A Synchrotron-Based Fourier-Synthesis Custom-Coherence Illuminator

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Abstract. Scanning illumination systems provide for a powerful and flexible means for controlling illumination coherence properties. Here we present a synchrotron-based scanning-mirror Fourier synthesis illuminator that enables sources with intrinsically high spatial coherence, such as undulators, to be used in situations demanding less coherence. The application considered here involves microfield extreme ultraviolet (EUV) lithography, however, the same methods are applicable to conventional microscopy as well as coherence-imaging techniques. This flexible illuminator allows the coherence to be tuned in situ enabling the illumination to be tailored to the specific pattern being imaged. The effectiveness of the system is demonstrated through a variety of lithographic print experiments. These include the use of resolution enhancing coherence functions, which enable the printing of 50-nm line-space features using a lithographic optic with a NA of 0.1 and an operational wavelength of 13.4 nm.

MOTIVATION

Extreme ultraviolet (EUV) lithography[1] remains the top candidate for the technology to be used for the 32-nm generation of nano-electronics expected to enter volume production in 2009. Achieving this target requires early availability of systems capable of these resolutions and finer. Although not under serious consideration for manufacturing applications, synchrotron radiation provides a convenient well-characterized debris-free source ideal for such advanced research systems. The problem with synchrotron radiation, however, is the poor match between its intrinsic coherence properties and those required of a lithographic tool. Although particularly true for undulator radiation,[2] in practice, this statement also holds for bend-magnet radiation.

The ultimate imaging performance of any optical system depends not only on the quality of the imaging optics, but also in large part on the coherence properties of the illumination.[3] Additionally, the ideal illumination is pattern specific, making controllable illumination coherence a valuable attribute to general-purpose imaging systems.[4] Here we describe a synchrotron-based scanning illumination system with programmable coherence. Moreover, these coherence control capabilities are achieved without scatter plates or source-shaping apertures, making the system very efficient. The implementation and specific motivation described here is related to synchrotron-based EUV lithography, however, the method is relevant to a much broader class of instruments and wavelengths. For example, the methods described here are also relevant to imaging microscopes working in virtually any wavelength range.

SHAPING THE COHERENCE

The well-known Wiener-Khinchin theorem,[5] teaches us that there exists a Fourier transform relationship between spectral bandwidth and temporal coherence. In a similar manner, we can interpret the Van Cittert-Zernike theorem[5] as specifying an equivalent Fourier transform relationship between spatial bandwidth and spatial coherence. Thus, it is evident that spatial coherence can be controlled by shaping the spatial bandwith of the illumination.

At visible wavelengths, a common method for controllably reducing spatial coherence is to use a random phase modulator conveniently implemented as rotating ground glass.[6,7] While potentially feasible at EUV using a relective

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scatter plate, such a system would likely not be adequately efficient, especially if arbitrary coherence shaping is also desired. Moreover, the method would become considerable more complicated at even shorter wavelengths.

An alternative coherence-control method, more suitable to short-wavelength applications, involves a process by which the desired illumination spatial-frequency spectrum is effectively synthesized through a scanning process.[8,9] An example Fourier synthesis illuminator is shown in Fig. 1. The input beam, which has a higher degree of coherence than desired, is scanned through a range of angles to produce the desired spatial-frequency spectrum. Assuming the observation, or image integration, time to be long relative to the scan rate, it can be shown that the coherence properties of the illumination produced by this system will be indistinguishable from those of a traditional source with the same spatial spectrum, provided that the individual spatial-frequency components are mutually incoherent.[10-11] We note that the scanning system presented here guarantees the individual spatial-frequency components to be mutually incoherent by virtue of the components not coexisting in time.

The requirement that the integration time to be long relative to the scan rate, in practice, means that the exposure should be at least as long as it takes to fully scan the desired spectrum once. Additionally, the exposure time should be constrained to an integer multiple of the full spectrum scan time. If this condition is not satisfied, some portions of the spectrum would receive higher weighting than others, thereby changing the coherence properties relative to those corresponding to the intended spectrum.

The system in Fig. 1 assumes a reflective object, as is the case in EUV lithography, however, the illuminator could be modified to work with transmissive objects. Also, the use of a nominally 45-degree scanning mirror and near-normal incidence spherical mirror, requires these elements to be multilayer coated for short-wavelength use. While this is of little concern for the EUV lithography application presented here where the object and the imaging optics also require multilayer coatings, this configuration could be somewhat limiting in a more generalized microscopy setting. For microscopy it would likely be preferable to implement a dual-element grazing incidence scanner along with grazing-incidence imaging optics to re-image the scanners to the object plane. For example, in Fig. 1 the scanning functionality could be integrated into the Kirkpatrick-Baez collimating optics and a second Kirkpatrick Baez optic pair could be added to serve the role of the spherical mirror. Such changes would permit the system to be used over a much broader range of wavelengths.

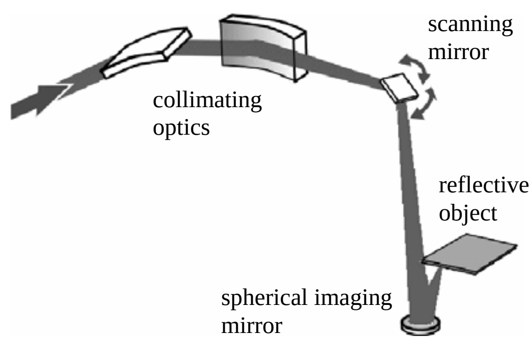

FIGURE 1. Schematic of scanning Fourier-synthesis illuminator. A 2-D angle scanning turning mirror serves as an effective source that is re-imaged to the object plane using a spherical mirror. The spatial bandwidth (coherence) of the effective source is synthesized through the scanning process.

AN EUV LITHOGRAPHY ILLUMINATOR

The Fourier synthesis concept described above has been used to implement a custom coherence illuminator for an EUV microstepper implemented at an undulator beamline at Lawrence Berkeley National Laboratory's Advanced Light Source synchrotron radiation facility.[12] This undulator beamline has previously been demonstrated to intrinsically provide illumination of nearly complete spatial coherence.[2] Referring to Fig. 1, the undulator beam is nominally collimated using a Kirkpatrick-Baez mirror configuration. The 2D angle scanning functionality is provided by a multilayer-coated fold mirror. The scanning mirror is re-imaged to the lithographic mask using a multilayer-coated spherical mirror. The illumination size at the mask is nominally 400 μm in diameter as set by the beamline-determined illumination size on the scanning mirror in conjunction with the factor of 3.35 optical demagnification from the scanner to the reticle. Because the illuminator optical demagnification has an inverse effect on angle, the angle range required of the scanning mirror is 3.35 times smaller than the angular range sought at the mask. To achieve a σ of up to 1 given the 0.025 entrance numerical aperture (NA) of the lithography optic, we require a maximum deflection of $0.025/3.35 = 7.5$ mrad (~0.4°) from the scanning mirror (σ is defined as the ratio of the illumination divergence to the entrance NA of the lithographic optic).

Viewing the scanning mirror as the new effective source, the illuminator in Fig. 1 can be recognized as a critical illumination system, meaning that the source is imaged to the object. We note that the scanning illuminator is not restricted to being implemented to provide critical illumination and, although not described here, could just as readily be implemented as a Köhler system.[13]

Figure 2 shows a series of EUV pupil fills generated by the Fourier synthesis system described here. The images were recorded using a back-thinned back-illuminated EUV CCD camera positioned to capture the projection of the lithographic optic pupil. The image integration time was 1 second, matching the source scan time. The black background represents the full 0.1-NA optic pupil.

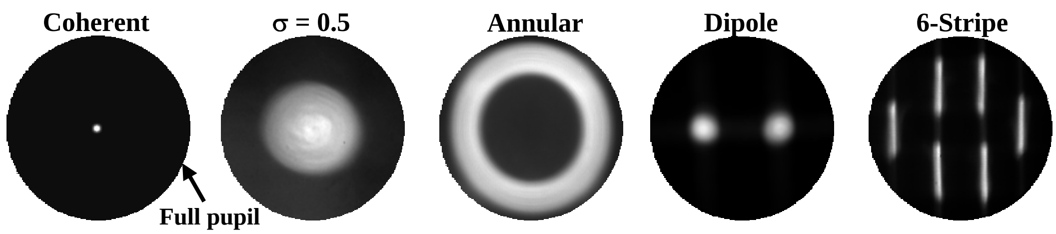

FIGURE 2. Series of EUV pupil fills generated by the scanning system described above and recorded through the lithographic ETS Set-2 optic. A back-thinned back-illuminated EUV CCD camera is used to capture the pupil-fill images.

LITHOGRAPHIC DEMONSTRATION

The functionality of the above-described illuminator has been demonstrated through lithographic experiments using a 0.1-NA, four-mirror, 4×-reduction, lithographic optic.[14] This state-of-the-art diffraction-limited optic[15] is the second of two optical systems fabricated as part of an industry consortium (the EUV LLC) effort developing EUV lithography in collaboration with Lawrence Berkeley, Lawrence Livermore, and Sandia National laboratories.

Figure 3 shows 70-nm elbow patterns both in focus and 0.5-μm out of focus with coherent illumination (scanning illuminator disabled) and partially coherent illumination with a σ of 0.8. At 140-nm period, the features are very close to the ideal coherent cut-off period of 134-nm (λ/NA), explaining why the features are barely resolved under coherent illumination. Going out of focus, the characteristic coherent ringing becomes even more evident. The partially-coherent case, on the other hand, shows dramatic imaging performance improvement both in focus and out of focus. The resolution is improved due to the improved cut-off frequency provided for by the partially coherent illumination[3] and the ringing artifacts are suppressed by virtue of the reduced coherence.

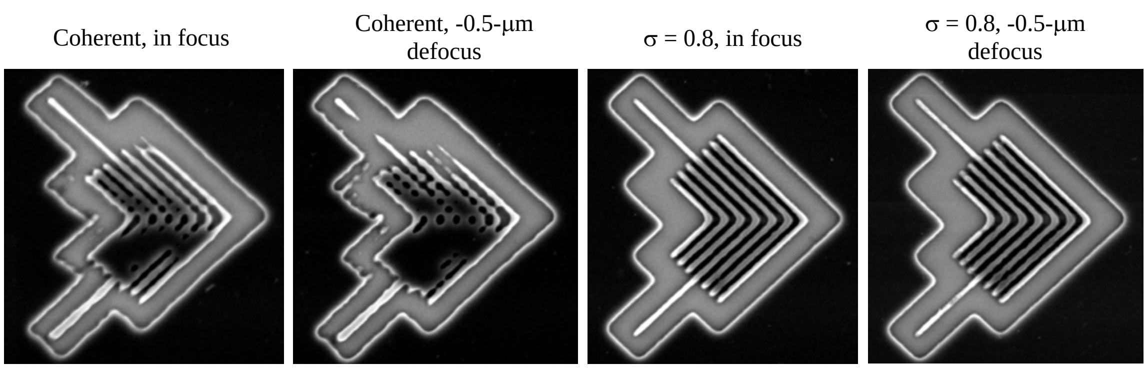

FIGURE 3. 70-nm elbow patterns both in focus and 0.5-mm out of focus with coherent illumination (scanning illuminator disabled) and partially coherent illumination with a σ of 0.8.

It is possible to further enhance the resolution of the system for certain features by using structured illumination such as annular or dipole (Fig. 2). For general patterns containing features with a variety of orientations, annular has the advantage of being isotropic in its effects. On the other hand, when single-orientation line-space patterns are being imaged, as is often the case in lithographic applications, the anisotropic nature of dipole illumination becomes preferable. Figure 4 shows a series of 50-nm line-space patterns printed with three different illumination types: conventional disk illumination with $\sigma = 0.8$, annular $0.8 < \sigma < 0.9$, and dipole where each pole has $\sigma = 0.16$ and the pole offset from center is $\sigma = 0.42$. Under conventional illumination, the 50-nm half-period features do not have enough contrast to print properly in resist. Taking into consideration the actual measured wavefront error,[15] the modeled aerial-image contrast with $\sigma = 0.8$ disk illumination is approximately 34%. Employing annular illumination boosts the contrasts enough for the lines to print in resist, however large line-width variations remain as a result of the contrast being too close to minimum contrast tolerated by the resist. In this case, the modeled aerial-image contrast is approximately 48%. Finally employing dipole illumination geared to enhancing resolution only in one direction to the detriment of the orthogonal direction, the printed lines in resist become well defined. Here modeling shows the aerial-image contrast to be approximately 75%.

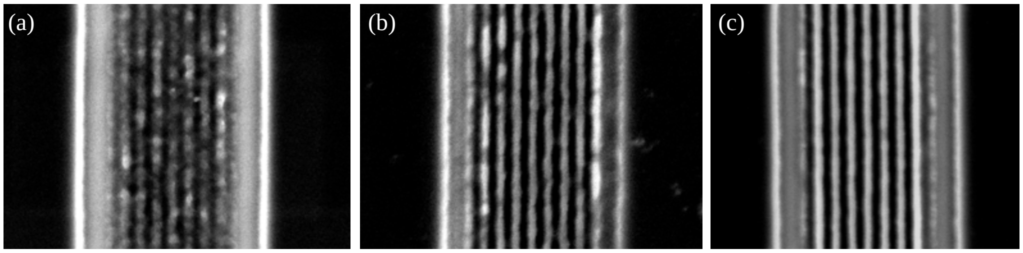

FIGURE 4. 50-nm line-space patterns printed with various illumination types: (a) $\sigma = 0.8$, (b) annular $0.8 < \sigma < 0.9$, and (c) dipole where each pole has $\sigma = 0.16$ and the pole offset from center is $\sigma = 0.42$.

SUMMARY

In conclusion, a Fourier-synthesis illuminator has been demonstrated at EUV allowing intrinsically coherent undulator radiation to be used for lithographic applications. The illuminator allows for in-situ coherence control making it an effective technique for general-purpose imaging systems. Using the illuminator to generate resolution enhancing coherence functions, we have demonstrated the printing of 50-nm lines and spaces with a 0.1-NA optic operating at a wavlength of 13.4 nm. In addition to the lithography application presented here, this illuminator is applicable to a variety of areas such as microscopy and coherence imaging.

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