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Nanolithography of the future will use multilayer optics composed of elements like Ru/Be and Rh/Sr.

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Abstract:

Next-generation nanolithography is considered, along with the potential shift to 10.5 and 11.2 nm wavelengths rather than 6.7 and 13.5nm. At their respective operating wavelengths, the performance of ten-mirror optical systems based on Ru/Be, Mo/Be, Rh/Sr, Mo/Si, and La/B multilayers was compared. It is shown that moving to wavelengths of 10.5 nm and 11.2 nm might improve projection system performance and resolution. Author's property during the year 2013 (s). Unless where otherwise specified, all of the material of this article is licenced under a Creative Commons Attribution 3.0 Unparted License.

INTRODUCTION

Extreme ultraviolet (EUV) lithography equipment for use at = 13.5 nm is now the focus of several research groups and major chip-maker firms. Indeed, at this wavelength, ASML's NXE:3100 technology has achieved a half-pitch (hp) spatial resolution of 16 nm. 1 Yet, getting the numerical aperture of the projection lens up to 0.7 is essential for making progress towards decreasing critical dimensions (CDs), sub-10 nm. There are a number of issues with this strategy. To begin, the projection lens must have a Dog of less than 30 nm. Two more mirrors in the projection lens reduce performance by more than a factor of two. Finally, it is currently difficult to manufacture a high-aperture objective. Other methods include using shorter wavelengths. Nanolithography systems using La/B multilayer optics at 6.7 nm (beyond extreme ultraviolet (BEUV)) have been shown to outperform those using Mo/Si optics at 13.5 nm in terms of both efficiency and spatial resolution, according to performance calculations (see Table I and Ref. 2). As a result, there has been a surge in recent study of the fundamentals of BEUV lithography. 3 An overview of the current status of La/B multilayer structure-based optics research for 6.7 nm BEUV lithography is provided in this article. Existing experimental data leads to the conclusion that La/B multilayer optics advancements will have a significant impact on the economic potential of this wavelength. We believe it is time to start looking at other spectral ranges in parallel with research in the field at 6.7 nm due to the existing risks in achieving high reflectance mirrors (greater than 70%) and the more than two times lower sensitivity of the organic photoresist (due to the greater transmission at this wavelength compared with 13.5 nm). The biggest issue with EUV lithography at 13.5 nm is the slow production rate; the NXE:3100 can produce four 300 mm diameter wafers per hour1,4 and the NXE:3300B, which is expected to be delivered by ASML in the second half of 2013, can produce 43 wafers per hour. In light of this, while selecting a new wavelength, it is important to think about boosting both the spatial resolution and the performance of the system in order to achieve the target rate of more than 100 wafers per hour. In this study, we argue that, in the case of conventional ultraviolet lithography, the transition to a BEUV lithographer's new operating wavelength should be gradual rather than revolutionary (as in the 6.7 nm example). Except for 10.5 nm, we believe the wavelengths of 10.5, 10.8, and 11 nm to be the most promising. 5,6 For what it's worth, here's our take on

TABLEI.

Analysing the best optical system characteristics and radiation sources for BEUV lithography.

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λ, nm	Ion material	MLS	d, nm	R_m^{10}	Δλ, nm	Δλ/λ,%	CE, % (in band Δλ)	$E = R_m^{10}CE$
13.5	Sn	Mo/Si	6.9	0.044	0.27	2	4.5	0.20
13.5	Xe	Mo/Si	6.9	0.044	0.27	2	0.8	0.033
11.18	Xe	Ru/Be	5.65	0.086	0.19	1.7	3.6	0.31
11.18	Xe	Mo/Be	5.61	0.070	0.14	1.3	2.7*	0.19
10.8	Xe	Rh/Sr	5.52	0.050	0.19	1.8	3.6	0.18
10.5	Cs	Rh/Sr	5.38	0.055	0.14	1.3	?	?
6.62	Tb	La/B	3.32	0.15	0.045	0.6	1.7	0.255

Table notation: : wavelength; MLS: multilayer structure; d: period of the MLS; Rm10: the calculated peak transmittance of the optical system of ten multilayer mirrors; : spectral band width of the ten mirror optical system; /: band width expressed in percentage; CE: conversion efficiency of the radiation source in the spectral region of the optical system's band width, *: CE is corrected according to the lower of the Mo/Be

SELECTIONOFTHEWORKINGWAVELENGTH

We consider the power and spectral properties of the radiation source as well as the reflectivity of the multilayer mirrors when deciding on a working wavelength for (B)EUV lithography. The incident radiation power PW incident on the wafer is proportional to the (B)EUV source power PS, the integral of the product of the source's spectral power density S(), and the spectral dependence of the reflectance of the multi-mirror (for example, ten-mirror) system, which is the product of the reflection curves R() of each mirror.

$$P_W \rightarrow \mathrm{P}_S \cdot \int_0^\infty S(\lambda) \cdot R^{10}(\lambda) d\lambda.$$

As an alternative to expression(1), the following ratio is often used in practise to accurately compare the efficacy of different sources and optical systems in general while also accounting for the restricted bandwidth of these systems.

$$E = R_m^{10} \cdot S(\lambda_W) \cdot \Delta\lambda = R_m^{10} \cdot CE,$$

where CE is the conversion efficiency, which is the proportion of the total energy provided to the source that is radiated by the source in the half-space in the spectral band-width of the optical system (for example, the laser energy incident on the target); and W is the working wave-length. Hence, CE is affected by the characteristics of the light source and the optical system's band-pass. The highest reflectance of multilayer interference mirrors is only reached in limited spectral areas near to the region of anomalous dispersion of the weakly-absorbing material (spacer), where the least absorption and maximum contrast of the refractive index at the borders occur. Si (L-absorption edge:12.4 nm), Be (K-absorption edge:11.1 nm), B (K-absorption edge:6.6 nm), and C are the only options for such materials in the 4-14 nm range (Kabsorptionedge4.4nm). You can get reflectivity's of over 60% and 70%, respectively, using materials like Y (M-absorption edge below 9nm) and Sr (M-absorption edge below 10nm).While first investigating EUV lithography, researchers had to decide between Mo/Be and Mo/Si optics, operating at 11.3 and 13.5 nm, for their primary wavelengths of interest.7 Multi-charge ion sources such as Xe and Li are explored as potential radiation generators. It was decided to go with 13.5 nm, using Mo/Si optics, even though the Mo/Be mirrors had greater reflectance owing to the lower spectral bandwidth of the ten-mirror system. As a result, tin ions became the primary EUV radiation source for 13.5 nm lithography because of their high conversion efficiency of input energy into output light (CE 4.5%).

ISSUES OF MULTILAYER La/B OPTICS FOR BEUV AT 6.7 nm

Current studies in the area of 6.7 nm radiation sources have enabled us to pinpoint the most promising materials (Gd and Tb) whose highly charged ions create radiation in the neighbourhood of 6.7 nm, with Ace= 1.65% of CO2 laser energy into BEUV and a spectral band width of 0.6% in the half-space. 8–10 Table I shows that although the total theoretical efficiency of the scanner at 6.7 nm is higher than the efficiency at 13.5 nm, this figure is roughly three times lower than the conversion efficiency of the tin source at 13.5 nm. Researchers want to improve CE by, among other things, adjusting target material composition and hot plasma production parameters. 11 The biggest challenge is reaching the target reflection coefficient values for multilayer La/B mirrors. La/B4C MLSs exhibited the highest reflectivity out of a systematic comparison of La/B, La/B4C, La/B9C, and La2O3/B4C normal-incidence multilayer mirrors. 12–15 Maximum reflection coefficients observed so far are 44% at = 6.7 nm12 and 48.9% at =6.68 nm. 15 The experimental findings differ significantly from the theoretical calculation, by more than 80%. The fundamental cause of this difference is that the transition borders in the multilayer structures have widened as a result of material mixing. 13,14 It is also shown in Refs. 13 and 16 that lanthanum forms compounds with boron and carbon in La/B4C multilayers (LaB6 and LaC2). Thus, the electron density profile during a period of the MLS is asymmetric. When La is placed upon B4C (the attenuator's roughness parameter equivalent), the mixing depth may reach up to 1.5 nm. When B4C is deposited onto La, the Debye factor for the amplitude reflection coefficient is 1 =0.75 nm) and 0.5 nm (2 = 0.25 nm). Recently, a La/B4C/C MLS with carbon anti diffusion barrier layers reached a record high reflectance of over 60%. 17 The depth to which the film components were mixed was successfully reduced when the barriers were applied. A comparison of the reflection coefficients' angular and spectral dependence led to the following estimates: 1 = 0.6 nm and 2 = 0.25 nm. Reflectance spectra, R10(), of ten-mirror optical systems are shown in Fig. 1 for the instances of an ideal (1,2 = 0) La/B MLS (upper curve), an ideal La/B4C MLS (middle curve), and a La/B4C MLS with empirically acquired record values of 1 = 0.6 nm and 2 = 0.25 nm. N = 200 periods were used in the MLS calculations. The optical constants were used from in our calculations. 18 As can be observed in the picture, both the peak reflectance and the spectral bandwidth experience a dramatic decrease due to the interfacial roughness (mixing of the materials). In particular, the actual structure, despite its present unparalleled performance, falls short of the theoretical limit by a factor of 16 for the integral reflection coefficient R10()•. It is reasonable to anticipate that the total productivity of lithography at 6.7 nm is around two orders of magnitude lower than at 13.5 nm because to the much reduced sensitivity of current photoresists and CE. Second, the roughness and form accuracy requirements of the optical elements need to be raised by the same amount as the decrease in wavelength. It is recommended that projection lens aberrations be fewer than 0.3 nm if one wants to get a diffraction-limited picture. For lateral dimensions between 1 nm and 1 mm, this requires surface roughness of more than 0.1-0.2 nm and mirror-like accuracy of shape. These features are at least twice as precise as what is now possible with optical components, thus ground-breaking innovations will be required to realise them. Concluding, it is important to stress that all of these deficiencies represent major challenges, and remedies are not now available. In light of this, we believe it is time to explore shifting to a different frequency. It's not enough to just aim for better spatial resolution; one must also seek for more efficient optical systems and radiation generators.

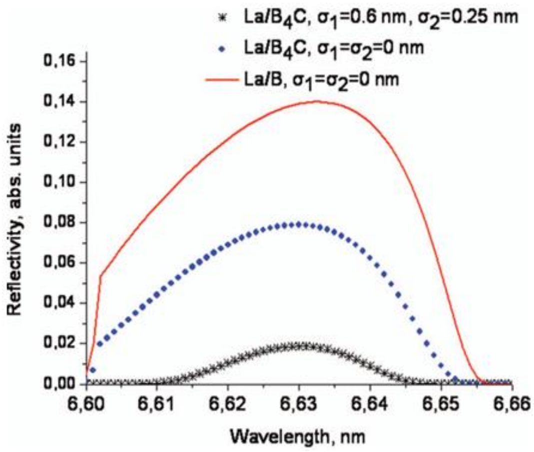

FIG. 2. The spectral dependence of the reflection coefficients of Mo/Be and Ru/Be MLSs.

MULTILAYER Be- AND Sr-BASED OPTICS FOR BEUV AT 11 nm

Studies of Mo/Be MLSs have been conducted for possible use as mirrors in the 11 nm spectral range. Early findings demonstrated a high reflection coefficient (Reap = 70.1%); the upper limit is Roth = 75.6%. Even for

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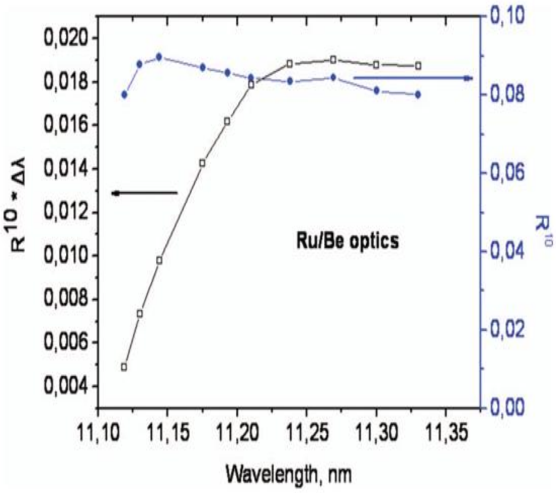
experimental materials, the peak reflectivity of 5 is higher than that of the Mo/Si mirrors. Their spectral bandwidth, however, is much lower. In order to improve the performance of Be-based MLSs, we offer an alternative, the Ru/Be MLS. The Mo/Be and Ru/Be MLSs' computed reflectance spectra are shown in Fig. 2 with centre wavelengths of and, respectively.



the maximum reflectance at 11.3 nm. The figure demonstrates that Ru/Be optics have much better peak reflectance (77.8% vs. 75.9%) and spectral bandwidth at half maximum (0.407 nm vs. 0.331 nm). As can be seen in Table I, the overall integral gain of the ten-mirror system is 1.7 times. In Fig. 3, we see how the predicted integral R10()• and the peak ref laitance R10() of the ten-mirror system based on Ru/Be optics vary with wavelength. Use these correlations to determine which BEUV radiation wavelengths will be most effective. The figure shows that the integral reflection coefficient peaks at a wavelength of around 11.2 nm and then fluctuates somewhat with additional increases in wavelength. It is important to note that the Ru/Be mirror maintains its high peak reflectance down to 11.12 nm even when the spectral line width is lower than the bandwidth of the multi-mirror system. By utilising a lightly absorbing material like Sr, MLS provides the maximum reflectivity in the spectral band below 11 nm. The reflecting properties of Mo/Sr mirrors were studied experimentally and found to be rather good. 6 Specific results include a 48.3% reflection coefficient at 10.5 nm and normal incidence, with a theoretical maximum of 65%. The calculated peak and integral reflection coefficients of Rh/Sr MLSs are much greater than those of Mo/Sr MLSs. In instance, reflectance is more than 70% at a wavelength of 9.711.3 nm. As can be seen in Table I, the ten-mirror system has an essentially identical integral reflection (a product of reflectivity and spectral band-pass) at 10.8 nm as it does at 13.5 nm with Mo/Si optics.

EFFICIENCY COMPARISON OF BEUV AT 11 nmANDEUVAT13.5nm

Mo/Si multilayer optics are used in EUV lithography, and the theoretical reflectance of the ten-mirror system is 4.4%. Tin plasma is a very efficient radiation source in this spectral band, with a conversion efficiency of 4.5%. According to Table I, the combined efficiency of these optics and the CE of the tin source, indicated by (2), is 0.198. The xenon plasma emission spectra at the optimal temperature for production at 13.5 nm is shown in Fig. 4. The bandwidth of a 10-mirror system using Mo/Si MLSs is shown by the "bell" on the right. Rh/Sr MLSs follow the curve seen on the left. Bandwidth is represented by circles of the same size.

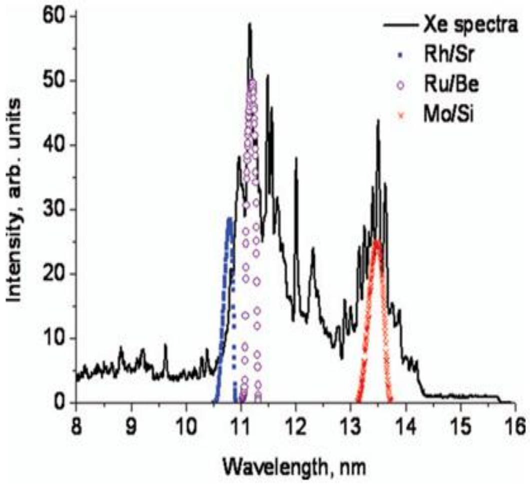


FIG. 4. The emission spectrum of Xe plasma (line). The plasma temperature is optimized for maximum wavelength in the vicinity of 13.5 nm. Symbols denote the spectral band-pass of the ten-mirror systems: left: Rh/Sr; central: Ru/Be; and right: Mo/Si MLSs.

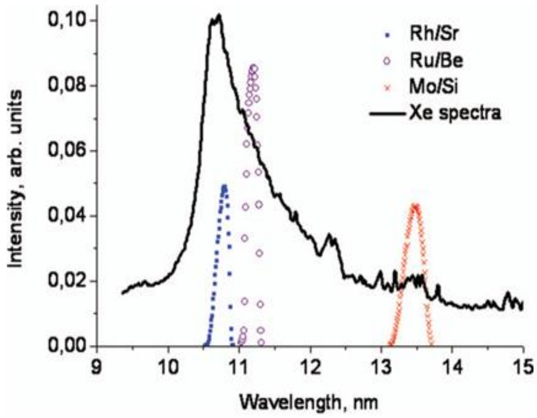


FIG. 5. The same as in Fig. 4, but the plasma temperature is optimized to generate emission in the region of 11 nm.

Ru/Be multilayer mirror optical setup. Spectral information identical to that previously offered was provided by K. Koshelev and Kravtsov of the Institute for Spectroscopy at the Russian Academy of Sciences in Troitsky. 19 In this study, we looked for material combinations for MLSs that would have the maximum theoretical reflectance over the broadest range of possible plasma source wavelengths. Discharge energy is converted into EUV radiation with an efficiency of roughly 0.8% in a spectral range of about 13.5 nm. It is clear that at 11 nm, both the source's efficacy and the optical system's integral transmission are better than at 13.5 nm. The resolution is improved by about 20% because to the shorter wavelengths. Sources of tin ions with conversion efficiencies of up to 4.5% are used in practise for 13.5 nm lithography (Table I). 20,21 Optimizing the xenon plasma temperature, as shown in Fig. 5, may greatly improve efficiency in the short wavelength region. 19,22 Although there is more concrete information on 13.5 nm Xe source conversion efficiencies, the literature only provides estimations for 11 nm Xe sources. Referring in particular to Ref. 21, we learn that the 13.5 nm Sn source and the 11 nm Xe source have similar conversion efficiency. The radiation intensity observed in the 11 nm band is four to five times greater than at 13.5 nm. 19,22–25 There have been reports in of calculated spectra of Xe plasmas at various temperatures and electron concentrations. 26 They demonstrate that the ratio of radiation intensities at 11 nm and 13.5 nm and the location of the spectral maxima are both dynamic. Furthermore, there exist spectra with a ratio of intensity of around four. Finding the separate contributions to the spectra of ions of varying charge states was a particularly fascinating outcome. It is shown in particular that Xe^{+10} ions are primarily responsible for the emission of 13.5 nm light. At 11 nm, the spectrum peaks. For this scenario, the intensity ratio is at around six. A substantial peak at 11.3 nm can be seen in the Xe^{+9} ion emission spectra; this peak is almost six times as intense as the peak at 13.5 nm. First, it gives us reason to believe that the estimated conversion efficiency of the Xe source in the region of 11 nm is conservative, and could be improved upon by optimising the parameters of the plasma (CE11 = 0.8 4.5 = 3.6%, where 0.8 is the CE of the Xe source optimised for generation in the f field of 13.5 nm, as confirmed in a number of papers, for example19, and 4.5 is the ratio of the intensities in the regions of See Fig. 3 for an explanation of why this last point is so crucial; mirrors made from beryllium have a short-wave boundary of the reflection coefficients at about Be = 11.1 nm. Reflectance of Ru/Be mirrors and CE =3.6% are included into the projected performance of the lithographic facility, which results in a value of 0.310. This value is 50% higher than the performance at 13.5 nm (see Table I). The peak of the xenon UTA spectrum, seen in Fig. 5, occurs at a wavelength of 10.8 nm. To recap, Rh/Sr MLSs provide the maximum reflectance at this wavelength. Table I shows that the machine's efficiency drops by around 10% while operating at a wavelength of 13.5 nm, assuming CE= 3.6%. The 10.5 nm wavelength is promising for BEUV lithography. Although the reflection coefficients of Rh/Sr MLSs at this wavelength are equivalent to those of Mo/Si MLSs at 13.5 nm, this wavelength also happens to be near the centre of the UTA emission of caesium's multiple charged ions. More efficiency is to be expected from the source given the shape of the caesium spectrum around 10 nm.27 So, the source's conversion efficiency determines how promising the utilisation of this wavelength is for BEUV lithography.

CONCLUSION

The presented results suggests that developing multilayer mirrors with high reflectivity will be an important step towards the future of 6.7 nm BEUV lithography. While ten-mirror optical systems have the potential to boost reflectivity by more than an order of magnitude, current results fall 16 times short of the theoretical limit for integral reflectivity. We think it's important to consider alternatives to BEUV lithography at 6.7 nm in order to minimise the dangers involved. Rh/Sr multilayer optics at 10.5 and 10.8 nm, and Ru/Be MLSs at about 11 nm, are the most promising. Multilayer mirrors performed substantially better at these wavelengths than at 6.7 nm in the outset. Mo/Be MLSs, in particular, were created and studied as early as 1998. Theoretically, the maximum reflection coefficient is 75.6%, however measurements at 11.3 nm with normal incidence yielded just 70.1%. While lower than the theoretical limit of 65%, the 48.3% reflection coefficient at 10.5 nm6 achieved for a Mo/Sr mirror is encouraging. There are two primary factors that will determine how successful BEUV lithography will be with Sr-based optical systems. To begin, oxidation is known to reduce the reflectivity of Mo/Sr MLS mirrors. 6 Thesecondisthatthemostpromisingwavelengthforthisopticsis10.5nm. In the case of caesium, this wavelength is dead centre of the UTA emission from ions with multiple charges. The shape of the caesium spectrum in the 10 nm range27 suggests that this range will have a very high source efficiency. This means that measuring the conversion efficiency of the Cs source is important for understanding the future of this wavelength's use in BEUV lithography. As the Ru/Be MLS provides the maximum reflectivity (given the 78% theoretical limit) at 11 nm, this seems to be the most practical wavelength for next-generation nanolithography in the BEUV region. There is no doubt that this wavelength will help the resolution of the projection scheme. The experimental Mo/Be MLS reflection data suggests that the optical system transmission is likely to be more than 13.5 nm. The efficiency of conversion from Xe sources that have been tuned for 11 nm is unknown at the present time. The authors can only hope that their choice of 13.5 nm for the optimal CE of the Sn source is supported by the experimental evidence available in the literature. The optimal ion composition of the Xe source determines the operating wavelength, which is between 11 and 12 nm. Xe+10 ions, for instance, produce light at roughly 11 nm, whereas Xe+9 ions do so at around 11.3 nm. To decide between 11 nm and 13.5 nm, it's important to remember that the Xe source generates far less debris than the Sn source, which may have a beneficial influence on its efficiency. Incorporating even a trace number of silicon atoms into a polymer molecule, which is rather natural given the suggested wavelengths, results in a strong absorption of light at the working wavelength. Hence, despite the lower wavelength, the photoresist sensitivity may even rise in comparison to that at 13.5 nm, yet the sensitivity to mirror contamination by hydrocarbons drops by almost 1.5 times. As there is less absorption at this wavelength, spectral purity filters and protective mask pellicles should let more light through, allowing for improved lithography performance at 11 nm compared to 13.5 nm. Prior research emphasised the need of taking precautions while handling beryllium. Yet we think that if there are technological or other reasons to utilise risky materials like nuclear or deadly ones, then such things may be used with proper precautions. For example, windows made of beryllium are often employed in standard X-ray tubes used in technical, medical, and scientific settings.

SUGGESTIONS FOR FURTHER WORK

Studying highly reflective Ru/Be MLSs, optimising them, and measuring the conversion efficiency of Xe sources in the range of 11 nm are the first steps towards using BEUV lithography in the area. From an optical perspective, the best wavelength to go with is more than 11.2 nm. Research into Rh/Sr MLSs and measuring the conversion efficiencies of Xe at 10.8 nm and Csat10.5 nm sources are the initial steps towards BEUV lithography below 11 nm. No major financial outlay is necessary to conduct these tests, and the results will definitively answer the issue of whether or not a large-scale research into the area of BEUV lithography about 11 nm is advisable.

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