Thermal Management of Masks for Deep X-Ray Lithography

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ABSTRACT

This paper addresses some options and techniques in the thermal management of masks used in deep x-ray lithography. The x-ray masks are thin plates made of low-atomic-number materials on which a patterned thin film of a high-atomic-number metal has been deposited. When they are exposed to an x-ray beam, part of the radiation is transmitted to replicate the pattern on a downstream photoresist, and the remainder is absorbed in the mask in the form of heat. This heat load can cause deformation of the mask and thus image distortion in the lithography process.

The mask geometry considered in the present study is 100 mm x 100 mm in area, and about 0.1 to 2 mm thick. The incident radiation is a bending magnet x-ray beam having a footprint of 60 mm x 4 mm at the mask. The mask is scanned vertically about ± 30 mm so that a 60 mm x 60 mm area is exposed. The maximum absorbed heat load in the mask is 80 W, which is significantly greater than a few watts encountered in previous systems.

In this paper, cooling techniques, substrate material selection, transient and steady state thermal and structural behavior, and other thermo-mechanical aspects of mask design are discussed. It is shown that, while diamond and graphite remain attractive candidates, at present beryllium is a more suitable material for this purpose and, when properly cooled, can provide the necessary dimensional tolerance.

Keywords: X-ray lithography, mask, bending magnet radiation, thermal management, high heat flux, beryllium, diamond, graphite, silicon

1. INTRODUCTION

Standard x-ray lithography (XRL) is one of the techniques used in fabrication of microelectronic components in a one-to-one replication. The process consists of transferring a pattern deposited onto a mask to a photoresist plate, which is then developed and electroplated to generate the desired component. Deep x-ray lithography (DXRL) using synchrotron radiation is essentially an extension of the XRL technique and it is the primary step in the micromachining of *high-aspect-ratio* microstructures by the LIGA (German for Lithographie Galvanoformung Abformung) process, a process based on lithography, electroplating, and molding (Ehrfeld, et al., 1988). This process is used to fabricate micromechanical, micro-optical, and other components whose length scales are between those produced by the standard x-ray lithography technique and state-of-the-art machine tool processes. Structures greater than 1-mm-high but only microns wide can be produced using high-power x-ray beams from the bend magnets of electron storage rings, such as the Advanced Photon Source (APS). A by-product of using such high-power and high-energy beams is the potential for increased throughput in an otherwise slow process.

An important problem associated with the utilization of high-power x-ray beams in DXRL is the effect of the beam heat load on the lithography mask and on the photoresist plate. A typical mask for DXRL consists of a low-Z (atomic number) substrate that is relatively transparent to the x-rays on which a high-Z absorber film (the absorber) has been patterned (Khan Malek, et al., 1996). Significant fractions of the incident x-ray beam are absorbed in the mask and in the photoresist, and this requires cooling of these components. The absorbed heat load must be dissipated. In addition, the x-ray masks and the photoresist must maintain their dimensional precision. This requires dimensional stability and tolerable or controllable geometric deformation during the entire replication process. In principle, certain components of thermal deformations in the mask, such as magnification, can be compensated by either predicting and accounting for it during the patterning process or adjusting the coolant temperature during the replication process.

Thermal deformation of such masks has been recognized as a limiting factor in the replication process (Freitag, et al., 1995). Design of a suitable mask is the subject of this paper. Since for a typical 1-mm-high structure and an aspect ratio

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of 100:1, the precision of the pattern transfer should be better than 1 micron, this can be assigned as the upper limit for the *uncontrollable* shift in the replicated features on the *photoresist* due to thermal deformation in the *mask*.

The thermoplastic deformation of masks for soft XRL has previously been extensively studied (Wells, et al., 1988; Vladimirovsky et al., 1989; Yamazaki et al., 1994; Neumann et al., 1997). However, these studies involve exposures at significantly lower x-ray power than at the APS and use thin membranes and absorber coatings.

Many materials can be used as the absorber, but due to practical and technical considerations almost all masks for DXRL are electroformed using gold. The mask substrate, however, can be selected from a few materials (Table 1) with sufficient x-ray transparency and suitable thermomechanical properties, cost of manufacture, and finish.

TABLE 1: Properties of several candidate materials for deep x-ray lithography mask substrate.

Material Property	Be	Graphite*	Diamond	Si	SiC	BN
Density, ρ [kg/m ³]	1850	900-2200	3500	2300	3200	3400
Atomic Number	4	6	6	14	-	-
Coefficient of Thermal Expansion, α [$\times 10^{-6}$ /K]	11.4	0.1-25	0.8	2.4	2.4	3.7
Specific Heat, C [J/kg-K]	1880	710	520	750	700	510
Thermal Conductivity k [W/m-K]	216	~ 1 - 1200	2100	125	200	600
Elastic Modulus, E [GPa]	350	1-30	1050	113	466	850
Thickness for 90% Transmission[mm]:						
10 keV Photons	0.85	0.38	0.12	0.013	0.013	0.11
20 keV Photons	2.5	2.0	0.67	0.10	0.10	0.63

*Many graphite specimens (pyrolytic, flexible, rigid, glassy) with varying properties are available; some are highly anisotropic. For transmission calculations here, a density of 1500 kg/m³ is assumed.

2. Thermal Management of the DXRL Mask

The design of a DXRL mask for use on high-heat-load x-ray beamlines is essentially a thermal management problem—removal of heat from the mask while satisfying thermal, structural, and other requirements. These requirements and other pertinent information in mask design are summarized below.

2.1 Mask Requirements

The mask substrate should have high x-ray transparency. Typical mask dimensions at the APS are 100 mm x 100 mm, and the thickness depending on the material and design, can be in the hundreds-of-microns to millimeter range.

The mask is patterned with an absorber such that excellent contrast is produced; typically no more than 0.1% of the x-ray beam is transmitted through the absorber layer. A gold layer of about 50-100 μ m is presently used for this purpose.

The mask dimensional precision must be maintained at about the 1- μ m level under the thermal load of the incident beam. Moreover, it should be robust enough to withstand handling, mounting, and scanning processes without failure.

2.2 Thermal Load

The radiation source for the lithographic exposures at the APS is bending magnet (Lai, et al., 1996). Radiation from a bending magnet, after passing through some filters, strikes a vertically deflecting mirror at 0.15° and the reflected beam, after passing through various windows, is incident on the mask. The purpose of the filters and the mirror is to remove, respectively, low- and high-energy photons from the beam. The platinum-coated mirror reflects photons with energies up to 35 keV. Horizontally, only 2 mrad out of 6 mrad of the bending magnet radiation is used. With the mirror 26 m from the source, the beam is 52 mm wide horizontally. Vertically, the intercepted beam is limited by the size of the mirror and the angle of incidence. At 0.15° angle, a 1.2-m mirror admits only a 3.2-mm-high beam, or 120 μ rad at the source. With the mask located 30 m from the source, the beam illuminates an area that extends 3.6 mm vertically by 60 mm horizontally.

The total power of the beam incident on the mirror is 125 W, and the reflected beam with a cut off energy of 35 keV has a total power of 80 W. This is the maximum possible power loading for the mask. In the analyses to follow, a uniform beam with a 4 mm x 60 mm footprint and a total power of 80 W is assumed.

2.3 Mask Material

The transparency requirement for the x-rays limits the candidate materials for x-ray masks to those with low atomic number, such as beryllium, carbon (graphite, diamond, etc.), boron nitride, silicon, and silicon carbide. Silicon is the least expensive high-quality material because it is produced and used in large volumes for microelectronics fabrication. Very thin silicon and silicon-compound substrates are used in XRL, but in light of the much higher power loads for DXRL at sources

such as the APS, one must reexamine various potential mask materials for suitable design selection. Fig. 1 shows the transmission of 10 and 20 keV photons through several materials. The thermal and mechanical properties of these materials are listed in Table 1. Of particular interest is the specific heat of the material (the greater it is, the less the temperature oscillations during scanning of the mask) and the ratio of thermal conductivity over thermal expansion coefficient, which is a figure of merit for thermal expansion in substrates (the higher it is, the less the thermal strain for a given heat load).

In addition to transparency to x-rays and thermomechanical properties, there are other considerations in material selections, including quality, cost, robustness, and availability. All of these aspects are summarized in Table 2.

Figure 1. Transmission of 10 keV (left figure) and 20 keV (right figure) photons in various candidate materials for DXRL masks.

Table 2: Overall comparison of select materials for mask substrate.

Material	X-ray Transparency	Thermophysical Properties	Cost	Quality	Robustness	Availability
Beryllium	Excellent	good	Expensive	Good	Good	Good
Diamond	Moderate	Excellent	Very Expensive	Good	Good	Good
Graphite	Good	Poor to Good	Moderate	Poor to Good	Poor to Good	Good
cBN	Moderate	Good	Moderate	Good	Good	Limited
Silicon	Poor	Good	Inexpensive	Excellent	Fragile	Very Good
Silicon Carbide	Poor	Good	Moderate	Good	Excellent	Good

2.4 Cooling Options

Given the relatively high power load on the mask at the APS and the tight distortion tolerances imposed, a robust cooling scheme must be devised. Because the masks are thin, there is an inadequate path for the transfer of the heat from the heated zone to the edge of the mask for edge cooling. A mask substrate consisting of a uniformly thin central part (i.e., the exposure area), which thickens outside the exposure area is ruled out at this time because of the fabrication cost. Other options considered are rim cooling (cooling the face of the mask outside the exposure field by, for example, a cooled plate in thermal contact with this area) and face cooling. In face cooling, the entire downstream surface of the mask is cooled by flowing a coolant over it. This is the most effective cooling method, but the coolant will absorb some radiation, its pressure can cause some deformation in the mask, and the design of the cooling and mounting provisions for the mask are more complex.

Concentration here is on face cooling. Both gaseous helium and water were considered. The cooling scheme considered consists of flowing a sheet of coolant parallel to the mask between the mask and another low-Z plate, such as a beryllium wafer.

Gaseous helium cooling at moderate flow speed has been considered. Flowing helium at 5 m/s over the face of the mask at room temperature and pressure leads to a heat transfer coefficient of about 70 W/m²-K, which results in very high temperature in the mask.

Assuming one gallon per minutes of water flowing in a 1-mm-high channel cooling the downstream side of the mask, a heat transfer coefficient of $2500 \text{ W/m}^2\text{-K}$ is obtained. Flow velocity is 0.6 m/s and the flow is laminar. Increasing the flow rate or modifying the geometry can lead to turbulent flow and more enhanced cooling but more vibration. Vibration can be a serious issue, and the coolant flow passages should be designed with that in mind.

Figure 2: Frontal view of the lithography mask (left figure). Mask and exposure field areas are 100 mm x 100 mm and 60 mm x 60 mm, respectively. A 4 mm x 60 mm beam scans vertically up and down as shown. The thickness of the mask is in the sub-mm range, depending on the material and design adapted. A side view of the mask assembly is sketched on the right.

3. ANALYSES

The lithography mask consisting of a substrate and a thin coating of gold is analyzed. Since analysis based on a specific gold pattern cannot be generalized, for simplicity and without loss of generality, it is conservatively assumed that the gold absorber layer covers the entire face of the mask substrate. This assumption is justifiable because it corresponds to maximum absorption and thus possible distortion in the mask. Transient thermal and structural analyses are performed using the finite element method. The scanning of the mask against fixed incident beam (Fig. 2) is simulated by applying a moving heat load on the gold absorber layer. The x-ray beam has a 4 X 60 mm footprint moving up and down the exposure field at a particular scan velocity. The position of the applied heat load at any particular time is a function of scan velocity. One assumption made to simplify the analyses is that the beam moves stepwise, moving 4 mm at a time. The error is typically on the order of several percent. Smaller step sizes lead to a smoother scan, more steps, and a corresponding increase in computational time.

The variables studied include substrate material, cooling method, thickness of the substrate, and the scan velocity.

3.1 Mask Material

Beryllium is the mask material used for most analyses. In addition, Si, SiC, diamond, and graphite were evaluated. Beryllium, having excellent thermal mechanical properties, combined with the quality of having the lowest x-ray absorption coefficient of all the materials, seems to be a suitable choice. Si and SiC have lower x-ray transparency and thus can only be used as thin and thus delicate mask substrates and may not be suitable for face cooling. Diamond substrates are expensive but have good x-ray transparency and are stronger than beryllium. Graphites have a range of material properties and are interesting candidates for further study. Gold is the absorber layer in all cases analyzed.

3.2 Geometric Variables

Two gold absorber thicknesses of 0.05 mm and 0.1 mm were analyzed as well as the case of no gold coating at all. Several substrate material thicknesses were considered, depending on the material. Mask thicknesses analyzed were 0.5, 1.0, and 2.0 mm beryllium, 0.3 and 0.5 mm silicon, 0.3 mm silicon carbide, 0.1 and 0.5 mm diamond, and 0.5 and 1.0 mm graphite.

3.3 Scan Velocity

A scan speed of 120 mm/s has been used throughout. To investigate the affect of scan speed, a slower 40 mm/s has also been studied to characterize the relation between temperature distribution and scan speed.

3.4 Cooling

Water cooling is applied to the entire back side of the substrate in most cases studied. In addition, rim cooling (by clamping a cooling block to the unexposed area of the mask) is analyzed. This is done by setting the temperature of the

unexposed area at a fixed value. Face cooling with water is simulated by cooling the entire back side of the mask at a rate of $2500 \text{ W/m}^2\text{K}$. The dependency of temperature distribution and distortion on the cooling location is thus investigated.

3.5 Thermal Strains and Boundary Conditions

As the mask scans the beam, the temperature and strain field in the mask change. In the lithography process, strains and dislocations (from their initial positions) are relevant *only* in the irradiated part of the mask at the instant it is irradiated. Strains at other locations in the mask are inconsequential at that moment (except to the extent that they contribute to a net displacement in the position of the area being irradiated.) Therefore, in the analyses, one concentrates on the instantaneous deformation of the irradiated part of the mask.

In order to conservatively estimate the thermal strains, a structurally free-standing mask is assumed. This is done to allow the mask to expand freely, introducing the largest possible lateral (in-plane) distortion. This is also a realistic assumption even for cases in which the mask is clamped.

4. RESULTS

From a large number of designs studied, a few select results are presented here. Transient and steady-state cyclic thermal and structural behaviors of the mask under the scanning x-ray beam are discussed.

4.1 Thermal Results

For a comparative study of the various designs, a 1-mm-thick beryllium substrate coated with $50 \mu\text{m}$ of gold over its entire surface and scanned at 120 mm/s in 4-mm scanning steps is used as the "standard mask." The x-ray beam footprint is $4 \text{ mm} \times 60 \text{ mm}$, and the absorbed heat flux is uniform with a total load of 80 W . The entire back face of the mask is cooled at a rate of $2500 \text{ W/m}^2\text{-K}$. The beam is stationary over each 4 mm of the exposure field for 0.033 seconds.

Figure 3: Instantaneous temperature rise ($^{\circ}\text{C}$) contours in standard 1-mm-thick beryllium mask being scanned at 120 mm/s after reaching steady state. Two instants are shown corresponding to two positions of the beam ($4 \text{ mm} \times 60 \text{ mm}$ marked by thick lines) illuminating (a) the bottom of exposed area of the mask and (b) the center of the mask. The mask has a $50\text{-}\mu\text{m}$ gold coating and receives 80 W of power.

Computation of the mask temperature starts with the beam illuminating the top 4 mm of the exposure field. The mask then moves up to expose the next 4 mm of the exposure field and so on. When the bottom of the field is reached, the mask reverses direction and moves down in a similar stepwise manner until the top 4 mm of the exposure field is once again exposed. This completes the first scan cycle, which repeats itself for entire exposure time. Figure 3 shows a typical instantaneous temperature rise profile of the standard 1-mm-thick beryllium mask with the locations of the beam indicated.

With a 4-mm-high scanning step, a minimum of 30 temperature fields for each scan are computed. From this voluminous data set the maximum, minimum, local, or area-averaged temperatures over time can be obtained.

The temperature field in the mask is weakly dependent on the thin (10-100 μm thickness) absorbing gold layer provided that the substrate is much thicker, as is the case in most of the present cases studied.

Figure 4 shows a time history of the maximum (corresponding to the instantaneously irradiated area), minimum, and area-averaged temperatures in the standard mask. It is seen that in about 5 seconds (5 scans), the area-averaged temperature rise in the mask (exposure field or entire mask) approaches a steady state value of about 3°C . The maximum temperature in the mask approaches a cyclic equilibrium temperature within the same period. Figure 4 shows, in particular, that the maximum temperature in the mask oscillates, and it attains its minimum when the top or bottom of the mask is being scanned, and its maximum when the beam is near the center. Results are affected by how the mask reverses direction when its top or bottom is irradiated. In this study, it is conservatively assumed that the mask reverses direction *immediately* when its extremes are illuminated (thus not allowing time for the mask to cool down). If the mask remains unexposed for more than a fraction of a second between scans, the cooling down of the mask within that period and the resulting displacements must be evaluated. This is not considered here because a 0.1-second lapse between scans changes the standard Be mask average temperature by about 0.3°C only. Further details of the behavior of the temperature profile in the mask are analytically interesting but practically otiose. Note that the slight asymmetry of the time-varying temperature profiles seen in Figs. 5-7 is merely due to the fact that the plots are for a point close to but not exactly at the center of the mask.

Figure 4: Maximum, average, and minimum temperature rise in the entire standard 1-mm Be mask being scanned under the APS bending magnet at 120 mm/s. The beam power is 80 W with a 4 mm x 60 mm footprint; the beam is stationary over each vertical 4 mm of the exposed area for 0.033 s. Scanning begins by the beam striking the top of the mask. The maximum temperature rise, at any instance, occurs in the instantaneously exposed area.

Figure 5 illustrates the effect of scanning speed on mask temperature as exemplified by the temperature rise at a location near the center of the mask. Scanning speeds of 40 and 120 mm/s are considered. As expected, higher scanning speeds lead to smaller temperature oscillations, but the temperature rise time-averaged over each scan remains unchanged. The extremes of scanning speed are a very slowly moving 4 mm x 60 mm beam with a heat flux of 0.33 W/mm^2 (leading to large temperature oscillations) and a very fast moving beam effectively depositing 80 W uniformly over the 60 mm x 60 mm exposure area with a heat flux of 0.022 W/mm^2 (having the smallest temperature oscillation).

Figure 5. Comparison of the temperature rise at the center of the standard 1-mm-thick Be mask for the scanning speeds 120 and 40 mm/s.

Figure 6. Comparison of the temperature rise at the center of the standard 1-mm-thick Be mask with those of a thicker and a thinner mask. Scanning speed is 120 mm/s.

Figure 6 shows the effect of mask thickness on temperature. A thicker substrate has a larger thermal mass and, for the same heat load, shows less temperature rise (due to lateral heat transfer) and less temperature oscillation as the mask is scanned under the beam. This comes at the expense of some additional beam attenuation and increased distance between the gold-coated surface and the photoresist, which, however, might be acceptable for masks made of beryllium and illuminated by the relatively well-collimated x-ray beam of the APS, which does not require close proximity of the mask and photoresist.

Next, silicon and diamond are compared to the standard beryllium mask, with the results shown in Figure 7. The thickness of diamond is taken to be 0.5 mm because of the high cost of thicker substrates, and that of silicon to be 0.3 mm because of unacceptable x-ray attenuation by thicker wafers. Temperature oscillations of the silicon substrate are noteworthy.

Three aspects of the thermal behavior of the masks analyzed (Figures 4-7) are noteworthy: time constant, time-averaged temperature rise, and the magnitude of temperature oscillation. The primary factor responsible for the observed behavior is the relative thermal mass ($= \text{density} \times \text{specific heat} \times \text{thickness}$) of the substrates. For example, from Table 1, the relative thermal masses of beryllium, diamond, and silicon masks used in Figure 7 are 7, 2, and 1, respectively. By fitting imaginary smooth curves on Fig. 7 (not shown) through the temperature data for each mask, one can estimate the time constant, time-averaged temperature rise, and the magnitude of temperature oscillations for the three substrates. These are listed in Table 3.

Table 3: Key thermal results of a comparison between Be, diamond, and Si masks depicted in Figure 7.

Item	Beryllium	Diamond	Silicon
Relative thermal mass	7	2	1
Time Constant (s)	8	1	1
Oscillating magnitude	2	6	14
Average temperature rise	8	6	10

Primarily, for a given cooling condition, the time constant for a substrate to reach steady state while scanned through the beam is proportional to its thermal mass. The oscillating amplitudes of the temperature profiles over time, on the other hand, are inversely proportional to the thermal mass—the smaller the thermal mass, the faster the system adjusts to a heating condition and the larger the thermal oscillations. Thus, the silicon substrate having the smallest thermal mass has the largest oscillation amplitude. Time constant and oscillation amplitudes are affected to a lesser degree by the thermal conductivity of the substrate. Lastly, the average temperature rise of the substrates relates both to the thermal mass and to the ability of the mask to spread (conduct) the heat over unheated areas of the mask to be cooled by the cooling. This conduction term is proportional to the product of thermal conductivity and substrate thickness. This explains why diamond has the smallest average temperature rise (Fig. 7).

Much of this heuristic argument can be developed by rigorous analyses. For example, the substrate can be treated as a fin, with an oscillating base temperature. The key results of the preceding and other analyses performed can be summarized as follows (see also Table 4):

- Substrate temperature oscillations are reduced by increasing mask scanning speed; the time-averaged temperature of the mask or any spot on the mask, however, is not affected.
- Substrate temperature is lower and the amplitudes of the temperature oscillations are smaller in thicker substrates, due to larger thermal mass.
- A higher cooling rate (heat transfer coefficient) lowers the temperatures in the mask and the magnitude of temperature oscillations.
- The time constant for a mask face-cooled with water is typically under 10 s, which is rather small in comparison with typical exposure times of several minutes and more.
- Highly conductive substrates are thermally advantageous only if they are thick enough for lateral transfer of heat. Otherwise, they offer no advantage from this standpoint and may deform under coolant pressure if too thin.
- For all cases studied, the maximum temperature rise of the masks is in the 10-20 °C range.
- Cooling the mask at just the unexposed area near the perimeter will lead to higher temperatures in the mask and a longer time to reach steady state. For example, the standard 1-mm Be mask will show about a 20°C temperature rise compared with 8 °C when the entire mask is cooled. The amplitude of the temperature oscillations remains unaffected, however.

Figure 7. Comparison of the temperature rise at the center of the standard 1-mm-thick Be mask with those of diamond and silicon. Scanning speed is 120 mm/s.

Table 4: Key results of several substrate options for the lithography mask.

Material	Thickness (mm)	Scan Speed (mm/s)	$\Delta T_{\max}$ (°C)	ΔT_{osci} (°C)	Maximum y-Displacement (μm)
Be	1.0	120	9.7	2	4.6
Be	1.0	40	13.1	6	4.7
Be	0.5	120	12.1	5	5.7
Si	0.3	120	22.5	14	3.0
Diamond	0.5	120	9.4	5	1.0

4.2 Structural Results

From the point of view of the replication process, both transient and steady-state deformations in the substrates can be important. However, since exposure times for DXRL can be long (hours), and the time constant for a typical face-cooled mask is short (seconds), exposure during transition to the steady state can be ignored. Alternatively, exposing only the mask for the first few seconds until it reaches steady state would eliminate recording of the transient changes on the photoresist. In any case, analysis can be confined to structural changes occurring during the steady state.

As previously mentioned, only the instantaneous distortions in the area illuminated by the scanning beam are transferred to the photoresist. Therefore, in order to identify and illustrate the distortions in the mask that are transferred to the photoresist, a composite distortion field can be created. Ignoring any time lag, the strains in only the illuminated row are selected for each time step during a scan from top to bottom of the mask. The example of in-plane displacements for the standard 1-mm-thick beryllium is shown in Fig. 8a.

Figure 8. Composite strain fields for the standard 1-mm-thick beryllium mask. Outer squares represent mask boundary and the inner meshed lines represent the exposure area of the mask prior to exposure. In (a) solid mesh indicates direction and relative magnitude of in-plane displacements when exposed the BM radiation. In (b), solid mesh indicates *residual* displacement, which is the distortions shown in (a) with best fit linear expansions in vertical and horizontal subtracted. The magnitude of residuals in (b) has been scaled 5x greater than those in (a) for clarity.

The maximum transferred displacement in Fig. 8a is about $4\text{ }\mu\text{m}$ and appears to be due primarily to the expansion of the mask from the single fixed point 'A', with reference to which all distortions were calculated. This predictable simple displacement can be accounted for by compensating during patterning of the mask or by adjusting the coolant temperature to shrink the mask.

Figure 8b shows the residual strains obtained by subtracting x and y linear expansion term from the displacements in Fig. 8a. For clarity, the display of the residual strains are scaled up by a factor of 5x compared to the original displacements. The maximum residual displacement is about $1\text{ }\mu\text{m}$.

Similar composite strain fields of transferred displacements can be made for other mask designs, omitted here for brevity. From analysis of these, one can arrive at a few key conclusions. Given the excellent x-ray transparency of beryllium and that the maximum uncorrected displacement in the 1-mm-thick beryllium mask subjected to 80 W is about $4\text{ }\mu\text{m}$, it is reasonable to expect that, under more typical conditions where a greater part of the x-ray beam is transmitted and not absorbed in the mask, a substantially smaller maximum displacement will result. Such a mask, thus, may be acceptable. If not, much of the displacement can be compensated for by including a magnification correction factor in the original patterning or lowering the coolant temperature to shrink the mask, resulting in $1\text{-}\mu\text{m}$ accuracy in transferring the desired pattern. At that precision,

nonthermal effects, such as mask mounting and x-ray beam characteristics, become as important in determining the accuracy of pattern transfer.

If the x-ray absorption by a 300-500- μm -thick silicon substrate can be tolerated, then silicon is an attractive alternative to beryllium. If extreme precision is needed, and cost is not an issue, 500- μm -thick diamond is clearly the ultimate material of choice, capable of providing submicron accuracy. Pyrolytic graphites offer a compromise in properties at reasonable cost that warrant further investigation once it has been determined which materials are suitable for mask fabrication.

Increased cooling efficiency also reduces thermal distortions in the mask, but elaborate schemes are expensive, may reduce reliability, and might introduce vibrations and increased distortions in the mask. Comparison of face cooling and rim cooling suggest that both temperature and strains are similar. Moreover, the design of a face-cooled mask is more expensive and the absorption of x-rays in the coolant reduces photon flux. For a very x-ray transparent material like beryllium, it may be sufficient to rim cool but increase the thickness of the substrate.

5. CONCLUSIONS

A beryllium mask 1-2 mm in thickness with face or rim cooling can be used to achieve 1- μm accuracy in pattern transfer for DXRL using the APS bending magnet beamline. Beryllium combines excellent x-ray transparency, good thermomechanical properties, moderate price, ready availability, and excellent mechanical strength and machinability. If a much better accuracy is needed, the choices are a compensation in the patterning of the beryllium mask, thermal control of the mask by adjusting coolant temperature, use of thick ($>300\ \mu\text{m}$) silicon or silicon carbide with a loss in x-ray transparency, and finally use of thick ($>500\ \mu\text{m}$) diamond at great expense. Pyrolytic graphites are promising materials needing further investigation.

Ongoing plans include design, fabrication and testing of several masks and analyses of their performance under precise experimental conditions. Thermal and structural behavior of the resist will also be analyzed to establish an overall understanding of the relative importance of various contributions to the final replicated component.

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