the position of the overlay-registration points and iterate the temperature difference applied to each actuator.

The performance of the control algorithm is strongly affected by the number and location of both the thermoelastic actuators and the overlay-registration points. It has been shown that the condition number of the actuation influence matrix gives a good indication of the performance of the error correction system[2]. An influence matrix with a low condition number can be inverted with great accuracy, thus introducing minimal mathematical errors to the applied temperature solution. The magnitude of the condition number of the influence matrix can therefore be used as a good measure in evaluating various actuator and overlay-registration point scenarios.

The position of the overlay-registration points can be precisely controlled only if there are an equal number of thermoelastic actuators as degrees of freedom for the overlay-registration points. Typical production mask membranes have many features with critical dimensions, thus it is unlikely that there will be as many thermoelastic actuators as overlay-registration points. With more degrees of freedom than actuators, the x and y positions of each overlay-registration point cannot be precisely controlled, and accordingly this method cannot correct random localized distortions in the mask. This method is best suited to correct global or systemic mask distortions. However, it is possible that displacing nearby overlay-registration points may reduce localized errors in excess of an allowable threshold.

A two dimensional, plane stress, finite element method model was created to simulate the deformations in the mask due to applied temperatures in the wafer. Eight thermoelastic actuators were positioned on a silicon wafer around the perimeter of a silicon carbide mask, see Figure 2. As this simulation was 2D, the appropriate mask material properties were scaled to approximate its two-micron thickness and convective heat loss from the top and bottom surfaces of the wafer were neglected. Four overlay-registration points with eight degrees of freedom (x and y displacements) were chosen at locations symmetric about the center of the mask where $(x_1, y_1)=(0.009, 0.009)$, $(x_2, y_2)=(-0.009, 0.009)$, etc (all displacements in meters). The thermoelastic influence matrix was determined from finite element simulations where a single temperature difference was applied with each actuator and the motion of the overlay-registration was recorded. Figure 3(a&b) shows typical results of the finite element models of temperature and displacement.

The result of the finite element simulations was that the a one degree Kelvin change in temperature at the thermoelastic actuator produces displacements of the overlay-registration points as large as 55 nm. A 0.1 degree Kelvin change in temperature at the thermoelastic actuator produces displacements of the overlay-registration points as large as 5.5 nm. Under the idealized conditions of a 2D finite element simulation, eight thermoelectric actuators can precisely control the displacement of the overlay-registration points.

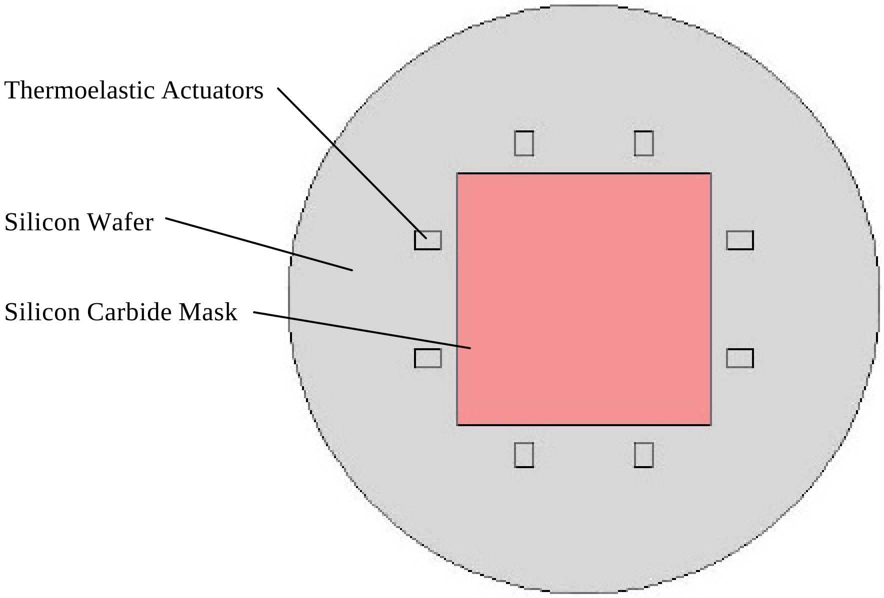


Figure 2: Schematic of finite element thermoelastic actuation model

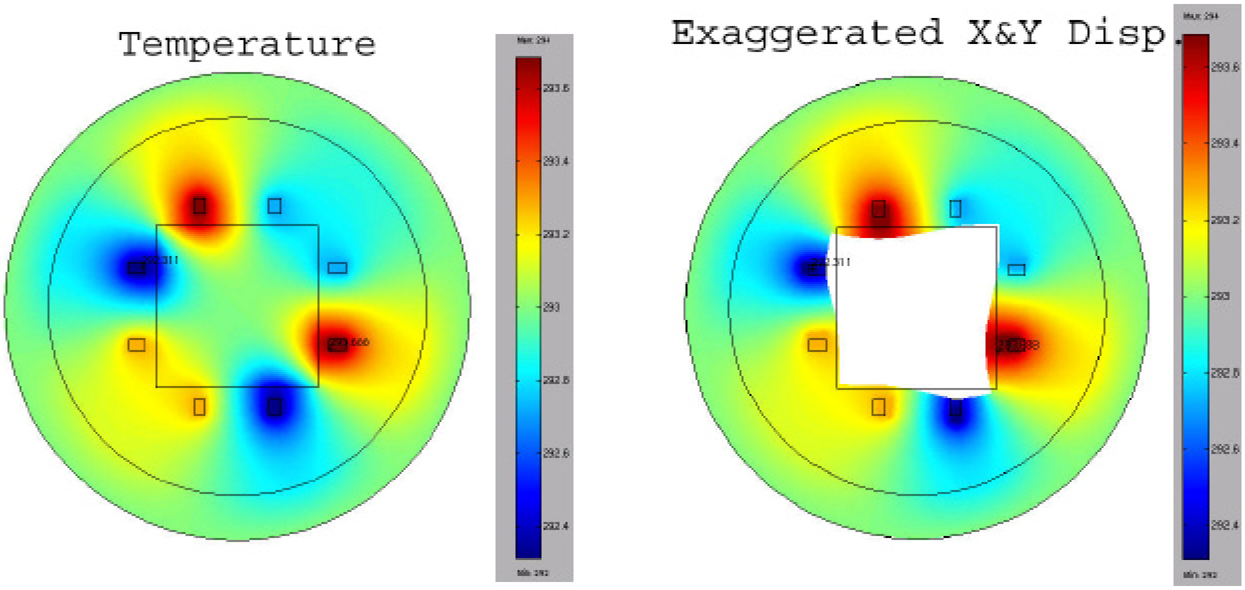


Figure 3: a. FEM temperatures

b. FEM deformation exaggerated

The finite element model not only simulated mask deformation due to applied temperatures in the wafer, but also served as a useful tool to quickly evaluate (along with the matrix condition number) the performance of various thermal actuator arrangements. Similar simulations were conducted on wafers with holes positioned around the mask to alleviate out of plane mask distortion due to aerodynamics. As expected the holes around the mask served as flexures and made the distortions in the mask slightly easier to control with slightly less heat required for actuation.

Based on the encouraging results of the finite element simulations, an experimental program was initiated to verify the efficacy of the technique. The first set of experiments was intended to determine how well thermoelastic actuation can control the displacement in a silicon wafer. The tests used a resistive heater and a resistive temperature device (RTD) to monitor temperature as various temperature differences were applied to a piece of silicon wafer. Deformations in the edge of the wafer were observed using a CCD digital camera connected to a Lietz 1000X microscope. These deformations were recorded by manually counting the change in pixels between images captured at ambient temperature and at an elevated temperature. Using a microscale the diameter of the field of view was determined which related pixels to microns. The results from this experiment are plotted in Figure 4.

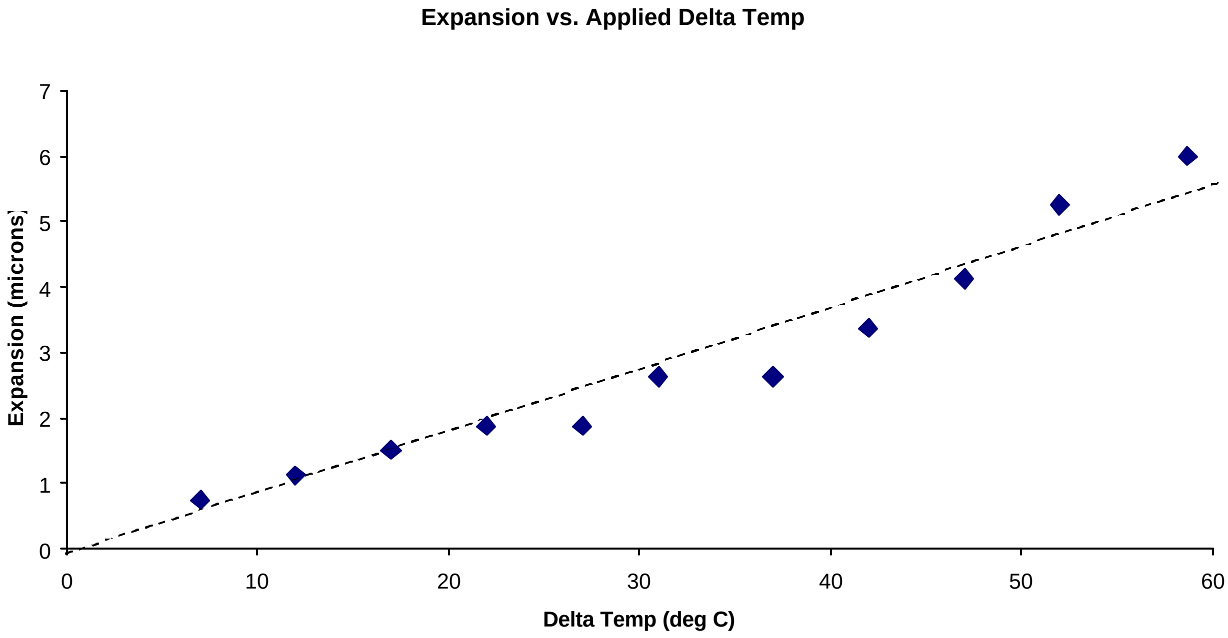


Figure 4: Wafer edge deformation vs. Applied temperature difference

The data were slightly scattered which can be attributed, for the most part, to the wafer slipping on its fixture in the opposite direction of the thermal expansion. Although only a preliminary proof-of-concept experiment, it demonstrated a reasonable level of deformation control in a silicon wafer using thermal actuation

The next logical step in experimentation was to demonstrate single axis control of deformation in an actual mask membrane. Two thermoelectric modules were positioned on a silicon wafer around the perimeter of an X-ray lithography mask, as shown in Figure 5.

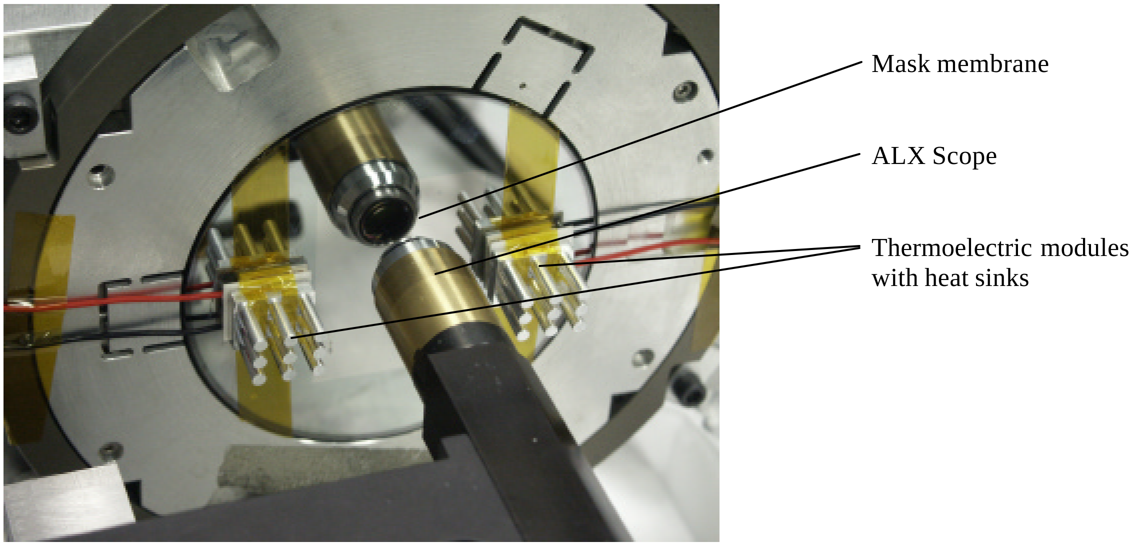


Figure 5: Thermoelastic actuators mounted on wafer

The temperature was controlled at each thermoelastic actuator with an RTD and thermoelectric temperature controller. Elevated temperatures were applied via the thermoelectrics at each actuator site while deformations in the mask membrane were observed using a SUSS ALX alignment system. The SUSS ALX is a three-camera video based system that is used to set the alignment and gap between the mask and the wafer substrate in an X-ray lithography tool. Developed by SUSS in 1991[5], the ALX auto-focuses on a specified alignment target pattern of white bars against a dark background, shown in Figure 6a. The intensity of each pixel is then summed by row and column, forming X and Y vectors of intensity summation values for each axis across the entire field of view. A sample plot of intensity summation values vs. pixels is shown in Figure 6b. From this plot, the position of the outside edges of each bar may be determined, as indicated by the dual minimum peaks for each of the four bars in the target. Thus the position of the center of each bar may be determined and accordingly the position of the center of the target, with respect to the field of view, may be determined. This process yields an interpolation beyond the diffraction limit and can be used as a metrology tool with an accuracy of approximately 5 nm.

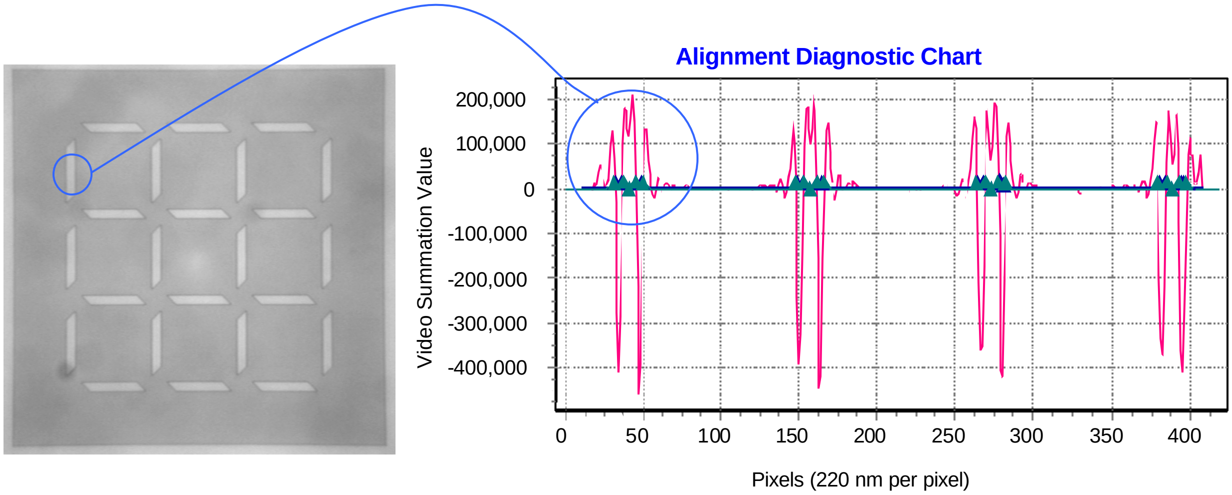


Figure 6: a. ALX Target

b. Video Summation Plot

Unfortunately, despite every effort to reduce environmental and mechanical interference, the ALX maintained a steady drift between 2 and 10 nm per minute. This drift made it exceedingly difficult to decipher the steady state change in position after imposing elevated temperatures. However, deformations were noticeable (over the drift) shortly after the elevated temperatures were imposed, and since the drift was consistent over time, it could be removed from the data points. Figure 7 is a plot of deformations observed (with drift removed) in the mask membrane, one minute after an elevated temperature was applied, versus various applied temperatures.

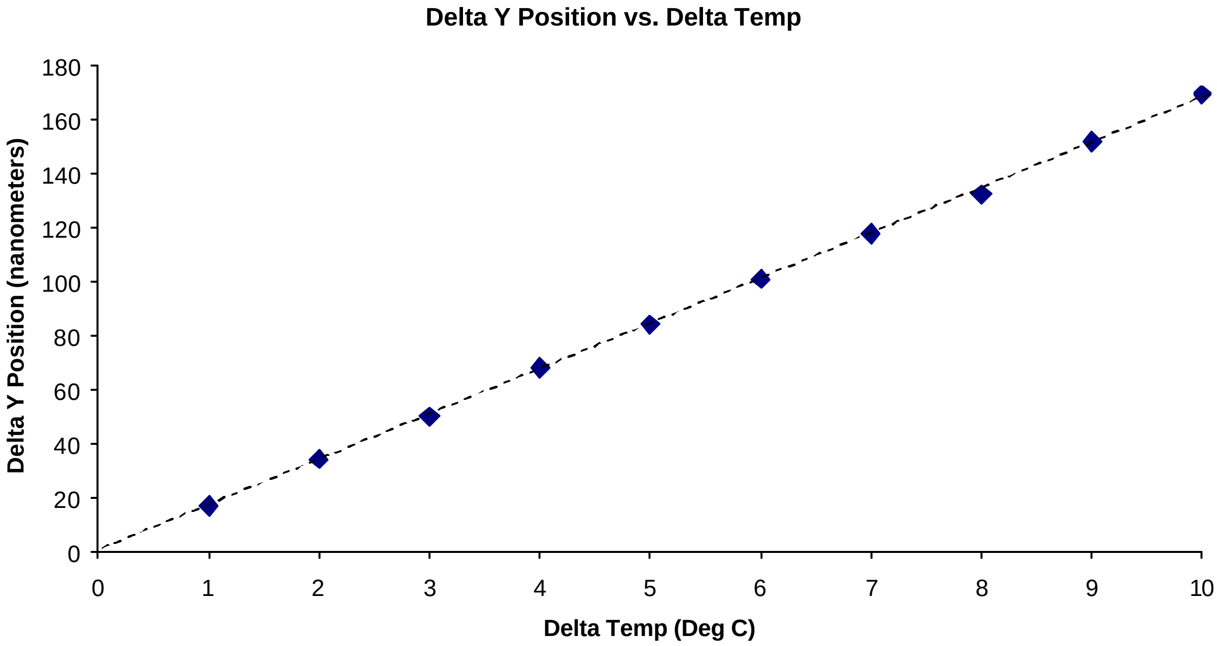


Figure 7: Delta Y-Position vs. Delta Temperature

As indicated by the linearity of the data in Figure 7, the initial response in the mask membrane to thermoelastic actuation was extremely consistent and thus shows some promise in the control of in-plane deformations as a means of correcting overlay errors. Future work will be aimed at improving metrology techniques to eliminate drift and accurately observe deformations in the 0-20 nm range and also to correlate these findings with a transient FEM simulation.

CONCLUSIONS

Membrane masks being flexible elastic structures can experience significant mechanical deformation that can affect performance in proximity lithography. Only in-plane distortions have been examined. Numerical simulations and experiments indicate that it may be possible to control modest in-plane distortions by thermoelastic actuation.

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REFERENCES

1. A. P. Boresi, and K. P. Chong, *Elasticity In Engineering Mechanics*, Elsevier Applied Science Publishers Ltd., New York, 1987, pg. 357.
2. D. Huston, and W. Sauter. “Mask Stretching for Next Generation Lithography Masks” IEEE Transactions on Semiconductor Manufacturing, 2001.
3. N. Mizusawa, K. Uda, Y. Tanaka, H. Ohta, and Y. Watanabe, “Technology and Performance of the Canon XRA-1000 Production X-ray Stepper” J. Vac. Sci. Technol. B 18(6), Nov/Dec 2000.
4. M. Feldman, H.I. Smith, K.-I. Murooka, and M.H. Lim, “Adaptive lithography membrane masks” U.S. Patent 6,404,481, June 11, 2002.
5. R. E. Hughlett, and K. A. Cooper, “A Video Based Alignment System for X-ray Lithography” SPIE Vol. 1465, 1991, pg 100-110.