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doi:10.15199/48.2017.08.46

# Influence of Semi-Conducting Layers Formation Technology on Electrical Parameters of Si Structures Used in Photovoltaics

***Abstract.*** *The aim of this work is to present the results of research, which was conducted to verify the possibility of quantum efficiency improvement by the means of ion-implantation. As the object of conducted research, four different samples of silicon solar cells have been chosen. Experiment included measurements of external quantum efficiency, I-V characteristics across certain operating temperature range and SEM imaging. Results have been analyzed in the aspect of ion-implantation applications as the way of introducing improvements in the field of solar cells efficiency.*

***Streszczenie.*** *W artykule zaprezentowano wyniki badań, które zostały przeprowadzone na potrzeby weryfikacji możliwości zwiększenia sprawności kwantowej ogniw fotowoltaicznych za pomocą implantacji jonowej. Jako obiekty badawcze wybrano cztery różne ogniwa słoneczne. Eksperyment uwzględniał pomiary zewnętrznej sprawności kwantowej, charakterystyk prądowo - napięciowych w określonym przedziale temperatur oraz obrazowanie SEM. Wyniki przeanalizowano w aspekcie możliwości zastosowania implantacji jonowej do poprawy sprawności ogniw słonecznych. (**Wpływ technologii wytwarzania warstw półprzewodzących na parametry elektryczne struktur krzemowych stosowanych w fotowoltaice**).*

**Keywords**: ion-implantation, solar cells, silicon, photovoltaics.
**Słowa kluczowe**: implantacja jonowa, ogniwa słoneczne, krzem, fotowoltaika.

## Introduction

Experimental research concerning formation and modification of silicon structures, applicable in the photovoltaic industry, aimed at achieving possibly high efficiency of solar energy conversion has been the subject of many scientific discussions [1, 2]. Particularly, analysis presented in [3] indicated that there is a necessity of introducing a multi-threaded approach to the solar cells designing process by applying mathematical models including areas, which have not already been taken into consideration, such as full-wave optics, thermal modeling and mechanisms of electric charge transport. Simultaneously, authors underlined that in order to obtain eligible precision during predetermining the performance of designed photovoltaic cells it is essential to combine several simulation models, each of which refers to fundamental material parameters. Subsequent experiments described in [4, 5] confirmed the possibility of using the ion implantation technology to produce silicon structures suitable for applications as a substrate material in the PV cells production. Concluding results of conducted research, authors emphasized development potential of the presented method, underlining a necessity of performing further analyses aimed at optimization of ion implantation conditions, in order to obtain silicon structure, which could be introduced as the substrate material for commonly produced solar cells, improving their performance. In addition, results of the experimental research presented in [6] showed that it is possible to produce silicon substrate which electrical parameters are thermally stable in a certain temperature range. However, in order to achieve this result, it is necessary to decide which silicon-based structure should be adopted for creating a model of the solar cell involving ion-implanted silicon layers that will ensure possibly high performance growth as well as minimize the losses simultaneously. Considering high-efficiency silicon solar cells technologies that are taking advantage of different internal structures, it is possible to distinguish them depending on the emitter formation techniques, as it was described in [7]. According to presented classification, the first group consists of cells based on the diffused-emitter (homojunction silicon solar cells), such as passivated emitter rear cell, passivated emitter rear locally diffused, emitter-wrap-through, metallization-wrap-through and interdigitated back contact structures. The second group includes cells with deposited-emitter (heterojunction silicon solar cells), such as heterojunction with intrinsic thin layer (alternatively with interdigitated back contact) and metal-insulator-semiconductor structures. As it was concluded in [7], the conversion efficiency of the mentioned types of PV cells could be characterized by the loss factor, which is the result of optical, electrical and quantum losses, wherein the last ones have dominating influence on the resultant efficiency, as it was presented in figure 1. Simultaneously, it needs to be underlined that detailed distribution of particular kinds of losses depends on the type of the internal structure of considered PV cell. In the context of potential ion-implantation applications, the quantum loss factor has significant impact, because quantum losses are related to the absorber material properties, such as the band gap, which could be modified by ion-implantation [8].

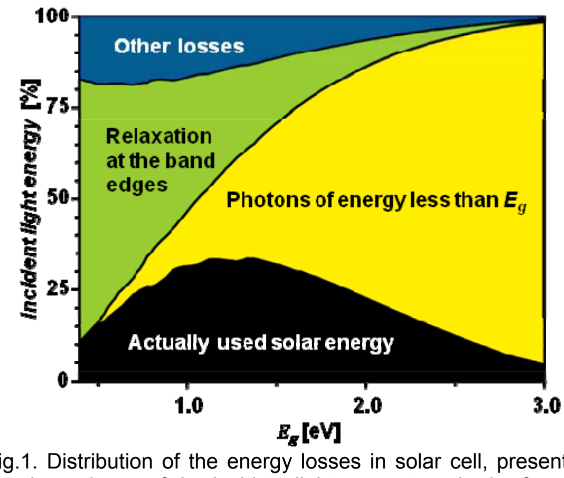


Fig.1. Distribution of the energy losses in solar cell, presented as the dependency of the incident light percentage in the function of band gap value $E_g$ [9]

In particular, it could be seen (fig.1) that there is strict correlation between the conversion efficiency $\eta$ and the value of band gap energy $E_g$, due to the fact that only certain part of absorbed photons have energy high enough to exceed the band gap and cause the excitation of the free electrons. For that reason, certain changes in the value of $E_g$ results in the increase of the number of excited charge carriers and thus the amount of produced energy.

Consequently, it is possible to improve the efficiency of silicon PV cell by introducing additional intrinsic layers of specified $E_g$ value into its structure, which causes reconfiguration in the energy levels in silicon. Such layers are formed by means of ion-implantation technology, during the process of solar cells production. Therefore, the question arises whether it is possible to optimize existing structures either by specifying different values of $E_g$ in the region of intrinsic buffer layer or by introducing new layers and what kind of structure would be the most appropriate.

Taking this into consideration it is justified to conduct research directed into investigating the potential of minimizing quantum loss factor, which characterizes certain crystalline silicon structures typically used in the PV cells production process, in the aspect of introducing ion-implantation technology as the way of modification the material properties of the c-Si.

The aim of this work is to present the results of experimental research, which was conducted to verify the possibility of quantum efficiency improvement by the means of ion-implantation in order to achieve solar-grade silicon of band gap and resistivity optimized for potential PV applications.

## Experiment

The main purpose of performed experiment was to confirm whether it is possible to increase the quantum efficiency of silicon solar cells by implementing ion-implantation technology in the PV cells production process, compared to other technologies of solar cells fabrication. In order to verify this assumption, as the object of conducted research four samples of silicon solar cells have been chosen. Each of selected samples varied in terms of applied manufacturing process and consequently, internal structure. Sample number 1 was the heterojunction monocrystalline PV cell with intrinsic thin layer and interdigitated back contacts (HIT-IBC), produced with support of ion-implantation. Sample number 2 and 3 were the emitter wrap through (EWT) and heterojunction with intrinsic thin layer (HIT) cells, respectively. Finally, sample number 4 was standard, screen-printed, monocrystalline silicon PV cell.

The first part of the experiment included measurements of external quantum efficiency ($EQE$), depending on the wavelength of incident light $\lambda$ ranging from 350 nm to 1100 nm. Tests of all samples have been conducted at the room temperature, using the Oriel IQE-200 system, dedicated for quantum efficiency measurements. In the second phase of the experiment, the sample, which the best $EQE$ results have been recorded for, was subjected to SEM imaging followed by dispersive spectroscopy analysis on the Hitachi TM3000 tabletop microscope with Oxford Instruments Swift ED3000 microanalysis system. Finally, the selected sample was measured on the test bench described in [10], under solar radiation energy $E$ = 1000 W/m$^2$, covering the operating temperature $T_p$ range from 253 K to 373 K, in order to determine the thermal stability ratio of basic electrical parameters that characterize PV cell performance.

## Analysis of the obtained results

In the first stage of experimental results analysis, the dependence of $EQE$ in the function of $\lambda$ was plotted for all tested samples (fig.2). As it can be seen, in all considered cases the function of $EQE$ = f($\lambda$) reaches local minima for values of $\lambda$ close to 360 nm and 1100 nm, however presented characteristics differs each other significantly in the matter of $EQE$ changes dynamics.

For sample 1, it is possible to observe relatively fast growth of the $EQE$ from 80% to over 100% along with the increase of $\lambda$ from about 360 nm to 460 nm. Then, the $EQE$ stabilizes reaching the values from the range 100% ÷ 103% and subsequently falls after $\lambda$ exceeds 940 nm to reach almost 50% at 1100 nm.

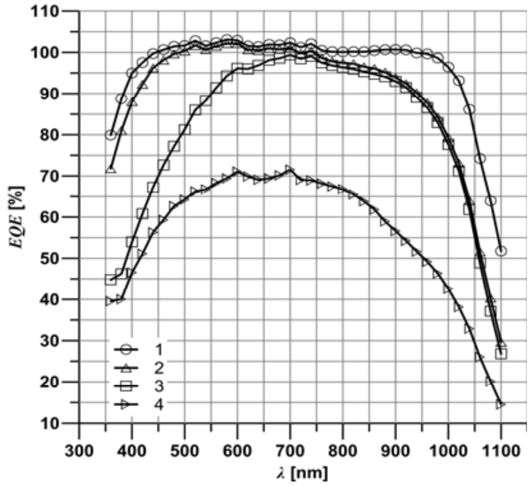


Fig.2. Dependences $EQE$ = f($\lambda$) for different types of c-Si solar cells: 1 – HIT-IBC, 2 – EWT, 3 – HIT, 4 – conventional cell

Sample 2 initially shows a similar tendency to increase in the $EQE$ value from 72% at 360 nm to 100% at 480 nm and its further stabilization at this level, although in this case the $EQE$ starts to decrease for lower wavelengths, such as 760 nm, and gradually falls to 30% at the end of the range of $\lambda$.

It is possible to notice that in case of samples 3 and 4 the $EQE$ grows much more slower as well as reaches generally lower values compared to samples 1 and 2. Consequently, the range of wavelengths wherein the $EQE$ is possibly high and stable is limited to (600 ÷ 750) nm. In this range, the $EQE$ varies between 95% and 99% for sample 3 and oscillates around 70% for sample 4.

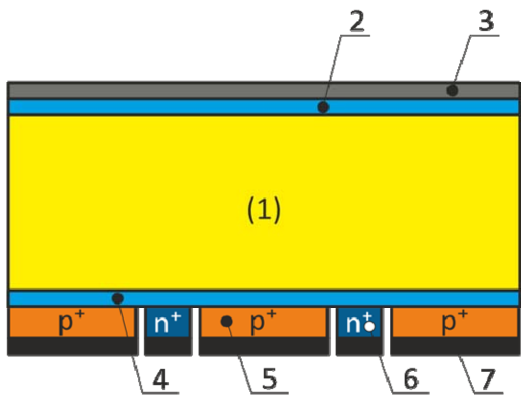


Fig.3. Schematic diagram of the tested HIT-IBC solar cell structure (sample 1): 1 – *n*-type silicon substrate, 2 – front passivation layer, 3 – anti-reflective coating, 4 – a-Si intrinsic thin layer, 5 – $p^+$ - type region, 6 – $n^+$ - type region, 7 – electrode

Taking this into consideration, sample 1 has been chosen for further analysis, as the one that has the greatest photoconversion potential. Schematic diagram of the selected sample has been presented in figure 3. As it can be seen, the structure of heterojunction PV cells with intrinsic thin layer and interdigitated back contacts besides the n-type monocrystalline substrate includes also two thin layers of amorphous silicon. Because all contacts of the cell are located at the rear side it is possible to increase the area of the incident light absorption without changing cell dimensions. In terms of operation principles, characteristic feature for this type of structure is two-dimensional mechanism of charge carrier transport. What is also typical, the intrinsic layer in the HIT-IBC type cell is not illuminated. Therefore, it does not generate charge carriers.

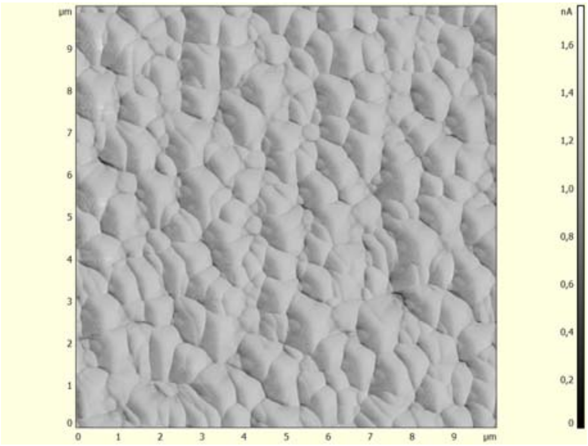


Fig.4. SEM micrograph showing the front surface of the examined HIT-IBC solar cell

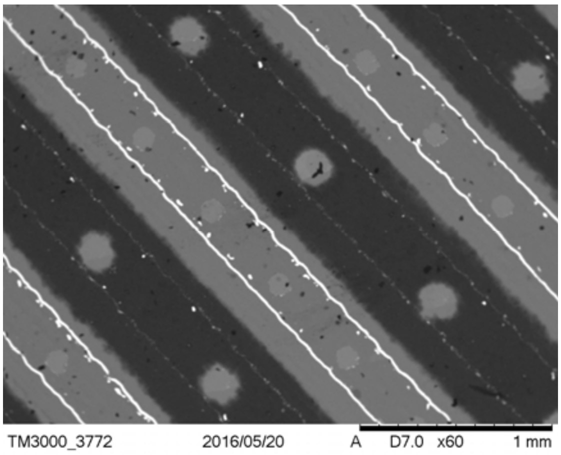


Fig.5. SEM micrograph showing the rear surface of the examined HIT-IBC solar cell

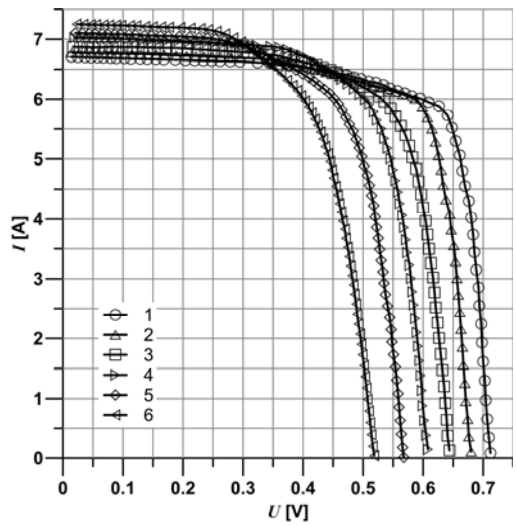


Fig.6. Dependences $I$ = f($U$) of HIT-IBC solar cell recorded for $E$ = 1000 W/m$^2$ and different operating temperatures $T_p$: 1 – 253 K, 2 – 273 K, 3 – 298 K, 4 – 323 K, 5 – 348 K, 6 – 373 K

The second part of analysis covered SEM imaging of the chosen sample. Its results in the form of micrographs of the front and the rear side of the cell have been presented in figure 4 and figure 5, respectively. It is possible to notice pyramidal structure formed after texturing the front surface and interdigitated back contacts made of Al and Ti on the rear side.

In order to determine the influence of operating temperature on performance of the analyzed structure, the I-V characteristics have been plotted for sample 1, including different values of $T_p$ (fig.6). Despite the fact that measured cell achieves relatively high efficiency $\eta$ = 22,5% at $T_p$ = 298 K, it is possible to observe significant performance loss along with increasing temperature. Calculated temperature coefficients of short-circuit current ($\Delta I_{SC}$), open-circuit voltage ($\Delta U_{OC}$) and maximum power ($\Delta P_{MAX}$) revealed the following level of thermal degradation of those basic electrical parameters: $\Delta I_{SC}$ = 0,063 %/K, $\Delta U_{OC}$ = -0,23 %/K, $\Delta P_{MAX}$ = -0,29 %/K.

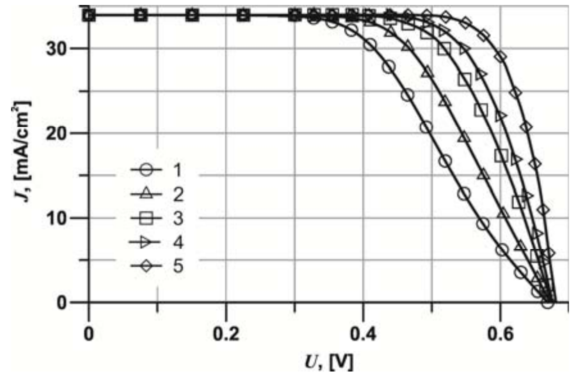


Fig.7. Simulation of dependences $J$ = f($U$) of illuminated HIT-IBC solar cell, calculated for different values of band gap $E_g$ of the intrinsic a-Si buffer layer: 1 – 1,72 eV, 2 – 1,70 eV, 3 – 1,68 eV, 4 – 1,665 eV, 5 – 1,65 eV [12]

**Conclusions**

As it is known, the quantum efficiency is an indicator of the capability of a device under test to produce electric charge from incident photons. It describes the response of a PV cell to different wavelengths of light and is expected to be equal to zero for photons with energy less than the absorber band gap [11]. Comparative analysis presented above allowed specifying which sample has the best rate of the number of electric charge carriers collected by the solar cell in relation to the number of incident photons. It has been clearly showed that among all examined samples, the HIT-IBC structure based on the ion-implanted silicon has the greatest photogeneration potential, which results in achieving the $EQE$ values exceeding 100% in relatively wide range of wavelengths. According to the definition of the $EQE$, this means that photons which energy is much more than the band gap excite more than one electron on average. Such tendency could be probably explained by occurrence of the phenomenon of carrier multiplication in the tested material, wherein the absorption of a one photon causes the excitation of several electrons across the band gap.

Despite the fact, that ion-implanted solar cells revealed relatively good ability to generate electric charge, it is still possible to observe considerable deterioration of the examined cells performance under the conditions of increasing temperature. On the other hand, in our previous work it has been confirmed that thermally stable silicon substrate could be produced by the means of ion implantation [6]. What is more, the computer simulation presented in [12] showed that in considered HIT-IBC structure slight shift in the value of band gap of the intrinsic a-Si buffer layer causes substantial increase of the simulated cells fill factor ($FF$). As it can be seen in figure 7, character of the dependence $J$ = f($U$) plotted for HIT-IBC solar cell under illumination is strictly correlated with the value of band gap of intrinsic a-Si layer. As it has been demonstrated, along with decrease of $E_g$ from 1,72 eV to 1,65 eV it is possible to observe considerable increase of $FF$ from 55% to over 78% (fig.7). Such effect could be a consequence of the fact that a-Si intrinsic layer enhance the valence band offset and thus acts as the carrier transport barrier, which negative impact is partially deteriorated by narrowing the band gap.

Assuming that ion-implantation enables to control the band gap by changing the arrangement of energy bands it should be considered as the way of introducing further improvements in the field of solar cells efficiency. Taking above conclusions into consideration it is justified to conduct subsequent research, directed into development and optimization of ion-implantation technology in the aspect of possible applications in PV cells production process. Especially, it should be investigated whether there is a possibility to use the ion-implantation in order to reconfigure energy levels distribution in the band model of the silicon-based photovoltaic structures in a way that ensures photoconversion efficiency improvement. Therefore, experimental verification of the influence of band gap value on the performance of silicon-based structures dedicated for photovoltaics will be the issue of the subsequent works.

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