Phase Control in Spatial Frequency Multiplication

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For two-beam single-exposure interference lithography, the period of the interference pattern is determined by $\lambda/(2n \sin\theta)$, where λ is the optical wavelength, n is the index of refraction of the medium, and θ is the incidence angle. The maximum spatial frequency of a single-exposure grating pattern is $2n/\lambda$ [1]. One approach to achieving a spatial frequency higher than $2n/\lambda$ is to insert new grating patterns among previous ones, which is feasible thanks to the nonlinearity of modern photoresists (i.e., there is a sharp threshold between exposed and unexposed regions). This technique allows the spatial frequency of patterns to be extended by integral factors 2, 3, 4, … beyond the limit of $2n/\lambda$ by applying a nonlinear process between exposures. Compared to previous techniques of multiplying the spatial frequency of patterns [2, 3], the technique reported here is able to perform spatial frequency multiplication over large areas with small phase errors. We will also quantitatively measure the phase errors of the patterns of spatial frequency multiplication over the area.

In this paper we utilized multiple-exposure scanning beam interference lithography (SBIL) [4, 5] to multiply the spatial frequency of patterns over large areas. One of the main technical issues when applying spatial frequency multiplication is how to correctly place the patterns on the substrate with respect to previous patterns. Precise pattern overlay requires obtaining accurate grating angle, period, and phase information from alignment grating. The result of spatial frequency doubling (from 574.0 nm-pitch patterns down to 287.0 nm-pitch patterns) is shown in Fig. 1, and Fig. 2 summarizes how we achieved this result. The first step is to form a grating pattern in the surrounding-area photoresist, which is developed and etched into the silicon substrate as the "alignment grating." The wafer is then coated with new ARC and photo resist in the central area. In the second step, after measuring the grating angle, period, and the phase of the alignment grating, the first-layer pattern is placed on the substrate in the central area with the same grating angle and period as the alignment grating and a $\pi/2$ phase shift with respect to the alignment grating. This pattern is then developed and etched into a silicon substrate. Afterwards new ARC and photoresist are spun in the central area. In the final step, we place the second-layer pattern with the same grating angle and period as the alignment grating and a $3\pi/2$ phase shift with respect to the alignment grating. Therefore, we achieve a π phase shift between the first-layer pattern and the second-layer pattern in the central area, which means the spatial frequency of the grating pattern is doubled. Fig. 3 shows the overlay phase error between the first-layer pattern and the second-layer pattern over a 12 mm by 12 mm area, demonstrating an average overlay error of 3 nm and a 3σ overlay error of 18 nm.

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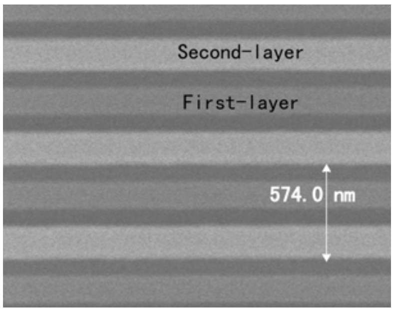

Fig. 1: SEM image of spatial frequency doubling of a 574.0 nm-period graing

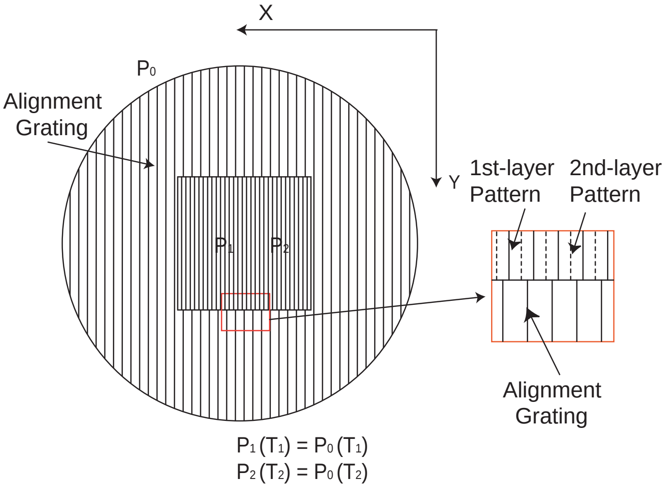

Fig. 2: Depiction of the spatial frequency doubling technique

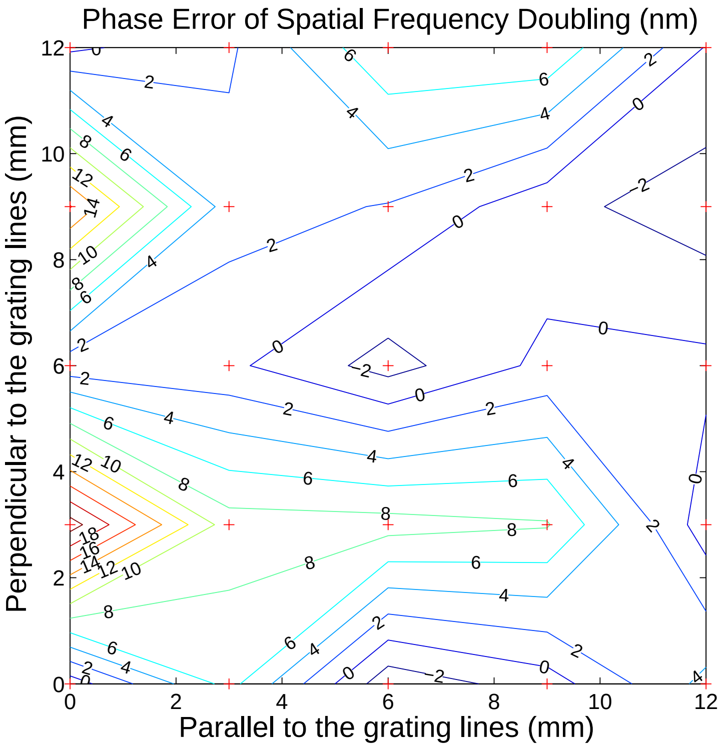

Fig. 3: Contour plot of phase error of spatial frequency doubling. (crosses represent measurement locations.)