Improved Mask Technology for X-ray Lithography

Personnel

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Producing features with sizes of 100 nm and below with X-ray lithography requires the mask-to-substrate gap, G, to be less than ~10 µm. To ensure the uniformity of such a small gap, the mask should be considerably flatter than 1 µm, preferably ~100 nm. Our mask technology is based on low-stress, Si-rich silicon nitride (SiN_x) membranes produced in a vertical LPCVD reactor. Although radiation hardness for SiN_x membranes remains a problem at dose levels corresponding to production (i.e., millions of exposures), the material is entirely acceptable for research purposes. These membranes can be cleaned and processed in conventional ways. Prior to resist coating, a Ti/Au plating base is deposited on the membrane. We use Interferometric Lithography (IL) to pattern periodic structures on the X-ray masks, and ebeam lithography to create patterns of arbitrary geometry. After resist coating, exposure, and development, absorber patterns are electroplated onto the membrane in gold, using a specially designed apparatus. A high resolution LEO SEM and a Digital Instruments STM/AFM are used to inspect xray masks for defects.

Because the SiN_x membranes we use are thin, between 1 and 2 microns, they are easily distorted by intrinsic stresses in the absorber pattern. Residual stresses in the absorber cause both in-plane and out-of-plane distortion of the membrane. To meet the overlay requirements of future electronic and optical devices this distortion, particularly in-plane distortion, must be controlled and minimized. Thus far, the X-ray lithography community has approached this problem by trying to develop very-low-stress absorbers.

We are pursuing a new approach to the distortion problem in which the distortion is first measured and then corrected. This approach is akin to the adaptive-optics approach in astronomical telescopes, i.e., since the distortion of the atmosphere cannot be eliminated, one adapts to it by appropriately distorting the telescope's mirror surfaces. We call our new approach the "adaptive membrane." It has the added virtue that if the substrate distorts, for example due to high temperature processing, a compensating distortion can be produced in the mask. The adaptive-membrane approach requires: (1) a means of accurately measuring the in-plane distortion, and (2) a means of introducing intentionally a controlled in-plane correction.

To measure distortion, we have developed a broadly applicable, nondestructive, global, membrane-distortion measurement technique called Holographic-Phase-Shifting Interferometry (HPSI). The HPSI system is based on the IL system we use to generate large-area, highly-coherent gratings. Figure 10 is a schematic of the IL apparatus, configured as a HPSI system. The IL system splits a laser beam (λ=325 nm) and forms two mutually coherent spherical waves, which interfere at the membrane at a half-angle q. The standing wave created at the membrane surface is used to expose photoresist. After development, the grating is present in the remaining photoresist. This grating can be used directly, or can be used to etch a shallow grating into the membrane itself, as we do when using the HPSI to measure in-plane distortion. The IL system is used as a holographic interferometer by mounting the membrane, with IL-generated grating, in the HPSI, and placing a fluorescent screen in front of one, or both, of the spatial filters, as depicted in Figure 10. A fringe pattern appears on the screen due to the superposition of two wave fronts: one reflected from the membrane surface, and the other back-diffracted from the grating. If the grating has not distorted between exposure and reinsertion, the reflected and back-diffracted beams will be identical, and no fringes will appear on the screen. Any in-plane distortion of the grating will cause a fringe pattern. To increase the precision of the phase measurement, a phase-shifting technique is implemented by changing the relative phase of the two arms. A CCD camera is used to capture several images of the fringes.

We have developed techniques that then analyze the captured images, and determine the in-plane distortion present in the grating, and therefore the membrane.

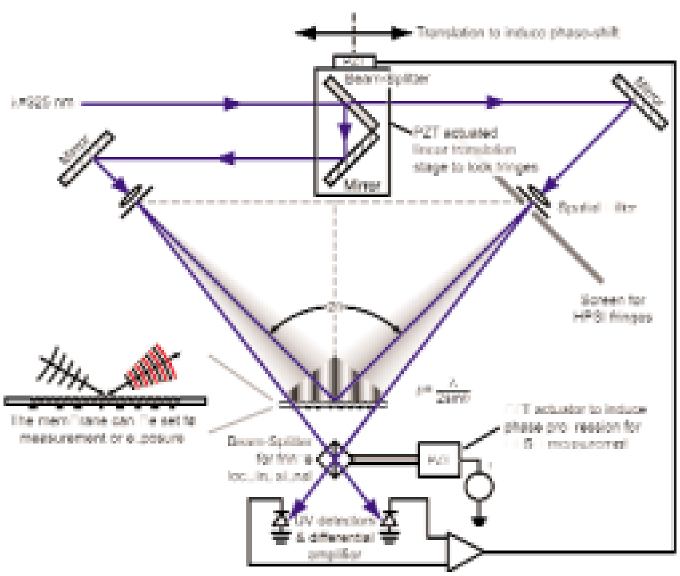

Fig. 10: A schematic of the Holographic Phase Shifting Interferometer (HPSI) based on the interferometric lithography system that we use to generate highly-coherent gratings.

We have developed an analytical technique that predicts both in-plane distortion and out-of-plane distortion arising from arbitrary 2D stress distributions. Moreover, we can also solve the inverse problem; i.e., we can predict the stress distribution which, when applied to any existing distortion, eliminates it. The calculational techniques are based on the variational method. It is relatively straightforward to formulate the total energy due to membrane distortion, even for a very complicated stress distribution. We calculate the true distortion by minimizing the total membrane energy due to placement of the stressed absorber; the total energy is straightforward to formulate for even complicated absorber distributions.

Assuming that the in-plane distortion is accurately measured by HPSI, and that the stress distribution that one must introduce to compensate for the membrane distortion is properly calculated, the next question is how to introduce that correcting stress distribution. We follow a suggestion by M. Feldman of Louisiana State University and introduce a temperature distribution, using a Texas Instruments Digital Micromirror Device spatial light modulator to generate and project patterns of light onto the membrane, inducing thermal stresses that correct the distortion.

To date, we have developed several of the individual parts of the adaptive membrane approach. Ideally, when completed the system we are developing will be able to correct for membrane distortion in real-time. If successful, this should allow X-ray nanolithography to be used in applications requiring overlay at the 1 nm level.

In the long run we anticipate that the adaptive membrane mask approach could become dominant in nanolithography in the same way that adaptive optics has revolutionized astronomy and certain other fields. Both adaptive optics and the adaptive membrane mask approach depend on measurement and feedback to correct for the shortcomings of rigid systems. Experience has shown time and again that feedback is the magic solution to engineering problems, and we anticipate that that message will be repeated in mask-based nanolithography.