Longer Wavelength EUV Lithography (LW-EUVL)

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ABSTRACT

Extreme UV Lithography (EUVL) is generally accepted as the leading candidate for next generation lithography. Several challenges remain for EUVL, especially as its insertion point is pushed to finer resolution. Although diffractive scaling may suggest a transition to shorter EUVL wavelengths, several issues arise that would make that difficult. Challenges involve issues such as flare, multilayer (ML) bandwidth, and reflector throughput which tend to worsen with decreasing wavelength. In this study, we have evaluated the tradeoff between flare scaling effects and diffractive scaling effects for EUVL, where flare induced image degradation is likely to dominate as sub-13.5 nm wavelengths are considered. With surface scatter effects scaling as $1/\lambda^2$, the idea of longer wavelength (LW-EUVL) becomes interesting. Since a working wavelength is driven by the selection of ML materials (which are molybdenum and silicon for 13.5 nm), the identification of suitable alternatives is an initial challenge. We have optimized aluminum and various refractory metals at 17.2 nm and present results. The optimized combination of aluminum with yttrium, zirconium, and other metals result in theoretical reflectivity values above 75%. We also describe possibilities for alternative LW-EUVL sources for 17.2 nm operation as well as the impact on resist absorption, especially through halogens of higher molar absorption (such as fluorine). The impact on mask absorber materials is also presented, which may also exhibit increased absorbance, leading to a lowering of film thickness requirements.

Keywords: EUVL, flare, multilayers, reflectivity, source, LW-EUVL, mask absorber.

1. INTRODUCTION

Extreme UV Lithography (EUVL) has been principally associated with a 13.5 nm wavelength as a consequence of the molybdenum (Mo) and silicon (Si) multilayer (ML) reflective film stack. The current Mo/Si ML film stack provides the required material compatibility, stability and high reflectivity in the EUV regime. Decreasing the wavelength to as low as 6.7 nm has been discussed as 16 nm half-pitch resolution and below is considered.[1] In this study, the motive for moving to longer wavelengths EUVL (LW-EUVL) is the scaling of optical scatter and flare, which can decrease as $1/\lambda^2$. Alternatively, a decrease in wavelength to 6.7 nm can increase flare on the order of 4x compared to that at 13.5 nm. Very little work has been carried out for longer wavelength EUV MLs or the potential of LW-EUVL. In this paper, we explore the advantages that LW-EUVL could have on ML mirrors, source power, photoresist sensitivity, and mask absorber materials.

2. OPTICAL PROPERTIES OF MULTILAYERS IN THE EUV REGIME

The optical properties of materials for EUV and X-ray frequencies differ from visible and UV wavelengths. In the visible and UV, interactions of radiation with valence electrons determine optical properties. In the EUV and X-ray regime, radiation interacts with both valence and inner electrons. Indices of refraction (n and k) are derived from the complex scattering factors (f), and are expressed as:[2]

$$\begin{aligned} n_r &= 1 - \frac{\lambda^2 r_0}{2\pi \sum N_a \left[f_{1a}(0) + j f_{2a}(0) \right]} \\ &= 1 - \delta - j\beta = n - jk. \end{aligned} \tag{1}$$

In this equation, r_0 is the classical electron radius, and N_a is the number of atoms of type a per unit volume. Refractive index is equated to optical constants delta (which is 1-n) and beta (which is equivalent to k). These optical constants have been tabulated in the EUV regime. Figure 1 shows delta and beta for aluminum. It is important to note that in order to achieve high reflectivity, beta in the region of interest must be low. For aluminum in the EUV regime, this targets photon energies around 70 eV (corresponding to a wavelength around 17.5 nm).

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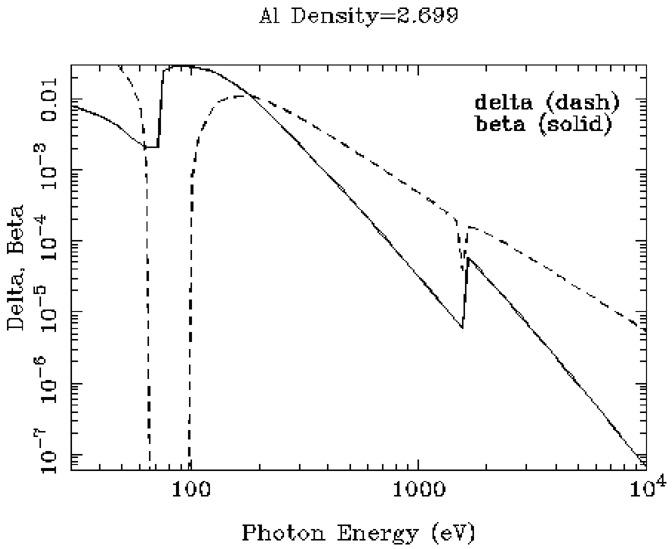

Figure 1. Optical constants of aluminum in the 30 ev – 10000 eV range.[2]

To fabricate a ML mirror with high reflectivity, the alternating layers must both have low absorption coefficients and their indices of refraction must be sufficiently separated. A recurrent formula which relates the reflection amplitudes in two nearest layers is used to iteratively calculate the reflectivity of a multilayer structure. It is challenging to find multilayers with high reflectivity since most materials in the EUV regime have indices of refraction close to unity. Mo/Si ML coatings have high reflectivity at 13.5 nm, but other material combinations also show high reflectivity at other wavelengths. Mo and Si have been optimized to demonstrate theoretical peak reflectivity of ~76% at 13.5 nm, as seen in Figure 2.

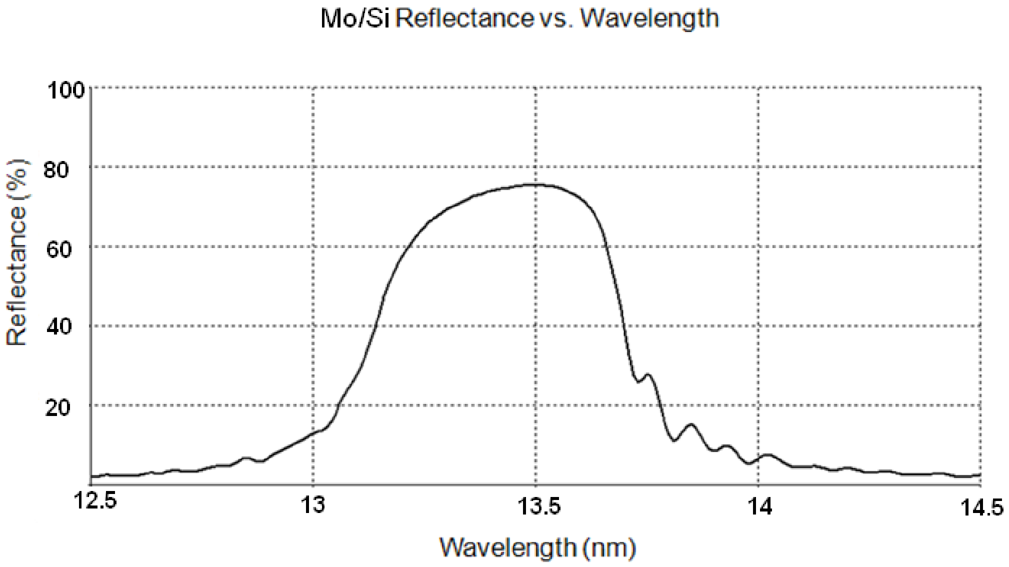

Figure 2. An optimized Mo/Si coating for 13.5 nm.

As a consequence of low beta and positive delta values, we have found aluminum to provide strong reflectivity in a ML for use at 17.2 nm (~72 eV). Aluminum must be combined with another material with low beta and a smaller delta value in order for a multilayer mirror to achieve maximum reflectance. Two materials that exhibit these properties at 17.2 nm are yttrium (Y) and zirconium (Zr), as seen in Figure 3.

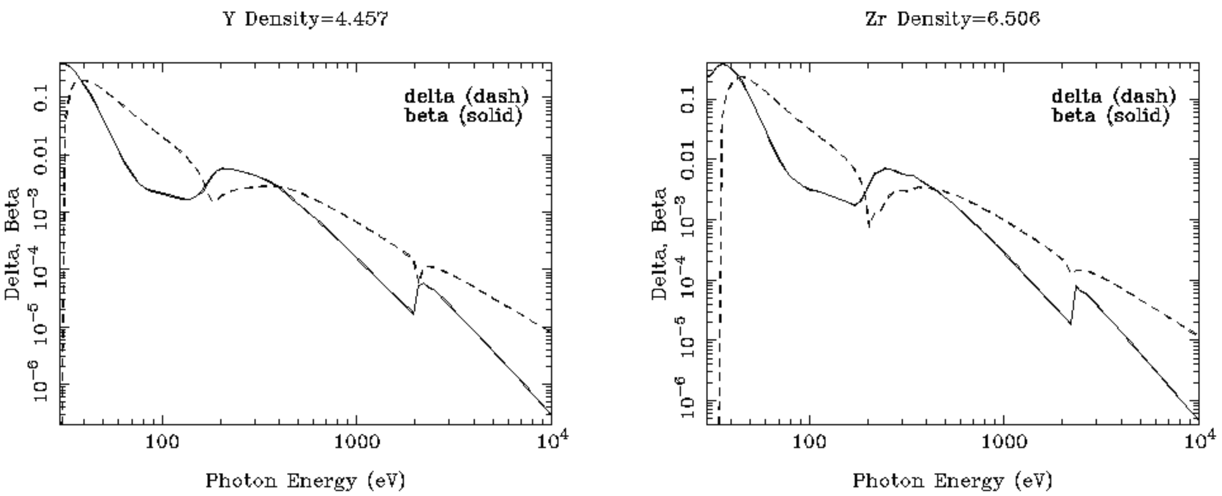

Figure 3. Optical constants of yttrium (left) and zirconium (right) in the 30 ev – 10000 eV range.[2]

Aluminum based ML stacks display high reflectivity at 17.2 nm and may be good candidates for EUV reflectors. Optimized simulation results have shown Al multilayer films with reflection near 80%. Peak reflectivity above 75% near 17 nm is seen in the Y/Al, Zr/Al, Be/Al and Ca/Al ML stacks. Worth noting is that the Al based MLs for 17.2 nm operation (such as Y/Al and Zr/Al) exhibit potentially larger spectral and angular bandwidth that what can be achieved with Mo/Si. This could lead to a significant benefit with respect to system throughput especially for large angles. This behavior is opposite of what is being found for shorter wavelength EUV MLs. Additional work is currently underway and will be reported on in the future. Al based LW-EUVL coatings are viable candidates based on our initial modeling and material combination analysis but other issues could hinder the performance of these reflectors. In previous research, it has been proven that Y/Al film stacks can degrade over time.[3] However, Zr/Al has been found to be stable over time, and considering a theoretical peak reflectivity of 78% may be a promising option, as shown in Figures 4 and 5. Our work continues as we study interfacial effects, materials lifetimes, thermal effects, stress behavior, and other issues.

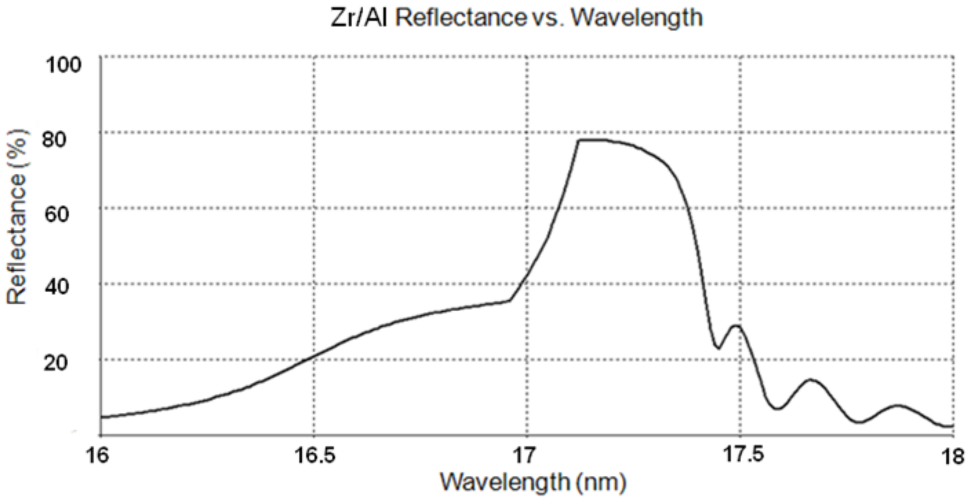

Figure 4. An optimized Zr/Al coating for 17.2 nm showing peak reflectance of 78%.

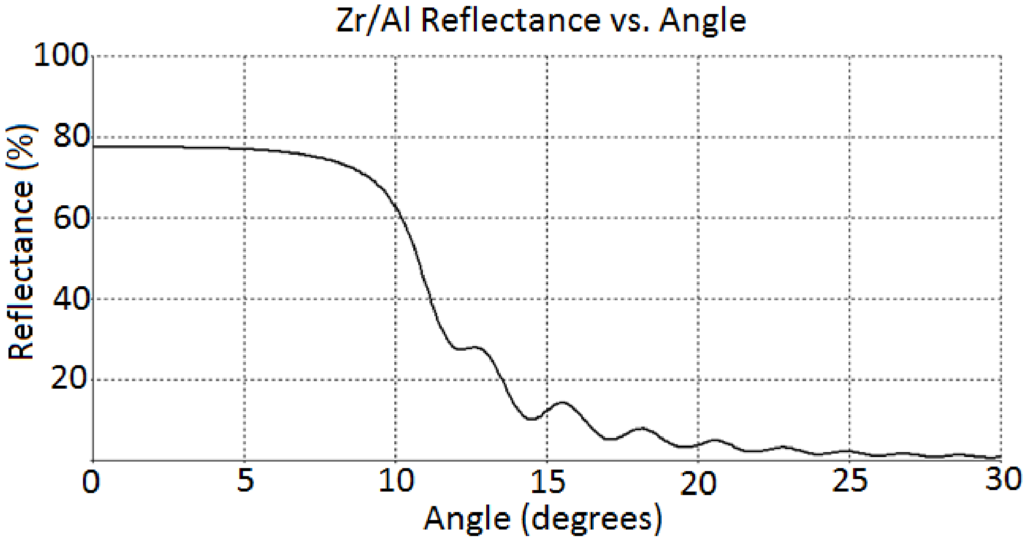

Figure 5. An optimized Zr/Al coating for 17.2 nm.

3. WAVELENGTH AND FLARE EFFECTS

In general, low, mid and high spatial-frequency range (SFR) mirror surface roughness cause scattering of incident radiation. The impact that flare has to EUVL has been studied previously.[4] Figure 6 shows how flare scales with EUVL wavelength, based on a $1/\lambda^2$ relationship. Several cases are shown, where a given amount of flare at 13.5 nm (from 4% to 16%) is scaled for wavelengths from 6 nm to 27 nm. As seen, the effects are detrimental at shorter wavelengths but even high levels of flare at 13.5 nm scale to reasonably low levels at higher wavelength.

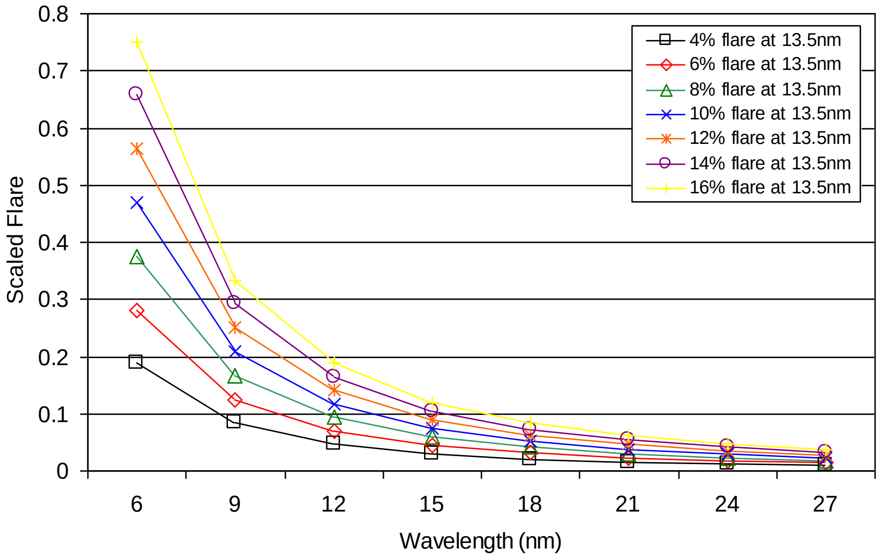

Figure 6. Flare scaling with wavelength.

The effect of flare on image modulation is plotted as in Figure 7. This plot shows how small amounts of flare can degrade image contrast (modulation). Tolerable flare levels below a few percent are desirable. Above this, image degradation will reduce the ability to image small k_1 geometry.

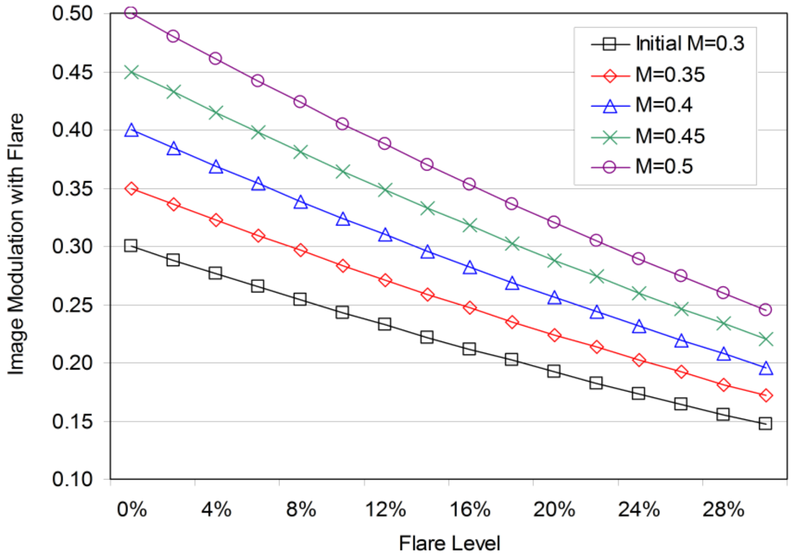

Figure 7. Flare impact on image modulation for initial modulation levels from 0.3 to 0.5 and flare levels up to 28%.

4. EUV SOURCES

If longer wavelengths are to be utilized, alternative sources must be investigated. There are elements that provide higher power at longer wavelengths than that of xenon (Xe) and tin (Sn) at 13.5 nm. Oxygen has an emission line near 17 nm with a measured output power that is greater than that of xenon at 13.5 nm as seen in Figure 8.[5] Since oxygen is reactive, shorter maintenance intervals might be expected. However, there are certain inert gasses that emit photons near 17 nm that have similar power output to that of xenon. Argon and neon both have emission lines in this region and also could act as a possible source for LW-EUVL.[6] Additional exploration of LW-EUVL sources is warranted, together with the spectral bandwidth requirements of MLs, which may be broader than those for 13.5 nm (and moreover 6.7 nm).

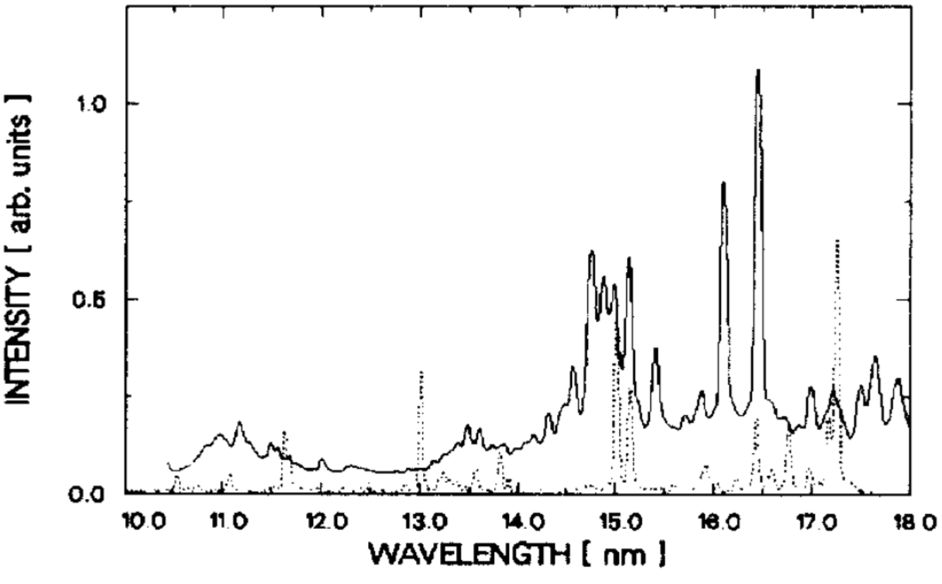

Figure 8. Spectrum of xenon (solid line) compared to the spectrum obtained from oxygen (dashed line).[5]

5. FLUORINATED PHOTORESISTS

Challenges for EUV photoresist include those of sensitivity, resolution and line edge roughness (LER). Recently, halogens such as fluorine have been added to photoresists, which can lead to increases in absorption efficiency at 13.5 nm. Fluorine has a higher absorption coefficient at 17.5 nm than it does at 13.5 nm resulting in increased quantum efficiency and a potential improvement in LER.[7] Figure 10 shows a typical photoresist (PMMA) and its fluorinated derivative. These two photoresist experience nearly a doubling in their absorption efficiency when moving from 13.5 nm to 17.5 nm, as seen in Figure 11.

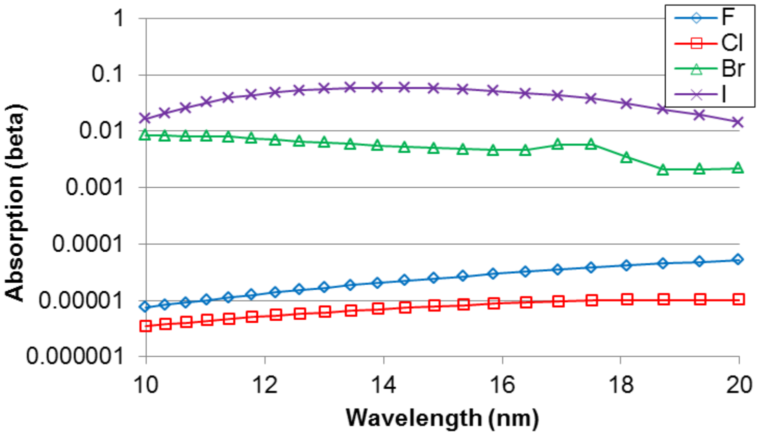

Figure 9. Absorption coefficient (beta) versus wavelength for halogens.

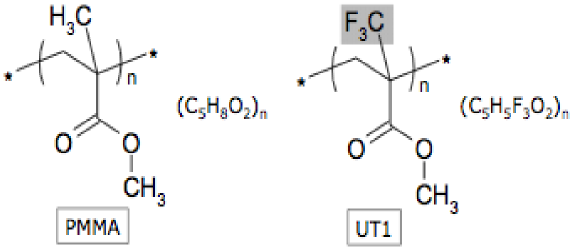

Figure 10. Chemical structures of PMMA and its fluorinated derivative (UT1).[7]

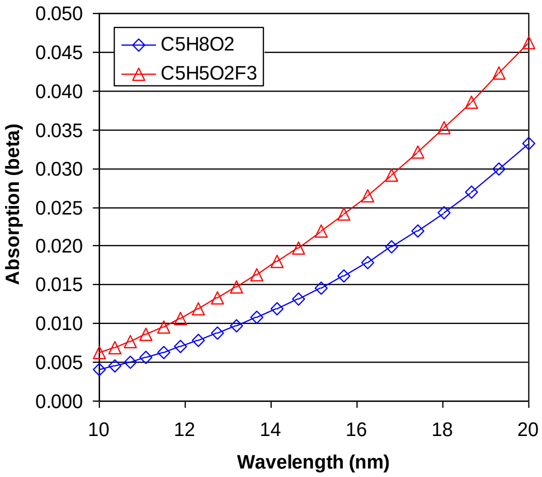

Figure 11. Absorption coefficient (beta) versus wavelength for PMMA and its fluorinated derivative.

6. MASK ABSORBER

A variety of options have been considered as the absorber material for EUV masks. Materials such as Al-Cu, Ti, TiN, Ta, TaN and Cr have all been evaluated. EUV mask absorber requirements, etch process and cleaning durability have all been assessed for these materials.[8] TaN has been the leading candidate due to its processing compatibility as well as its high absorbance in the EUV regime.[9] Films that are more absorbent can be deposited thinner and can still attenuate radiation down to the process requirement. Having a thinner absorber reduces the effect of shadowing from oblique illumination. When considering alternative wavelengths, it would be desirable for the absorption coefficient to increase. Figure 12 shows the relationship between the absorption coefficient for TaN and wavelength.

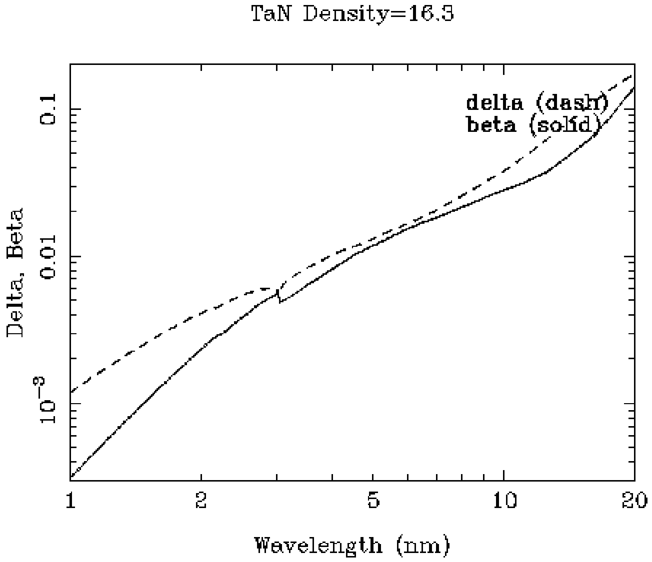

Figure 12. Optical constants of TaN in the 1 nm – 20 nm range.[2]

7. CONCLUSIONS

We propose that LW-EUVL has merits worth further exploration as an alternative to shorter wavelength EUVL. By using aluminum based MLs, combined with various refractory metals such as yttrium and zirconium, lithography at 17.2 nm may be enabled. Although increasing wavelength is a counter-intuitive notion, the diffractive losses experienced may be compensated for by gains in other ways. Primarily, the potential reduction in flare and its effects for wavelength longer than 13.5 nm could allow for higher k_1 imaging through improved image modulation. Also, if brighter sources are available at a longer wavelength, system throughput may be improved. Further gains could be realized if ML bandwidth improves. This may also allow for the increase in the number of mirrors with less throughput loss, helping to enable higher NA systems. Resist issues such as contrast and LER may benefit from reduction in flare as well. Combined with the possibility of lower photon shot noise through reduced photon energy, a larger impact to LER reduction might be possible. Lastly, current mask absorber materials may be more effective at longer wavelengths and could therefore be deposited at thinner thicknesses. LW-EUVL has the potential to overcome many of the current complications for EUVL. Timing of the introduction of an additional EUVL wavelength will be important. Whether EUVL at 17.2 nm could offer benefits depends on the requirements necessary to modify the current 13.5 nm infrastructure. Since EUVL is a reflective technology, primary issues involve those associated with reflective ML coatings. We have introduced issues involved with other associated aspects. Their complexities require additional exploration.

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