Semiconductor Physics, Quantum Electronics & Optoelectronics, 2025. V. 28, No 1. P. 093-101.

Optoelectronics and optoelectronic devices

Prospects for the creation of the technology of maskless photolithography based on direct laser recording

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Abstract. The principles of formation of micro- and sub-microrelief structures using traditional contact lithography exploiting a phototemplate are compared with the approach of direct laser recording. The disadvantage of conventional contact lithography is the phototemplate damage, which limits the number of patterns that can be recorded using it. The perspective of introducing optical-mechanical systems for the microrelief structure formation based on maskless photolithography is outlined. The general principles of a photolithographic system with a spatial light modulator and direct laser recording are analyzed. The technology of maskless photolithography using established circular laser recording technology is presented. Recording systems in polar coordinates have significant advantages over conventional X-Y systems, the movement of the components of the corresponding optical-mechanical system can be controlled with high precision due to the simplification of rotationally symmetric optics. Further optimization of the maskless photolithography method to form submicron structures includes using a beam with a non-Gaussian intensity distribution. A brief literature review of materials for the successful application of maskless (laser) photolithography is provided.

Keywords: maskless photolithography, photoresist, direct laser recording, circular laser recording station, diffraction optical elements.

https://doi.org/10.15407/spqeo28.01.093
PACS 42.79.Ci, 42.79.-e

Manuscript received 13.11.24; revised version received 15.01.25; accepted for publication 12.03.25;

1. Introduction

Conventional photolithography as a method of forming relief structures on the surface of the substrate includes the production of a photomask (phototemplate) and the use of a special exposure unit to transfer the patterned image from the appropriate template to the substrate with a layer of photoresist. Implementing the mentioned procedure requires high-accuracy matching of the photo template and the substrate with a photoresist layer when forming submicron-sized patterns. The disadvantage of conventional contact lithography is the rapid damage in the phototemplate due to the solid particles trapped in the gap between the template and the substrate. The presence of these particles not only creates local gaps between the substrate and template but also leads to damage to the surface of the template. Therefore, it can be ascertained that the defects on the substrates are caused by violations of the technology of cleaning the glass substrates before applying the chrome layer and imperfection of the vacuum system during the technological operations applying the chrome layer and photoresist, as well as exposing the photoresist layer. Repeated contact exposure of the photoresist leads to gradual degradation of the photopattern caused by the puncture formation. Thus, one of the key problems in forming the microrelief structures by the method of contact lithography is the limited number of photoresist exposures, which corresponds to the limitation of the total number of patterns using the appropriate template.

An alternative method of the photolithography system organization, which shows high efficiency for many applications of creating microrelief structures, is maskless photolithography [1, 2]. This method is based on the most relevant, highly accurate and extremely flexible optical recording technology, which is widely used in research and production, where the requirement is the rapid creation of structures with the minimum size of constituent elements close to 1 μm. The technique of maskless photolithography allows you to shorten the long process of making a photo template and to transfer the lithographic pattern directly to the substrate with a photoresist. In maskless photolithography, the pattern is formed by exposing a layer of photoresist on the surface of the substrate to modulated laser radiation using a spatial light modulator acting as a "dynamic photo-pattern". This allows you to rapidly create the necessary patterns on the surface of substrates with photoresist in a short time compared to contact lithography, which includes the use of phototemplates. The general scheme of the maskless photolithographic system is shown in Fig. 1 [3]. It is characteristic that the capabilities of the corresponding optical-mechanical system are determined mainly by the characteristics of the spatial light modulator. To ensure the high-speed recording of microrelief images, it was suggested to project the pattern directly onto the surface of the photoresist substrate using a high-resolution projector.

Nowadays, a maskless lithography system, with a projector pattern of 1920×1080, a brightness of 3500 lumens and a contrast ratio of 1:13000 focused using an optical microscope on an area of 8×6 mm^2 was implemented. At the same time, the minimum pixel size in the exposure plane reaches 5.5 μm [4]. However, as mentioned above, for many applications, high-speed formation of microrelief structures should have a high resolution, which is not provided by this approach.

For a long time, contour-beam photolithography was also considered as a low-productivity method, which led to limitations in its application, despite the high speed of the microstructure formation [5]. Nevertheless, the creation of technology for manufacturing powerful small-sized lasers in the UV range and high-speed laser scanning systems allows the effective use of the mentioned approach, where direct laser recording turned into a promising technology of maskless photolithography [6–8]. One of the unique features of maskless photolithography based on direct laser recording is that a program for scanning laser radiation replaces the phototemplate. Compared to other methods of maskless photolithography, direct laser recording allows for high resolution. Fig. 2 shows a general diagram of the process of manufacturing microstructures using direct laser recording.

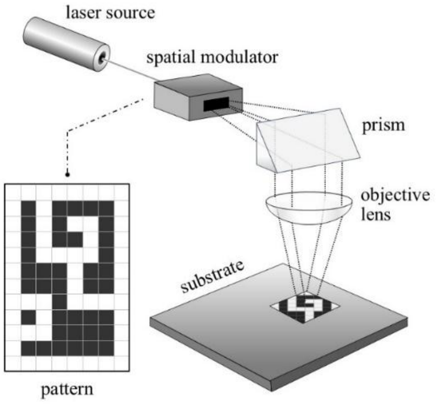


Fig. 1. A schematic view of a photolithographic system with a spatial light modulator [3].

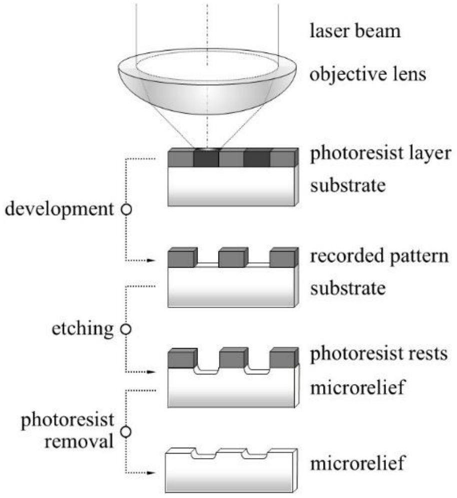


Fig. 2. General diagram of the process of manufacturing microstructures using direct laser recording.

Thus, the technology of maskless photolithography can be considered competitive only under the conditions of ensuring high resolution and speed of recording structures on substrates with photoresist. At the same time, in the field of maskless photolithography, it is possible to distinguish several technologies with advantages determined by the task, namely interference lithography (IL), dynamic mask lithography (DML), and stereolithography (SL). It is worth noting that while IL and DML are parallel processes, SL is essentially a sequential process. However, a separate type of SL called projection stereolithography (PSL) combines SL and DML, which increases fabrication productivity [9].

2. Maskless photolithography using circular laser recording stations

In the technology of maskless photolithography with direct laser recording, the choice of the scheme for scanning the surface of the photoresist with a laser beam is of great importance. The first samples of diffractive optical elements (DOE) were produced using a laser generator of X-Y images in the Cartesian coordinate system [7]. However, these systems have a low exposure speed and some other limitations. The exposure system in the polar coordinates has greater opportunities for creating microrelief structures using direct laser recording. In addition, there are certain types of DOE, where the optimal approach is image generation in polar geometry. Recording systems in polar coordinates have significant advantages over conventional X-Y systems. Their axes are completely independent. In this case, the movement of the components of the optical-mechanical system can be controlled with high precision owing to the simplification of rotationally symmetrical optics. At the same time, the specified approach allows for high scanning speed, which is especially important for large, high-resolution patterns created based on software algorithms. It is mentioned that in some cases, polar coordinate pattern generators provide the only possible approach to DOE manufacturing with the required accuracy. Choosing a manufacturing method should account the DOE specification. Examples include optical focusing systems, wavefront correctors, non-diffracting beam generators, and general-purpose limbs. Patterns with circular symmetry are optimally produced using equipment with circular symmetry. When recording the corresponding patterns, the rotation of the substrate provides circular motion, and the recording head provides radial motion. Circular laser optical recording systems are the most efficient and modifiable tool for DOE synthesis. They are based on local exposure of the substrate with a layer of recording material by its continuous rotation and stepwise movement of the focused laser beam along the radius. The pattern arrays are generated by precisely moving the substrate under a focused scanning laser beam with a defined wavelength. These systems can be used to manufacture photo-lithographic masks or for direct processing of material on flat substrates. It is worth noting that in addition to microlithographic applications, the optical system and the motion control system of the image generator substrate can also be used for surface inspection during diagnostic control. Therefore, one opto-mechanical system can be used to make a template and to check the results at different stages of production. Thus, the proposed technology is universal for solving several applied problems in the creation of focusing optical elements and code discs of wide purpose.

One of the first DOE laser recording systems was reported in Ref. [10]. A modern system of direct laser recording, based on the mentioned approach, which allows parallel recording of microstructure elements, is presented in [11]. To manufacture ring diffraction elements, laser recording stations were used, which allow the manufacture of microrelief structures of complex shapes [12, 13]. Circular laser recording stations, after appropriate modernization, allow forming more complex microrelief structures using direct laser recording owing to the modification of the optical-mechanical scheme.

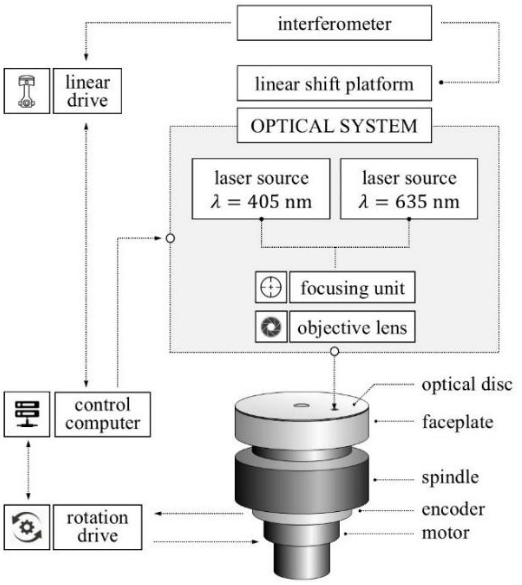


Fig. 3. Functional scheme of the system of radial optical structures formation using direct laser recording.

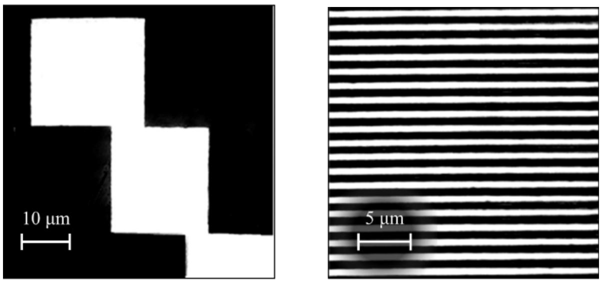
Fig. 3 presents a functional diagram of the system for forming radial optical structures by the method of direct laser recording. To eliminate unwanted mechanical vibrations, the opto-mechanical unit is placed on a granite slab equipped with specially designed supports.

To improve the accuracy of measurement of the coordinate of the platform of linear movement of the positioner, a control scheme for the linear drive of the positioner was developed based on a laser digital interference range finder with absolute coordinate reading and high resolution. The processing of interference signals for controlling the linear motor of the positioner is performed at the software level [14].

3. Methodology for evaluating the resolution of maskless photolithography systems

The resolution of the formed radial optical structures on the substrate using direct laser recording is estimated with an account of two parameters. Along the *y*-axis, the specified indicator is determined by the positioner movement step, and on the *x*-axis – by the number of sector labels of the angular reference encoder. When moving away from the center of rotation of the substrate with an increase in the radial distance, the linear speed of scanning increases, which leads to a decrease in the exposure time of the photoresist on the substrate. To compensate for this effect, it is necessary to reduce the angular speed of rotation of the spindle as the radial coordinate increases so that the linear speed of rotation is constant according to the expression: $f(t) = V_{\text{const}}/(2\pi \cdot R(t))$, where V is a constant linear speed, f is the rotation frequency, R is the current recording radius. Fig. 4 presents images of radial optical structures recorded on a circular laser recording system using direct laser recording. The data preparation system allows recording not only strokes (Fig. 4b), which simplifies the image formation algorithm, but also small-sized elements of an arbitrary shape (Fig. 4a). One of the directions of the development of direct laser recording technology is to increase the spatial resolution in the production of submicron structures.

The technology of direct laser recording for high-aperture DOEs is based on the formation of submicron structures. The spatial resolution of direct recording systems is limited, as a rule, by the diffraction limit of the recording focusing beam, as well as by the features of the optical channel of the lithographic system. To increase the spatial resolution of photosensitive materials with a threshold exposure characteristic for DOE recording, it is important to choose the optimal form of the intensity distribution of the recording beam. In this case, a promising solution is to use a beam with a non-Gaussian intensity distribution, which is characterized by a pronounced central peak and less pronounced side shoulders. Since the recording is carried out only when



(a) (b)

Fig. 4. Images of radial optical structures recorded on a circular laser recording system by the method of direct laser recording: a) the size of the structure element is 20×20 μm; b) angular scale bars with a period of 1.5 μm.

the threshold power is reached, the lateral maxima of the focused light on the surface of the photosensitive material practically do not affect the recording process. A particular case of a non-Gaussian beam can be a beam with an intensity distribution according to the zero-order Bessel function. This topic was discussed in some recent works [15–18]. The use of a non-Gaussian beam to record image elements on photosensitive material with a non-linear (threshold) characteristic allows for reducing geometric dimensions by approximately 40%. To implement the recording mode with increased resolution, it is necessary to ensure strict control of the recording energy values calculated using a mathematical model. The appropriate recording mode can be implemented with strict control of the power of the recording laser and accurate operation of the automatic focusing system of the laser radiation. Thus, special attention should be paid to the creation of laser power stabilization systems, which is the basis of a high-precision automatic laser generation system for DOE recording. A detailed analysis of the methods of increasing the resolution is presented early in our work [19]. The resolution of the maskless direct laser recording system is significantly influenced by the mode of selective etching of the positive photoresist.

4. Examples of application of direct (maskless) optical lithography to various materials

One of the most frequently used materials in maskless laser lithography is carbon and carbon-based ones [20]. Many different devices have been fabricated by patterning the graphene epitaxially grown on some semi-insulating substrates. In Ref. [21] magnetoresistance devices with a strip pattern geometry were fabricated on SiC substrate. Flexible plasmonic graphene oxide heterostructures for dual-channel detection have been proposed for electrochemical and plasmonic nanostructure-based surface-enhanced Raman spectroscopy (SERS) [22]. The interference lithography exploiting two crossed linear patterns of light formed by the same laser has been used to fabricate laterally ordered nanostructures for SERS, surface plasmon resonance-based sensors, and many other applications [23–26].

The feasibility of a combination of laser annealing of α-Si thin films, laser activation of doping ions, and mask-assisted local laser annealing of photonic devices was validated for amorphous/polycrystalline silicon hybrid photonics on CMOS (complementary metal-oxide semiconductor) in Ref. [27]. Controllable modification of the surface properties of other semiconductors has also been demonstrated [28].

A lithography-free method to fabricate VO_2 devices, where the VO_2 region synthesis, isolation, and contact formation are all made in continuity using direct laser writing (DLW) on vanadium (V) thin films [29]. This approach is considered as a promising alternative to conventional VO_2 device fabrication technology, which involves VO_2 deposition, lithography for film patterning/etching, and contact formation, and is complex, time-consuming, costly, and requires harmful chemicals.

In Ref. [30], an ultrafast (a few seconds) method of synthesizing micrometer-sized areas of VO_2 under ambient conditions using laser direct writing on a V_5S_8 "canvas" was proposed. The successful synthesis of VO_2 under ambient conditions was attributed to the ultrafast local heating and cooling process. A Mott memristor based on a V_5S_8–VO_2–V_5S_8 lateral heterostructure was fabricated and integrated with a MoS_2 channel, delivering a transistor with abrupt switching transfer characteristics. The other device with a VS_xO_y channel exhibits a large negative temperature coefficient of approximately 4.5%/K, which is highly desirable for microbolometers [31].

Comparison of conventional and maskless lithographic techniques for many post-processing of CMOS chips shows that in many cases using chip-based processing through the multi-project wafer route that is frequently employed in research, early-stage development and low-volume production has its applicability for large-scale production lines. This review identifies that spray-based photoresist deposition combined with optical maskless lithography demonstrates sufficient performance combined with low cost and operational convenience to offer an attractive alternative to conventional optical lithography, where the spin-coated photoresist is exposed through a patterned photomask [32].

Fabrication of micro-optic elements with arbitrary surface profiles is possible with one-step maskless grayscale lithography (Fig. 5) [33, 34]. However, not only the relationship between the grayscale levels of the digital micro-mirror device (DMD) and the exposure dose on the photoresist, but also the dependence of the exposure depth on the exposure dose results in numerous errors within the complicated fabrication process.

Therefore, further intense research is aimed at finding a way of compensating the two nonlinear effects and ensuring precise control of the surface profile of the structure to be fabricated [35]. Maskless lithography has been used for the versatile and low-cost fabrication of various polymer-based micro-optical structures [35].

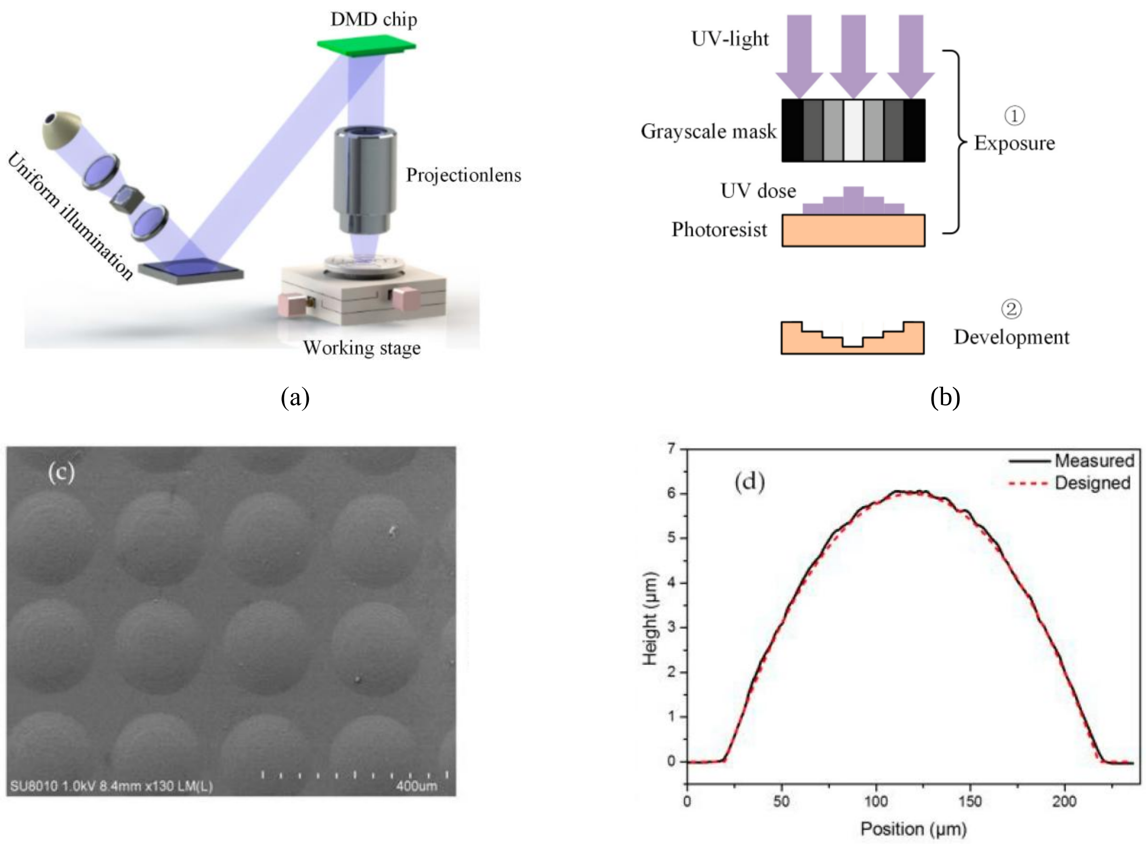


Fig. 5. (a) Schematic view of the digital micro-mirror-based maskless photolithography system; (b) the fabrication procedure based on grayscale mask exposure; (c) SEM image of a convex spherical MLA in polydimethylsiloxane (PDMS); and (d) the measured and designed cross-sections of the convex spherical MLA [33].

Although semiconductor quantum dots (QDs) or nanocrystals (NCs) have been intensively studied for decades due to their unique optical and electronic properties, solution processibility and printing compatibility [36], the creation of QD-based devices is still hindered by poor electrical charge transport between QDs, particularly in the QD film [37], and non-compatibility with traditional lithographic processes.

Direct optical patterning is considered as a promising tool for modifying QD film properties, patterning it into pixels and encapsulation for display application [38, 39]. The research is focused on engineering the surface stabilizer (ligand molecules) with account that illuminating it with laser light converts them into different molecules, which can quench the QD photoluminescence, change the local conductivity or other properties of the QD film [40, 41]. Due to the spectrally selective absorption of light by different materials, lithographic processing can be performed not only on the top layer of certain multilayer structures but on underlying layers, without affecting the upper one(s) [42].

More powerful devices, known as laser scribers, are used for the precise processing of solar cells and other thin film devices. Laser irradiation provides a cleaner and more accurate pattern with less debris formation, compared to mechanical scribing [43]. However, laser scribing is a rather complex thermomechanical technique and still requires a better understanding of melting, evaporation, and plasma formation mechanisms to optimize the process for various materials.

Standard photolithography, popular for the fabrication of two-dimensional structures, is based on one-photon absorption in a photo-sensitive medium. Two-photon lithography (TPL) is a unique microfabrication technique exploiting the nonlinear dependence of the polymerization rate on the intensity of irradiating light to produce true 3D structures with feature sizes beyond the diffraction limit [44].

5. Conclusions

An analysis of the peculiarities of the application of optical-mechanical systems to form microrelief structures based on maskless photolithography was carried out. The following methodological recommendations were ascertained:

1. The basis of an effective system of maskless photolithography is the use of direct laser recording of microrelief structures on a substrate with a photoresist. The advantage of this approach is the replacement of the phototemplate with a software algorithm for controlling the laser recording system, which allows an increasing in the speed and simplifies the photolithography procedure.

2. To fabricate a wide class of diffractive optical elements, modernized stations for laser recording of original discs can be used, namely a system for forming radial optical structures by direct laser recording.

3. The high-resolution micro-images formed by direct laser recording are ensured by using high-aperture micro-lenses to focus the exposing radiation and carefully select the photoresist etching modes.

4. An algorithm to reduce the angular speed of the spindle rotation with an increase in the radial coordinate is proposed to compensate for the growth of the linear scanning speed when the recording area is moved away from the center of substrate rotation.

It is shown that the optical-mechanical system of direct laser recording allows recording elements of arbitrary shape up to 1.5 μm with the possibility of increasing the resolution due to using a beam with a non-Gaussian intensity distribution.

The given brief review indicates the significant potential for the manufacture of laboratory samples and small-scale production by applying maskless (laser) photolithography to form the elements of individual devices and microcircuits.

Acknowledgment

The work was financially supported by National Research foundation, grant # 2023.04/0004 for A.A.K., V.V.P., I.V.K., S.M.S., Ie.V.B. and grant # 2023.05/0022 for M.S.B., V.V.S., K.V.S., O.M.K., A.A.K., V.M.D.

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Перспективи створення технології безмаскової фотолітографії на основі прямого лазерного запису

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Анотація. Проведено порівняння принципів формування мікро- та субмікрорельєфних структур традиційною контактною літографією з використанням фотошаблона і при застосуванні прямого лазерного запису. Недоліком традиційної контактної літографії є пошкодження фотошаблона, що обмежує загальну кількість візерунків, які можна записати за його допомогою. Окреслено перспективу впровадження оптико-механічних систем формування мікрорельєфних структур на основі безмаскової фотолітографії. Проаналізовано загальні принципи роботи фотолітографічної системи з просторовим модулятором світла та прямим лазерним записом. Представлено технологію безмаскової фотолітографії з використанням усталеної технології кругового лазерного запису, яка базується на полярних координатах, а тому має значні переваги перед традиційними системами на основі декартових координат, оскільки рухом компонентів відповідної оптико-механічної системи можна керувати з високою точністю внаслідок спрощення ротаційно-симетричної оптики. Подальша оптимізація методу безмаскової фотолітографії, з метою формування субмікронних структур, передбачає використання пучка з негауссовим розподілом інтенсивності. Наведено короткий огляд літератури щодо матеріалів, для яких продемонстроване успішне застосування безмаскової (лазерної) фотолітографії.

Ключові слова: безмаскова фотолітографія, фоторезист, прямий лазерний запис, кругова лазерна записуюча станція, дифракційні оптичні елементи.