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PROTON BEAM WRITING DEVICE BASED ON ELECTROSTATIC ACCELERATOR FOR 3D MICRO- AND NANO-STRUCTURE FABRICATION

Introduction. *Surface micro- and nanostructures have been being used in various physical applications such as X-ray optics, photonics, microelectromechanical systems, metamaterials, etc.*

Problem Statement. *The existing methods for fabricating such structures either are expensive or do not meet certain requirements (the aspect ratio and the quality of side wall surface).*

Purpose. *To create a device for proton beam writing, which enables fabricating surface micro- and nanostructures with required parameters.*

Materials and Methods. *One of alternative methods for fabricating the mentioned surface structures is proton beam writing. Silicon substrates coated with a positive resistive polymethyl methacrylate layer are used as samples for fabricating the surface structures.*

Results. *A proton-beam lithography device based on an electrostatic accelerator has been developed, the configuration and specifications have been presented. The main parameters (demagnifications, proton beam current, and minimum probe dimensions) have been specified. Advantages of using quadrupole optics in fabricating micro-diffraction gratings have been shown. The first experiments on fabrication of source grating in X-ray phase-contrast tomographs with a characteristic line width of about 20 μm have been carried out.*

Conclusions. *A new probe-forming system based on a separated magnetic quadrupole lense pentuplet has been used in the proposed device. The use of an electrostatic scanning system ensures a high accuracy of positioning the focused beam in a closed scanning cycle. The scanning process is controlled using a multifunctional reconfigurable input-output module with programmable logic.*

Keywords: proton beam writing, electrostatic accelerator, and magnetic quadrupole lens.

Proton beam writing (PBW) is a high-resolution lithographic technology that can be used to fabricate 3D micro- and nanostructures of various applications [1, 2]. The main characteristic of the technology is the ability to quickly reproduce any structure in a polymer with a high degree of accuracy. The fabricated structures can have a high aspect ratio (> 50) and an extremely small roughness of the sidewall surface (2—3 nm), since the trajectories of the protons with energies of several MeV in material slightly deviate from straight lines when interacting with the electrons of the sample atoms because of a large difference in mass between proton and electron. Similarly, the energy of the secondary electrons is low, which causes a small effect of proximity. This enables to create structures with almost vertical side walls. The smoothness of the side walls of the microstructures is a specific feature of the PBW, which is crucial for reducing the scattering losses in optical components, such as waveguides and X-ray diffraction gratings [3]. The basic com-

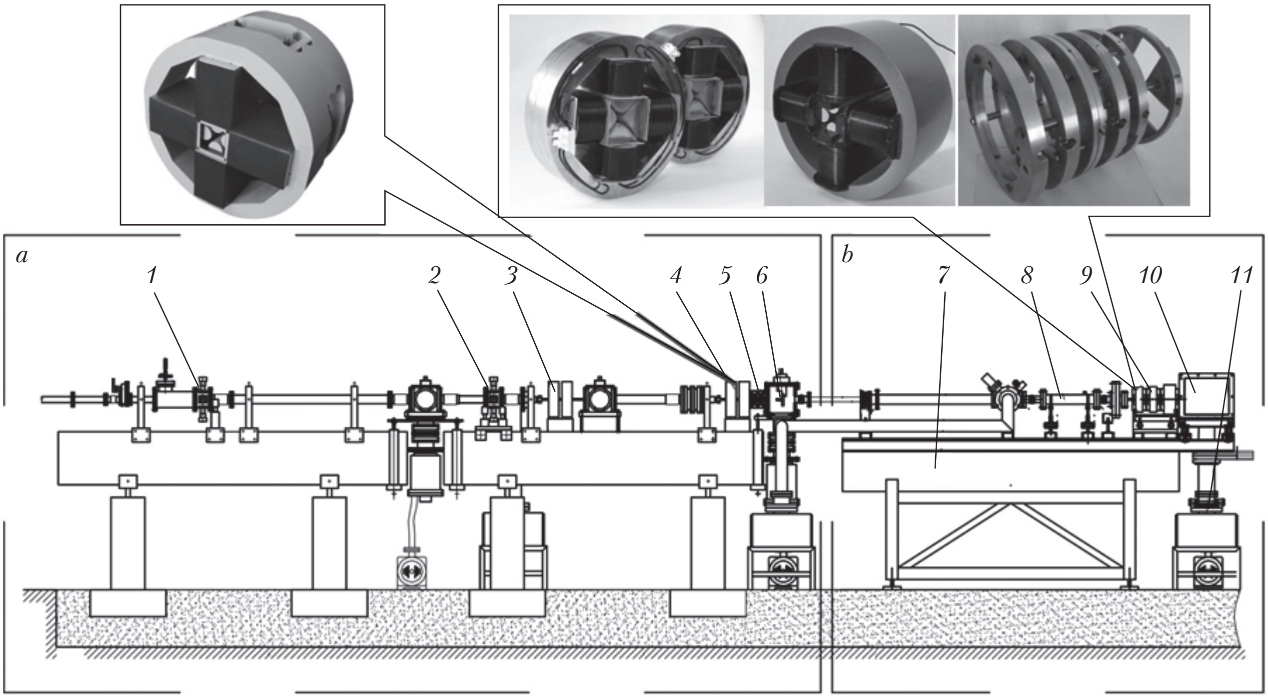


Fig. 1. General scheme of the micro-probe (*a*) and PBW device (*b*): *1* — objective collimator; *2* — aperture collimator; *3*, *4* — doublet of magnetic quadrupole lenses; 5 — ferromagnetic scanner; *6* — chamber with samples of the micro-probe; *7* — granite girder; *8* — electrostatic scanner; *9* — triplet of magnetic quadrupole lenses; *10* — chamber with PBW samples; *11* — ion beam line with vacuum pumps

ponent for PBW devices is a nuclear scanning microprobe that uses protons accelerated to energies of several MeV and focused into a probe lesser than 100 nm. Due to vector electrostatic scanning, the proton probe moves across the resist sample surface changing the physicochemical properties of the irradiated area. Proper processing of this area enables obtaining almost any structure.

The nuclear scanning microprobe hardware complex at the Institute of Applied Physics of the NAS of Ukraine was commissioned in 2008, on the basis of a small-sized electrostatic accelerator with a maximum voltage of 2 MV at a high-voltage terminal and a minimum probe size of 2 μm with a proton beam current of about 100 pA [4, 5]. The probe-forming system of the microprobe has a small demagnificatoin (28) due to the ferromagnetic scanning system located behind the last magnetic quadrupole lens. Therefore, such a focusing system with a total length of about 4 m has a large working distance of 22 cm. Over the past decade, the microprobes have been used in various applications for microanalysis [6—8]. The motivation behind the development of a proton beam writing device is the need to reduce the probe size, which can be obtained at higher demagnificatoins. The requirements for high accuracy of the scanning process necessitates the development of a new proton beam control system based on an electrostatic scanner.

PARAMETERS OF PROTON BEAM WRITING DEVICE

Taking into account the peculiarities of the equipment arrangement in the experimental room, the PBW device was designed as a continuation of the operating microprobe (Fig. 1, *a*, *b*). Therefore, the device has a common optical axis with the microprobe and uses its object and aperture collimators (*1*, *2*) together with one of the doublets of the magnetic quadrupole lenses (*4*). The first doublet (*3*) and the ferromagnetic scan-

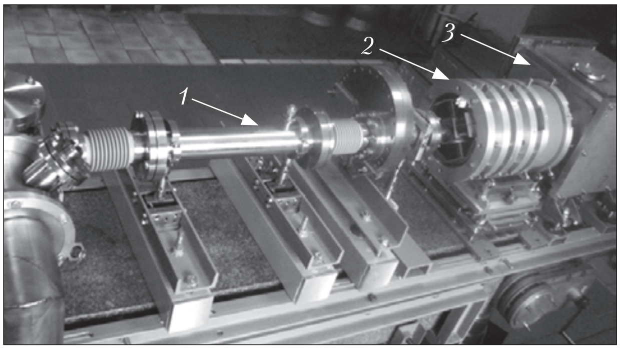


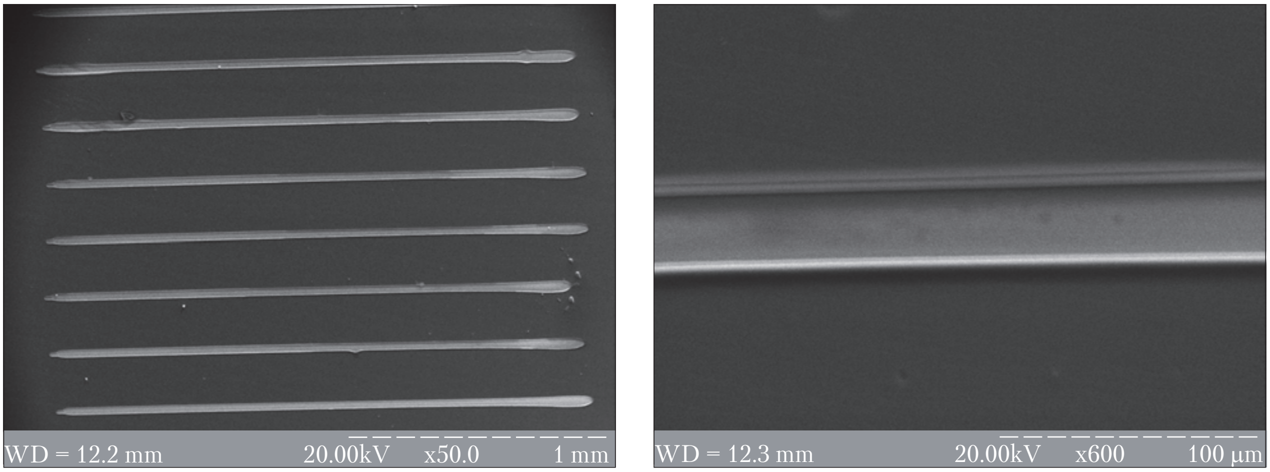
Fig. 2. General view of PBW device: *1* — electrostatic scanner; *2* — triplet of magnetic quadrupole lenses in rigid frame; *3* — chamber with samples

ner (*5*) are not used in the operation of the PBW device.

The granite girder (*7*) placed on anti-vibration supports is located behind the chamber with the studied microprobe samples (*6*). On this beam, there is mounted the PBW device components: the ion beam line with pumps (*11*), the electrostatic scanner (*8*), the triplet of magnetic quadrupole lenses (*9*), and the new rectangular chamber with samples (*10*), which is equipped with an optical microscope, a secondary electron detector, a charged particle detector, and a mechanism for positioning of the samples. The triplet lenses of magnetic quadrupole lenses are placed in a rigid frame, each having an error of misalignment with the common triplet axis of <0.3 mrad and <10 μm for angular and transverse displacements, respectively. The method that enables the triplet to be adjusted with such accuracy has been described in [9]. The triplet is mounted on the positioning table with five degrees of freedom and is adjusted as single whole with respect to the beam axis. The doublet of magnetic quadrupole lenses (*4*) is an integrated device, the yoke of which is made of a solid piece of magnetic soft iron using the electrical discharge machining method [10]. This ensures the positioning accuracy of each lens relative to the common axis of the doublet: a slope of <0.2 mrad and a transverse shift of <10 μm [11]. All misalignment errors take into account hysteresis. A general view of the electrostatic scanner, the triplet of quadrupole lenses in a rigid frame, and the new sample chamber of the PBW device is given in Fig. 2.

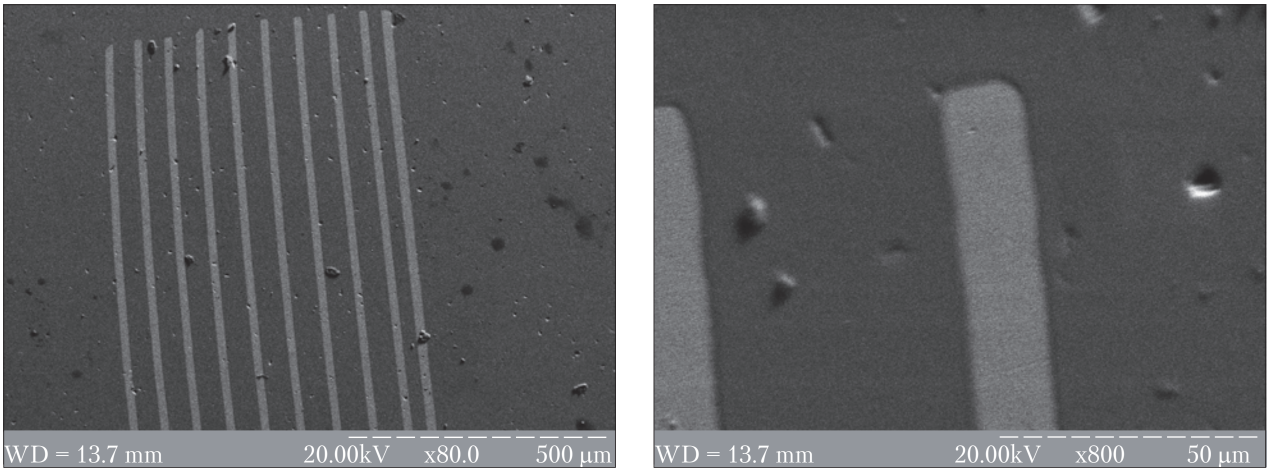
The ion optics of the device is based on the five-lens probe-forming system (integrated doublet and triplet of magnetic quadrupole lenses) with four independent power supply sources of lenses. The first and the second triplet lenses are connected to one source, while all other lenses have independent power supply sources. This probe-forming system enables to vary the demagnificatoins within 10—400. The proton beam current can vary from 10^{-12} A to 10^{-8} A, due to varying dimensions of the collimators. The probe minimum size is 100 nm, and the current density in the probe ranges within 100—350 pA/μm^2.

The electrostatic scanner has three pairs of parallel plates with a gap of 8 mm. The first and the last pairs of plates are connected in opposite polarity. The length of the plates is chosen to compensate for the negative effect of the triplet lenses in the xOz plane. All plates are powered by a high-speed dual bipolar high-voltage amplifier (HVA). The beam scanning process is controlled with the use of a multifunctional reconfigurable I/O module NI 852R that positions the focused beam on the sample according to the specified scan profile. This profile is a one-dimensional array of data, the sequence of coordinates (x_i;y_i), that define the scan pattern. Exposure time can be set both common to all points and individually for each point (t_i). In addition, the exposure time of each point (pixel) can be normalized by fluence (radiation dose). The signal from the beam current integrator (for the conducting samples) or from the charged particle detector (for the non-conducting samples) is used as a signal proportional to fluence. In this mode, the beam “stays” in the current pixel until the preset number of pulses from the current converter or the detector is accumulated. In the module, the independent internal-clock-based process consistently transmits the current beam coordinates (x_i;y_i) to the built-in digital-to-analog converters (DAC). Analog voltages proportional to the beam coordinates are supplied from the DAC outputs to the HVA inputs. The ampli-



a *b*

Fig. 3. Images of a micro-diffraction grating pattern on a silicon substrate coated with a 5 μm thick layer of PMMA: *a* — general view; *b* — enlarged image of a stroke



a *b*

Fig. 4. Micro-diffraction grating pattern on a silicon substrate coated with a thin layer of copper and a 5 μm thick layer of PMMA after electroplating: *a* — general view; *b* — enlarged image of a stroke

fied signals from the HVA outputs are fed to the deflection plates of the respective channels *X* and *Y* of the electrostatic scanner.

FABRICATION OF X-RAY OPTICS MICRODIFFRACTION GRATINGS

Microdiffraction gratings are used to obtain phase contrast images as a result of interference of incoherent radiation of a conventional X-ray tube. In most researches on the use of proton lithography, the beam is focused into spots of equal dimensions along the transverse coordinates. This is explained by sophisticated shape of the pattern. However, if the pattern consists of parallel strokes, the most optimal is to obtain a focused beam in the form of a thin line. This can be done using quadrupole ion optics. In this case, the size of one spot is measured in micrometers, while that of the other spot is counted in millimeters. This method of focusing can significantly accelerate the irradiation of resistive material to obtain micrometric gratings.

For the first experiments, the dimensions of the source grating of a phase contrast interferometer with a characteristic stroke width of about 20 μm were taken. To focus the beam of MeV protons in a line with the given dimensions, an approach that enables to calculate the optimal sizes of collimators and excitation currents of magnetic quadrupole lenses has been proposed [12]. The input parameters are the distribution of beam brightness in the phase space in the object collimator plane and the ion-optical characteristics of the probe-forming system. The samples are prepared in the form of silicon plates coated with a 5 μm thick layer of resistive poly(methyl methacrylate) (PMMA). The samples are irradiated with a beam of protons focused into a line and, after a 0.5 s exposure, scanned by a beam in the direction perpendicular to the larger line dimension. Having treated the irradiated areas, patterns with dimensions of 23.4 × 2060 μm^2 that are measured using a scanning electron microscope are obtained (Fig. 3). Fig. 4 shows similar patterns filled with bismuth as a result of electroplating process when a thin layer of copper is pre-applied to a silicon substrate.

CONCLUSIONS

The physical parameters of the interaction of protons accelerated to several MeV energies are the decisive factor for creating 3D small-sized structures that have a high aspect ratio (> 50) and almost vertical sidewalls with a surface roughness of no more than a few nanometers. This explains the use of the proton beam writing method for the fabrication of optical components, as it is crucial for reducing the scattering losses in waveguides and X-ray diffraction gratings.

The PBW device is an upgrade of the existing nuclear scanning microprobe. The motivation for its development was the need to reduce the probe size to 100 nm and to create a new scanning control system based on an electrostatic scanner, which makes it possible to avoid inaccurate positioning of the focused beam due to hysteresis, in the case of using a ferromagnetic scanner of the microprobe. The use of new electronic vector position control system enables the creation of almost any spatial structure. The most effective technique for fabricating microdiffraction gratings is to use focusing the proton beam into line, which significantly reduces the exposure time. Therefore, a method for specific focusing with the given probe sizes has been developed, and the first experiments on the fabrication of microdiffraction source gratings for X-ray phase contrast interferometer have been carried out.

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УСТАНОВКА ПРОТОННО-ЛУЧЕВОЙ ЛИТОГРАФИИ НА БАЗЕ ЭЛЕКТРОСТАТИЧЕСКОГО УСКОРИТЕЛЯ ДЛЯ ФАБРИКАЦИИ 3D МИКРО- И НАНОСТРУКТУР

Введение. Поверхностные микро- и наноструктуры находят свое применение в различных физических приложениях, таких как рентгеновская оптика, фотоника, микроэлектромеханические системы, метаматериалы и др.

Проблематика. Существующие методы фабрикации таких структур являются либо дорогостоящими, либо не удовлетворяют определенным требованиям (величина аспектного отношения и качество поверхности их боковых стенок).

Цель. Создание установки для протонно-лучевой литографии, позволяющей создавать поверхностные микро- и наноструктуры с требуемыми параметрами.

Материалы и методы. Одним из альтернативных методов фабрикации вышеупомянутых поверхностных структур является протонно-лучевая литография. В качестве образцов для фабрикации поверхностных структур применяются подложки из кремния с нанесенным слоем позитивного резистивного материала полиметилметакрилата.

Результаты. Разработана установка протонно-лучевой литографии на базе электростатического ускорителя, рассмотрены ее компоновка и особенности конструкции. Приведены основные параметры установки: коэффициенты уменьшения, ток протонного пучка, минимальные размеры зонда. Показаны преимущества применения квадрупольной оптики при фабрикации микродифракционных решеток. Проведены первые эксперименты по фабрикации решетки-источника в рентгеновских фазоконтрастных томографах с характерной шириной линии около 20 мкм.

Выводы. В предлагаемой установке применяется новая зондоформирующая система, основанная на распределенном пентуплете магнитных квадрупольных линз. Применение электростатической сканирующей системы обеспечивает высокую точность позиционирования сфокусированного пучка в замкнутом цикле сканирования. Управление процессом сканирования обеспечивается за счет применения многофункционального реконфигурируемого модуля ввода-вывода с программируемой логикой.

Ключевые слова: протонно-лучевая литография, электростатический ускоритель, магнитная квадрупольная линза.

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УСТАТКУВАННЯ ПРОТОННО-ПРОМЕНЕВОЇ ЛІТОГРАФІЇ НА БАЗІ ЕЛЕКТРОСТАТИЧНОГО ПРИСКОРЮВАЧА ДЛЯ ФАБРИКАЦІЇ 3D МІКРО- І НАНОСТРУКТУР

Вступ. Поверхневі мікро- і наноструктури використовують в різних фізичних додатках, таких як рентгенівська оптика, фотоніка, мікроелектромеханічні системи, метаматеріали тощо.

Проблематика. Наявні методи фабрикації таких структур є або високовартісними, або не задовольняють певним вимогам (величина аспектного відношення та якість поверхні їхніх бічних стінок).

Мета. Розробка установки для протонно-променевої літографії, яка дозволяє створювати поверхневі мікро- та наноструктури з заданими параметрами.

Матеріали й методи. Одним з альтернативних методів фабрикації вищезгаданих поверхневих структур є протонно-променева літографія. Як зразки для фабрикації поверхневих структур використовують підкладки з кремнію з нанесеним шаром позитивного резистивного матеріалу поліметилметакрилату.

Результати. Розроблено установку протонно-променевої літографії на базі електростатичного прискорювача, наведено її складові та особливості конструкції. Наведено основні параметри установки: коефіцієнти зменшення, струм протонного пучка, мінімальні розміри зонду. Показано переваги застосування квадрупольної оптики для фабрикації мікродифракційних ґраток. Проведено перші експерименти з фабрикації ґратки-джерела в рентгенівських фазоконтрастних томографах з характерною шириною лінії близько 20 мкм.

Висновки. У пропонованій установці застосовується нова зондоформуюча система, яка базується на розподіленому пентуплеті магнітних квадрупольних лінз. Застосування електростатичної скануючої системи забезпечує високу точність позиціонування сфокусованого пучка в замкнутому циклі сканування. Управління процесом сканування забезпечується за рахунок застосування багатофункціонального реконфігурованого модуля введення-виведення з програмованою логікою.

Ключові слова: протонно-променева літографія, електростатичний прискорювач, магнітна квадрупольна лінза.