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4.2. РАСШИРЕНИЕ СПЕКТРА ЭФФЕКТИВНОГО ПОГЛОЩЕНИЯ СОЛНЕЧНЫХ ЭЛЕМЕНТОВ С НАНОВКЛЮЧЕНИЯМИ

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Аннотация. В работе исследована возможность расширения спектра эффективного поглощения в солнечных элементах с нановключениями. Показана возможность положительного влияния локальных примесных и дефектных центров на расширение спектра эффективного поглощения. Показано, что наличие глубоких примесных уровней приводит к увеличению коэффициента поглощения, а в совокупности с возникающим под действием нановключений, длинным полем области пространственного заряда приводит к расширению спектра эффективного поглощения в инфракрасную область. Расширение в ультрафиолетовую область происходит благодаря термализации высокоэнергичных электронно-дырочных пар и их разделению в приповерхностном поле новой контактной структуры.

Ключевые слова: примесное поглощение, расширение спектра эффективного поглощения, нанокристаллическая подложка, нановключения.

4.2. EXPANSION OF THE EFFECTIVE ABSORPTION SPECTRUM IN SOLAR CELLS WITH NANOINCLUSIONS

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Abstract. The possibility of expanding the effective absorption spectrum in noncrystalline solar cells using nanoinclusions is shown in the work. The effect of deep centers of local impurities and defects on the expansion of the effective absorption spectrum in solar cells based on a new contact structure is investigated. For example, expansion into the infrared region is due to absorption in impurity centers, and absorption into the ultraviolet region is due to the thermalization process of the resulting electron-hole pairs. the main difference between the proposed structure is that the appearance of electron-hole pairs arises in a region with an integrated electrostatic field. This factor significantly reduces the influence of recombination processes.

Keywords: impurity absorption, expansion of the spectrum, increase in efficiency, noncrystalline substrate, nanoinclusions.

1. Introduction

The conversion process of solar radiation into electricity occurs in an open environment, under various climatic factors and temperature variations. Therefore, the effectiveness of silicon solar cells (SC) under such conditions can be said, bearing in mind the cheapness of the technology for the production of solar cells, the use of cheap materials, durability, stability and stability of their functioning. Therefore, the efficiency of silicon solar cells (SC) in such conditions depends on the cheapness of the solar cells production technology, and the using cheap materials, durability and functional stability.

Consider some factors that are able to limit the effectiveness of solar cells. One of such negative reasons is the narrowness of the spectrum of effective absorption of light. For example, the efficiency spectrum of silicon is equal to the interval from 1.0 to ~2 eV, which ideally is 31.43 % of the total intensity spectrum (see the highlighted part of table 1).

If two more adjacent intervals of the spectrum are involved in the effective absorption of light (in the table the shaded parts), then the width of the intensity spectrum would increase by 23.57 % (IR shift 5.71 %, UV shift – 17.86 %). In this case, the maximum effective spectrum, and with it the theoretical limit of the efficiency of the solar cell, could increase to 55 %.

Table 1

Expansion of the spectrum of effective absorption of a silicon solar cell from 31.43 to 55% due a new contact structure

Spectral range, eV	0–0,5	0,5–1	1,0–1,5	1,5–2	2–2,5	2,5–3	3–3,5	3,5–4	4–4,5	4,5–5	>5
Intensity spectrum, %	6,43		64,29				27,14				2,14
	6,43		31,43		32,86		17,14		10,0		2,14
	0,72	5,71	13,57	17,86	17,86	15,0	10,0	7,14	5,71	4,29	2,14
		IR expansion		UV expansion							

Such a subjunctive formulation of the issue can be translated into the plane of real embodiment only when the achievements of two modern rapidly developing technologies are combined: the technology of obtaining functional nano materials and the technology of semiconductor materials for solar cells.

2. The role of the phonon interaction in the processes of thermalization of energy in the solar cell

The process of converting solar radiation into electricity occurs in an open environment, with different climatic factors and temperature spread. In this mode of operation, the long and normal functioning of solar cells (SC) is possible, if the semiconductor material of its substrate is able to provide a sufficiently rapid rate of thermalization of heated current carriers. This is due to the fact that in parallel with the effective absorption of a rather narrow spectrum of solar radiation (creating electricity), there is also absorption of the rest, the most intense part of the emission spectrum, which leads only to unwanted heating of the solar cell. Therefore, in order to minimize the negative effect of such heating, the mechanism of thermalization of charge carriers in the solar cell is considered.

3. Features of thermalization of charge carriers

The mechanism of thermalization of charge carriers in solar cells is associated, mainly, with the interaction of charge carriers with optical and acoustic lattice vibrations. At high temperatures of operation of solar cells and excitation of high-energy electron-hole pairs, interaction with longitudinal optical phonons (LO phonons) is more important. If the excitation of high-energy electron-hole pairs occurs in the presence of an electric field, it is the emission of LO phonons that is mainly responsible for establishing the so-called saturation rate, which determines the mobility of electrons in the semiconductor.

The role of phonons and phonon interaction is important in calculating the mobility of charge carriers or their transport processes in electric fields, as well as in studying the dynamics of the thermalization of energy in semiconductors used as a substrate for solar cells. [1].

The material of the SC substrate is, as a rule, macroscopic isotropic solids with a cubic or hexagonal crystal structure (wurtzite type or zinc blende type structure). The rate and the relaxation time of the carrier energy undergo a strong dependence on the lifetime of the LO phonons. It is determined by the frequency of emission of LO-phonons. In silicon, the characteristic energy of LO phonons is 20–40 meV, and the relaxation of their energy occurs over times of the order of 2–3 ps [1]. During this time at room temperatures, the photoexcited electron after the emission of the LO phonon runs through a distance of the order of 10^{-7} m, acquiring a saturation velocity of $\approx 10^5$ m/s.

4. The consequence of thermalization of charge carriers

I. The described process of energy relaxation and the parameters of the photoexcited electron arising upon the absorption of high-energy photons (with an energy much greater than the width of the forbidden band) is characteristic both for conventional solar cells and for solar cells with new contact structures (NCS) [2–5]. However, there is a significant difference: in conventional solar cells, the free path of high-energy carriers with the emission of LO phonons is completed by their recombination, so that they practically do not contribute to the photocurrent. A completely different picture occurs in solar cells with NCS, in which a long built-in electrostatic contact field $E(x)$ exists directly at the surface [2]. Although this field is much weaker than in traditional pn junctions, it is very long (one or two dozen microns) and practically covers the entire volume in which light is absorbed. Therefore, a photoexcited electron, emitting an LO phonon at distances $\sim 10^{-7}$ m, practically continues in the thermalized state in this long built-in electrostatic contact field $E(x)$.

The emission of LO phonons (and hence the process of thermalization of photoexcited carriers) occurs in a much shorter time than the lifetime of the current carriers. They manage to reach the electrodes in the contact field $E(x)$ without recombination and thus contribute to the photocurrent, that is, to increase the contribution of the absorption of high-energy photons, which is not observed in solar cells from strictly crystalline materials.

This is the first advantage of solar cells with new contact structures (NCS): the contribution to the photocurrent of electron-hole pairs produced by the absorption of high-energy photons increases.

Advantage of solar cells with new contact structures (NCS) due to the realization of effective phonon thermalization of hot carriers:

a violet shift of the effective light absorption spectrum occurs

II. Another distinguishing feature of a solar cell with a NCS is a strong weakening of the reflectivity of its substrate. It is a substrate of a non-strictly crystalline material (technical silicon) with a large concentration of spatial inhomogeneities and various mutually compensating structural defects (both donor and acceptor nature). Such a decrease in reflectivity leads to an increase in the absorption of light with the production of electron-hole pairs, their separation into an electron and a hole directly in the region of space charge. The presence of a large number of different mutually compensating structural defects reduces the efficiency of recombination centers and increases the corresponding photocurrent (in the spectrum of effective light absorption, an additional small violet shift).

The advantage of SC with new contact structures (NCS) due to the weakening of the reflectivity of its substrate: **an additional small violet shift of the effective light absorption spectrum is realized**

III. The electro-optical properties of a substrate made of non-strictly crystalline technical silicon with a large concentration of spatial inhomogeneities and various mutually compensating structural defects (both donor and acceptor nature) are very similar to the corresponding properties of amorphous silicon. This is due to the fact that the defects form in the forbidden band numerous discrete localized deep states of electrons whose spectrum along the forbidden band is called the energy density states.

The depth of the tailings of the density of states can characterize the observed in the experiments the decrease in the band gap and the light absorption with energy $\hbar\omega < \Delta E_g$ (ΔE_g is the width of the forbidden band of the substrate material). The localized deep states forming the tails of the density of states are many, they are close to each other and therefore hopping conductivity of the current carriers is realized through them. It is precisely such properties of the substrate of a solar cell with an NCS that lead to the possibility of photoexcitation of electron-hole pairs upon absorption of light with energy $\hbar\omega < \Delta E_g$, that is, for silicon SEs, absorption of IR light. All four processes (absorption of light, creation of electron-hole pairs, separation into electrons and holes, transport of current carriers to the corresponding electrodes) occur near the surface within the built-in electrostatic contact field and complete with the formation of an additional photocurrent. We are dealing with an explicit infrared shift of the spectrum of effective light absorption.

The advantage of SC with new contact structures (NCS) due to a large concentration of structural defects and the formation of discrete localized deep states: **a small infrared shift of the spectrum of effective light absorption**

IV. There is another economically important advantage of SE with new contact structures: the built-in electrostatic contact extended field (10–20 μm) is located directly at the surface of the substrate, which makes it possible to reduce the total thickness of the solar cell with the NCS by two or three times compared to the thickness of the substrate in traditional p - n -junctions or heterojunctions.

Economically in silicon solar cells with NCS: **the possibility of a two to threefold decrease in the total thickness of the substrate**

Conclusion

When nanoinclusions are applied to the surface of a silicon substrate, ordered nano-sized islets arise. Under certain conditions, these nano-islands create a space-charge region near the surface. An electrostatic field located near the surface provides an instantaneous separation of electron-hole pairs that arise when a photon is absorbed. At the same time, non-purified silicon using guarantees the presence of a large concentration of impurities. These impurities are activated at energies less than the fundamental absorption energy. As a result, the spectrum of the effect absorption in the infrared region is expanding in this structure. In conventional silicon solar cells, when a photon is absorbed from the violet or ultraviolet region, superactive electron-hole pairs is arise. These electron-hole pairs live very short time and recombine without reaching the space charge region. However, in the proposed structure, electron-hole pairs arise and lose energy due to the thermalization process in the space charge region. It is relaxed with further separation into an electron and a hole. The proposed structure makes it possible to extend the theoretical limit for silicon solar cells from 31.43 to 55 %.

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