A holographic phase-shifting interferometer technique to measure in-plane distortion

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We describe the use of holographic phase-shifting interferometry (HPSI) to measure in-plane distortion of a substrate in which a shallow grating, produced by interferometric lithography, has been etched. The diffractive metrology inherent in HPSI should enable one to study process-induced distortions down to the level of a few nanometers. We used HPSI to investigate distortion introduced by the anodic bonding of silicon nitride membranes to Pyrex frames in x-ray lithography masks. This was part of an effort to develop an inverted x-ray mask configuration. The HPSI technique gave quantitative measurements of the linear and nonlinear components of distortions in one-dimension. The high levels of distortion found were presumably introduced by the high temperatures used in anodic bonding, combined with the asymmetric manner in which the membranes were brought into contact with the Pyrex frame. The comprehensive, quantitative measurement of distortion provided by HPSI should enable us to modify the mask making process so as to avoid steps that introduce distortion. © 1999 American Vacuum Society.

[I. INTRODUCTION]

In lithography, it is useful to define in-plane distortion as the deviation of pattern features from their assigned locations on an abstract Cartesian grid. Distortion defined in this manner is typically not a concern in the fabrication of integrated circuits (ICs), as long as it is repeatable and not too large. In IC applications, overlay and the control of critical dimensions are the most important considerations; the exact location of features need not be on an ideal Cartesian grid if the distortion is repeatable.

Many applications of advanced lithography, such as certain integrated optical devices, require freedom from distortion at the 1 nm level. Future ICs, with sub-100 nm minimum features, will require placement accuracy at the 10 nm level. Measurement of distortion is, of course, the first step in eliminating it.

In this article we describe the operation and application of a tool, based on diffractive metrology, for measuring in-plane distortion. We call the technique holographic-phase-shifting interferometry (HPSI). One first uses interference lithography to create a coherent grating or grid on the substrate to be studied. The grating or grid is then analyzed in the HPSI for spatial-phase shifts. Other grid-based techniques to measure in-plane distortion have been described by Ruby et al. and Ku et al. In both of these techniques the system that generated the grid and the system that measured the grid were not matched; this can result in ambiguity since one does not know whether the measured in-plane distortion is real or simply an effect of the mismatched systems. In the HPSI system, the gratings or grids are generated in the same system in which they are measured.

[II. DESCRIPTION OF HPSI SYSTEM]

The HPSI system, illustrated schematically in Fig. 1, is based on the interferometric lithography (IL) system we use routinely to generate large area, highly coherent gratings. The IL system splits a laser beam (λ = 351 nm) and forms two mutually coherent spherical waves, which interfere at the substrate at a half-angle θ. The standing wave created at the substrate surface is used to expose a grating or grid in photore sist, which can then be used as a template for further processing.

The IL system is configured as a holographic interferometer simply by mounting the IL-generated grating on the substrate platform and placing a fluorescent screen in front of one of the spatial filters, as depicted in Fig. 1. A fringe pattern appears on the screen, which is due to the superposition of two wave fronts: one reflected from the substrate surface and the other backdiffracted from the grating. If the grating has suffered no distortion between exposure and reinsertion, the reflected and backdiffracted beams will be identical and no fringes will be observed on the screen. Any in-plane distortion of the grating will result in a fringe pattern. A CCD camera is used to record the fringe patterns.

In order to increase the sensitivity of the interferometer, a phase-shifting system was implemented. A piezoelectric transducer pushes the beamsplitter, and in so doing drives the Pockels’ cell to change the phase of one of the arms. Several images are acquired, recorded, and processed using the Hariharan phase-shifting algorithm. The acquisition and processing time takes less than 1 min.

As a first application of HPSI we analyzed the in-plane distortion introduced into membranes by the anodic bonding step of an experimental “flip-bonded” x-ray mask fabrication process. We first etched IL-generated gratings into the membranes. Because the IL system uses spherical wave-
fronts the period of the grating exposed depends on the substrate’s position along an axis perpendicular to the substrate (i.e., the $\hat{z}$ axis defined in Fig. 1). To ensure that the substrate’s position upon reinsertion is exactly the same as when it was exposed, we also expose a reference grating. Prior to measurements on the membranes, the reference grating is reinserted into the HPSI system and its $\hat{z}$ position adjusted until the fringes on the screen are minimized. After the reference grating is positioned and the HPSI system aligned, we use a Michelson interferometer to ensure that the gratings to be measured are in exactly the same plane as the reference grating. The Michelson interferometer uses the surface of the reference grating in one arm and a reference mirror in the other arm. The precision of this adjustment depends on the coherence length of the light source, i.e., the shorter the coherence length the closer one can match the arms of the Michelson interferometer. Our light source is a semiconductor laser, with a coherence length of 100 $\mu$m.

### III. MASK FABRICATION

The “flip-bonded” x-ray mask fabrication begins with a silicon wafer (100 mm diameter) uniformly coated with $1 \mu$m of LPCVD silicon-rich nitride (Si$_x$N$_{1-x}$) on both the front and backside. A 54-mm-diameter circular opening is reactive-ion etched (RIE) through the nitride on the backside, and the Si is etched in KOH at 90 $^\circ$C. Interferometric lithography was done on the backside of the resulting membrane, using a trilevel process, to yield a 400-nm-period grating. This grating is then etched 100 nm deep into the Si$_x$N$_{1-x}$ membrane. As illustrated in Fig. 2(a), the 54-mm-diameter Si$_x$N$_{1-x}$ membrane, with shallow grating etched into it, is supported by a Si annulus which remains from the original Si wafer.

To form the flip-bonded x-ray masks, we anodically bonded the membranes to Pyrex support rings. We set one membrane aside, as the reference grating to align the HPSI system, and deposited a 30 nm layer of Ni on the front surfaces of the remaining membranes. To ensure that the distortion measured came from the flip-bonding step, the reference grating was processed identically to the measured samples, with the exception of the final flip-bonding step.

In the final step, we flipped the membranes over, and anodically bonded the Ni to Pyrex rings, as illustrated in Fig. 2(b). The anodic bonding took place at 350–400 $^\circ$C with a bias voltage of 1.1–1.3 kV. We used Ni as the bonding interface layer (BIL), but in principle any metal that oxidizes can be anodically bonded to Pyrex (or any other borosilicate glass). In the past we have used TaB and polysilicon as the BIL. The silicon annulus and extraneous membranes were removed [Fig. 2(c)] by breaking the membrane outside of the Pyrex ring, while using adhesive tape to retain the shards of Si$_x$N$_{1-x}$.

### IV. MEASUREMENT RESULTS AND DISCUSSION

We report HPSI distortion measurements on two samples, MITa598 and MITa599. A typical measurement, shown in Fig. 3(a), illustrates the system’s ability to create a map of the in-plane distortion.

By separating the distortion data into linear and nonlinear components, shown in Figs. 3(b) and 3(c), respectively, we can more easily interpret the data. The linear distortion indicates an overall change in period, which represents a magnification distortion. The nonlinear component is indicative of distortion that occurs over a shorter length scale.
The change in period can be extracted from the linear-phase data. The change in linear phase over distance, $\Delta \varphi$, (i.e., the slope of the phase tilt, with units of radians/meter) can be related to the resulting change in period by the simple expression:

$$\Delta p_c = \frac{\Delta \varphi}{2 \pi} p^2,$$

where $p$ is the period of the original gratings, and $\Delta p_c$ is the calculated amount that the period has changed. By applying Eq. (1) to the linear data for MITa598, where $\Delta \varphi = 1.413 \times 10^3$ radians/meter, we calculate that $\Delta p_c = 0.036$ nm. For MITa599, $\Delta \varphi = 1.210 \times 10^3$ radians/meter which implies that $\Delta p_c = -0.031$ nm. Clearly both samples experienced period compression.

As mentioned above, the period of the standing wave at the substrate surface can be changed by moving the substrate forward or backward, in a direction perpendicular to its surface as indicated in Fig. 4. The relation between the motion, $\Delta b$, and the change in period, $\Delta p_m$, is given by

$$\Delta p_m = \frac{\lambda}{2} \frac{1}{b \sin \theta (1 + \tan^2 \theta)} \Delta b,$$

where $\theta$ is the half-angle of recombination of the two beam arms and $b$ is the perpendicular distance from the substrate (see Fig. 4). One can measure the change in grating period by moving the substrate forward or backward from the reference position until the number of fringes is minimized. For sample MITa598 this required a change in $b$ of $\Delta b = -131 \mu m$. Given $b = 1.093$ m, and $\theta = 26.02^\circ$, this corresponds to $\Delta p_m = -0.0387$ nm, which agrees closely with the value obtained directly from the HPSI analysis. For MITa599 we obtained $\Delta p_m = -0.0325$ nm. These results are summarized in Table I.

The linear distortion map of MITa598 shows that there is a 1.53 $\mu m$ contraction near the edges of the membrane. Using the thermal expansion coefficient of $Si_3N_4 \ (\alpha \approx 2.7 \times 10^{-6}/K)$ and Pyrex ($\alpha \approx 3.2 \times 10^{-6}/K$) to predict differential expansions at the 350–400°C anodic bonding temperature, we calculate that the diameter of the Pyrex ring will expand ~6 $\mu m$ more than the same area of the Si$_3$N$_4$ membrane. The HPSI linear distortion results give a diameter change of 3.06 $\mu m$, which agrees to within a factor of 2.

The nonlinear distortion map shows a maximum displacement of 0.38 $\mu m$. This is probably caused by the irregular deformation of the Pyrex ring, which was observed to occur during anodic bonding. In fact, alignment marks on the raised Pyrex rim shifted anywhere from 1 to 3 $\mu m$ after going through a heating/cooling cycle.

Ideally, when the reference grating is repositioned in the HPSI there should be no fringes on the readout screen. This means that the reference grating is placed in exactly the same position as when the grating was originally exposed by IL, and that the samples to be measured will be similarly placed. Ferrera has analyzed in detail the phase errors resulting from differences in position and rotation between IL exposure and reinsertion for HPSI analysis. The presence of fringes on the readout screen, when the reference grating is reinserted, enables one to calculate an upper limit on the absolute accuracy of the HPSI measurements. In the cases described in this article, the reference grating produced ~1/4 fringe on the readout screen, which corresponds to a phase excursion of $\pi/2$ radians. This in turn implies that our in-plane distortion measurements have an accuracy of ~100 nm across the entire field.

TABLE I. Summary of comparison between measured and calculated period changes.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\Delta \varphi$ (rad/mm)</th>
<th>$\Delta p_c$ (nm)</th>
<th>$\Delta b$ ($\mu m$)</th>
<th>$\Delta p_m$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MITa598</td>
<td>1.413</td>
<td>-0.036</td>
<td>131</td>
<td>-0.0387</td>
</tr>
<tr>
<td>MITa599</td>
<td>1.210</td>
<td>-0.031</td>
<td>110</td>
<td>-0.0325</td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

We have demonstrated a system that measures in-plane distortion rapidly and used this system to analyze the distor-
tions that occur during a flip-bonding process. In these initial experiments the sample stage adjustment limited the accuracy to $\sim 100$ nm. We believe this can be easily reduced to 10 nm with improved staging, and perhaps to 1 nm with algorithmic improvements. Extension of the HPSI to 2D measurements will require the utilization of grids in place of gratings.

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