Some features of selection conditions and manufacturing technology for highly efficient thin-film solar cells based on Si

Shoirbek Olimov 1,*, Noufu Chen1, and Anarkhan Kasimakhunova 2

1 School of Renewable Energy, North China Electric Power University, Beijing 102206, China;
2 Fergana polytechnic institute, Fergana, Uzbekistan

Abstract. The main objective of this study is to find the most advanced production technology for semi-voltaic energy converters. The paper presents the results of analysis, production and research of solar cells that have a thin film intersection on Si p-type. The authors also carried out technical analysis of manufacturing and study of heterostructured solar cells of thin layers of crystalline and amorphous silicon. The basic requirements for the production of the most effective light barriers discussed.

1 Introduction

Interest in solar cells made from heterostructures is constantly growing. The main reason or this is the highest efficiency, reflected in large values of the coefficient of performance (efficiency). Nowadays, there are many developed hetero structural elements. It is well known that systematic research of heterostructural elements began long ago [1-13]. They started with research of solar cells obtained by liquid-phase epitaxy from n-GaAs/p-AlxGa1-xAs substances. Subsequently, various structures with different conductivities were obtained. These samples, due to the presence of a wide-gap layer on the surface of the solar cell, contributed to a decrease in the surface recombination of electron-hole as a result of which it was possible to significantly increase the efficiency values. Solar cells based on monocrystalline silicon currently occupy more than 85% global market for terrestrial solar energy. The main reasons for silicon solar cells leadership are the comparable cheapness of the base material, the stability of the properties and the efficiency of its manufacturing technology. Monocrystalline silicon solar cells has the highest conversion efficiency of solar radiation. They consist of silicon plates with a thickness of 300 μm by admixing their mixtures of donor and acceptor, forming contacts are consequence and texturing. The c-Si solar cells record efficiency is 24.7% when using the passivated emitter and locally distributed contact Design [14]. The main disadvantage of c-Si solar cells is the significant consumption of high-purity monocrystalline Si, most of which serves as a passive substrate. To reduce the cost of silicon solar cells, microcrystalline [12] and amorphous [15] silicon

* Corresponding author: shoirbekolimov@yandex.ru
absorber layers with a thickness of 0.1-3 μm. The efficiency of such a thin-film SE is about 10%. Success at a-Si: H and nc-Si:H and the latest news on the possibility of growth of thin films oxidized silicon microcrystalline (nc-Si:O) [16] point to the fundamental technological possibility of creating the cascade silicon solar cells.

Since then, a lot of work has been done and research is going on. In recent years, the most active interest has been shown in thin-film heterostructures based on silicon. They are called HIT (Heterojunction with Intrinsic Thin Layer) elements [16-19]. Silicon heterojunction technology, consisting of thin amorphous silicon layers on monocrystalline silicon wafers allows the production of photovoltaic solar cells with energy conversion efficiencies above 20 %, also at industrial-production level. This article reports how this may be achieved. First, we focus on the surface-passivation mechanism of intrinsic and doped amorphous silicon films in such solar cells, needed to enable record-high values for the open-circuit voltage. Next, the industrial upscaling in large-area reactors of such film deposition is discussed, including the fabrication of solar cells with energy-conversion efficiencies up to 21% in such systems.

2 Methods

Structures consisting of a C-Si/a-Si heterojunction (Fig.1) were selected as the objects of research, which are the base part of HIT-type solar cells.

Fig. 1. Design of heterogeneous land mass of the solar cell based on silicon

The main difference between solar cells manufactured by HIT technologies, from classic solar cells on crystalline silicon (c-Si) is the presence of its own layer of amorphous silicon (a-Si:H). Purpose this layer: formation of a heterojunction and passivation of defects on the surface of c-Si wafers. Passivation of defects is necessary to reduce recombination of non-equilibrium carriers via surface states.

Insufficient passivation of the surface of c-Si plates leads to a decrease in no-load voltage, which leads to reduced efficiency. Thus, the passivation quality of the surface of c-Si plates is one of the most critical parameters to create high-performance solar cells based on HIT structure. Quality assessment passivation is produced by measuring the lifetime of nonequilibrium charge carriers, the value of which is used to create high-performance HIT.

Experimental studies were carried out on a specially assembled setup for measurements in a wide temperature range of light intensities. A xenon arc discharge lamp was taken as a radiation source. This choice is explained by the proximity of the graphs of the spectral distribution of wavelengths of this radiation simulator and the sun. The light intensity and temperature of the sample were kept constant values using an automatic controller. The power of the light flux (photometry of the light spot) entering the front surface of the solar cell was measured by determining the power of light on each surface with an area of 2.0 mm². Then the powers of all measured surfaces were summed. The area of the measured capacities was almost equal to the area of the solar cell.

The light intensity was automatically measured and recorded on a self-cleaning device. In addition, this parameter was additionally monitored using a light sensor. The short
circuit current of the light intensity sensor, as determined by the measurement results, was proportional to the power of light radiation. The temperature of the sample was measured with a chromel-alumel thermocouple. The thermocouple head was soldered from the back of the sample using a well conductive paste KTP-8. It was also protected by a special reflective screen. The surface of the screen, having a hole equal to the frontal area of the solar cell, was carefully polished. This made it possible to have unnecessary part of the light to reflect, and thereby prevent the likelihood of spurious temperature gradients.

The cooling system consisted of a source of cold source (a Dewar vessel with liquid nitrogen), a system for automatically controlling the temperature of the sample, and a system for monitoring and recording temperature. The Dewar vessel was connected to the element substrate by a tube with a diameter of 10 mm². The substrate on which the element was mounted had a hollow interior made in the form of a coil, which allowed nitrogen vapor to circulate freely throughout the volume.

3 Results and discussion

The energy band diagram of the obtained element is shown in Fig. 2. Here $E_F$ means the Fermi energy level. It is located near the valence band of the p and p+ layers and closer to the bottom of the conduction band of the n+ layer. The luminous flux received through a wide-band window is absorbed by the p-layer and creates electron-hole pairs in the of the p-layer (c-Si) volume [13, 17-20].

The main charge carriers generated by light excitation begin to diffuse toward the pulling electric field of the p-n+ junction. A relatively small recombination process was observed in the p-layer volume. A slight difference in the transition of the conduction band $\Delta E_c$ does not prevent the transfer of carriers from one layer to another. Therefore, a good exchange, of charge carriers is maintained through the contact.

![Band diagram of the solar cell](image)

**Fig. 2.** Energy band diagram of the solar cell (SC)

Light of a certain wavelength, even if it is absorbed on the surface p+ layer and creates electron-hole pairs, and these generated pairs can run through the diffusion before the p-i-n junction. Presumably, this also contributes to the total current. Gaps in the conduction bands $\Delta E_c$ and in the valence band $\Delta E_v$ do not show any particular obstacles. Thus, these elements have good advantages in efficiently converting the energy of sunlight into electrical energy.
Experience shows that if you create a donor level in the volume of the p-layer, this leads to the first transition from the donor level of the arrangement of charge carriers to the conduction band at the moment of illumination of the front surface of the element. Photons with the lowest energy, compared with the energy of the band gap, can be raised to this level, and this is limited to individual carrier generations.

To increase sensitivity to the density of surface layers, a proven method was used to assess the quality of the Si:H/c-Si transition. The essence of the method is to conduct studies of diffusion capacity under illumination and a bias near the no-load voltage (V_{OC}). In our samples it has been proven that they are characteristic of those heterophotoelements whose influence is the recombination of carriers on the heterojunction interface of the diffusion capacity. This allows quantitative and qualitative assess the quality of the rear and front boundaries of the partition.

The authors report a large dissemination of data on experimentally measured values for $\Delta E_s$, $\Delta E_v$ for the limit a-Si: H / c-Si [20]. This leads to the need for a more thorough conduct of the entire research.

In our studies, we also used one of the most popular methods to study the HIT heterostructures, namely capacitance measurement-voltage properties. The results of the research have shown the probability of forming a region of reverse conductivity at the boundary of heterojunctions [16, 20], which suggests to us that the application of the traditional method of determining interruptions of areas based on volt Farad measurements can lead to unreliable results.

It should be noted that the conversion efficiency also depends on the concentration of donor and acceptor levels. The presence of donor levels in thin-film structures at relatively low concentrations leads to an increase in the efficiency of the heterostructure element. The maximum efficiency was achieved at a concentration of donor impurities equal $n_d=10^{16}$ см$^{-3}$. Then there is a monotonic decrease in efficiency.

![Fig. 3. The dependence of the efficiency of the photoconverters from the temperature.](image)

The spectral dependences of the electroluminescence of HIT elements were also measured. The verification was carried out in the temperature range from 150 to 350 K. It was revealed that the positions of the electroluminescence maxima and its intensity shift in these samples with a change in temperature. The position of the electroluminescence peak reaches the wavelength region at an intensity of $h\nu=1.07$ eV. The electroluminescence peaks in the characteristics are linearly shifted to the long-wavelength region. The dependence of electroluminescence on temperature is nonmonotonic. Perhaps this is due to recombination processes. The authors also carried out technical analysis of manufacturing and study of
heterostructured solar cells of thin layers of crystalline and amorphous silicon. Information about this was given in works [21-27].

The next sample of the solar cell with a maximum decrease in the value of $R_{pp}$ was still exposed to the heat treatment. Fig. 2 shows the temperature dependence of the efficiency of a photoelectric converter. It can be seen that with the decrease in the effect of the sample series resistance of the sample, the decrease in the recombination process, the light conversion factor is increasing [28].

4 Conclusions

In order to create highly effective HIT elements, it is necessary to carefully select the preliminary materials. It has been established that one of the reasons for the high efficiency of HIT batteries is that they have a unique heterojunction structure from a thin layer of amorphous silicon. It was revealed that the amorphous silicon layer is used not only to complete the preparation of p-n junctions, but also to complete the surface of single-crystal silicon. An important role of passivation in the regulation of the displacement of the energy zone and a decrease in the density of the interface state is revealed [23-24]. The effect of reducing the density of the state of the interface on a significant decrease in the leakage current at the surface and the interface is determined. One reason for this is an increase in open circuit voltage. This improves battery conversion efficiency. Summarizing all of the above mentioned, it concluded that HIT solar cells have a very good prospect of application. Obtained dates opens up a wide range of development technologies for manufacturing highly efficient heterostructured solar cells.

The results obtained here can be used as a methodological basis for characterization of highly efficient Si-based solar cells.

References

1. Z.I. Alferov, V.M. Andreyev, S.G. Konnikov, V.R. Larionov, and G.N. Shelovanova, Kristall Und Technik 10(2), 103–110 (1975)
2. Z.I. Alferov, V.M. Andreyev, A.Z. Mercurtsa, A.V. Syrbu, and V.P. Yakovlev, Applied Physics Letters 57(27), 2873–2875 (1990)
3. Z.I. Alferov, Russian Chemical Reviews 82(7), 587–596 (2013)
4. Z.I. Alferov, V.M. Andreyev, and V.D. Rumyantsev, Semiconductors 38(8), 899–908 (2004)
5. M.O. Watanabe, and Y. Ohba, Appl. Phys. Lett. 50, 906–908 (1987)
6. Z.I. Alferov, In.: Proceedings of the IEEE 101(10), 2176–2182 (2013)
7. E.K. Iordanishvili, Technical Physics Letters 32, 1077-1078 (2006)
8. M.A. Green, Prog. Photovolt: Res. Appl. 17, 183 (2009).
9. Z.I. Alferov, International Journal of Modern Physics B 16(05), 647–675 (2002)
10. Z.I. Alferov, In.: IEEE Journal of Selected Topics in Quantum Electronics 6(6), 832–840 (2000)
11. Z.I. Alferov, Semiconductors 32(1), 1–14 (1998)
12. T. Mishima, M. Taguchi, H. Sakata, and E. Maruyama, Solar Energy Materials and Solar Cells 95(1), 18–21 (2011)
13. W.D.A.M. de Boer, D. Timmerman, and K. Dohnalova, Nat. Nanotechnol. 5, 878 (2010)
14. K.S. Cho, N.M. Park, T.Y. Kim, Appl. Phys. Lett. 86, 1909 (2005)
15. S. Takeoka, M. Fujii, S. Hayashi, Phys. Rev. B. 62, 16820 (2000)
16. Ch. Huh., T-Y. Kim, Ch-G. An, and B.K Kim, Appl. Phys. Lett. 106, 211103 (2015)
17. A.V. Emelyanov, A.G. Kazanskii, and M.V. Khenkin, Appl. Phys. Lett. 101, 81902 (2012)
18. A.V. Emelyanov, A.G. Kazanskii, and P.A. Forsh, J. Nanoelectron. Optoelectron. 10, 649 (2015)
19. C-Y Wei, C-H Lin, H-T Hsiao, P-C Yang, C-M Wang, and Y-C Pan, Materials 6(11), 5440–5446 (2013)
20. M. Taguchi, E. Maruyama, and M Tanaka, Japanese Journal of Applied Physics 47(2), 814–818 (2008)
21. A.M. Kasimakhunova, S.A. Olimov, R. Nurdinova, T. Iqbal, and L.K. Mamadalieva, Journal of Applied Mathematics and Physics 06(03), 520–529 (2018)
22. A.M. Kasimakhunova, S.A. Olimov, L.K. Mamadalieva, M. Norbutaev, S.S. Nazirjanova, and S.R. Laraib, Journal of Applied Mathematics and Physics 07(06), 1263–1271 (2019)
23. S.A. Olimov, C. Nuo-fu A.M. Kasimakhunova, S.J. Ali Shah, K. Yousaf, N. Abbas, and Y XiYu., In.: Proceedings of 2nd International Conference on Computing, Mathematics and Engineering Technologies (ICoMET),1–5 (2019)
24. A M Kasimakhunova, S A Olimov. Scientific-technical journal. 22(2), 25 (2018)
25. A.V. Sachenko, Yu.V. Kryuchenko, V.P. Kostylyov, A.V. Bobyl, E.I. Terukov, S.N. Abolmasov, A.S. Abramov, D.A. Andronikov, M.Z. Shvarts, I.O. Sokolovskyi, and M. Evstigneev, J. Appl. Phys. 119, 225702 (2016).
26. N Latukhina, A Rogozin, G Puzynnaya, D Lizunkova, A Gurtov, and S. Ivkov. Procedia Engineering 104, 157–161 (2015)
27. L Zhao, C.L. Zhou, H.L. Li, H.W. Diao, and W.J. Wang. Solar Energy Materials and Solar Cells. 92(6), 673–681 (2008)
28. Chen Chen, Jia Rui, and Zhu Chenxi, Physics 39(2), 123-129 (2010)