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INVESTIGATION OF PASSIVATION OF SURFACE STATES OF SINGLE CRYSTALLINE SILICON IN HETEROSTRUCTURES WITH AN INTEGRATED THIN AMORPHOUS LAYER

Abstract. This work presented in this publication is a continuation of works [1] and [2]. We have shown that in solar cells of the HIT structure, when the thickness of the embedded amorphous layer increases, the efficiency of the solar cell increases, but to a certain point of maximum. The increase in characteristics is due to an increase in the lifetime of non-basic charge carriers in a crystalline silicon substrate. This behaviour of the system can be explained by better passivation of surface States on the silicon substrate. The decrease in the efficiency of the solar cell after reaching the maximum is due to the increase of the resistance structure, which with a point contributes more to the characteristics of the solar cell than the contribution from the passivation of surface states.

Using the PECVD method, amorphous silicon films with a thickness of 7, 30 and 50 nm were grown on a single-crystal commercial silicon substrate on both sides. Then, the lifetime of non-basic charge carriers was measured using the contactless Sinton method on these structures. Further, the samples were examined by photoluminescence at room temperature. Using this method, it was possible to obtain the dependence of the concentration of non-equilibrium charge carriers on the intensity of photoluminescence radiation. These dependences showed that the intensity is lower on samples with a lower thickness of amorphous silicon than in samples with a higher thickness of the amorphous layer.

The detailed results of this work were first presented by the corresponding author in his dissertation [3], the theses of the work were presented at the conference of young scientists of KazNU [4] and only now the results are published as a full-fledged article in the journal.

Key words: Solar cell, amorphous silicon, HIT, hetero-junction, surface defects.

Introduction. In contrast to the traditional process of doping impurities of the same type of conductivity into a substrate having the opposite type of conductivity, the heterojunction technology is based on plasmochemical deposition of thin films of amorphous silicon of the required type of conductivity with a thickness of several tens of nanometers. This significantly increases the control over the created barrier semiconductor structure, providing sharp boundaries between regions of different types of conductivity if necessary. At the same time, however, high requirements remain for the quality of the semiconductor surface on which thin films are deposited. The state of the surface of a crystalline silicon substrate is determined by three factors: 1) corrugation or relief texturing of the surface to reduce the reflection coefficient / increase the amount of light absorbed by the solar cell, 2) effective surface cleaning from foreign contamination, 3) passivation of the silicon surface to "heal" broken bonds and reduce the surface density of defects. The influence of the latter two factors on the efficiency of a solar cell is determined by the effective lifetime of non-primary carriers, which should be as long as possible to achieve high efficiency, while:

$$1/\tau_{\text{eff}} = 1/\tau_b + 1/\tau_s,$$

where τ_{eff} – the effective lifetime of carriers, τ_b – the volume lifetime, τ_s – the surface lifetime. Thus, measuring the effective lifetime of carriers in a plate is the main tool for controlling the quality of its surface. A complementary type of measurement to identify the nature of surface states associated with defects is infrared spectroscopy, including Raman spectroscopy.

HIT solar cells are the market leader in solar energy in terms of "price/quality". Laboratory samples achieve an efficiency of up to 26.7% [5-9]. The record results were the result of optimization and research of the structure of the HIT solar cell [10,11]. Optimization can be carried out in three directions: improving materials and production methods, optimizing the internal parameters of the solar cell (thickness, layer concentration) and changing the design [12].

Early studies have demonstrated the effectiveness of self-conducting amorphous silicon in surface passivation of crystalline silicon wafers. The built-in layer of amorphous conduction silicon is used in the HIT photocell for passivation of heterojunction defects, however, the presence of this layer leads to undesirable consequences for the photocell, namely, due to the qualities of the amorphous material itself, there is a drop in the diffusion length of charge carriers in the section and, as a result, a decrease in the efficiency of the photocell. One of the possibilities for further improving the efficiency of a heterojunction silicon solar cell is to increase the length of the diffusion path of charge carriers in the region of the heterojunction [1,12,13,14].

Experiment and results. At the first stage of the work, the thickness of the embedded layer of amorphous silicon of its own type of conductivity in a heterojunction silicon solar cell of the HIT structure is optimized by computer modeling. The model of the photocell was optimized using the software package FORS-HET [1,2]. The software package is designed for modeling heterojunction solar cells based on crystalline and amorphous silicon, and includes a database of parameters of these materials. The detailed principle of operation of the software package FORS-HET is described in [15-18]. In addition to the numerical calculation, real samples of solar cells were grown and their optimization was performed experimentally based on the thickness of the embedded layer of its own conductivity. Comparison of the obtained data with the results of the experiment showed that the optimal value of the experimental thickness of the amorphous layer (7 nm) does not coincide with the numerical calculation data (1 nm). However, further research has shown that passivation of surface states on a crystalline silicon substrate is better the thicker the thickness of the amorphous layer. It is shown in [19] that the lifetime of non-basic charge carriers increases with increasing thickness of the amorphous silicon layer.

At the second stage of the work, using the PECVD method, amorphous silicon films with a thickness of 7, 30 and 50 nm were grown on a single-crystal commercial silicon substrate on both sides. Then, the lifetime of non-basic charge carriers was measured using the contactless Sinton method on these structures, which confirmed the qualitative dependence of the results [19, 20]. Further, the samples were examined by photoluminescence at room temperature. Using this method, it was possible to obtain the dependence of the concentration of non-equilibrium charge carriers on the intensity of photoluminescence radiation. These dependences showed that the intensity is lower on samples with a lower thickness of amorphous silicon than in samples with a higher thickness of the amorphous layer. These results are in good agreement with the previous ones.

One of the most important factors affecting the efficiency of the solar cell of the HIT structure is the passivation of surface States on the plate of the crystal substrate. To study the effect of passivation of crystalline silicon by an amorphous silicon film using the PECVD method, amorphous silicon films with a thickness of 7, 30 and 50 nm were grown on a single-crystal commercial silicon substrate on both sides. Then a non-contact method of Synton measurement was used on the manufactured samples to determine the lifetime values of non-basic charge carriers. The results of measuring the characteristics of samples are shown in the table 1.

Table -Results of measurements of the life time of the NNZ by non-contact method of single-crystal silicon wafers with a resistance of $R = 1.5 \text{ Ohms}\cdot\text{cm}$, covered with an amorphous film with a thickness of 7 nm (for samples kz_12 – kz_15), 30 nm (for samples kz_02 – kz_05) and 50 nm (for samples kz_06 – kz_11)

The name of the sample	The life time (τ), microsecond
kz_02	1063
kz_03	1020
kz_04	1278
kz_05	1070
kz_06	2295
kz_07	1890
kz_08	1621
kz_09	2016
kz_10	2461
kz_11	2009
kz_12	924
kz_13	630
kz_14	1053
kz_15	655

As can be seen from the table, the greater the thickness of the amorphous film deposited on the crystal substrate, the greater the value of the lifetime of non-basic charge carriers. The results of the study confirmed the qualitative dependence of the results of other authors' work [7].

Figure 1 shows the dependence of the lifetime of non-primary charge carriers on their concentration when illuminated by light, during measurement. It is obvious that the best value of the lifetime is shown by the functional corresponding to the greater thickness of the amorphous passivating layer, equal to 50 nm

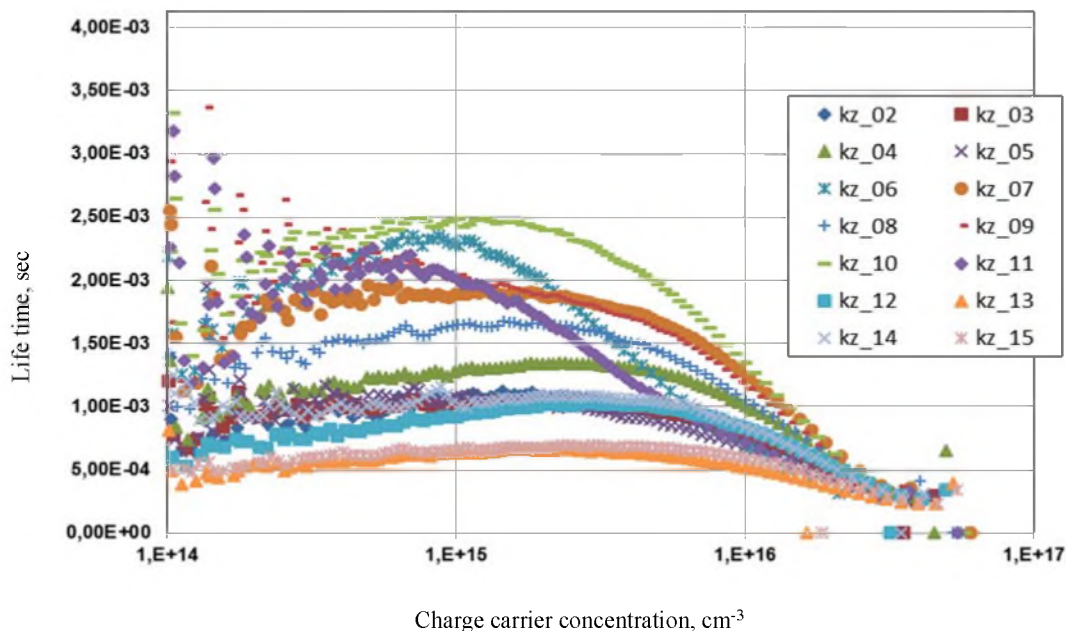


Figure 1 - dependence of the lifetime of non-basic charge carriers on their concentration at different thickness of the amorphous film

Further, the samples were examined by photoluminescence at room temperature (figure 2-4). In figures 2-4, images with higher brightness correspond to a higher concentration of non-equilibrium charge carriers. Using this method, it was possible to obtain the dependence of the concentration of non-equilibrium charge carriers on the intensity of photoluminescence radiation. These dependences showed that the intensity is lower on samples with a lower thickness of amorphous silicon than in samples with a

higher thickness of the amorphous layer. The distribution of radiation intensity is consistent with the data of measurement of the lifetime of non-basic charge carriers in the studied structures.

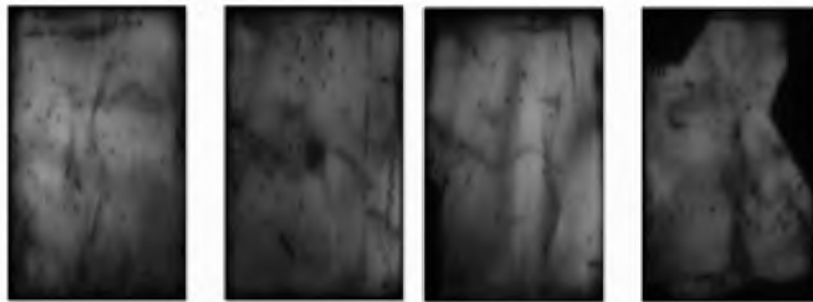


Figure 2-Photoluminescence of silicon wafer samples at 7 nm thick amorphous silicon film deposited on them at room temperature

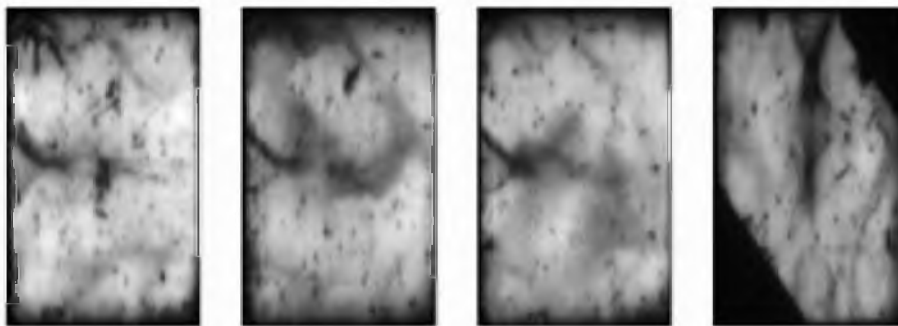


Figure 3-Photoluminescence of silicon wafer samples at 30 nm thick amorphous silicon film deposited on them at room temperature

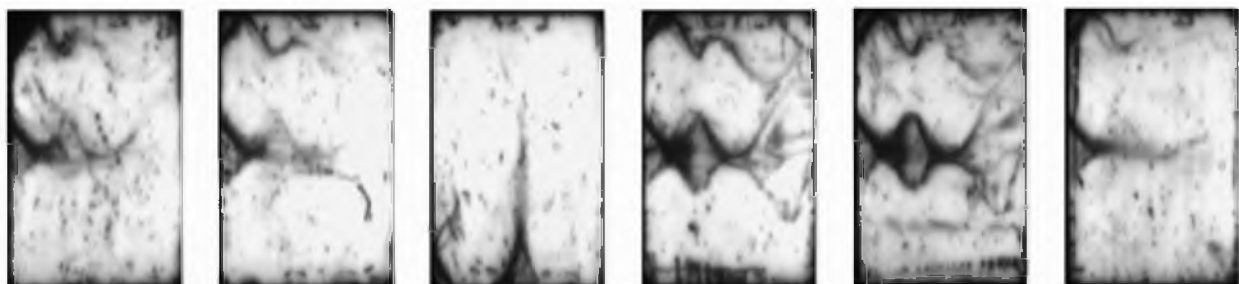


Figure 4-Photoluminescence of silicon wafer samples at 50 nm thick amorphous silicon film deposited on them at room temperature

Consequently of experiments, it show that in HIT structure solar cells, the efficiency of the solar cell increases with increasing thickness of the built-in native layer, but up to a certain point of maximum [2]. The increase in characteristics is due to an increase in the lifetime of non-basic charge carriers in a crystalline silicon substrate. This can be explained by better passivation of surface states on a silicon substrate. The decrease in the efficiency of the solar cell after reaching the extreme point explained by the fact that with increasing thickness, the consistent resistance of the structure increases, which from a certain point on makes a greater contribution to the characteristics of the solar cell than the contribution from passivation of surface states.

However, the results of this work cause to new questions about how exactly the passivation of the surface states of crystalline silicon occurs, as long as the formation of new bonds presumably takes place at distances of no more than 1 nm. Nevertheless, the growth of positive electrical properties for the operation of the solar cell continues to the thickness of the passivating film of a dozen nanometers. In search of this answer, we plan to conduct a cathodoluminescent analysis that will show the energy of

charge carrier transitions between levels and sublevels on the zone diagram of the "single-crystal silicon-amorphous silicon" heterojunction. It is also planning to conduct optical analyses of the structure in the infrared region of the spectrum. It is planning to repeat this experiment, but with films obtained by a different method (PVD method).

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ҚҰРЫЛЫМЫНДА ЖҰҚА АМОΡФТЫ ҚАБАТЫ БАР ГЕТЕРОҚҰРЫЛЫМДАРДАҒЫ МОНОКРИСТАЛДЫ КРЕМНИЙДІҢ БЕТКІ КҮЙІНІҢ ПАССИВТЕЛУІН ЗЕРТТЕУ

Аннотация. Мақалада [1] айналысып жатқан жұмыстардың жалғасы [2] берілді. Біз НІТ құрылымы фотоэлементтерінде кіріктірілген аморфты қабат қалыңдығының артуы негізінде белгілі бір максималды нүктеге дейін фотоэлемент тиімділігі артады. Сипаттамалардың жоғарылауы кристалды кремний субстратындағы негізгі емес тасымалдаушы өмірінің ұзаруына байланысты. Жүйенің бұл әрекетін кремний субстратындағы беткі күйдің үздік пассивациясы негізінде түсіндіруге болады. Максималды нүктеге жеткеннен кейін фотоэлемент тиімділігінің азаюы құрылым кедергісінің жоғарылауына байланысты, ол белгілі бір сәттен бастап беттік күй пассивациясынан гөрі фотоэлемент сипаттамаларына көбірек үлес қосады.

PECVD әдісімен қалыңдығы 7, 30 және 50 нм аморфты кремний пленкалары екі жағынан да монокристалды коммерциялық кремний субстраттарында өсірілді. Содан кейін бұл құрылымдардағы байланыссыз синтон әдісімен негізгі емес заряд тасымалдаушының өмір сүру уақыты өлшенді. Әрі қарай үлгілер бөлме температурасында фотолюминесценция әдісімен зерттелді. Осы әдісті қолдана отырып, тепе-тең емес заряд тасымалдаушы концентрация фотолюминесценцияның сәулелену қарқындылығына тәуелділігін алуға болады. Бұл тәуелділік аморфты кремнийдің қалыңдығы аз кездесетін үлгілерде қарқындылығы аморфты қабаттың алдыңғыға қарағанда аз болатындығын көрсетті.

Жұмыстың егжей-тегжейлі нәтижелерін бірінші кезекте автор-корреспондент өзінің диссертациясында ұсынды [3], жұмыс тезистері ҚазҰУ-дың жас ғалымдарының конференциясында ұсынылды [4] және оның нәтижелері журналда толыққанды мақала ретінде жариялануда.

Түйін сөздер: күн элементі, аморфты кремний, НІТ, гетеротекел, беткі ақаулар.

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ИССЛЕДОВАНИЕ ПАССИВАЦИИ ПОВЕРХНОСТНЫХ СОСТОЯНИЙ МОНОКРИСТАЛЛИЧЕСКОГО КРЕМНИЯ В ГЕТЕРОСТРУКТУРАХ СО ВСТРОЕННЫМ ТОНКИМ АМОΡФНЫМ СЛОЕМ

Аннотация. Настоящая работа, представленная в данной публикации, является продолжением работ [1] и [2]. Мы показали, что в фотоэлементах структуры НІТ при увеличении толщины встроенного аморфного слоя растёт эффективность фотоэлемента, но до определённой точки максимума. Рост характеристик обусловлен увеличением времени жизни неосновных носителей заряда в подложке кристаллического кремния. Такое поведение системы можно объяснить лучшей пассивацией поверхностных состояний на

подложке кремния. Падение эффективности фотоэлемента после достижения точки максимума связано с увеличением сопротивления структуры, которое с определённого момента вносит больший вклад в характеристики фотоэлемента, чем вклад от пассивации поверхностных состояний.

Методом PECVD на монокристаллической коммерческой подложке кремния с обеих сторон были выращены плёнки аморфного кремния толщиной 7, 30 и 50 нм. Затем бесконтактным методом Синтона на этих структурах было измерено время жизни неосновных носителей заряда. Далее образцы были исследованы методом фотолюминесценции при комнатной температуре. С помощью данного метода удалось получить зависимость концентрации неравновесных носителей заряда от интенсивности излучения фотолюминесценции. Данные зависимости показали, что на образцах с меньшей толщиной аморфного кремния интенсивность меньше, нежели в образцах с большей толщиной аморфного слоя.

Подробные результаты настоящей работы в первую очередь были представлены автором-корреспондентом в своей диссертации [3], тезисы работы были представлены на конференции молодых учёных КазНУ [4] и только сейчас результаты публикуются в виде полноценной статьи в журнале.

Ключевые слова: солнечный элемент, аморфный кремний, HIT, гетеропереход, поверхностные дефекты.

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