9. Interference Lithography

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Interference lithography (IL) is the preferred method for fabricating periodic and quasi-periodic patterns that must be spatially coherent over large areas. IL is a conceptually simple process where two coherent beams interfere to produce a standing wave, which can be recorded in a photoresist. In principle, the spatial-period $P$ of a grating can be as small as half the wavelength of the interfering light ($\lambda$). In practice, we can produce patterns with periods as small as 170 nm using a 325 nm HeCd laser, and as small as 100 nm using a 193 nm ArF laser. One can think of the high-contrast sinusoidal intensity images produced with this technique as the building blocks from which more complex images can be formed. Thus, one can study the process of lithography using the gratings formed with IL just as one would study an electronic or acoustical system using sinusoids rather than arbitrary signals. The periodicity of gratings produced by IL is given by

$$P = \frac{\lambda}{2\sin(\theta)}$$

where $\theta$ is half the angle of beam intersection.

The NanoStructures Lab has been developing IL technology for over 30 years. We currently operate 5 different IL systems for a wide variety of applications. One system, shown schematically in Figure 1, is known as the Mach-Zehnder system. It uses a HeCd laser with a wavelength of 325 nm, and is typically configured to expose gratings with a period of 230 nm. This system functions both as an exposure tool and an analysis tool. Using a technique known as holographic phase-shifting interferometry (HPSI), the linearity and spatial phase of gratings produced in this system can be quantitatively measured and mapped with an accuracy of a few parts per million. The hyperbolic progression in the spatial-phase of gratings created using the Mach-Zehnder IL are responsible for changes in periodicity of a few tenths of a nanometer (for a 200 nm period grating) over a 100 mm wafer. Although seemingly small, distortions of this scale can be highly significant, especially in metrological applications such as the fiducial grids for spatial-phase locked electron-beam lithography. Using the HPSI, we have been able to investigate innovative techniques for reducing these grid distortion levels. One method, based on the controlled bending of the substrate during exposure, has demonstrated a reduction of the distortion pattern from 2D to 1D as well as reducing the magnitude of the distortion by almost an order of magnitude.
Figure 1. Schematic of the Mach-Zehnder interference lithography system. This setup can be used as an interference lithography system to write reference grids as well as a holographic-phase-shifting interferometer to measure grid distortion.

The Lloyds-mirror interferometer, shown schematically in Figure 2, also uses a 325 nm HeCd laser. A single point source, located 2 meters distant, is used in conjunction with a mirror placed normal to the substrate, which creates an image of a second source. The primary advantage of the Lloyds-mirror is that the spatial-period of the exposed gratings can be easily and continuously varied from many microns down to ~170 nm with an accuracy better than 1 part in 1000 without re-aligning the optical path as would be required in the Mach-Zehnder system. This has opened the door to new possibilities such as varied aspect ratio grids (different periodicities in the two axes of the grid) for patterned magnetic media and MRAM (magnetic random access memory) devices. Among the many other applications of IL supported by the Lloyds-mirror are alignment templates for organic crystals, semiconductor quantum dots, and patterning for studies of templated self assembly of block copolymers, metal particles and nanowires. Distributed feedback (DFB) structures for quantum dot lasers and photonic bandgap devices have also been made using the Lloyds mirror system.
Figure 2  Schematic of a Lloyds-mirror interferometer. The substrate and mirror are fixed at a 90˚ angle to one another, and centered in a single incident beam. Rotating the substrate/mirror assembly as indicated varies the spatial-period of the exposed grating. The micrograph shows a grating with 70 nm lines on a 170 nm pitch exposed using the Lloyds-mirror.

For spatial periods of the order of 100 nm, we use a 193 nm ArF laser. To compensate for the limited temporal coherence of the source, we utilize an achromatic scheme shown in Figure 3. In this configuration the spatial period of the exposed grating is dependent only on the period of the parent gratings, regardless of the wavelength and temporal coherence of the source. Thus, gratings and grids produced with this tool are extremely repeatable. Figure 3 also shows a 100 nm-period grid of 13 nm-diameter posts etched into Si, produced with achromatic interferometric lithography (AIL) and a sequence of etching steps. Applications of AIL include patterned magnetic media, free-standing gratings for atom-beam interferometry, and templated self-assembly.
Using a grating-based achromatic interferometer, the period of the exposed grating is exactly half that of the parent gratings. This invites a "bootstrapping" technique where we use the 100 nm gratings made with the 193 nm AIL as parent gratings for 50 nm period exposures. We are currently developing a new generation of interference lithography tools to accomplish this. However, for a given wavelength, the smallest period possible is $\lambda/2$, which means that a photon source of $\lambda<100$ nm is necessary for the next generation of tools. The limited availability of sources, as well as poor optical properties of materials in this wavelength regime are major design obstacles. One option for circumventing both of these problems is to use immersion in a high-index medium to reduce the effective wavelength ($\lambda_e$) of a source such as the 193 nm ArF laser, or a 157 nm F$_2$ laser. For example, in a medium with refractive index $n=1.6$, the effective wavelength of the ArF laser is $\lambda_e = 121$ nm, and for the F$_2$ laser $\lambda_e = 98$ nm. Thus, grating periodicities in the 50-60 nm range should be possible with currently available laser sources. We have demonstrated the use of immersion to enable exposures with periodicity below $\lambda/2$. Figure 4 shows a 90 nm period grating exposed via the spatial-frequency doubling of a 180 nm-period
parent grating using 193 nm light. We are currently working towards implementing this process at shorter periods. Other possibilities under investigation are free-standing gratings etched in a thin membrane for use with soft x-rays, or an analogous AIL scheme based on reflection gratings, which could be used at any wavelength despite high material absorption.

![Figure 4](image.png)

**Figure 4** 90 nm period grating exposed in PMMA using 193 nm light in a medium with refractive index $n=1.53$. An anti-reflection coating (XHRi) is used between the substrate and the photoresist (PMMA) to improve the exposure profile.

One further system is operated in conjunction with the Space Nanotechnology Lab (SNL). This system also employs the Mach-Zehnder configuration, but is specially designed for high stability and repeatability. It is capable of producing metrological quality gratings and grids up to 100 mm in diameter at spatial periods down to 200 nm. Used primarily for satellite applications, gratings produced with this tool have flown on numerous missions, most notably, the Chandra x-ray astronomy satellite launched in August of 1999 which included hundreds of matched, high-precision gratings. SNL also operates a more advanced system which is capable of making nearly perfect gratings over substrates up to 300 mm diameter. This system, called the NanoRuler, employs scanning-beam interference lithography (SBIL) and is described in a separate section of the report.