The obtained results showed high levels of absorption of electromagnetic energy by structures based on nanoscale gold films in a 3-cm wavelengths and prospects of using these structures in the design of real RAM.

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РАДІОПОГЛИНАЮЧІ ВЛАСТИВОСТІ ТОНКИХ ПЛІВОК ЗОЛОТА В ДІАПАЗОНІ ЧАСТОТ 8÷11,6 ГГЦ

Наведені результати вимірювання поглинаючих властивостей плівок золота товщиною 8–20 нм, що нанесені полімерну підкладку в смузі частот 8 ÷ 11,6 ГГц електромагнітного випромінювання.

Ключові слова: електромагнітне випромінювання, радіопоглинаючих матеріалів нанорозмірних плівок золота, КСХН, 3 сантиметровий діапазон довжин хвиль.

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РАДИОПОГЛОЩАЮЩИЕ СВОЙСТВА ТОНКИХ ПЛЕНОК ЗОЛОТА В ДИАПАЗОНЕ ЧАСТОТ 8÷11,6 ГГЦ

Приведены результаты измерения поглощающих свойсте пленок золота толщиной 8–20 нм, нанесены полимерную подложку в полосе частот 8 ÷ 11,6 ГГц электромагнитного излучения.

Ключевые слова: электромагнитное излучение, радиопоглощающие материалы наноразмерных пленок золота, КСВН, 3 сантиметровый диапазон длин волн.

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ZONED TARGET IN THE EXPERIMENTAL INVESTIGATION OF THE MAGNETRON SPUTTERING DEVICE WITH TWO EROSION ZONES

The Monte Carlo computer simulation program of the magnetron sputtering device with two erosion zones was build, in which the searching algorithm of the self-consistent starting positions of the secondary electrons on cathode was introduced. For the verification of the simulation results the zoned test target for the magnetron sputtering device was designed, which provides the measurements of the discharge current distributions along it surface. The comparison of the experimental results to the simulation demonstrates their compliance in the identical conditions.

Key words: zoned target, magnetron sputtering device, cathode sheath, computer simulation, Monte Carlo method

Introduction. Magnetron sputtering devices on direct current (hereafter – MSD) had found a wide application in the technology of coating of the conductive materials and their composites [12, 16, 17, 10]. Some of the latest investigations have shown the possibilities of carbon nanotubes synthesis by the magnetron sputter deposition method for wide sphere of technical applications [1–4].

The magnetic and electric fields in MSD are rather complicated, and this makes impossible an analytical description of the particles motion in them. The computer simulations of MSD based on the integration of particle motion equations and Monte Carlo collisions description are widely used now to predict the shape of erosion zone of the cathode-target [13, 14]. In the work [15] the Monte Carlo method was used to find the starting positions of secondary electrons at the cathode, which correspond to the steady state discharge operation mode and for indirect prediction of current-voltage characteristics of the discharge. The simple methods [13–15] were used for low working pressure (< 10 Pa) and they neglect the electric field changes in the cathode sheath, which provided by any variation of heavy particles (ions) density. This circumstance is eliminated in "particle-in-cell and Monte Carlo collision" method (PIC/MCC), in which every plasma species are presented as a limited ensemble of super-particles, and the Poisson equation is used to calculate the fully self-consistent electrical potential [8, 9]. This method requires more computer resources, but provides the most comprehensive description of the physical processes in MSD.

In the works [8, 9, 13–15] the MSD with single erosion zone of cathode-target ("race track") were investigated. The numerical model of the MSD with two erosion zones of the cathode-target (hereafter – CT), based on the Monte Carlo method, was built previously in the works [5, 6, 7] by authors. In the article [7] the searching algorithm of the self-consistent starting positions of the secondary electrons on the CT and the estimation of the cathode sheath thickness, based on the Child-Langmuir law, were presented. Modeling results in [6, 7] were compared with experimental data of sputtering of the multilayer target from the non-magnetic materials. There were obtained the dimensions of the internal and external CT erosion zones in the two characteristic opposite cases. There are the case of "low" discharge currents (≤ 15 mA), in which only the external discharge zone was able to ignite, and the case of the "high" currents (≥ 40 mA), when both discharge zones were ignited. Unfortunately, it was impossible to obtain from these measurements the absolute values of discharge current in the corresponding zone, which is important for checking the results of computer simulation.

The MSD with two erosion zones [11] is the module of the industrial vacuum system VUP-5 and has the area of the cathode unit about $4{,}5 \cdot 10^3 \text{mm}^2$, on which the diskshaped target with same size is mounted. The target area, which is efficiently used in $1{,}9..2{,}0\cdot 10^3 \text{mm}^2$ [6, 7]. On the surface of the cathode the magnetic induction could reach up to $B_t = 0{,}084\,\text{T}$ and decreases on the up distance h according to the $\sim \exp(-h/L)$ law, in which L is characteristic length (in the internal discharge zone it is $L_1 = 3{,}2\,\text{mm}$, in the external – $L_2 = 6{,}4\,\text{mm}$). This feature of magnetic field makes impossible ignition of the internal zone of discharge at current $\leq 15\,\text{mA}$, when the cathode sheath d_E is much bigger than L_1 [5].

In order to estimate abilities of this MSD for carbon nanotubes synthesis, like in [1–4], in this article the approach of definition of ion current distribution on the CT surface has been proposed. Also the cathode sheath thickness along the CT radius has been estimated. It was made both in experimental and the computer simulation ways.

Modeling and experiment. Both at the experiment and in the computer model the reference point of cylindrical coordinate system was chosen in the centre of CT surface. If at the beginning of calculation the secondary electrons are randomly placed on the CT surface, according to the magnetic confinement there are two discharge zones be able to appear [5]. Then for the acceleration of computer calculation, the electrons were started on the CT areas, where the discharge is maintained the most effectively (on the radius r: in internal zone – $5..10\,\text{mm}$, in external – $21..26\,\text{mm}$). The discharge voltage U_d and work gas pressure p must be defined from the experiment. Hereafter is accepted that U_d predominantly applied on the discharge cathode sheath.

The cathode sheath thickness also needs the definition. In order to improve the computer simulation at the small thickness of the cathode sheath d_E ($d_E \leq 3{,}2\,\text{mm}$) it was perfected the shape of model cathode sheath (in compare with [5-7]). In the articles [5-7] the d_E was steady on the whole CT surface (as in [14, 15]) and was chosen in maxima of magnetic field induction. Now this value is marked as $d_{E\,Min}$. Now, the d_E depends on the magnetic induction value, which is parallel to the CT surface along radius r (Fig. 1).

The algorithm of self-consistency of the secondary electrons starting positions is the distinguishing feature of this computer model. The several tracing cycles of secondary electrons from the surface of CT are performed. If at first cycle the electron's positions on the CT are random, but then they are defined by ionization acts positions. The secondary electrons quantity is estimated by secondary ion-electron emission ratio $\gamma < 0{,}1$ [12, 15]. In comparison with the previous work [7], it is a new criterion of evaluation of steady state of the discharge. It is based on the comparison of the average quantity of ionization acts per one secondary electron – n_i, created on this cycle to the previous. If difference is less than $5\,\%$, the steady state mode of the discharge is reached (like in [15]). After that we can to calculate the ion motion, the radial distribution of the ions relative number and energy, like in [5].

Distribution of the discharge current could be associated to the ion distribution at CT surface, because only there ions define the discharge current. If the discharge current I_d is known experimentally in this discharge operation mode, the distribution of the discharge current could be estimated in easy way.

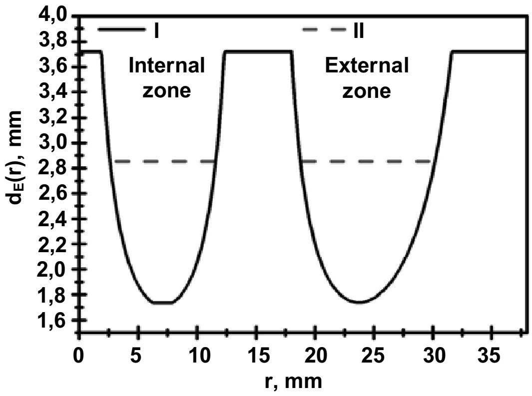

Fig. 1. The cathode sheath thickness at the computer modeling. (The curves I – at $d_{E\,Min} = 1{,}737\,\text{mm}$, and II – at $d_{E\,Min} = 2{,}834\,\text{mm}$)

The zoned test target was made in order to check the results of simulation (Fig. 2). It consists of eight flat rings from non-magnetic steel (its thickness is of 1 mm) and central platform. There are placed on the isolating mica substrate with a thickness of $0{,}1\,\text{mm}$. Every zone-ring is connected individually to the common power source, and can be commutated for the immediate current measurement on itself. Radial position of the ring's middle r_i was determined by this formula, in which central zone was taken in account as the ring (the dimension units – mm):

$$r_i = (4i - 2{,}5), \tag{1}$$

where i – the ring number from 1 to 9.

According to the previous radius formula (1) the ring's area is (the dimension units – mm^2):

$$S_i(r_i) = 2\pi \cdot a \cdot r_i, \quad 2)$$

where r_i – the radial position (1); a – the thickness of zoned target ring, which equals $a = 3\,\text{mm}$ (and the distance between rings equals $1\,\text{mm}$ (Fig.2)). The similar method of the cathode-target division was used in computer modeling, but the distance between rings was 0, and rings thickness was $1\,\text{mm}$.

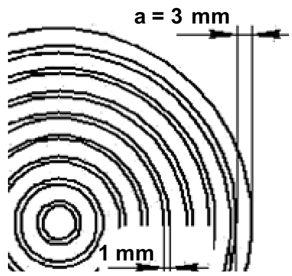

Fig. 2. Zoned target layout

If ion current on the ring i is I_i, according to the (2) the current density $j_i(r_i)$ could be determined as:

$$j_i(r_i) = I_i / S_i(r_i). \tag{3}$$

In our article j_i will have the dimension mA/cm^2. The ion current density is less than discharge current density in $(1+\gamma)$ times, where γ – is the coefficient of the secondary ion-electron emission ($\gamma < 0{,}1$).

The Child-Langmuir law could be used to estimate the cathode sheath thickness d_E under the condition of low pressure and big mean free path of ions [12 p.98]. The following formula is being used for determination of d_E (dimension of d_E is mm):

$$d_E(r) = 2{,}43 \cdot 10^{-3} \cdot \left(V_d^{0,75} \Big/ \left(M_i^{0,25} \cdot \left(j_i(r) \right)^{0,5} \right) \right), \qquad (4)$$

where V_d – is the voltage fall on the cathode sheath similar to the interelectrode space of flat gas-filled diode, and as mentioned before $V_d \approx U_d$; M_i – is ion mass of working gas Ar in atomic mass units ($M_i = 40$); $j_i(r_i)$ – is density of ion current on the cathode surface from (3), but in this case in $\mathrm{A/cm^2}$ like in [7, 12].

In this article the value $d_E(r)$ from (4) is called as "effective thickness" of the cathode sheath.

The experimental results obtained on the zoned target. Measuring of the radial distribution of discharge current was made at three pressures of working gas Ar: $p_1 = 0{,}67$ Pa, $p_2 = 1{,}33$ Pa, $p_3 = 6{,}65$ Pa, and also at four discharge currents I_d, of 15 mA, 45 mA, 90 mA, 150 mA. In such conditions the discharge voltage U_d was changed in the range from 240 V to 480 V. There are presented the data by two typical currents. In the case of the discharge current $I_d = 15$ mA only the external discharge zone is ignited as in [5]. If the current is $I_d = 90$ mA both zones are ignited.

For the cases $I_d = 15$ mA and $I_d = 90$ mA there are presented the radial distributions of the ion current density on the cathode target given according to (1)-(3) (Fig. 3, 5). Efficient thickness of cathode sheath $d_E(r)$ is presented on the Fig. 4 and Fig. 6. There are taken in account the ratio of the secondary ion-electron emission $\gamma = 0{,}1$.

The discharge mode at $I_d = 15$ mA shows the existence of intensive external discharge zone, in which ion current density is much bigger then in internal zone (Fig. 3).

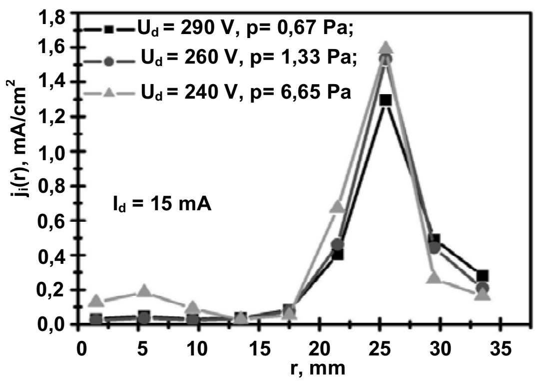

Fig. 3. The ion current density radial distribution on zoned target at $I_d = 15$ mA

In such conditions in external zone effective cathode sheath thickness (4) goes down to $d_E = 2$ mm for every pressure. This value is lesser than mentioned before value $L_2 = 6{,}4$ mm for the magnetic field (*Fig. 4*). In the internal zone the cathode sheath does not have big differences at pressures $p_1 = 0{,}67$ Pa and $p_2 = 1{,}33$ Pa. The characteristic length $L_1 = 3{,}2$ mm is strongly exceeded. Vice versa, if the pressure of working gas argon amount to $p_3 = 6{,}65$ Pa, the cathode sheath in the internal zone is close to L_1 (Fig. 4). It provides better conditions for effective magnetic confinement of electrons in the zone of acceleration on the electric potential, which suitable for discharge ignition in this zone.

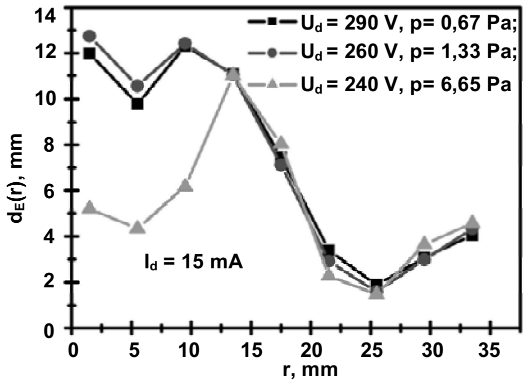

Fig. 4. The radial distribution of effective thickness of the cathode sheath on zoned target at $I_d = 15$ mA

If the discharge current is $I_d \geq 45$ mA, the simultaneously increasing of ion current density corresponded to noticeable decreasing of the cathode sheath thickness in both zones. If current is $I_d = 90\,mA$ (Fig. 5), the value of $d_E(r)$ in the internal zone are lesser than L_1 (Fig. 6). It automatically provides acceptable conditions for discharge in this zone. At the pressure $p_3 = 6{,}65\,Pa$ the current density in internal zone begins to exceed the ones in external zone (Fig. 6).

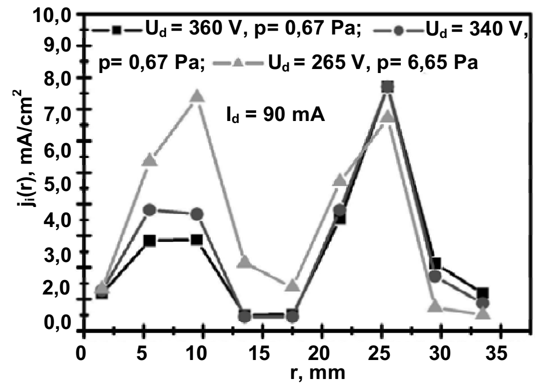

Fig. 5. The ion current density radial distribution on zoned target at $I_d = 90$ mA

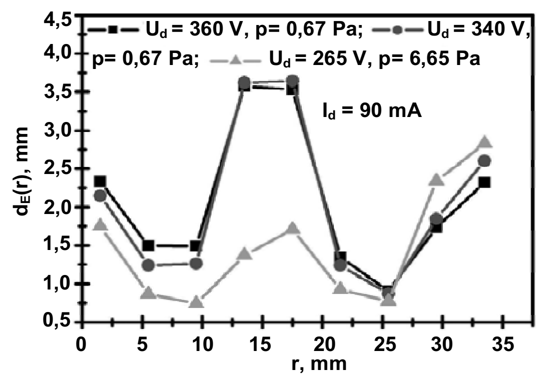

Fig. 6. The radial distribution of effective thickness of the cathode sheath on zoned target at $I_d = 90$ mA

For the CT area, limited by radius $r = 38$ mm, the average cathode sheath thickness d_E could be equals from 1,2 mm to 3,9 mm under the conditions of every experimental voltage U_d and appropriate currents I_d (from (4)). For the current $I_d = 90$ mA and more the cathode layer in both discharge zones (with area $2{,}0 \cdot 10^3 \mathrm{mm}^2$ [7]) should be approach to 1,0..1,5 mm at every pressures, which close to results of the work [8] for such magnetic field.

Comparison of the computer simulation results with zoned target data. In the computer simulation at the conditions of discharge current $I_d = 90$ mA, Ar pressure 6,65 Pa and cathode sheath voltage $V_d = 265$ V, the minimal starting cathode sheath thickness was chosen as $d_{E\,Min} = 1{,}737$ mm (Fig. 1). At the pressures 1,33 Pa and 0,67 Pa ($V_d = 340$ V and $V_d = 350$ V) it was chosen $d_{E\,Min} = 2{,}834$ mm (Fig. 1). Only at these values of $d_{E\,Min}$ the conditions of the steady state of the discharge were reached.

The cathode sheath potential $-V_d$, gives to the secondary electron the energy eV_d, where $-e$ is the electron charge. Dividing the eV_d on the average quantity of ionization acts on the one secondary electron n_i we could to obtain the energetic ionization cost. In the computer simulation results for the pressures 0,67 Pa and 1,33 Pa, this value is close to 31 eV, which corresponds to the well-known experimental facts for Ar [10, 15].

The Fig. 7–9 presents the simulation results of effective cathode sheath thickness $d_E(r)$ at the current $I_d = 90$ mA and the results by zoned target at appropriate pressures and voltages for the comparison. (In this figures and simulation $\gamma = 0{,}073$, which looks more realistic).

Obviously, that the simulation results make possible to predict the distribution of discharge current density on radius more accurate than measurement on the zoned target. As we can see from Fig. 7-9, the suppositions, which were made for the form of the cathode sheath (Fig. 1), could be automatically improve in process of finding of self-consistent starting positions of secondary electrons on the CT. Obtained plots demonstrate good coincidence with experimental results at pressures 0,67 Pa and 1,33 Pa (Fig. 7. and Fig. 8.). For the pressure 0,67 Pa it was chosen $V_d = 350$ V because of the best coincidence with experimental results (Fig 7).

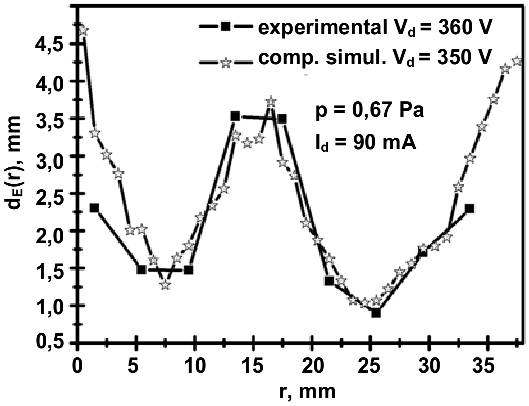

Fig. 7. The comparison of computer simulation results with results on the zoned target at $I_d = 90$ mA, $p = 0{,}67$ Pa

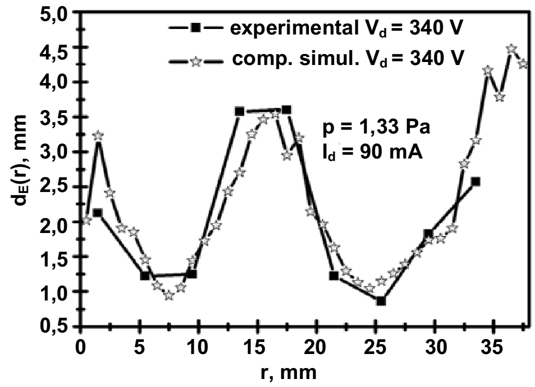

Fig. 8. The comparison of computer simulation results with results on the zoned target at $I_d = 90$ mA, $p = 1{,}33$ Pa

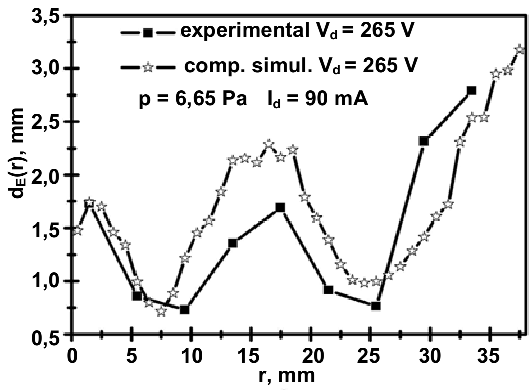

Fig. 9. The comparison of computer simulation results with results on the zoned target at $I_d = 90$ mA, $p = 6{,}65$ Pa

Noticeable differences are taken place at pressure 6,65 Pa (Fig. 9). It could be related with overstated initial value of the cathode sheath thickness between zones at such conditions (Fig. 1). But difference of distribution for the internal zone versus the external one is even stronger.

Conclusions. For the investigation of the distribution of discharge current on the cathode-target of MSD with two erosion zones the zoned target was used. The measurements (at the three pressures of working gas Ar – 0,67 Pa, 1,33 Pa, 6,65 Pa) of the distribution of the discharge current in MSD along cathode-target radius converted to the cathode sheath with using of the Child-Langmuir law [12, 7] were held. This results have confirmed the assumption about influence of the confinement magnetic field variation in the MSD along the vertical distance from the cathode on the discharge current distribution on the cathode at the "low" (15 mA) and "high" (90 mA) discharge currents. At discharge current 90 *mA* the comparison of experimental dependencies with values from the computer simulation has been made.

The discharge simulation program based on the Monte Carlo method [5–7] has been improved with taking into account the non-homogeneity of the cathode sheath, which depends on the magnetic field induction along the cathode radius. Algorithm of self-consistency of starting positions of secondary electrons also was improved.

The results of computer simulation at 90 mA are demonstrated coincidence to the data received by experiments on the zoned target. In experiment as well as in simulation results were demonstrated the locating of the maximal current density in the internal zone of discharge at 90 mA and working pressure 6,65 Pa were demonstrated.

Thus, the Monte Carlo numerical model of MSD with two erosion zones which was designed in previous articles [5–7] and has been improved in present work, clearly describes the discharge behavior in practically useful cases. It could be used for foreseeing the target sputtering efficiency on this magnetron sputtering device, which is important at thin film production.

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ЗОНОВАНА МІШЕНЬ В ЕКСПЕРИМЕНТАЛЬНОМУ ДОСЛІДЖЕННІ МАГНЕТРОННОГО РОЗПИЛЮВАЛЬНОГО ПРИСТРОЮ З ДВОМА ЗОНАМИ ЕРОЗІЇ

Побудовано комп'ютерну модель магнетронного розпилювального пристрою з двома зонами ерозії, засновану на методі Монте-Карло, де введено алгоритм пошуку самоузгоджених стартових позицій вторинних електронів на катоді. Для перевірки результатів комп'ютерного моделювання було виготовлено зоновану тестову мішень для даного магнетронного розпилювального пристрою, яка забезпечила вимірювання розподілів розрядного струму по своїй поверхні. Порівняння результатів експерименту та моделювання продемонстрували їх відповідність за однакових умов.

Ключові слова: зонована мішень, магнетронний розпилювальний пристрій, катодний шар, комп'ютерне моделювання, метод Монте-Карло.

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ЗОНИРОВАННАЯ МИШЕНЬ В ЭКСПЕРИМЕНТАЛЬНОМ ИССЛЕДОВАНИИ МАГНЕТРОННОГО РАСПЫЛИТЕЛЬНОГО УСТРОЙСТВА С ДВУМЯ ЗОНАМИ ЭРОЗИИ

Построена компьютерная модель магнетронного распылительного устройства с двумя зонами эрозии, основанная на методе Монте-Карло, в которой введен алгоритм поиска самосогласованных стартовых позиций вторичных электронов на катоде. Для проверки результатов компьютерного моделирования была изготовлена зонированная тестовая мишень для данного магнетронного распылительного устройства, которая обеспечила измерения распределений разрядного тока по своей поверхности. Сравнение результатов эксперимента и моделирования продемонстрировало их соответствие при одинаковых условиях.

Ключевые слова: зонированная мишень, магнетронный распылительное устройство, катодный слой, компьютерное моделирование, метод Монте-Карло.

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SUBNANOSECOND STIMULATED RAMAN SCATTERING PULSES OF Q-SWITCHED LASER AT SELF-FOCUSING

The results of experimental study confirm the availability of using self-focusing media for creation of highly efficient transformers of laser radiation based on stimulated Raman scattering. It has been shown that due to the self-focusing dynamics, such transformers can change frequency and compress giant pulses of multimode lasers more than in ten times, utilizing a simple scheme. The proposed and implemented scheme is suitable for generation of initiating subnanosecond Stokes pulses, which further can be used for compression of giant laser pulses with a corresponding increasing of power.

Keywords: laser, self-focusing, stimulated Raman scattering.

Introduction. It is known that SRS (stimulated Raman scattering) is successfully used in transformers of laser radiation for frequency tuning, pulse compression and improving of optical beam quality [6, 1]. However, SRS-