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Status and Prospects of Thin-Film Solar Cells Based on the Compound $CuIn_{1-x}Ga_xSe_2$

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ABSTRACT: This article discusses the prospects for the development, production and use of solar cells, the achievements and expected results of research in this area.

KEYWORDS:solar cells, thin-film technologies, connections, sunlight, radiation resistance of modules, structure, selenization,

I. INTRODUCTION

Currently, solar cell (SB) technologies based on crystalline silicon dominate on an industrial scale. However, high cost is the main reason preventing their application on a larger scale. Therefore, the attention of scientists and manufacturers is riveted to the development of efficient technologies for thin-film solar cells (SCs). In recent decades, two main thin-film technologies have emerged based on CdTe and CuIn1-xGaxSe2 (CIGS) compounds. These SCs have a conversion efficiency in the range of 15-20%, which is comparable to that of silicon-based SCs. However, the increase in the production of solar cells based on CdTe is affected by the cost and shortage of tellurium, as well as the toxicity of cadmium. Therefore, thin-film SCs based on CIGS have recently attracted much attention from both researchers and manufacturers [1–3]. This report presents an analysis of the state and prospects for the use of CIGS technology for the production of solar cells.

Main advantages . Although chalcopyrites(CIS, CGS, etc.) have been known for a long time, studies of the possibility of using them to obtain solar cells began in the 1980s [4,5]. Due to the direct energy band and large optical absorption coefficient, CIS compounds and CIGS alloys are considered promising for the creation of thin-film SCs.
The first industrial production of solar cells based on them was launched in 2007. The ShoveShellcompany created the first industrial line for the production of PV modules with an efficiency of 13.4% [6]. Currently, more than 6% of all solar cells produced in the world are produced on the basis of CIGS.
Thin-film solar cells are attractive due to the ability to operate under conditions of scattered radiation, i.e. and on cloudy days, even in winter. They are produced on the basis of polycrystalline silicon films, CdTe and CIGS. Among these materials, the latter is one of the most promising for thin-film solar cells. Interest in this compound is determined by the following factors:

1). The band gap of solid solutions $CuIn_{1-x}Ga_xSe_2$ varies within 1.0-1.68 eV when the gallium content changes from 0 to 1.0. Its value can be ideally matched to the optimal value for solar photoconverters;
2). The high value of the absorption of sunlight ($3\cdot10^5$-$6\cdot10^5$ cm^{-2}) compared with other semiconductor materials, so the thickness of the absorbing layer is only 2-5 microns;
3). The efficiency of solar cells based on CIGS obtained in the laboratory is 20.9%, industrial modules have an efficiency of more than 15%, which is comparable to the efficiency of solar cells on single-crystal silicon;
4). CIGS absorber layers can be formed in a variety of ways using process equipment widely used in the industry;
5). High radiation resistance of modules. CIGS-based structures have radiation hardness 50 times higher than those based on silicon and GaAs ;
6). Low cost of SE. For the production of 1 kW of solar cells, 60 g of the compound material will be required. The cost of a CIGS module with a power of 30 MW or more is $0.6 per kW of energy.

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However, there is conflicting information in the literature about the degradation of SC CIGS parameters. The authors of [7, 8] argue about the high stability of the SC characteristics during continuous operation. According to their results, after operation for $7 \cdot 10^{5}$ hours under conditions of continuous illumination with the help of a solar radiation simulator and a module temperature of 60 ^{0} C, the SC parameters remain unchanged. The work shows the possibility of increasing the efficiency of CIGS SC by 15–20% during heat treatment in air. An improvement in the SC parameters was also found in the case of their long-term operation at room temperature [9]. However, the mechanism of the effect has not been fully elucidated. The authors of [10] point out the instability of the properties of CIGS layers during long-term operation in atmospheric conditions. To clarify this issue, it is necessary to conduct a thorough study of the degradation of the parameters of CIGS layers and the characteristics of structures based on it.

SE structure. The structure of the traditionally used thin-film SC based on CIGS is shown in Fig. . 1. As can be seen from the figure, the structure contains an absorbing CIGS layer, a layer for creating a separating heterojunction barrier, and a transparent conductive oxide layer. As the latter, ZnO , ITO , etc. are usually used . CdS layers have been used so far to create a separating barrier , recently there have been attempts to use instead of CdS (Cd is an environmentally harmful element), without cadmium films - ZnS , ZnSe , In_2S_3, etc. .d. In most cases, a thin layer of molybdenum is used as a back contact. Molybdenum has good adhesion to glass, is heat resistant and has high conductivity, which is important for use as a back contact. Soda silicate glass or flexible stainless steel or polyimide substrates are used as substrates [11]. A molybdenum layer 1 µm thick is deposited at room temperature. The thickness of the CIGS absorbing layer is 1-2 µm, a buffer layer of CdS (~70 nm) or ZnS is applied on top of it , the uppermost transparent conductive layer of ZnO is taken with a thickness of ~350 nm .

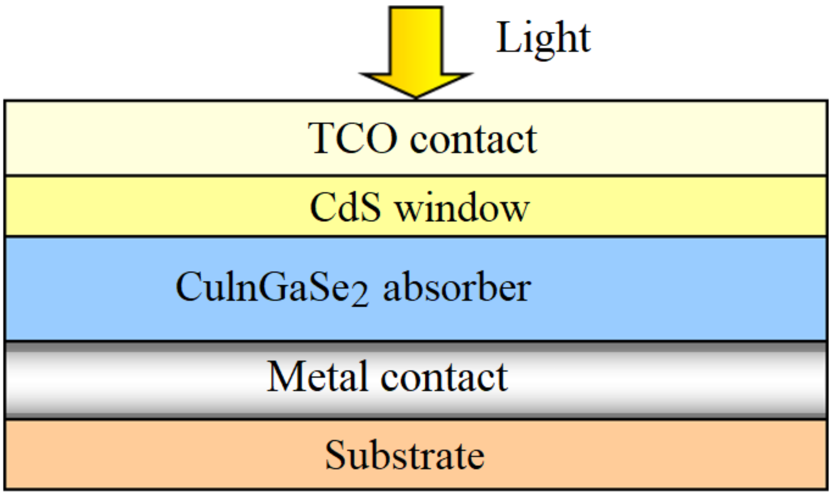

Fig.1. Structure of a thin-film SC based on CIGS [12].

The disadvantages of CIGS SCs are the difficulty of obtaining a high-quality absorbing layer and the degradation of the characteristics of structures during long-term operation in natural conditions. To increase the reliability and service life of SCs, it is necessary to develop an efficient technology for obtaining perfect films and to elucidate the mechanism of degradation of the properties of CIGS films during long-term operation of SCs based on it.

Obtaining thin CIGS films. As is known, the methods of obtaining films significantly affect their properties, as well as the characteristics of solar cells based on them. There are various ways to obtain thin CIGS films [13, 14, 15]. The main methods used are selenization of pre-deposited base layers, simultaneous evaporation of components from several sources, electrodeposition , physical and chemical vapor deposition. Each of these methods have their own advantages and disadvantages. The most perfect films are obtained in the case of using the methods of selenization of preformed base layers and with the evaporation of the constituent components of the compound. Coarse-grained polycrystalline CIGS layers are obtained by varying the content of copper and indium. The most important issue in the formation of CIGS films is to ensure the stoichiometric composition of the compound; it is especially important to control the Cu /In ratio. Even a slight deviation of the composition of the compound from the stoichiometric one can lead to a significant change in the parameters of the film and the characteristics of solar cells based on it. The effect of the Cu /In(Ga) and In/ In+Ga ratio on the properties of the CIGS-based film and module should be carefully studied.

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The general requirement for perfection is that the film surface must be smooth, the polycrystalline structure must consist of densely packed crystallite grains oriented along the (112) direction. Moreover, the surface of the film must be somewhat depleted of copper so that a compound with ordered vacancies is formed on the surface of depleted copper. It is extremely important that the film does not contain any secondary phases. For example, the presence of the $CuSe_{2\ phase}$ is very undesirable, since copper diselenide , having a high conductivity, leads to an increase in the dark current p-n of the SC structure.
One of the promising technologies for the production of thin-film SCs based on CIGS is the selinization of pre-applied base layers. Another promising manufacturing technology is the ink-printingprocess (ISET).

Efficiency of solar cells based on CIGS. In the first SCs based on CIGS with a sufficiently high efficiency was obtained in the early nineties of the last century, then an efficiency of 16% [16] was achieved , at present the record efficiency of this material is more than 20% [17,18]. The main characteristics of SCs based on CIGS thin films with different structures are shown in Table 1. The analysis shows that thin-film CIGS SCs have a high potential due to the high optical absorption coefficient and the possibility of changing the band gap (within 1.0-1.68 eV) material by varying the content of gallium in the range from 0 to 100%. The best results are shown by SCs based on CIGS films with a gallium content in the range of 20–30% , the band gap of which varies within 1.1–1.2 eV [19].

Last year, it was announced that SolarFrontier and NEDO (New Energy and Industrial Technology Development Organization) have achieved a 20.9% solar conversion efficiency as a result of joint research in a CIGS solar cell [21]. Experts believe that this is not the limit for this material, therefore, studies are intensively ongoing to establish the optimal composition , the ratio of components Cu /In(G a), the material for the barrier junction heteropair , and the optimization of the CIGS solar cell formation technology. In addition, the production of CIGS modules requires 60% less energy than the production of crystalline silicon modules. CIGS modules generate more electricity (kWh) in actual use than silicon crystalline modules.

The SC efficiency is significantly affected by sodium and oxygen atoms, which enter the CIGS film due to diffusion from sodium-containing glass [19]. The study of the interaction of oxygen with the surface of the films showed that thermal treatment in air affects the parameters of SCs based on CIGS. For example, the work [9] shows the possibility of increasing the efficiency of CIGS SCs by 15–20% during heat treatment in air. An improvement in the SC parameters was also found in the case of their long-term operation at room temperature [10, 21]. However, the mechanism of the effect has not been fully elucidated. Possibly, this is due to the formation of indium oxide (In_2O_3), which can cause a change in the parameters of devices based on CIGS.

Table 1. Performance of solar cells based on CIGS[6].

Structure	S_{total},cm^2	U_{OS} ,mV	J_{SC} ,mA/cm^2	*ff*,%	Efficiency,%	Manufacturer
MgF_2 / ZnO / CdS / CuIn (Ga)Se_2 /Mo	0.41	674	34.0	77.3	17.7	NREL
CuIn(Ga) $_{Se2}$	0.48	678	32.0	75.8	17.6	Matsushit
MgF_2 / ZnO / CdS / CuIn (Ga)Se_2 /Mo	-	558	41.0	71	16.2	SiemensSolar
MgF_2 / ZnO / CdS / CuIn (Ga)Se_2 /Mo	0.25	641	31.1	76	15.4	IPE
CuIn(Ga) $_{Se2}$	0.164	600	33.8	73.3	14.9	DEEE
MgF_2 / ZnO / CdS / CuIn (Ga)Se_2 /Mo	0.33	641	35.8	73	16.9	IPE/KTH
CdS / CuIn (Ga)Se_2 /Mo/ss	-	575	32.3	75	13.9	KTH
CdS / CuIn (Ga)Se_2 /Mo/ Al+NaF	-	582	32.7	75	14.3	KTH
MgF_2 / CdS / CuIn (Ga)Se_2	-	620	32.5	77	15.5	IPE
$CuIn_{0.7}Ga_{0.3}Se_2$	-	688	29.8	74.1	15.2	IPE
CuIn(Ga) $_{Se2}$	0.125	679	35.07	77.7	19.2	NREL

An analysis of the situation with SCs based on CIGS shows that they have great potential both in terms of choosing the optimal ratio of Ga / In + Ga components and improving the technological mode of production. Since, due to insufficient knowledge, the optimal technology for the synthesis of thin films of CIGS and the creation of heterostructures based on it has not yet been developed. The solution of this issue certainly leads to an improvement in the characteristics of solar cells in comparison with traditional solar cells, which have almost reached the optimal production technology.

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II. CONCLUSION

An analysis of the known methods shows that the most effective method for the synthesis of CIGS films is the selenization of the base metal layers, which ensures the production of films of sufficient area with a controlled composition. The second effective method for obtaining CIGS films is the ink-printing process (ISET).

The best efficiency of CIGS SC is observed at the ratio of components of copper and indium(gallium) 0.86≤Cu/ In(Ga)≤0.96. It is necessary to further improve the technology for the synthesis of thin films of CIGS and the creation of heterostructures based on it using a cadmium-free material. The influence of the deviation from the stoichiometric composition and the ratio of the components Cu /In(Ga) and In/ In + Ga on the properties of the film and module based on CIGS should be carefully studied.

It is necessary to study the degradation of the characteristics of structures during long-term operation in natural conditions. To improve the reliability and service life of SCs, it is necessary to elucidate the mechanism of degradation of the properties of CIGS films during long-term operation of SCs based on it.

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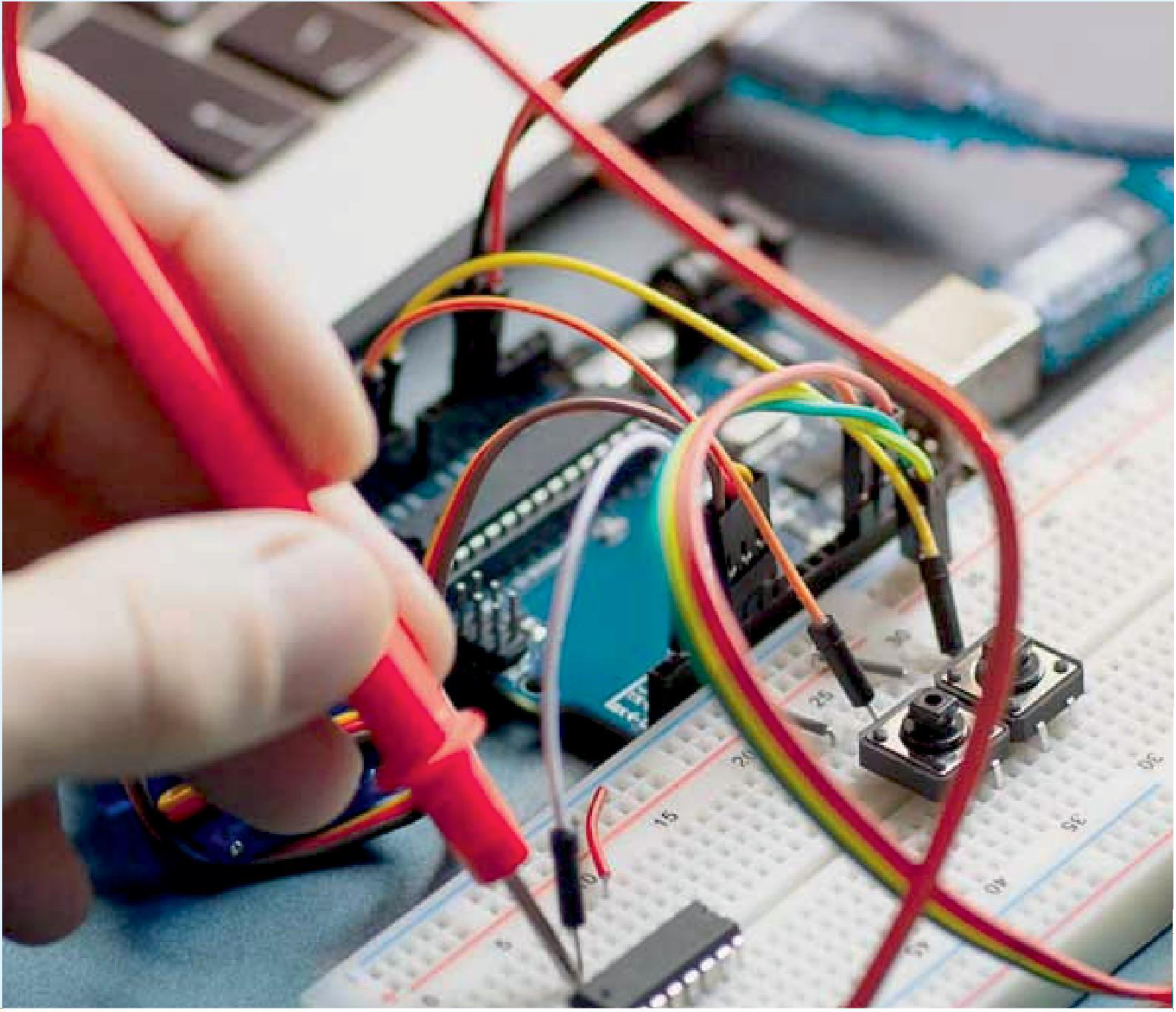

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