

# SOLAR CELLS ON THE NEW CONTACT STRUCTURE BASIS

T. A. Djalalov

**Abstract**— In the work presented a theory of absolutely new type of solar cell. In view of certain technological factors of their creation, they are becoming cheap, durable and stable. Similar advantages (especially their cheapness) arise due to the use the homogenized technical silicon as a solar cell substrate.

**Index Terms**— solar cell, Solar panel, price reduction, stability properties, p-n junctions, new contact structure, electrical properties, nanoscale p-n junction, semiconductor-nanoinclusion contact .

## 1 INTRODUCTION

THE monocrystalline silicon to was used for created of a lot of semiconductor devices, because devices often work in conditions with a combination of large displacement and density currents on the switching regime [1]. On the high-purity monocrystalline silicon (purity  $<10^{-8}$ ) to was used also for created of effective solar converters.

However, using the monocrystal silicon as the basis of solar cells is not always justified from a commercial point of view, since manufacturing of solar radiation converters - mass production produces such as solar panels for helio- electric power stations, is expensive and requires sophisticated technology.

The everyday expanding market of products on solar energy puts more stringent requirements on the parameters of solar energy efficiency. First of all, this concerns the need to:

- price reduction of used materials,
- extension of the guaranteed life of the structures,
- provide sustainability and stability properties of the solar cell.

These demands of market are stimulate the innovative approaches and more efficient technologies. On the paper we propose one of the prospects for the variants of solving this problem.

## 2. THE SEARCH DIRECTION

The idea of approaching the problem in the present study was borrowed by us from [2], in which the high efficiency of conversion of visible light radiation into electricity is achieved by two factors:

- division of photocell (p-n junction) to many separate same type p-n junctions,
- use of silicon with a high level defect (enough

defective silicon) substrate as a photocell.

Dividing technology was that the surface of the semiconductor substrate, the conductive thin photocell tire was broken into small pieces and then combining them in the current electrodes parallel circuit. Experiments to transform such photocell light confirmed that the greater the numbers of partitions, the better become the photocell converting properties.

So it seemed, was not to be, because the partition leads to a reduction of certain parameters of the same type p-n junctions, including the value of its photocurrent and, accordingly, the power generated by them. And in the experiment observed the opposite: efficiency increase. Most likely, this is connected with a decrease of thermal loss due to activation of the so-called defect-free areas of the photocell (the authors call them "capillaries"). The number of defect-free regions increases proportionally, firstly, granularity and, secondly, the number of different structural defects. It was in this defect-free areas that appear at the boundaries of structural defects.

According to [2], these two factors (division photocell many p-n junctions and the use of silicon with a high level defect) were decisive to increase the efficiency of the photocell.

Increased substrate defects not only prevented, but on the contrary, only helped to improve the conversion parameters

## 3. NEW CONTACT STRUCTURE AND ITS DISTINGUISHING PECULIARITIES

3-a. Attempting to apply the idea of partitioning the contact's structures and the idea of using highly defective materials to massive solar cells (SC) solar electric power stations (solar stations), usually working a long time in the open area, has been carried out in the [3]. As a result, a model of principally new contact structure (NCS) was developed and carried out theoretical calculations of all its electrical properties.

• Temur A.Djalalov: senior teacher of TUIT, [tdjalalov@gmail.com](mailto:tdjalalov@gmail.com)  
(Tel:998935153609)

3-b. The material of substrate of new contact structure's is homogeneous silicon with a single kind of conductivity. This is not a traditional generally accepted of p-n junction with two different layers of silicon (p- and n-) conductivity types. This is same type of semiconductor substrate from inexpensive silicon (or p- or n-type). A lot of small individual contact structures with nanoscale parameters was created on its illuminated surface. This means that on the solar cell, for example, with an area of 400 mm<sup>2</sup> placed not hundreds or thousands (as in [2]), and 1,5 ÷ 3 millions nanosized's contacts.

Division of p-n junction in [2] carried conductor bars. At the same time they served as electrodes for take down of photocurrent.

3-c. The partition in the new contact structure, as such, do not exist. By ion implantation [4] the illuminated surface of the substrate is covered nanoinclusions (NI) from very anomalous high electric capacity's semiconductor, but other than the silicon. In the process of establishment of thermodynamic equilibrium between nanoinclusions on the substrate surface and its volume appear a peculiar contact structure (Figure 1).

The electrostatic field of such contact is shaped like a safety pin: electric capacity nanoinclusion - is a "head" pins, and a long series of ionized donors - is "needle" pins. "Head" pins has  $q$  - a charge and  $R$  - a transverse dimension ( $q=N \cdot e$ , there  $e$ -electron's charge,  $R$  - of the order of a few nanometers), and "needle" pins - consist  $N$  item donors the order of several microns deep into the substrate.

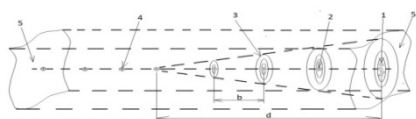


Figure 1. An enlarged view of one "nanoscale p-n junction" - NSPJ:

- 1- nanoinclusions; 2- ionized donors; 3 - lines of force of the field; 4 - neutral donors; 5 - part illuminated substrate and a back surface; b - the average distance between impurities; d - the thickness of the space charge region

It is contact with a separate nanoinclusions called us [3-6] NSPJ - "nanoscale p-n junction".

3-d. The expression nanoscale p-n junction take in inverted commas, because its have another nature then a traditional structure. It is not p-n junction (single kind semiconductors), it is not getero-junction (different kind semiconductors) one it is not a metal-semiconductor contact (a different kind of materials).

It is contact of two a different kind geometrical and material formation - it is contact of semiconductors nanoinclusions with macro-object from another semiconductor.

3-e. Material nanoinclusions which use at the creation "nanoscale p-n junction" must to satisfy following factors:

- means cross sizes of nanoinclusions were relatively small (about 10÷35 nm),
- nanoinclusions coverage the area of substrate surface does not exceed 5÷8%;
- material of nanoinclusions must have a very large value of the dielectric constant  $\epsilon_N$  (electrical capacitance  $C_o$  is large);
- the work function of nanoinclusions ( $A_{QD}$ ) should be quite different from  $A_{Si}$  - the work function of Si.

In this case, it achieved a sufficiently high value  $\phi_k(x)$  - the contact potential difference (CPD):

$$A_{QD} - A_{n-Si} = \Delta\mu = C_o \cdot \phi_o^2 / 2; \quad \phi_k(x=0) = \phi_o \quad (3.1)$$

where  $\phi_o$  - CPD at the substrate surface.

Formation "nanoscale p-n junction" is accompanied by the work on the establishment of thermodynamic equilibrium with the alignment of the Fermi levels between the contacting materials. This work is carried out by  $\Delta\mu$  energy equal to the difference between the work functions (3.1).

Lead telluride (PbSe, PbS or PbTe) suited as best material for nanoinclusions, because they have  $\epsilon_N \gg 1$  ( $\epsilon_N=250$  at the PbSe,  $\epsilon_N=175$  at the PbS,  $\epsilon_N=450$  at the PbTe) [6].

3-f. "Capacity" nanoinclusion (number of received charge  $N$ ) is determined by (3.1): the difference between the work functions of  $\Delta\mu$ , capacitance  $C_o$  and the potential  $\phi_o$ . In the proposed model the thermodynamic value of electric capacity should be large enough to contain a small space of nanoinclusion to concentrate a large negative charge  $q=N \cdot e$ .

For big "capacity" nanoinclusion must to be big thermodynamic the electrical capacitance ( $C_o$ ).

Concentrated charge  $q$  is proportional to the electrical capacitance ( $C_o$ ), and it, in turn, is proportional to  $\epsilon_N$  and  $R$  - cross nanoinclusion size, it has a large electric capacity of solar cells is determined by high values of:  $R$ ,  $q$  and  $\epsilon_N$ .

3-f. Number nanoinclusions applied to the solar cell, and therefore the number "nanoscale p-n junctions" agree with surface concentration  $N_D^{2/3}$  residual impurities.

Technically silicon has  $N_D$  about  $10^{12} \div 10^{13} m^{-2}$ , that is, only extremely a few. At the same time, extremely high average distance between the residual impurities  $b = N_D^{-1/3}$ .

Heavily defective silicon with extremely low value of the concentration of donors  $N_D$  (or residual impurities) is almost own! a semiconductor with a small value of conductivity.  $N$  electrons go to the every nanoinclusion in the process of establishing thermodynamics equilibrium. A contact area forms on the substrate. Its length equal:

$$d \approx b \cdot N = N \cdot N_D^{-1/3} \tag{3.2}$$

Since the order of the scope of influence  $b$  equal  $0.4 \div 1.0$  micron, even if a small amount of contact occurs  $N$  electrostatic field will have a fundamentally new structure: it has long needles.

All contact structure can be represented as a pile (set) of growing deeper into the substrate parallel planes, some of which ( $N+1$  pieces) - charged (Figure 2).

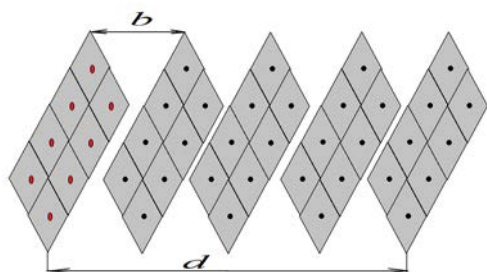


Figure 2a

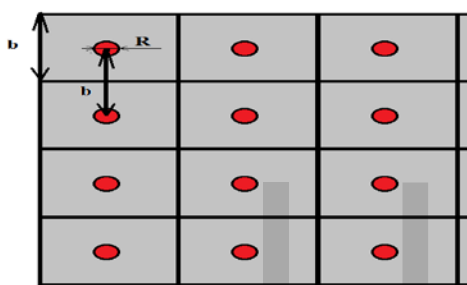


Figure 2b

The first plate (2b) - this surface of the substrate with local negatively charged ( $q = N \cdot e^-$ ) nanoinclusions ( $N$  electrons went from the residual impurities). And the rest of her plate (2a) - contain uniformly distributed residual impurities ( $N$  pieces of them - positively charged ionized donors  $q = e^+$ . And the rest of plate - neutral plate).

It can be seen that

-for each negatively charged nanoinclusion (p-region) is a long line of ionized donors. (n-region);

-thus was formed the contact structure in which the p-and n-regions of the contact structure are of different nature;

-nanoinclusions localized on these  $N$  electrons ( $N$  pieces) forming the p-region and have the size of the cross  $10^2 \div 35$  nm - that is nano sized, because can to regard nano inclusion as quantum dots, which have (consist)  $10^2 \div 10^5$  atoms;

-the combination of all separately contact structure near every nanoinclusion (which was to cover illuminated surface of the substrate) formed of principle new contact structure (NCS) or the combination of all "nanoscale p-n junctions", formed on the substrate.

The monocrystalline silicon to was used for created of a lot of semiconductor devices, because devices often work in conditions with a combination of

large displacement and density currents on the switching regime [1]. On the high-purity monocrystalline silicon (purity  $< 10^{-8}$ ) to was used also for created of effective solar converters.

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#### 4. NANODIMENSIONAL PN JUNCTION

4-a. Calculating according to Gauss theorem, [3-6] vector of the electrostatic field  $E_k(r)$  through an arbitrary closed surface covering new contact structure (Fig. 2a shows its substrate as a stack of parallel planes) it allowed us to obtain the electrical parameters of the new contact structure.

In particular, for the strength of the electrostatic field along the "nanoscale pn junction" axis obtained the equation:

$$E_k(x) = - (\gamma/b) \cdot (N - [x_k]) \tag{4.1}$$

and coordinate dependence of contact potential difference between the illuminated surface of the substrate and the point  $x = x_k$  (or  $\varphi_k(x)$  - the potential at the point  $x$ ) determined by the expression:

$$\varphi_k(x) = - \int E_k(x) dx; \quad \varphi_k(x=0) = \varphi_0 = \gamma \cdot N \cdot (N+1)/2 \tag{4.2}$$

where  $\varphi_0$  - potential of  $\varphi_k(x)$  at  $x = 0$ ;  $\gamma = 4 \cdot \pi \cdot \kappa \cdot e^+ / (\epsilon_{Si} \cdot b)$ ;  $\kappa = 1 / (4 \cdot \pi \cdot \epsilon_0)$ ;  $[x_k]$  - in  $b$  units the integer of  $x$ -coordinate ( $k$  varies  $0 \leq k \leq N$ );  $\epsilon_0$  - dielectric constant,  $\epsilon_{Si}$  - dielectric permittivity of the Si.

Coordinate dependence (3.1 and 3.2) were obtained under the following boundary conditions:

$x = x_N = d$	
$E_N(x=x_N=d)=0$	$\varphi_k(x_k)=\varphi_k(x=x_N=d)=0$
$x = 0$	
$E_0(x=0)=E_0=-\gamma \cdot N/b,$	$\varphi_k(x_k)=\varphi_k(x=0)=\varphi_0$

Figure 3 shows (in the case of  $N = 8$ ), the coordinate depending of the electrostatic field  $E(x)$  (4.1) and the contact potential difference  $\varphi(x)$  (4.2):

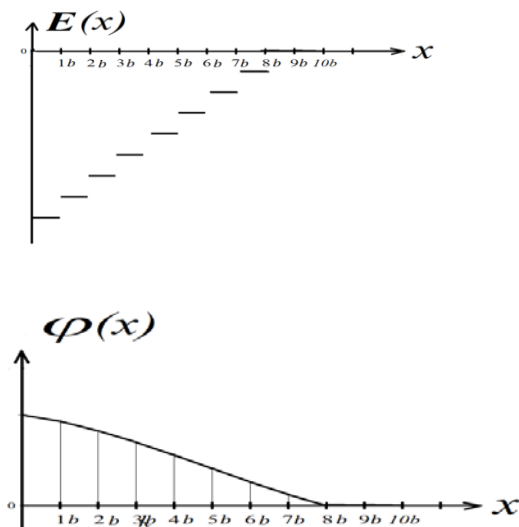


Figure 3

It follows from the analysis (4.1 and 4.2):

-  $E(x)$  of each "nanoscale pn junction" along its axis discontinuously uniform and field lines are directed to the substrate surface and stepwise lines, the quantity of each jump is  $\gamma/b$ ;

-  $E(x)$  nonuniform in the transverse direction (in the range of hundreds of nm) and field lines are concentric circles, similar to the coaxial tapered solid angles are inserted into each other (field line 3 in Figure 1);

-  $\varphi_k(x)$  is continuous (but not monotone) - decreases to zero in a broken line at  $x = d$ , interplanar spaces inside - varies linearly, instead square as a standard p-n junctions ;

-  $\varphi_k(x)$  decreases sufficiently slowly ( $\varphi_k(x) \approx 0,5 \cdot \varphi_0$ ) in the middle of the space charge region).

4-b. With the help of the relations (3.1 and 3.2), and taking into account (2.1 and 2.2), the width of the space charge region (SCR) of the new contact structure has been determined:

$$d = (2\epsilon_N \cdot R \cdot b^2 \cdot \Delta\mu / (\kappa e^2))^{1/2} \quad (3.3)$$

A numerical estimate is shown that the  $d$  values can take from a few to tens of microns and depending on the  $R$ ,  $\epsilon_N$  and  $b$  ( $b = N_D^{-1/3}$ ), that is superior to the diffusion length of electrons in the silicon, and the penetration length of light in the solar cell.

The  $d$  substantially depends on the dielectric constant  $\epsilon_N$ .

Therefore, the use of lead chalcogenides [10] with the anomalously high values of  $\epsilon_N$  can provide a strong elongation of the space charge region.

4-c. But this means that in a solar cell new contact structure based all of micro-processes associated with the conversion of light:

- light absorption;

- production of electron-hole pairs;
- charge separation;
- drift of separated charges through the field to the respective electrodes

will mainly occur in the region where there is an active electrostatic field.

This fact determines the innovative properties of solar cells based on new contact structures.

## 5. SOLAR PANEL'S STRUCTURE

5-a. Above, we considered the properties of the isolated individual "nanodimensional p-n junction".

The electrical circuit (Figure 4), formed from a plurality parallel-connected individual "nanodimensional p-n junctions", is a fundamentally new contact structure (NCS). This new contact structure is capable to make cost-effective the photoelectric conversion.

New contact structure - a set of many parallel-connected "nanodimensional pn junctions" on a substrate of a solar cell

The space charge region (SCR) of the new contact structure formed by "nanodimensional p-n junctions", created by nanoinclusions on the illuminated surface of the substrate of the solar cell, (Figure 4).

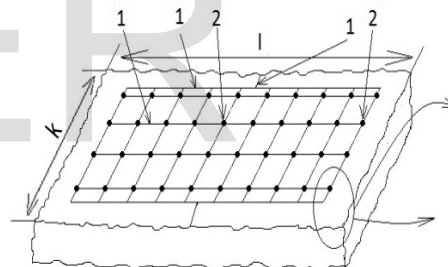


Figure 4. Model of of the solar cell

1-carbon nanotubes form the current collection grid, connecting all nanodimensional p-n junctions in a parallel circuit.

2 point - it is one with nanoinclusion with nanodimensional p-n junction (the space charge region goes deep into the substrate).

5-b. The parallel connection of the individual "nanodimensional p-n junctions" and the current collection function is performed by a single-layer grid of carbon nanotubes.

This grid provides:

- optical transparency of the substrate (carbon nanotubes are nanoscale lateral dimensions);
- the most optimal and efficient current collection due to high electrical conductivity (conductivity of carbon nanotubes is several times greater than the conductivity of copper).

The spaces between the carbon nanotubes filled special gel heat-resistant and transparent for the light [9].

The resulting film is able to provide protection and long-term operation of a solar cell.

5-c. From a consideration (Figure 4) the properties of the isolated individual solar cell on the new contact structure basis, move on to the solar panel (Figure 5).

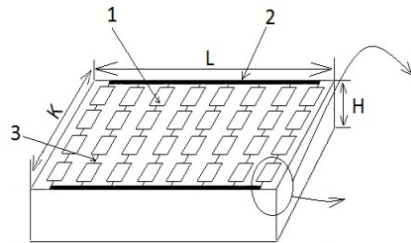


Figure is 5 in an enlarged form.

1 - Panel of mosaic located and completely independent individual solar cells.

2 - Metal electrodes.

3 -  $K/k$  units is series connection.

The solar cell in a circle includes  $L/l$  parallel connected units is given in Figure 4.

Solar panel - is the electrical circuit with the required electrical parameters, consisting of many solar cells partly connected parallel, partly in series [10].

This structure of solar panel provides the optimal selection of parameters and the most efficient mode of its functioning.

5-d. Carry out a quantitative assessment of the optimal parameters of the solar panel.

Introduce the notation of the electrical characteristics of a separate "nanodimensional p-n junction"  $i_o$  - photocurrent,  $\varphi_o$  - contact potential difference and  $p_o$  ( $p_o = i_o \cdot \varphi_o$ ) - power output. These parameters depend, of course, from semiconductor parameters and, above all, the surface concentration of residual impurities  $N_D^{2/3} = b^{-2}$ .

The solar cell is defined by its area  $s$  ( $s = k \cdot l$ ), length  $k$  and width  $l$  (Figure 4), and the number  $\nu = k \cdot l / b^2$  - of parallel connected "nanodimensional p-n junctions".

The  $\nu$  parallel connection - «nanodimensional pn junctions" on one solar cell together provide the total photocurrent:

$$i = \nu \cdot i_o = (k \cdot l / b^2) \cdot i_o \quad (5.1)$$

and the total generated power equals:

$$p = i \cdot \varphi_o = \nu \cdot i_o \cdot \varphi_o = (k \cdot l / b^2) \cdot \varphi_o \cdot i_o = (k \cdot l / b^2) \cdot p_o = \nu \cdot p_o \quad (5.2)$$

Similarly, for the solar panel, enter the area  $S$  ( $S = K \cdot L$ ), the length  $K$  and width  $L$  (Figure 5).

Denoted by  $\Phi_o$  - output voltage and  $I$  - output current of solar panels.

Along the length of the solar panel are connected in series in a number of  $K/k$  units of solar cells with a total voltage

$$\Phi_o = \varphi_o \cdot K/k, \quad (5.3)$$

and along the width of the solar panel are connected in parallel with the total photocurrent

$$I = i \cdot L/l. \quad (5.4)$$

Full output power  $P$ , generated by the solar panel will be:

$$P = I \cdot \Phi_o = \varphi_o \cdot i \cdot (K/k) \cdot (L/l) = \varphi_o \cdot i_o \cdot (K/k) \cdot (k \cdot l / b^2) \cdot (L/l) = p_o \cdot (K \cdot L) / b^2 \quad (5.5)$$

Equations (5.3-5.5) provide a selection of the most optimal solar panel parameters with a view to finding an effective regime of its functioning and addition demonstrate a decisive role "nanodimensional p-n junctions" in the process of converting sunlight into electricity.

5-e. Evaluation of these relations held with the following parameters of the solar panel:  $K = 0.8 \text{ m}$  and  $L = 0.6 \text{ m}$ ;  $k = 2.2 \cdot 10^{-2} \text{ m}$  and  $l = 2 \cdot 10^{-2} \text{ m}$ ;  $N_D = 10^{18} \text{ m}^{-3}$ ;  $b^2 = 10^{-12} \text{ m}^2$ ;  $\varphi_o = 0.2 \text{ V}$ ,  $i_o = 2 \cdot 10^{-9} \text{ A}$  and  $p_o = 4 \cdot 10^{-10} \text{ W}$ .

The calculation shows that

-Output voltage  $\Phi_o = 7.3 \text{ V}$ ,

-Output photocurrent  $I = 26.4 \text{ A}$ ,

-Output power  $P = 192 \text{ W}$ .

Industrial solar panels of similar dimensions derived from expensive monocrystalline silicon, have almost the same power (about  $180 \div 200 \text{ W}$ ).

## 6. THE REQUIREMENTS TO THE SUBSTRATE MATERIAL.

6-a. The unique features of the solar cell based on the new contact structure appear because it uses defective and non-crystalline silicon as substrate solar cells! Nothing was like this before. How can we explain such properties?

In the crystalline silicon (or not purified technically silicon) band gap is literally crammed with different local energy states for electrons [11]. In such materials instead of the traditional concepts of the "band gap" ( $\Delta E_g$ ) arise new concepts such as "conductivity gap", and the concept of the "tails" of the density of states and others. It is this strong defectiveness of the crystal was considered as a negative factor.

In solar cells based on the new contact structure observed the situation is different: its photoelectric properties (especially the photocurrent and photoconductivity) depend on a combination of different types of defects in the substrate and on the size of their binding energy  $E$ .

6-b. Classification of defects in the crystal is shown in the table:

Table

SD - structural defects deep ( $E \gg kT$ )	RD-residual defects shallow ( $E \approx kT$ )
SD create deep electronic localized states in the band gap	RD create small electronic localized states in the band gap
SD - it is neutral defects. Are activated when $E \gg kT$	RD - is neutral defects. Are activated when $E \approx kT$
SD - a defect either strictly acceptor (NDA), or strictly donor (NDD), or mixed donor-acceptor nature (NDA + NDD).	RD - are not doped defects, have a natural residual nature, arise in the process of growing Si.
SD - is vacancy, foreign atoms in the lattice sites, interstitial, doubles, breaks of the chemical and intermolecular bonds, small imperfections and heterogeneity of structure, and etc.	RD - act as doped and may be either strictly acceptors NA or strictly donors ND
Extremely high concentrations: $\approx 10^{24} \div 10^{26} \text{ m}^3$ The average distance between them: $4 \div 10 \text{ nm}$	Extremely low concentrations: $\approx 10^{18} \div 10^{19} \text{ m}^3$ Average distance $\approx 3 \div 60 \text{ }\mu\text{m}$

The magnitude and - electron ionization energy of the defects will be divided into small ( $E \approx kT$ ) and deep ( $E \gg kT$ ). Structural defect can be donor ( $N_{DD}$ ) or acceptor ( $N_{DA}$ ), or mixed donor-acceptor ( $N_{DA} + N_{DD}$ ) according to the nature participation in physical phenomena, and in interaction with the energy bands.

The residual impurities are responsible for the emergence and formation of the electrostatic field of "nanoscale p-n junctions."

The concentration of structural defects is extremely high. It is assumed that they are uniformly and randomly distributed throughout the crystal. From this it follows that the location in the neighborhood of two defects acceptor and donor nature is more probable than the proximity of two acceptors or two donors.

In solar cells on the new contact structure based a silicon substrate is used. Structural defects in silicon are distributed evenly and quasi-uniform, that is, the crystal is close to the thermodynamic equilibrium, in which the entropy changes of its properties (aging) occur long enough.

Consequently,

- the speed of possible phase transitions greatly decrease,

- realized long-term stability of the solar cell properties,
- degradation occurs more slowly,
- increased service life of solar cells.

Structural defects is a multiatom system and they size usually significantly superior to residual impurities. Therefore, in any order in the arrangement of structural defects in the crystal, the area formed as an excess of structural defects and the regions with their drawback (and sometimes even without them). Two any areas of increased concentration of structural defects can be separated by a thin defect-free pure crystalline layer, along which the rare residual defects can stay very comfortably. They are specific purity areas or the mono crystalline zones.

Defect-free region (as capillaries for vegetation) have a special electrical conductivity.

6-c. From the point of view of the photovoltaic properties the high defectiveness solar cells based on the new contact structure have greater prospects for development than pure samples.

The defectiveness of the substrate material goes from the category of deficiencies crystal into the category of advantages!

### 7. THE PROCESS OF FORMATION THE IMPURITY INFRARED PHOTOCONDUCTIVITY IN SOLAR CELLSON NEW CONTACT STRUCTURES BASED .

7-a. We will show a stimulating role of defects for example, the impurity IR photoconductivity observed in the experiment [2]. Look at one-electron approximation (fig.6) the gradual process of formation of impurity IR - photoconductivity in solar cells the new contact structure based (energy is measured from the top of the valence band,  $N_{DD}$  - concentration of deep donors, and  $N_{DA}$  - deep acceptors).

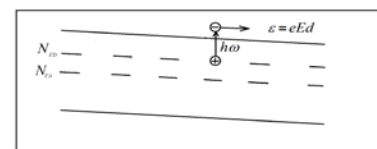


Fig. 6-a photo excitation of electrons

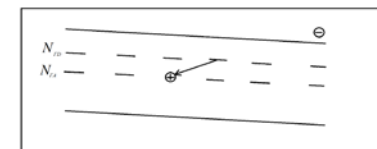


Fig. 6-b the hole tunneling

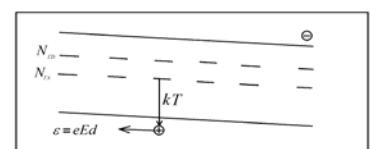


Fig. 6-c thermal ionization of the hole

In the first stage (fig.6-a) is the process of photoionization of deep donor from  $E_{DD}$  level. As a result, an electron is in the conduction band and an electrostatic field sends it to the external positive electrode.

In the second stage (fig. 6- b) an electron, in the Coulomb field of the ionized deep donor, goes to a deep acceptor level EDA by hopping way. As a result, deep donor again neutral, and the deep acceptor is ionized and ready to thermal capture an electron from the valence band.

The cycle completes (fig. 6-c) when an electron is captures from the valence band by thermal process. As a result, a deep acceptor becomes neutral, and the hole that appears in the valence band (by the thermal capture of electron) directed by electrostatic field to the negative external electrode.

So, a cycle of full conversion solar infrared to the electricity (impurity absorption in silicon!) consists of three processes: the birth of a pair, their separation and transport to the electrodes. The cycle of these three processes is called the effective absorption of light.

Energy levels of deep electron states in the band gap (deep donor levels  $E_{DA}$  and deep acceptor levels  $E_{DD}$ ) are located near the center of the band gap, i.e.  $E_{DA}$  and  $E_{DD}$  are order  $\Delta E_g/2$

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