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Conducting Climatic and Mechanical Tests for Solar Modules Made of Heterojunction PV Cells with a Copper Contact Grid

Sergey Abolmasov[1], Artem Kochergin[1,2], Eugene Terukov[1,2,3], German Shelopin[1]

[1] *Scientific and Technical Center of Thin Film Technologies in Power Engineering, Saint-Petersburg, Russia*
[2] *St. Petersburg Electrotechnical University "LETI", Saint-Petersburg, Russia*
[3] *Ioffe Institute, Saint-Petersburg, Russia*
[*] *Corresponding author. Email: tem47@mail.ru*

ABSTRACT

The article describes the influence of climate conditions on a solar module consisting of photovoltaic (PV) cells with a copper contact grid. The technological sequence of formation of copper contact grid on the surface of silicon heterojunction solar cell is described. The article compares the traditional method of creating a contact grid using screen printing silver paste and an alternative method using electrochemical deposition of copper. The results of tests determining the resistance of solar cells to mechanical damage are shown. It is determined that the use of galvanized copper mesh allows reducing the degradation of the electrical parameters by 10%. It is shown that the solar modules, consisting of solar cells with a copper contact grid, successfully pass climatic tests.

Keywords: *Solar energy, Heterojunction photovoltaic cell, Metallization, Electrochemical deposition of copper, Climatic tests.*

1. INTRODUCTION

Crystalline silicon solar cells occupy the major share of the market for ground-based photovoltaic systems [1].

Heterojunction solar cells based on crystalline silicon are one of the most promising technologies, in terms of the efficiency ratio and cost. This type of cells is abbreviated to HIT (Heterojunction with Intrinsic Thin-layer solar cell). The manufacturing of HIT solar cells consists of several basic technological operations [2]: chemical processing, texturing, plasma-enhanced chemical vapour deposition of amorphous silicon layers, physical vapour deposition of antireflection layer and metallization. At the metallization stage a contact grid is formed, which performs the collection of electric charge carriers.

The traditional method of creating the contact grid is the screen printing method with pastes containing silver. This technology has proven to be highly reliable and simple process. About 85 % of solar cells based on crystalline silicon are made using screen printing [3]. Prospects for the development of the efficiency of this method are to find and advance new approaches to create silver-containing pastes. However, this technology has its disadvantages: limitations on the size of busbars and the high cost of the main component of the paste – silver.

The consumption of silver in the photovoltaic industry as of 2020 was more than 6% of the world silver supply [4]. PV production capacity is expected to grow from 132 GW in 2020 to 200–500 GW in 2025 and to terawatts in the next decades to meet climate goals. Increased demand for silver could lead to higher prices. Due to this prediction, among the researchers of renewable solar energy there is scientific interest in developing an alternative way to create a contact grid for solar cells. One possible alternative material to replace silver as a raw material for the contact grid is copper [5].

Table 1 compares the properties and cost of copper (Cu) and silver (Ag). It can be seen that the specific conductivity of Cu is only 3.7% lower than Ag, while the price is about 100 times lower. The main disadvantage of Cu is its diffusion into silicon, which leads to the formation of recombination centers in silicon.

Table 1. Comparison of silver and copper features.

Features	Ag	Cu
Conductivity (10^6 Cm/m)	61.4	59.1
Density (g/cm3)	10.5	8.9
Price ($/kg)	431.0	4.5

The implementation of replacement silver for copper could contribute to creating thinner busbars with high specific conductivity of contacts. The significant difference in the materials cost can make the copper contact grid a serious competitor to the standard contact grid based on silver conductive paste.

The work by A. Lachowicz presents a comparison of the outlay costs for different methods of creating a contact grid at the stage of metallization a solar cell [6]. The results of this work are presented in Figure 1. This diagram shows that taking into account all the components included in this technological stage, the cost of metallization using copper has the lowest value, part of which is the cost of depreciation of equipment, in view of a more complex technological process of creating a contact mesh.

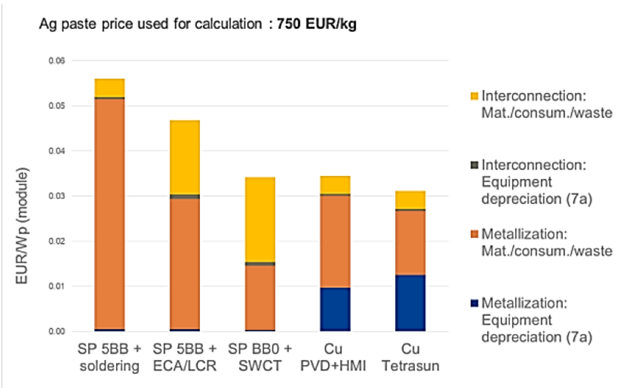


Figure 1 Comparison of the outlay costs for the contact grid metallization.

2. COPPER CONTACT GRID

A few years ago, Meyer Burger began to consider nickel busbars for front and rear metallization, while Fraunhofer (Institute for Solar Energy Systems (ISE)) was already conducting research based on copper metallization [7].

The highest reported efficiency for solar cells created with HIT technology was 26.6 % [8], while a simple contact pattern on both sides with copper metallization achieved 25.1 % [9].

Nowadays there are different methods for creating copper metallization, which vary in the way of forming the contact grid pattern: with photolithography, dielectric layer, and inkjet printing.

Standard printed circuit board (PCB) and semiconductor manufacturing processes, including metal seed layer and photolithography, can be applied to solar cell production. In the past, Silevo used a dry film resist to produce tunnelling oxide junction cells [10]; photolithography was reported by Sun Supreme [11].

Another approach is to use a dielectric layer such as silicon nitride (Si_3N_4) or silicon oxide (SiO) to prevent coating on the transparent conducting oxide (TCO) [12]. The dielectric layer can remain on the cell and serve as a second anti-reflective coating, which also reduces the thickness of the TCO.

3. METHODOLOGY FOR CREATING A COPPER CONTACT MESH

In this work, an electrochemical deposition method is used to create a copper contact grid. The sequence of the process flow is shown in Figure 2.

The sequence of the technological process is:

1. Physical vapour deposition of adhesive and copper conductive layer;
2. Formation of the contact grid pattern;
3. Electrochemical deposition of copper;
4. Removal of protective mask and etching the adhesion and copper layer.

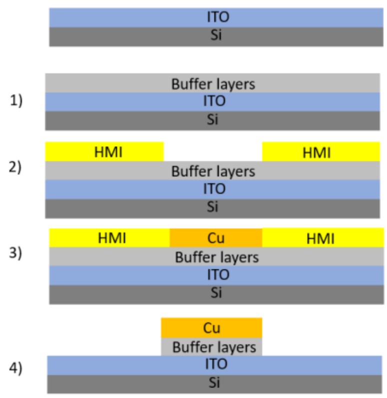


Figure 2 Technological sequence of copper contour mesh forming.

In the first step of the technological process, adhesion and conductive copper layers are applied to the surface of crystalline silicon coated with a layer of indium tin oxide (ITO), acting as an anti-reflective coating, by magnetron sputtering. For the direct formation of a copper contact grid with electrochemical deposition, the ITO surface has insufficient adhesion, an additional adhesion layer is applied to solve this problem. The copper layer is necessary to increase the conductivity of the electric current during the electrochemical deposition of copper on the PV cell surface.

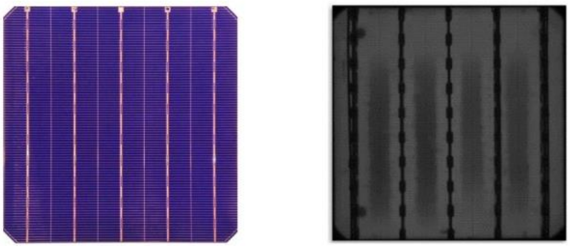
At the next step, a contact grid pattern is formed on the surface. For this step, refractory organic inks (HMI - Hot Melt Inks) and an inkjet printer are used.

This is followed by the electrochemical deposition of copper. At the final step, the protective mask is removed and the adhesion and conductive copper layer underneath the mask is stripped.

4. EXPERIMENTAL RESULTS

4.1. PV cell with copper contact grid

The formation of the copper contact grid was performed on full-size heterojunction solar cell with a size of 156.75 × 156.75 mm. The study results of the main parameters of solar cells with a copper contact grid are presented in the work [13]. Images of one of the produced solar cells with a copper contact grid and a snapshot of its electroluminescence are shown in Figure 3.



a) b)

Figure 3 Images of manufactured samples: a) frontal surface of solar cell; b) image of electroluminescence.

The obtained electroluminescence image shows that the copper contact grid does not shade the active surface of the cell and acts as a collection of charge carriers.

4.2. Study of mechanical damage resistance of solar cells with copper contact grid

This work studies and compares the resistance to mechanical damage of solar cells with silver paste and with galvanized copper mesh.

Two flexible single-cell modules were made for the experiment. The first module consisted of cells with a standard silver paste-based contact grid, and the second module consisted of cells with a copper contact grid.

The resistance of the modules to mechanical stress was examined by bending them horizontally and vertically. Photoluminescence images of single-cell modules before and after mechanical stresses are shown in Figures 4 and 5.

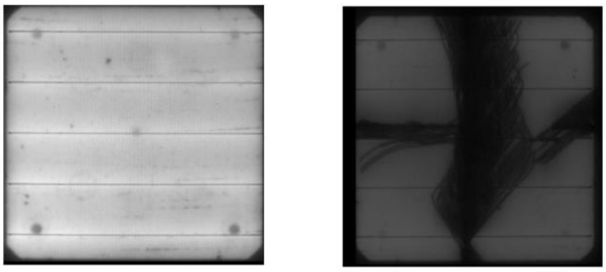


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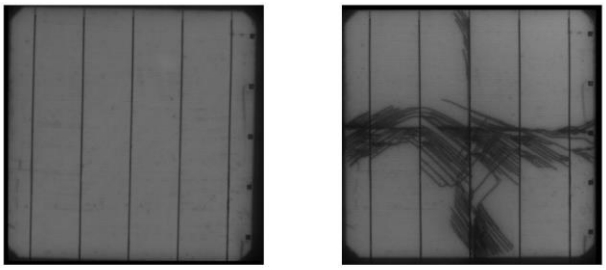
Figure 4 Photoluminescence images of solar cells with a silver contact grid: a) before the mechanical impacts; b) after the mechanical impacts.



a) b)

Figure 5 Photoluminescence images of solar cells with a copper contact grid: a) before the mechanical impacts; b) after the mechanical impacts.

The results showed that after the damage, the module with a copper contact grid remains more intact in comparison to the module with the silver paste contact grid, performing better current draw from the damaged parts of the cell. This result shows that the copper contact grid, consisting of several layers, acts as a wire, which unlike the silver contact mesh, does not break and does not stop contacting with the broken fragments after the mechanical impact, continuing to connect them and conduct electric current.

Due to the reduction of the active area after the mechanical impact, there is a decrease in the electrical characteristics of the cell. Studies of changes in maximum power (Pmpp) of the modules with silver and copper contact grid, before and after mechanical impacts are presented in Table 2.

Table 2. Parameters of the solar modules before and after tests

Samples	Pmpp, W	Degradation Pmpp, %
PV cell (Ag) before	5,06	
PV cell (Ag) after	3,84	24,11
PV cell (Cu) before	4,87	
PV cell (Cu) after	4,20	13,73

The degradation in Pmpp of the module with silver paste is significantly higher and is 24.11 %, while the degradation on the modules with galvanized copper mesh is only about 14 %. The difference of 10 % in Pmpp makes the copper-meshed modules a priority for flexible modules.

4.3. Study of the influence of climatic factors on the solar module

One of the most important parameters of solar photovoltaic modules, along with the rated peak power, is the long-term stability of electrical characteristics. This parameter is currently estimated as a guarantee of maintaining peak power at 90 % of nominal capacity after 10 years of operation and at 80% of nominal capacity after 25 years of operation. Long-term stability depends on many factors [14], which can be divided into four groups:

• factors due to the quality of design and construction; determined by many physical, chemical, electrical, optical, and mechanical properties of the materials and solar cells used;

• factors caused by the quality of manufacturing; determined by the quality of technological process control, especially, as a rule, soldering operations and installation of the junction box;

• factors caused by the quality of installation in the system; determined by the degree of coordination of the elements in the system, the correct choice of the components, including cables, connectors, electronic devices; the choice of the mounting structure;

• the actual climatic and other external factors.

The influence of all these factors has been repeatedly monitored, and, as a result, the test methods have been developed, combined into standard test sequences and published in IEC 61215 standard [15].

In order to study the effect of different climatic conditions on a solar module, consisting of PV cells with a copper contact grid, two solar modules of 4x5 configuration have been manufactured. These solar modules were subjected to technical tests: thermal cycling and damp heat.

The thermal cycling test is a test of the module's ability to withstand temperature changes. In this test, the module is placed in an environmental chamber and the insulation resistance is continuously monitored. The module is exposed to a series of temperature cycles from -40ºC to +85ºC, the test duration was 200 cycles. The criterion for passing the module is a decrease in Pmpp by no more than 5 %.

The results of thermal cycling solar module test, which passed 225 cycles, are presented in Table 3.

Table 3. Results of thermal cycling test of solar module

Solar module	Isc, A	Uoc, V	Pmpp, W	FF, %
0 cycles	8,908	14,54	98,07	75,73
225 cycles	8,899	14,52	97,36	75,33
Ratio degradation coefficient	0,1%	0,1%	0,7%	0,5%

Table 3 shows that the Pmpp of the solar module decreased after the thermal cycling test, which is associated with the degradation of the module active area, indicated by the decrease in the fill factor (FF). The Pmpp degradation factor of 0.7 % indicates that the module consisting of a solar cell with a copper contact grid successfully passed the technical test – thermal cycling.

For a detailed study of the Pmpp degradation moment of the solar module, a graph of the dependence of cycles number on Pmpp was plotted, see Figure 6.

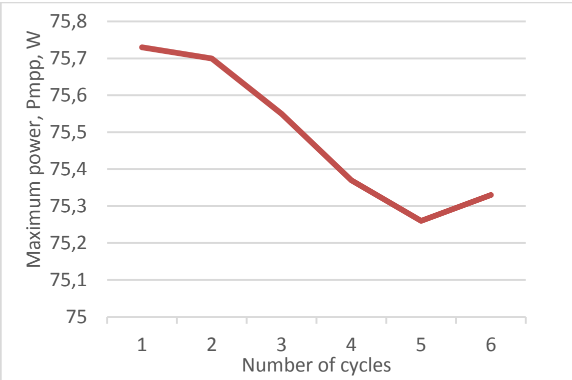


Figure 6 Dependency graph of Pmpp solar module on the number of cycles passed in the climatic chamber, during thermal cycling test.

According to Figure 6, we can say that the main decline in Pmpp occurred in the first 125 cycles, the next 100 cycles Pmpp value practically did not change.

The second solar module underwent a technical test - damp heat, in which the resistance of the module to prolonged exposure to temperature and high humidity is studied. During the test, the module is placed in an environmental chamber and the insulation resistance is continuously monitored. The module is exposed to temperature of +85 ºC and relative humidity of 85 %, the test duration is 1000 hours. The criterion for passing the solar module is a decrease in peak power by no more than 5 %.

The results of the damp heat test are presented in Table 4.

Table 4. Results of damp heat test of solar module

Time to pass the test	Isc, A	Uoc. V	Pmpp, W	FF, %
0 hours	9.11	14.55	101.00	76.19
1000 hours	9.02	14.55	99.37	75.71
Ratio degradation coefficient	1,1%	0,4%	3,1%	1,6%

As can be seen from Table 4, the following electrical parameters were severely degraded after the damp heat test: short-circuit current (Isc), FF, and Pmpp.

The peak Pmpp value of the solar module after passing the technical damp heat test was 3.1 %, indicating that this module, consisting of copper contact grid solar cells, successfully passed this technical test.

For a detailed study of the moment of Pmpp solar module degradation, a graph of the test time dependence on Pmpp was plotted, see Figure 7.

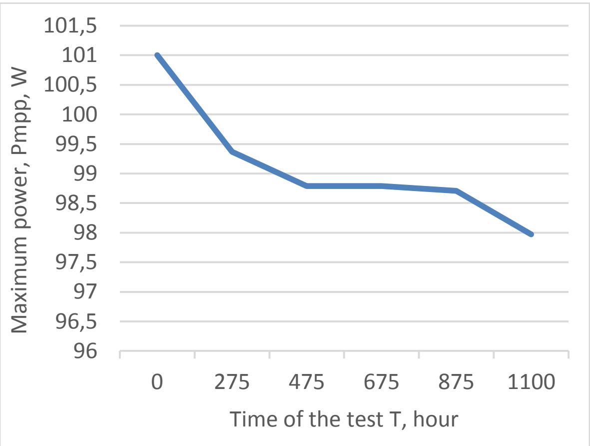


Figure 7 Dependency graph of Pmpp solar module on the time in the climatic chamber when the damp heat test is passed.

Figure 7 shows a sharp decrease in Pmpp at the beginning of the test. To study this point, a photoluminescence image of the solar module after 275 hours in the climatic chamber was studied, see Figure 8.

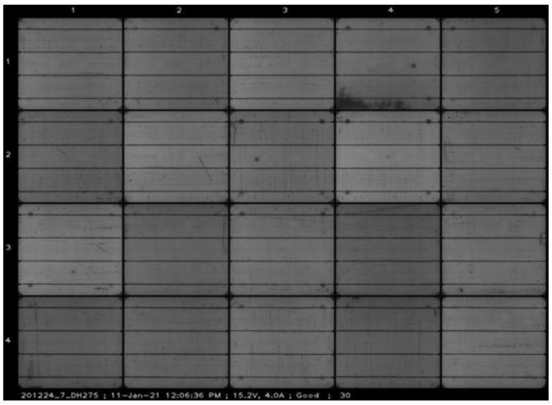


Figure 8 Photoluminescence image of a solar module with copper contact grid solar cell after testing in a chamber of high humidity and temperature.

A study of the photoluminescence image of the module after 275 hours in the climatic chamber showed that a 3.1 % drop in Pmpp is most likely due to a defect in a single PV cell (delamination of the contact grid).

4. CONCLUSION

A method of creating a copper contact grid for a heterojunction silicon solar cell was developed. The results of the study of solar cells with a copper contact grid showed that the manufactured grid has good adhesion to the surface of the PV cell and sufficient electrical conductivity, necessary for the collection of electric charge carriers.

According to the results of the study of the solar cell resistance to mechanical damage, it can be concluded that the copper contact grid is less susceptible to a decrease in the electrical characteristics than the contact grid based on silver paste.

Solar module consisting of solar cells with copper contact grid after passing the technical tests: thermal cycling and damp heat, under their prolonged exposure, showed low Pmpp degradation results, 0.7 % and 3.1 %, respectively. This fact indicates that the modules made of HIT solar cells with a copper contact grid successfully passed the climatic tests.

This work shows the possibility of switching from the traditional method of contact grid creation by screen printing with silver paste to electrochemical deposition of copper.

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