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# Effect of temperature on photovoltaic characteristics of PV modules based on CIGS solar cells

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**ABSTRACT**: The article presents the experimental results of the temperature dependence of the load current-voltage characteristics of a solar photovoltaic (PV) module based on a polycrystalline semiconductor binary compound $Cu(In,Ga)Se_2$ under normal sunlight $P_{rad}=800\pm5$ W/m$^2$, in a temperature range of (32÷60) ºC. The PV module efficiency decreases linearly with increasing temperature, from 12.5% to 11.45%, and a linear dependence with two slopes is observed. The CIGS PV module, in the temperature range of 300 – 310 ºK, had a temperature coefficient of efficiency $K_{Eff1} \approx$ -0.0342 % / ºK, and in the range of 310 - 320 ºK had a temperature coefficient of efficiency $K_{Eff2} \approx$ -0.0917 % /ºK. The conducted experimental studies have shown that the PV module based on CIGS solar cells, under conditions close to the average real illumination conditions $P_{rad} \approx$ 800 W/m$^2$ in the temperature range of 300 ‑ 320 ºC, has a negative temperature coefficient of change in efficiency $K_{Eff1} \approx$-0.0342%/ ºK and $K_{Eff2} \approx$-0.0917%/ ºK.

**KEY WORDS**: solar photovoltaic module, polycrystalline semiconductor, $Cu(In,Ga)Se_2$, solar radiation, efficiency, short-circuit current, open circuit voltage.

## I.INTRODUCTION

Currently, in order to meet the growing needs of developing industries and consumer needs, the world needs to increase electricity generation, especially in an environmentally friendly way. In this regard, in recent years much attention has been paid to the use of solar energy by directly converting it into electrical energy using photovoltaic devices [1,2]. One of the promising areas in this area is the creation of photovoltaic stations, since the electrical energy they receive is environmentally friendly, and solar energy is inexhaustible. In this regard, the development of thin-film solar cells is of great interest. Such thin-film solar cells, due to the high value of the layer absorption coefficient, make it possible to significantly reduce the material consumption for the production of solar cells, since a layer with a thickness of only ~ 2.0–2.5 µm is sufficient to absorb most of the solar radiation spectrum. One of such third-generation thin-film solar cells is a solar cell created on the basis of a copper (Cu) – indium (In) – gallium (Ga) diselenide ($Se_2$) compound, that is, a $Cu(In_{1-x}Ga_x)Se_2$ – CIGS compound [3,4]. The technology of manufacturing thin-film solar cells based on CIGS has a number of advantages over the technology of obtaining silicon solar cells, one of which is the use of the conveyor technology "roll-to-roll", which allows reducing the cost of manufacturing thin film solar cells. Taking into account all of the above, it can be noted that the CIGS compound is a very promising material for the manufacture of inexpensive, non-toxic and highly efficient photoconverters of the new generation, and research conducted in this direction is relevant.

## II. METHODOLOGY

In this article, studies were conducted on the influence of on a foil covered roof, on the output energy parameters of PV modules based on CIGS solar cells. The studies were conducted under normal sunlight conditions in May 2024 in Tashkent. The solar illumination power $P_{rad}$ incident on the solar cell was 800 W/m$^2$. Under the influence of sunlight, the temperature of the solar cell changed in the range from 32°C to 60°C, at an ambient temperature of T=32°C. The studied solar cell consisted of 36 series-connected solar cells with an effective area of 27.8×27.8 cm$^2$. The incident solar radiation power was measured using a wireless analyzer Solmetric Sol Sensor. The temperature on the surface of the solar cell was measured using a Fluke 62 MAX infrared thermometer. The load I-V characteristics of the solar cell were studied using a PROVA-210 Solar Module Analyzer.

## III. EXPERIMENTAL RESULTS

Fig.1 and Fig.2 show the experimental results of the temperature dependence of the short-circuit current $I_{sc}$ and the open-circuit voltage $V_{oc}$ of CIGS photovoltaic modules [5-7]. From Fig.1 it follows that $I_{sc}$ increases linearly with temperature in the range from 0.45 A to 0.49 A, with two slope angles. In the temperature range of 300 – 310 °K, the temperature coefficient of $I_{sc}$ of CIGS photovoltaic modules has a value of $K_{sc1} \approx$ 0.051 mA/cm$^{2o}$K, and in the range of 310–320 °K, the temperature coefficient of $I_{sc}$ of CIGS photovoltaic modules, $K_{sc2} \approx$0.162 mA/cm$^{2o}$K.
The temperature dependence of the short-circuit current $I_{sc}$ observed in Fig.1, with two slopes, in the second section the current increases sharply with temperature, which is associated with a decrease in the recombination of photo-generated minority charge carriers in the elevated temperature region, due to the filling of these levels with thermally generated electrons. A decrease in the recombination centers leads to recharging of defective states due to an increase in thermally generated charge carriers. In the photoactive layer of p-CIGS, they cease to act as a recombination center for minority electrons responsible for the photogeneration process. From Fig.2 it follows that $V_{oc}$ CIGS PEM linearly decreases with increasing temperature from 23.2 V to 22.07 V, in the entire studied temperature range from 300 ‑ 320 °K, with one slope, its temperature coefficient $K_{oc} \approx$–1.71 mV/°K.

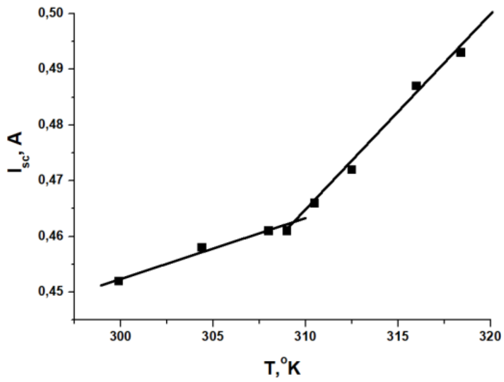

Fig.1. Temperature dependence of $I_{sc}$ of CIGS PVM

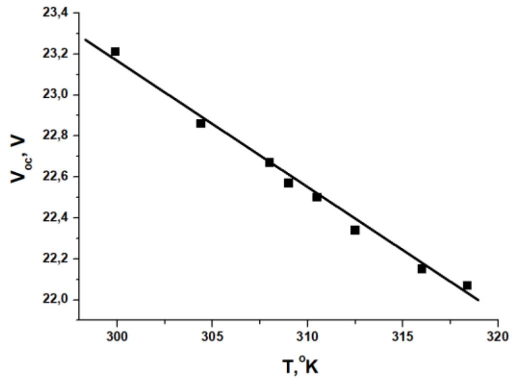

Fig.2. Temperature dependence of $V_{oc}$ of CIGS PVM

The experimental results of the temperature dependence of the photocurrent $I_{phmax}$ and the photogenerated voltage $V_{phmax}$ shown in Fig.3 and Fig.4 were measured at the maximum output power of the CIGS photovoltaic cell. It follows from the experiment that $I_{phmax}$, unlike $I_{sc}$, increases linearly with temperature, with one slope, from 0.41 A to 0.44 A. In the temperature range of 300 ‑ 320 °K, the temperature coefficient of the photocurrent of the CIGS photovoltaic cell has the value $I_{phmax}$, $K_{Iphmax} \approx$ 0.076 mA/cm$^2$ °K. It is evident from Fig.4 that $V_{phmax}$, as in the case of $V_{oc}$, decreases linearly from 17.9 V to 16.5 V with increasing temperature with one slope. It follows from the experiments that in the entire studied temperature range of 300 – 320 °K, the temperature coefficient of voltage $K_{Vphmax}$ of CIGS PV for a single element is equal to $K_{Vphmax} \approx$ - 2.14 mV/°K.

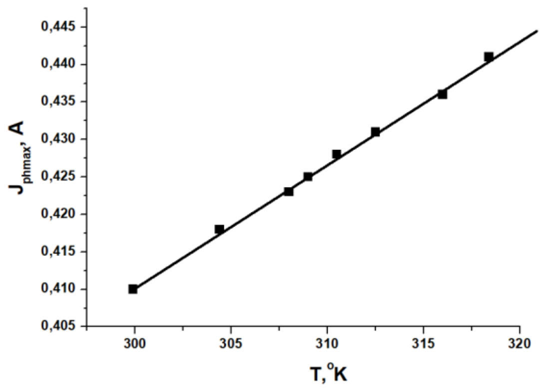

Fig.3. Temperature dependence of $I_{phmax}$ of CIGS PVM

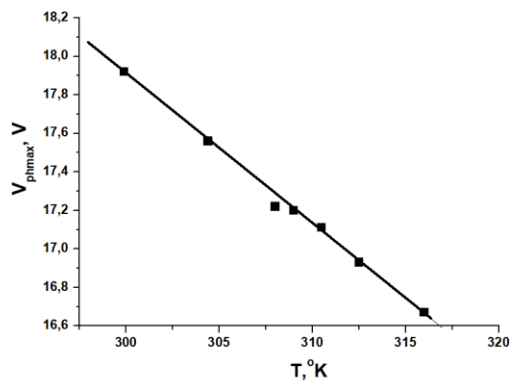

Fig.4. Temperature dependence of $V_{phmax}$ of CIGS PVM

Fig.5 and Fig.6 show the experimental results of the temperature dependence of the maximum output power $P_{max}$ and the fill factor (FF) of CIGS PV. It follows from the experiment that $P_{max}$ decreases linearly with temperature, from 7.35 W to 7.27 W, with one slope in the temperature range of 300–320 °K, the temperature coefficient $P_{max}$ of CIGS PV is $K_{Pmax} \approx$ - 0.092 mW/cm$^{2o}$K. The fill factor FF of CIGS PV in Fig.6 decreases linearly with increasing temperature from 70.13 to 66.8%, in the temperature range of 310 – 320 K, with the temperature coefficient $K_{FF} \approx$ - 0.4075 %/°K. In the temperature range of 300 – 310 °K, the FF of CIGS PV has a constant value of ≈ 70.13%.

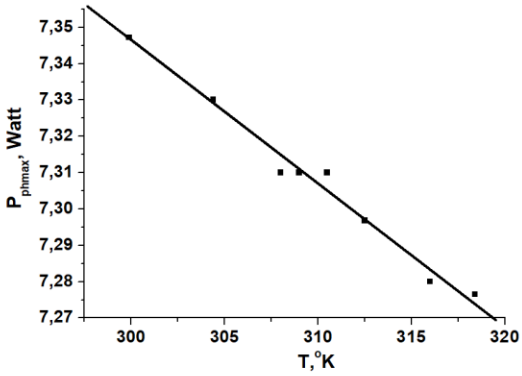

Fig.5. Temperature dependence of $P_{max}$ of CIGS PVM

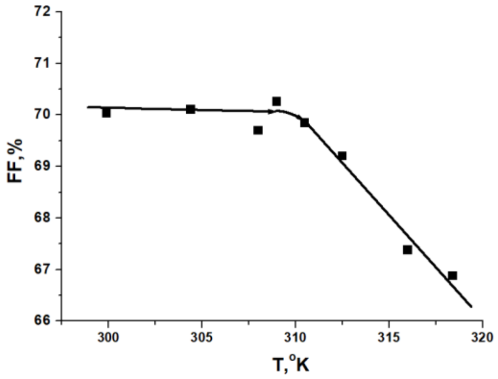

Fig.6. Temperature dependence of FF CIGS PVM

Fig.7 shows the experimental results of the temperature dependence of the CIGS PV module efficiency. The PV efficiency decreases linearly with increasing temperature, from 12.5% to 11.45%, and a linear dependence with two slopes is observed. The CIGS PV, in the temperature range of 300 – 310 °K, had a temperature coefficient of efficiency $K_{Eff1} \approx$ -0.0342 %/°K, and in the range of 310 – 320 °K it had a temperature coefficient of efficiency $K_{Eff2} \approx$ -0.0917 %/°K. The conducted experimental studies have shown that the PV module based on CIGS solar cells, under conditions close to the average real illumination conditions $P_{rad} \approx$ 800 W/m$^2$ in the temperature range of 25 – 50 °C, has a negative temperature coefficient of change in efficiency $K_{Eff1} \approx$-0.0342%/°K and $K_{Eff2} \approx$-0.0917%/°K.

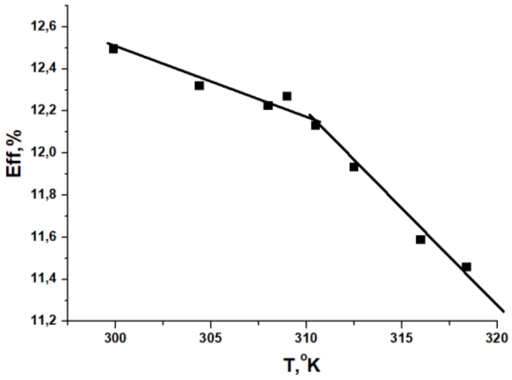

Fig.7. Temperature dependence of the efficiency of CIGS PVM

The observed experimental results of the dependence of the CIGS solar cell efficiency from Fig.7 can be explained based on the analysis of the real structure of the solar cell, by analogy with the solar cell. The real structure of the solar cell is characterized by the presence of series $R_{ser}$ and shunt resistance $R_{sh}$ of the CIGS solar cell.

Fig.8 and Fig.9 show the experimental results of the temperature dependence of the series $R_{ser}$ and shunt resistance $R_{sh}$ of the CIGS solar cell, calculated from the load I-V characteristic. At a temperature of T=300°K, the CIGS solar cell has $R_{ser}$=8.6 Ohm and $R_{sh}$=4060 Ohm. As expected, with increasing temperature, the values of $R_{ser}$ and $R_{sh}$ decrease, and at a temperature of T=319°K, they have the values $R_{ser}$=6 Ohm and $R_{sh}$=3580 Ohm, respectively, under conditions of an incident radiation power of 780 ± 30 W/m$^2$ [8-10].

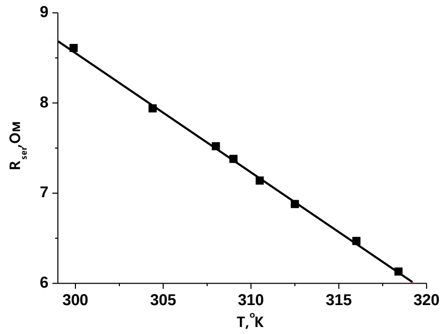

Fig.8. Temperature dependence of series resistance $R_{ser}$ of CIGS PVM

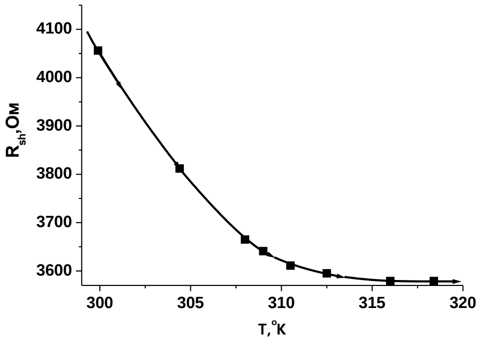

Fig.9. Temperature dependence of shunt resistance $R_{sh}$ of CIGS PVM

## IV. CONCLUSION AND FUTURE WORK

The conducted experimental studies have shown that the PV module based on CIGS solar cells under conditions close to the average real conditions of solar radiation illumination $P_{rad} \approx 780 \pm 30$ W/m$^2$, in the temperature range of 25 ‑ 50 ºC, has a negative temperature coefficient of efficiency change $K_{Eff1} \approx$-0.0342 %/ºK and $K_{Eff2} \approx$-0.0917 %/ºK from Fig. 4.7. This experimental fact is explained by the temperature dependence of $R_{sh}$, leading to losses of photogenerated minority charge carriers through leakage channels in the CIGS layer and a decrease in the efficiency of the PV module based on CIGS solar cells.

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