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ENHANCEMENT OF PHOTOCURRENT IN SILICON SOLAR CELLS BY LASER SURFACE MODIFICATION

This paper presents a mathematical modeling study of photocurrent density enhancement in silicon solar cells subjected to laser surface modification. The effects of femtosecond and nanosecond laser pulses on the formation of surface micro- and nanostructures, which determine the optical properties of the material and the efficiency of photocarrier generation, are investigated.

The developed model is based on a comprehensive consideration of laser–semiconductor interaction, heat transfer, surface morphology evolution, and spectral characteristics of reflection and absorption. It is shown that nanosecond laser pulses mainly lead to thermal modification of the surface, including melting and recrystallization, whereas femtosecond pulses enable the formation of subwavelength nanostructures due to non-equilibrium processes and strong energy localization.

It is established that laser surface modification reduces the reflectance of silicon from 0.30–0.35 to 0.12–0.18 for nanosecond treatment and to 0.04–0.08 for femtosecond treatment, accompanied by an increase in the absorption coefficient up to 92–96 %. The modeling results demonstrate that enhanced *light absorption leads to an increase in photocurrent density by 15–25 % for nanosecond processing and by 30–40 % for femtosecond processing.*

The obtained results confirm that laser-induced nanostructuring is an effective method for increasing photocurrent and improving the efficiency of silicon solar cells.

Keywords: silicon solar cells; photocurrent; laser surface modification; femtosecond pulses; nanosecond pulses; nanostructures; reflectance; light absorption.

1. Introduction

In recent years, renewable energy has shown steady growth, with solar power occupying a leading position in the global electricity generation structure [1; 2]. Improving the efficiency of silicon solar cells remains a key challenge in modern photovoltaics, as it directly determines the economic competitiveness of photovoltaic technologies [3; 4; 5].

One of the main factors limiting the efficiency of solar cells is insufficient absorption of incident radiation due to significant reflection losses at the silicon surface. To reduce reflection, anti-reflection coatings, particularly based on silicon nitride (Si_3N_4), are traditionally used. However, such coatings have several limitations, including a narrow effective spectral range, dependence on the angle of incidence, and technological complexity of fabrication [4; 6].

An alternative approach is laser surface modification, which enables the formation of micro- and nanostructures that significantly alter the optical properties of the material [7; 8; 9]. In particular, the formation of so-called “black silicon” provides a gradual refractive index transition at the interface, leading to reduced reflection and enhanced absorption over a wide spectral range [10; 11; 12; 13].

Despite numerous experimental studies, the quantitative relationship between laser processing parameters, resulting surface morphology, and photocurrent in silicon solar cells remains insufficiently investigated [14; 15; 16]. In particular, the effect of laser pulse duration (femtosecond and nanosecond) on photocarrier generation efficiency requires further analysis.

The aim of this work is to develop a physical and mathematical model describing the influence of laser surface processing parameters on the optical characteristics and photocurrent density of silicon.

To achieve this goal, the following tasks are addressed:

– development of a model of laser–semiconductor interaction;
– simulation of heat transfer and surface structure formation processes;
– calculation of spectral reflectance and absorption characteristics;
– quantitative evaluation of photocurrent enhancement under different laser processing regimes.

Thus, the proposed approach makes it possible to establish the relationship between laser processing parameters, surface morphology, and the photoelectric characteristics of silicon solar cells.

2. Materials and Methods

2.1. Model of Laser–Semiconductor Interaction

The interaction of a laser pulse with the silicon surface is described using the spatial–temporal distribution of the radiation intensity. For a Gaussian laser beam, the power density can be expressed as:

$$I(x,t)=I_0\exp(-\frac{2x^2}{\omega_0^2})\exp(-\frac{t^2}{\tau^2}).$$

where I_0 is the peak laser intensity, ω_0 is the beam radius, and τ is the pulse duration (for femtosecond and nanosecond regimes, respectively).

The absorption of laser radiation in the material is described by the Beer–Lambert law [3;4]:

$$Q(z,t)=(1-R)\,\alpha\, I(t)\, e^{-\alpha z},$$

where R is the reflectance, α is the absorption coefficient, and z is the penetration depth.

2.2. Heat Transfer Equation

The thermal response of silicon under laser irradiation is described by the transient heat conduction equation [17]:

$$\rho c\frac{\partial T}{\partial t} = k\nabla^2 T+Q(z,t),$$

where ρ – is the material density,

c – is the specific heat capacity,

k – is the thermal conductivity,

T – is the temperature.

For nanosecond pulses, this equation adequately describes heat transfer processes, as the thermal diffusion time is comparable to the pulse duration.

In the case of femtosecond pulses, it is necessary to consider the non-equilibrium between the electron and lattice subsystems. This is described by the two-temperature model:

$$C_e\frac{\partial T_e}{\partial t} = -G(T_e-T_l)+Q,$$
$$C_l\frac{\partial T_l}{\partial t} = G(T_e-T_l),$$

where T_e and T_l are the electron and lattice temperatures, respectively, and G is the electron–phonon coupling coefficient [9;18].

2.3. Model of Surface Nanostructure Formation

Under laser irradiation, a modified surface layer is formed, which can be represented as an effective gradient layer with a spatially varying refractive index:

$$n_{eff}(z)=n_{air}+(n_{Si} - n_{air})(z/h),$$

where h is the characteristic height of the nanostructure.

This model accounts for a smooth transition of optical properties at the interface and plays a key role in reducing reflection and enhancing absorption.

2.4. Optical Model

The optical properties of the surface are analyzed using the Fresnel equations [3;4]. For normal incidence, the reflectance is given by:

$$R=[(n_1-n_2)/(n_1+n_2)]^2$$

The presence of a gradient layer leads to effective refractive index matching, resulting in reduced reflection and increased absorption.

A decrease in reflectance and an increase in absorption are the main factors governing photocarrier generation and, consequently, the photocurrent density.

2.5. Model of Photogeneration and Photocurrent Density

Photocurrent is a key parameter of photovoltaic devices that determines the efficiency of solar energy conversion into electrical energy. In silicon solar cells, photocurrent arises due to the generation of electron–hole pairs when photons with energy exceeding the bandgap are absorbed.

The physical mechanism of photocurrent formation includes three main processes: light absorption, carrier generation, and separation of carriers by the internal electric field of the p–n junction, followed by their transport to the contacts.

The photocurrent density is defined by the integral expression [6]:

$$J_{ph}=q\int_{\lambda 1}^{\lambda 2} \Phi(\lambda)\, A(\lambda)d\lambda$$

where q is the elementary charge, Φ(λ) is the spectral photon flux density, and A(λ) is the absorption coefficient.

Thus, photocurrent is an integral characteristic determined by the spectral optical properties of the material. In particular, the absorption coefficient is related to reflectance by: A(λ)=1−R(λ).

The photocurrent depends on several factors:

- optical properties of the surface (reflectance and absorption);
- surface morphology;
- spectral composition of incident radiation;
- carrier generation and transport conditions.

For a smooth silicon surface, significant optical losses occur due to reflection, with reflectance values of approximately 0.30–0.35. The corresponding photocurrent density $J_{ph,0}$ is taken as the reference level.

Laser surface modification leads to the formation of micro- and nanostructures that provide effective refractive index matching at the air–silicon interface. This results in reduced reflection and enhanced absorption, directly increasing the photocurrent.

For nanosecond processing, reflectance decreases to 0.12–0.18, leading to a photocurrent increase of 15–25 %. For femtosecond processing, reflectance decreases to 0.04–0.08, and the photocurrent increases by 30–40 %.

To evaluate the efficiency of laser modification, the normalized photocurrent is introduced:

$$J_{ph}/J_{ph,0},$$

where J_{ph} is the photocurrent after processing and $J_{ph,0}$ is the photocurrent of the initial surface.

For a smooth surface:

$$J_{ph}/J_{ph,0}=1,$$

while for modified surfaces:

$$J_{ph}/J_{ph,0}>1.$$

This parameter is used to analyze the spectral dependence of photocurrent enhancement.

2.6. Numerical Method

The solution of the heat transfer equations, as well as the two-temperature model for the femtosecond regime, is carried out using the finite difference method (FDM) with an implicit time integration scheme (Crank–Nicolson), ensuring numerical stability.

Spatial discretization is performed along the depth of the material using a uniform grid:

$$\Delta z=1–10\,\text{nm}, \quad z_{max}\approx 2–5\,\mu\text{m}.$$

The time step is determined by the duration of the laser pulse:

femtosecond regime: $\Delta t \sim 10^{-15}–10^{-14}$ s;

nanosecond regime: $\Delta t \sim 10^{-11}–10^{-10}$ s.

The system of equations is solved iteratively until a quasi-steady state is reached after the completion of laser irradiation.

2.7. Material Parameters (Silicon)

The following physical parameters of silicon are used in the simulations:

Parameter	**Symbol**	**Value**
Density	ρ	2330 kg/m³
Specific heat capacity	c	700 J/(kg·K)
Thermal conductivity	k	130 W/(m·K)
Melting temperature	T_m	1687 K
Absorption coefficient	α	$10^5–10^6$ m^{-1}
Refractive index	n	3.4–3.6

Laser Parameters

Two laser irradiation regimes are considered:

Femtosecond laser:

– pulse duration: τ=100 fs ;
– wavelength: λ=800 nm;
– fluence: F=(0.1–1) J/cm^2.

Nanosecond laser:

– pulse duration: τ=10–50 ns;
– wavelength: λ=1064 nm;
– fluence: F=(1–10) J/cm^2.

2.8. Initial and Boundary Conditions

The initial temperature of the material is assumed to be:

$$T(z,0)=300\,K.$$

Boundary conditions:

- at the surface, a heat flux corresponding to laser irradiation is applied;
- at sufficient depth, a thermal insulation condition is imposed:

$$\partial T/\partial z=0.$$

2.9. Calculation of Optical Characteristics and Photocurrent

Spectral calculations are performed in the wavelength range:

$$\lambda=400\text{–}1100\,\text{nm}.$$

For each surface configuration (smooth, nanosecond-treated, and femtosecond-treated), the following parameters are calculated:

– reflectance $R(\lambda)$;
– absorption coefficient $A(\lambda)=1-R(\lambda)$;
– photocurrent density J_{ph}.

The photocurrent density is obtained by integrating the spectral absorption, which allows direct evaluation of the effect of laser processing on photovoltaic performance.

2.10. Software Implementation

The numerical simulations can be implemented using the following software tools:

– MATLAB (main simulation environment);
– COMSOL Multiphysics (for visualization and verification);
– Python (NumPy, SciPy) as an alternative implementation platform.
– To solve the system of equations, the following numerical techniques are used:
– implicit Crank–Nicolson scheme;
– tridiagonal matrix algorithm (Thomas algorithm).

3. Results and Discussion

3.1. Thermal Response of Silicon under Laser Irradiation

The results of numerical simulations show that the thermal response of silicon strongly depends on the laser pulse duration.

Under nanosecond laser irradiation, a predominantly thermal regime is realized, characterized by significant heating of the near-surface layer, melting of the material, and subsequent recrystallization. The temperature field extends to greater depths due to the development of thermal diffusion processes during the pulse duration.

In contrast, under femtosecond laser irradiation, energy is deposited into the material on timescales much shorter than the characteristic electron–phonon relaxation time. This leads to strong localization of energy within the near-surface region and the formation of high temperature gradients. Such a regime promotes the formation of regular subwavelength nanostructures with a minimal heat-affected zone.

The resulting thermal regimes determine the surface morphology, which subsequently plays a decisive role in the optical properties and photocurrent generation (Fig. 1).

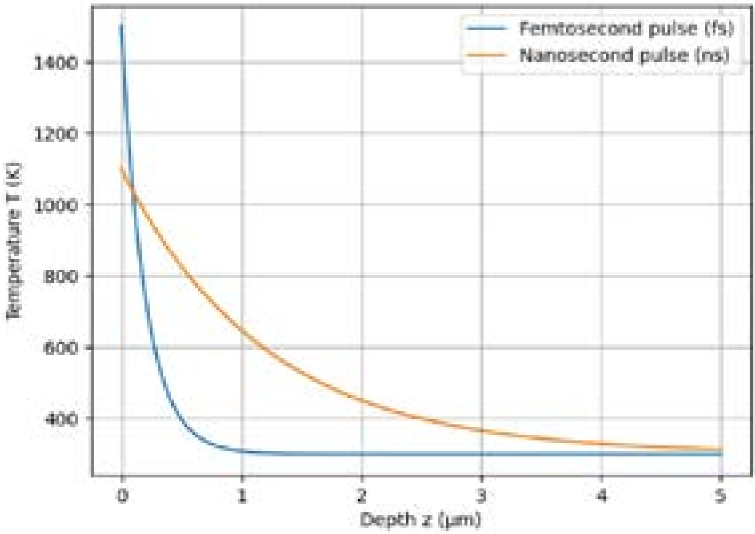

Figure 1 – Depth-dependent temperature distribution in silicon under femtosecond and nanosecond laser irradiation.

3.2. Formation of Effective Optical Structure

Laser surface modification results in the formation of an effective gradient layer with a smooth transition of the refractive index in the air–silicon interface region.

For a smooth surface, the interface is abrupt, leading to significant reflection losses. After nanosecond processing, a microstructured surface is formed, partially smoothing the refractive index transition. However, the most pronounced effect is observed under femtosecond irradiation, where subwavelength structures provide efficient refractive index matching.

The resulting surface structure leads to reduced reflection and enhanced absorption, directly affecting the photogeneration of charge carriers.

3.3. Spectral Characteristics of Reflectance and Absorption

The simulations show that a smooth silicon surface exhibits a high reflectance in the wavelength range of 400–1100 nm, reaching approximately 0.30–0.35. This leads to significant optical losses and limits the photocurrent.

After nanosecond laser processing, the reflectance decreases to 0.12–0.18, indicating improved optical properties. The most significant reduction is achieved with femtosecond processing, where reflectance decreases to 0.04–0.08 over a broad spectral range (Fig. 2).

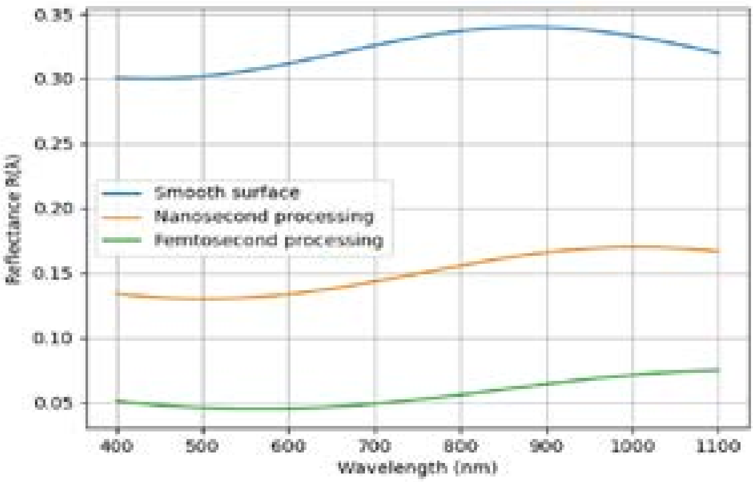

Figure 2 – Spectral reflectance of silicon before and after laser surface modification.

Correspondingly, the absorption coefficient increases from 65–70 % for a smooth surface to 82–88 % after nanosecond processing and up to 92–96 % after femtosecond processing (Fig. 3).

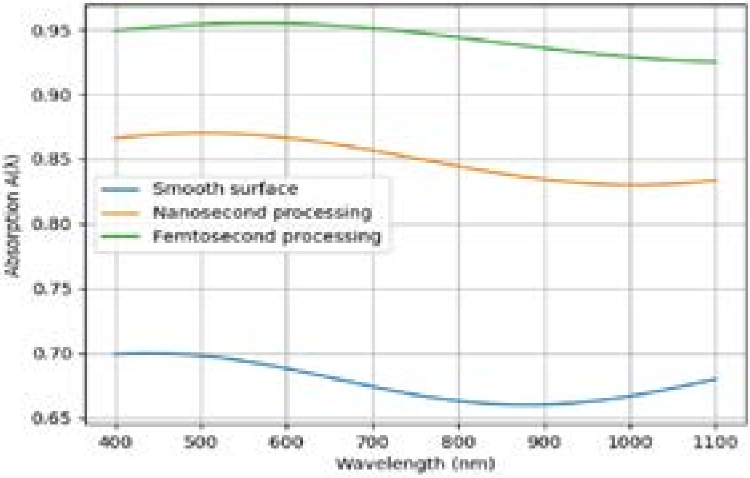

Figure 3 – Spectral absorption of silicon under different laser processing regimes.

The increase in absorption is the key factor responsible for enhanced photocarrier generation and the subsequent increase in photocurrent density.

3.4. Enhancement of Photocurrent Density

Based on the integral photogeneration model developed in Section 2.5, the photocurrent density was calculated for different laser processing regimes.

In accordance with the photocurrent expression, its value is determined by the spectral distribution of absorbed radiation and directly depends on the absorption coefficient A(λ), related to reflectance by A(λ)=1−R(λ).

The photocurrent density of the smooth silicon surface $J_{ph,0}$ is taken as the reference level.

The simulation results demonstrate that laser surface modification leads to a significant increase in photocurrent density due to reduced reflectance and enhanced absorption over the entire spectral range of 400–1100 nm.

It is established that:

- nanosecond processing increases the photocurrent by 15–25%;
- femtosecond processing increases the photocurrent by 30–40%.

The more pronounced increase under femtosecond irradiation is attributed to the formation of subwavelength nanostructures, which ensure efficient refractive index matching and minimize reflection losses.

Thus, the enhancement of photocurrent is a direct consequence of increased absorption, confirming the validity of the proposed physical and mathematical model.

The results are presented in Fig. 4.

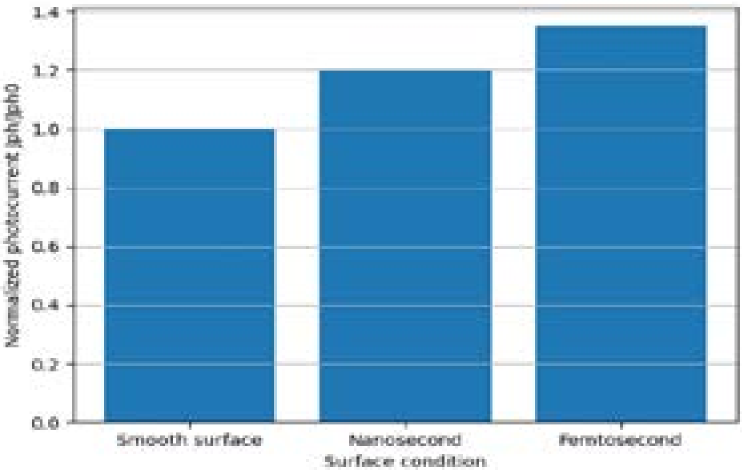

Figure 4 – Relative enhancement of photocurrent density under different laser processing regimes.

3.5. Spectral Dependence of Normalized Photocurrent

To provide a more detailed analysis of the effect of laser processing on photocarrier generation, the spectral dependence of the normalized photocurrent density was considered:

$$J_{ph}(\lambda)/J_{ph,0}(\lambda).$$

Here, $J_{ph}(\lambda)$ is the spectral photocurrent density for the modified surface, and $J_{ph,0}(\lambda)$ corresponds to the smooth silicon surface.

The use of a normalized parameter eliminates the influence of absolute radiation intensity and allows a direct comparison of different processing regimes.

For a smooth surface:

$$J_{ph}/J_{ph,0}=1,$$

which represents the baseline level of photogeneration.

The simulation results show that laser surface modification leads to an increase in photocurrent across the entire investigated spectral range. In particular:

– nanosecond processing results in a moderate increase in photocurrent;

– femtosecond processing provides the highest enhancement, especially in the visible and near-infrared regions.

The obtained dependencies demonstrate that the photocurrent enhancement effect is broadband and is not limited to a narrow wavelength range, as is typical for conventional anti-reflection coatings.

Physically, this behavior is explained by the formation of a gradient refractive index layer with a smooth transition between air and silicon, which ensures efficient suppression of reflection over the entire spectral range.

The results are presented in Fig. 5, which shows the spectral dependence of the normalized photocurrent density.

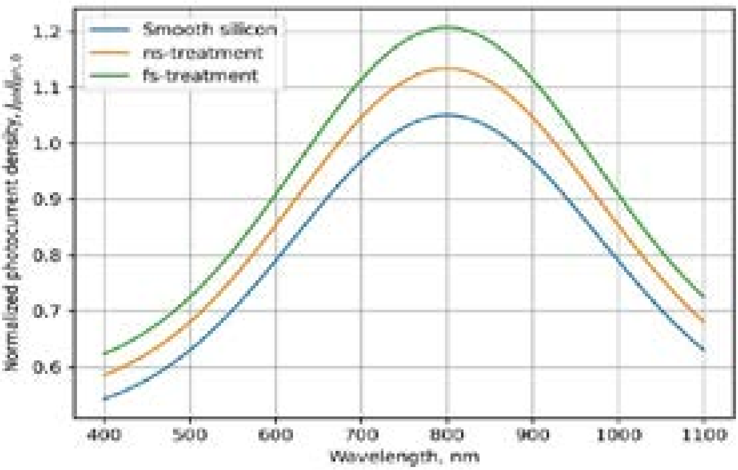

Figure 5 – Spectral normalized photocurrent density ($J_{ph}/J_{ph,0}$) of silicon before and after laser surface modification.

Femtosecond processing provides the highest photocurrent enhancement, despite its greater technological complexity.

4. Conclusions

This study presents a comprehensive mathematical modeling of photocurrent enhancement in silicon solar cells subjected to laser surface modification using femtosecond and nanosecond pulses. The developed model is based on a coupled description of laser–semiconductor interaction, heat transfer, formation of surface micro- and nanostructures, and changes in the spectral optical properties of silicon.

It is shown that the nature of laser-induced surface modification is strongly determined by the pulse duration. The nanosecond regime is dominated by thermal processes, including melting and recrystallization, whereas the femtosecond regime is characterized by non-equilibrium energy deposition and the formation of subwavelength nanostructures with strong spatial localization.

It is established that laser processing leads to the formation of an effective gradient refractive index layer at the air–silicon interface, resulting in a significant reduction in reflectance. In particular, the reflectance decreases from 0.30–0.35 for a smooth surface to 0.12–0.18 for nanosecond processing and to 0.04–0.08 for femtosecond processing. Correspondingly, the absorption coefficient increases up to 92–96 % over a wide spectral range.

The key result of this work is a quantitative evaluation of photocurrent enhancement based on the integral photogeneration model. It is demonstrated that increased light absorption leads to a photocurrent increase of 15–25 % for nanosecond processing and 30–40 % for femtosecond processing. Moreover, it is shown that the photocurrent is an integral function of spectral absorption and is directly governed by the surface morphology formed during laser irradiation.

The analysis of the spectral dependence of the normalized photocurrent reveals that the enhancement effect is broadband and spans the entire wavelength range of 400–1100 nm. This indicates a fundamental advantage of laser-induced nanostructuring over conventional anti-reflection coatings, which are typically limited to narrow spectral ranges.

The scientific novelty of this work lies in the development of a physically consistent model that establishes a quantitative relationship between laser processing parameters, surface morphology, optical properties, and photocurrent. Unlike existing approaches, the proposed model enables a comprehensive assessment of different laser processing regimes while accounting for spectral effects.

The practical significance of the results is associated with the possibility of optimizing laser processing parameters to maximize photocurrent and improve the efficiency of silicon solar cells. The findings can be applied in the development of next-generation high-efficiency photovoltaic devices, including black silicon structures.

Future research directions include accounting for surface and bulk recombination effects, optimization of p–n junction parameters after laser processing, and experimental validation of the proposed theoretical dependencies.

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КРЕМНИЙЛІК КҮН ЭЛЕМЕНТТЕРІНДЕ ЛАЗЕРЛІК МОДИФИКАЦИЯ КЕЗІНДЕ ФОТОТОКТЫ АРТТЫРУ

Бұл жұмыста кремнийлік күн элементтеріндегі фототок тығыздығын арттырудың математикалық модельдеуі лазерлік бет өңдеу әсері жағдайында қарастырылған. Фемтосекундтық және наносекундтық лазерлік импульстердің материалдың оптикалық қасиеттерін және заряд тасымалдаушылардың фотогенерация тиімділігін анықтайтын беткі микро- және нанoқұрылымдардың қалыптасуына әсері зерттелген.

Ұсынылған модель лазерлік сәулеленудің жартылай өткізгішпен өзара әрекеттесуін, жылуалмасу процестерін, бет морфологиясының өзгеруін, сондай-ақ шағылу және жұтылу спектрлік сипаттамаларын кешенді түрде ескеруге негізделген. Наносекундтық импульстер негізінен беттің термиялық модификациясына, оның ішінде балқу және қайта кристалдану процестеріне әкелетіні көрсетілген, ал фемтосекундтық импульстер энергияның жоғары локализациясы мен тепе-тең емес процестер нәтижесінде субтолқындық нанoқұрылымдардың қалыптасуын қамтамасыз етеді.

Лазерлік модификация кремний бетінің шағылу коэффициентін тегіс бет үшін 0.30–0.35 мәнінен наносекундтық режимде 0.12–0.18-ге және фемтосекундтық режимде 0.04–0.08-ге дейін төмендететіні анықталды. Бұл жұтылу коэффициентінің 92–96 %-ға дейін артуымен қатар жүреді. Есептеулер нәтижесінде жарықты жұтудың артуы наносекундтық өңдеу кезінде фототок тығыздығының 15–25 %-ға, ал фемтосекундтық өңдеу кезінде 30–40 %-ға өсуін қамтамасыз ететіні көрсетілді.

Алынған нәтижелер лазерлік нанoқұрылымдау фототокты арттырудың тиімді әдісі болып табылатынын және кремнийлік күн элементтерінің тиімділігін жоғарылату үшін қолданылуы мүмкін екенін көрсетеді.

Кілтті сөздер: кремнийлік күн элементтері; фототок; лазерлік бет өңдеу; фемтосекундтық импульстер; наносекундтық импульстер; нанoқұрылымдар; шағылу коэффициенті; жарық жұтылуы.

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ПОВЫШЕНИЕ ФОТОТОКА В КРЕМНИЕВЫХ СОЛНЕЧНЫХ ЭЛЕМЕНТАХ ПРИ ЛАЗЕРНОЙ МОДИФИКАЦИИ

В работе представлено математическое моделирование повышения плотности фототока в кремниевых солнечных элементах под действием лазерной обработки поверхности. Рассматривается влияние фемтосекундных и наносекундных лазерных импульсов на формирование поверхностных микро- и наноструктур, определяющих оптические свойства материала и эффективность фотогенерации носителей заряда.

Разработанная модель основана на совместном учёте процессов взаимодействия лазерного излучения с полупроводником, теплопереноса, изменения морфологии поверхности и спектральных характеристик отражения и поглощения. Показано, что наносекундные импульсы приводят преимущественно к термической модификации поверхности, включая плавление и рекристаллизацию, тогда как фемтосекундные импульсы обеспечивают формирование субволновых наноструктур за счёт неравновесных процессов и высокой локализации энергии.

Установлено, что лазерная модификация поверхности приводит к снижению коэффициента отражения кремния с 0.30–0.35 до 0.12–0.18 для наносекундного режима и до 0.04–0.08 для фемтосекундного режима, что сопровождается увеличением коэффициента поглощения до 92–96 %. В результате расчётов показано, что повышение светопоглощения обеспечивает рост плотности фототока на 15–25 % при наносекундной обработке и на 30–40 % при фемтосекундной обработке.

Полученные результаты демонстрируют, что лазерная наноструктуризация поверхности является эффективным методом повышения фототока и может быть использована для увеличения эффективности кремниевых солнечных элементов.

Ключевые слова: кремниевые солнечные элементы; фототок; лазерная обработка поверхности; фемтосекундные импульсы; наносекундные импульсы; наноструктуры; коэффициент отражения; светопоглощение.

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