Coherence reduction in accelerator-based lithography systems

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Extremely high spatial coherence is often viewed as a unique and enabling characteristic of accelerator-based light sources in the extreme ultraviolet (EUV) and x-ray regimes. In the realm of lithography, however, this asset becomes a liability as coherent interference artifacts lead to unacceptable impacts on critical dimension uniformity and through focus behavior. In fact, from the perspective of lithography, even coherence that is relatively mild from the traditional optical point of view can be problematic. For example, once the coherence area is on the order of 10x larger than the resolution limit of the optical system, the system practically behaves as a coherent system. For a high numerical aperture (NA) EUV system, this can translate to a coherence area as small as a few hundred nanometers in the mask (illumination) plane. Alternatively, from the perspective of intrinsic divergence, this corresponds to on the order of 15 mrad which is much, much larger than the divergence expected from typical accelerator-based sources.

Even though accelerator-based sources are not intrinsically well matched to lithography needs from the perspective of spatial coherence, such sources have many other characteristics which render them attractive including, but not limited to, spectral purity, cleanliness, extremely high theoretical power, high wall-plug efficiency, and polarization control. In fact, accelerator sources have historically served a pivotal role in the development of EUV lithography with synchrotrons enabling both the first 0.3x-NA and 0.5x-NA EUV microfield lithography tools [1,2]. This was enabled by coherence reduction/control which is an essential feature of these systems. The synchrotron-based research and development tools achieved coherence control using a technique known as Fourier synthesis illumination [3] which relies on spatial mode time multiplexing in order to alter the illumination coherence characteristics. Although both highly effective and flexible, the Fourier synthesis method is, unfortunately, not suitable for high speed imaging cases since it requires the entire illumination k-space to be scanned within the effective image acquisition time. For example, in a high throughput lithography application, the slit scan time needs to be on the order of 100 ms meaning that one would need to be able to scan out the full two-dimensional illumination angle space within that time and ideally even faster. Assuming one wanted to be able to address up to 1,000 points in illumination angle space, that would correspond to an angle scanning step rate of at least 0.1 ms or 10 kHz. The constraint becomes even more problematic when considering the case of single ultra-fast pulse imaging, which may represent an important solution to future metrology needs. Clearly, high speed applications cannot realistically rely on time multiplexing methods for coherence reduction. Moreover, spatial scanning diffuser type methods also technically fall within the category of time multiplexing methods, rendering them equally ineffective in high speed cases. These time multiplexing challenges, however, can be overcome by recognizing that although accelerator-based sources in the EUV regime tend to have extremely high spatial coherence, the temporal coherence can be quite short and that we can in fact convert those temporal modes into mutually incoherent spatial modes.

In this presentation I will describe the importance of coherence control in lithography and imaging in general, including actual examples in the EUV regime. I will also describe the Fourier synthesis method and its implementation on synchrotron systems. Finally, I will describe the temporal to spatial mode conversion method suitable for high speed applications and present a related application of the method as utilized on the 0.3-NA EUV microfield exposure tool at Lawrence Berkeley National Laboratory to improve spatial uniformity of the illumination.

References

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Author Bio

Patrick Naulleau received his B.S. and M.S. degrees in electrical engineering from the Rochester Institute of Technology, Rochester, NY, in 1991 and 1993, respectively. He received his Ph.D. in electrical engineering from the University of Michigan, Ann Arbor in 1997 specializing in optical signal processing and coherence theory. In 1997 Dr. Naulleau joined Berkeley Lab on the EUV LLC program building the world’s first EUV scanner. From June 2005 through March 2008, Dr. Naulleau additionally joined the faculty at the University at Albany, SUNY as Associate Professor, also concentrating in the area of EUV lithography. In April 2010 Dr. Naulleau took the position of Director of the Center for X-ray Optic at Lawrence Berkeley National Laboratory. In August 2022, Dr. Naulleau became CEO of EUV Tech Inc., a leading supplier of EUV metrology equipment. Dr. Naulleau has over 400 publications as well as 19 Patents and is a Fellow of OSA (now Optica) and SPIE.