USING OF PROTON BEAM WRITING TECHNIQUES FOR FABRICATION OF MICRO DIFRACTION GRATINGS

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To obtain micrometric gratings with a high aspect ratio by lithographic technique, it is proposed to use a proton beam focused in a line and electromagnetic scanning in the transverse direction to irradiate the resistive material. Numerical modeling is carried out to optimize the parameters of the probe forming system for this task. The calculations were confirmed during the experimental implementation of the proposed technique. A grating from the 23.4×2060 μm lines was made.

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INTRODUCTION

Micro diffraction gratings are used to obtain a phase contrast image using interference from incoherent radiation from a conventional X-ray tube [1 - 3]. Another trend of micro gratings application is generators using diffraction radiation from moving electrons. Such generators are promising in the submillimeter wavelength range. One of the most complex parts of a submillimeter diffraction radiation generator is a reflective diffraction grating [4]. The grating period for submillimeter wavelength diapason should be <100 μm and, as the wavelength decreases, the grating period should also decrease. An important requirement in both cases is the three-dimensional nature of grating with a high aspect ratio, and when the ratio of the planar dimensions of the lamellas and their height should be in a certain proportion. At present, there are several methods for obtaining micro diffraction gratings using X-ray photolithographic methods that require precise photomasks. In this paper an alternative method of irradiating a resistive layer using a focused beam of protons of Megaelectronvolt energies is used. This method of exposure is straightforward and does not require photomasks. The process of focusing a proton beam accelerated by means of an electrostatic accelerator to energy of several Megaelectronvolt is carried out with precision magnetic quadrupole lenses (MQL). With the electromagnetic deflection system, the beam is scanned over the surface of a homogeneous layer of resistive material in accordance with a given digital pattern [4 - 6]. This lithographic process is called Proton Beam Writing (PBW).

In most works on the application of PBW, the beam is focused into a spot with similar dimensions along transverse coordinates. This is due to the complexity of the pattern form. In the case where the pattern consists of parallel lines, it is most optimal to obtain a focused beam in the form of a thin elongated line. In this case, one spot size has micrometric dimensions, and the other is measured in millimeters. This makes it possible to significantly accelerate the irradiation of the resistive material to produce micrometric gratings, which later on, when the electroplating process is developed, is formed into diffraction gratings. In the present work, numerical simulation of beam focusing to a line with given dimensions and maximum current density in the irradiated region is considered. The experimental part shows the beam focusing procedure, the determination of real micrometric dimensions, and the result of producing of a micro diffraction grating pattern.

1. SIMULATION OF PROTON BEAM FOCUSING

Quadrupole optics is used to focus the charged particle beam into the line, which is related to the physical principles of the quadrupole lens, which has a focusing effect in one transverse direction to the beam and defocuses the beam in the other transverse direction. However, it is not effective to use one quadrupole lens in the process of beam formation into a line. This is due to the fact that it is possible to obtain a specific beam size in the micrometric direction by appropriately selecting the collimator size in this direction at a known quadrupole lens demagnification factor. You can also obtain a different size by choosing the size of the collimator that will increase in the target plane. From these considerations we can conclude that in this case we will have a low current density in the region of irradiation of the resistive material, which is due to the inability to control the focusing process in the millimeter range. Therefore, in a focusing system there must be at least two quadrupole lenses, with two free excitation parameters of each lens. Usually, the focusing system is calculated from the condition of stigmatic focusing of the beam. In this case, it is necessary to select the power of the lenses in such a way that the required beam size on the target is provided in the micrometric direction, in accordance with the stigmatization of the focusing system in this direction. And in the millimeter direction, the lens power is selected to provide the desired beam size with the maximum resulting beam current density.

To simulate this focusing process a probe-forming system of a nuclear scanning microprobe of the Analytical Accelerator Complex of the Institute of Applied Physics of the NAS of Ukraine [7] was chosen. Only one doublet of MQL of the final focusing was used, which is located near the target camera. The geometric parameters of the focusing system: The length of the system (from the object collimator to the target) l = 3553 mm; working distance (from the output of the effective field of the last lens to the target) g = 236 mm; effective field lengths MQL L_1= 50.67 mm, L_2 = 71.41 mm; the distance between the boundaries of the effective field of the lens is a_1 = 39.4 mm. The ion-optical characteristics of the focusing system: demagnification factors $Dx \times Dy$ = (-22.3)×(-5.7); chromatic aberrations C_{px} = 76 , C_{py}=82 μm/mrad%; spherical aberrations $\langle x/x'^3 \rangle$ = -17 μm/mrad^3, $\langle x/x'y'^2 \rangle$ = -11 μm/mrad^3, $\langle y/y'^3 \rangle$ = -7 μm/mrad^3, $\langle y/x'^2y' \rangle$ =

44 μm/mrad^3. During the formation of a 1 MeV proton beam, the measured beam brightness distribution in the plane of the object collimator [8] was used on the target, which is the Gaussian distribution in the form

$$b(x,x',y,y')=b_0 b_x(x,x')b_y(y,y'), \quad (1)$$

$$b_\tau = \exp\left\{-\frac{1}{2(1-k_\tau^2)}\left(\frac{\tau^2}{\sigma_\tau^2}-2k_\tau\frac{\tau\tau'}{\sigma_\tau\sigma_{\tau'}}+\frac{\tau'^2}{\sigma_{\tau'}^2}\right)\right\}$$

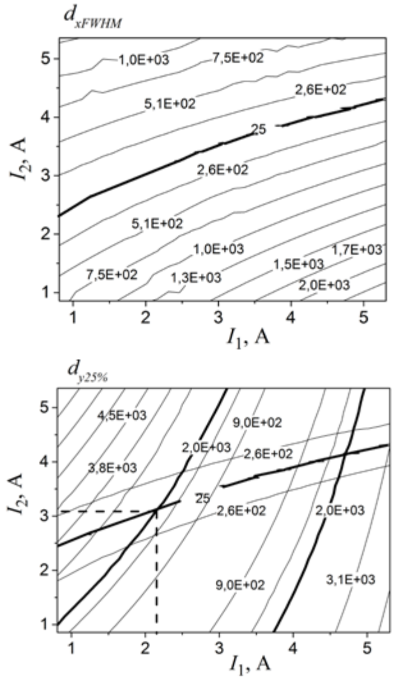
$\tau=(x,y)$;

$b_0=7$ pA/μm^2 mrad^2;

$\sigma_x=621$ μm, $\sigma_{x'}=0{,}088$ mrad, $k_x=-0.41$;

$\sigma_y=667$ μm, $\sigma_{y'}=0{,}098$ mrad, $k_{y'}=-0.89$.

The dimensions of the collimators were chosen from the condition for obtaining a focused beam with dimensions of 25×2000 μm. Taking into account the ion-optical characteristics, the sizes of the object collimator were chosen equal to $2rx$ = 550 μm. In the y direction, the object collimator was completely opened $2yr$ = 4000 μm. The dimensions of the angular collimator in the x direction were chosen to exclude the influence of chromatic and spherical aberrations $2Rx$ = 720 μm. In the y direction, the angular collimator was completely opened $2Ry$ = 4000 μm. The process of focusing the beam with a nonuniform distribution in the phase space in the form (1) with allowance for its clipping by object and angular collimators with rectangular windows was performed using the procedure described in detail in [9, 10]. Under the condition of stigmatic focusing, the beam dimensions on the target at the half-height of the current density distribution were $d_{xFWHM} \times d_{y25\%}$ = 25×280 μm. To obtain the required dimensions, it was necessary to change the lenses excitation to preserve the x dimension and to reach the needed y dimension.



a

b

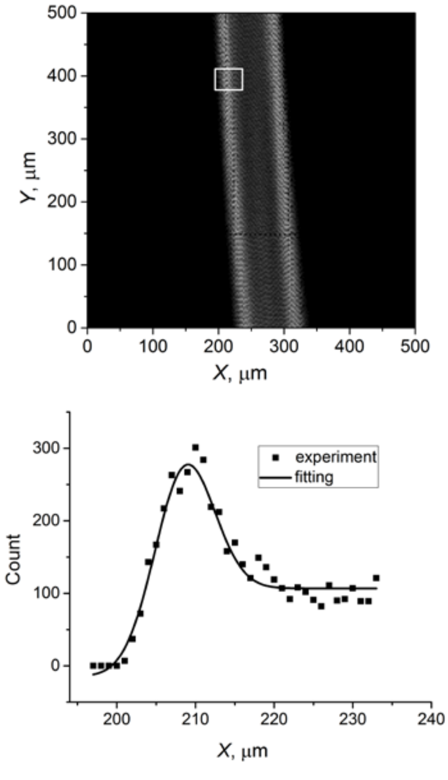
Fig. 1. The contours of the dependence of the beam size change on the target on the currents in the MQL coils: a) in the x direction at the half-height of the current density distribution; b) in the y direction at the 25% of the distribution maximum

In Fig. 1 shows the contours of the dependence of the beam dimensions when the supply currents of the exciting coils of the lenses change. In Fig. 1,b, the contours of the beam size change at the half-height of the current density distribution in the x direction d_{xFWHM} shown in Fig. 1,a are superimposed with the size change contours in the direction at 25% of the maximum of this distribution. From Fig. 1,b there are two solutions for powering the lenses that provide focusing to a spot with dimensions $d_{xFWHM} \times d_{y25\%}$ = 25×2000 μm. A variant with smaller values of the lens current was chosen for the experiment.

2. EXPERIMENTAL PROCEDURE

The calculated values of the MQL excitation currents, which ensure the beam focusing in a line with the specified dimensions, were determined on the basis of the experimental dependence of the magnetic induction on the poles of the lenses on the currents in the coils given in [11]. Due to the hysteresis it was necessary to carry out additional focusing on the visual image of the beam on the quartz screen to minimize the beam size in the x direction. In the y direction the size was determined from the visual image.

The width of the line is d_{xFWHM} of the focused beam was determined as a result of a standard procedure for scanning a vertically located 75 μm diameter copper wire and detecting the yield of secondary electron emission (SEE) during the interaction of protons with a wire. Since the direction of the wire does not coincide with the beam line, in order to reduce the error of determining the beam dimensions, the vertical slits of the object and angular collimators were reduced to 200 μm. As a result, the shape of the focused beam was about the square. In Fig. 2,a shows a secondary electrons wire image in a scan 500×500 μm.



a

b

Fig. 2. The secondary electrons image of a copper wire (a) and the distribution profile of the current density (b)

The processing of the raster consisted of the selection of a series of linear profiles of the yield of secondary electrons when the beam moved horizontally. The rectangular profile selection area is shown in Fig. 2,a. The method for determining the beam dimensions at a half-height of the current density distribution is given in [12] on the basis of an analysis of the rise front of the yield of secondary electrons. This allows us to determine the distribution profile of the current density of the focused beam, and hence the fool width at the maximum height of the distribution in the cross section. The processing of a sample of the SEE output profiles from 20 series (see the region shown in Fig. 2,a) is performed. In Fig. 2,b shows one of the profiles of the SEE output and an adjustable curve that allows determining the line width d_{xFWHM}. As a result of processing a series of output profiles of the SEE, the size of the focused beam in the line d_{xFWHM} = 22 ± 5 µm was obtained. The measurement error is about 20% and is caused by instability in time of the beam current from the electrostatic accelerator. The measured beam current was ≈ 8 nA. Thus, the rate of exposure dose was ≈180 nC/mm^2·s. Based on the data given in [13], the required dose for the selected PMMA resist in the production of three-dimensional structures should be> 90 nC/mm^2 for a proton beam of MeV energies. Silicon substrates with a layer of PMMA of thickness ≈5 µm were chosen as the samples. The process of exposure of the resistive surface of the sample to obtain a periodic structure was carried out by the focused beam in a line for 1 s.

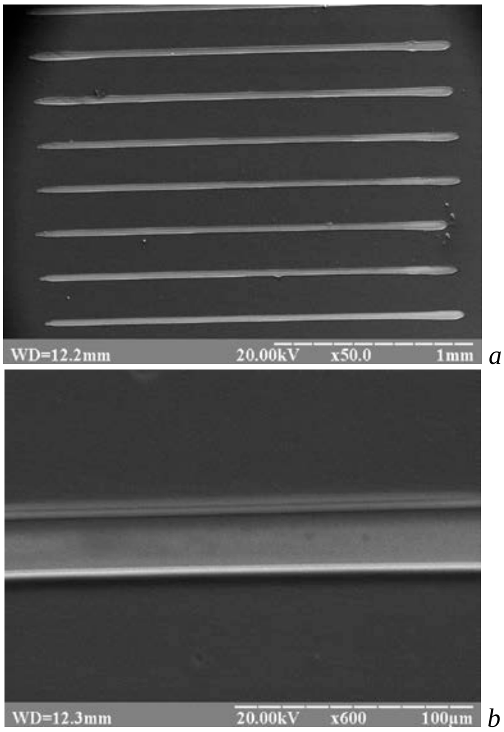


Fig. 3. The secondary electrons image of the irradiated and developed region of the resistive layer on a silicon substrate for different magnitudes of the scanning electron microscope magnification

In Fig. 3 shows the images of the developed samples obtained with the help of a scanning electron microscope. It can be seen from these figures that the experimental result agrees satisfactorily with the results of numerical simulation from the sizes of the focused lines, which amounted to ≈23.4×2060 µm. However, it should be noted that there are fillets at the ends of the lines, which is due to the absence of a limitation of the beam brightness distribution in the *y* direction.

CONCLUSIONS

To focus the proton beam of Megaelectronvolt energies in a line with given dimensions an approach is proposed that allows to calculate the optimum sizes of collimators and excitation currents of MQL. The input parameters are the beam brightness distribution in the phase space in the object collimator plane and the ion-optical characteristics of the probe-forming system. The results of the numerical simulation are confirmed experimentally. The width of the line-focused beam d_{xFWHM} = 22±5 µm is determined by the method of transverse scanning of a 75 µm wire and mathematical processing of the SEE output profiles. After the exposure of silicon substrates with a layer of resistive PMMA material applied and the development, the lines sizes were ≈23.4×2060 µm^2 as measured using a scanning electron microscope.

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ПРИМЕНЕНИЕ ПРОТОННО-ЛУЧЕВОЙ ЛИТОГРАФИИ ДЛЯ ФАБРИКАЦИИ МИКРОДИФРАКЦИОННЫХ РЕШЕТОК

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Для получения микродифракционных решеток с высоким аспектным соотношением методом литографии предложено использовать для облучения фоторезиста протонный пучок, сфокусированный в линию, и электромагнитное сканирование в поперечном направлении. Проведено численное моделирование по оптимизации параметров ЗФС для данной задачи. Расчеты подтверждены при экспериментальной реализации предложенного метода, получена решетка из полос размерами 23,4×2060 мкм.

ВИКОРИСТАННЯ ПРОТОННО-ПРОМЕНЕВОЇ ЛІТОГРАФІЇ ДЛЯ ФАБРИКАЦІЇ МІКРОДИФРАКЦІЙНИХ ГРАТОК

О.Г. Пономарьов, С.В. Колінько, В.А. Ребров, В.М. Коломієць, С.М. Кравченко

Для виробництва мікродифракційних граток з великим аспектним співвідношенням методом літографії запропоновано застосувати для опромінення фоторезисту протонний пучок, сфокусований в лінію, та електромагнітне сканування в поперечному напрямку. Проведене чисельне моделювання з оптимізації параметрів ЗФС для даної задачі. Розрахунки підтверджено при експериментальній реалізації запропонованого методу, виготовлено гратку зі смугами розмірами 23,4×2060 мкм.