Towards the ultimate resolution in photolithography

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Optical lithography has been the driving force of semiconductor device manufacturing for the past 50 years, due to its high throughput, yield, and scalability. As feature sizes shrink and device density increases, predicted and guided by Moore's Law, new lithography methods are needed to increase the resolution. Currently, optical patterning approaches such as multiple patterning and DUV immersion are reaching their technological and physical limits. Extreme ultraviolet (EUV) lithography at the wavelength of 13.5 nm is the most promising candidate for the future technology nodes [1-2]. Much research has been done on efficient optics, sources, and photoresists for this wavelength. An important tool in this respect is interference lithography (EUV-IL), which is able to pattern features at single digit nm resolution, enabling research for the timely development of EUV resists.

Lithographic pattern resolution is ultimately limited by the wavelength of light used. By decreasing the wavelength down to 13.5 nm, the theoretical patterning limit becomes 3.4 nm. Using EUV light, the XIL-II beamline at the Swiss Light Source, Paul Scherrer Institute, is able to pattern features down to 6 nm half-pitch [3-5]. Spatially coherent light with 4% bandwidth from a synchrotron undulator source is incident upon a transmission mask. The mask is composed of diffraction gratings made of metal or inorganic photoresist and a zeroth order photon stop, supported on a silicon nitride membrane. The diffracted beams from the mask then interfere to produce a sinusoidal areal image, which can then be recorded in a photoresist.

The periodicity of the interference pattern, p, is given by:

$$p = \frac{\lambda}{2\sin(\theta)} = \frac{g}{2m}$$

where g is the grating period, m is the diffraction order, θ is the diffraction angle, and λ is the light wavelength. The patterning resolution is therefore restricted by the diffraction mask resolution. Some advantages of this method include very large depth of focus up to 10 mm, very high throughput (10 s per exposure), large area patterning (up to 5x5 mm^2) and well-defined aerial image with pitch-independent contrast.

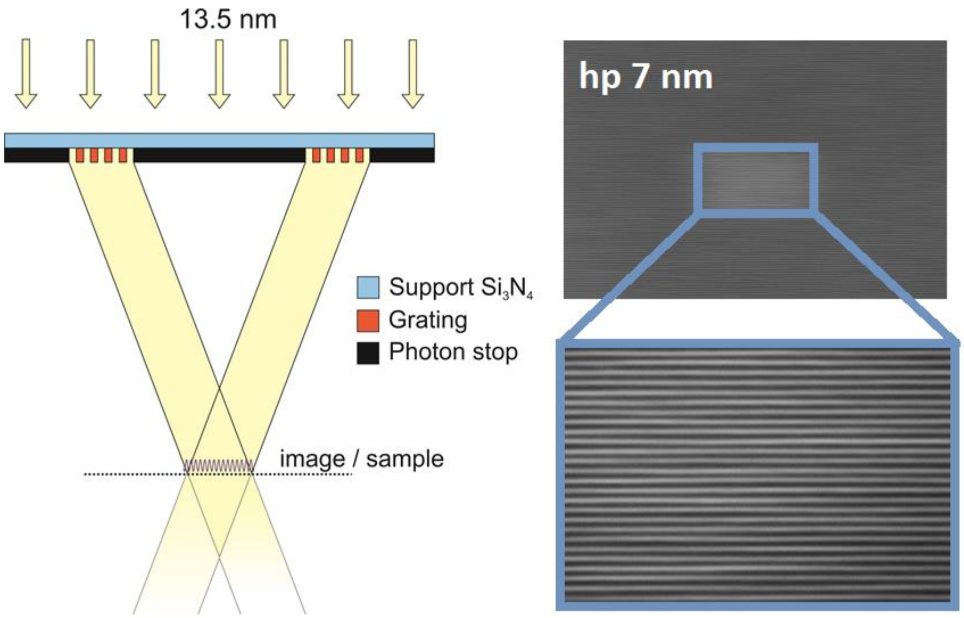

Figure 1. Left: schematic of interference lithography where coherent light is diffracted and the interference pattern is recorded. The zeroth order light is blocked by photon stops. Right: 7 nm half-pitch lines recorded in photoresist using EUV-IL.

Two-beam interference provides line/space patterns. By increasing the number of interfering beams, different types of periodic patterns can be formed. These include dots and holes (4 beams), honeycomb and kagome lattices (6 beams), quasi-periodic tilings

(5, 8, n beams), as well as non-diffracting Bessel beams [6-9]. Moreover, by subtly changing the grating position on the transmission mask, we are able to control the relative phase between interfering waves, and therefore control the aerial image, for example between dots and holes in 4-beam interference. These structures can be used in a wide variety of applications, such as the investigation of nano-catalysis using dot arrays, studying magnetic frustration using kagome lattices, and serial beam writing over topographical surfaces using non-diffracting Bessel beams.

Another interesting method for producing periodic structures is through the use of the Talbot effect, where the self-image of the grating is recorded. This method in the achromatic regime has no depth of focus, gives large area patterns, and also has self-healing properties. Furthermore, since it is composed of the interference of all diffraction orders, the required dose is much less, and the mask is much more efficient [10].

Due to the high resolutions achieved, the XIL-II has been used as a research tool to evaluate EUV photoresists for possible future application in industry. The major challenge in EUV resists technology is the tradeoff between resolution, line edge roughness, and sensitivity. Since future EUV sources will have low power, high sensitivity resists are required. With its well-defined and high-resolution aerial image, EUV-IL enables development of EUV resists before high-NA tools become available [11].

Sub-10 nm half-pitch features are also a very exciting regime regarding device physics, where quantum effects can play a role. Work has been done in our group in pattern transfer and fabrication of silicon nanowires to systematically characterize their physical properties. Large area periodic dots are being used as model nano-catalytic systems to study the mechanism of hydrogen spillover. Other scientific applications which use XIL-II fabricated patterns include their use as templates for the study of protein immobilization, protein crystal growth, cell growth, and directed self-assembly, as well as the use of periodic structures in the investigation of frustrated nano-magnetic systems, nanoimprint stamps, and micro and nano-fluidics.

The resolution of photolithography has been steadily improving over the past 50 years. EUV lithography is an exciting candidate to continue the improvement in resolution into the single digit nanometer regime. We demonstrate 7 nm half-pitch features and a wide variety of periodic patterns used in a number of scientific investigations. Further improvements in resolution will necessitate new mask fabrication strategies and better photoresists, while pattern transfer at such high resolution is also a significant challenge. We are currently evaluating smaller wavelengths such as 6.5 nm (beyond EUV) [12, 13] as well as 4.5 and 2.5 nm wavelengths in order to continue to push towards the ultimate resolution in photolithography.

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