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Vasyl Stefanyk Precarpathian National University

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D.Yu. Manko, Ie.V. Beliak, O.M. Butok, Yu.I. Chehil, A.V. Pankratova, A.A. Kryuchyn

Analysis of methods for detecting opaque defects on the surface of modulation disks (review)

Institute for information recording, NAS of Ukraine, Kyiv, Ukraine, dmitriy.manko@gmail.com

The study explores modulation disks as high-precision optical sensors for measuring angular positions and rotational velocities, crucial for industrial and military use. Laser ablation is employed to refine microstructure formation, ensuring precise etching, defect elimination, and chromium residue removal. A classification of opaque defects on disk substrates identifies key causes and mitigation challenges, including risks of damaging adjacent structures during ablation. A mathematical model based on the heat conduction equation in cylindrical coordinates describes defect behavior under laser irradiation, optimizing ablation depth and minimizing thermal damage. Numerical simulations reveal thermal behavior, temperature distribution, and material removal dynamics, guiding laser parameter optimization. Experiments using a pulsed nitrogen laser (337.1 nm, 20 ns pulse) demonstrated selective chromium defect removal (5–50 μm) with minimal substrate damage. Non-metallic contaminants remained unaffected, confirming method selectivity. Microimages of the sample surface revealed the successful elimination of chromium residues and thin residual metal films under optimal laser conditions.

Keywords: modulation disks, opaque defects removal, laser ablation, heat conduction model.

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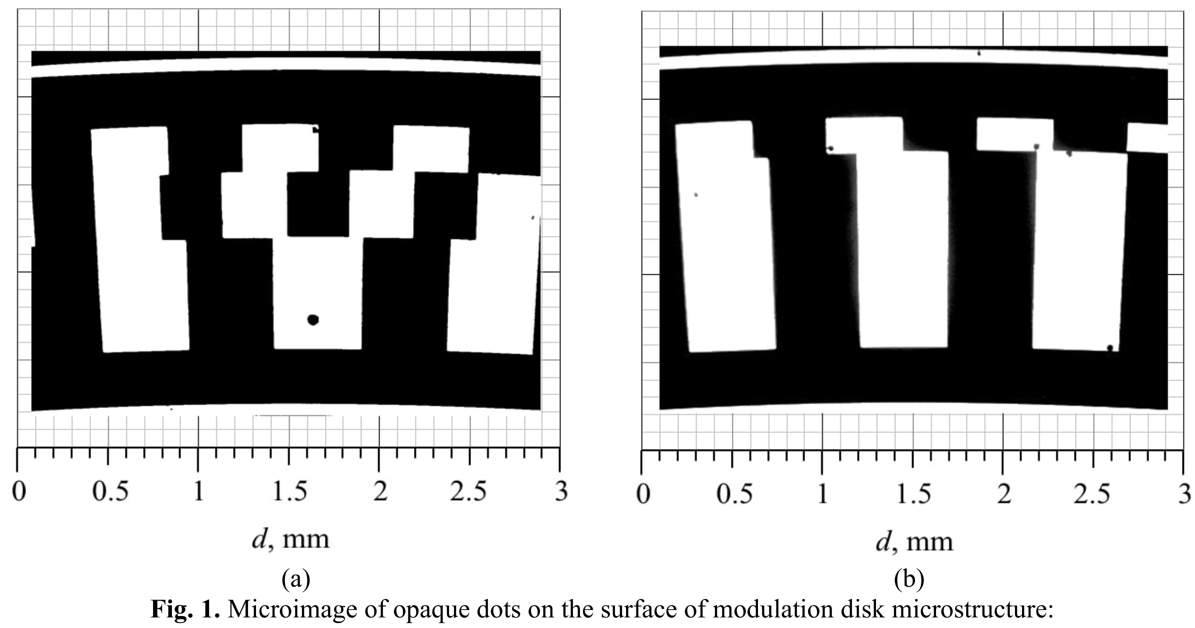
Content

Introduction

Modulation disks, recognized as precision optical sensors for measuring angular positions and rotational velocities, are extensively utilized in diverse industrial applications. These encompass automated manufacturing systems [1-5], such as computer numerical control (CNC) systems, high-speed communication systems and motion control frameworks, including aviation and navigation systems. Of particular significance are their applications in military-grade drones, where the accurate determination of position and orientation is critical for maintaining flight stability and executing high-precision maneuvers [5]. The fabrication of modulation disks imposes stringent technological requirements, as the quality of the optical recording system, precision in pattern inscription, and robustness of the disk surface directly influence the operational reliability of the sensors [6]. A notable concern involves defects that may arise during manufacturing, including inaccuracies in the deposition of optical patterns and inconsistencies in surface integrity. One critical requirement for modulation disks is the absence of opaque dots or streaks in the transparent zones of the working area following chemical processing. Such defects typically result from selective etching of chromium through windows in the photoresist layer, leaving fragments of the chromium film on the substrate surface.

The size of these chromium residues can vary significantly, ranging from 1 to 50 µm. The presence of these defects adversely affects the optical and functional characteristics of the modulation disks, underscoring the necessity for precise control over the etching process. To address this challenge, it is essential to refine the etching technology for chromium films and implement subsequent substrate processing methods that ensure the complete removal of chromium residues from the working area. Furthermore, advanced techniques for detecting and removing such defects must be developed, accompanied by innovative approaches to eliminate opaque imperfections effectively. A representative chromium microstructure with an opaque dot on the substrate surface is depicted in Fig. 1. The figure illustrates two samples, "1A" and "1B", both exhibiting defects of varying sizes. This visual evidence emphasizes that the size, position relative to the informational structure elements, and the density of such defects are critical factors determining the modulation disk's performance and operational efficiency. Addressing the challenge of opaque defects on the surface of modulation disks requires the adoption of cutting-edge technologies, with laser ablation emerging as a *leading solution*. This method, particularly with the use of femtosecond and nanosecond lasers, offers exceptional precision and efficiency in surface modification. The interaction of laser energy with materials enables controlled changes in surface morphology, which are critical for achieving the high-quality standards demanded by advanced optical devices. Given the necessity of meeting these stringent requirements, research into laser ablation has become highly relevant, positioning this approach as a key enabler of innovative solutions in the production of modulation disks.

Analysis of scientific research dedicated to the issues of implementing laser ablation procedure for surface modification highlights its significant potential in addressing opaque defects on modulation disks. Femtosecond laser ablation, characterized by its short pulse duration and high peak power, facilitates a nonlinear absorption process in dielectric materials, enabling the excitation of electrons from the valence band to the conduction band. This results in efficient material removal with minimal thermal damage [7]. The ability to control the energy deposition at such short timescales allows for precise ablation of defects without adversely affecting the surrounding material. This characteristic is particularly advantageous when dealing with opaque defects, minimizing the risk of collateral damage often associated with longer pulse durations [8]. Research has also shown that the effectiveness of laser ablation in defect removal is influenced by the initial surface conditions. The defect model suggests that defects can trap laser light, leading to localized heating, which enhances the ablation efficiency [9]. This effect is particularly relevant for modulation disks, where the presence of defects can significantly alter the interaction of laser energy with the material, potentially causing uneven ablation and compromised surface quality. Furthermore, optimizing laser parameters such as pulse energy, repetition rate, and scanning speed is crucial for achieving the desired outcomes in the ablation process. Studies indicate that fine-tuning these parameters can improve surface roughness and reduce defect density [10]. For instance, increasing pulse energy while maintaining an appropriate scanning speed can accelerate the ablation process, making the removal of defects more efficient [11]. Such optimization is vital for obtaining the high-quality surfaces necessary for performance-critical applications. Hybrid laser ablation techniques, including laser-induced plasma-assisted ablation (LIPAA), have also been explored to improve the efficiency of the process. By utilizing surface-adherent absorbing layers, these methods enhance laser energy absorption, leading to more effective material removal [12]. This approach not only improves ablation efficiency but also offers greater control over surface morphology, which is crucial for applications where surface texture is a



(a) (b)

Fig. 1. Microimage of opaque dots on the surface of modulation disk microstructure: (a) sample "1A"; (b) sample "1B".

key factor in performance. The post-ablation treatment of surfaces plays a crucial role in modifying the final properties of modulation disks. Techniques like hydrothermal treatment can be employed after laser ablation to alter surface structures and enhance properties such as anti-icing capabilities [13]. This dual approach (laser ablation followed by surface treatments) helps achieve surfaces with reduced defect density and improved functional properties. In addition to defect removal, the broader applications of laser ablation in surface engineering are evident while laser ablation procedure can create hierarchical nanostructures that modify wettability and adhesion properties [14]. These findings underscore the versatility of laser ablation, positioning it not only as a method for defect removal but also as a powerful tool for enhancing surface functionalities.

The general research presented faces *unresolved issues* related to the high complexity and cost of the laser ablation systems, as well as the lack of integration between heterogeneous studies. The systems often operate in isolated frameworks without a unified methodology, which hinders the development of practical applications, especially in fields requiring precision and efficiency. *The goal of this work* is to develop a comprehensive methodology that integrates mathematical modeling with experimental studies of laser ablation and microstructure formation in modulation disks. By creating a holistic framework that links modeling and experimentation, this research will provide solutions for optimizing the surface characteristics of modulation disks, ultimately leading to more efficient, high-performance systems.

I. Prospective technologies for defect removal on substrates of modulation disks

As mentioned above, defect removal on substrates of modulation disks is a critical step to ensure high performance and reliability. The choice of appropriate defect removal technology plays a crucial role in maintaining the integrity of the optoelectronic device's functionality and its long-term performance. In this regard, it is important to build a comprehensive methodology for defect removal that accounts for the nature of the defects, the materials involved, and the specific requirements of the device. Given the wide range of possible defect types the classification of defects is of paramount importance when selecting the most suitable removal technique. An accurate classification ensures that each method is applied to the defects for which it is most effective, thereby optimizing the efficiency and precision of the overall defect removal process. Prospective technologies for this purpose include a variety of advanced methods, each designed to address specific types of defects and materials with precision and efficiency (Fig. 2):

- laser ablation techniques;
- plasma etching techniques;
- chemical-mechanical polishing techniques;
- ultrasonic cleaning techniques;
- advanced wet etching techniques;
- inspection and metrology methods.

Laser ablation method [7-14] stands out for its precision and non-contact nature, making it particularly advantageous in defect removal processes. By utilizing focused laser beams, laser ablation vaporizes defect material with minimal heat transfer to the substrate, thus avoiding potential damage to the underlying structure. This technique is especially effective for addressing small, localized defects, such as opaque particles or streaks, which may otherwise be difficult to remove using traditional mechanical methods. Additionally, laser ablation offers a high degree of control over the depth and area of material removal, enabling fine-tuned defect management and ensuring the preservation of the substrate's integrity. Plasma etching [15] is a highly controlled process in which ionized gas is used to selectively remove material from the substrate's surface. This method is characterized by its precision, ensuring a uniform etching process with minimal damage to the underlying material. The versatility of plasma etching allows for the removal of a wide range of defects, while its low-temperature operation prevents thermal damage, making it suitable for sensitive materials. Chemical-mechanical polishing [16] combines chemical etching and mechanical abrasion to effectively smooth and clean the substrate surface. This technique is particularly efficient in eliminating both superficial scratches and embedded defects, as the chemical etching works to remove contaminants, while the mechanical polishing ensures a uniform, smooth finish.

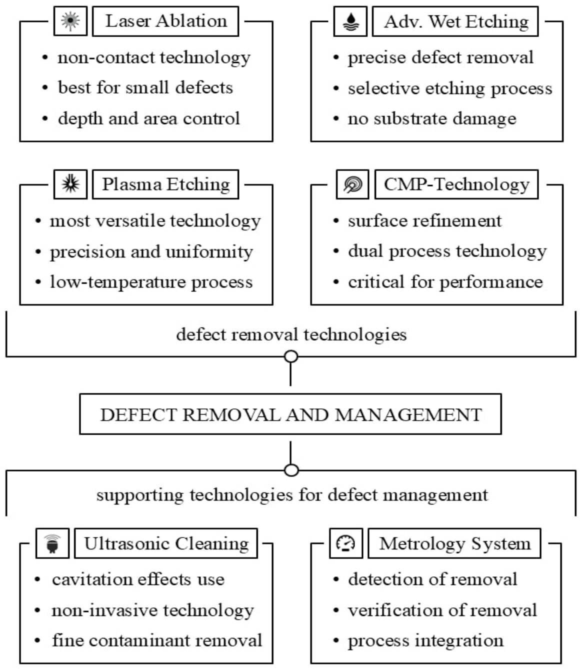


Fig. 2. Classification of defect removal and management technologies.

By balancing these two processes, CMP achieves a high level of surface refinement that is critical for the performance of optoelectronic devices. Ultrasonic cleaning technique [17] leverages high-frequency sound waves in a liquid medium to dislodge and remove particles and residues from the substrate surface. The cavitation effects generated by the sound waves create microbubbles that, upon collapsing, generate localized high-pressure forces, effectively cleaning the surface without causing mechanical damage. Ultrasonic cleaning is highly effective in removing fine contaminants and residues that might otherwise be difficult to eliminate using conventional methods. Advanced wet etching techniques [18] utilize improved formulations and highly controlled processing conditions to achieve thorough removal of unwanted materials, such as residual chromium films. These techniques ensure that defects are removed with high precision, minimizing the risk of damaging the substrate. The selective etching properties of these processes make them particularly useful in eliminating surface contaminants while preserving the integrity of the underlying material. Finally, inspection and metrology systems [19] play a crucial role in the defect removal process, as they are essential for identifying, analyzing, and verifying the complete elimination of defects from the substrate. High-resolution imaging and advanced metrology tools allow for the detection of even the most subtle defects that might otherwise go unnoticed, ensuring that the defect removal process meets the required standards for performance and reliability. When integrated with defect removal technologies, these systems contribute to the overall effectiveness and precision of the defect management process.

Thereby, laser ablation presents significant advantages in meeting the stringent technical requirements for forming microrelief structures on modulation disks. Its precision and non-contact nature enable the effective removal of small defects, such as opaque particles and streaks, without compromising the substrate's integrity. This makes it an ideal method for ensuring the high performance and reliability of the disks, especially in applications requiring intricate optical patterning. However, to fully exploit the potential of laser ablation, it is essential to develop an adequate mathematical model that can predict and control the material removal process with high accuracy. Furthermore, experimental research is crucial to validate these models and refine the process parameters. Given the complexity of the task, which involves multiple variables and potential sources of error, an experimental investigation will be indispensable in optimizing the laser ablation technique for practical implementation.

II. Analysis of methods for minimizing opaque regions in modulation disk production

The technological process of defect correction has gained significant traction, particularly as the minimum sizes of optical elements continue to decrease. This miniaturization necessitates the precise correction of smaller defects in areas characterized by high element density. Achieving high-quality optical elements requires identifying technical solutions that facilitate the production of modulation disks with minimal defects. Among the primary types of defects opaque defects present the greatest challenge for any specific optical element. These defects, which can range in size from 1 to 50 µm, may appear either as localized anomalies or as distributed imperfections across the surface of the optical element. Furthermore, the presence of opaque defects is often associated with foreign materials, adding an additional layer of complexity to their resolution [20]. The classification of defects on optical elements as hard defects or soft defects has proven to be a highly relevant and practical framework for addressing the challenges associated with defect identification and remediation. Hard defects consist of materials identical to those used in the mask, primarily absorbers, that form the desired pattern on the substrate. Conversely, soft defects – often referred to as foreign contaminants – are composed of materials distinct from those used in the mask. These contaminants typically originate from environmental factors or the fabrication process. Both types of defects can disrupt the intended pattern on the substrate, but their differing nature necessitates distinct approaches for resolution. Soft defects, in particular, require removal through cleaning processes, which may involve more aggressive methods depending on the severity and persistence of the contamination [21]. The occurrence of opaque hard defects on the surface of modulation disks, made of metallic layers, is associated with several factors:

Formation of air bubbles during substrate processing. Air bubbles can form when the substrate is immersed in solutions, such as developers and etchants. These bubbles hinder the uniform access of the solutions to the photoresist or masking layer, leading to incomplete chemical reactions. This issue becomes particularly problematic in high-precision processes, where uniformity is critical for maintaining the integrity of the optical element.

Dust particles on the photoresist-coated substrate. Dust or microscopic debris that settles on the substrate prior to laser exposure can act as a shield, preventing uniform exposure of the photoresist film. This results in incomplete or distorted patterns on the substrate, which may require additional corrective steps or even lead to the rejection of the defective disk. Strict cleanroom protocols are essential to minimize this issue.

Oily contaminants. Fingerprints, smudges, or residues from handling the substrate introduce localized regions of contamination. These contaminants disrupt the adhesion of the photoresist layer or interfere with subsequent chemical processes, leaving defects that are difficult to correct. Preventive measures, such as automated handling systems, are critical to reducing these risks.

Mechanical particles in unfiltered working solutions. Unfiltered solutions used during processing may contain small mechanical particles that inadvertently deposit on the substrate. These particles can create localized areas of metallization or other defects. Regular filtration and quality control of working solutions are necessary to prevent this type of contamination.

During the production of photomasks for modulation disks, opaque defects unrelated to chemical contamination frequently occur. These defects are typically associated with metallized coatings appearing in unintended areas, such as spots, expansions, or bridges between elements of the information structure. Such anomalies disrupt the functionality of the modulation disks and require precise inspection techniques to identify and remove them [22].

Figure 3 presents samples "2A" and "2B" microimages depicting the most common opaque defects encountered during the manufacturing process of modulation disk. These defects include isolated opaque spots, which often appear as small, localized imperfections; opaque lines, typically resulting from unintended material deposition or processing errors; and opaque bridges between chromium lines, which interfere with the intended pattern structure and compromise the functionality of the modulation disk.

Thereby, the manufacturing process of coded disk substrates is prone to various types of opaque defects, which can significantly impact the functionality and quality of the final product. Effective defect mitigation requires addressing contamination sources, improving process controls, and refining manufacturing techniques. However, since the resolution of laser-based defect removal systems is limited, the use of laser ablation for defect removal carries the risk of damaging adjacent lines, underscoring the need for precise control and alternative defect removal strategies to ensure optimal substrate performance.

III. Analysis of the ablation-based defect removal process on photomasks

Laser ablation has emerged as a highly effective and technologically advanced method for eliminating opaque defects formed during the fabrication of modulation disks. By employing lasers, this approach enables the precise and efficient removal of such defects from photomasks through the process of ablation, ensuring the integrity of the light field. Modern advancements in laser ablation techniques have significantly enhanced its efficiency, particularly with the adoption of ultraviolet (UV) lasers. UV lasers are preferred in optical systems for defect removal due to their superior resolution capabilities and the high absorption of chromium in this spectral range, which facilitates precise material removal. For instance, femtosecond pulsed lasers with wavelengths of 206 nm, 337 nm and 357 nm represent one of the most cutting-edge solutions available today [23]. These lasers are particularly suitable for laser ablation owing to their ability to achieve high precision and their compatibility with the requirements of modern optical systems.

The principle of laser ablation involves directing a laser beam onto the defect and eliminating it through short pulses of laser radiation, with pulse durations ranging from tens of nanoseconds to hundreds of femtoseconds. When the power density of the laser pulse is sufficiently high, it raises the temperature of the irradiated surface to or beyond the evaporation threshold T_E under normal atmospheric pressure, accounting for the latent heat of melting L_M and evaporation L_E. This process leads to the vaporization of the thin-film material. Inclusions located at the interface between the substrate and the metal film play a critical role in the laser ablation of thin films. These inclusions serve dual functions: they reduce the adhesion of the thin film, thereby facilitating defect removal. Additionally, rapid laser heating with short pulses induces excessive pressure at the interface, caused by the thermal desorption of gas molecules adsorbed at defect sites. This pressure arises due to the thermal desorption of gas molecules adsorbed at defect sites, further enhancing the efficiency of material removal. For substrates with a lower melting or evaporation temperature, the thermal decomposition of the heated substrate surface can contribute to the generation of high-pressure vapor beneath the thin film. This vapor exerts sufficient force to detach and remove the film. When the temperature of the thin film T_{TF} remains below its melting point T_M, thermal expansion occurs in both the thin film and the substrate. Localized heating and thermal expansion create thermal stresses, which can result in cracking within the thin film or the substrate during or after laser heating. These

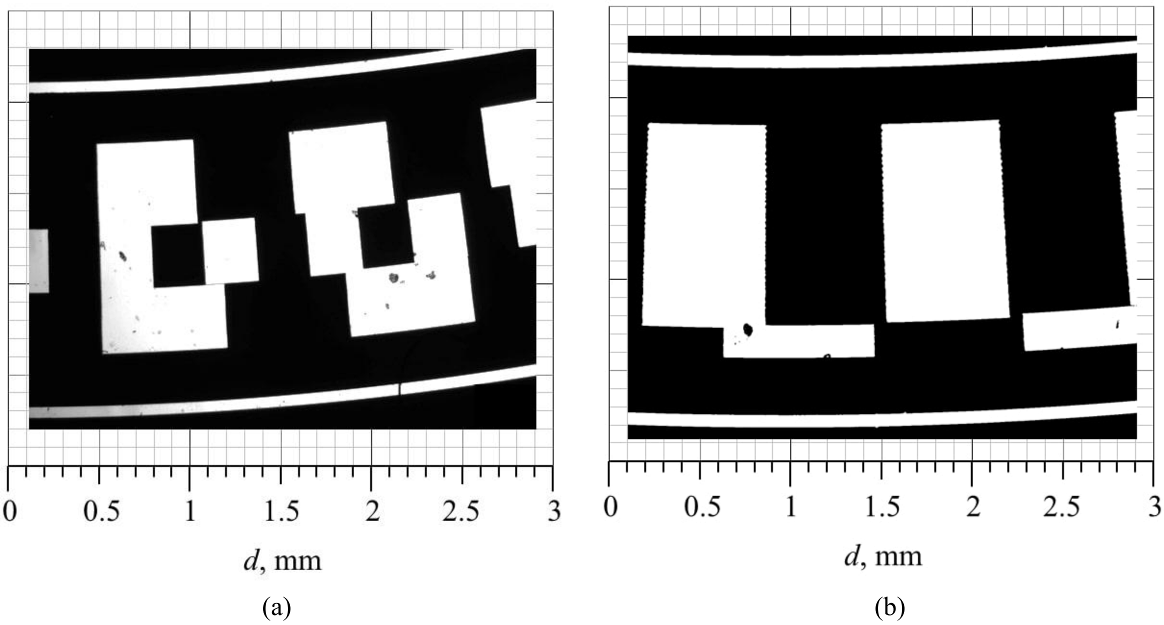


Fig. 3. Microimages of the opaque defects occurring during the fabrication process on modulation disk substrates: (a) sample "2A"; (b) sample "2B".

mechanical stresses may become intense enough to detach a portion of the film or, in some cases, the entire film from the substrate surface. For defects that exceed the diameter of the focused laser beam, the beam must be scanned across the defect to ensure complete removal. Given the random distribution and varying sizes of defects, femtosecond lasers operating in the deep ultraviolet (DUV) range are commonly used for defect removal from photomasks and optical elements. This approach has demonstrated its reliability through consistent success in long-term applications.

During laser ablation for defect removal, a substantial amount of thermal energy is delivered by the laser beam to the substrate covered with the chromium film. This energy not only melts and evaporates the undesired metallic defect but may also cause damage to the substrate material beneath or near the opaque defect, resulting in surface roughness [24]. Experimental studies indicate that exceeding the threshold energy of femtosecond laser pulses during the removal of opaque defects can result in localized damage to the glass substrate surface of the modulation disk as it was shown on Fig. 4. To prevent such damage, it is essential to carefully select processing parameters that minimize the risk of harming the glass substrate surface at the points of pulsed laser radiation impact. Additionally, the process must ensure that residual metal mask material is not scattered across the substrate field. Any such scattering could reduce the transparency of the clear sections of the modulation disk, which is unacceptable for maintaining the optical quality and functionality of the disk.

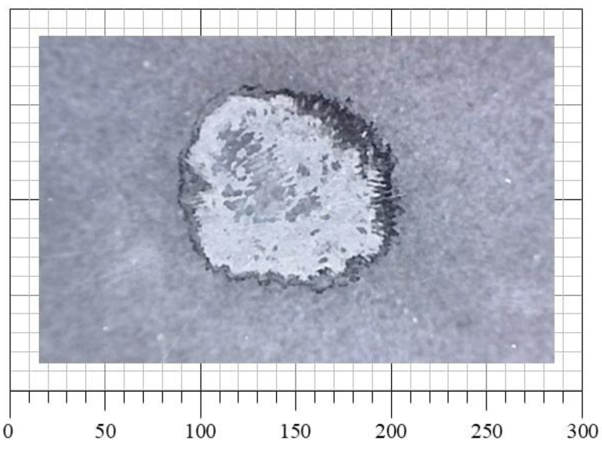


Fig. 4. Microimage of the damage region on the modulation disk substrate surface caused by a focused femtosecond laser pulse.

Nowadays ultrashort laser pulses are widely used for the ablation of metal films to reduce thermal damage to the substrate and enhance resolution in the removal of absorbing defects [25]. Picosecond laser pulses enable the absorption of light energy, followed by localized heating and material removal through evaporation, without significantly affecting the substrate material. This approach minimizes excessive energy accumulation outside the laser irradiation zone, thereby improving precision. Ultrafast laser ablation is particularly effective for minimizing the heat-affected zone across various materials [25]. The use of ultrashort femtosecond pulses in the DUV range has demonstrated exceptional efficiency in the repair of photomasks during mask production. This method allows for the selective removal of defects from the mask surface through cold ablation, ensuring the integrity of the optically transparent substrate remains unaffected [26].

IV. Mathematical modeling of the laser ablation process of opaque metallic defects

Laser ablation is a complex physical process that involves the precise interaction of laser energy with materials, leading to localized heating, phase transitions, and material removal. The mathematical modeling of this process is crucial for understanding and optimizing the removal of opaque metallic defects on modulation disks, where precise control of ablation depth and thermal effects is required. The developed model incorporates heat transfer dynamics, laser energy absorption, phase change phenomena, and stress analysis to describe the behavior of defect materials under laser irradiation. By capturing the interplay between thermal and mechanical effects, this model provides insights into the ablation process, paving the way for enhanced defect mitigation strategies and improved manufacturing precision.

The heat transfer equation plays a central role in modeling the temperature distribution, $T(x, y, z, t)$, within the defect material and substrate during laser irradiation. This equation accounts for the conduction of heat, laser energy absorption, and the time-dependent behavior of the temperature field. It is expressed as:

$$\frac{\partial T}{\partial t} = \frac{\nabla\cdot(k\cdot\nabla T)+Q(x,y,z,t)}{\rho\cdot c_p}, \quad (1)$$

where ρ is density of material, c_p is specific heat capacity, k is thermal conductivity, Q is heat source term representing laser energy absorption. The heat transfer equation is critical for understanding how laser energy propagates through the defect material and its substrate. Accurate solutions to this equation enable the prediction of temperature gradients, which are fundamental for determining the onset of phase changes, material ablation, and potential thermal damage. These insights guide the design of laser parameters for optimal ablation while minimizing unintended effects, such as substrate overheating or cracking.

The heat source term, $Q(x, y, z, t)$, represents the distribution of laser energy absorbed by the defect material during irradiation. This parameter is fundamental for describing how laser energy interacts with the material and contributes to localized heating. The heat source is modeled as:

$$Q(x, y, z, t) = \alpha \cdot I(x, y, t) \cdot e^{-\alpha z}, \quad (2)$$

where α is absorption coefficient, I is laser intensity distribution.

For Gaussian laser beam:

$$I(x,y,t) = \frac{2P}{\pi \cdot r^2} \cdot e^{-2\frac{x^2+y^2}{r^2}}, \quad (3)$$

where P is laser source power, r is beam radius. This Gaussian profile reflects the non-uniform distribution of laser intensity, with the maximum intensity at the beam center and a gradual decrease toward the edges. The combination of equations (2) and (3) provides a precise description of the laser energy absorption process in the material. This model enables the calculation of the spatial and temporal distribution of the absorbed energy, which directly influences the temperature gradients and subsequent ablation dynamics.

Material ablation during laser irradiation occurs when the surface temperature of the defect material reaches or exceeds its evaporation temperature, T_E. At this point, the material undergoes a phase change from solid (or liquid) to vapor, which requires a specific amount of energy. This energy, referred to as the latent heat of evaporation, is given by

$$Q_{PH} = \rho \cdot L_E, \quad (4)$$

where L_E is latent heat of evaporation.

The surface ablation depth δz per laser pulse is estimated as:

$$\delta z = \frac{1}{\rho} \cdot \int_0^{T_{LP}} \frac{Q}{L_E} dt, \quad (5)$$

where T_{LP} is laser pulse duration. This expression integrates the energy input over time to calculate the depth of material removed. The phase change condition is critical for determining the efficiency and precision of the laser ablation process. By controlling parameters such as laser pulse energy, duration, and repetition rate, it is possible to optimize ablation depth while minimizing thermal damage to surrounding areas. This model provides a foundation for predicting the material removal rate and ensuring consistent ablation across the defect surface. It highlights the importance of balancing energy delivery with material properties, such as ρ and L_E, to achieve the desired results.

To accurately model the temperature distribution and energy transfer during laser ablation, appropriate boundary conditions must be defined for the modulation disk and the substrate-defect interface. These conditions account for heat exchange mechanisms, ensuring a realistic representation of the physical processes. At the surface of modulation disk ($z = 0$):

$$-k \cdot \frac{\partial T}{\partial z} = h \cdot (T - T_\infty) + \sigma\epsilon \cdot (T^4 - T_\infty^4), \quad (6)$$

where σ is Stefan-Boltzmann constant ($\sigma = 5.67 \cdot 10^{-8}\ \mathrm{W/m^2K^4}$), h is connective heat transfer coefficient, ϵ is emissivity, T_∞ is ambient temperature.

At the substrate-defect interface:

$$\begin{cases} T_D = T_S \\ k_D \cdot \frac{\partial T}{\partial z} = k_S \cdot \frac{\partial T}{\partial z} \end{cases}, \quad (7)$$

where T_D and k_D are temperature and thermal conductivity of defect region, T_S and k_S are temperature and thermal conductivity of modulation disk surface. The first equation ensures that the temperature remains continuous across the interface, while the second equation enforces the conservation of heat flux, accounting for differences in thermal conductivity between the defect and substrate. By incorporating both convective and radiative effects, as well as continuity conditions, the model captures the complex thermal dynamics involved in laser ablation.

Rapid heating and cooling during laser ablation induce thermal stresses in the material, which can significantly impact the structural integrity of the modulation disk. The thermal stresses are calculated using the following relationship:

$$\sigma = E\alpha_T \cdot (T - T_\infty), \quad (8)$$

where E is Young's modulus, α_T is thermal expansion coefficient. Excessive stress can cause cracking or detachment of the thin film. Understanding the development and consequences of thermal stresses is crucial for predicting the mechanical stability of the modulation disk during laser ablation. By accurately calculating stress levels, the risk of material damage can be minimized, and process parameters such as laser intensity and pulse duration can be optimized to ensure controlled ablation.

The theoretical framework outlined above provides the foundation for understanding the thermal and mechanical dynamics of laser ablation. However, the efficiency and precision of the process are also highly influenced by the temporal characteristics of the laser pulses used. Different pulse durations (nanosecond, picosecond, and femtosecond pulses) significantly alter the interaction mechanisms, heat diffusion, and the extent of material damage. Nanosecond pulses lead to significant heat diffusion, resulting in a large heat-affected zone and thermal evaporation as the dominant ablation mechanism. The threshold fluence for ablation in this regime is relatively high, typically ranging from 1 to 10 J/cm². In contrast, picosecond pulses exhibit more localized heat diffusion, with ablation occurring through a combination of thermal evaporation and photomechanical effects. The damage zone in this case is minimal, and the threshold fluence falls within the moderate range of 0.1 to 1 J/cm². Femtosecond pulses, on the other hand, minimize heat diffusion almost entirely, leading to a predominantly photomechanical ablation process. This results in minimal material damage and a significantly lower threshold fluence, typically in the range of 0.01 to 0.1 J/cm². These variations in pulse duration and their respective effects are critical for tailoring laser parameters to specific applications, such as defect removal on modulation disks, where precision and minimal collateral damage are paramount.

To further refine the understanding of laser ablation dynamics, a detailed mathematical model has been developed based on the heat conduction equation in cylindrical coordinates. This model focuses on the thermal response of the material, capturing temperature distribution $T(r,z,t)$ within the defect region. By leveraging the symmetry of the laser pulse and its interaction with the material, the model assumes no angular dependence, simplifying the analysis to radial and depth dimensions. The governing heat conduction equation is expressed as:

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{1}{r}\cdot\frac{\partial}{\partial r}\left(r\cdot\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right), \quad (9)$$

where $\alpha = k/(\rho \cdot c)$ is thermal diffusivity (c is specific heat conductivity), r is radial distance and z is depth.

To accurately represent the laser-material interaction during ablation, the following boundary and initial conditions are applied:

Neumann boundary condition at the surface ($z = 0$). The absorbed heat flux at the surface, $Q'(r, t)$, drives the temperature evolution:

$$-k\frac{\partial T}{\partial z} = Q'(r, t), \quad (10)$$

where $Q'(r, t)$ is given by:

$$Q'(r, t) = \frac{A\cdot P\cdot e^{-\frac{r^2}{2R^2}}}{4\pi\tau\cdot R^2}, \quad (11)$$

whith A being the absorbance of the material, P being the laser pulse energy, τ being the pulse duration and R being the focal radius.

Insulated boundaries. The boundaries at the center $r = 0$ and the depth $z = L_z$ are assumed to be thermally insulated:

$$\begin{cases} \frac{\partial T}{\partial r} = 0 \text{ at } r = 0 \\ \frac{\partial T}{\partial z} = 0 \text{ at } z = L_z \end{cases}. \quad (12)$$

Initial condition. At the initial time ($t = 0$), the material is at ambient temperature T_{IN}:

$$T(r, z, t) = T_{IN} \text{ for } t = 0. \quad (13)$$

This mathematical framework captures the spatial and temporal evolution of temperature in response to laser irradiation. By incorporating the energy deposition profile, material properties, and boundary conditions, the model enables precise predictions of the thermal behavior during ablation. These insights are crucial for optimizing laser parameters, ensuring controlled material removal while minimizing undesired effects such as thermal damage or residual stress.

Based on the proposed mathematical model, numerical simulations of heat conduction processes during laser ablation of materials were performed. The modeling results provide deeper insight into thermal processes during laser ablation, which is critically important for optimizing technological parameters such as pulse energy, duration, and focal distance. This enables precise prediction of the outcomes of laser-material interactions in various technological processes, including creation of high-precision optical elements. The results demonstrate temperature distributions and the evolution of material layer thickness over time, revealing key trends in laser ablation dynamics. The radial temperature distribution in the laser beam impact zone (Fig. 5-a) shows a maximum temperature of 3000 K at the center of the spot, which gradually decreases with radius, approaching zero at the boundary of the impact area. The dependence of the residual thickness of the material layer on the duration of laser exposure (Fig. 5-b) indicates a linear decrease in layer thickness with increasing time, corresponding to a constant ablation rate. Additionally, the two-dimensional temperature distribution in the laser impact zone (Fig. 5-c) exhibits a symmetric temperature field, with heating intensity increasing toward the center of the spot.

These results provide valuable insights into the thermal dynamics of laser ablation, enabling a more accurate prediction of material behavior under laser exposure and supporting the optimization of process parameters for various industrial applications.

V. Results of experimental studies on the removal of opaque defects using the laser evaporation method

Research on the removal of opaque defects (chromium particles) was conducted using a laser irradiation system equipped with a pulsed nitrogen laser, operating at a wavelength of 337.1 nm with a pulse duration of 20 ns. The laser beam was focused to achieve an irradiation zone diameter of 20 µm, enabling precise targeting of defects. The experiments were designed to investigate the selective removal of opaque defects while minimizing damage to the surrounding material and preserving the micro-relief structure of the substrate. The pulsed laser radiation was effective in removing chromium residues ranging in size from 5 to 50 µm. For larger defects, the removal process involved scanning the laser beam across the defect's surface with overlapping irradiated areas, ensuring complete ablation. It was observed that non-metallic opaque defects, such as contaminants or other particles, did not evaporate under the influence of the laser pulses, confirming the selective nature of the method for metallic defects. Microimage of the sample surface with a micro-relief structure before (Fig. 6-a) and after (Fig. 6-b) the removal of residual metal film using focused laser radiation demonstrate the effectiveness of the method. The images reveal the successful elimination of chromium residues while preserving the underlying micro-relief structure. The removal process also highlighted the presence of a thin metal film that remained after the selective etching of the chromium film. This residual layer was completely ablated under optimal laser irradiation conditions, leaving a clean surface.

In summary, the experimental studies confirmed the high precision and selectivity of the pulsed nitrogen laser for the removal of opaque metallic defects, ensuring minimal damage to the surrounding material. The results highlight its effectiveness in achieving controlled ablation with a well-defined impact zone, making it particularly suitable for delicate and high-precision applications. Furthermore, the demonstrated capabilities of this laser system suggest significant potential for industrial

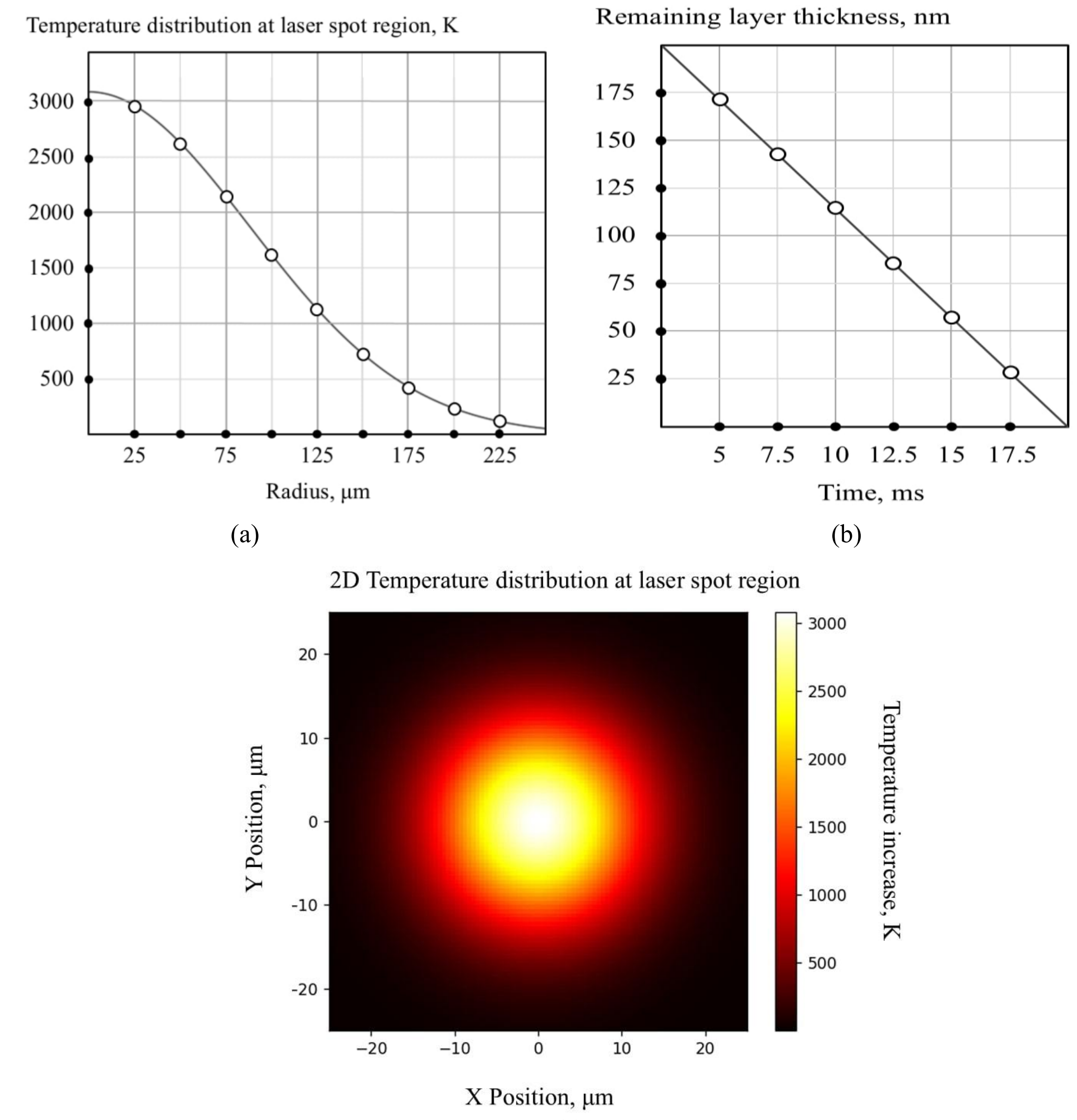


Fig. 5. Numerical modeling results of laser ablation: (a) radial temperature distribution, (b) residual layer thickness, (c) 2D temperature distribution.

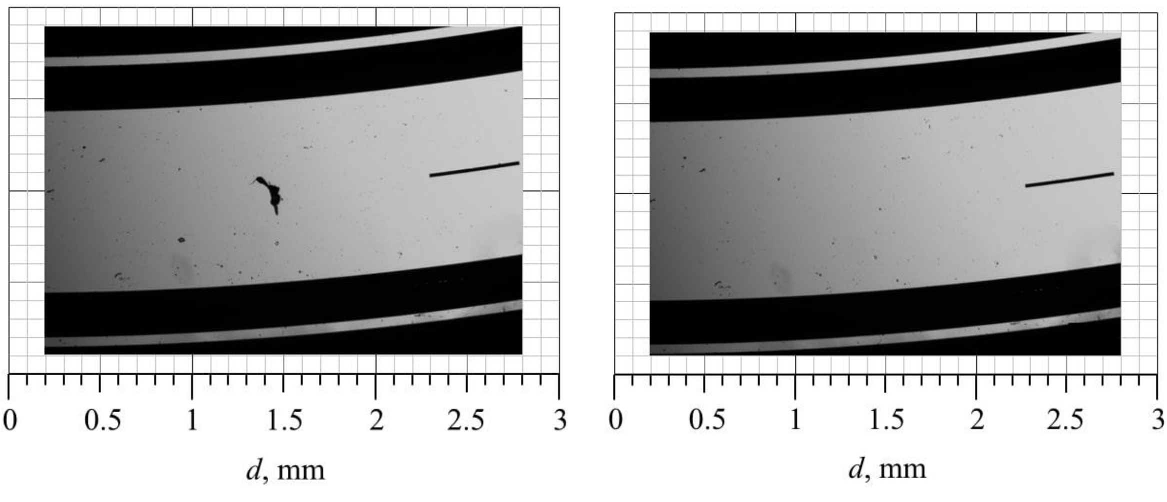


Fig. 6. Images of the sample surface with a micro-relief struct ure before (a) and after (b) the removal of residual metal film using focused laser radiation.

applications in surface cleaning and defect correction, especially for substrates with complex micro-relief structures, where conventional methods may lack the necessary precision or risk unintended material damage.

Conclusions

The relevance of laser ablation for addressing defects in modulation disks was determined by the need to meet stringent technological requirements for high-precision optical sensors used in industrial and military applications. The study emphasized the necessity of precise defect removal methods to ensure the reliability and accuracy of these critical components.

Key findings of the research:

A heat conduction-based mathematical model in cylindrical coordinates was proposed to simulate laser-material interaction. The model integrates heat transfer, phase transitions, and stress analysis, providing insights into the spatial and temporal temperature evolution, heat flux, and layer removal dynamics.

Simulations revealed key thermal behaviors such as radial temperature profiles and the evolution of residual layer thickness, enabling precise optimization of laser parameters (pulse energy, duration, and focal radius).

Experiments demonstrated the selective removal of chromium residues (5–50 µm) using a pulsed nitrogen laser, operating at 337.1 nm with a 20 ns pulse duration. The laser system achieved precise targeting with an irradiation zone diameter of 20 µm, preserving the microstructure while minimizing damage to surrounding material.

The study confirmed the high precision and selectivity of pulsed laser ablation for removing metallic defects, particularly chromium residues, without collateral damage. The proposed mathematical model and experimental results demonstrate the potential of laser ablation for refining microstructures of modulated disks, enabling advancements in manufacturing high-precision optical elements.

Conflicts of interest

There are no conflicts to declare.

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Manko D.Yu. – Candidate of Physical and Mathematical Sciences, Senior Researcher;
Beliak Ie.V. – Candidate of Technical Sciences, Senior Researcher;
Butok O.M. – research fellow;
Chehil Yu.I. – research fellow;
Pankratova A.V. – Senior Researcher;
Kryuchyn A.A. – Doctor of Technical Sciences, Professor.

[1] M. Hossain, J. K. Rakshit, & M. Pal Singh, *Numerical Analysis of all-optical silicon microring resonator-based cyclic redundancy check encoder*, Journal of Nanophotonics, 16 (03), 036007-1 (2022); https://doi.org/10.1117/1.jnp.16.036007.

[2] Y. Liu, W. Gu, Z. Mei, D. Sun, *Efficient FPGA-based LDPC encoder implementation for Optical Communication Systems*, 2023 21st International Conference on Optical Communications and Networks (ICOCN), 1–3 (2023); https://doi.org/10.1109/icocn 59242.2023.10236181.

[3] C. Patruno, V. Renò, M. Nitti, G. Pernisco, N. Mosca, *Optical encoder neural network: A CNN-based optical encoder for robot localization,* Optical Engineering, 62 (04), 041402-1 (2022); https://doi.org/10.1117/1.oe.62.4.041402.

[4] R. K. Megalingam, S. A. Anil, J. M. Varghese, *FPGA based navigation platform for fixed path navigation with distance estimation using rotation encoder,* 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), 3134 (2016); https://doi.org/10.1109/iceeot.2016.7755279.

[5] B. Ali, R. N. Sadekov, V. V. Tsodokova, *A review of navigation algorithms for unmanned aerial vehicles based on Computer Vision Systems,* Gyroscopy and Navigation, 13 (4), 241 (2022); https://doi.org/10.1134/s2075108722040022.

[6] I.V. Kosyak, D.Yu. Manko, Ie.V. Beliak, A.A. Kryuchyn, *Methodology for transforming code sequences according to the modulation disk coordinate system,* Electronic Modeling, 46 (5), 35 (2024); https://doi.org/10.15407/emodel.46.05.035.

[7] K. Eberhardt, S. Esser, H. Haider, *Abstract feature codes: The building blocks of the implicit learning system*, Journal of Experimental Psychology: Human Perception and Performance, 43 (7), 1275 (2017); https://doi.org/10.1037/xhp0000380.

[8] P.K. Panigrahi, S.K. Bisoy, *Localization strategies for autonomous mobile robots: a review*, J. King Saud Univ. - Comput. Inf. Sci., 34 (8B), 6019 (2021); https://doi.org/10.1016/j.jksuci.2021.02.015.

[9] J. Seybold, A. Bülau, K. P. Fritz, A. Frank, C. Scherjon, J. Burghartz, A. Zimmermann. *Miniaturized optical encoder with micro-structured encoder disc*, Applied Sciences, 9 (3), 452 (2019); https://doi.org/10.3390/app9030452.

[10] S. Liu, H. C. Zhang, L. Zhang, Q. L. Yang, Q. Xu, J. Gu, Y. Yang, X. Y. Zhou, J. Han, Q. Cheng, W. Zhang, T. J. Cui, *Full-state controls of terahertz waves using tensor coding metasurfaces*. ACS Applied Materials & Interfaces, 9 (25), 21503 (2017); https://doi.org/10.1021/acsami.7b02789.

[11] S. Liu, T. J. Cui, *Flexible controls of terahertz waves using coding and programmable metasurfaces*. IEEE Journal of Selected Topics in Quantum Electronics, 23 (4), 1 (2017); https://doi.org/10.1109/jstqe.2016.2599273.

[12] M. Hossain, J. K. Rakshit, M. Pal Singh, *Numerical Analysis of all-optical silicon micro-ring resonator-based cyclic redundancy check encoder.* Journal of Nanophotonics, 16 (03). 036007-1 (2022); https://doi.org/10.1117/1.jnp.16.036007.

[13] R. K. Megalingam, S. A. Anil, J. M. Varghese, *FPGA based navigation platform for fixed path navigation with distance estimation using rotation encoder,* 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), 3134–3138. https://doi.org/10.1109/iceeot.2016.7755279.

[14] B. Ali, R. N. Sadekov, V. V. Tsodokova, *A review of navigation algorithms for unmanned aerial vehicles based on Computer Vision Systems*. Gyroscopy and Navigation, 13(4), 241 (2022); https://doi.org/10.1134/s2075108722040022.

[15] M. Darnon, *Plasma etching in Microelectronics,* Plasma Etching Processes for CMOS Devices Realization 23 (2017); https://doi.org/10.1016/b978-1-78548-096-6.50002-x.

[16] F. Tian, T. Wang, X. Lu, *Endpoint detection based on optical method in chemical mechanical polishing*, Micromachines, 14 (11), 2053 (2023); https://doi.org/10.3390/mi14112053.

[17] T. Ding, Y. Xie, Z. Shen, X. Cheng, Z. Wang, *Ultrasonic cleaning optimization research for ultrasmooth optical substrate with artificial micron/submicron silica spheres*, Optical Engineering, 53 (12), 122514 (2014); https://doi.org/10.1117/1.oe.53.12.122514.

[18] B. Tang, K. Sato, Advanced surfactant-modified wet anisotropic etching (Microelectromechanical Systems and Devices, 2012); https://doi.org/10.5772/26901.

[19] Y. Zhou, L. Zhao, Y. Tang, Q. Deng, S. Hu*, Dimensional Metrology of micro structure based on modulation depth in Scanning Broadband Light Interferometry*, Applied Optical Metrology II, 10373(38), 103730G-1 (2017); https://doi.org/10.1117/12.2280001.

[20] M. R. Schmidt, P. Flanigan, D. Thibault, *Photomask repair using an advanced laser-based repair system (MARS2),* SPIE Proceedings, 4889, 1023 (2002); https://doi.org/10.1117/12.467505.

[21] T.E. Robinson, J.Le Claire, *Advanced Laser repair of EUV photomasks*. Photomask Japan 2019: XXVI Symposium on Photomask and Next-Generation Lithography Mask Technology, 10; 111780K01 (2019); https://doi.org/10.1117/12.2534759.

[22] T.E. Robinson, J.Le Claire, *Update on the performance of photomask repair and clean with DUV femtosecond laser processes*, Photomask Japan 2018: XXV Symposium on Photomask and Next-Generation Lithography Mask Technology, 10807091 (2018); https://doi.org/10.1117/12.2325009.

[23] D. Stonyte, V. Jukna, D. Paipulas, *Direct laser ablation of glasses with low surface roughness using femtosecond UV laser pulses,* Journal of Laser Micro/Nanoengineering, 17 (2), 121 (2022); https://doi.org/10.2961/jlmn.2022.02.2008.

[24] B. Kim, H. K. Nam, Y. J. Kim, S. W. Kim, *Lift-off ablation of metal thin films for micropatterning using ultrashort laser pulses,* Metals, 11 (10), 1586 (2021). https://doi.org/10.3390/met11101586.

[25] S. Brose, *Stand-alone EUV setups for photomask related inspection tasks*, Photomask Japan 2022: XXVIII Symposium on Photomask and Next-Generation Lithography Mask Technology, 49 (2022); https://doi.org/10.1117/12.2656141.

[26] T. Robinson, D. Yi, R. White, R. Bozak, M. Archuletta, D. Lee, *Nanomachining of non-orthogonal mask patterns.* SPIE Proceedings, 77481H1 (2010); https://doi.org/10.1117/12.865198.

Д.Ю. Манько, Є.В. Беляк, О.М. Буток, Ю.І. Чегіль, А.В. Панкратова, А.А. Крючин

Аналіз методів виявлення непрозорих дефектів на поверхні модуляційних дисків (огляд)

Інститут проблем реєстрації інформації НАН України, вул. Шпака, 2, 03113, Київ, Україна, dmitriy.manko@gmail.com

Дослідження присвячене модуляційним дискам як високоточним оптичним сенсорам для вимірювання кутових положень і швидкостей обертання, що є важливими для промислового та військового застосування. Для формування мікроструктур із високою точністю пропонується впровадження лазерної абляції, що забезпечує прецизійну обробку поверхні, усунення дефектів і видалення залишків хрому. Проведено класифікацію непрозорих дефектів на підкладках дисків, визначено основні причини їх виникнення та труднощі усунення, зокрема ризики пошкодження сусідніх структур під час абляції. Розроблено математичну модель, засновану на рівнянні теплопровідності у циліндричних координатах, що описує поведінку дефектів під впливом лазерного випромінювання, оптимізуючи глибину абляції та мінімізуючи термічне пошкодження. Чисельне моделювання дозволило визначити особливості теплового режиму, розподіл температури та динаміку видалення матеріалу, що стало основою для вибору оптимальних параметрів лазерної обробки. Експериментальні дослідження з використанням імпульсного азотного лазера (337,1 нм, тривалість імпульсу 20 нс) продемонстрували можливість селективного видалення хромових дефектів (5-50 мкм) із мінімальним пошкодженням підкладки. Показано, що наявність неметалевих забруднень не впливає на проведення зазначених процедур, що підтверджує вибірковість методу. Мікрозображення поверхні зразків засвідчили успішне усунення залишків хрому та тонких залишкових металевих плівок за умов налаштування оптимальних параметрів лазерного опромінення.

Ключові слова: модуляційні диски, видалення непрозорих дефектів, лазерна абляція, модель теплопровідності.