Enhancement of photolithography resolution by fractional Fourier domain filtering

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Abstract

A new spatial filtering technique is proposed for improving image contrast and depth of focus in projection photolithography. The technique is based on fractional Fourier domain filtering. Unlike the current pupil filtering method, the fractional filter can be placed at any location along the projection optical path other than the pupil plane. The theory of partial coherent diffraction combined with fractional Fourier domain filtering is presented. Phase filters for contact hole and line-space patterns have been designed. Computer simulation of complete imaging process including fractional Fourier domain filtering have been carried out. The simulation has demonstrated that the new filtering technique can significantly improve image fidelity, reduce the optical proximity effect and increase the depth of focus. Because of the flexibility in filter location, it is predicted to be easier to implement in a practical optical lithography system.

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1. Introduction

It has been widely recognised that wave front engineering is a powerful tool to improve imaging quality in optical lithography. A number of techniques have been developed in the last decade. These techniques are generally divided into two groups according to their implementation methods; the techniques applied to optical masks, such as phase shifting and optical proximity correction, and the techniques applied to projection system, such as off-axis illumination and spatial filtering. The spatial

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filtering technique is to insert a filter at the optical path of a projection lens system to modulate either phase or amplitude to restore those high frequency components which have been lost in a conventional imaging system. One successful spatial filtering technique was to place a filter at lens pupil plane to modulate the amplitude distribution. Both image contrast and depth of focus have been improved by the pupil filtering method [1].

In this paper, a new spatial filtering method is proposed. The method is based on fractional Fourier domain filtering. In contrast to the pupil filtering where the filter can only be at the pupil plane, fractional Fourier domain filtering can have the filters at any locations along the optical path other than the pupil plane. It provides the flexibility not only on where the filters can be placed but also how the image phase and amplitude can be modulated. In the following sections, the principle of fractional Fourier domain filtering is introduced. Computer simulation results are presented to demonstrate the advantages of fractional Fourier domain filtering. As examples, imaging of both contact hole and line-space patterns are compared with and without fractional Fourier domain filtering. It is shown that the new filtering method can significantly improve the image quality of optical projection lithography. With fractional Fourier domain filtering it is much easier to optimise the image formation process, therefore, enhancement of resolution with the least modification to existing projection imaging systems.

2. Principle of fractional Fourier domain filtering

Optical imaging process is mathematically a Fourier transform process. The ordinary Fourier transform of a mask pattern is obtained at the lens pupil plane. The fractional Fourier transform is a generalisation of the ordinary Fourier transform with an order \( p \) [2]. The \( p \)th order Fourier transform has the form of (1):

\[
F^p\{f(x)\} = \int_{-\infty}^{\infty} f(x)B_p(x,u)dx
\]

(1)

where \( f(x) \) is the input function and \( B_p(x,u) \) is the integral kernel function expressed as:

\[
B_p(x,u) = \frac{\exp[-i(\pi\hat{\phi}/4 - \phi/2)]}{\sin \hat{\phi}^{1/2}} \exp[i\pi(x^2 \cot \phi - 2xu \csc \phi + u^2 \cot \phi)]
\]

(2)

with \( \phi = p\pi/2 \) and \( \hat{\phi} = \text{sgn}(\sin \phi) \). \( p \) is the fractional order.

Mathematically, the \( p \)th order fractional Fourier transform is the \( p \)th power of the ordinary Fourier transform. The first-order \((P = 1)\) fractional transform is the ordinary Fourier transform. With \( P = 1 \) Eq. (2) becomes \( B_1(x,u) = \exp(-i2\pi xu) \). Then Eq. (1) becomes \( F^1\{f(x)\} = \int_{-\infty}^{\infty} f(x)e^{-i2\pi xu} dx \), which is the common Fourier transform. The zeroth order fractional transform is the function itself. Thus, the fractional Fourier transform discussed here is the transform with \( p \) order between 0 and \( \pm 1 \). The plus and minus sign indicates the filter either before or after the pupil plane. Fractional Fourier transform has received considerable interests since the early 1990s, with wide applications in image processing.
signal recovery and pattern recognition [3]. However, no reports have been published to apply the technique for the resolution enhancement in optical projection lithography.

Based on partial coherent imaging theory, the Fourier transform of optical projection lithography system is in the form of (3):

$$I(x, y) = \sigma \int \int I_{\text{eff}}(x, y) \int U(f_x, f_y)H(x - f, y - f) \times \exp[j2\pi(f_x x + f_y y)]df_x df_y dx dy$$

$$= \sigma \int \int I_{\text{eff}}(x, y)|F^{-1}[F^{1}\text{[MASK}(x, y)]H(x - f, y - f)]|^2 dx dy$$

where $I_{\text{eff}}(x, y)$ is the effective illumination source, $H(f_x, f_y)$ is the pupil function, $\text{MASK}(x, y)$ is the mask function and $U(f_x, f_y) = F^{1}\text{[MASK}(x, y)]$ is the frequency domain equivalent of the mask function. It can also expressed as $U(f_x, f_y) = F^{-1-p}F^{p}[\text{MASK}(x, y)]$. Therefore, the partial coherent imaging in fractional Fourier domain takes the form of (4):

$$I(x, y) = \sigma \int \int I_{\text{eff}}(x, y)dx dy$$

$$|F^{-1-p}F^{p}[F^{-1-p}F^{p}[\text{MASK}(x, y)]H(x - f, y - f)]|^2$$

Eq. (4) indicates that Fourier transform in fractional order can be performed to the imaging process, which implies the possibility of introducing spatial filtering in the fractional Fourier domain. The conventional pupil filtering can be viewed as a special case of fractional Fourier domain filtering, where the fractional order $p = 1$. While for pupil filtering the filter has to be at the pupil plane, the general fractional filtering can have filters at any locations other than the pupil plane. It can use more than one filter. Fig. 1 shows the fractional Fourier domain filtering process, where two filters are placed before and after the pupil plane. Assuming the filter functions are $f_{p_1}(f_x, f_y)$ and $f_{p_2}(f_x, f_y)$, the intensity distribution at image plane after the spatial filtering operation can be expressed as:

$$I(x, y) = \sigma \int \int I_{\text{eff}}(x, y)dx dy$$

$$|F^{-1-p_2}F^{p_2}[F^{-1-p_1}F^{p_1}[\text{MASK}(x, y)]H(x - f, y - f)]|^2$$

Fig. 1. Schematic of fractional Fourier domain filtering.
Compared with pupil filtering, the fractional Fourier domain filtering provides additional freedoms on where the filters should be placed and how the image transfer process can be manipulated.

3. Simulation examples

The key process for fractional Fourier domain filtering is to design the filter and determine the location of the filter. Computer programme has been developed for fractional filter design and optimisation. Combined with previously developed simulation programmes [4], the complete optical imaging process, including fractional filtering and final photoresist image can be simulated. Fig. 2a shows a 0.4-μm contact hole pattern. Assuming the illumination wavelength at 248 nm, the partial coherence factor 0.5 and numerical aperture 0.4, the optimised filter for the contact hole pattern is shown in Fig. 2b. This is a phase modulation filter with 16 phase steps. Different phases are represented by different grey scales in the figure. The filter can be fabricated by the techniques similar for fabricating diffractive optical elements. The pure phase modulation scheme is advantageous compared with amplitude modulation in that the filter is easier to fabricate and no heating effect, because there is no light-absorbing layer in the filter. The choice of fractional order \( p \) has to be matched with both the projection system parameters and optimisation of filtering effect. In this case the fractional order \( p = -0.4 \). The minor sign means that the filter is placed after the pupil plane. Fig. 3a is the intensity distribution at image plane without fractional filtering and Fig. 3b is the distribution after the filtering. It is apparent that with the fractional Fourier domain filtering, the image distortion due to diffraction has been significantly restored. To quantitatively compare the filtering results, the image area evaluation method is used [5]. Fig. 3c is the real image without filtering compared with the ideal image. The image area deviation is 20.9%. Fig. 3d is the real image with filtering compared with the ideal image. The image area deviation is 2.3%. Fig. 4a,b gives the comparison of 3D photoresist profiles for the contact hole with and without fractional Fourier domain filtering.

Line and space pattern is also simulated with fractional Fourier domain filtering. Fig. 5a shows three 0.2-μm lines with 0.2 μm between the lines. With the same projection optics as for the contact
Fig. 3. Image intensity distribution without filter (a) and with filter (b). Image contour compared with original design without filter (c) and with filter (d).

hole and fractional order $p = -0.4$, the optimised filter is shown in Fig. 5b, which is the 3D profile of phase distribution, and the filter is placed after the pupil plane. The intensity distribution the lines at image plane without filtering is shown in Fig. 6a. The distribution with filtering is shown in Fig. 6b. The intensity profiles are compared more clearly in Fig. 7 where the filtering has significantly improved the image contrast. The quantitative analysis of image area has revealed severe optical proximity effect for conventional projection optics. The linewidth for the middle line has deviated 29.5% from design linewidth. The line end shortening is over 26%. Even the outer lines have line end

Fig. 4. Simulated 3D photoresist image of the contact hole without filter (a) and with filter (b).
Fig. 5. (a) Mask pattern for 0.2-μm lines; (b) optimised fractional Fourier domain filter (phase modulation).

Fig. 6. Image intensity distribution without filter (a) and with filter (b).

Fig. 7. Aerial images of line-space pattern without filter (dash line) and with filter (solid line).
shortening up to 19.9%. The total image area deviation is 38.3%. With Fractional Fourier domain filtering, the linewidth deviation is no more than 10%. The line end shortening has been controlled under 1.5% and the total image area deviation is 6.8%. The fractional Fourier domain filtering not only can significantly improve image contrast but also depth of focus. Fig. 8 shows the aerial image of the three lines at 0.65 µm defocus. Compared with Fig. 7, the defocus has little effect on the image contrast and intensity when the fractional filter is used, while noticeable deterioration of image contrast is seen for conventional imaging without the fractional filter.

4. Conclusions

The fractional Fourier domain filtering has been introduced for the first time to improve the image quality of optical projection lithography. Compared with existing pupil filtering method, the fractional Fourier domain filtering can offer flexibility of placing the filter at a position other than the pupil plane. More than one filter can be used to optimise the projection imaging process. A filter can be optimised for a specific pattern structure to maximise the improvement. Phase modulation filters have been designed for contact hole and line-space patterns. Significant improvements in pattern fidelity and depth of focus are demonstrated by computer simulation. Because of the freedom of locating a filter in an optical lithography system, it can offer the improvement with the least modification to the projection system. The choice of fractional order depends on an actual projection system where the filter can be placed while achieving the maximum improvement. This work is the first attempt to prove the feasibility of fractional Fourier domain filtering for resolution enhancement of optical projection lithography. Further investigation is underway to explore its potential, to design filters for general mask patterns and its implementation in practical optical lithography systems.
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References