DIFFRACTION LIMIT OF THE X-RAY REFRACTIVE LENSES

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A compound X-ray lenses is an array of microlenses with a common axis. The resolution limited by aberration and by diffraction. Aberration can be corrected by shaping refractive surfaces for the experiment geometry. Due to the small value of refractive index the ideal shape of the surface is similar to the parabola. Diffraction limit comes from single slit theory based on absorption aperture of the compound refractive lenses. X-rays passing through lenses form Airy pattern. The size of Airy disk depends on absorption in the material of the compound X-ray lens. Results of calculation of diffraction resolution limit for X-ray lenses are discussed.

Introduction

X-ray radiation can be used for semiconductor lithography for the exposing photoresists with submicron resolution. Optical photolithography technique goes to UV and VUV spectrum because of diffraction effects. Diffraction limit for hard X-rays is less then 1A. Scanning and steppers systems are two major classes of X-ray lithography tools. Scanning projection printing employs reflective X-ray optics. Steppers should employ refractive optics. Up to now using refractive optics were unreasonable due to small value of refraction index and large value of absorbtion. The appearance of refractive lenses for X-rays and synchrotron experiments open new possibility for X-ray microscopy and lithography.

Refractive optics are used for 5-100 keV X-rays from 1996 [1]. In small angle approximation the beam deflection angle after refraction doesn't exceed $(2\delta)^{1/2}$, δ is the decrement of refraction index ($n=1-\delta$). Thus the focal length of the individual lens is inappropriate for practical using. But the stack of the refractive lenses is suitable for synchrotron experiments. To the present time number of designs of X-ray lenses are known. All designs can be divided to one-dimensional focusing lenses and two dimensional focusing lenses. One-dimensional focusing lenses are system of holes, planar parabolic structures, kinoform lenses, alligator lens, Fresnel lenses, clessidra lens, which can focus or collimate X-rays. Two-dimensional focusing lens are compound parabolic lens, microcapillary refractive lens [2] and theoretically proposed - adiabatic lens and three-dimensional arrays of microlenses which can produce X-ray images. The refractive lenses is used for focusing, collimating and producing images. Synchrotrons, X-ray tubes, plasma sources are used as X-ray sources. The main parameters of the refractive lenses are aperture 5-500 microns, the number of refracting lenses 1-500, focal length 0,1-2 m, transmission 0,1-90%. Spot size formed by refractive lens is equal to size of X-ray source image. Gain or concentration of the flux is equal to ratio areas of the lens aperture to the X-ray source image multiply to lens transmission. The experimental synchrotron gain of the refractive lens is about 1-100. To the present time the value of the gain is limited by the X-ray source size used for experiment. Distinction of the source image size from the diffraction limit spot size gives perspectives for the progress in gain and lens design development.

Diffraction limit

The reason for the limited resolution of an microscope is diffraction. An Airy disk is the central bright circular region of the pattern produced by light diffracted when passing through a small circular aperture. The central disk is surrounded by less intense concentric rings, so light intensity takes local maximum and minimum while it decreases away from the center. The distance between the central maximum and the first minimum is the size of an Airy disk [3]. The size of an Airy disk depends on the wavelength of the light and the size of the aperture. Thus, if the aperture is the objective of a microscope with numerical aperture *NA*, the diameter d_A of the Airy disk at the focal plane is:

$$d_A = \frac{1{,}22\lambda}{NA}, \tag{1}$$

Using dimensionless coordinates, the radius of an Airy disk equals 3.83 in optical units ($\lambda/(2\pi NA)$)). About 84% of the total light intensity is in the central Airy disk, the remainder 16 % is distributed in the concentric rings.

The Rayleigh criterion for the diffraction limit to resolution states that two images are just resolvable when the center of the diffraction pattern of one is directly over the first minimum of the diffraction pattern of the other. The first minimum is at an angle of θ, so that two point objects are just resolvable if they are separated by the angle:

$$\Theta = 1.22\lambda/D, \tag{2}$$

where D is the diameter of circular aperture. About 80% of the Airy disk intensity is in the space between two Airy disks for incoherent sources and resolvable two point objects.

It can be seen that the greater the diameter of the lens or its aperture, the greater the resolution.

$$R_{diff} = 0{,}61\lambda \frac{F}{R_d} \cdot \tag{3}$$

The diffraction theory for resolution are defined d_A, θ, R_{diff} for transparent optical systems. Refractive X-ray lens is multielement biconcave lens the diameter of the lens aperture is strongly depends on absorption. Due to the real part of refractive index $n=1-\delta$ is less then 1 the focusing lens is concave. Absorption of X-rays in lens material lead to small transparent central part of the lens. The central part of the lens is transparent for X-ray due to small thickness and the outer part of the lens absorb x-ray radiation. For hard X-rays low absorbing materials are used for X-ray refractive lens.

Low absorbing materials have small refractive index thus X-ray lens consists of large number (100-500) refractive surfaces or microlenses. It is proposed that compound refractive microlenses acts like one lens with increased complex index of refraction due to the optical way in lens much smaller then focal distance:

$$n = 1 - \delta N + i \beta N , \tag{4}$$

Here we discuss diffraction limit of the lens with increased refractive index and investigate dependence of diffraction limit on absorption.

Results of calculation

Distribution of x-ray radiation in a refracting x-ray lens can be described by theory of monochromatic electromagnetic plane waves. Light in the form of a plane wave in space is said to be linearly polarized. It allows to describe a light wave in scalar approach. The monochromatic electromagnetic plane waves is described as follows:

$$E = A \cos (wt - kr) \tag{5}$$

where w – frequency, r – radius vector, k – wave vector.

A wavefront is the locus of points having the same phase $kr=const$. The plane waves change amplitude and a phase in refractive x-ray lens. The amplitude may be described by law $P(x)$ taking into account absorption due to thickness of the lens material. The X-ray refractive lens is spherical biconcave and the thickness of the lens material at high h measured form optical axes of the X-ray refractive lens equal:

$$L (x) = - (2R+d) N + 2N (R^2 - h^2)^{1/2}. \tag{6}$$

A wavefront at the exit of lens doesn't plane, it is described by law φ (x):

$$\varphi (x) = k \, \delta \, L (x), \tag{7}$$

These changes of amplitude and phase can be described by complex function of a transmission T:

$$T (x) = P (x) \exp (i \, \varphi (x)) \tag{8}$$

Intensity distribution in the focal plane is described as:

$$I = \left(\int_0^R \int_0^{2\pi} U e^{-\mu L(x)} e^{-iqr \mathrm{Cos}\varphi} r \, d\varphi \, dr \right)^2 \tag{9}$$

where μ - linear coefficient of absorption of a material, q-defines change of a wave vector at diffraction. Condition $I=0$ defines the size of Airy disk and diffraction limit of the refractive X-ray lens. Results of calculations $I(q$) for refractive X-ray lens (100 microlenses, radius equal 100 microns) for different absorption coefficient are shown in fig.1.

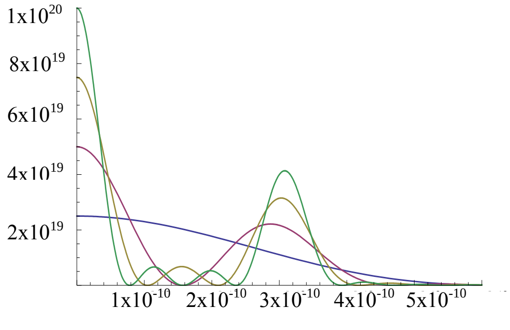

Fig. 1. Intensity distribution in the focal plane of the lens

The size of Airy disk depends on absorption in the material of the compound X-ray lens. Calculations show that for small values of linear coefficient of absorption of the material μ ($RN\mu<<1$) the diffraction results are similar to transparent optical systems and equations (1-3) are valid. Dependence of the diffraction radius in optical units ($2\pi/\lambda$) is shown in fig. 2. Equations (1-3) are valid up to and up to $\mu=0,0001\ cm^{-1}$. Absorption leads to reduction of intensity of diffraction peaks and insignificant increasing of the Airy disk size. At small values of absorption the radius of an effective diaphragm of R_d is equal to the radius of X-ray lens R. Increase of absorption of a material ($RN\mu\cong0.1$) blurs of the diffraction picture that corresponds to reduction of radius of an effective diaphragm R_d. Distribution of intensity is described by a classical diffraction picture, decreasing intensity runs a number of maximums and minimums. Values of the size of an effective diaphragm Rd can be determined by a diffraction picture. At great values of absorption ($RN\mu>1$) diffraction picture is characterized by monotonously decreasing function I, the size of an effective diaphragm is proportional to $\mu^{-1/2}$.

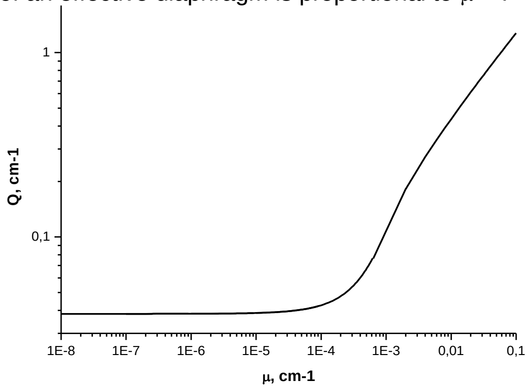

Fig. 2. Intensity distribution in the focal plane of the lens

Conclusion

A compound X-ray lenses is an array of microlenses with a common axis. The resolution limited by aberration and by diffraction. Aberration can be corrected by shaping refractive surfaces for the experiment geometry. Due to the small value of refractive index the ideal shape of the surface is similar to the parabola. Diffraction limit comes from single slit theory based on absorption aperture of the compound refractive lenses. X-rays passing through lenses form Airy pattern. The size of Airy disk depends on absorption in the material of the compound X-ray lens. Results of calculation of diffraction resolution limit for X-ray lenses are discussed.

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