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Upgrading design of the 3B1A beamline for x-ray nanometre lithography of microelectronic devices at BSRF*

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Beijing Synchrotron Radiation Facility is a partly dedicated synchrotron radiation source operated in either parasitic or dedicated mode. The 3B1A beamline, extracted from a bending magnet, was originally designed as a soft x-ray beamline for submicro x-ray lithography with critical lateral size just below 1μm in 1988 and no change has been made since it was built. But later the required resolution of x-ray lithography has changed from sub-micrometre to the nanometre in the critical lateral size. This beamline can longer more meet the requirement for x-ray nano lithography and has to be modified to fit the purpose.

To upgrade the design of the 3B1A beamline for x-ray nano lithography, a mirror is used to reflect and scan the x-ray beam for the nano lithography station, but the mirror's grazing angle is changed to 27.9mrad in the vertical direction, and the convex curve needs to be modified to fit the change; the tiny change of mirror scanning angle is firstly considered to improve the uniformity of the x-ray spot on the wafer by controlling the convex curve.

Keywords: synchrotron radiation, x-ray, x-ray lithography, synchrotron radiation beamline
PACC: 6180C, 3220R, 9580N

1. Introduction

Beijing Synchrotron Radiation Facility (BSRF) is a partly dedicated synchrotron radiation source which can be operated in either parasitic or dedicated mode. In the dedicated mode for the synchrotron radiation (SR), the storage ring of BEPC is operated at 2.2GeV with electronic current of about 100mA. The bending magnet of the storage ring has magnetic field of 0.7T with a bending radius of 10.345m during the operation of BEPC at 2.2GeV and produces SR with critical energy at 2.5keV.[1−2]

The SR is used to copy pattern from the x-ray mask to the resist for the x-ray nano lithography and deep x-ray lithography. The pattern on the mask is formed by gold absorber structures with enough thickness to absorb the x-ray. The thickness of gold absorber structures on the mask will depend on both the spectrum of x-ray radiated on the resist and the fabricating technique of the absorber pattern. For the submicro x-ray lithography with the critical lateral size below 1μm, the gold absorber pattern can be fabricated with the thickness of 1μm. But for nano x-ray lithography, the absorber structures are very difficult to make with the thickness of 1μm, and it should be below 0.5μm. So the spectrum of x-ray used for nano lithography should be softer than for the submicro lithography.[3]

The 3B1A beamline was originally designed for submicro x-ray lithography, and its spectrum from 0.8–3keV, produced by a gold coating mirror with the grazing angle of 26.2mrad (1.5°) and the SiN membrane of mask with 2μm thickness, can no longer meet the requirement for the x-ray nano lithography. A mirror is used to form a uniform x-ray scanning spot on the mask and wafer located in a high vacuum chamber for scanning.

The upgraded design uses chromium as the coating material of the mirror with a grazing angle of 27.9mrad (1.6°) instead of gold. The influence of the

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change of the grazing angle during the mirror's scanning on the uniformity of x-ray scanning spot on the wafer will be considered in the updating of the design which will significantly improve the uniformity of x-ray spot on the wafer .[4]

For the x-ray nano lithography, many elements of x-ray properties should be considered, such as the spectrum of x-ray, the power density, the uniformity of x-ray scanning spot on the wafer and the parallelism of the x-ray. Figure 1 shows the optical layout of the upgraded beamline dedicated to nano lithography. The mirror with external size of 110mm width and 240mm length will be located at 14.8m from the SR source and accept the SR with 6mrad in the horizontal direction and 0.4mrad in the vertical direction, limited by a slit before the mirror. In order to increase the power intensity on the wafer and provide a small collecting x-ray to the requirement of x-ray nano lithography, the surface of the mirror is designed to have a cylindrical shape to focus the SR light in the horizontal direction at 44.4m from the mirror while the parallelism is 1mrad at the edges of the x-ray in the horizontal direction.[1]

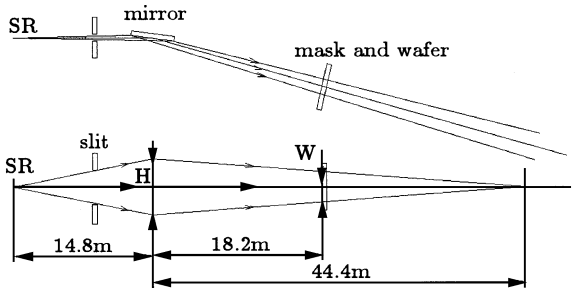


Fig.1. Optical layout of the 3B1A beamline dedicated to x-ray nano lithography.

2. Design of x-ray spectrum

The x-ray spectrum is a very important factor for the x-ray nano lithography which uses the x-ray to copy the mask pattern to the resist on the wafer. The mask mainly consists of a membrane and the absorber structures. The membrane of the mask, which is a film of very thin thickness about 2μm made of low atomic weight material such as Be, SiN, SiC or diamond, permits x-ray to transmit to the resist and supports the absorber structures, while the absorber structures of the mask will absorb the x-ray and form an x-ray image on the resist. The resist pattern is made after exposure to x-ray and development in the solvent.

In the mask fabricating process, the thickness of the absorber structures closely depends on the lateral width of the fine line of the electronic device and is only about 0.4μm with the later fine line below 0.1μm. Therefore the x-ray spectrum, which can be absorbed enough by the mask with 0.4μm thickness, must be controlled to the soft range. On the other hand, the membrane will absorb the much softer x-ray seriously and will not allow it to reach the surface of the resist. So the spectrum should be determined carefully by these two aspects.[3,5−9]

The gold, used as the coating material of the mirror, produces a peak in the spectrum at 2.5keV by its absorption edge at 2.2keV. The x-ray power at the peak of 2.5keV will transmit from the gold absorber pattern a large portion to the resist and cause a difficult problem in the later development of the resist. This gold coating material of the mirror does not meet the requirement of the x-ray spectrum for nano lithography. Chromium can be better used here as the coating material for the nano lithography. Figure 2 shows the spectra of the gold and chromium materials for the mirror at the grazing angle of 26.2mrad. The membrane for the mask is the SiN with 2μm thickness.

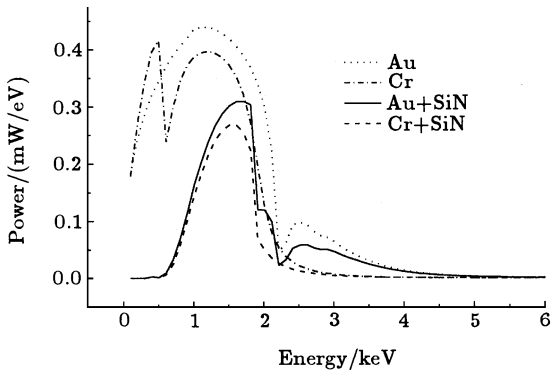


Fig.2. Spectra of gold and chromium materials for the mirror at the grazing angle of 26.2mrad.

From Fig.2, we can find that the absorption edge of silicon is 1.8keV, which can not transmit enough x-ray to the resist at this energy. To reduce the burden of absorber structures of the mask to absorb x-ray, the grazing angle of the mirror should be increased to cut the x-ray energy above the absorption edge of silicon at 1.8keV. Figure 3 shows the spectra with the chromium coating material for the mirror at the grazing angle of 26.2mrad (1.5°) and 27.9mrad (1.6°). The spectrum has been moved to the softer x-ray range with 27.9mrad rather than 26.2mrad and this will reduce the burden of the absorber of the mask.

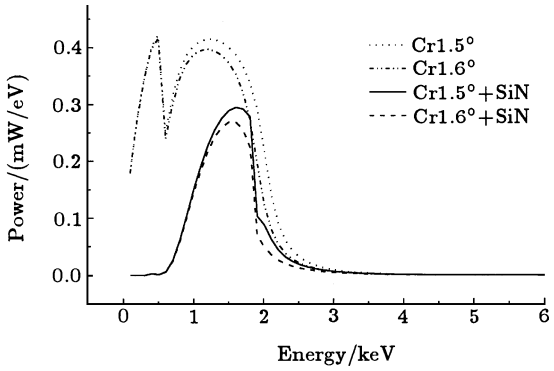


Fig.3. Spectra with the chromium coating material for the mirror at the grazing angle of 1.5° and 1.6°.

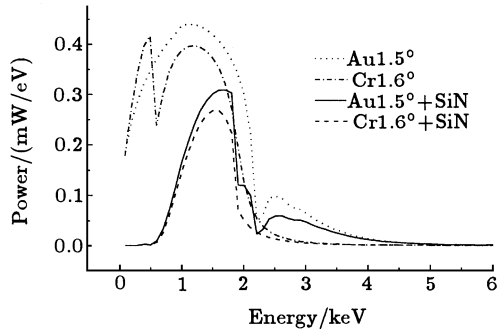


Fig.4. Spectra with gold coating material at the grazing angle of 1.5° and the chromium coating material at 1.6° for the mirror.

By using the chromium coating material and increasing the grazing angle of the mirror, the spectrum has been changed greatly and is more suitable for the x-ray nano lithography. Figure 4 shows the spectra with gold material at the grazing angle of 26.2 mrad of the present situation and the chromium material at 27.9mrad for the upgraded design to the mirror. The upgraded design will provide a much better spectrum for the x-ray nano lithography.

3. Calculation of x-ray power

The power of the x-ray on the wafer, which will affect the exposure time of the resist, is reduced in many aspects in the upgrading design of the beamline. The enlarging of x-ray scanning spot on the wafer, the reduction of receiving angle from 7.5mrad to 6mrad on the horizontal direction, the change of mirror coating material of chromium instead of gold and the increasing of mirror grazing angle from 26.2mrad to 27.9mrad, all these cause a decrease of the x-ray power on the wafer. Table 1 shows the transmission of the x-ray power from the SR source to the bottom of PMMA resist with the two coating materials and grazing angles of the mirror.[1]

Table 1. Transmission of the x-ray power from the SR source to the bottom of the PMMA resist with the two coating materials and grazing angles of the mirror.

Optical elements	x-ray power/(W/mrad)	Optical elements	x-ray power/(W/mrad)
SR	2.492	SR	2.492
M(Au26.2mrad)	0.7143	M(Cr27.9mrad)	0.5636
F(SiN2μm)	0.3132	F(SiN2μm)	0.2214
PMMA(0.5μm)/Au(0.5μm)	0.2932/0.04397	PMMA(0.5μm)/Au(0.5μm)	0.2043/0.02643

From Table 1, the x-ray power after the mirror will be reduced to 79% (0.5636/0.7143) as a result of both the application of the chromium coating material and the increasing of the grazing angle of the mirror from 26.2mrad to 27.9mrad. Considering all elements affecting the x-ray power on the wafer, such as the reduction of acceptance angle in the horizontal and the increase of x-ray scanning spot on the wafer, the total x-ray power on the wafer will be reduced to about 50%, which means that the exposure time will be doubled. This doubled exposure time should not cause much problem for the nano x-ray lithography because the time is still as short as several minutes.

The contrast of the mask, which is the ratio of the x-ray power between the incident x-ray before the absorber structures of the mask to the transmitted x-ray after the absorber structures, will be improved from 7.1(0.3132/0.04397) with the current beamline to 8.4(0.2214/0.02643) with the upgraded design. On the other hand, the absorption doses of PMMA with 0.5μm thickness are respectively 0.01998 (0.3132–0.2932) for current beamline and 0.0171(0.2214–0.2043) for the upgraded beamline, i.e. the absorption dose is reduced to 86%(0.01706/0.01998) of the original.

4. Uniformity control of x-ray scanning spot on the wafer

The x-ray radiated from the storage ring is uniform in the horizontal direction but a Gaussian distribution exists in the vertical direction. The x-ray must

be scanned in the vertical direction to form a uniform scanning spot on the wafer surface for the exposure of x-ray nano lithography. A convex wheel has been introduced to control the scanning movement of the mirror which has been proved successful for the x-ray submicro lithography.

The mirror with cylindrical surface focuses the x-ray on the horizontal direction to form a parallel x-ray on the wafer and increases the x-ray power, compared with a plane mirror. The relation of the source and its image is given by geometric optics as

$$\frac{1}{l'} + \frac{1}{l} = \frac{1}{f}. \tag{1}$$

Here l' is the distance of image from the mirror, l the distance of mirror from the SR source, f the focus of the mirror and equal to 11.1m with l'=44.4m and l=14.8m.

For the mirror with small grazing angle, we have

$$R = 2f \sin\alpha. \tag{2}$$

Here α is the grazing angle of the mirror, R is the radius of the cylindrical mirror and is equal to 620mm with the grazing angle of 27.9mrad and f=11.1m.

During the scanning of the mirror, the grazing angle of the mirror and the width of the x-ray spot on the wafer in the horizontal direction will change and bring a variation of x-ray power density on the wafer at different vertical positions. These two reasons must be considered in the upgrading design.

For the influence of the width (W) of the x-ray spot in horizontal direction on the uniformity of x-ray scanning spot, we can consider using the geometric optics relation. Considering the size and the shape of the spot in the horizontal direction, the scanning distance of x-ray on the wafer can be determined as 49.9mm with the uniform scanning distance of 30mm, size of 13.5mm and the intermediate area of 6.4mm. The scanning angle (α) of mirror should be from 26.9–28.9mrad because the deviation of α is 2mrad to form the scanning distance of 36.4mm in Fig.1. From the geometric relationship in Fig.1 and the formulae (1) and (2), the width (W) can be described as

$$W = \frac{240 \times \left(l\dfrac{R}{2\sin(\alpha)} - 18.2\left(l - \dfrac{R}{2\sin(\alpha)}\right)\right)}{l\dfrac{R}{2\sin(\alpha)}}. \tag{3}$$

The relation between W and the grazing angle α is illustrated in Fig.5 according to Eq.(3). The width is directly proportional to the grazing angle in the small ranges and the largest deviation of x-ray power reaches 20% [(65–53)/60=0.2] at two ends of scanning grazing angle for the width of x-ray spot.

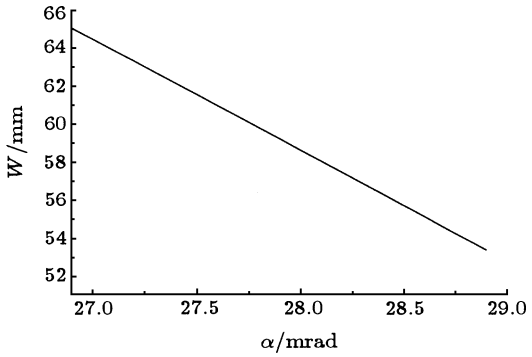


Fig.5. Width of x-ray spot on wafer in horizontal direction at different grazing angles.

The effect of the change of the grazing angle on the uniformity of x-ray scanning spot can be determined by calculating the reflectivity of the mirror at different grazing angles. According to the formulae of the reflectivity for the mirror, we have

$$R = \frac{h - \left(\dfrac{\alpha}{\alpha_c}\right)\sqrt{2}(h-1)^{1/2}}{h + \left(\dfrac{\alpha}{\alpha_c}\right)\sqrt{2}(h-1)^{1/2}},$$

$$h = \left(\frac{\alpha}{\alpha_c}\right)^2 + \left\{\left[\left(\frac{\alpha}{\alpha_c}\right)^2 - 1\right]^2 + \left(\frac{f_2}{f_1}\right)^2\right\}^{1/2}, \tag{4}$$

f_1 and f_2 are the atomic scattering factors, α_c the critical grazing angle and α_c=27.9mrad here.

At the peak wavelength of λ=0.83nm (E= 1.5keV) from Fig.3 for chromium coating of the mirror, f_1=–0.1676 and f_2=4.861. We can calculate the relationship between the grazing angle and the reflectivity from the given values. Figure 6 shows the reflectivity of the mirror at different grazing angles. The reflectivity of the mirror is directly proportional to the grazing angle in the given range. The largest deviation of the mirror reflectivity can reach 3.7% [(0.6069–0.5849)/0.59=0.037] at the ends of the scanning angle and must be considered at the scanning of the mirror to form a uniform scanning spot on the wafer.

To form a uniform x-ray scanning spot on the wafer, the scanning velocity of x-ray in vertical direction must be adjusted by the rotation of a convex wheel which is used to control the movement of the mirror scanning.

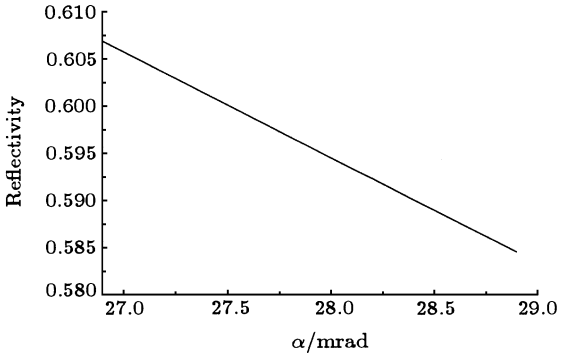


Fig.6. Reflectivity of the mirror at different grazing angles.

The exposure dose (F) on the wafer is directly proportional to the exposure time (t) and can be expressed as $F = kt$. The dose density (E) on the wafer can be shown as

$$E = \frac{F}{S} = \frac{kt}{VtW} = \frac{k}{VW}. \quad (5)$$

Here k is a constant, S the exposure area on the wafer, V the scanning velocity of x-ray scanning spot on the wafer. To get the uniform x-ray spot on the wafer, the density should be fixed at any position of x-ray spot and this results in the relation $VW = V_{\rm u}W_{\rm u} = V_{\rm d}W_{\rm d}$. On the other hand, the scanning velocity can be expressed as $V = V_{\rm d} - a\theta$ and at the 'up' position of x-ray spot, it can be written as

$$V_u = \frac{W_{\rm d}}{W_{\rm u}}V_{\rm d} = V_{\rm d} - a\theta. \quad (6)$$

Here, $V_{\rm d}$ and $W_{\rm d}$ are respectively the scanning velocity and the width of x-ray spot at the down position on the wafer and $W_{\rm d}$=53.32mm, $V_{\rm u}$ and $W_{\rm u}$ at the up position and $W_{\rm u}$=65.06mm; a is the constant of acceleration for the convex wheel, and θ the rotation angle of the wheel. Considering the influence of the mirror reflectivity on the uniformity of x-ray scanning spot at different grazing angles, Eq.(5) can be modified as

$$V_{\rm u} = \frac{W_{\rm d}}{W_{\rm u}} \times \frac{R_{\rm u}}{R_{\rm d}}V_{\rm d} = V_{\rm d} - a\theta, \quad (7)$$

where $R_{\rm u}$ is the reflectivity of the mirror at the up position of the x-ray spot on the wafer and $R_{\rm u}$=0.5849, $R_{\rm d}$ at the down position and $R_{\rm d}$=0.6069.

For the convex wheel, the distance deviation (X), being directly proportional to the moving distance of x-ray scanning spot on the wafer, can be written as

$$X = V_{\rm d} \times \theta - \frac{1}{2}a\theta^2. \quad (8)$$

When θ=180°, $X_{\rm u}$=0.3mm. The $V_{\rm d}$ and the constant a can be calculated from Eqs.(6) and (7) with the above definite parameters, $V_{\rm d}$=1.958×10^{-3} mm/degree and a=1.621× 10^{-6} mm/degree^2. In Eq.(8), the first term represents the scanning velocity of x-ray spot on the wafer and the second term shows the acceleration which corrects the deviation of x-ray power density at different vertical positions. The curve of convex wheel can be described as

$$X = 1.958 \times 10^{-3} \times \theta - \frac{1}{2} \times 1.621 \times 10^{-6}\theta^2. \quad (9)$$

5. Discussion

In the former design of 3B1A, the influence of change of grazing angle on the uniformity of x-ray scanning spot on the wafer during the scanning of mirror was not considered and has caused many problems for the x-ray nano lithography. From the above calculation, we can find the influence of the scanning angle on the uniformity of the x-ray spot. When this influence is not considered in Eqs.(7) and (8), the curve of the convex wheel will be calculated as

$$X = 1.83 \times 10^{-3} \times \theta - \frac{1}{2} \times 1.83 \times 10^{-6}\theta^2. \quad (10)$$

In Eq.(9), with the influence of change of grazing angle, the acceleration of 1.83× 10^{-6} mm/degree^2 is smaller than that of 1.621×10^{-6} mm/degree^2 in Eqs.(1)–(10) and this means that the influence of change of the grazing angle does have an effect on the uniformity of x-ray scanning spot during the mirror scanning of about 12% [(1.83×10^{-6}–1.621×10^{-6})/1.72×10^{-6}=0.12].

Usually the uniformity of the x-ray scanning spot on the wafer should be less than ±5% for nano x-ray lithography. This influence of grazing angle changing during scanning is very serious considering the above requirement and must be solved in the designing. In our advanced design for the nano x-ray lithography, we first consider the influence of the change of scanning grazing angle on the uniformity of the x-ray scanning spot and solve the problem by controlling the convex wheel curve. The beamline with this design is now under construction.

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