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Linewidth control by overexposure in laser lithography

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In micro-electronic and micro-optical manufacturing, especially in the fabrication of linewidth-variation-sensitive devices, we sometimes care getting stable or precise linewidth rather than creating a thinner line. In laser lithography, the energy distribution of a focused laser spot is of Gaussian form, and the modification of an exposure dose or exposure threshold will cause linewidth variation. If the peak of energy distribution of a laser spot is a little higher than the exposure threshold of a photoresist layer, the produced linewidth may be small but unstable, and if the peak is considerably higher than the threshold, in other words in the case of overexposure, the linewidth will be relatively stable. The test was carried out in a polar laser lithographic system through a continuously changing exposure dose. The experimental result shows that the dose-induced linewidth variation velocity is different under a variant exposure dose. The higher the exposure dose, the lower the linewidth variation velocity.

Keywords: linewidth, overexposure, laser lithography.

1. Introduction

Fabrication of much smaller linewidth is always the main objective in in micro-electronic or micro-optical manufacturing industry. Researchers have studied lithographic techniques from ultraviolet lithography to extreme ultraviolet lithography [1], as well as various resolution enhancement techniques [2]. Sometimes we much think about how to achieve stable and precise linewidth, especially in the fabrication of certain micro-optical elements, for example, integrated optical gyroscope [3] with linewidth in several micrometers, which requires the line as uniform as possible to diminish energy loss.

Laser lithography is an efficient method in fabricating micro-optical elements [4, 5], which directly writes a pattern on the surface of a substrate without any masks. Focusing is a quite important technique for the fabrication of stable and precise linewidth in a laser lithographic system, and if defocus amount is less than focal depth of optics, the achieved linewidth will be stable. The exposure dose and exposure threshold are also very important in impacting linewidth, which means that the linewidth may be unstable or imprecise even with an excellent focusing unit.

Here we discuss exposure problems in a polar laser lithographic system, and explore the possibility to stabilize linewidth variation by a unique exposure control.

2. Exposure in laser lithography

Laser lithography is different from traditional projection lithography whose illumination is of large area and uniform. It focuses a collimated laser beam into a very small spot with a diameter of one micrometer or smaller, whose energy distribution is of Gaussian form (see Fig. 1). The laser spot moves on the photoresist layer of a substrate and exposes where has been scanned. The width of this exposed line is relevant to the spot diameter, defocus amount, exposure dose and exposure threshold. For a fixed optics, especially with one objective lens, the spot diameter is fixed, which depends on the given optical parameters. The defocus amount will always be smaller than focal depth if a focusing unit is in a closed loop, unless defocusing lithography [6] is applied, and here we only consider focusing lithography. Except the spot diameter and defocus amount, the exposure dose and exposure threshold become the main factors in impacting linewidth.

In laboratory, the revolution coating is a typical technique in the fabrication of a photoresist layer. The thickness distribution of the photoresist layer made by the revolution coating is radial and varies from the center to periphery of the substrate surface. On the other hand, even if the coat homogeneity of the same substrate is better, the coat thickness of different substrates still may be slightly different. So, we can find out that the exposure threshold of different substrates or different parts in one substrate are to some extent uncertain.

In polar laser lithography, the actual exposure dose is decided by both light intensity and exposure time, and for a given exposure dose, there are many sorts of combinations to be chosen. Unlike the photoresist layer, the light intensity can be precisely controlled, but if we consider different mechanisms of the light intensity and

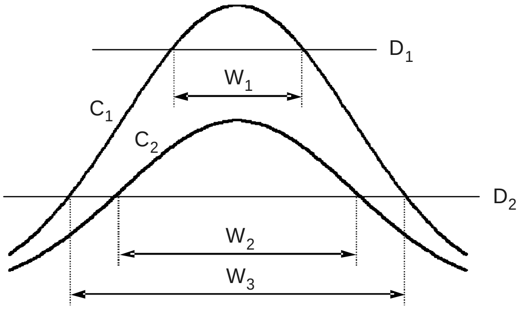

Fig. 1. Influence of exposure dose and exposure threshold on linewidth. Each of C_1 and C_2 is exposure dose curve. Each of D_1 and D_2 is exposure threshold. Each of W_1, W_2 and W_3 corresponds to linewidth.

exposure time effect on the linewidth, the same exposure dose with various light intensities and exposure times may lead to uncertain linewidth.

Figure 1 illustrates the influence of energy density (*i.e.*, exposure dose) and exposure threshold on linewidth. For a given energy density curve C_1, different exposure thresholds D_1 and D_2 will result in different linewidths W_1 and W_3, or on the contrary, if there are two energy density curves C_1 and C_2, the same exposure threshold D_2 will result in different linewidths W_2 and W_3.

In actual laser lithography, the produced linewidth is easily affected by both the exposure dose curve and the exposure threshold. If the exposure threshold is determinate, the large exposure dose, that is to say, overexposure, will generate stable linewidth, because the overexposure makes the peak of the exposure curve far away from the exposure threshold.

3. Principle of overexposure

In the laser lithographic system, the collimated laser beam is of Gaussian form, which passes through an objective and focuses on the substrate surface. The energy distribution of a laser spot still appropriately keeps Gaussian form. The illuminance distribution on a focal plane is given by

$$E = E_0 \exp\left(-\frac{2r^2}{\omega^2}\right) \tag{1}$$

where E_0 is the peak illuminance, and ω is the beam waist radius. The linewidth depends on the exposure dose, not only on the illuminance, so Eq. (1) should be transformed into the following equation

$$D = E_0 t \exp\left(-\frac{2r^2}{\omega^2}\right) = D_0 \exp\left(-\frac{2r^2}{\omega^2}\right) \tag{2}$$

where D_0 is the peak energy density. Making $D = D_t$ (D_t is the exposure threshold) and substituting it into Eq. (2), the corresponding linewidth W can be calculated as

$$W = 2r = \sqrt{2}\,\omega \sqrt{\ln\frac{D_0}{D_t}} \tag{3}$$

The formula indicates that the linewidth depends on the beam waist radius ω and the ratio of D_0 to D_t. Considering the diffraction of the objective, the beam waist radius can be written as $\omega = k\lambda/\mathrm{NA}$, and substituting it into Eq. (3), we will get

$$W = \sqrt{2}\,\frac{k\lambda}{\mathrm{NA}} \sqrt{\ln\frac{D_0}{D_t}} \tag{4}$$

where the wavelength λ is 0.442 μm, the coefficient k is 0.6, and the numerical aperture NA is from 0.05 to 0.8.

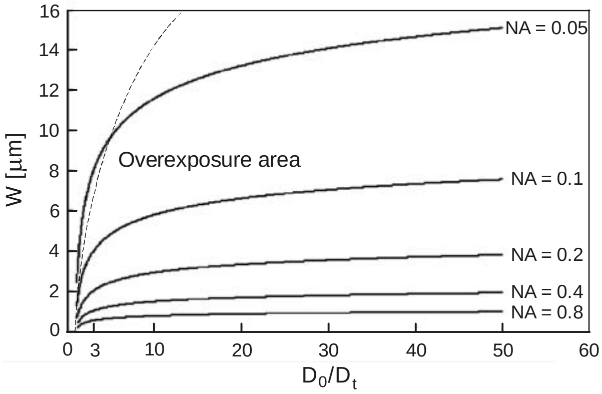

Fig. 2. Relationship between linewidth *W* and ratio D_0/D_t under different NA.

The simulated linewidth is illustrated in Fig. 2, which reflects the increment velocity of the linewidth relative to the ratio of D_0/D_t. When the ratio is lower, the linewidth increases very fast, and when the ratio gets higher, the increment velocity of the linewidth gradually gets slower. Various NA corresponds to various linewidths, but their trend is similar. The large NA is better than small NA in stabilizing the linewidth but the former can only fabricate a thinner line. In Figure 2, we may regard the right side of a dash line as the overexposure area, in which the linewidth keeps relatively stable.

In the actual laser lithographic process, just as what has been discussed in the last section, each of the peak exposure dose D_0 and the exposure threshold D_t is somewhat uncertain, so the ratio of D_0/D_t is uncertain, which will induce instable or imprecise linewidth. Generally, the exposure threshold is given and the exposure dose can be changed arbitrarily. According to the overexposure area in Fig. 2, we may choose suitable NA and larger exposure dose to create as stable and precise linewidth as it is possible.

4. Experiment and some result

The experimental device is a polar laser lithographic system [7] developed some years ago, which has been greatly improved in recent years. The wavelength of He-Cd laser is 0.442 µm and its intensity is controlled by acousto-optic modulator (AOM). Laser passes through an objective and focuses on the photoresist layer of the substrate surface. An intensity controller and spindle controller control the AOM and the spindle, respectively.

The photoresist layer was fabricated by a revolution coating method. According to the given time and rotation speed, the thickness of the photoresist layer is controlled in 0.6 µm. Total 20 rings were fabricated on the photoresist layer, and the space of neighboring rings is 250 µm. Every ring is made up of 24 segments of an arc line.

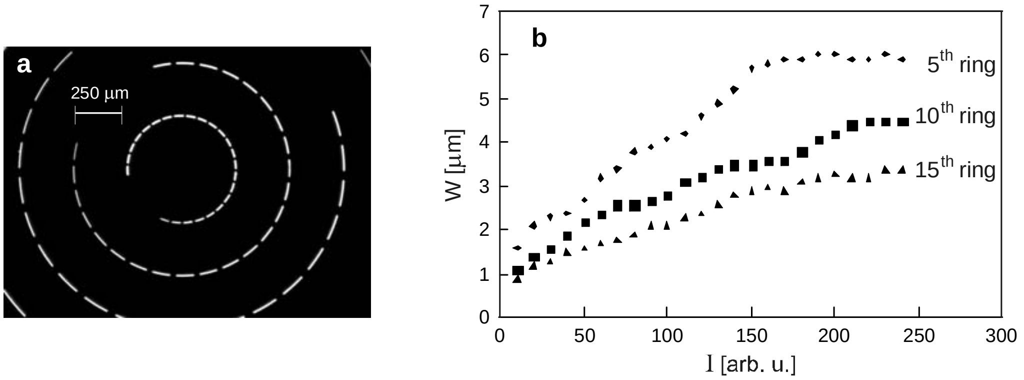

Fig. 3. Linewidth under different exposure dose. Micrograph of lithographic pattern; there are 20 rings and each ring consists of 24 segments (**a**); the relationship between linewidth *W* and intensity *I*; its data come from the 5th, 10th and 15th ring of lithographic pattern **a** (**b**).

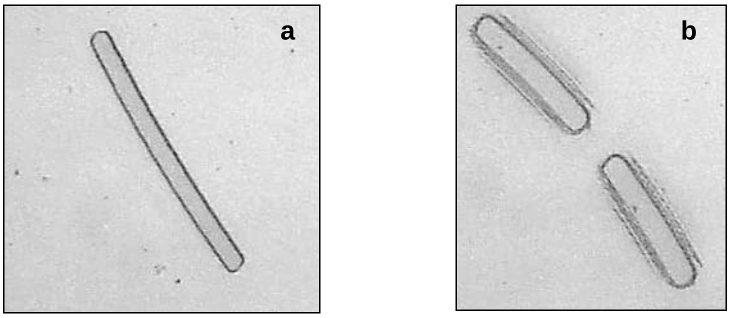

Fig. 4. Exposed line with suitable exposure or overexposure (**a**), and extreme overexposure (**b**). The bur appears about the line (**b**) because of extreme overexposure.

The exposure strategy is to vary the intensity in order to modify the exposure dose, so the exposure dose is in proportion to the intensity. It is to be noted that the exposure time in each ring is different due to different linear velocityies. After exposure, the photoresist layer was developed for 60 s.

Figure 3**a** is a micrograph of the produced lithographic pattern. The linewidth of each segment in one ring is gradually increasing, and the outboard line is thinner than the inboard one. Figure 3**b** is a spot map of the linewidth in the 5th, 10th, and 20th ring. The 5th ring shows the visible “saturation” trend as compared with the other rings.

The overexposure is an effective method of stabilizing the linewidth, but extreme overexposure will impact the line quality (see Fig. 4**b**). This is because when the exposure dose increases, the energy of other diffraction orders enlarges correspondingly, which results in a lot of bur about the line.

5. Conclusions

In laser lithography, the exposure dose and exposure threshold are to some extent uncertain. The former will make the actual linewidth deviate from the anticipated one. The latter will impact not only on the precision of the actual linewidth but also on the stableness of the produced linewidth. Overexposure is a better method in stabilizing linewidth and improving linewidth precision. It is fairly valuable for fabricating such devices which need stable or precise linewidth such as integrated optical gyroscope (IOG).

However, the advantages of the overexposure method are at the cost of efficiency and linewidth. This method wastes a great deal of energy and the produced linewidth is always larger than the minimum linewidth of a lithographic system. Furthermore, the overexposure should be controlled to avoid the bur about a line, and if you expect larger linewidth, replacing another objective with smaller NA will be available.

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