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1.5. THE DIFFERENCE BETWEEN THE CONTACT STRUCTURE WITH NANOSIZE INCLUSIONS FROM THE SEMICONDUCTOR PHOTODIODES

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Abstract: In the complex of works [1] has developed a fundamentally new model of the contact structure, which is formed on the illuminated surface of silicon by spraying nanoinclusions with great electrical capacitance from another semiconductor. Photovoltaic converters based on the new contact structure exhibit unique electrical properties.

In this paper we show the important structural differences between the new contact and the traditional semiconductor photodiodes.

Index terms: solar energy, solar cell, nanoinclusions, quantum dots, nanoscale contact structure, nanoscale «p-n junction».

INTRODUCTION

The problem of conversion of solar radiation into electricity consists of three main aspects of solar energy: production, transport and storage of solar energy.

The paper mainly studied ways to improve the efficiency of solar conversion process (or process development and production of alternative energy).

In many semiconductor devices used high purity single crystal silicon.

Application of single-crystal silicon in the manufacture of mass production solar inverters is not profitable from a commercial point of view, because of the complex an expensive technology of their production.

The problem of mass production solar energy in the world is solved a long time and some progress in this direction.

Despite this, the growing market for solar power products new demands for cheaper of materials used in solar energy, lengthening the guaranteed service life of solar energy systems, and improving their sustainability and stability.

Only some non-traditional approaches combining can satisfy these requirements, for example, the achievement a variety of modern innovative technologies.

In [1-5] l has been developed the model and defined electrical properties of solar cells on a fundamentally new contact structure based, which contains a large number of semiconductor nanoscale component (or nanoinclusions or semiconductor nanoheterostructures).

Since the properties of the material nanoinclusions largely determined by its geometric structure and quantitative parameters, it is quite obvious that the electrical properties of solar cells with a new contact structure are quite different than traditional solar cells.

The work is carried out a detailed examination of the distinctive features of the new solar cell contact structure (hereinafter, they are called "solar cells with nano-sized contact structure").

THE SOLAR CELL WITH NANO-SIZED CONTACT STRUCTURE

Unlike traditional solar cell, consisting of two layers of silicon with p- and n-type conductivity, the material of the solar cell substrate with nanoscale contact structure represents a single homogeneous silicon conductivity type (or p- or n-type)

The illuminating surface of the Si substrate is covered nanoinclusions (NI), with great electric capacity, by ion implantation (or molecular beam epitaxy and vapor phase), but from other than Si semiconductor (so they can be considered nanoheterostructures).

This factor leads to the appearance of differences of electro physical properties between the nano-sized contact structure solar cell, and the traditional contacts.

The nanoinclusions application on the illuminated surface of the substrate are the centers of formation of individual "nanoscale p-n junctions", which is a lot, and which is connected in parallel [6], to form an electrical circuit.

On the substrate is formed a lot of "nanoscale p-n junctions" at each nanoinclusions deposited on the illuminated surface of the solar cell substrate (about 1,5 ÷ 3 million on 400 mm^2).

Detail "nanoscale p-n junction" in the next section.

> *The solar cell with nano-sized contact structure – is electric circuit of a plurality many parallel-connected "nanoscale p-n junctions" on its substrate*

Another feature of the solar cell with the nanosized contact structure is cheap substrate of silicon, which is two orders less expensive that monocrystalline silicon and order less expensive of polycrystalline.

At the same time, solar panels on their basis can have almost the same performance parameters, as well as traditional industrial (and this in spite of the substantial substrate cheapness). In the solar cell substrate with nanoscale contact structure is formed the space charge region (SCR) with its contact electrostatic field. In this field absorbed solar radiation, born electron-hole pairs, the same field separates on the electron and the hole, and transports to the electrodes (electrons – the positive and the holes – to negative).

METHODS OF COATING NANO INCLUSIONS ON THE ILLUMINATED SURFACE

Nanoheterostructures possess unique physical properties of ideal quantum dots. They are perfect crystal and a high degree uniformity in size. Such structures can be obtained based on the effect of self-organization in semiconductor nanostructures geteroepitaksal semiconductor systems [7-9]. These structures exhibit unique physical properties of ideal quantum dots (although the dimensions may exceed the characteristic parameters of quantum dots, ie, 5-9 nm).

Spontaneous emergence on the surface periodically ordered nanoheterostructures is a manifestation of self-organization in condensed matter. Ordered nanostructures arise during annealing or during crystal growth. Ordered nanostructures adjacent different lattice constant. They are sources of long-range fields of elastic stresses. Experimental studies of arrays coherently strained islands showed the possibility of a narrow distribution of the islets in size, as well as the correlations in the distribution of islets, typical square lattice, that is spontaneous ordered nanostructure. The equilibrium state in the island system is achieved through the exchange of material between islands on the surface. The theoretical analysis of the interaction between the islands showed that if the change in the surface energy of the system during the formation of one island in the negative, then the system does not have a tendency to coalescence. In other words, in this case, an equilibrium may exist island array having a certain optimum size and arranged in a square lattice. Ordered arrays of islets were obtained by molecular beam epitaxy. Pyramidal islets array having a square base and a length of 14 nm, a thickness of the deposited with InAs at 4 monolayers. Arrays of vertically coupled quantum dots of indium arsenide InAs receive successive deposition of GaAs, is deposited and the amount of InAs is that only partially cover the InAs – pyramid.

Spontaneous Generation periodically ordered nanostructures on the surface and in the epitaxial semiconductor is a manifestation of self-organization in condensed matter. Ordered nanostructures may occur during annealing, or during crystal growth. All ordered nanostructures adjacent domains differ in lattice constant and / or surface structure, so the domain boundaries are sources of long-range fields of elastic stresses.

The use of quantum dots as the active medium in different heterostructures with electronic devices (such as diode lasers) provides Luciano properties compared with the same quantum well devices. Currently, semiconductor nanoheterostructures prepared essentially by molecular beam epitaxy and vapor phase.

INDIVIDUAL "NANOSCALE P-N JUNCTION"

According to the model used by the solar cell substrate with a contact structure coated nanoscale nanoinclusions strictly in an amount equal to the surface concentration of residual impurities $N_D^{2/3}m^2$ (N_D – the concentration of residual impurities, and $b = N_D^{-1/3}$ – means distance between them). The need for abnormally high electric capacity nanoinclusions material provided by the selection of a semiconductor other than Si, and an extremely large value ε_N – dielectric constant (at the silicon $\varepsilon_{Si} = 12$).

These substances exist in nature, for example, lead chalcogenides (PbS, PbTe and PbSe):

$$\varepsilon_{PbS} = 175,\ \varepsilon_{PbTl} = 450,\ \varepsilon_{PbSe} = 250.$$

Abnormal electrical capacitance nanoinclusions material provides intensive collection and accumulation of electric charges. The collection and accumulation of charge in nanoinclusions material is carried out in the process of establishment of thermodynamic equilibrium between the substrate materials (technical silicon) and nanoinclusions (PbS, PbTl or the PbSe). Speed and direction of flow of the charge in establishing thermodynamic equilibrium is determined by the difference between the work functions of the substrate material (A_{SI} – silicon) and nanoinclusions (A_N): $A_N – A_{SI}$.

Charges (electrons if the substrate Si n-type and holes, if the substrate Si p-type) are accumulated on the free discrete quantum energy electronic states nanoinclusions (on states, so-called "conduction band", as so-called "valence band" – is completely filled). The source of the accumulated charges are small residual impurities in the technical silicon. They naturally (material of the solar cell substrate is continuously at temperatures of the order of 300K and above) are always present in the silicon in a small amount (1017 ÷ 1019 m-3), and are always in an ionized state, that is in the form of ionized donors and free electron. Importantly, it is not doped with impurities, but the natural residual impurities! *The source of the accumulated charges on nanoinclusions are not doped impurities but natural residuals!*

These free charge carriers ionized subsurface residual shallow impurities flow and collected in a power-nanoinclusions (transverse dimension which may be in the range 5 ÷ 35 nm).

On the illuminated surface of the substrate in each power- nanoinclusions with localized electrons, a region of negative charge (nanoscale "p region"), and in the substrate with a long succession of ionized residual shallow impurities (donors) – an area of positive charge (macrodimension "n-region"). If each nanoinclusions concentrates the N electrons, the substrate is laid bare to the length d = b · N. Along the entire a new length contact, with contact electrostatic field. Deeper than d = b · N field is absent ($q = e^{+} \cdot e^{-} = 0$).

For example in fig. 1 shows the formation a contact electrostatic field of N = 4 capture electrons (depth d = 4b) in the substrate evenly (at a distance b) the distribution of the residual impurities.

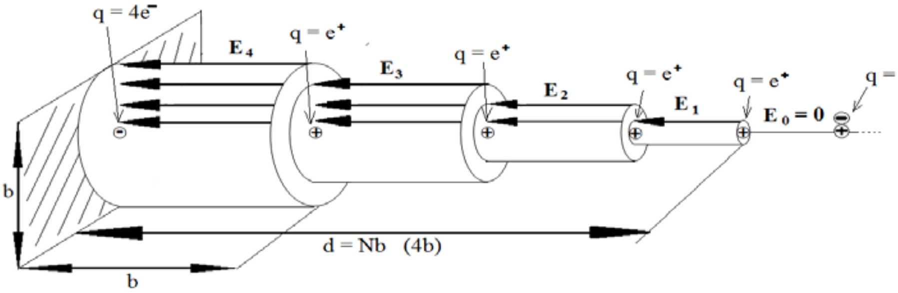


Figure 1. Formation of the contact field in the "nanoscale pn junction".

THE CHARACTERISTIC PARAMETERS OF "NANOSCALE PN JUNCTION"

Follows from the above that a new contact – a system of local area (almost a point) of the positive n-region (the range 5 ÷ 35 nm) and the long negative p-type region ($d = b \cdot N$, $b = N_D^{-1/3}$) . Along the length of the p-type region formed electrostatic contact field. As can reach several tens of microns depending on the concentration of residual impurities N_D length of the p-region.

Spatial parameters allow a new contact to call it "nanoscale", and electrical characteristics – "p-n transition." In general, therefore, it is – "nanoscale p-n junction" – NPNJ. The quotation marks in the title emphasize its nanoscale nature.

This is not a traditional pn junction (one semiconductor type), this is not a heterojunction (just different types of semiconductors), it does not contact metal-semiconductor (different types of materials).

It is the contact of two different geometrical and physical entities – contact between nanocrystal semiconductor and another semiconductor macro object.

The peculiarity of "nanoscale p-n transition," – is the contact between the electrostatic field of nano-objects and macro object

For the "nanoscale pn junction" is characterized by the following parameters:

The average size of each cross nanoinclusions R about 5 ÷ 35 nm. The area of coverage of the substrate surface does not exceed 5 ÷ 8%.

Material nanoinclusions must have a large ε_N relative permittivity, the value of electric capacity $C_o = \varepsilon_N \cdot R/\kappa$ was great ($\kappa = 1 / (4 \cdot \pi \cdot \varepsilon_o)$; εo – the dielectric constant).

The work function nanoinclusions material (A_{QD}) should be different from the work function Si (A_{Si}), so that at the point x along the axis of "nanoscale pn junction" contact potential difference $\phi_k(x)$ is determined by the difference between the value of $\Delta\mu = A_{QD} - A_{n\text{-}Si}$, ie $\varphi_k(x)=\Delta\mu/e = C_o \cdot \varphi_o^2/2$ ($\phi_0 = \phi_k(x = 0)$) – contact potential difference on the surface of the substrate).

Calculation of Gauss's theorem, the vector of the electrostatic field of the $E_k(x)$ along the axis of "nanoscale pn junction" leads to the relation:

$$E_k(x) = -(\gamma/b)\cdot(N - [x_k]), \qquad (1)$$

and for coordinate dependence ϕk (x) the relation:

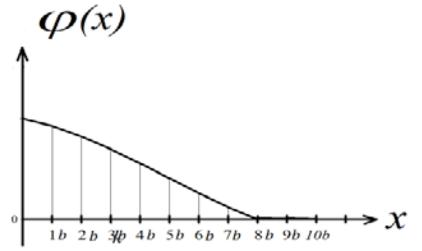
$$\phi_k(x) = -\int E_k(x)dx;\ \phi_k(x=0) = \phi_0 = \gamma\cdot N\cdot(N+1)/2 \qquad (2)$$

They were obtained under the following boundary conditions:

$\mathbf{E}_N(x=x_N=d) = 0$ and	$\phi_k(x_k) = \phi_k(x=x_N= d) = 0$	when $x = = x_N = d$
$\mathbf{E}_0(x=0) = \mathbf{E}_0 = = -\gamma\cdot N/b$ and	$\phi_k(x_k) = \phi_k(x=0) = \phi_0$	when $x = 0$

There $\gamma = 4\cdot\pi\cdot\kappa\cdot e^+/(\varepsilon_{Si}\cdot b)$; $[x_k]$ – integer x- coordinate in b terms (k varies $0 \le k \le N$).

Electrostatic contact field (1) shown in Fig.1 (where N = 4) and the contact potential difference $\phi_k(x)$ in accordance with equation (2) – on fig.2 (where N = 8).



Equations (1 and 2) also made it possible to determine the dependence of space charge region width d on the parameters of a new contact structure:

$$d = (2\varepsilon_N\cdot R\cdot b^2\cdot\Delta\mu/(\kappa\, e^2))^{1/2} \qquad (3)$$

It is seen that the larger the permittivity nanoinclusions, the greater d. The width of the space charge region may be greater than the electron diffusion length in Si or light penetration length of the solar cell. Hence, the efficiency of solar cells based on the "nanoscale pn junctions" can be controlled not only by varying the density nanoinclusions on the illuminated surface of the solar cell (or the number of "nanoscale pn junctions"), but also the selection of the material nanoinclusions (ε_N).

From the analysis of the relations (1-3), and Figures 1 and 2 that:

- to along each "nanoscale pn junction" contact electrostatic field – piecewise uniform and abruptly changing the value of γ / b;
- in the transverse direction (up to hundreds of nm2) field – is fragmented, and the E_k (x)the power line at each point – a concentric circle;
- the potential of ϕ_k (x) along the axis of "nanoscale pn junction" decreases linearly to zero at x = d (rather than square as the traditional p-n junctions), but the decline is slow (in the middle of the transition it is equal to $0{,}6 \cdot \phi_0$);
- the width of the space charge region d may be greater than the electron diffusion length in Si or light penetration length in the solar cell, so this is another factor in the efficiency of solar cells based management "nanoscale pn junctions" (changing ε_N manage value d).

FROM NANOWATTS ELEMENTS TO KILO AND MEGAWATT DEVICES

Many individual "nanoscale p-n junctions" forms an electrical circuit. The number of individual "nanoscale p-n junctions" is proportional to the surface density nanoinclusions. They are connected in parallel to one another, forming a solar cell (Figure 3-a). With the circuit current collection grid by means of carbon nanotubes, which connects between them all "nanoscale p-n transitions." The entire surface is covered with a special gel, forming a transparent protective layer.

Geometrical parameters of a solar cell are selected based on the technology of preparing its substrate and may be different.

In turn, the electrical circuit consisting of many solar cells connected partly parallel and partly in series, [6] form a solar panel (Figure 3-b). This solar panel structure provides the optimal selection of parameters and the most efficient mode of its operation.

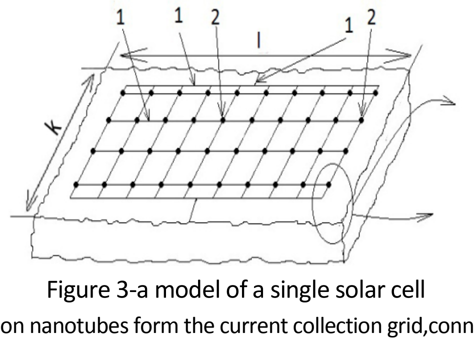


Figure 3-a model of a single solar cell

1-carbon nanotubes form the current collection grid,connecting all NPNJ in a parallel circuit. 2 each point – this one with NI NPNJ (CSR it goes deep into the substrate). One NI with NPNJ allocated in a circle. Its enlarged in Figure 1.

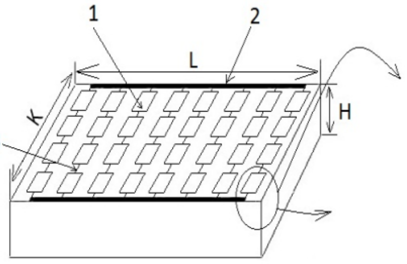


Figure 3-b. Layout separate solar panel

1-panels of mosaic located, fully autonomous individual solar cells. 2 -metal bus (electrodes). 3 – *K/k* pieces – series. SE in a circle *L/l* units are connected in parallel and is given in Figure 1a in an enlarged form 1b.

To quantify the properties of solar photovoltaic converters based on the "nanoscale pn junctions", we introduce the notation of the optimal parameters. Respectively,

for an individual "nanoscale p-n transition" (Figure 1)
i_o – photocurrent, ϕ_o – contact potential difference, $p_o = i_o \cdot \varphi_o$ – output power
for a solar cell (Figure 3-a)
the length = k, width= l, area $s = k \cdot l$, the number of parallel-connected "nanoscale pn junctions» $v = s / b^2 = k \cdot l / b^2$, b^2 – the surface area, which is separate nanoinclusions, the total photocurrent of v – transitions: $i = v \cdot i_o = (k \cdot l / b^2) \cdot i_o$ (4) produced the total power: $p = i \cdot \varphi_o = v \cdot i_o \cdot \varphi_o = (k \cdot l / b^2) \cdot \varphi_o \cdot i_o = (k \cdot l / b^2) \cdot p_o = N \cdot p_o$ (5)
for solar panels (Figure 3-b)
the length = K, the width = L, the area $S = K \cdot L$, Φ_o – output voltage I – current of the solar panel, along the length K in number are connected in series K / k solar cells, along the width L paralleled L / l rows the output voltage of the solar panel: $\Phi_o = \varphi_o \cdot K / k$ (6) the total photocurrent of a solar panel: $I = i \cdot L / l$ (7) The total power of the solar panel P: $P = I \cdot \Phi_o = \varphi_o \cdot (K/k) \cdot i \cdot (L/l) = \varphi_o \cdot (K/k) \cdot (k \cdot l/b^2) \cdot i_o \cdot (L/l) = p_o \cdot (K \cdot L)/b^2 = P$ *(8)*

Equations (4-8) provide a selection of the most optimal solar panel parameters with a view to finding an effective regime of its functioning. Furthermore, they demonstrate a crucial role "nanoscale pn junctions" in the process of converting sunlight into electricity.

Evaluation of these relations held with the following parameters of the solar panel:

$K = 0.8\ m,\ L = 0.6 m;\ k = 2 \cdot 10^{-2} m = l;\ N_D = 10^{18} m^{-3};$

$b^2 = 10^{-12}\ m^2;\ \varphi_o = 0.2V,\ i_o = 2 \cdot 10^{-9} A,\ p_o = 4 \cdot 10^{-10} W.$

Calculation shows that $\Phi_o = 8V,\ I = 24A,\ P = 192\ W$.

It follows from these estimates that

- Industrial solar panels of similar dimensions derived from expensive silicon single crystal, have almost the same power (about 180 ÷ 200 W);

- table impressive power ($P = 192W$) are obtained by adding a large number of (v) parallel-connected power (p_o) separate "nanoscale pn junctions", i.e. $v = 4 \cdot 10^8$ pieces, and $p_o = 0{,}4nW$;

- Change the size of the solar panel, it is possible to vary the value of the output photocurrent I and Фо voltage, leaving unchanged the value of the output power P;

- uvelichivaya square designs of solar panels can be quite easy to build a kilo and megawatt unit.

CONCLUSION

The work carried out to develop a theoretical model of the solar cells with nano-sized contact structures (SC NSCS). They (SC NSCS) are fundamentally different from traditional contacts in their electro physical properties and can provide the conditions for optimal and highly efficient conversion of solar radiation into electricity.

The use of solar cells with nano-sized contact structures are able to provide increased efficiency of alternative renewable energy sources (RES), as well as significantly reduce the cost of solar energy in general. In addition, improving the efficiency of solar conversion will speed up the process of transition from a hydrocarbon energy to other, alternative energy.

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