Filter windows for EUV lithography

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ABSTRACT

Extreme-ultraviolet (EUV) lithography based on reflective optics is expected to require at least one filter window to 1) reduce out-of-band radiation in the ultraviolet, visible and infrared, 2) partially protect the optics from debris from the radiation source and any outgassing from the resist on the wafer, and 3) perhaps to serve as a barrier for EUV absorbing gasses. To maximize wafer throughput, the filter window or windows will need to provide the highest possible transmittance at 13.4 nm. EUV filters must operate in a harsh vacuum environment. They will be irradiated with high energy EUV light and will absorb out-of-band radiation that will cause temperature increases of greater than 100°C. Outgassing from the filters must be minimal, and they must survive handling as well as pressure differentials during pump-down operation, and return-to-atmospheric pressure. Prototype filters were fabricated for Sandia's Engineering Test Stand (ETS) and are being utilized in on-going EUV lithography demonstrations. Their in and out-of-band transmittance has been measured and found to meet Sandia's performance specifications, and they have been exposed to various environments with good results.

Keywords: Filters, filter windows, extreme-ultraviolet, soft x-ray, EUV lithography, filter transmittance

INTRODUCTION

Luxel Corporation has been working to develop high throughput filters for the region between 4 and 17 nm since 1996. This research has been supported by NASA's Goddard Space Flight Center because of their interest in x-ray astronomy in general and solar astronomy in particular. NASA strongly encourages the use of technology developed under their R&D contracts for other applications. It is fortuitous that the development of filters that perform well in this region of the spectrum has been accomplished at the same time that the need for filters for EUV lithography emerged.

FILTER DESIGN AND PERFORMANCE

A number of materials have been considered for use as filter windows for EUV lithography. The prime consideration is that they have good transmissivity at 13.4 nm and provide some degree of out-of-band rejection. The best candidates include yttrium, silicon, zirconium, and niobium. Beryllium has good transmittance and light blocking properties, but its toxicity makes it unacceptable for this application. Yttrium seems attractive based on transmittance but it oxidizes readily; in fact, it will burn in air. All attempts to utilize it in thin film filters have failed. Silicon has good transmittance at 13.4 nm, but it does not provide much rejection for out-of-band radiation. Zirconium and niobium are somewhat similar, but zirconium has better transmissivity. Thus, zirconium has become the material of choice for this application.

The filter material is a thin foil with a thickness on the order of 1000Å, produced by vacuum deposition. It is difficult to fabricate and to handle. Some materials, such as aluminum, are relatively easier to fabricate by this method and have been in use as thin film filters for years. However, zirconium and the other materials that have good transmittance at 13.4 nm are difficult to fabricate as thin films. Zirconium has required the development of specialized techniques including the use of ion assist to obtain stress free submicron foils. Also, special care must be taken to avoid oxidation during the deposition and fabrication process. Metal foils this thin must be reinforced to withstand handling, and a metal mesh is used for this purpose.

Three full size (four inch diameter) spectral purity filters plus witness samples were fabricated from 1000Å zirconium on 70 line per inch nickel mesh and were delivered in July 1999 to Sandia for use in the ETS. A summary of the Filter Specification and the Achieved Performance is given in the following Table. As can be seen, the performance goals were met.

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Specification	***Achieved Performance***
45% throughput at 13.4 nm wavelength	Sandia measured 48% transmission on witness samples
± 1% transmission uniformity	Tests of deposited films displayed at most 2% film thickness variation. Sample transmission calculations varying film thickness by 2% yield about ±0.5% transmission variation
Visible light transmission 1×10^{-3}	Witness samples measured: R/N 7770-2: 3.69×10^{-4} R/N 7779-1: 1.94×10^{-4} R/N 7801-2: 3.25×10^{-4}
At least 77% mesh transmittance	2 prototype filters used 82% transmitting mesh, 1 used 78.8% transmitting mesh
Mesh blemishes ≤ 50 μm	R/N 7770-2: 6 breaks > 25 μm and <125 μm R/N 7779-1: 0 breaks > 25 μm and <125 μm R/N 7801-2: 2 breaks > 25 μm and <125 μm 1 nickel ball > 50 μm

Transmittance of the ETS filters was calculated and measured as shown on Figure 1. The dashed curve is the calculated transmittance based on Henke absorption coefficients. The curve from 10.8 nm to 15.8 nm is transmittance as measured at Lawrence Berkeley National Laboratory (LBNL). The transmittance is about ten percent less than the calculated value because of oxidization of the zirconium foil. The curve from 200nm to 1200nm is transmittance as measured by Sandia on a Perkin Elmer UV/Vis/NIR spectrometer. The solid circle shown at 500 nm is a measurement of the visible light transmission taken on Luxel's Visible light Photometer that averages the transmission from 300 nm to 700 nm. This measurement correlates well with the Sandia data taken on the Perkin Elmer spectrometer.

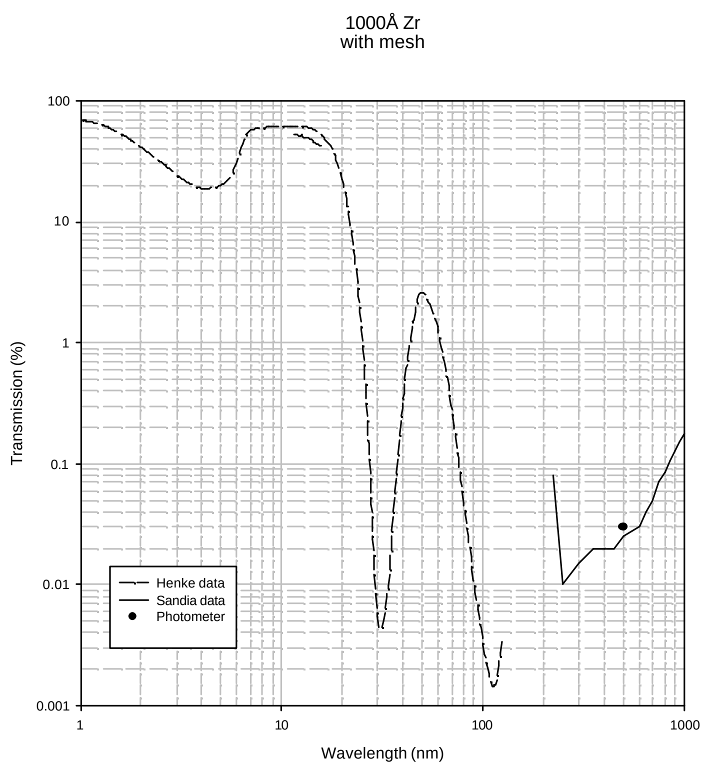


Figure 1. ETS Filter Transmittance vs Wavelength

To increase the transmittance of the filter window and thus the throughput of the lithography machine, improvements must be made to eliminate or at least minimize the oxidation of the zirconium. Steps are being taken to reduce the oxidation that occurs during deposition and filter material processing. Preliminary test results suggest that significant improvements may come from passivation. Silicon seems to be more effective, and since it has good transmissivity at 13.4 nm, a multilayer composed of 500Å silicon/ 500Å zirconium/ 500Å silicon shows promise. The calculated transmittance of this combination is shown on Figure 2. Using measured absorption coefficients for these two materials, this filter would have a visible light rejection of 1.7×10^{-3}, which almost meets the original Sandia specification of 1×10^{-3}. This is potentially the best combination of materials available at this time. With current manufacturing processes, the actual measured transmittance of this filter will likely be les then 60% but with time a transmittance of 60% at 13.4 nm may be achieved. The transmittance of test filters with this combination of materials is being measured at LBNL. The results will be available in the near future.

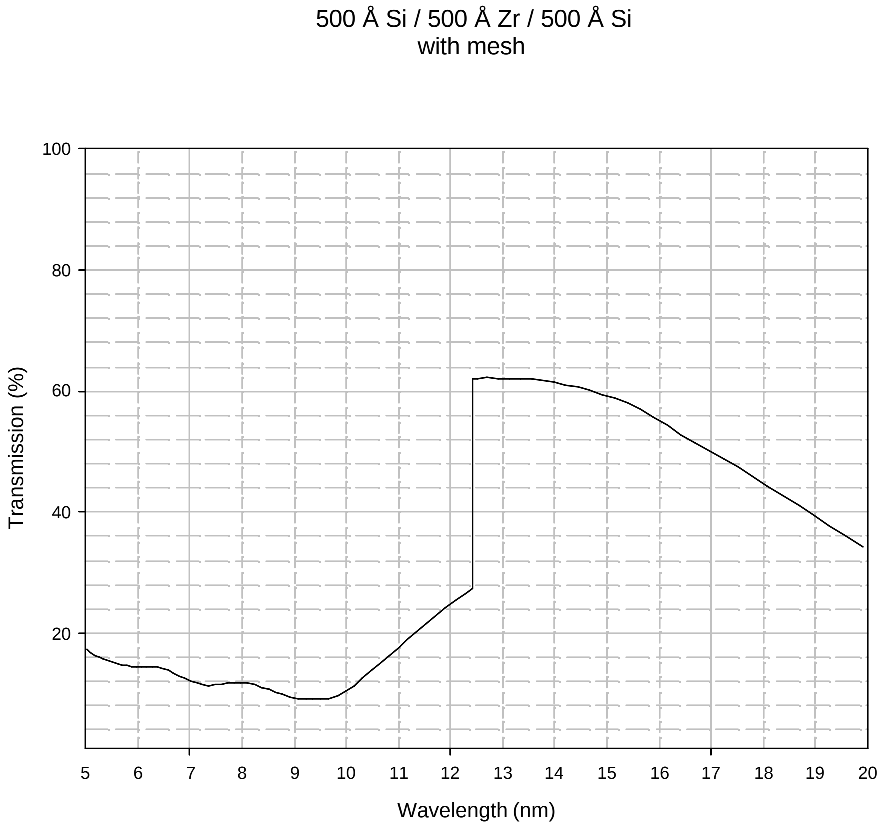
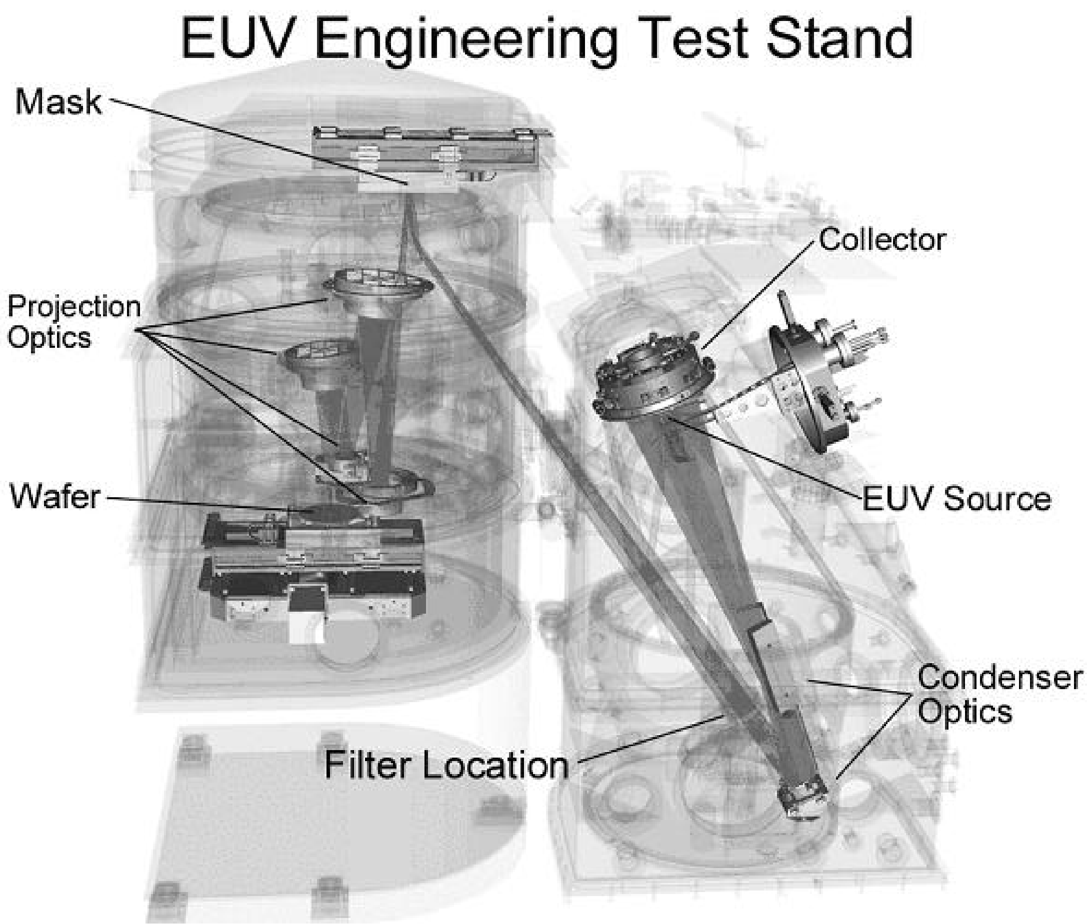


Figure 2. Si/Zr/Si filter transmittance vs wavelength

Another area where improvements are needed is in the mesh. The 70 lines per inch nickel mesh that is currently available transmits about 82%. The loss of 18% transmittance is significant, and work is proceeding with several manufactures to try to realize a mesh that has less loss for this application, and that has a higher manufacturing yield. Perhaps, when more is known about the handling, vibration environment and pressure differentials to which these filters will be subjected, a lighter higher transmission mesh will be found to be satisfactory. The improvement in overall throughput would be welcomed.

FILTER WINDOWS AND THE EUV ENGINEERING TEST STAND

The ETS is a full-field, alpha-class, step and scan extreme ultra-violet (EUV) lithography tool that has been developed by Sandia National Laboratories (SNL), Lawrence Livermore National Laboratories (LLNL), and the Lawrence Berkeley National Laboratory (LBNL). The ETS will serve as the basis for first-generation tool development by the commercial sector. It will also serve as the main testbed for EUV spectral filters. The major components of the ETS are shown in the figure below. Also shown is the location for the placement of a 4" diameter, mesh-supported, zirconium spectral filter manufactured by Luxel Corporation. The filter is located just downstream of the third set of mirrors in the optical train.



The ETS filter, and in general, all filters for EUV lithography, have many requirements placed upon them which can be categorized as optical, environmental, and mechanical. Optical requirements are that filters transmit as much EUV energy as possible while transmitting only a small percentage of out-of-band wavelengths. Unfortunately, these two requirements are often at odds such that increasing EUV transmittance usually results in increasing non-EUV transmittance. Another important requirement from an optical perspective is transmittance uniformity. Non-uniformity can cause aberrations in the printed features on the wafer. The specification for the ETS filters was an EUV transmittance uniformity of better than $\pm$ 1%. The filters produced by Luxel had uniformity that was better than $\pm$ 0.5%.

Environmental requirements for EUV filters are quite stringent. One main environmental concern is vacuum compatibility. EUV lithography must take place in a vacuum environment due to the high absorption of EUV photons by most gases. Therefore, an EUV filter must operate at vacuum, which means special material selection and handling. The materials used for the filters, including epoxies, have to be low outgassing, and the filters have to be manufactured in a clean environment. For the ETS, the filters had to pass a vacuum outgassing test with the requirement that they reach a high vacuum base pressure and not outgas carbon-containing molecules. This additional constraint was due to the fact that molecules containing carbon can be cracked by EUV energy, thus creating graphitic deposits on the surfaces of the EUV optics that would degrade reflectivity. Testing of zirconium filters showed no outgassing of carbonaceous species down to a vapor pressure detection limit of 3×10^{-12} Torr.

Another challenge presented by the filter environment is the heat load due to the absorbed radiation from the EUV source. It is estimated that the filter used in the ETS will absorb approximately 7.5 watts of energy and thus reach an operating temperature of about 160 °C. To simulate this thermal load, filters were placed in a vacuum furnace for a 24-hour period at a temperature of about 170°C. Filters were tested to see if differences in thermal expansion would cause pinholes to develop. Also, there was some concern that the epoxies used to fabricate the filters would not hold up to an elevated temperature. After the test the filters were examined with an optical microscope, and no physical damage was observed.

To rule out the possibility of damage to the filters due to the EUV irradiation by the ETS source, the filters were tested at beamline 12.0.1.2 at the Advanced Light Source facility at LBNL. Filters were tested with a spot of radiation approximately 1-mm square that was limited by a monochromater to a narrow bandwidth around 13.4 nm. The filters absorbed an EUV power flux for a 24 hour period that was about 10 times the EUV flux that ETS filters will absorb. The mesh supported zirconium filters showed no damage from the EUV irradiation. The only noticeable change to the filters was a thin layer of carbon deposited on the surface of the filters during each experiment.

Mechanically, filters must foremost survive handling. It is difficult to produce a 4" diameter foil at a thickness of 100 nm that can withstand being handled as well as transported. In addition, an EUV filter may experience pressure differentials during the processes of pumping down to vacuum or pressurizing to atmosphere. Gradients in pressure create forces on the filter surface that must be resisted.

Also, filters may serve as a barrier to limit the path length of EUV absorbing gases and therefore support a pressure differential during operation, as in the ETS. The ETS spectral purity filter is used to separate the EUV source system from the reticle, projection optics and wafer. This prevents the gas used to create the EUV-emitting plasma from attenuating the EUV power over the entire optical path. For the ETS this results in a throughput savings of at least 20%.

Four-inch diameter test filters manufactured by Luxel with 100 nm thick zirconium attached to a supporting nickel mesh structure have survived handling, shipping and operation in the ETS. Samples have been pressure tested and are expected to withstand pressures of up to 100 Torr.

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