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BEAM SCANNING CONTROL SYSTEM FOR PROTON BEAM WRITING†

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A scanning control system of the ion beam of MeV energies has been developed for the nuclear scanning microprobe and proton-beam writing channel as a part of accelerator-analytical complex based on the Sokol electrostatic accelerator of the Institute of Applied Physics of the National Academy of Sciences of Ukraine. The system was put into operation to replace the obsolete one based on microcontrollers. The scanning control system is based on a National Instruments reconfigurable module with a Field Programmable Gate Array. The module operates in real time and is connected to a personal computer by a high-speed PCI-Express interface with data buffering. The system provides two main modes of operation: exposure of sample areas with a given profile and raster secondary electrons imaging of the sample or a calibration grid. Profile exposure is possible both in raster and functional scanning modes. Automatic calibration of the profile scale and scan raster is also implemented. Using of reconfigurable logic makes it possible to quickly adjust the system to the conditions of a particular experiment and the available equipment. The hardware capabilities of the scanning control system allows in the future to connect up to 4 spectrometric ADC for mapping the elemental composition of samples using Proton Induced X-ray Emission and Proton Backscattering. The first experiments on the irradiation of polymethylmethacrylate have been carried out; images of the obtained microstructures taken with a scanning electron microscope are shown. The aim of this work is to develop a control system for scanning a high-energy focused beam in proton beam writing technique to create small-sized structures for special purposes, as well as to demonstrate the efficiency of the developed system.
Keywords: lithography, proton beam writing, scanning control, nuclear microprobe
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Scanning control systems (SCS) are an important part of the systems for collecting and processing data from the channels of a nuclear scanning microprobe and proton-beam writing, therefore, in the leading laboratories of the world, much attention is paid to their development and improvement. [1-5]. These systems, in addition to basic functions, are currently required versatility, modularity of design, interchangeability of modules, flexibility of the operation algorithm. Therefore, systems with a rigid logic of functioning gave way to reconfigurable systems based on a Field Programmable Gate Array (FPGA). The current level of development of FPGA technology allows the necessary functions in a single module to be implemented, and wide range of such modules is available for purchase. In particular, National Instruments company produces specialized reconfigurable data acquisition modules based on FPGAs manufactured by Xilinx, the functionality of which makes it possible to create a SCS based on them. An additional advantage of this approach is the possibility of widespread use of experimental equipment already available in laboratories as part of the designed SCS. From an economic point of view, using of modules with FPGAs is currently preferred.

The system is designed to control scanning a beam of charged particles both in raster and functional scanning modes. The raster mode (progressive scanning of the beam) is used to determine the dimension of the focused beam on the target and the scanning step size using the secondary electron image of the copper calibration grid. The functional mode is designed to expose specified areas of the sample in accordance with the digital scan profile. The movement of the beam in this mode obeys the rule of transition between the nearest neighboring pixels that require exposure.

SCANNING CONTROL SYSTEM

The SCS was developed and implemented on the channel of the nuclear scanning microprobe [6] and on the new channel of proton beam writing of the electrostatic accelerator Sokol of the Institute of Applied Physics of the National Academy of Sciences of Ukraine [7]. The basic features of the system are shown in Table 1.

Table 1. Basic features supported by the SCS.

Maximum resolution, points	65536×65536
Scan step	User-defined
Initial raster offset	User-defined
Scan type	Progressive, functional
Scan polarity	Unipolar, bipolar
Pixel exposure mode	By time, by fluence

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The block diagram of the SCS is shown in Fig. 1. The system consists of a scanner (Scan), two current-frequency converters for measuring the beam current on the target (Cur/Fre) and the current of secondary electrons (SE/Fre) (counting information channels), a reconfigurable input-output module (NI FPGA card) with a connector (Connector NI) and a connecting cable (Cable), a personal computer (PC). NI FPGA card is installed in the PCI-Express slot of a PC and is connected to all SCS modules via the supplied connecting cable and connector.

NI 7852R multifunctional reconfigurable I/O module contains 8 independent 16-bit ADCs and DACs, 96 universal digital I/O lines, user-configurable FPGA, high-speed PC communication interface. The FPGA includes 3 FIFO registers, which makes it possible to buffer data exchange with a PC. Digital logic circuits runs signals up to 40 MHz, the maximum sampling rate of the ADC is 750 kHz, the DAC is 1 MHz. The use of FPGA allows the system to be quickly configured for the specific requirements of the experiment and the required operation algorithm without mechanical reconnecting of circuits. The incomplete functional load of the module makes it possible to expand the functionality of the SCS by connecting additional equipment.

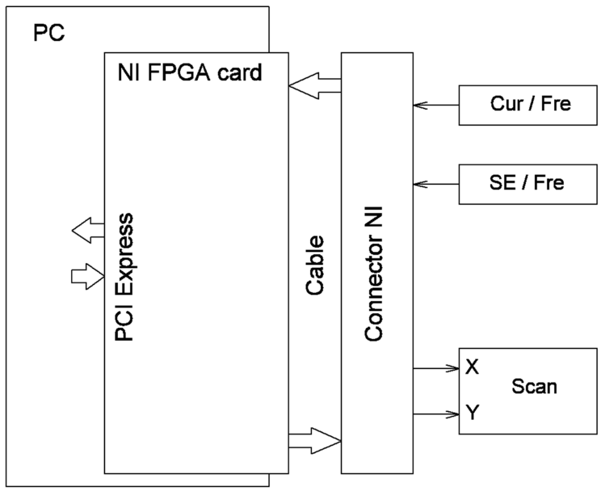

Figure 1. Block diagram of the SCS.

The functional diagram of the SCS is shown in Fig. 2. Sources of counting information are connected to the digital inputs-outputs of the NI FPGA card, which are configured by software during the system initialization. The analog inputs of the high-voltage amplifiers of the electrostatic scanner are connected to the outputs of two DACs X and Y of the NI FPGA card; the voltages across them determine the position of the focused beam (pixel) on the target. The NI FPGA card is connected to the system PCI slot of the computer, data exchange with the RAM is carried out by means of direct memory access. The configuration of the internal structure of the FPGA is carried out using specialized software with a convenient and intuitive graphical interface.

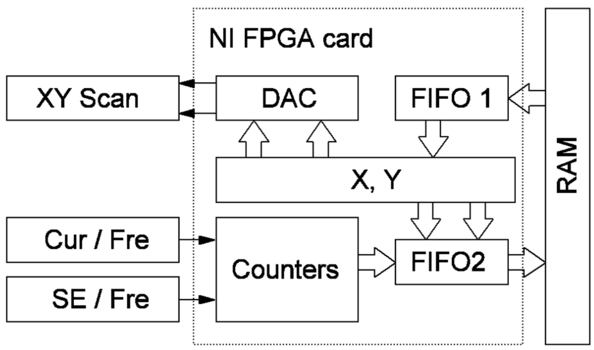

Figure. 2. Functional diagram of the SCS.

When initializing the NI FPGA card in FPGA counters and timers are configured to collect counting information and control the scanning system, as well as logical circuits that set the algorithm for the entire system. After initialization, the system works in real time using an internal timer, communication with the PC is carried out via direct memory access channels using FIFO registers ("first in - first out") to buffering the data exchange.

The FIFOs are assigned to the functional load as follows. In FIFO1, the input from the PC of the scanning profile (the sequence of positions of the focused beam on the target, specified by the coordinates X, Y) is buffered. By means of

FIFO2, the counting information from the current-frequency converters with reference to the pixel coordinates is displayed in the PC in the format {current (fluence or dwell time in a pixel)} {SE current} {pixel coordinates}. The FPGA core configuration diagram is shown in Fig. 3. The main processes are indicated by rounded rectangles and run in parallel.

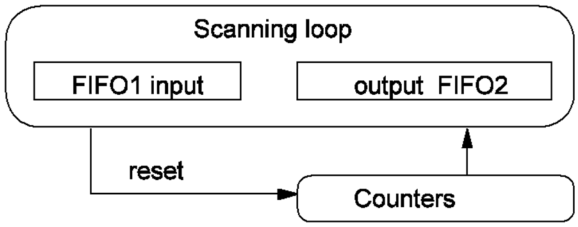

Figure 3. FPGA core configuration diagram.

The leader is the "Scanning loop", it is started by the operator with the "Start" command. At the beginning of the loop, the current coordinates of the scan profile are read from FIFO1 and fed to the DAC to control the scanner. At this time, a counter reset signal is generated, and after the time required to complete the transient process, a counting enable signal (Busy signal is passive) is generated. After the exposure time set in the internal timer has elapsed, counting is disabled (the Busy signal is active) and a word containing coordinates and counting information (fluence, SE current) is output to the FIFO2 register. Then the cycle repeats - the next pair of coordinates is read. The end of the cycle and the stop of data collection occurs on the signal of emptying FIFO1 or on the command of the operator "Stop".

When normalizing the accumulated dose in a pixel, the cycle duration is determined by counting pulses from a current-frequency converter or a scattered proton detector (SPD), and the fluence in the output data word is replaced by the pixel exposure time (if necessary).

The set of counters contains:

- fluence counter (signal from current-frequency converter or SPD),
- secondary electron current counter,
- pixel exposure time counter.

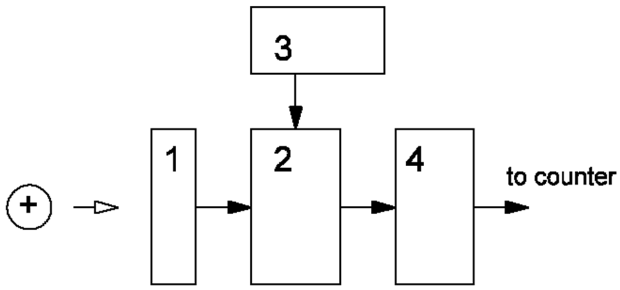

Figure 4. Block diagram of the SPD channel.

On the diagram, the numbers indicate:

1- surface-barrier charged particle detector,

2- preamplifier,

3- high voltage source for detector,

4- spectrometric amplifier-shaper.

Registration of secondary electrons is performed by a secondary electron multiplier (SEM). Secondary electrons are accelerated by a potential of 10 kV at the accelerating electrode and hit the scintillator SEM, at the output of which pulses are formed with a frequency proportional to the current of secondary electrons. The frequency signal is fed to the input of the counter in the NI FPGA card, the binary code at the output of which is proportional to the secondary electron current.

Normalization of the exposure time to fluence involves measuring the charge brought by the beam to the current pixel. For conducting samples, this problem is effectively solved using a charge-frequency converter. For non-conductive samples used in proton lithography, this method is unacceptable. Since the output of backscattered protons is proportional to the fluence, the signal from the counting output of the backscattered proton channel is used to control the radiation dose. The channel for detecting backscattered protons by the SPD is made according to the block diagram shown in Fig. 4.

The main program consists of two parts interacting with each other: a program in the NI FPGA card core (CORE) and a program in a PC with OS Windows (HOST). The CORE program is loaded into the NI FPGA card and initialized when the HOST program is started on the PC. During initialization, data on the number of pixels (Pixels), the exposure time of the pixel (Dwell) and the time sufficient for the transition of the beam between pixels (Busy) are transmitted to the core. Also, a sequence of coordinates for scanning is loaded into the FIFO1 register.

After initialization, the core cyclically reads the next coordinate from FIFO1 using an internal timer and outputs the X, Y values to the corresponding DACs. Then, after the Busy time has elapsed, the counters of secondary electrons and pulses from the current integrator are enabled for the Dwell time. When the exposure time expires, a word is sent to FIFO2 containing coordinates and data from counters. The counters are reset during the Busy signal. The number of cycles corresponds to the number of exposed pixels.

The program monitors the FIFO1 register and loads the coordinates as it is emptied, and also reads information from FIFO2 and displays it in a graphical form, and at the end of the scan saves it to a file in a two-dimensional array format (when scanning an image in secondary electrons).

The external view of the HOST program control panel is shown in Fig. 5. Purpose of controls from top to bottom:

FPI (SE) / LITOGR – switches the operating mode of the SCS scanning in secondary electrons / lithography.

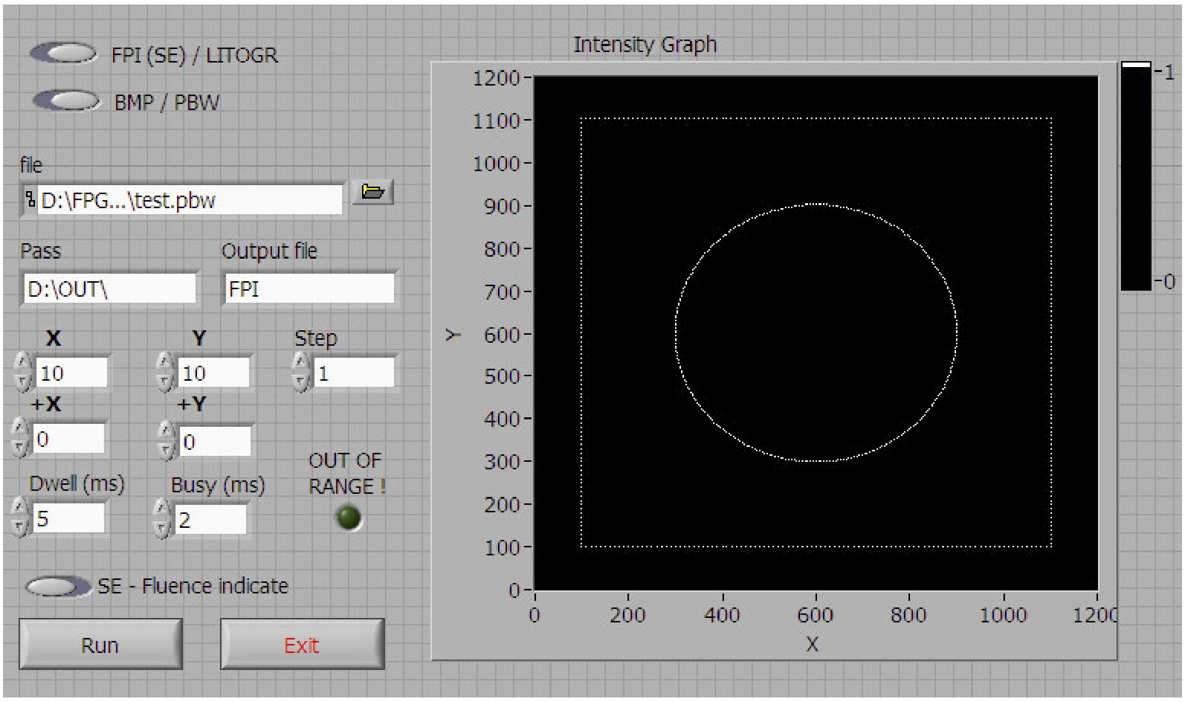

Figure 5. Appearance of the HOST program control panel.

BMP/PBW – allows with two formats of scanning profiles to be worked: directly graphic format *.BMP or functional sequence of coordinates *.PBW.

file – menu for selecting a scan profile file.

Pass, Output file – path and name for the output file of the SE scan.

X, Y, Step – raster sizes and scanning step value.

+X, +Y – scan raster offset.

Dwell, Busy – exposure and transient process time.

OUT_OF_RANGE! – out of coordinates range indicator.

SE-Fluence indicate – switch for displaying counting information sources on the chart.

In addition to the main program, a number of auxiliary programs have been developed to solve the following tasks:

- creating a scanning profile *.PBW from lines and parts of a circle.
- visualization of the scan profile file *.PBW.
- creation and conversion of raster *.BMP files into *.PBW scan profile format.
- converting a raster sequence of pixels into a functional one.

The algorithm for converting a raster sequence of pixels into a functional one is similar to that described in [8], but optimized for images with a high aspect ratio, which consist mainly of monospaced lines.

SCANNING CONTROL SYSTEM CALIBRATION

Functionally, the SCS provides control of the scanner's power supplies by setting the current in the coils or the voltage on the deflecting plates, depending on what type of scanner is used, ferromagnetic or electrostatic. To calibrate the scale of the scanning step and the size of the focused beam, a raster image in the secondary electrons of a calibration copper grid with a grid period of 400 mesh / inch is used (Fig. 6).

Initially, the size of the scanning step is determined based on the number of pixels in one period of the grid. Further, the size of the focused beam at half maximum of the distribution of the beam current density, which is proportional to the yield of secondary electrons, is determined from the size of the scanning step. In this case, the function of the exit of secondary electrons in the direction of *X* or *Y* coordinates in the form is used.

$$T_{\nu}(\nu_0, \lambda, \tau, \gamma, f_{\nu}, a_{\nu}) = \frac{\lambda}{2}\left[1 + Erf\left(\frac{2\sqrt{\ln 2}}{f_{\nu}}(a_{\nu} - \nu_0)\right)\right] + \\ + \frac{\tau}{f_{\nu}}\sqrt{\frac{\ln 2}{\pi}}\exp\left[-\frac{\ln 16}{f_{\nu}^2}(a_{\nu} - \nu_0)^2\right] + \gamma, \qquad (1)$$

where λ – parameter describing the intensity of the output of secondary electrons from the grid surface perpendicular to the beam axis;

τ – parameter describing the intensity of the output of secondary electrons from the inner surface of the grid cells;

γ – the output of secondary electrons in the cavities of the grid, if the grid itself is located on the substrate;

Erf(*z*) – error function,

f_{ν} - the size of the beam in the direction of the coordinate ν = (*X*, *Y*), which is determined by the full width at half maximum (FWHM) of the current density distribution of the focused beam,

a_{ν}, ν_0 – determine the position of the beam.

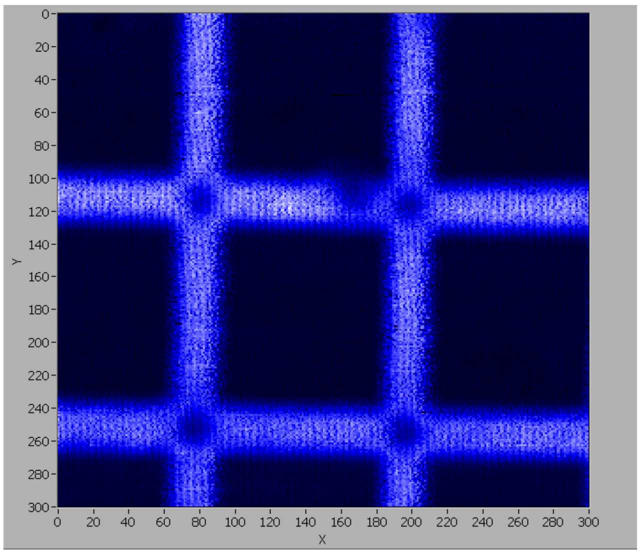

Figure 6. Secondary electron image of a copper calibration grid (scale in pixels).

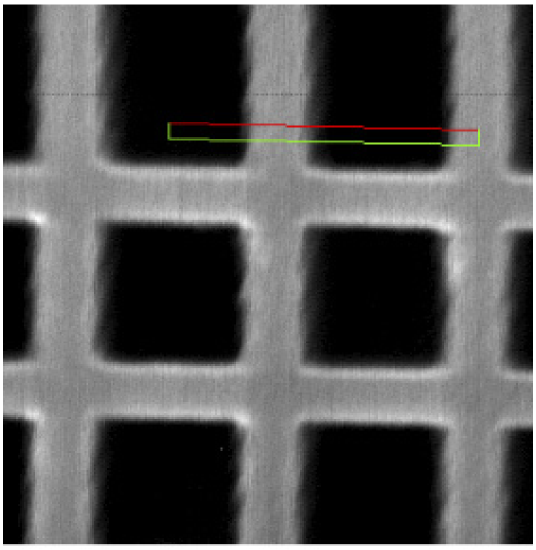

Figure 7. Selection of ten lines for processing experimental data for copper grid with 1000 mesh/inch period

Mathematical fitting of function (1) for the experimental data of the scanning line in the *X*, *Y* direction is carried out using the nonlinear Levenberg - Marquardt method. The initial data is taken on the grid image along the lines, the angle of inclination of which corresponds to the angle of inclination of the grid. Measurement along each axis uses ten parallel, side-by-side lines of equal length. The intensity values for each point are averaged (the arithmetic mean over the points of the same serial number in 10 lines). The line selection location is set manually in the graphical interface, as shown in Fig. 7.

Measurement results (shape and size of the beam) are displayed immediately after measurement. The division value (micron per pixel) is also calculated. This data is necessary to determine the geometry and dimensions of images obtained by lithography.

SCANNING CONTROL SYSTEM TESTING

The SCS testing was carried out in the proton-beam writing mode on samples where plates with a surface roughness of 50 nm and a layer of PMMA positive resist with a layer thickness of about 5 μm were used as a substrate. The samples were irradiated according to the specified templates. After processing the irradiated areas, images in secondary electrons were obtained using a scanning electron microscope, which are shown in Fig. 8. Bright artifacts visible in the images are due to poor-quality deposition of a metal coating, which is necessary for electron microscopy of non-conductive samples.

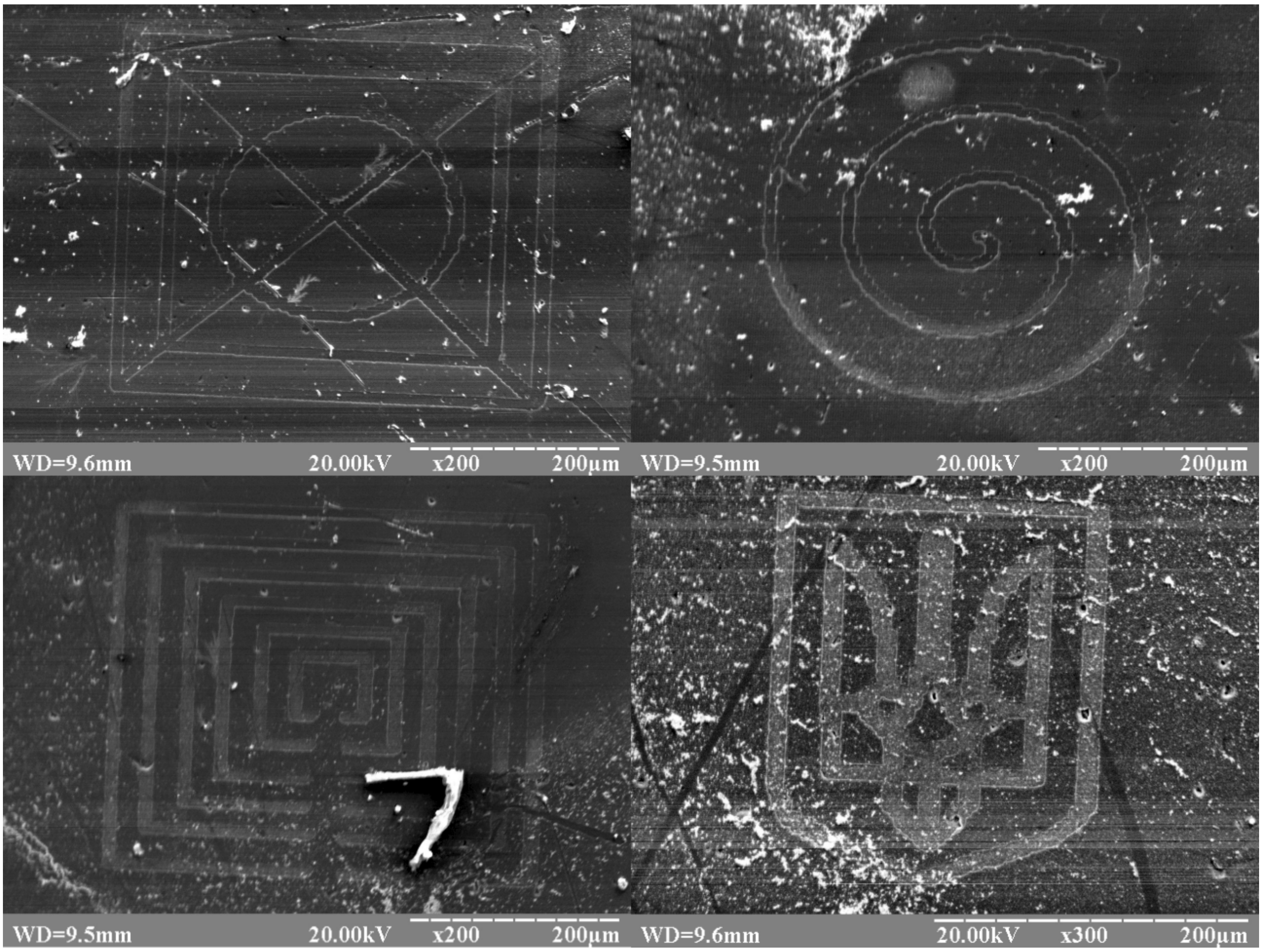

Figure 8. Scanning electron microscopy of test profiles on PMMA.

CONCLUSION

The new scanning control system for the channel of the nuclear scanning microprobe and the channel of proton-beam writing based on the Sokol electrostatic accelerator of the Institute of Applied Physics of the National Academy of Sciences of Ukraine is built on a modern platform and meets all the requirements for efficiently solving the problems of creating three-dimensional microstructures for various fields of engineering and technology, including number of X-ray optics [9, 10]. In the future, it is planned to expand this system with facility for collecting spectrometric information for use as a part of new microprobe [11]. It is also planned to improve the software with the addition of vector proton direct writing lithography.

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СИСТЕМА КЕРУВАННЯ СКАНУВАННЯМ ПУЧКА ДЛЯ ПРОТОННОЇ ПРОМЕНЕВОЇ ЛІТОГРАФІЇ

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Розроблено систему керування скануванням іонного пучку МеВ-них енергій для каналів ядерного скануючого мікрозонду та протонної літографії в складі прискорювально-аналітичного комплексу на базі електростатичного прискорювача “Сокіл” ІПФ НАН України. Систему введено в експлуатацію на заміну застарілій, яка працювала на мікроконтролерах. Систему побудовано на реконфігурованому модулі виробництва National Instruments з програмованою логічною інтегральною схемою (FPGA). Модуль працює в режимі реального часу та з’єднаний з комп’ютером швидодіючим інтерфейсом PCI-Express з буферизацією даних, що передаються. Система забезпечує два основних режими функціонування: експонування ділянок зразку за заданим профілем та отримання растрового зображення зразку або калібрувальної сітки у вторинних електронах. Експонування профілю можливе в режимах растрового та функціонального сканування. Також реалізовано автоматичне калібрування масштабу профілю та растру сканування. Застосування перепрограмованої логіки дає можливість оперативно налаштовувати систему під умови конкретного експерименту та наявне обладнання. Апаратні можливості системи дозволяють в подальшому під’єднати до 4 спектрометричних перетворювачів для отримання картини елементного складу зразків методами характеристичного рентгенівського випромінювання та зворотного розсіювання протонів. Проведені перші експерименти з опромінення поліметилметакрилату, наведено зображення отриманих мікроструктур, зняті на растровому електронному мікроскопі. Метою цієї роботи є розробка системи управління скануванням високоенергетичного сфокусованого пучка в протонно променевої літографії для створення малорозмірних структур спеціального призначення, а також демонстрація ефективності розробленої системи.

Ключові слова: літографія, протонна літографія, система управління скануванням, ядерний мікрозонд