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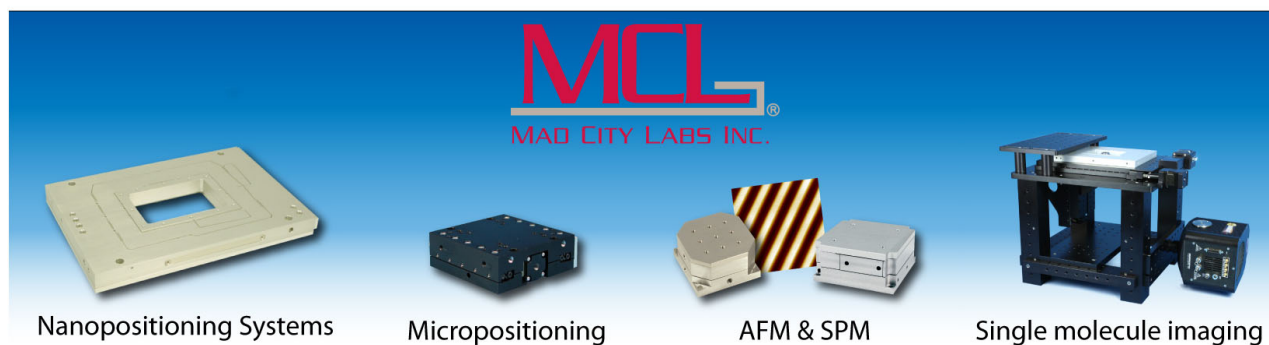
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Note: Thermally stable thin-film filters for high-power extreme-ultraviolet applications

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We investigated several types of thin-film filters for high intensity work in the extreme-ultraviolet (EUV) spectral range. In our application, with a peak EUV intensity of 2.7 W cm^{-2} , Ni-mesh-backed Zr filters have a typical lifetime of 20 h, at which point they suffer from pinholes and a 50% loss of transmission. Initial trials with Si filters on Ni meshes resulted in rupture of the filters in less than an hour. A simple thermal calculation showed that the temperature rise in those filters to be about 634 K. A similar calculation indicated that using a finer mesh with thicker wires and made of Cu reduces the temperature increase to about 60 K. We have exposed a Si filter backed by such a mesh for more than 60 h with little loss of transmission and no leaks. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4935468>]

Thin-film filters for extreme ultraviolet (EUV) light are used to remove multiple-order light or long-wavelength light that is scattered from grating spectrometers.¹ To remove multiple-order light, the filter material is selected for its in-band transmittance and the position of an absorption edge. For example, aluminum is suitable for the band from 17 nm to 34 nm since it transmits well in that region but is highly absorbing below the L_{23} edge at 17.1 nm.² Long-wavelength scatter is blocked by most filter materials due to their high reflectance and absorbance in the vacuum UV to EUV. Thin-film filters are used also as gas barriers that allow the introduction of a contaminant gas without upstreaming that would damage optical components and light sources.³

We recently developed a facility that measures the optics contamination caused by EUV photoresists.⁴ It co-exposes a witness-sample mirror and a resist-coated silicon wafer to EUV radiation from the NIST Synchrotron Ultraviolet Radiation Facility (SURF III, Ref. 5), after which the contamination growth on the witness sample is measured. During the exposure, organic molecules outgassed by the resist adsorb on the witness-sample surface and are cracked by the EUV. The intensity on the witness sample must be high enough that the contamination is mass-limited, namely, high enough that every adsorbed molecule is either cracked or photodesorbed.

To achieve the high intensity required for the test, the beamline has only two optical components. The first is a Rh-coated toroidal mirror that collects light from SURF III at a 10° grazing angle of incidence and focuses it in a small spot on the sample. It intercepts 25 mrad of the horizontal emittance and virtually all of the vertical emittance at wavelengths below 50 nm, and its reflectance is above 50% at wavelengths longer than 8 nm. The other optical component is a thin-film filter captured in the gate of a valve; it limits the spectral range and prevents upstreaming of outgas molecules. The original filters were made of Zr, chosen for its transmission profile and toughness. The witness samples are Ru-capped

Mo/Si multilayer mirrors that reflect over 60% at near-normal incidence at 13 nm, so that the photoresist is exposed to the same wavelength as in an EUV scanner.

Figure 1 shows the spectral power reflected from the mirror and the transmittance of the Zr filter, showing that the Zr transmittance is well-matched to the SURF output. However, the filter transmits little power above 20 nm, which is not ideal for studying mass-limited optics contamination. Hill *et al.* made measurements of contamination vs wavelength for several organic molecules⁶ and found that the contamination is as much as 10 times greater for EUV wavelengths longer than 20 nm.

By transmitting at longer wavelengths, a different filter material can significantly improve our ability to study contamination. Figure 2 shows the transmitted power as a function of wavelength for 200 nm thicknesses of Zr, Si, and Be. The integrated throughputs for Si and Be are within 10% of that for Zr; however, both Si and Be are superior for our purposes because they have spectra that are weighted more toward the longer wavelengths that promote contamination.

Our first attempts to use alternative filters resulted in ruptured filters. We tested filters made of Be, B, and Si, each held by a thick 24 mm diameter aluminum disc with a 6 mm by 18 mm aperture, as shown in Fig. 3. Some filters were freestanding, and some were supported by a $12.5 \mu\text{m}$ thick Ni mesh with 0.36-mm period and 83% open area. Due to the toxicity of Be, and the less-desirable transmittance of B, we limited subsequent tests to Si.

The likely failure mode for all the filters is thermal. There is about 1 W incident on the filter with a footprint that is uniform in the horizontal dimension and Gaussian with a full-width at half-maximum of 2 mm in the vertical dimension. Of the incident radiation about 70% is absorbed. We assumed initially that there is no conductance of heat from the filter, so that the maximum possible temperature T could be calculated using the Stefan-Boltzmann formula, $I = \epsilon\sigma T^4$. Here, ϵ is the emissivity (0.2 for Si, Ref. 7) and σ is the Stefan-Boltzmann

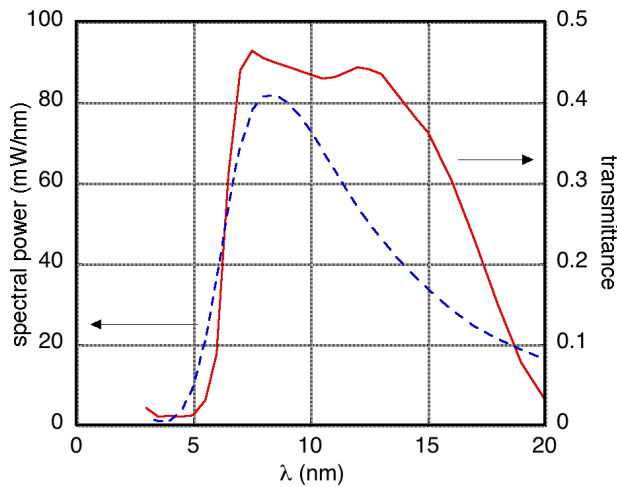


FIG. 1. Spectral power incident on the filter (dashed line, left-hand scale) and transmittance of a 250 nm thick Zr filter (solid line, right-hand scale).

constant. In this case, I is not the incident intensity, but instead the absorbed power density. The maximum incident intensity is 2.7 W cm^{-2} ; the spectrally resolved absorption reduces this by about 30%, giving $I = 1.9 \text{ W cm}^{-2}$. Noting that the filter emits from both the upstream and downstream surfaces, the Stefan-Boltzmann formula gives a temperature of 955 K or 682 °C, high enough to destroy the filter. This result ignores the thermal conductance from the filter to the thermally grounded mount. The calculation of the conductance has two parts: the first describes the temperature rise within one square of the mesh T_{sq} , and the second describes the temperature rise associated with the entire mesh T_{mesh} .

We first consider the temperature rise within one window of the Ni mesh, with width $d_{sq} = 0.33 \text{ mm}$. The temperature distribution that describes uniform heating in a thermally grounded square is a rapidly converging series.⁸ Using only the first term of that series gives to within 1% the temperature difference between the middle and the edge of the square,

$$\Delta T_{sq} = \left[\frac{1}{8} - \frac{4}{\pi^3 \cosh(\pi/2)} \right] \frac{I d_{sq}^2}{kL}, \quad (1)$$

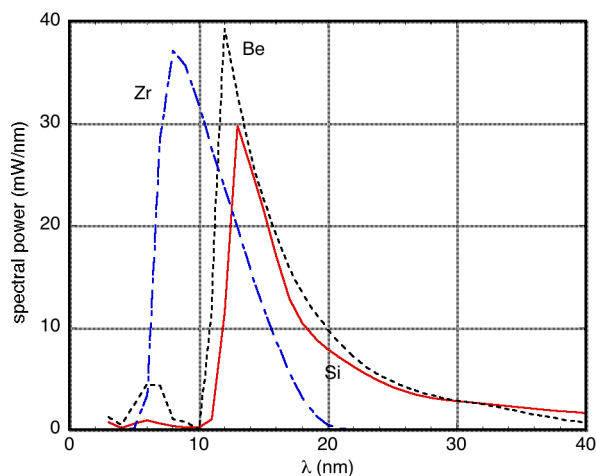


FIG. 2. Spectral power transmitted by 200 nm thicknesses of Zr (chain line), Si (solid line), and Be (dashed line).

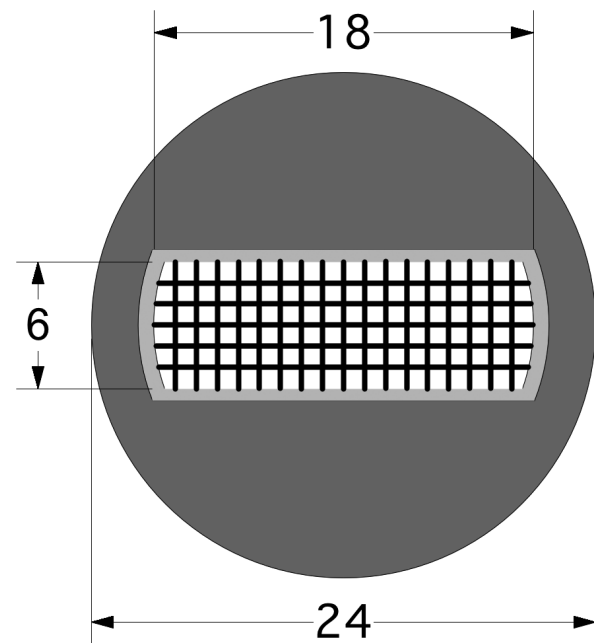


FIG. 3. Schematic drawing of a filter ring. All dimensions are in mm; the mesh is shown 3 times larger for clarity.

where k and L are, respectively, the thermal conductivity and thickness of the silicon film. Using the value for k of polycrystalline silicon ($14 \text{ W m}^{-1} \text{ K}^{-1}$, Ref. 9) yields a temperature rise of 54 K. The filter is attached to the mesh with a low-outgassing organic adhesive. The adhesive is of order 100 nm thick and assuming a thermal conductivity of $0.2 \text{ W m}^{-1} \text{ K}^{-1}$, there is a temperature rise of less than 1 K from the adhesive.

The other part of the heat conduction is the support mesh. The mesh must conduct away the power absorbed in the filter, plus the power absorbed in the mesh itself. The mesh is 18% of the filter area and absorbs 100% of the incoming radiation in that area. The total power absorbed is about 0.75 W. We assume as a worst case that all of this falls in a stripe in the center of the filter window and that all conduction is via the wires along the short axis of the mesh, in which case the temperature rise is

$$\Delta T_{mesh} = \frac{PW}{4Ak}. \quad (2)$$

Here, P is the absorbed power, W is the width of the window (6 mm), and A the total cross section area of the wires.

The period of our original Ni mesh was such that it conducted heat along 50 parallel wires, each with a cross section of $12.5 \mu\text{m}$ by $34 \mu\text{m}$. Using the corresponding value of A and the thermal conductivity of Ni, $90 \text{ W m}^{-1} \text{ K}^{-1}$ (Ref. 10) in Eq. (2) leads to a temperature rise of $T_{mesh} = 580 \text{ K}$, and a total rise of 634 K including the rise within a square. In other words, the temperature rise including conductance is not much lower than the rise due to blackbody heating without the mesh. With a filter temperature of about 655 °C, it is little wonder that the Zr filter quickly degraded and that the Si filter quickly failed.

It is possible to lower the temperature of the filter by changing the geometry and material of the mesh support. Finer

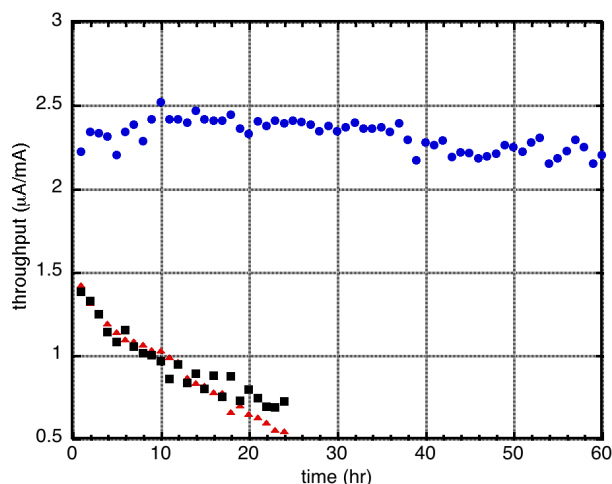


FIG. 4. Throughput (ratio of transmitted photocurrent to stored electron-beam current) for two Zr filters with Ni mesh (triangles and squares) and one Si filter with Cu mesh (circles).

meshes are available, but these tend to have less open area. We tested a combination of a slightly finer mesh (0.254 mm period, 73% open area) made from thicker Cu (30 μm). The smaller windows lead to a modest reduction in the temperature rise relative to the mesh (maximum of 23 K rather than 54 K). However, the gain in conduction of the mesh is huge: Copper has a thermal conductivity of $390 \text{ W m}^{-1} \text{ K}^{-1}$, 4.3 times that of Ni; factors of 1.4 from the density of wires and 2.7 from the cross section of the wires (70 wires each 30 μm by 37 μm). Thus, the calculated temperature rise between the thermally grounded frame and the center of the grid is 37 K, and the calculated maximum temperature at the center of a window has been reduced from about 655 $^{\circ}\text{C}$ to about 80 $^{\circ}\text{C}$.

Figure 4 shows the performance of two Zr filters and one Si filter. Prior to use in the beamline, the silicon filter underwent a test bake of 100 $^{\circ}\text{C}$ in vacuum for 4 h to verify its viability under our expected conditions. The horizontal axis is the amount of time the filter was exposed to EUV radiation, while the vertical axis is the effective throughput, defined as the ratio of the photocurrent measured by a photodiode after the witness sample to the stored electron-beam current in SURF III. Two important observations are apparent from

this figure. First, the Si foil with the copper mesh transmits more 13 nm radiation despite the mesh reduced open area of the mesh. Second, the Zr filters continually degrade with exposure, presumably due to accelerated chemical reactions with either organic contaminants or trace water vapor. After 20 h of exposure, the Zr filters show a reduction in throughput of about 50%, while after 60 h, the Si filter shows a 1% reduction from the initial value and 10% reduction from the maximum.

The filter has also been tested for gas leaks. Initially, the filter was tested for mechanical soundness with nitrogen leaked into the sample chamber up to 1 mbar while monitoring an ion gauge in a chamber pumped by a 40 l/s ion pump upstream of the filter. In this initial test, the upstream pressure rise was less than 10^{-8} mbar. On a daily basis it is tested for leaks by closing the valve to the sample chamber cryopump so that the pressure rises to 10^{-6} mbar. After 60 h exposure, any upstreaming is below our detection limit of 10^{-9} mbar, indicating that no pinhole leaks have developed.

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