Simple Low-Cost Technology of Silicon Solar Cells and PV Modules Fabrication

L.Bruk, A.Simashkevich, D.Sherban, Yu.Usatii, P.Morvillo, E.Bobeico, V.Fedorov.

Institute of Applied Physics, Chisinau, Republic of Moldova, bruk@usm.md

ABSTRACT

Solar cells (SC) fabricated on the basis of semiconductor-insulator-semiconductor (SIS) structures are obtained by spraying deposition of ITO layers on a Si surface. Films with conductivity $4.7 \cdot 10^3 Ohm^{-1}cm^{-1}$ and the transmission coefficient of 87% in the visible range of the spectrum were obtained from solutions containing 90% $InCl_3$ and 10% $SnCl_4$ at the substrate temperature ~ 450°C. For SIS structures fabrication nSi wafers oriented in the (100) plane with the concentration $\sim 10^{15}cm^{-3}$-$10^{16}cm^{-3}$ were used as substrate. A back surface field (BSF) region has been fabricated at the rear contact. The efficiency of 10.11% was obtained for solar cells with active area of $24 cm^2$ in AM1.5 conditions.

These structures containing only isotype junctions are very promising, as it is not necessary to obtain a p-n junction. Their advantages are the following: the frontal junction is obtained with a simple spray technique at low temperatures; the double diffusion process is not necessary; the frontal ITO layer is both the collecting electrode and antireflection coating.

Keywords: solar cell, ITO, SIS structures, spray pyrolysis.

1 INTRODUCTION

The lowering of the cost of electrical energy produced by SC is now one of the main issues of the PV industry. SC on the base of SIS structures are very perspective, as it is not necessary to produce a p-n junction. Such SIS structures are obtained by the deposition of thin films of transparent conducting oxides on the oxidized crystal surface [1-5]. One of the principal advantages of SIS based SC is the elimination of the high temperature diffusion process from the technological chain.

The main purpose of this work is to demonstrate the possibility of fabrication of SC and solar modules based on SIS structures using the spray pyrolysis technique.

2 EXPERIMENTAL

Thin films, sprayed at 450^oC on the nSi crystals surface, are used for the formation of n^+ITO-SiO_2-n-n^+Si structures with a shallow junction. The ITO layers are deposited on the nSi crystals surface by spraying of ethyl alcohol solution of $InCl_3$ and $SnCl_4$ in different proportions using the special designed installation [6] which contains four main units: the spraying system; the system of displacement and rotation of the support on which the substrate is fixed; the system of heating the substrate and the system of the evacuation of the residual products of the pyrolysis (Figure 1).

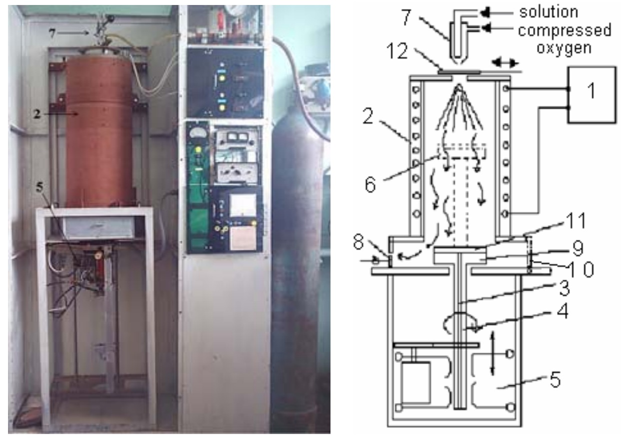

Figure 1: General and schematic view of the installation for ITO thin films deposition.

1-power unit; 2-electric furnace; 3-thermocouple; 4-rotating basis; 5-mechanism of basis rotation and moving; 6-basis position during layer reception; 7-system of spraying; 8-system of exhaust ventilation; 9-basis position during loading of silicon wafer; 10-cover; 11- silicon wafer; 12-shielding plate.

The silicon wafers are located on the support and with the aid of the displacement mechanism are moved in the deposition zone of the electric furnace. The construction of this mechanism provides the rotation of the support with the velocity of 60 rotations per minute that is necessary for obtaining ITO thin films with uniform thickness on the all wafer surface. The ethyl alcohol solution of $InCl_3$ and $SnCl_4$ is sprayed with the aid of compressed oxygen into the stove on the silicon wafer substrate, where the ITO thin film is formed due to thermal decomposition of the solution and the oxidation reaction. On the heated substrate there are the following chemical reactions:

$$4InCl_3+3O_2=2In_2O_3+12Cl$$
$$SnCl_4+O_2=SnO_2+4Cl \qquad (1)$$

Before the spraying, SiO_2 insulator layers were obtained on the silicon wafers surface by different methods: anodic, thermal or chemical oxidation. The best results have been obtained at the utilization of the two latter methods. The chemical oxidation of the silicon surface was carried out by immersing the silicon wafer into the concentrated nitric acid for 15 seconds. Tunnel-transparent for minority carriers insulator layers at the ITO-Si interface have been obtained thermally, if the ITO layers deposition occurs in an oxygen containing atmosphere Ellipsometrical measurement showed that the thickness of the SiO_2 insulator layer is 30-60*Å*. Silicon wafers oriented in the (100) plane with different electron concentration $10^{15}cm^{-3}$-$10^{16}cm^{-3}$ were used as substrates for the fabrication of SIS structures. A back n-n$^+$ junction, which is an usual BSF structure [7] of highly doped n-Si layer obtained by P diffusion, was fabricated on the top of the unpolished side of the wafer by a diffusion process starting from $POCl_3$ gas mixture. The junction formation ends with a wet chemical etching of $POCl_3$ residual in a 10*%* HF bath. A junction depth of 1*μm* has been chosen in order to minimize recombination. To reduce the surface recombination velocity the wafers have been thermally oxidized at a temperature of 850^o*C*. Both frontal grid and rear contact obtained by copper evaporation in vacuum were deposited on the frontal and back surfaces. Figure 2 shows the structure of the obtained SC.

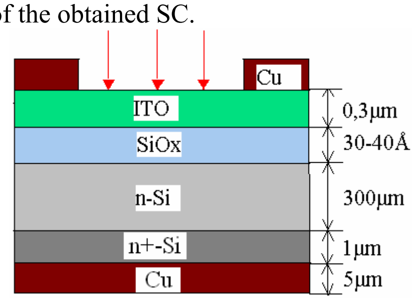

Figure 2: The schematic view of Cu/n$^+$ITO/SiO_2/nSi/n$^+$Si/Cu solar cell.

The steps of the SC fabrication are presented in Figure 3.

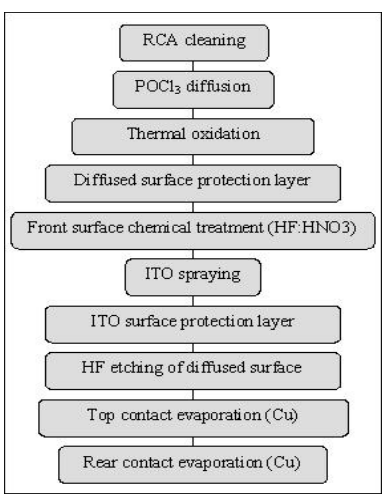

Figure 3: Fabrication steps of the Cu/n$^+$ITO/SiO_2/nSi/n$^+$Si/Cu solar cells.

ITO-SiO_2-n-n$^+$Si SC with active area of 8.1cm^2, 24cm^2 and 48.6cm^2 have been fabricated.

3 RESULTS

3.1. Properties of ITO Layers

The properties of the thus obtained ITO films depend on the concentration of indium chloride and tin chloride in the solution, the temperature of the substrate, the time of spraying and the deposition speed. X-ray analysis showed that the ITO films had a microcrystalline structure that was influenced by the crystal lattice of the support. They have cubic structure with the lattice constant 10.12*Å*.

ITO thin films with maximum conductivity $4.7\cdot10^3 Ohm^{-1}\cdot cm^{-1}$ and the maximum transmission coefficient in the visible range of the spectrum (87*%*) were obtained from solutions containing 90*%* $InCl_3$ and 10*%* $SnCl_4$ and under following conditions: substrate temperature ~ 450°*C*, deposition rate ~ 100*Å/s*, and spraying time ~ 45s. The band gap width determined from the spectral dependence of the transmission coefficient is changing only for the content of 90-100*%* of $InCl_3$ in the spraying solution. For the content of $InCl_3$ less than 90*%* the band gap remains constant and equal to 3.9*eV* showing that In_2O_3 mixture solid solutions are formed only near In_2O_3. The thickness of ITO layers in dependence to the quantity of pulverized solution has been evaluated from the spectral distribution of the light reflection coefficient from the surface of the deposited layers. The variation of the solution quantity lead to the variation of the maximum and minimum number, which resulted from the light interference reflected from the layer surface and layer-substrate interface. The location of the maximums and minimums is determined by the well known relation [8]:

$$n = \frac{\lambda_1 \lambda_2}{(\lambda_2 - \lambda_1)2d} \qquad (2),$$

where: *n*-refraction index equal to 1.8 for ITO [9]; λ-the wavelengths for the two neighboring maximum and minimum; *d*-the thickness of the ITO layer. Using this relation the thickness of ITO layers deposited on the nSi wafer surface in dependence to the quantity of the pulverized solution has been determined. This relation is linear and the layer thickness varies from 0.35*μm* up to 0.5*μm*. The ITO thickness value of 0.35*μm* was chosen for the solar cell fabrication.

3.2 Electrical Properties of ITO-nSi Structures

The temperature dependence of dark I-V characteristics was studied (Figure 4). Two mechanisms of direct current flow observed. At voltages less than 0.3V tunneling-recombination mechanism is observed described in [10]:

$$J = Jo \exp(AV) \exp(BT) \quad (3),$$

where: $A=15V^{-1}$; $B=0.045K^{-1}$. At voltages more than 0.3V current-voltage characteristics can be approximated by the relation (4), which indicates on the over barrier emission [11]:

$$I=C \exp(-\varphi_B/kT) [\exp(eV/AkT)-1] \quad (4),$$

where A=1.66, the diffusion potential (V_D) is equal to 0.42*V*. The reduction of the influence of the first current flow mechanism will lead to increased solar energy conversion efficiency.

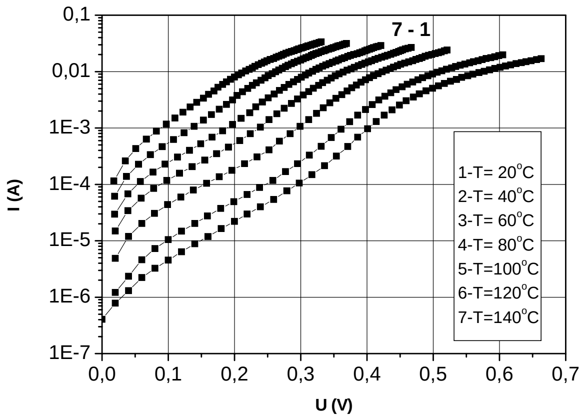

Figure 4: Direct branches of dark I-V characteristics of the ITO-nSi structure at different temperatures.

The height of the potential barrier (φ_B) at the ITO-nSi contact can be determined from the relation of lnI=f (1/kT). This dependence is presented in Figure 5.

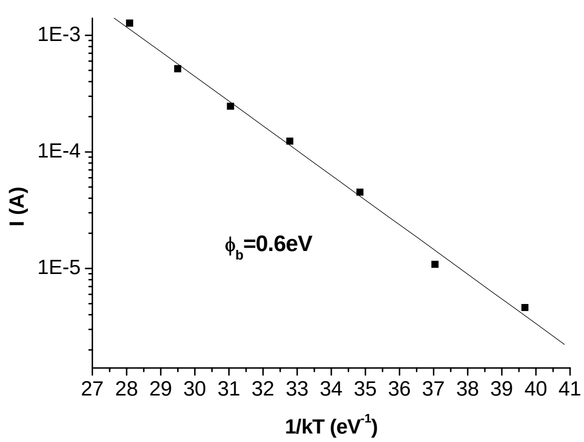

Figure 5: Dependence I_s = f (1/kT) of ITO-nSi structure.

The study of dark current-voltage and capacitance-voltage characteristics of these structures indicates that they are abrupt SIS heterostructures. The structures thus obtained are asymmetric doped barrier structures in which the wide band gap oxide semiconductor play the role of transparent metal.

3.3 Properties of ITO-nSi Solar Cells

The spectral distribution of the quantum efficiency *Q* and the photosensitivity of the obtained PV cells have been studied (Figure 6). The monochromatic light from the spectrograph is falling on a semitransparent mirror and is divided into two equal fluxes. One flux falls on the surface of a calibrated solar cell for the determination of the incident flux energy and the number (*N*) of incident photons. The second flux falls on the surface of the analyzed sample and the short circuit current I_{sc} is measured, thus permitting to calculate the number "*q*" of charge carriers, generated by the light and separated by the junction, and then the quantum efficiency $\eta=q/N$ for each wavelength.

The spectral distribution of the quantum efficiency of the n^+ITO-SiO_2-n-n^+Si structure is presented in Figure 6 (curve 1).

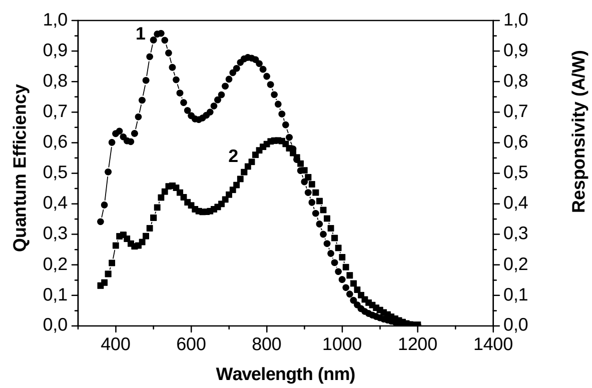

Figure 6: Spectral distribution of the quantum efficiency (1) and sensibility (2) of the n^+ITO-SiO_2-n-n^+Si solar cells.

It is seen that in the region of wavelengths from 400*nm* to 870*nm* the value of η changes on the limits 0.6-0.97. The photosensitivity measured in *A/W* for a fixed wavelength is determined from the ratio of I_{sc} and the incident light energy. Curve 2 (Figure 6) represents the spectral distribution of the photosensitivity for the same sample. The photosensitivity is observed in the wavelength range of 350-1200*nm* and in the wavelength range of 485-920*nm* its value is more than 0.45*A/W*.

The obtained n^+ITO-SiO_2-n-n^+Si structures were used as photovoltaic converters. For solar cells with active area of 24cm^2 at the AM1.5 illumination conditions the following photoelectric parameters were obtained: the short circuit current 35.1mA/cm^2, the open circuit voltage 446*mV*, the fill factor 64.7%, the efficiency 10.11% (Figure 7).

The reproducibility of the process and the performance of the devices during samples fabrication were checked in each batch of samples as well as batch-to-batch. The viability of the developed technology for the obtaining of solar cells in laboratory conditions was demonstrated by fabrication of the PV modules each of them formed by 36 cells and possessing the active area of ~1750cm^2 and the output power of 15*W*.

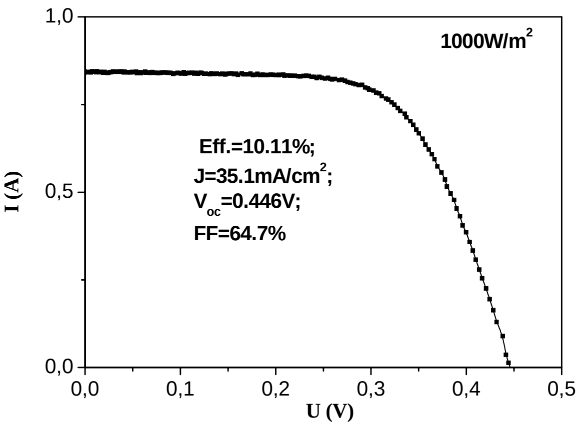

Figure 7: The load I-V characteristic of the fabricated SC.

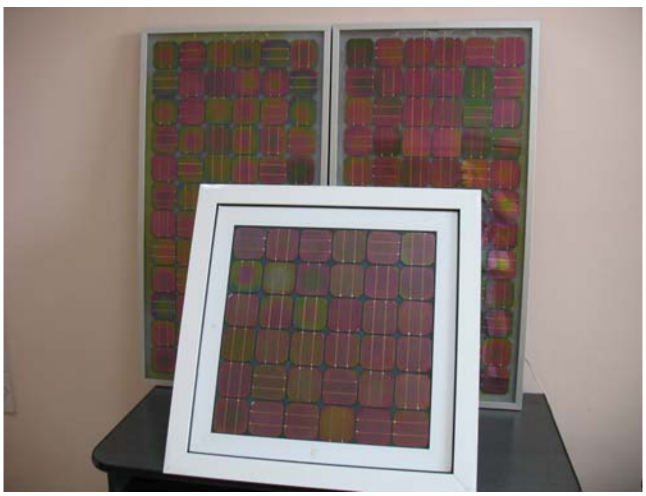

Figure 8: PV solar modules.

Also PV modules with the output power up to 30*W* have been fabricated on the base of 72 such solar cells with active area ~3500cm^2 (Figure 8).

4 CONCLUSIONS

The technology of ITO layers spray deposition with area up to 50cm^2 was developed. ITO films with maximum conductivity $4.7\cdot10^3 Ohm^{-1}cm^{-1}$ and maximum transmission coefficient in the visible range of the spectrum (87%) were obtained from the solutions containing 90% $InCl_3$ and 10% $SnCl_4$ and under the following condition: substrate temperature ~450°*C*, deposition rate ~100*Å/s*, spraying time ~45*s*. Solar cells fabricated on the basis of semiconductor-insulator-semiconductor (SIS) structures are obtained by spraying deposition of ITO layers on a Si crystal surface. In such a way a novel type of solar cells containing only isotype junctions was developed. Their advantages consist in the following: the frontal junction is obtained with a simple spray technique at low temperatures; the double diffusion process is not necessary; the frontal ITO layer is both the collecting electrode and antireflection coating. For solar cells with an active area of 24cm^2 at the AM1.5 illumination conditions the following photoelectric parameters were obtained: the short circuit current 35.1mA/cm^2, the open circuit voltage 446*mV*, the fill factor 64.7%, the efficiency 10.11%. PV modules with the output power up to 30*W* have been fabricated on the base of 72 such solar cells.

REFERENCES

[1] J. Shewchun, G. Dubow, A. Myszkowsky and R. Singh, J. Appl. Phys, 49(9), 855, 1978.
[2] N. Adeeb, I. Kretsu, D. Sherban et al, Solar Energy Materials, 15, 9, 1987.
[3] V. Vasu, A. Subrahmanyam, Semiconductor Science and Technology, 7, 320, 1992.
[4] L. Gagara, L. Gorcheac, C. Radu, S. Radu, A. Simashkevich and D. Sherban, Proc. Int. Conf. Euro-Sun 96, 2, 665, 1996.
[5] A. Simashkevich, E. Do Quoc Hung, L. Bobeico, D. Gorceac and D. Sherban, Proc. 3rd Int. Workshop on Material Sciences, 1, 56, 1999.
[6] Simashkevich, D. Sherban, L. Bruk et al, Proceedings 20th European Photovoltaic Solar Energy Conference, 3, 980, 2005.
[7] M. A. Green, "Silicon Solar Cells. Advanced Principles & Practice", Centre for Photovoltaic Devices and Systems University of New South Wales Sydney, N.S.W., 201-233, 1995.
[8] T.S. Moss, G.J. Burrell, B. Ellis, Semiconductor Opto-Electronics, Butterworths, London, 23-28, 1973.
[9] Hartnagel Hans, A. L. Dawar, A. K. Jain, C Jagadish, Semiconducting Transparent Thin Films, Institute of Physics Pub., Bristol England and Philadelphia, PA, 358, 1995.
[10] R.A. Riben and D.L. Feucht, Int. J. Electronics, 20, 583, 1966.
[11] A.G. Milnes, D.L. Feucht, Heterojunctions and Metal–Semiconductor Junctions, Academic Press, New York and London, 173-187, 1972.

Clean Technology 2009, www.ct-si.org, ISBN 978-1-4398-1787-2