Quantifying distortions in soft lithography

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This article describes a moiré technique for determining distortions in soft lithography. We use the technique to investigate distortions when soft lithography is performed in a variety of configurations; a method is identified for limiting maximum distortions to less than 1 μm over areas ~ 1 cm^2. We also suggest an approach for actively controlling these distortions, and we demonstrate in a simple way its feasibility. © *1998 American Vacuum Society.* [S0734-211X(98)01801-0]

I. INTRODUCTION

The demand for low cost processes for manufacturing structures with nanometer to micrometer feature sizes has stimulated the development of new strategies for micro- and nanofabrication. One new set of techniques, which we refer to as "soft lithography," relies on elastomeric elements to print patterns of "inks" (microcontact printing, or μCP[1]), to mold polymers (micromolding in capillaries, or MIMIC,[2] microtransfer molding, or μTM,[3] or replica molding[4,5]) or to perform photolithography in the near optical field.[6] Although these methods are simple, intrinsically inexpensive, applicable to large areas in a single process step, and able to pattern non-planar substrates, it has not been demonstrated that they meet the requirements for registration and for low defects for fabrication of complex microelectronic and microelectromechanical systems (MEMS). While the densities of defects in patterns of inks of alkanethiols formed by μCP have been evaluated,[7] the errors in registration of patterns produced by μCP have not been determined. These errors and those produced with other soft lithographic methods, such as μTM and MIMIC, have three sources: (i) inaccuracies in positioning the elastomeric element relative to the substrate, (ii) intrinsic distortions of the element introduced during its fabrication, and (iii) distortions caused by elastic deformation of the element when it is brought into contact with the substrate. The first of these contributions is present in conventional lithographic schemes, and we do not expect it to be any more or less significant in soft lithography. We believe that distortion of the elastomer, which is analogous to optical aberration in projection mode photolithography, represents a larger uncertainty for achieving accurate registration in soft lithography. Two kinds of distortions are of particular interest: (i) *absolute* distortions of patterns compared to their desired geometries and (ii) *relative* distortions of patterns compared to one another.

In this article we describe a convenient means for quantifying both types of distortions. The technique uses moiré patterns generated with test grids on the surfaces of, or produced by, elastomeric elements used for soft lithography, and reference grids on rigid substrates. This approach enables routine measurement of distortions as small as ~ 500 nm over macroscopic areas without the need for high resolution microscopy. The article begins with a brief description of moiré patterns and of how they can be used for determining distortions in soft lithography. The basic principles are illustrated by determining known distortions in opaque macroscopic patterns on transparent film. We then use this technique to determine (i) *absolute* distortions of elastomeric elements used for soft lithography (i.e., distortions associated with the elements themselves), (ii) *absolute* distortions of these elements after they are brought into conformal contact with rigid substrates (i.e., distortions associated with pattern transfer), and (iii) *relative* distortions of pairs of patterns generated with these elements using μCP (i.e., distortions important for fabricating multilevel structures with soft lithography). The results indicate that thin (~ 0.1 mm) elements cast against rigid supports have the smallest absolute distortions both before and after contacting a substrate. For this system, we find absolute maximum distortions ~ 500 nm over square areas ~ 1 cm^2. Other results show that relative distortions of pairs of patterns produced with μCP by hand can be ~ 500 nm over square areas ~ 0.25 cm^2 when thick (~ 8 mm) elements with high modulus are used. Finally, using the typical magnitudes of the measured distortions, we offer a plausible argument for an approach for actively controlling and eliminating the distortions; we demonstrate in a simple way the feasibility of this approach.

II. THEORY

A. Qualitative description

Overlay of two periodic or quasiperiodic structures whose periodicities and alignment are similar produces a new coarse structure, known as a moiré pattern. For many years, these patterns have been used as powerful tools in scientific and engineering metrology. To evaluate distortions in soft lithography, we applied moiré patterns produced by overlay of square grid patterns with micron feature sizes. We begin by describing those formed with arrays of parallel lines. Results obtained from this special case can be applied in a straightforward way to analysis of moiré patterns formed from grids with micron dimensions.

Figure 1 illustrates two situations that will be relevant here. The moiré patterns in the left frames are produced by arrays of lines with equal periodicities superimposed at a

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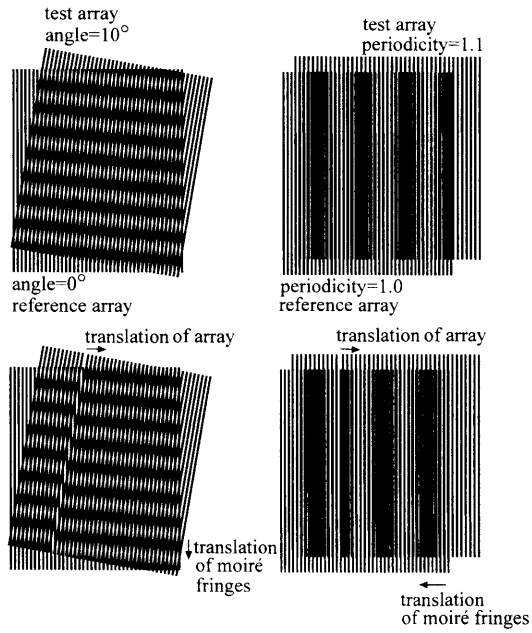

FIG. 1. Illustration of the relationship between distortions of a moiré pattern and those of a test array. For simplicity, moiré patterns formed by two arrays of parallel lines (one reference array and one test array) are shown. Two cases are illustrated: (i) Left frames: The periodicities of the reference and test arrays are the same and the angle between them is small and (ii) right frames: the periodicities of the reference and test arrays are slightly different and the angle between them is zero. In the first case, the moiré fringes are approximately perpendicular to lines of the arrays; distortions of the fringes are determined by the angle between the lines, their periodicity, and the distortion of the test array. In the second case, the moiré fringes are parallel to the lines of the arrays; distortions of the fringes in this case are determined by the periodicities of the reference and the test arrays and by distortions of the test array. In both cases, a translation of part of one of the arrays by ~1/2 of the period of the array produces a translation of part of the moiré fringes by ~1/2 of the period of the moiré pattern.

small angle. Translation, or distortion, of part of one of the arrays by a fraction of its period in a direction perpendicular to the lines causes a translation, or distortion, of the moiré pattern by a similar fraction of its period in a direction perpendicular to its fringes. The patterns illustrated in the right frames of Fig. 1 are associated with arrays of lines with slightly different periodicities superimposed at zero angle. Translations, or distortions, of part of one of these arrays by a fraction of its period in a direction perpendicular to its lines causes translations or distortions of the moiré pattern by a similar fraction of its period in the same direction. An important point for our purposes is that in both cases the moiré patterns amplify distortions of the arrays; amplification factors of ~100 can be achieved easily.

B. Quantitative analysis

Quantitative determination of distortions of the arrays from distortions of the moiré patterns requires a description of the patterns and their relation to the geometry of the underlying arrays. For simplicity, consider moiré patterns produced with a reference array of lines with periodicity d and a test array of lines with periodicity ad, where a is a constant.

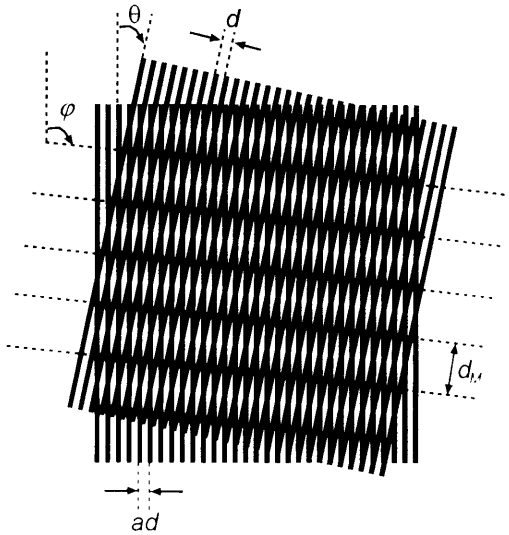

FIG. 2. Moiré fringes formed by two linear arrays of lines and spaces. d is the reference array periodicity, and ad is the test array periodicity, where a is a constant. θ is the angle between the two arrays, which gives d_M the periodicity of the moiré pattern and φ, its angular orientation. The symbols are defined in the text.

Figure 2 illustrates the geometry. The periodicity of the moiré pattern, d_M, and its angular orientation, φ, depend on the angle, θ, between the two arrays of lines, and the values of a and d in the following fashion[8]

$$d_M=\frac{a}{(1+a^2-2a\cos\theta)^{1/2}}d$$

and

$$\sin\varphi=\frac{\sin\theta}{(1+a^2-2a\cos\theta)^{1/2}}. \quad (1)$$

The constant of proportionality relating d_M to d determines the sensitivity of the positions of the moiré fringes to distortions of the test array. Small values of θ maximize this constant and, therefore, the sensitivity. For moiré patterns in this article, θ will be close to zero and a will be close to one. In particular, two limits will be important: (i) $|1-a|\ll\theta\ll 1$ and (ii) $|\theta|\ll|1-a|\ll 1$. In the first limit, Eq. (1) reduces to

$$d_M\approx\frac{d}{|\theta|}$$

and

$$\sin\varphi\approx 1, \text{ for } |1-a|\ll|\theta|\ll 1. \quad (2)$$

In this case, the angle between the reference and test arrays determines the spacing of the fringes in the moiré pattern and their sensitivity to distortions of the test array. In particular, distortions of the test array along x with magnitude Δd cause distortions of the moiré fringes along y with magnitude $\Delta d/\theta$. When $\theta>0$, distortions of the moiré pattern and distortions of the array have opposite signs. For $\theta<0$, they have the same sign. θ is typically set experimentally.

In the second limit, Eq. (1) reduces to

$$d_M \approx \frac{1}{|1-a|} d$$

and

$$\sin \varphi \approx 0, \text{ for } |\theta| \ll |1-a| \ll 1. \quad (3)$$

In this case, the difference in periodicities of the reference and the test arrays determines the spacing of the fringes in the moiré pattern and their sensitivity to distortions of the test array. In particular, distortions of the test array along x with magnitude Δd produce distortions of the moiré fringes along x with magnitude $\Delta d/|1-a|$. For $a>1$, distortions of the moiré pattern are opposite in sign to distortions of the test array. When $a<1$, they have the same sign. For situations encountered in this article, a is close to one, but its exact value is unknown. For example, if the reference array is produced using the same template as a test array on an elastomeric element, then a measures the (unknown) isotropic shrinkage or expansion of the element during or after its fabrication. The quantity $|1-a|$ can be determined from the periodicities of the moiré pattern and the reference array. The sign of a can be determined by rotating the reference array and observing the sense of rotation of the moiré fringes. If the fringes rotate in the same direction as the reference array, $a>1$; if the fringes rotate in the opposite direction, $a<1$.

C. Verification of the method

To verify Eqs. (2) and (3) and conclusions drawn from them, we examined moiré patterns produced with grids with known geometries and distortions. We used commercially available software and a high resolution printer to generate opaque undistorted grids (250 μm lines and 250 μm spaces) and those with known distortions (amplitudes <200 μm) on transparent film. Moiré patterns produced by overlaying two pieces of film were recorded with a charge coupled device (CCD) camera and then analyzed; Figure 3 summarizes the steps. The 8-bit gray-scale images were first digitally manipulated to replace all black pixels (i.e., all pixels with gray-scale values of 0) with gray pixels (i.e., pixels with gray-scale values of 3). We then used commercially available software to insert by hand black pixels at the crossing points of moiré fringes. Specially designed software located the black pixels, recorded their position, and determined the average periodicity of the moiré pattern from the average separation of adjacent black pixels. The software then generated a square grid with this average periodicity and fitted the grid to the measured moiré pattern by translating (and in some cases by slightly rotating) the grid to minimize the sum of squared differences between positions of intersections of the lines of the grid and positions of intersections of moiré fringes (i.e., the black pixels) in the measured pattern. The mismatch between the fitted square grid and the measured moiré pattern defines the distortion of the pattern; expressions given in Sec. II B relate the magnitudes of these distortions to distortions of the test grid.

To verify this approach, we studied patterns produced with: (i) square reference grids overlayed at small positive and negative angles on test grids with the same average periodicity that contained well-defined distortions and (ii) square reference grids overlayed at zero angle on test grids with slightly larger and smaller average periodicities that contained well-defined distortions. Figures 4 and 5 summarize these cases and their analysis using Eqs. (2) and (3). Although distortions of the moiré patterns vary widely, the calculated distortions of the test grids are the same. Furthermore, they agree with the actual distortions; see Fig. 6. We also note that the a parameter determined from data illustrated in Fig. 5 agrees with the known value.

III. EXPERIMENT

We now describe the use of the moiré technique to determine distortions encountered in soft lithography. The test and reference grids were produced from square grid patterns in photoresist that were generated using photolithography. Elastomeric elements with surface relief in the same geometry as the resist were formed by casting and curing polydimethylsiloxane (PDMS) against the patterned resist. The surface relief on these elements, or grids produced with them using μCP, were used as test grids. For evaluating relative distortions, grids fabricated with μCP also served as reference grids. Grids formed on glass and silicon substrates with lift-off using the patterned photoresist served as reference grids for determining absolute distortions. Figure 7 illustrates the procedures for fabricating the various test and reference grids.

A. Absolute distortions of elastomeric elements used for soft lithography

We used the approach described above to study absolute intrinsic distortions of the elements, absolute distortions induced by contacting a substrate, and the dependence of these distortions on the construction of the elastomeric elements. All measurements were collected with reference grids formed by lift-off and using the apparatus shown in Fig. 8. We used this apparatus to set the angle between the test and reference grids to within ~ 0.01 degrees, and to control the separation of the elastomeric elements and the reference grids.

We established our limit of sensitivity by examining moiré patterns formed with grids of gold (~ 400 Å) on glass and on silicon. Equation (2) was used for analyzing the patterns; Figure 9 illustrates typical results. The measurements indicate that the moiré technique enables determination of absolute distortions with amplitudes as small as a few hundred nanometers over square areas of ~ 1 cm^2.

Distortions in elastomeric elements with surface relief (depth ~ 1 μm) in the geometry of grids were examined before and after coming into contact with silicon wafers that supported reference grids of gold or silver. In spite of the fact that the elastomeric elements were optically transparent, we observed moiré patterns when these elements were brought close (<0.5 mm) to the reference grids. We believe that contrast necessary to produce the patterns was provided by diffraction induced by surface relief on these elements. In

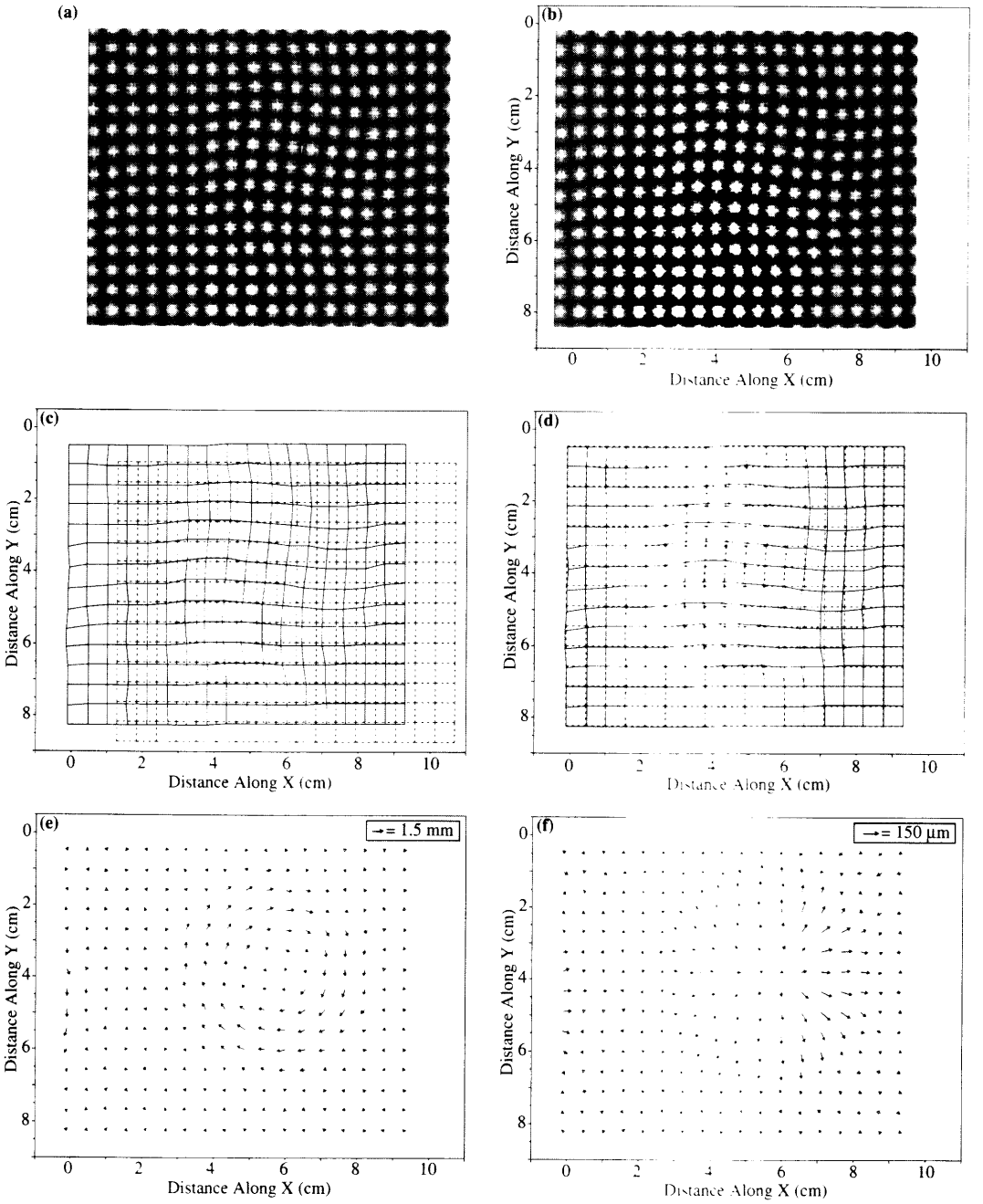

FIG. 3. Steps for interpreting moiré patterns. (a) A moiré pattern is formed using square reference and test grids (in the example shown here, 250 μm lines and 250 μm spaces). The pattern is digitized using a microscope with low magnification and a CCD camera. (b) Intersections of fringes of the moiré pattern are located by eye and marked with black pixels. The positions of these black pixels are evaluated and recorded. (c) The average periodicity of the moiré pattern defines the dimensions of a square grid. (d) The square grid is translated (and in some cases slightly rotated) until the sum of squared differences between the positions of intersections of lines of the square grid and positions of intersections of fringes in the moiré pattern is minimized. (e) The difference between the positions of intersections of lines in the fitted grid and intersections of fringes of the moiré pattern defines the distortion of the moiré pattern. (f) The periodicity and distortion of the moiré pattern and the periodicity of the underlying reference grid determine the distortions of the test grid.

order to verify that the moiré patterns generated in this manner are the same as those generated with soft lithography, we performed μCP and compared the moiré patterns produced with the stamp in contact with the substrate (i.e., during the pattern transfer step and in the configuration used for the measurements described below) to those produced after etching the stamped substrate (i.e., after the pattern transfer step). In all cases, we found the geometries of the moiré patterns to be the same.

Our study of absolute distortions included recording and analyzing moiré patterns for elastomeric elements (i) with thicknesses ~3 cm supported by bringing them into contact[9] with rigid glass supports, (ii) with thicknesses ~3 cm cast against rigid glass supports, and (iii) with thicknesses

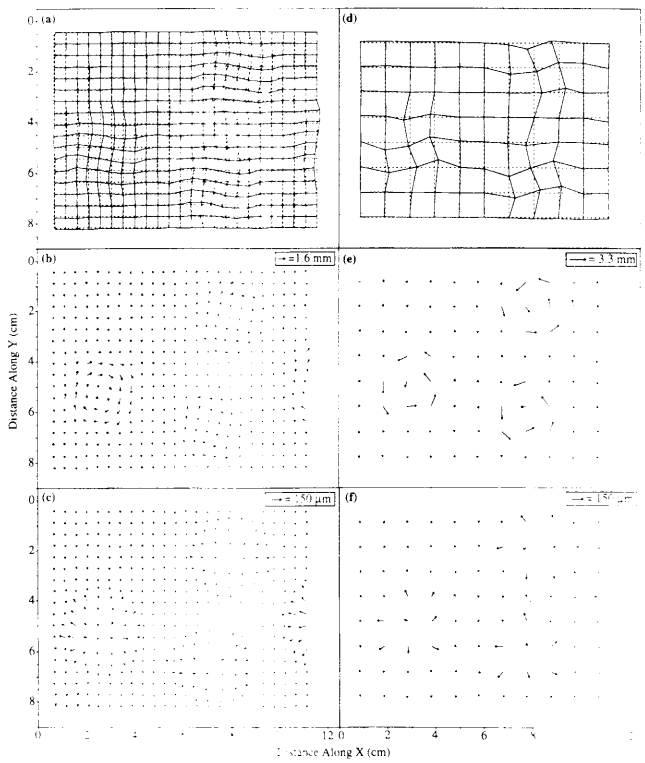

FIG. 4. Interpretation of moiré patterns produced with opaque reference grids and test grids (250 μm lines and 250 μm spaces) with known distortions generated on transparent film using a printer with high resolution. The periodicities of the reference and test grids are the same (i.e., $a = 1$) and the angle between them is small. Shown are results obtained with small positive (left) and negative (right) angles between the grids. The upper frames show the distorted moiré patterns (solid lines) and the fitted square grids (dotted lines). The middle frames show vector diagrams illustrating the distortions of the moiré patterns. The bottom frames show distortions of the test grids determined using Eq. (2).

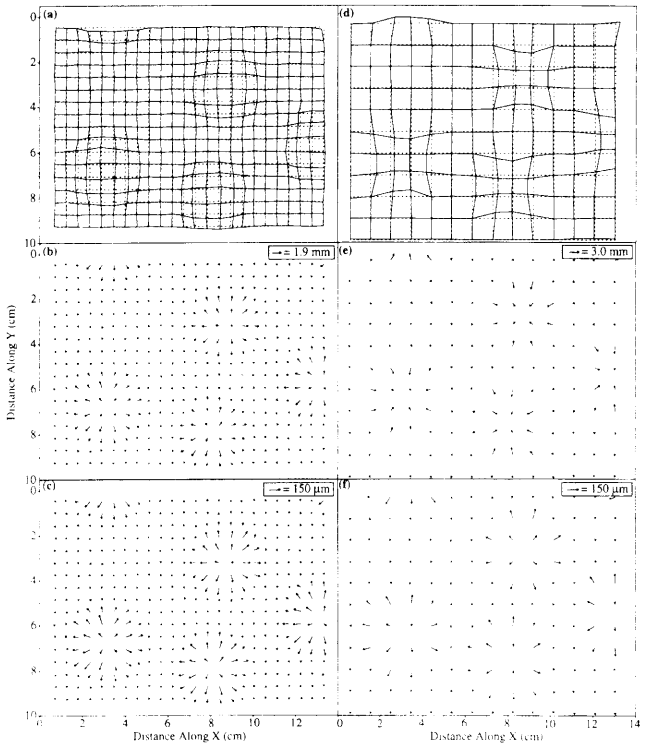

FIG. 5. Interpretation of moiré patterns produced with opaque reference grids and test grids (250 μm lines and 250 μm spaces) with known distortions generated on transparent film using a printer with high resolution. The periodicities of the reference and test grids in this case are slightly different and the angle between the two grids is zero. Shown are results for moiré patterns produced with test grids with average periodicities 5% smaller (left) and 10% larger (right) than the reference grids. The upper frames show the distorted moiré patterns (solid lines) and the fitted square grids (dotted lines). The middle frames show vector diagrams illustrating distortions of the moiré patterns. The bottom frames show distortions of the test grid determined using Eq. (3).

~0.1 mm cast against rigid glass supports. For each case, we evaluated distortions for elements made with the PDMS elastomer formed with two different amounts of curing agent.[10] Although we did not measure the difference, the elastomer made with more curing agent was stiffer than the elastomer made with less curing agent amount.

B. Relative distortions of patterns produced with μCP by hand

Although the absolute distortions described above are important, relative distortions between multiple imprints of the same pattern determine the feasibility of using soft lithography for generating multilayer structures that have features in different layers aligned relative to one another. For this reason, and because we wished to evaluate distortions when soft lithography is performed without the use of the apparatus illustrated in Fig. 8, we generated moiré patterns by (i) using μCP to print grid patterns twice (with a slight displacement and rotation between them) by hand on silver films on silicon wafers and then (ii) removing the unprotected silver with a wet chemical etch. Figure 7 illustrates the procedure. In these patterns, both the reference and test grids (that is, the two printed patterns) are distorted. Our analysis assigns all distortions to one of these grids; it therefore provides a measure of the relative distortions of the two grids. We examined moiré patterns formed with thick (~8 mm) and thin (~4 mm) elements formed with the PDMS elastomer having two different amounts of curing agent.

IV. RESULTS AND DISCUSSION

A. Absolute distortions

Figure 10 illustrates results of measurements of absolute distortions. For elastomeric elements brought into contact with rigid supports, we measured moiré fringe spacings at zero angle to be ~0.9 mm and ~1.2 mm for elements made with PDMS with more and less curing agent respectively. Rotation of the reference grid showed that the fringes in both cases rotated in the opposite direction. These two facts indicated 1.0%–1.3% and 0.7%–0.9% isotropic shrinkage for the systems with more and less curing agent, respectively. Figures 10(a) and 10(b) illustrate typical distortions before and after bringing these elements into contact with substrates. Measurements were performed at zero angle, and dis-

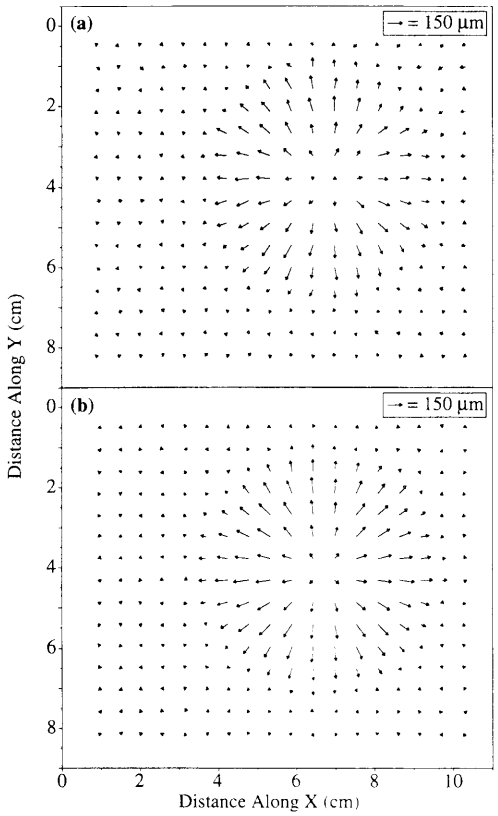

FIG. 6. Distortions of a test grid determined from analysis of a moiré pattern (top frame), and distortions measured directly from this grid (bottom frame). These data verify the method for analyzing the moiré patterns.

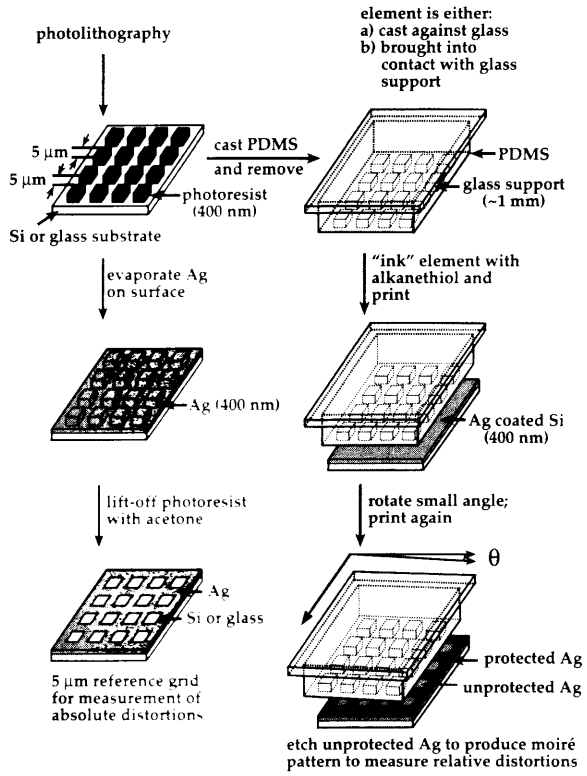

FIG. 7. Steps for fabricating test and reference grids for determining distortions in soft lithography. We formed elastomeric elements by casting and curing PDMS against photoresist patterned using photolithography. The elements themselves (either brought against or cured against rigid supports) or patterns generated by them served as test grids. Reference grids for determining absolute distortions were produced using patterned photoresist and lift-off. The lateral dimensions of the grids were ~2 cm × 2 cm.

tortions were analyzed using Eq. (3). We observed some (<15%) variation in the maximum amplitude of the distortions from measurement to measurement. Differences observed with the elastomer with different stiffnesses were within these variations. Distortions were, however, sensitive to how carefully the element was brought into contact with its support; allowing the stamp to come into contact with the support without using applied force minimized the distortions.

In an attempt to eliminate distortions introduced by placing the elements against their supports, we examined elements cast and cured directly against the supports. With thick elements fabricated in this way, we observed isotropic shrinkages similar to those observed when the elements were not cast against rigid supports; non-uniform distortions were much greater, however. We believe that the distortions were predominately caused by stresses generated upon cooling the thermally cured PDMS while it was bound to the glass substrates. Figure 11 illustrates finite element modeling of the effect of these stresses on the shape of the elastomer. The curvature of the surface induces severe distortions in the features; these distortions tend to increase when the elastomer is forced into contact for pattern transfer. Figure 10(c) illustrates typical distortions measured with the surface of the elastomer in contact with the substrate.

To avoid the curvature and to minimize shrinkage, we examined thin (~0.1 mm) elements cast against rigid supports. Measurements of the moiré patterns formed with these elements at angles close to zero indicated that the fringe spacing was larger than the size of observation (~1 cm). We concluded that the isotropic shrinkage or expansion for these elements was < 0.1%. Because the a parameter was very small, measurements for these systems were conducted in the regime where Eq. (2) applies. Figures 10(d) and 10(e) show typical results that demonstrate distortions on the order of the uncertainty of the measurement both before and after bringing the elements into contact with the substrate; this configuration represents the best case that we examined.

B. Relative distortions

Figure 12 shows typical results of distortions in moiré patterns generated using μCP to print two grids by hand. For the configurations that we examined, we observed smallest distortions for thick elements fabricated with the PDMS elastomer having a relatively large amount of curing agent. There was, nevertheless, significant (>50%) variation in the maximum amplitude of the distortions from pattern to pattern. Figure 13 summarizes results for several trials. Distortions were sensitive to how carefully the element was

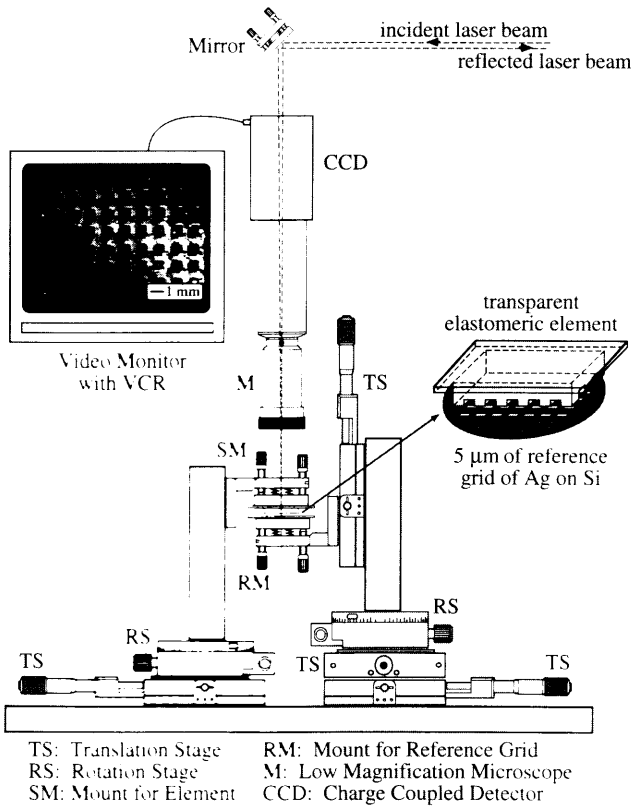

FIG. 8. Apparatus for placing and recording moiré patterns using elastomeric elements with surface relief in the geometry of grids, and reference grids on a rigid substrate. Moiré patterns were recorded with the elements close to and in conformal contact with the reference grids.

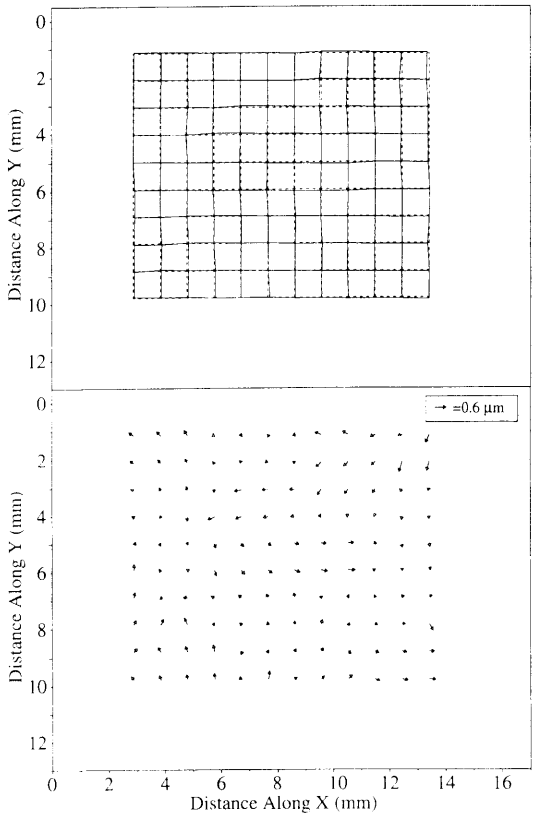

FIG. 9. Results from analysis of moiré patterns formed by placing a glass wafer with a gold grid (5 μm lines and 5 μm spaces) on its surface near (on top of one another) a grid of silver on a silicon wafer. Actual and fitted square grids corresponding to fringes in the moiré pattern are shown on the left. Actual distortions inferred from analysis of distortions of the moiré pattern are shown in the bottom frame. Distortions illustrated here determine the limit of sensitivity of our approach, and are likely due to (i) distortions introduced by the optics used for recording the moiré patterns, (ii) distortions caused by slight curvature of the silicon and glass wafers, (iii) distortions associated with the photolithography, and (iv) distortions arising from uncertainties in determining the positions of intersections of the fringes in the moiré pattern.

brought into contact with the substrate during the printing; allowing the stamp to come into contact with the support without using applied force minimized the distortions.

V. CONCLUSIONS

In this article, we described the use of moiré patterns for determining distortions that occur in soft lithography. We demonstrated that when thin ($\sim$0.1 mm) elastomeric elements cast against rigid supports are used for soft lithography and the lithography is controlled with translation stages, absolute distortions are $\sim$500 nm over square areas $\sim$1 cm^2. When the lithography is performed by hand, relative distortions of pairs of patterns can be as small as $\sim$500 nm over $\sim$0.25 cm^2 if stiff, thick stamps are used. The distortions in both of these cases are comparable to the limit of sensitivity of the measurements.

Although the thin elements cast against rigid supports showed small absolute distortions, these elements have disadvantages. The primary characteristic that makes distortions small in these systems (i.e., the restricted ability of the elastomer to move while bound to a rigid support) also makes them less easy to use: (i) bringing these elements into conformal contact with a substrate requires careful control of the alignment of the element and the substrate and (ii) these elements, unlike thick ones, cannot be used for performing lithography over significant surface relief. While it may be possible to design elements that yield small distortions but do not have these disadvantages, it is possible that it will be necessary to control actively and intelligently distortions in thick elements in order to design a robust lithographic system that meets the demanding requirements for registration in microelectronics. The results summarized in this article indicate that eliminating distortions that occur when soft lithography is conducted in a reasonably controlled manner will require application of strains with amplitudes in the range of 1 μm per 1 mm, or about 0.1%, and displacements in the range of a few microns. There are many ways to accomplish this control; one attractive means might use heating induced by absorption of light to change local dimensions of an element. Two properties of PDMS make it an attractive material for this purpose: (i) its thermal expansion coefficient is large (3×10^{-4} mm/mm/°C), and (ii) its thermal conductivity is small [3.5×10^{4} cal/(s cm °C)]. To demonstrate the feasibility of the approach, we focused part of the output of a 200 W light bulb onto an elastomeric element of PDMS dyed

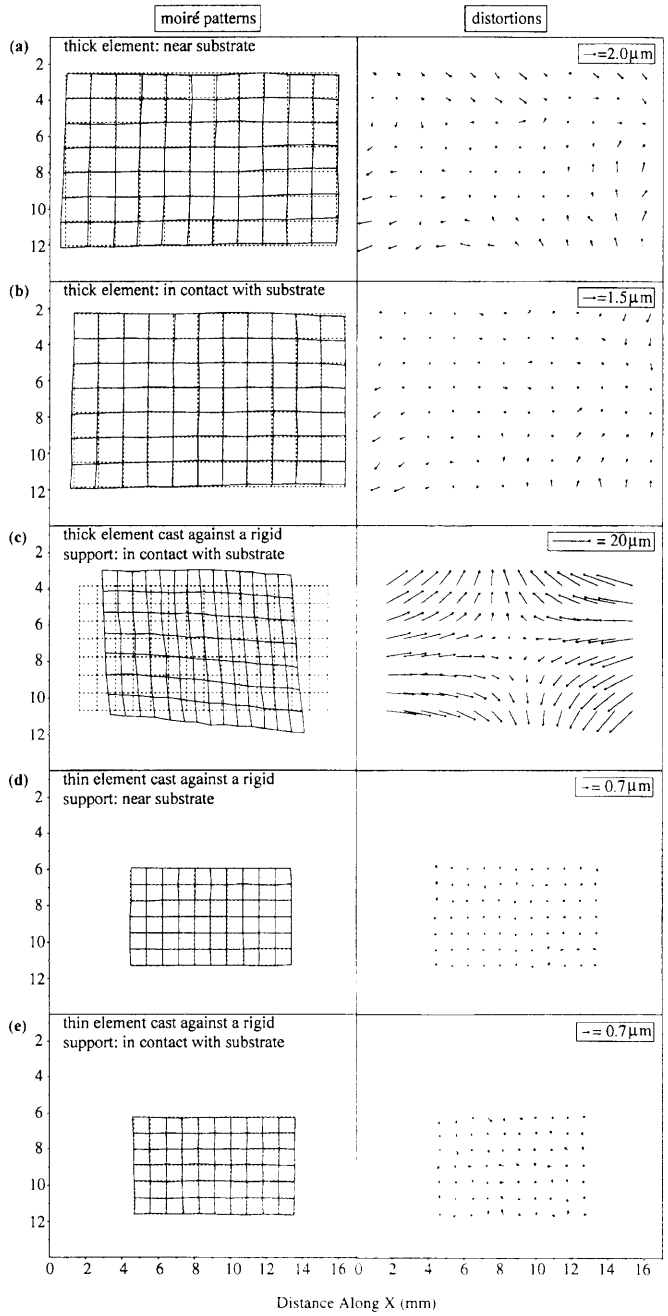

FIG. 10. Results from analysis of moiré patterns formed using surface relief on elastomeric elements for test grids and patterns of gold on silicon wafers for reference grids. Frames on the left show actual and fitted square grids corresponding to fringes in the moiré pattern. Frames on the right show distortions of the elastomeric elements inferred from analysis of distortions of the moiré pattern. (a), (b) summarize results obtained with thick elastomeric elements supported but not cured against glass supports before and after coming into contact with the reference grids, respectively. The distortions illustrated here are slightly smaller than typical; variations from pattern to pattern were on the order of 10%–20%. (c) shows typical results obtained with thick (~3 cm) elastomeric elements cast against rigid glass wafers and brought into contact with reference grids on silicon wafers. (d) and (e) show typical results obtained with thin (~0.1 mm) elastomeric elements cast against glass substrates before and after coming into contact with the reference grids, respectively. These patterns reveal distortions <700 nm over an area of ~10 mm ×6 mm. Within our measurement uncertainties (see Fig. 9), these distortions are negligible. With elements constructed in this fashion, we observed very little variation in the amplitude of the distortions from pattern to pattern.

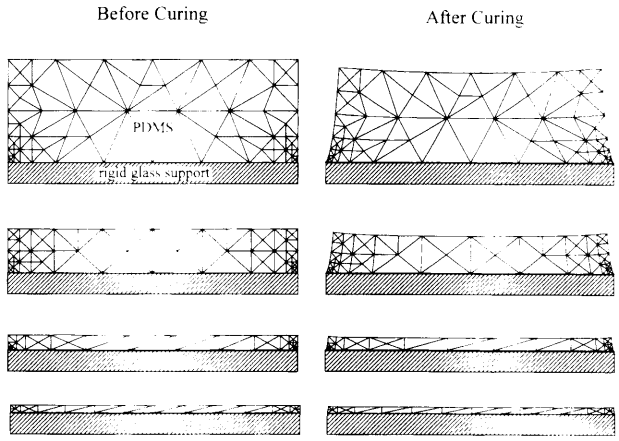

FIG. 11. Results of finite element calculations of shrinkage of an elastomer (Poisson's ratio [illegible]) tightly bound to a rigid support. The results suggest that elastomeric elements cast against rigid supports are bowed at the surface. The bowing disappears as the thickness approaches zero.

(Calco Oil Red ZMQ) to absorb green and blue light; the moiré pattern produced by surface relief on this element and an undistorted reference grid allowed real-time measurement of the thermally induced deformations. Figure 14 illustrates the experimental setup. Figure 15 shows moiré patterns observed before, 1 second after, and ~3 minutes after heating with the light bulb. The results indicate reversible strains and displacements ([illegible] 0.1% and 10 μm, respectively) in excess of those needed to eliminate distortions in soft lithogra-

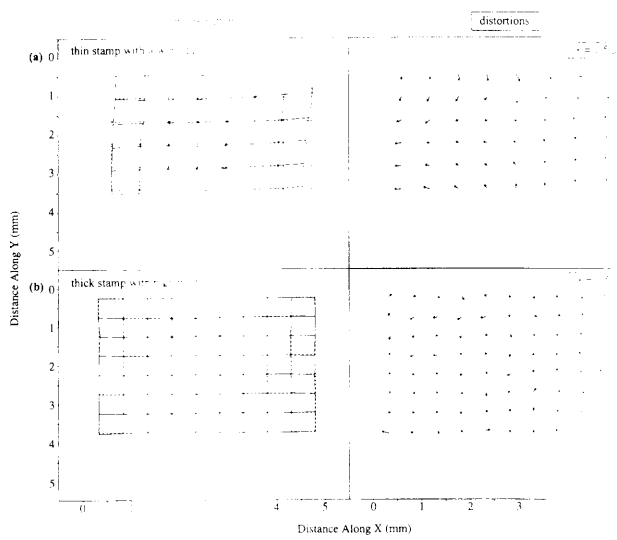

FIG. 12. Results from analysis of moiré patterns formed by hand [illegible] Frames on the left show actual and fitted square grids corresp[illegible] fringes in the moiré patterns. Frames on the right show relative dis[illegible] the printed patterns inferred from analysis of distortions of the [illegible]terns. (a) summarizes slightly better than typical results for 4 [illegible] elements made from the PDMS elastomer with a relatively small [illegible] curing agent. (b) summarizes the best case results for 8 mm thick [illegible] made from the PDMS elastomer with a relatively large amount [illegible] agent. We observed significant variations (~50%) in the distort[illegible] pattern to pattern, but noticed that distortions tended to be smallest for thick, stiff stamps.

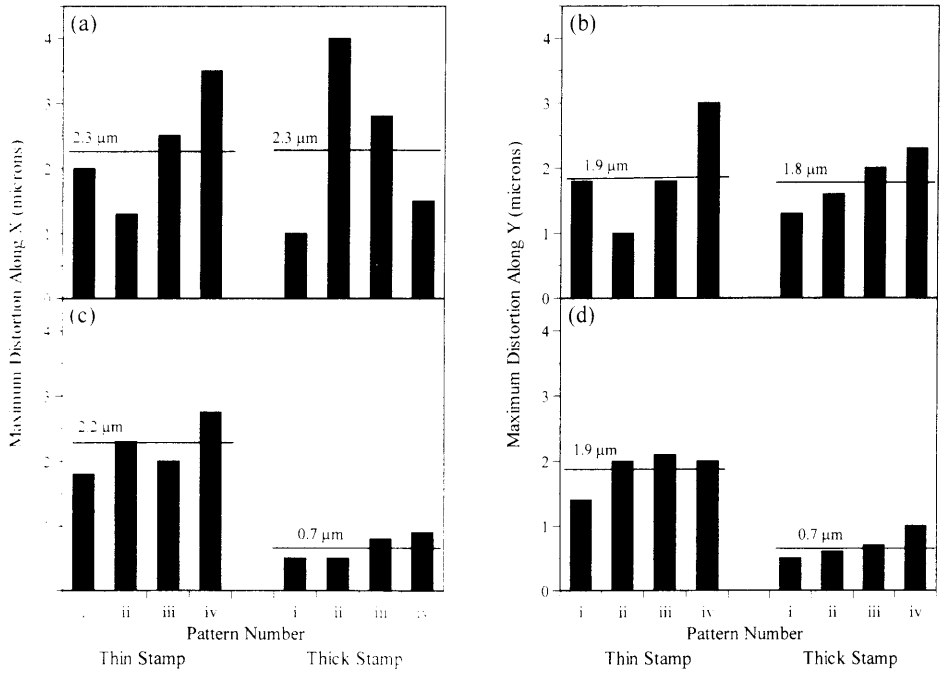

FIG. 13. Summary of maximum relative distortions observed in patterns produced over a square area ~0.25 cm^2 with μCP using stamps with different thicknesses and stiffnesses. (a) and (b) show maximum x and y distortions in patterns produced with thick (~8 mm) and thin (~4 mm) stamps formed with the PDMS elastomer with a relatively small amount of curing agent. (c) and (d) show maximum x and y distortions in patterns produced with thick (~8 mm) and thin (~4 mm) stamps made from the PDMS elastomer with a relatively large amount of curing agent. The horizontal bars indicate averages. The results indicate (i) the distortions tend to be isotropic; the magnitudes of the maximum distortions along x are similar to those along y. (ii) For 4 mm thick stamps, the modulus of the stamp has little effect on the magnitude of the maximum distortion. (iii) For 8 mm thick stamps, patterns produced using stamps made of the PDMS elastomer with a relatively large amount of curing agent exhibit smaller distortions than those made using stamps made with the PDMS elastomer with a relatively small amount. (iv) There is significant variation in the distortions from pattern to pattern.

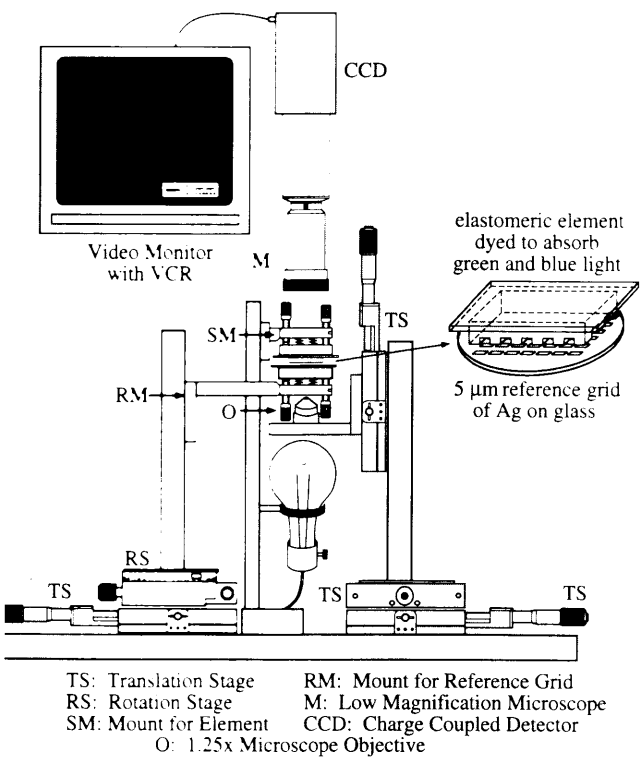

FIG. 14. Apparatus for inducing and observing deformations in elastomeric elements caused by heating associated with absorption of light. Part of the output of a light bulb is focused onto an elastomeric element containing dye that absorbs green and blue light. Heat deposited in the element leads to thermal expansion. A CCD camera records the geometry of a moiré pattern produced by surface relief on the element and a reference grid on glass.

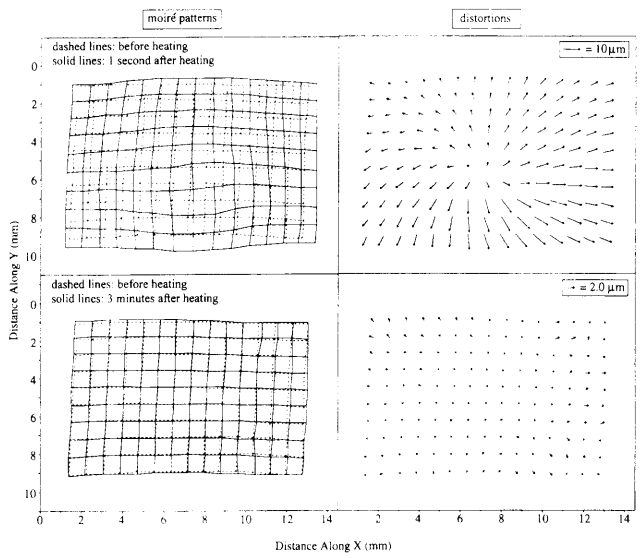

FIG. 15. Results from analysis of moiré patterns formed with a relief grid on the surface of an elastomeric element (~1 cm × 1 cm, thickness ~5 mm) and a gold reference grid on a glass wafer, measured immediately (~1 s) and long (~3 min) after heating the element for ~30 s with the focused output of a 200 W light bulb. The upper left frame shows grids corresponding to moiré patterns formed before (dashed lines) and immediately (~1 s) after heating. (The image of the filament of the light bulb was located at approximately $x = 7$ mm and $y = 7$ mm.) The lower left frame shows grids corresponding to moiré patterns formed before (dashed lines) and long after (~3 min) heating. Frames on the upper and lower right show displacements of the elastomeric element measured relative to its configuration before heating. The data illustrate that heating can induce reversible distortions with amplitudes >10 μm and strains >0.5%. These values correspond to a temperature increase of ~10–15 °C.

phy. We are currently investigating the use of spatial light modulators for programmably controlling the geometry of the heating, and a means for limiting thermal diffusion, which tends to wash out the distributions of heat.

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[9]Elastomeric elements of PDMS spontaneously "wet" clean glass surfaces. This "wetting" causes the elements to stick to the glass; they can be removed nondestructively by peeling them off by hand.

[10]There are two components for preparing the elastomer (Sylgard 184, Dow Corning, Midland, MI): (i) oligomeric dimethylsiloxane $[H_2C{=}CH(Si(CH_3)_2O)_nSi(CH_3)_2CH{=}CH_2]$ with $n \approx 250$, and (ii) $[(H_3C)_3Si(OSiH(CH_3))_2(OSi(CH_3)_2)_3OSi(CH_3)_3]$ and a platinum complex as cross linking agents and catalysts, respectively, for the hydrosilation reaction. The first of these components is referred to as the prepolymer and the second as the curing agent. To form the elastomer, the two parts are mixed together at room temperature, and then held at 65 °C for 2 hours. The amount of curing agent determines the extent of cross linking in the polymer, and therefore affects the modulus of the material. As might be expected, we observed that the modulus increased with increasing amounts of curing agent; we did not measure the differences. Experiments described in this article were conducted with the elastomer 1:10 and with 1:5 and 1:20 parts curing agent to prepolymer by weight.