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High Efficiency Photovoltaics

The global needs for energy have been increasing continually. Solar electricity provides still low but grooving portion of total electricity consumption on the world energy market. Cheaper and more efficient solar cells and modules are required in order to increase solar electricity involvement. In present paper we try to point out and to discuss some aspects and actual ways toward high efficiency photovoltaics (PV).

Keywords: PV Materials, Efficiency Limits, Technology

I. INTRODUCTION

Photovoltaic activities and production are characterized by continuing dominance of crystalline silicon wafer based solar cells and modules, at present (so called first generation), while more other compound materials are applied in thin film photovoltaics (second generation). The portion of thin film based photovoltaics increases year after year (see Fig. 1) [1]. Thin film photovoltaics operates mainly with amorphous and microcrystalline silicone and with quite wide group of binary and ternary compounds based on II-VI and III-V semiconductor alloys. The general aim of photovoltaic activities, both research and commercial, is to increase the efficiency, limited by thermodynamic rules, and lower the price (third generation PV). The path toward lower price is lower and cheaper material consumption and lower energetic technology steps. Theoretical and technological aspects in combination with good experimental skill presume conditions for increasing the efficiency of produced PV cells and modules, either in laboratory conditions or commercially produced. Efficiency and cost regimes are presented in Fig. 2 [2].

Actual and future development is expected within all three generations of photovoltaics, mainly with regard to commercialisation of first two generations, in order to produce stable and reliable PV cells and modules.

Inevitable part of PV modules is encapsulation which should protect interconnected PV cells and create one compact piece easy to handle and transport. Transparency, mechanical and insulation properties of the encapsulant are its important features taken into account when PV module is designed. More organic foils, like EVA, PVB, silicon rubber are used as encapsulant.

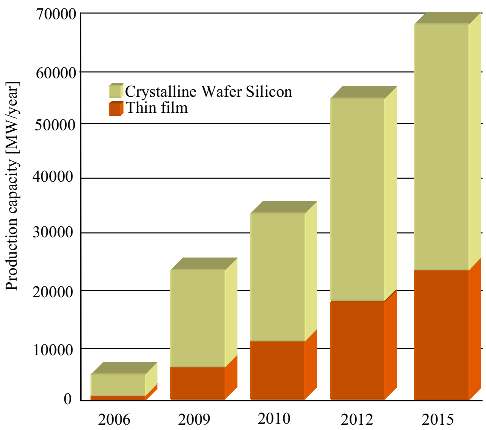

Fig. 1 Proportions of crystalline and thin film photovoltaics

The choice depends on specific requirements and purpose and the type of produced PV modules. EVA is most common material for PV modules but also other encapsulants are used eg for transparent facades or thin film modules.

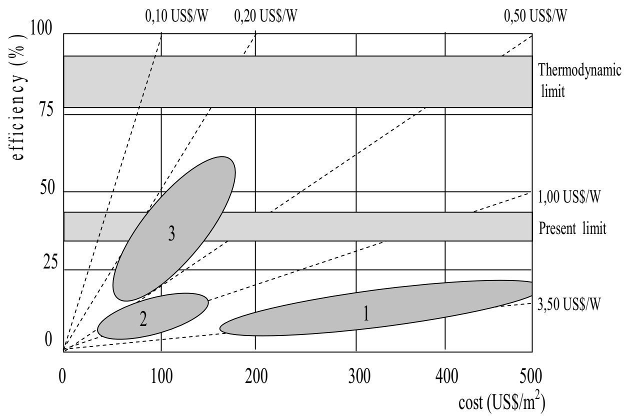

Fig. 2 Efficiency and cost relations of three generations of photovoltaics

II. PV CELLS PARAMETERS

The efficiency limits result from thermodynamics which represents the condition what is allowed. Limitting efficiency is 93.3% (Sun is the radiator at 6000 K and solar converter is at temperature 300 K). The influence of entropy associated with dispersion in atmosphere gives efficiency about 74 % [2].

Generated current limits

The energy from the Sun is transferred to solar converter by means of photons. Photons above certain threshold energy are absorbed and create electron-hole pair which can give rise current flowing in external circuit. The process responsible for the generation of electron-hole pairs is quantified by absorption coefficient and quantum efficiency. Effective absorption required sufficient thickness of absorbing material. In the case of silicon it is hundreds of microns. Any real solar cell is of finite thickness and responding output current.

Open circuit voltage limits

Voltage across the solar cell draws power from the cell. The less the recombination processes throughout the cell, the higher the open circuit voltage. That is a pity but as the voltage across cell increases also the recombination rates throughout the cell increases. Recombination via defects can be eliminated by eliminating the defects, so the recombination rate is governed by radiative recombination at thermal equilibrium and Auger recombination. Auger recombination is more severe [3]. With regard to carrier recombination the thickness of the cell must be much less than minority carrier diffusion length what is in discrepancy with high current requirements.

Fill factor limits

The shape of current-voltage curve of the diode is characterised by diode ideality factor. Ideality factor will be unity under low injection conditions and increases to 2 under high injection. The effect of the low value of ideality factor increases the limit on the cell fill factor. As a standard, PV cell is characterised by double-diode equivalent circuit with two different diode ideality factors or by simplified one-diode model.

III. SOLAR CELL STRUCTURE

P-N junction is the active part of solar cell which ensure the electron-hole pairs separation, generation of voltage and drawing current into external circuit. Except of P-N junction, P-I-N or M-I-S structures are common. In order to appreciate the solar cell behaviour, it is important to take into account the bulk properties of the semiconductor, the front surface and its ability to lower the reflectance, to lower the surface recombination and the ability of effective current collection. The properties of back side and back electric contact are also important [4]. Back surface field (created by P-P+ structure) is prevailing arrangement.

In order to diminish the front surface reflection loss, surface texturization and antireflective coatings are applied. Texturization is such surface shapeing that the light interacts with the surface in multiple way and the absorbance is increased. Passivation layer at the top decreases the surface recombination and the current loss. Finally, solar cell is a complex layered structure which generates electric power.

IV. PHOTOVOLTAIC MATERIALS

The efficiency of produced solar cells, either in laboratory conditions or in commercial production, is measured at certified laboratories under defined conditions – light radiation and temperature, with regard to technical standards. Simulated global radiation AM 1,5 G is applicable. Some examples of recent results obtained on various PV materials and structures are presented in Tab.I [5].

Tab. I Peak solar cell parameters

Material	Efficiency (%)	Area (cm^2)	V_{oc} (V)	Jsc (mA/cm^2)	FF
Si (crystalline)	25,0	4,0	0,706	42,7	0,828
Si (multicrystalline)	20,4	1,0	0,664	38	0,809
Si (amorphous)	10,1	1,04	0,886	16,75	0,67
GaAs – thin film	27,6	0,999	1,107	29,6	0,841
CIGS	19,6	0,996	0,713	34,8	0,792
CdTe	16,7	1,032	0,845	21,2	0,705
Dye sesitized	10,4	1,004	0,729	19,4	0,714
Organic polymer	8,3	1,031	0,816	14,46	0,702

The semiconductor materials for PV application have to be able to absorb a large part of solar radiation spectrum. Dependent on the absorption properties of the semiconductor, the radiation is absorbed in area more or less close to the surface and various thickness of absorbing material is then required. With regard to the development during photovoltaic era, many semiconductor materials have been involved into photovoltaic technology [6].

Photons with lower energy than energy gap of used semiconductor are not absorbed and those with higher energy are reduced to gap energy by thermalization of the photogenerated current. The dependencies of the conversion efficiency on the energy gap of semiconductors are shown in Fig. 3

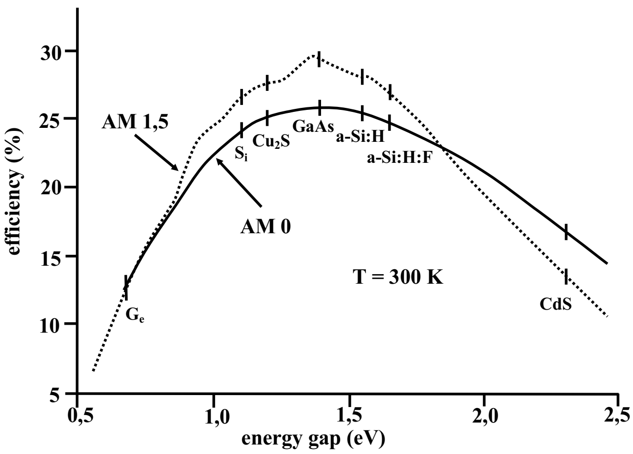

Fig. 3 Dependencies efficiency of respective solar cells on semiconductor energy gap

Crystalline silicon still creates the basis for current photovoltaics. Progress has lead to lower material consumption which finally has approached the crystalline silicon thin-film concept. Both, monocrystalline and polycrystalline silicon solar cells are broadly commercialized. P-type silicon has been used for many years in photovoltaic application. Recently the interest in N-type silicon increases again. While solar cells produced from Czochralski silicon undergo a moderate degradation, phosphorus doped Czochralski silicon shows no degradation. It was estimated that concentration of free oxygen can play important role in life-time degradation.

Basic considerations concerning thin film crystalline silicon concept lead to optical confinement for light path enhancement in order to avoid the needs for thick silicon substrate. The thickness of the active silicon layer is typically 5 – 50 μm.

First amorphous silicon solar cell was reported in 1976. Amorphous silicon undergoes light induced degradation. At present this problem is partly solved. The challenge is to produce a material with well defined disorder. Amorphous silicon is convenient material for production of tandem cells. The nature of energy gap of amorphous silicone causes a material-inherent reduction of maximum obtainable efficiency. Basis for material production is chemical vapour deposition process. Today´s substrate size reaches orders of m^2.

Alloys based on Cu, In, Se, S, Ga – CIS or CIGS represent a very challenging thin film technology promising the increase of efficiency. Mentioned materials provide broad scale for ternary or multinary alloys and their parameters control. Thin film solar cells CIS or CIGS require substrate which can be for example glass. Due to the high flexibility in producing compounds and their properties design, the improvement is expected in the future.

CdTe solar cells have a long tradition but were long-time denied for toxic input raw material. CdTe is a nearly ideal material for thin film photovoltaics with more advantageous properties. CdTe solar cells are deposited onto glass substrate and the high efficiency cells use CdS-CdTe heterojunction structure. The creation of heterojunction is a key problem. At present, CdTe PV modules are safe elements without any environmental threat.

Dye-sensitized and organic solar cells are promising technology but the time stability is a challenging problem. Dye-sensitized solar cells are nanocrystalline structures in which the element responsible for light absorption (the dye) is separated from the charge transport. Conduction mechanism is based on majority carrier transport in comparison with standard inorganic materials where minority carries are transported.

Very important feature of organic polymers for solar cells is extremely high optical absorption coefficient which allows the production of very thin solar cells. In comparison with inorganic photovoltaics, the advantage of organic polymeric materials is simple large scale manufacturing and low cost and low temperature processing.

Third generation concept comes out from the efficiency limit postulated on thermodynamic considerations. Except more other concept, multitandems provide the obvious path to the third generation.

V. CONCENTRATOR PHOTOVOLTAICS

The efficiency of the solar cells depends on the irradiance level. The output electric current is proportional to the number of photons which incidence the solar cell surface and the output voltage increases logarithmically with concentration ratios. The efficiency at very high concentrations is limited by construction insufficiencies like series resistance limitation. The more complex cell design is required with regard to high current density at high level irradiance. The dependence of the efficiency on the light concentration and the influence of temperature is shown in Fig. 4 [7]. The increased light radiation results in increased temperature. In order to keep the cell efficiency, it is important to avoid overheating while the efficiency obeys following relation

$$\eta_c = \eta_0 - \beta\, (T_c - T_{ref}) \qquad (1)$$

where η_c is the cell efficiency at the reference temperature T_{ref} and β is the temperature coefficient of the efficiency.

Nowadays, two different concepts are involved: high efficiency silicon solar cells and multijunction solar cells based mainly on AIII BV semiconductor alloys at irradiation levels more hundred suns. The highest efficiencies have achieved 27.6 % in the case of silicon and 42.3 % in the case of bi-facial solar cells with complex structure InGaP/GaAs/InGaAs (two terminal) [5]. Of course, the efficiencies of the concentrator PV cells/modules for market is lower in comparison with those, developed for laboratory tests. The increase of the price of the whole PV system, when concentrator is applied, is compensated with lower consumption of very expensive semiconductor material. The surface area of the solar cells is very small in comparison with standard photovoltaics. Cheaper plastic optical devices improve the price balance.

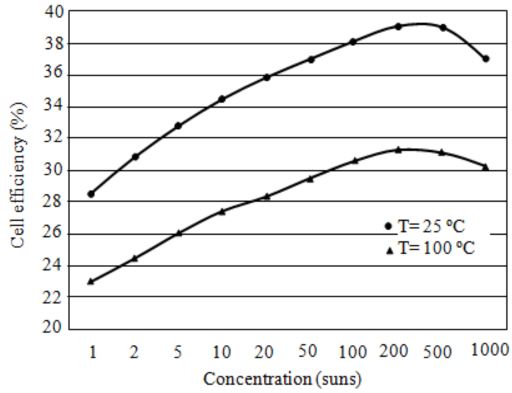

Fig. 4 The efficiency evolution versus concentration ratio at two different temperatures

The increase of efficiency is reached with increasing number of cells that make the multijunction stack. On the other hand the efficiency of the multijunction solar cell is not proportional to the number of the cells stacked together while the complexity of the system is too high. Not more than 5, 6 cells in the same stack is expected [7]. The presented efficiency data forecast concentrator photovoltaics to be an attractive alternative which could be profitable in both energy and efficiency

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