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CIS, CIGS and CIBS thin film solar cells and possibilities of their application in BIPV

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Photovoltaic thin–film solar cells have gained more and more popularity in recent years. As well as high efficiency, they have a number of properties allowing their application in BIPV. The paper presents thin film copper indium diselenide cells (CuInSe2 – CIS) and their modifications. Their electric and optical properties are characterised. The subject of presentation includes phenomena, which take place in these solutions as well as issues related to selection of absorbing–generating layers and a window layer, including the possibilities of solving these issues to obtain high efficiency of photovoltaic conversion. At present, the photovoltaic conversion is already at the level of 22.3% in laboratory conditions [29]. The examples of roof and facade applications of CIS with regards to buildings are provided.

KEYWORDS: solar cell, CIS, heterojunction, Light Soaking effect, BIPV

1. Introduction

Cells characterised by flexible properties, low weight and costs, and above all very high absorption coefficient are sought after in photovoltaics. Such properties enable a broad range of applications such as integration of cells with elements of building facades, vehicle bodies, textile and plastic surfaces. The criteria listed above are fulfilled by thin film copper indium diselenide cells and their modifications. The technology of thin film heterojunction cells is a cheaper solution in comparison with the most popular technology based on the p – n homojunction in monocrystalline silicon. [2, 7, 19].

The thin film CIS cells with the layer thickness of 2 – 3 μm are placed on the glass layer with the thickness of 3 mm [31], which ensures significant savings in terms of material and energy (manufacturing process). At present, the cells of this type, in particular, structures combined with gallium ($CuIn_{1-x}Ga_xSe_2$) become more and more popular among thin film cells. [18].

Tests of homojunction CIS structures were conducted already back in the seventies of the 20th century [1, 9]. The first tests related to heterojunction thin film cells ($CuInSe_2$/CdS) were carried out by Kazmerski et al. [8]. In reference to the efficiency of crystalline cells of this type, reaching at that time 12%, the efficiency of the latter ones was not impressive as it hardly amounted to 5.7%. A few years later, the efficiency value for the solution developed in the U.S. (Boeing Aerospace Thin Film Laboratory) reached 9.4%, and in the case of application of an additional anti–reflective layer – 11% respectively. Similar results were achieved in the middle of the eighties during tests conducted at the Solar Research Institute Golden Colorado. In the case of the latter solution, double layers of $CuInSe_2$ and CdS with varied thicknesses and resistivities are characteristic. A cell with double layers was described in more detail in [8, 9]. In the following years, thin film heterojunction $CuInSe_2$/CdS cells with higher and higher efficiency were developed, that is 12% (NREL, year: 2000), and in laboratory conditions (year: 2005) – 19.9% respectively [15]. The maximum theoretical efficiency is determined at the level of 27%, and on a mass scale – 17% respectively. In the year 2014, as has been described in the Fraunhofer report, the efficiency equal to 21% was achieved in the case of a single cell with the area of 1 cm^2, and for the module – 17.5% respectively. The latest result is 22.3% [29].

2. Characteristics of the optical and electrical properties of CIS cells

Copper indium diselenide ($CuInSe_2$) is a polycrystalline thin film material with the structure of chalcopyrite, characterised by a very high absorption coefficient, as a result of which as many as 99% of the incident sunlight is absorbed already in the layer with the thickness of one micrometer. The colour of the cells is black; there are no distinctive cells in the module, which create a uniform surface. The band gap of copper indium diselenide cells is equal to 1.05, thus, it differs significantly from the optimal gap and does not guarantee high efficiency which is achieved in other solutions [11].

The cell parameters are stable over time, but only at the temperature that does not exceed 90°C [13]. In order to provide protection against external factors, cells are placed in a glass housing, but even then their life does not exceed 10 years. It is also necessary to take into consideration the fact that selenium and indium are toxic elements. In addition to this, natural indium resources are limited. Production of indium per year amounts to 500 tonnes [9, 13, 17]. The price of CIS cells is relatively low, according to a consulting company; it is estimated at 0.8 USD/W_p. However, this has not been confirmed by manufacturers.

Figure 1 shows the layer structure of a solar cell made of copper indium diselenide, based on [9, 28]. The properties of the copper indium diselenide, both the optical ones and electrical ones, depend, to great extent on the crystalline structure of the material and the share of both components – copper and indium – included in it. Concentration of holes decreases with a decrease in the share of copper in relation to indium, whereby the hole mobility may reach even 20 cm^2/Vs [6, 18].

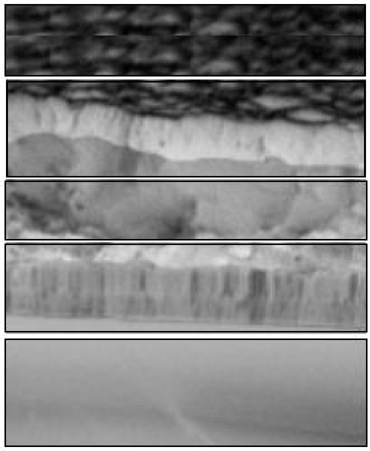

Fig. 1. Copper indium diselenide solar cell – the layer structure

Table 1 provides exemplary physical and electric parameters of CIS modules [16].

Table 1. Selected parameters of CIS modules manufactured by Shell

Module type	Shell ST5	Shell ST10	Shell ST20	Shell ST36	Shell ST40
Module characteristics					
Number of cells	42	42	42	42	42
Type of cell	Thin film CIS	Thin film CIS	Thin film CIS	Thin film CIS	Thin film CIS
Electric characteristics					
Maximum power [W_p]	5	10	20	36	42
Voltage at PMM* [V]	15.6	15.6	15.6	15.8	16.6
Open circuit voltage [V]	22.9	22.9	22.9	22.9	23.3
Short–circuit current [A]	0.39	0.77	1.54	2.68	2.68
Rated voltage [V]	12	12	12	12	12
Construction parameters					
Length [mm]	329	359	748	1293	1293
Width [mm]	206	329	329	329	329
Weight [kg]	1.4	2.4	4.1	7	7
Typical applications					
	Autonomous/ Industrial	Autonomous/ Industrial	Autonomous/ Industrial	Autonomous/ Industrial	Network

*PMM – Maximum power point

At the Ängström Laboratory, Uppsala University, cells based on copper, indium and selenium compounds were obtained. The thickness of their active layers was 4 microns. Therefore, already 20 – 30 grams of material ensures coverage of 1 m^2 with such cells. In the case of a traditional silicon cell, this is about 1 kg of silicon respectively.

An example of the CIS cell is characterised by the following parameters: short–circuit current density I_{zw} = 38 mA/cm^2, open circuit voltage U_0 = 0.49 V, filling factor FF = 0.60 and efficiency η = 12% [10]. It is also characterised by good temperature tolerance. There is no Stabler – Wronski effect here, as a result of which the efficiency of the amorphous silicon cells is reduced [8], but rather the positive *Light Soaking Effect,* described in further sections of the paper.

3. Different efficiency–enhancing thin film CIS cell solutions

In the late seventies and early eighties of the previous century, numerous modifications different than the prototype were introduced. They were supposed to ensure enhanced efficiency of the described cells [9].

Further sections of the paper present exemplary solutions of CIS cells. One of the first cells made of copper indium diselenide and cadmium sulphide was proposed in the year 1985 by scientists from Solar Research Institute Golden Colorado. Cross–section through the cell is shown in figure 2 [9].

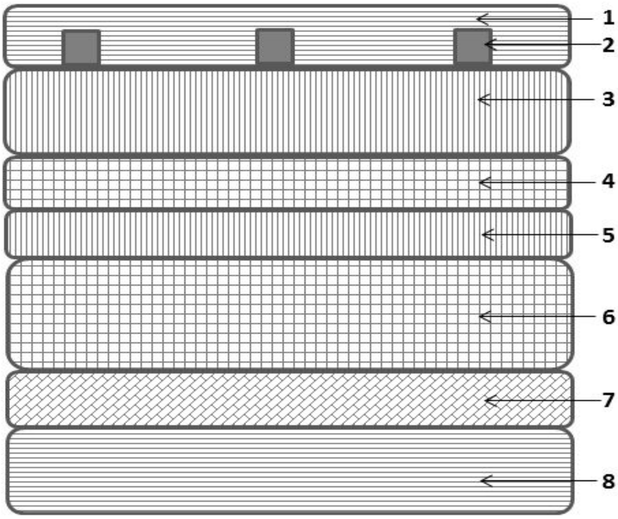

Fig. 2. Multilayer structure of $CuInSe_2$/CdS proposed by Solar Research Institute Golden Colorado. Designations: anti–reflective layer (1), meshed aluminium electrode with the thickness of 2 μm (2), CdS layer (2 μm) (3), CdS (0.8 μm) (4), $CuInSe_2$ with the thickness of 0.8 μm (5), $CuInSe_2$ with the thickness of 3 μm (6), molybdenum electrode obtained using the sputter deposition technique (7), substrate made of aluminium oxide (8)

Layers (4) and (5) are characterised by high resistivity and layers (3) and (6) have low resistivity.

As can be seen in Figure 2, the characteristic features of the constructed cell include the double CIS and CdS material (absorber) layers. The layer of $CuInSe_2$ (0.8 μm), with high resistivity has a slight deficiency of Cu (up to 5%). Its application on the CdS layer (0.8 μm), which also has high resistivity, was supposed to prevent the formation of copper nuggets within the junction.

CIS and CdS layers (absorber, 3 μm), with low resistivities, obtained as a consequence of the vapour deposition technology are supposed to result in a decrease of unwanted serial resistivity of the cell. The layer of $CuInSe_2$ (absorber, 3 μm), with the composition similar to the stechiometric one, is applied to the molybdenum–metalized aluminium oxide substrate. The second CdS layer contains an admixture of indium (about 3 %) [9].

Both layers of $CuInSe_2$ vary in concentration of carriers and their mobility, resistivity and type of conductivity. Between these layers, an additional layer with intermediate properties is formed spontaneously [8].

The efficiency of the described cell reached 7%, and after additional technological processes were conducted, it was increased to 10 % [8].

As has already been mentioned in the preceding section, the homojunction solutions enable the absorption of the majority of photons with energy $h\nu > E_g$. Such limitations are not present in tandem cells, where absorption of photons from the difference in energy of band gaps of component cells is also possible. Even the double cell solution may theoretically achieve the efficiency of 36%.

The first tandem cell with CdS/(CdHg)Te and CdS/$CuInSe_2$ layers was constructed in the year 1985 by R.W. Birkmire. However, its efficiency was just 3% [8]. The cell is presented in Figure 3 [8].

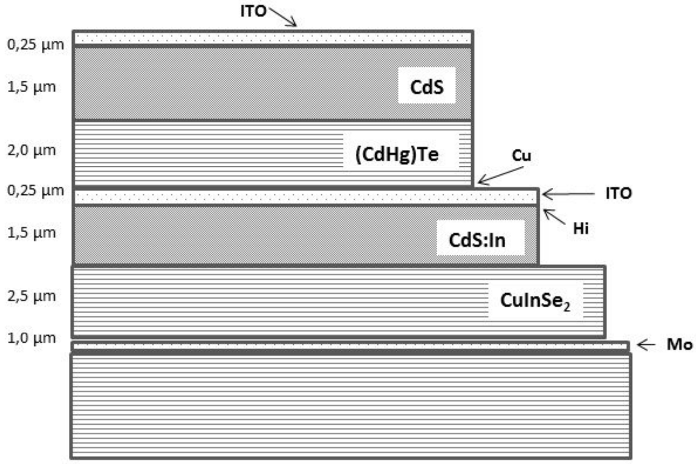

Fig. 3. Cross section through the tandem cell

4. Modifications of CIS cells with gallium and boron

Also solutions with gallium are applied (CIGS), which can be written as $CuIn_xGa_{(1-x)}Se_2$, whereby x = 1 (*Copper Indium Selenide*) to 0 *(Copper Gallium Selenide*). Gallium increases a relatively small band gap of the material. The band gap ranges between 1.0 eV (CIS) and 1.7 eV (CIGS). Because of the high absorption coefficient – 10^5/cm, which characterises the CIGS cells, it is possible to reduce the absorbing layer to 0.5 μm (then it absorbs as many as 90% of sunlight), and in certain solutions even up to 0.2 μm, (i.e. about 100 times in comparison with crystalline silicon) [12, 24].

CIGS are manufactured as thin film polycrystalline cells with a heterojunction structure, where Cu $(In,Ga)Se_2$ fulfils the role of the ZnO absorber – the window layer, and CdS serves as a kind of buffer. Sometimes, doping of sulphur is applied. These modifications increase the band gap to 1.7 eV and enhance efficiency [5, 8].

Figure 4 shows the layer structure of the CIGS cell.

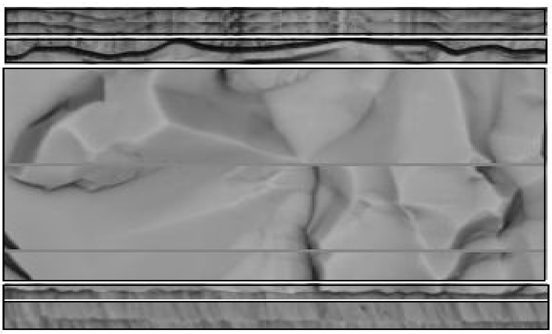

Fig. 4. Solar cell made of copper indium diselenide including gallium, the layer structure

Ultimately the CIGS structure consists of many layers, whereby the layer of $CuInGaSe_2$ per se constitutes a p–type semi–conductor. The role of the n–type semi–conductor is fulfilled by CdS and ZnO [12].

Both in the case of the discussed CIS cells and CIGS cells, hard (glass) and flexible (stainless steel, molybdenum – it improves the ohmic contact, or plastic, polyamide) substrate can be used. In the case of the molybdenum layer, its thickness ranges between 0.5 and 1.5 μm.

Cross–section through the layer structure of the cell is shown in Figure 5.

It is particularly beneficial to use CIGS composed of $CuIn_{0,8}Ga_{0,2}Se_2$ as an absorber. Although the band gap is not too big (1.2 eV) the achieved efficiency is high (20%). CdS forms then the window layer and ZnO acts as the buffer layer.

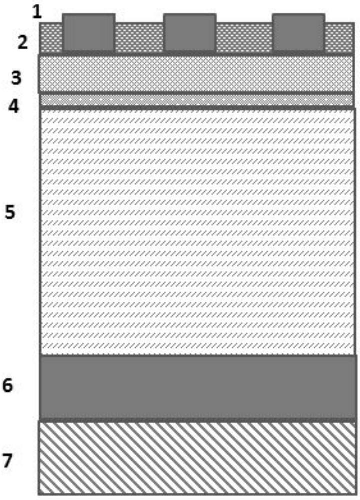

Fig. 5. CIGS with the modified window layer (ZnO+CdS), cross–section through layers: (1) front contact, (2) MgF_2 as the anti–reflective layer with the thickness of 0.08 – 0.12 μm, (3) ZnO window layer with the thickness of 0.25 – 0.50 μm, (4) CdS window (buffer) layer with the thickness of 0.05 μm, (5) CIGS absorbing layer – 2 – 4 μm, (6) Molybdenum as the back contact – 1 μm, (7) glass substrate

One of the possible solutions is also Lightfoil. This is a thin–film CIGS *(Copper Indium Gallium Diselenide)* cell on a thin titanium substrate. These cells are characterized by extremely high absorption, which allows their manufacturing in a version with uniquely small thickness (1 – 2 μm), equal to the thickness of aluminium foil, as well as high plasticity. They achieve the efficiency of 15.2% in atmospheric conditions (AM0). Lightfoil is fit mainly for military and aeronautical applications. It is produced e.g. by Day Star Technologies [3, 9].

The latest experiments described by authors of work [4] refer to the replacement of the indium atom with boron atom (CIBS).

5. Light soaking effect

CIS and CIGS cells are characterised by the occurrence of a positive phenomenon called *Light Soaking Effect,* which causes an increase in their power under the influence of the incident sunlight, by 1 – 3% in relation to their rated power, which in a way creates an energy yield. Standard modules made of silicon, quite contrarily, reduce the rated power by 1 – 3% at the beginning of their operation [8]. In the case of CIS and CIGS modules, an increase in efficiency is a result of saturation of the external layer of the p–n junction with photons, owing to which it becomes "similar" to the n–type layer. The limitation of the barrier for the movement of electrons from the CIGS area to the upper electrode is created. Another effect is an increase in the value of current (small) and voltage at the maximum power point (PMM) of the cell, and as a consequence of this, an increase in power [8].

The characteristic feature of the discussed modules is high efficiency in the conditions of poor lighting, e.g. when the weather is cloudy. The highest spectral response allows these cells to maintain efficiency in good lighting conditions. The use of CIGS solar cells entails a lot of benefits in our climatic conditions [9].

6. The issue of heterointerface

Thin film photovoltaic cells bearing popular names – CIS and CIGS, operate best based on a heterojunction.

In thin film cells, one of the materials of the junction (the one with the smallest band gap) is the absorber, and the other one acts as the window – the material with a wide band gap. The electron affinity of the layer which constitutes the window must match the corresponding one – the absorbing layer. The mismatch in every case is the cause of a decrease in the cell's efficiency.

The necessary condition for construction of a heterojunction is such a selection materials that ensures their similar fixed meshes, which limits their defects. Both materials (the absorber and the window) should also be characterised by a similar coefficient of thermal expansion; the conductance band pass is also important [8].

The material used for the window must be characterised by the possibility of strong doping so as to ensure absorption at the interface (the process efficiency is the greatest there). The inappropriate match of the two structures may result in the so called heterointerface – when as an effect of defects and dislocations, the recombination process takes place.

It must also be taken into consideration that the photovoltaic properties of the junction are very vulnerable to any changes in the stechiometric composition as well as any material–technological changes, which also result in an increase in defects and reduce the cell's efficiency [8].

In order to ensure a relatively high efficiency of $CuInSe_2$/CdS cells, it is required to solve the issue of discontinuity of conduction band edges, which in this case amounts to $\Delta E = 0.2$ eV (the edge of the conduction band of the $CuInSe_2$ absorber is located above the corresponding CdS edge with 0.2 eV) [8].

In connection with the fact that the problem of discontinuity of conduction band edges is not present in tandem cells, in the case of which cells with the gradually decreasing band gap are placed in a sequence, it is worth considering such a solution.

In the case of using CIGS as an absorber, a very good window layer is the ZnO layer with the thickness of 300 – 400 nm, with an admixture of Al. Also ZnS and ZnSe prove their value in these heterostructures. Their band gaps reach high values ranging between 2.7 eV and 3.54 eV. In this respect, ZnO is characterised by the best properties, however, provided that the buffer layer between ZnO and the absorber is applied. Particularly beneficial in this case is the CdS layer with the thickness of 40 – 50 nm. The task of the buffer layer is to match the edges of both materials.

7. Possibilities of CIS applications in buildings

Because of their properties (the possibility of reducing the material to the thickness which corresponds to 1% of the crystalline silicon thickness, dark uniform surface, flexible properties, aesthetic quality), the CIS modules are more and more often used in the buildings. The additional advantage consists in a relatively high resistance to temperature as well as numerous installation solutions and recyclability. The visual attractiveness depends, to a great extent, on the interaction of the absorber and the base material; appropriate combinations allow a broad range of colour effects to be obtained [21].

The CIS layer is applied on the base material, e.g. window glass with the thickness of 2–3 mm, in the atomisation process. It is possible to obtain a functional solution with the thickness of the semi–conductor layer even 50 times less than the hair thickness. In this case, an additional advantage is that the glass substrate may additionally fulfil the role of the capsule wall, which is required for the protection against external factors. Both (front and back) glass surfaces are laminated with foil or resin. Also the higher efficiency of the CIS module operation in worse conditions (in comparison with other solutions), i.e. when cloudiness is present, is of importance here.

Particularly high conversion efficiency in CIGS applications in the buildings was obtained by Q–Cells, as many as 12%, for its product – Q.SMART UF 70–90 [26].

Figure 6 presents the view of Q.SMART UF 70–90, its current–voltage characteristics for different sun exposure and temperature values [26],and later on – its construction–operational specifications were shown [20].

CIS modules are particularly "competitive" being installed both on facades and roofs. The GeneCIS modules (WÜRTH SOLAR), in this first case ensure energy yields range between 50 and 60 kWh/m^2 and in the case of installation on roofs, the yield is 70–90 kWh/m^2.

Installation in BIPV applications must take into account the relevant ventilation. Because of the negative effect of temperature on the PV cell characteristics, appropriate fixing profiles, which ensure additional distance (and thus the possibility of ventilation) between the wall and the module are applied, whereby even the adjustment of this distance is possible. In this space, it is possible to place cabling.

a) b)

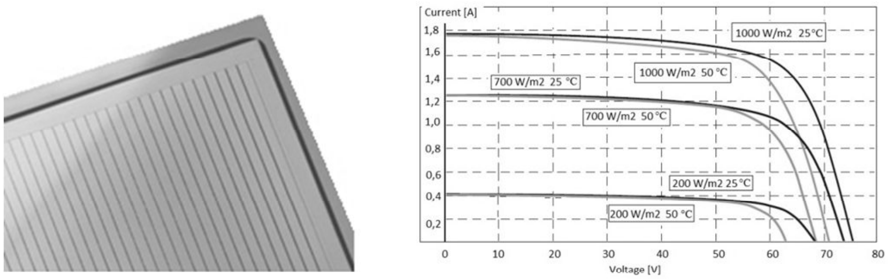

Fig. 6. Q.SMART UF 70–90 module (a) and its current–voltage characteristics (b). Own work based on [26]

Parameter	Unit	Value
Geometrical values	mm x mm x mm	1190 x 630 x 7.3
Weight	kg	13.2
Rated power	Wp	90
Voltage at PMM	V	59.2
Current at PMM	A	1.52
Open circuit voltage	V	75.1
Short–circuit current	A	1.69
Efficiency	%	12

For BIPV, the modules with the framing as well as laminates and roof solutions are used. Also, the so called solar cassettes manufactured by e.g. SULFURCELL (SCG–CC) are popular.

Figure 7. shows the solution of the module design including ventilation.

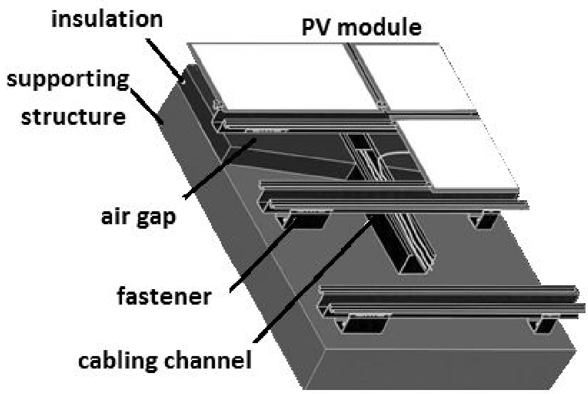

Fig. 7. Structure of the facade including the BIPV installation and ventilation. Own work based on [25]

8. Examples of applications of modules in BIPV

The OpTIC structure (Opto–electronics Technology and Incubation Centre) in Wales (St. Asaph) is provided with the biggest photovoltaic installation consisting of CIS modules. The modules are installed on the wall with the area of 1000 m^2. Power of the installation is 84 kWp, which allows the elimination of 22 tonnes of carbon dioxide per year [14, 22].

The described PV installation is presented in Figure 8 [22].

a.) View of OpTIC [22]

b.) PV CIS wall [22]

Fig. 8. The largest European BIPV CIS installation at Opto–electronics Technology and Incubation Centre in the North Wales

The external lighting is powered from CIS modules. Other additional installations include solar siphons, low–energy cooling and monitoring. At the base of the wall made of CIS modules, there is a rainwater reservoir. The collection of rainwater ensures water savings at the level of 1000 m^3 per year.

The CIS photovoltaic modules cover, among others, the facades of the highest grain silo in the world located in Ulm, Germany. It is 116 m high (including 125 m antennas) and may house 8500 tonnes of grain. The silo was constructed in the year 2005 for the needs of the Schapfenmühle mill, which has been in use since the year 1452. The installation includes 1306 CIS–based photovoltaic modules manufactured by Würth Solar, with the rated power of 98 kWp, supplying 70 000 kWh of energy in total. Modules cover walls up to the height of 102 m. As well as the described solution, Würth Solar [32]. offers other examples of applications characterised by high conversion efficiency.

The silo and the PV installation are shown in Figure 9 [23, 27, 30].

Another investment of this type is the roof–mounted CIS installation from the year 2003 on the Fridenskirche church in Tübingen. Standard modules with the area of 0.6 m x 1.2 m, with the unit power of 13 kWp, connected with the grid, were applied [9, 20]. It is presented in Figure 10.

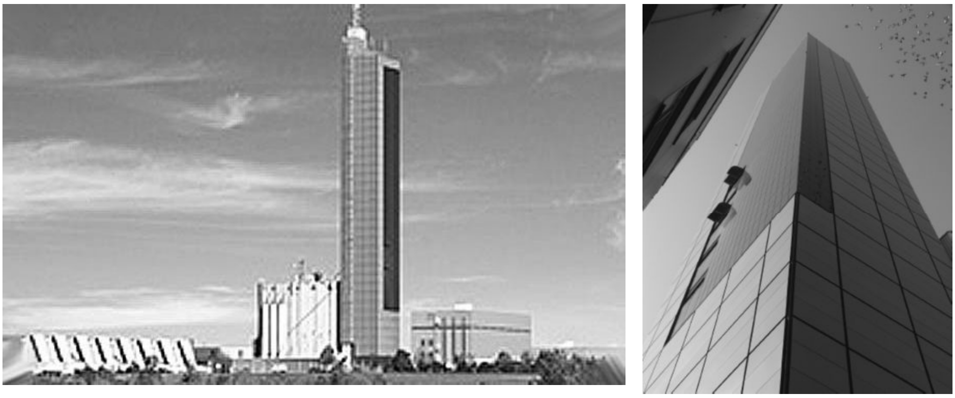

Fig. 9. Grain silo in Ulm including the PV installation [23, 27, 30]

Fig. 10. Roof–mounted CIS installation from the year 2003 on the Fridenskirche church in Tübingen [20]

The copper indium diselenide cells were also applied in Sweden, France and Switzerland [20].

9. Summary

CIS cells and their modifications are characterised by high efficiency both in conditions of low and high light intensity, as well as good tolerance to the temperature growth.

The technology of these cells is particularly simple and economical in terms of materials and energy. The comparison of the required minimum layer thicknesses of the respective materials for solar cells, which allow the efficiency at the level of about 15% to be ensured suggests that several millimetres for silicon and several dozens of micrometres for gallium arsenide, and only several micrometres for CdS/Cu_2S and $CdS/CuInSe_2$ will be sufficient. The Solar Frontier company from Japan, manufactures CIS modules at the plant in

Kunitomi with the efficiency of 13.8%, and has also reduced costs of manufacturing thin film CIGS cells by 30% in relation to products of other manufacturers. Last year new manufacturing lines for CIGS photovoltaic modules, with the efficiency of 15%, with the total power of 150 MW_p were commissioned in Tohoku [23].

On the other hand, the latest achievement of Solar Frontier is the 5 mm x 5mm CIGS cell with the efficiency of 22.3% obtained in laboratory conditions. No other thin film cells have achieved such a result so far.

The well–known manufacturers of thin film CIS cells also include Shell, Würth Solar and Global Solar (USA), which produces flexible photovoltaic tools based on $CuIn_xGa_{(1-x)}Se_2$ compounds.

CIS belongs to photovoltaic technologies with great prospects for the future. This is fully confirmed by tests conducted at the National Renewable Energy Laboratory in the U.S., where a conclusion was drawn that the CIS technology is presently the most advantageous among the thin film cell solutions.

The CIS cells and their modifications, because of high efficiency and excellent properties, become more and more popular in BIPV applications.

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