Chapter 1

Introduction, Past and Present Scenario of Solar Cell Materials

M. Rizwan^{1*}, Waheed S. Khan², A. Khadija³

¹ School of Physical Sciences, University of the Punjab, Lahore, Pakistan

² Nanobiotechnology Group, National Institute for Biotechnology and Genetic Engineering (NIBGE), Jhang Road, Faisalabad-38000, Pakistan

³ Department of Physics, University of Gujrat, Hafiz Hayat Campus, Gujrat City, Pakistan

*Corresponding Author: rizwan.sps@pu.edu.pk

Abstract

Solar cells convert sunlight into electricity directly. It is a reliable, non-toxic and pollution free source of electricity. Since 19th century researchers have been trying to investigate different materials for solar cell devices. Commercially, Si based solar are predominate in this field, however, with passage of time different materials have been reported. Solar cell techniques are based on three different generations. 1st generation is based on Si and 2nd generation includes thin-films of CuInGaSe, GaAs, CdTe and GaInP etc. whereas 3rd generation is based on organic, hybrid perovskites, quantum dot (QD)-sensitizers & dye-sensitizers solar cells. Among all these, the 3rd generation solar cells are the most efficient and more cost effective than 1nd and 2nd generation solar cells. The 2nd generation is less costly but also less efficient compared to 1st generation. 3rd generation faces degradation of the photovoltaic materials which is a major problem. In this chapter different reported materials since 19th century for solar cells are mentioned. The past and present scenarios of solar cells are discussed comprehensively. It is observed that Si-based and multijunction solar cells dominate the market. Although, theoretically it is reported that hybrid perovskites and quantum dot materials for solar cell are the most efficient materials for photovoltaic PV devices. In spite of the high efficiency the stability of organic, hybrid perovskites, QD-sensitizers & dye-sensitizer materials is a big challenge.

Keywords

Solar Cell, QD-Sensitisers, Dye-Sensitizers, Organic Materials, Hybrid Perovskites Materials

Contents

Introduction, Past and Present Scenario of Solar Cell Materials	1
1. Introduction.....	2
2. Past scenario of solar cell materials	3
3. Properties of solar cell materials.....	6
4. Categories of solar cell	6
4.1 First-generation solar cells.....	6
4.2 Second-generation solar cells	7
4.3 Third-generation solar cells	7
5. Different materials for solar cells.....	7
5.1 Crystalline material for solar cells.....	7
5.2 Material for organic-solar cells.....	8
5.3 Materials for DSSCs (dye-sensitized solar cells)	8
5.4 Materials for QDSSCs	10
5.5 Materials for hybrid perovskites solar cells.....	10
6. Present goal for solar cell materials.....	11
Conclusions	11
Acknowledgements.....	12
References	12

1. Introduction

Solar cells generate electricity when these interact with sunlight by absorbing photons of particular energy wavelength. These are semiconductor materials and produce electricity in the presence of sunlight. Solar cells cannot be recharged like batteries. They produce electricity when sunlight interacts with them. When there is no light, the electricity stops. The generated electric power is measured in watts or kilowatts. A solar cell device is fabricated by using semiconductor material. These materials have completely or partially filled valance band (V.B) and empty or partially filled conduction band (C.B). When the sunlight with energy $>E_g$ falls on solar cell the bonds are broken and loosely bonded electrons transfer from V.B to C.B. These electrons in the C.B are directed towards the

external contact. These free electrons generate electricity in the external circuit. They transfer their energy to the external device and return towards V.B with the same initial energy. Figure 1 demonstrates the working principle of a solar cell. When the photons with energy $>E_g$ (bandgap energy) interacts with solar cell it produces electrical power while photons with energy $<E_g$ are absorbed in material and produce heat in the presence of direct sunlight at ambient temperature. Therefore, solar cells can operate at lower temperature and produce electricity without moving parts such as heat engine or generator to produce electricity.

Figure 1 Schematic diagram of solar cell operation.

2. Past scenario of solar cell materials

The history of photovoltaic (PV) materials dates back to the 19th century. In 1883, commercially for the first time a solar cell was introduced by Fritts [1]. He foresaw today's technological manufacturing and applications of solar cell devices over centuries ago. The year 1954 was the modern era of the solar cell industry. In 1954, in the USA at Bell Lab, the researchers discovered that pn-junctions based diodes produced voltage in the presence of room lights and stopped when lights were off. This provided a new field of research. After this, they had made Si based pn-junction solar cells within a year with efficiency of 6 % [2]. In the same year, a group of researchers in the USA reported heterojunction thin film based ($\text{Cu}_2\text{S}/\text{CdS}$) solar cell with the same efficiency 6 % [3]. After one year, RCA Lab in USA reported GaAs based solar cells having efficiency of 6

% [4]. Since 1960, several researchers published theoretical key papers on the pn-junction solar cells based on the relationship between thermodynamics, band gap, efficiency, incident light spectrum, and temperature [5]. Furthermore, CdTe thin film based solar cells were also reported with efficiency of 6 % [6]. Since 1960 the US satellites systems utilized Si solar cell technology in space for powering satellites [6]. Li-doped Si improved the radiation tolerant efficiency of existing Si based solar cell devices [7]. In 1970, a team of researchers in USSR at Ioffe institute made heteroface solar cells of GaAlAs/GaAs that pointed the new way of this device structures [8]. GaAs based solar cells had high resistance to ionize the radiations in outer space as well as had high efficiency. Therefore, GaAs based solar developed great interest towards solar cells. Its efficiency improved in both technical and non-technical levels in 1973. The ‘violet cells’ enhanced the efficiency to about 30% relative to Si cells [9]. GaAs heteroface structures were made in USA at IBM with 13% efficiency [9]. Moreover, the first world “Oil Embargo” agency was established by Persian oil producers to encourage the researchers for renewable energy devices especially photovoltaic devices in 1973. This revolutionized the industrial world [9].

In 1980, the industry started to work on the cost and manufacturing of solar materials. Manufacturing facilities for Si based pn-junction devices were present in the USA, Europe and Japan [10]. New technological schemes were built to scale up the solar cell technology based on thin films of a-Si and CuInSe₂ resultant solar cells achieved efficiency of >10%. These solar cells were made for small area (1 cm²) by using controlled laboratory equipment [11]. It became more complicated for larger scale size due to insufficient facilities and equipment. Most the semiconductor companies in US gave their work. In 1990, the world largest company Arco solar worked in production of a-Si & n-Si thin films based PV devices and pre-commercialized thin films of CuInSe₂. In 1994 GaInP/GaAs multijunctions connector solar cells were made with efficiency of >30% [12]. Further, in 1998 thin films of Cu(InGa)Se₂ and triple-junctions solar cell (GaInP/GaAs/Ge) made by the US achieved high efficiency of > 19% [13]. Productions of CdTe and a-Si based thin films exceeded >100 MW/per year till 2002. In 2004, the efficiency of QDSSCs was reported of about 37% [14]. In 2007, the efficiency of thin-films solar cells based on Si (minimodule) was reported of >10% [15]. In 2012, the efficiency of GaAs materials was reported being 25% [16]. In 2013, efficiency of CZTSSe thin film based (thin film) solar cells was 12% [17]. After this in 2014 and 2016 the efficiency of CdTe materials was reported at 21% and 22% [18,19]. The efficiency of multicrystalline Si materials reached 22% in 2016 [20]. Moreover, till 2018 the efficiency of Si (crystalline) reached about >25% [21-24]. Recently, reported efficiency of Perovskites solar cell was 27.3% [25]. Furthermore, in 2019 the efficiency of organic

solar cells reached about 16%. In spite of all these, low efficiency and stability of dye-sensitizer solar cells (DSSCs), quantum dot sensitizer solar cells (QDSSCs) and perovskites based solar materials is major a problem. Different reported crystalline, organic, dye and perovskite materials for solar cells are mentioned in table 1 [21,22,26-34].

Table 1 Different reported materials for solar cells.

S. No.	Classification	Efficiency %	Reference
	Crystalline		
1	Si	26.7 ± 0.5	[21]
		25.0 ± 0.5	[22]
		24.5 ± 0.5	[21]
		27.6 ± 1.2	[24]
		25.8 ± 0.5	[23]
2	InP	24.2 ± 0.5	[26]
	Multicrystalline		
3	Si	22.3 ± 0.4	[35]
4	GaAs	18.4 ± 0.5	[36]
	Thin films		
5	Si	10.5 ± 0.3	[15]
6		GaAs	[16]
7	CdTe	21.0 ± 0.4	[18]
8		18.6 ± 0.5	[37]
9		22.1 ± 0.5	[19]
10	CZTSSe	12.6 ± 0.3	[17]
11	CZTS	11.0 ± 0.2	[38]
12	GaAs	28.3 ± 0.9	[39]
13	CIGS	23.3 ± 1.2	[40]
14		10.0 ± 0.2	[41]
15		19.2 ± 0.5	[42]
16	GaInP	22.0 ± 0.3	[43]
	Multijunctions		
17	InGaP/GaAs/InGaAs	37.9 ± 1.2	[44]
18	GaInP/GaAs/Si	35.9 ± 0.5	[45]
19	a - Si/nc - Si/nc - Si	14.0 ± 0.4	[46]
20	GaInP/GaAs/Si	33.3 ± 1.2	[47]
21	GaInP/GaAs/Si	22.3 ± 0.8	[48]
22	GaAsP/Si	20.1 ± 1.3	[49]
23	GaAs/Si	32.8 ± 0.5	[45]
24	InGaP/GaAs/InGaAs	31.2 ± 1.2	[50]
25	AlGaInP/AlGaAs/GaAs/GaInAs	47.1 ± 2.6	[51]
26	a - Si/nc - Si	12.7 ± 0.4	[52]
27	GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3	[53]

30	InGaP/GaAs/InGaAs	44.4 ± 2.6	[54]
31	GaInAsP/GaInAs	35.5 ± 1.2	[55]
	Perovskites		
32	Perovskite	24.2 ± 0.8	[30]
		20.9 ± 0.7	[31]
		17.25 ± 0.6	[29]
33	Organic	8.7 ± 0.3	[27]
		16.4 ± 0.2	[28]
34	Dye (cell)	11.9 ± 0.4	[33]
		10.7 ± 0.4	[32]
		8.8 ± 0.3	[34]

3. Properties of solar cell materials

Semiconductor materials are the potential materials for solar cells applications. These semiconductor materials have particular properties, which affect the efficiency of photovoltaic devices. Some of important properties are described as follows [56-58]:

- Material should have higher trapping states or defects
- Direct-bandgap b/w 1.1 eV to 1.7 eV
- Non-toxic & easily reproducible technique
- Suitable to make larger area solar cell
- Stability for a long time
- Soluble in suitable solvent
- Higher conversion efficiency
- Smooth morphology

4. Categories of solar cell

There are three different generations regarding materials for solar cell devices. These are mentioned as follow:

4.1 First-generation solar cells

They are also named as Si-based solar cell generation. The highest efficiency achieved by single crystal solar cells is about 25%. But it is expensive to produce c-Si from sand and to deposit its single crystalline structure on another substrate. Expensive manufacturing of c-Si and deposition techniques motivated to develop new less costly materials and techniques for solar cell technology. Despite all of these c-Si still dominate over 90% of the market [56].

4.2 Second-generation solar cells

2nd generation is cheaper in manufacturing, fabrication techniques and materials as compared to 1st generation. These materials include nc-Si(nano-crystalline silicon), CuInGaSe, CdTe and amorphous Si(a-Si). These materials are cheaper than Si because they have higher absorption coefficient as compared to Si, which reduces the amount as well as cost of the material to be used. Only a single layer of these materials is enough to absorb a large amount of light and produce high power electricity. The efficiency of CuInGaSe, nc-Si, a-Si and CdTe is reported to be 20.1%, 10.1%, 9.5% and 16.7% respectively. This shows that although 2nd generation solar cells are cheaper in manufacturing than 1st generation solar cells they are less efficient in performance [56].

4.3 Third-generation solar cells

The target is to achieve higher efficiency as well as less costly manufacturing techniques as compared to the first two generations. The novelty in this generation was the use of semiconductor nano-particles. It expected that efficiency of photovoltaic (PV) devices can be achieved of about 31 to 41% by using semiconductor nano-particles due novel concepts of nano-particles like impact ionization [59,60]. Organic, perovskites hybrid, quantum dot & DSSCs solar cells are included in category of 3rd generation [61,62].

5. Different materials for solar cells

Solar cell technology is based on semiconductor materials. Different materials for solar cells are described as follows:

5.1 Crystalline material for solar cells

Si in crystalline or multi-crystalline form is used frequently for solar cells applications. The 1st silicon based crystalline solar cell was developed by Chapin et al. [1] in 1954 with efficiency of >10% at Bell laboratories. After this it increased and reached >25% until 2017 [21-24]. The efficiency of multi-crystalline PV devices has reached about >22% in 2017 [15,36]. Conventional single crystalline materials were cost effective. In modern technology crystalline thin films, tri-crystalline solar cells were developed, which saved about 40% of material [63]. Although efficiency of polycrystalline or multi-crystalline Si based solar is lower than single crystal solar cells they are less costly than single crystal Si based solar cell. Single crystal Si based solar are expensive in fabrication. Furthermore, in place of Si different materials such as GaInP, CdTe, AlSb, GaN, GaP, (CIS), GaSbInNCZTSSe, AlN, AlP, AlAs, GaAs, InAs, and InSb and, InP thin films enhanced the efficiency of solar cells [58,64].

5.2 Material for organic-solar cells

The semiconducting organic materials in the field of solar opened a new door of research. Organic polymer materials have many extinguished properties over silicon. They have high absorption coefficient about $\approx 10^5$ [65]. Only a thin layer of polymers about ~ 100 nm can absorb a large amount of light for energy conversion over silicon-based solar cells. They have tunable band-gap in visible range and yield large amount of charge carriers during solar cell operation [65]. Typically, organic polymers have lower band gap, larger active layers and high binding energy, which affect the performance of the solar cell. Organic solar cells consist of two different types, donor materials and acceptor materials.

First organic solar was developed by Ching Tang [66] in 1985 with efficiency 1%. He prepared it by the combination of perylene pigment and copper phthalocyanine (CuPc). It was a fully organic solar cell. After this in the mid 1990s another organic cell with efficiency $>1\%$ was reported by Messiner [67]. He prepared it by using C-60 doping with zinc phthalocyanine (ZnPc). After this several C-60 based hetero-junction solar were investigated [68-70]. Heerger et al. [65] developed polymer-fullerene based organic solar cell having efficiency of 6.5%. The donor reported polymers are poly(2-methoxy-5-(30,70-dimethyloctyloxy))-1,4-phenylenevinylene) (MDMO-PPV) and poly-3-hexylthiophene (P3HT), where acceptors are PCBM polymers and fullerene molecules. Recently non- fullerene based acceptor are also reported such as “perylene-diimide”(PDI), “naphthalene-diimide”(NDI), “diketopyr-rolopyrrole”(DPP) and “phthalimide (PhI)”. These acceptors can also be used as potential candidates to achieve efficiency of solar cell up to ~ 13 to 14% [72-73]. But the average efficiency was between 8-10% till 2013 [74]. The limitation of organic materials for solar cell is their weak stability. They are unstable due to oxidation and degradation. To date efficiency of organic solar cells is about 10-15% [62].

5.3 Materials for DSSCs (dye-sensitized solar cells)

These materials move towards a new type of solar cells. The structure of DSSCs consists of four parts: electrolyte, photoanode, counter electrode and sensitizers as shown in figure 2. To improve the absorption rate of solar cells different dyes are used in DSSCs. Dyes are effective sensitizer to harvest photon up to the visible and IR region (400-800 nm) [56]. The first DDSCs was developed by Michel Gratzel et al. [75] in early 1990. The structure of TiO_2 nanocrystals with effective layer of molecule of dye had efficiency of about 12% [75-76]. TiO_3 in different morphologies such as rod, tubular, hierarchical and spherical shape affect the energy conversion efficiency of solar cell [56]. Nanocrystals of TiO_2 used as photoanode were coated on glass material such as FTO [56]. One of the

reported materials for photoelectrodes is ZnO [77-79]. There are several other semiconductor oxide materials which can be used as photo-electrodes such as In_2O_3 [80-81], SnO_2 [79,80,82], SrTiO_3 [79,83,84], NiO [75, 79] and Nb_2O_5 [79,81,86,87]. Among them TiO_2 is the best candidate. It is more efficient than other materials. Performance of other oxides materials is yet to exceed the performance of TiO_2 nanocrystals [88-89]. Presently, the researchers are working on combine photoelectrodes such as SnO_2/ZnO to achieve high efficiency comparable to TiO_2 . It was found that the efficiency of combined SnO_2/ZnO is greater than SnO_2 and ZnO on its own [90-91]. But to date TiO_2 based photoelectrodes are the most highly efficient. Zaban et al. [88] reported that efficiency of TiO_2 was improved by coating TiO_2 with Nb_2O_5 . Different reported materials for dyes are Ru-based dyes such as "4-0-dicarboxylate)ruthenium(II) (N3 or N-719 dye)" and "cis-di(thiocyanato)bis(2,20-bipyridyl)-4", other compounds are "osmium (II) complex", "porphyrin dyes", "metal-free dyes", "porphyrin dyes" and "organic dyes (eosin yellow, 9-phenylxanthene, Perylene dye, Coumarin dye, Cyanine dye and Merocyanine dye)" [92-99]. Natural dyes can be extracted from leaves, fruits and colorful plants. The natural dyes have lower efficiency than artificial dyes. To the date Ru-based dyes are highly efficient. Different reported electrolyte material as Redox, iodine/tri-iodide (I_2/I_3^-), $\text{SeCN}_2/(\text{SeCN})_3$ and $\text{Br}_2/\text{Br}_3^-$, $\text{SCN}_2/(\text{SCN})_3$ [100]. Among them Redox electrolyte showed the best performance [101]. The most commonly reported materials for counter electrodes are platinum and noble metals [56,102]. Other reported compounds are metal sulphide, transition metal nitrides, carbon-based materials, conducting polymers and carbides [102-104]. The efficiency of DSSCs is still reported 10 – 14% [105].

Figure 2 Schematic diagram of DSSC.

The limitations of DSSCs are their stability, contamination of photoelectrodes, degradation and desorption of dyes and leakage of electrolytes. Today researchers are working on to improve the efficiency of DSSCs.

5.4 Materials for QDSSCs

These materials have revolutionized the 3rd generation of solar cells. QDSSCs are based on quantum dots. The working principle of QDSSCs is similar to DSSCs. In QDSSCs dye is replaced by quantum dot. Quantum dot has tunable band gap properties, absorbs light up to IR region and produce multiple electrons to enhance efficiency of solar [14,106-109] cells. In recent years it is reported that quantum dots (QDs) of InAs with 5, 10 and 12 nm size have 1.071, 0.553 and 0.045 eV band gap respectively. The quantum dots at nano-scale harvest maximum amount of photons. Theoretically it was reported that for a single-junction solar cell device a single quantum dot could improve the energy conversion efficiency up to 31-44% [110]. In QDSSCs QDs are used as sensitizer with different photo-anodes. The different reported inorganic materials as QDs sensitizers are CdSe, CdTe, SnSe, CdS, PbSe, SnS and PbS. In recent years, the reported efficiency of QDSSCs is 8% [111]. Efficiency of QDSSCs can be affected by Pt-electrode. QDs are very sensitive to Pt. Researchers are working on Pt free electrode QDSSCs [56]. CdS-QDs-sensitized nanocrystalline under 1 sun illumination with TiO₂ had efficiency of 2.8% [112]. The assembly of CdSe-QDs along with CdS-QDs improved the absorption range from 550 (of CdS bulk) to 720 nm wavelength (of CdSe bulk) [112]. It improved efficiency up to 4.2% under one illumination. Assembly of quantum dots with different polymers can improve efficiency of solar cells [112].

5.5 Materials for hybrid perovskites solar cells

Hybrid perovskites follow the ABX₃ structure in which A is an organic cations (“CH₃NH₃⁺, C₂H₅NH₃⁺”), B is any metal cation (“Pb²⁺, Sn²⁺, Bi²⁺”, etc.) and X is any Halide anion (“Cl⁻, Br⁻, I⁻”). The class of perovskites is used as potential candidate in solar cell application. In 2009, the reported efficiency of first perovskite based solar was 3.81% [113]. It was reported that halide perovskites sensitizer showed higher absorption coefficient in visible range than other reported organic dyes. The perovskite “CH₃NH₃PbI₃” showed excellent ability to harvest the photons. Since 2009 to 2014, the recorded efficiency of “CH₃NH₃PbI₃”-based solar cell was increased from 3.8 to 16.7% [113-117]. The properties of perovskites could be tuned to improve efficiency of PV devices. Different materials such as “PEDOT:PSS”, “spiro-OMeTAD”, “poly-triarylamine (PTAA)”, “PCPDTBT”, “P₃HT”, “PCDTBT” and “CsSnI₃” were investigated with CH₃NH₃PbI₃ in PV device applications [56]. Their efficiency improved over DSSCs. It would be expected that it could be increased up to >25% in near future.

Recently reported efficiency was 27.3% [25]. In $\text{CH}_3\text{NH}_3\text{PbI}_3$ perovskite Pb is a toxic material. Researchers focused on lead free perovskites materials to enhance the device efficiency. In place of Pb reported material were stibium (Sb), bismuth (Bi) and tin (Sn). Recently, the efficiency of FASnI_3 perovskites has reached up to 9%. The stability of Bi based perovskites materials is higher than lead based materials. In 2018, the reported efficiency of Bi-based perovskites has reached about 3.17% [56]. Next target of hybride PSCs is to enhance the efficiency of lead free perovskites solar cells.

6. Present goal for solar cell materials

Currently most studied materials for solar cell applications are silicon and III-V group compounds. The efficiency of thin films or multijunctions solar cells of GaInP, GaAs, and Ge layers is reported up to 30%. Si is still a 99% commercial dominated material for PV devices. The concept of 3rd generation is under investigation. It does not overtake the market. The Commercially reported efficiency of 1st generation and 2nd generation solar cells is higher than 3rd generation solar cells. Dye-sensitizer (DS) solar cells, hybrid perovskites solar cells and quantum dot (QD) solar cells are less costly and have high efficiency but these are not yet commercially fabricated for solar cell applications. The stability factor of organic and inorganic sensitizers affects their efficiency. The hardly achieved efficiencies of DSSCs, QDSSCs, organic solar cell and hybrid-perovskites solar cell are 10-14, 10, 8-10 and 15% respectively [56]. Commercially Si based and multijunction solar cells achieved the highest efficiency up to 30% [14,37]. Commercially high efficient materials are more preferable than 3rd generation materials. Still the present research is to enhance the efficiency of multijunction solar devices such as “InGaP/GaAs/InGaAs, InGaP/GaAs/InGaAs, GaInP/GaAs/Si(waferbonded), GaInP/GaAs/Si (monolithic), AlGaInP/AlGaAs/GaAs/GaInAs, GaInP/GaAs/GaInAsP/GaInAs, GaInAsP/GaInAs, aSi/nc-Si/nc-Si and InGaP/GaAs/InGaAs” etc. [64]. There is need to investigate more stable and less costly materials for 3rd generation solar cells to gain higher efficiency.

Conclusions

All the discussion concluded that solar cell opened a new field of research. With increasing demand of solar efficiency and less costly fabrication researchers are working on different materials for solar cell devices and its applications. Commercially Si-based solar are high efficient with about >30%. Si-based technology attracted the attention of researchers. It showed high efficiency and stability. Different multijuncton solar cells materials such as “InGaP/GaAs/InGaAs, InGaP/GaAs/InGaAs, GaInP/GaAs/Si), GaInP/GaAs/Si(monolithic), AlGaInP/AlGaAs/GaAs/GaInAs,

GaInP/GaAs/GaInAsP/GaInAs, GaInAsP/GaInAs, amorphous-Si/nanocrystalline-Si/nanocrystalline-Si” had efficiency comparable to silicon. To the date average reported efficiency for organic, perovskites, dye-sensitizer and quantum dot sensitizer materials is 10, 15, 8-10 and 10% respectively. Due to degradation and environmental factors the stability of organic, perovskites, dye-sensitizer and quantum dot sensitizer materials is a big challenge. Theoretically, reported efficiency for quantum dot sensitizers is about >60% and perovskites >30%. Researchers are trying to discover high stable materials in the near future for the sake of potential applications of solar cell devices.

Acknowledgements

Authors are immensely grateful to Department of Physics, University of Gujrat, Gujrat-50700, Pakistan and National Institute for Biotechnology & Genetic Engineering (NIBGE), Faisalabad-38000, Pakistan for providing healthy and conducive environment for such work.

References

- [1] C.E. Fritts, On a new form of selenium cell, and some electrical discoveries made by its use, *Am. J. Sci.* 26 (1883) 465-472. <https://doi.org/10.2475/ajs.s3-26.156.465>
- [2] D.M. Chapin, C. Fuller, G. Pearson, A new silicon p-n junction photocell for converting solar radiation into electrical power, *J. Appl. Phys.* 25 (1954) 676-677 <https://doi.org/10.1063/1.1721711>
- [3] D. Reynolds, G. Leies, L. Antes, R. Marburger, Photovoltaic effect in cadmium sulfide, *Phys Rev.* 96 (1954) 533-534. <https://doi.org/10.1103/PhysRev.96.533>
- [4] D. Jenny, J. Loferski, P. Rappaport, Photovoltaic effect in GaAs p– n junctions and solar energy conversion, *Phys. Rev.* 101 (1956) 1208-1209. <https://doi.org/10.1103/PhysRev.101.1208>
- [5] M. Prince, Silicon solar energy converters, *J. Appl. Phys.* 26 (1955) 534-540. <https://doi.org/10.1063/1.1722034>
- [6] D. Cusano, CdTe solar cells and photovoltaic heterojunctions in II–VI compounds, *Solid State Electron.* 6 (1963) 217-232 [https://doi.org/10.1016/0038-1101\(63\)90078-9](https://doi.org/10.1016/0038-1101(63)90078-9)
- [7] J. Wysocki, Lithium-doped radiation-resistant silicon solar cells, *IEEE T Nucl. Sci.* 13 (1966) 168-173. <https://doi.org/10.1109/TNS.1996.4324358>

- [8] Z.I. Alferov, V. Andreev, M. Kagan, I. Protasov, V. Trofim, Solar-energy converters based on pn $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs heterojunctions, *Sov. Phys.-Semicond.(Engl. Transl.);(United States)*. 4 (1971) 16-25. <https://doi.org/10.1117/12.934271>.
- [9] J. Lindmayer, J. Allison, The violet cell: an improved silicon solar cell. *Sol. Cells* 29 (1990) 151-166 [https://doi.org/10.1016/0379-6787\(90\)90023-X](https://doi.org/10.1016/0379-6787(90)90023-X).
- [10] S. S. Hegedus, A. Luque, Status, trends, challenges and the bright future of solar electricity from photovoltaics. *Handbook of photovoltaic science and engineering*, John Wiley(2003)1-43. <https://doi.org/10.1002/0470014008>
- [11] R.Sinton, Y. Kwark, J. Gan, R.M. Swanson, 27.5-percent silicon concentrator solar cells. *IEEE Electron Device Lett.* 7 (1986) 567-569. <https://doi.org/10.1109/EDL.1986.26476>
- [12] D.Friedman, S.R. Kurtz, K. Bertness, A. Kibbler, C. Kramer, J. Olson, D. King, B. Hansen, J. Snyder, Accelerated publication 30.2% efficient GaInP/GaAs monolithic two terminal tandem concentrator cell. *Prog. Photovolt.* 3 (1995) 47-50. <https://doi.org/10.1002/pip.4670030105>
- [13] M.A. Contreras, B. Egaas, K. Ramanathan, J. Hiltner, A. Swartzlander, F. Hasoon, R. Noufi, Progress toward 20% efficiency in Cu (In, Ga) Se_2 polycrystalline thin film solar cells. *Prog. Photovolt.* 7 (1999) 311-316. <https://doi.org/10.1002/pip.4670030105>
- [14] R. King, C. Fetzer, K. Edmondson, D. Law, P. Colter, H. Cotal, R. Sherif, H. Yoon, T. Isshiki, D. Krut. Metamorphic III-V materials, sublattice disorder, and multijunction solar cell approaches with over 37% efficiency, 19th European photovoltaic solar energy conference and exhibition. (2004) 7-11.
- [15] M.J. Keevers, T.L. Young, U. Schubert, M.A. Green. 10% efficient CSG minimodules, 22nd European photovoltaic solar energy conference, (2007) 1783-1790.
- [16] L.S. Mattos, S.R. Scully, M. Syfu, E. Olson, L. Yang, C. Ling, B.M. Kayes, G. He. New module efficiency record: 23.5% under 1-sun illumination using thin-film single-junction GaAs solar cells. in 2012 38th IEEE photovoltaic specialists conference. 38 (2012) 1-4. <https://doi.org/10.1109/PVSC.2012.6318255>
- [17] W. Wang, M.T. Winkler, O. Gunawan, T. Gokmen, T.K. Todorov, Y. Zhu, D.B. Mitzi, Device characteristics of CZTSSe thin film solar cells with 12.6% efficiency. *Adv. Energy Mater.* 4 (2014) 1-5. <https://doi.org/10.1002/aenm.201301465>
- [18] F. Solar, First solar builds the highest efficiency thin film PV cell on record, 2014.
- [19] M. Tuteja, A.B. Mei, V. Palekis, A. Hall, S. MacLaren, C.S. Ferekides, A.A. Rockett, CdCl_2 treatment-induced enhanced conductivity in CdTe solar cells observed

- using conductive atomic force microscopy, *J. Phys. Chem. Lett.* 7 (2016) 4962-4967.
<https://doi.org/10.1021/acs.jpcllett.6b02399>
- [20] P. Verlinden, Will we have > 22% efficient multi crystalline silicon solar cells, *PVSEC.* 26 (2016) 24-28.
- [21] K. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, K. Nakano, T. Uto, D. Adachi, M. Kanematsu, H. Uzu, Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%, *Nat. Energy.* 2 (2017) 17-32.
<https://doi.org/10.1038/nenergy.2017.32>
- [22] J. Zhao, A. Wang, M.A. Green, F. Ferrazza, 19.8% efficient “honeycomb” textured multicrystalline and 24.4% monocrystalline silicon solar cells. *Appl. Phys. Lett.* 73 (1998) 1991-1993. <https://doi.org/10.1063/1.122345>
- [23] F. Haase, C. Hollemann, S. Schaefer, A. Merkle, M. Rienaeker, J. Krügener, R. Brendel, R. Peibst, Laser contact openings for local poly-Si-metal contacts enabling 26.1%-efficient POLO-IBC solar cells. *Sol. Energy Mater. Sol.* 186(2018) 184-193.
<https://doi.org/10.1016/j.solmat.2018.06.020>.
- [24] A. Richter, J. Benick, F. Feldmann, A. Fell, M. Hermle, and S.W. Glunz, n-Type Si solar cells with passivating electron contact: Identifying sources for efficiency limitations by wafer thickness and resistivity variation. *Sol. Energy. Mater. Sol.* 173 (2017) 96-105. <https://doi.org/10.1016/j.solmat.2017.05.042>
- [25] P. Oxford, Oxford PV sets world record for perovskite solar cell. 2018
- [26] M. Wanlass, Systems and methods for advanced ultra-high-performance InP solar cells: Google Patents. 2017.
- [27] M. Hosoya, H. Oooka, H. Nakao, T. Gotanda, S. Mori, N. Shida, R. Hayase, Y. Nakano, M. Saito. Organic thin film photovoltaic modules. in *Proceedings of the 93rd Annual Meeting of the Chemical Society of Japan.* 2013.
- [28] A. Laventure, C.R. Harding, E. Cieplechowiec, Z. Li, J. Wang, Y. Zou, G.C. Welch, Screening quinoxaline-type donor polymers for roll-to-roll processing compatible organic photovoltaics. *ACS Appl. Polym. Mater.* 1 (2019) 2168-2176.
<https://doi.org/10.1021/acsapm.9b00433>.
- [29] K. Unnikrishnan, Environmental chamber to regulate film morphology for solar energy materials printing using additive manufacturing and investigating the role of additives in perovskites, University of Washington Libraries, 2018.

- [30] E.H. Jung, N.J. Jeon, E.Y. Park, C.S. Moon, T.J. Shin, T.-Y. Yang, J.H. Noh, J. Seo, Efficient, stable and scalable perovskite solar cells using poly (3-hexylthiophene). *Nat.* 567 (2019) 511. <https://doi.org/10.1038/s41586-019-1036-3>
- [31] W.S. Yang, J.H. Noh, N.J. Jeon, Y.C. Kim, S. Ryu, J. Seo, S.I. Seok, High-performance photovoltaic perovskite layers fabricated through intramolecular exchange. *sci.* 348 (2015) 1234-1237. <https://doi.org/10.1126/science.aaa9272>
- [32] M. Kawai, High-durability dye improves efficiency of dye-sensitized solar cells. *Nikkei Electronics*, (2013).
- [33] R. Komiya, A. Fukui, N. Murofushi, N. Koide, R. Yamanaka, H. Katayama. Improvement of the conversion efficiency of a monolithic type dye-sensitized solar cell module. in *Technical Digest, 21st International photovoltaic science and engineering conference*. 2011.
- [34] S. Mori, H. Oh-oka, H. Nakao, T. Gotanda, Y. Nakano, H. Jung, A. Iida, R. Hayase, N. Shida, M. Saito, Organic photovoltaic module development with inverted device structure. *Mater. Res. Soc. Symp. Proc.* 1737 (2015) 27-15. <https://doi.org/10.1557/opl.2015.540>
- [35] J. Benick, A. Richter, R. Müller, H. Hauser, F. Feldmann, P. Krenckel, S. Riepe, F. Schindler, M.C. Schubert, M. Hermle, High-efficiency n-type HP mc silicon solar cells. *IEEE J. Photovolt.* 7 (2017) 1171-1175. <https://doi.org/10.1109/JPHOTOV.2017.2714139>.
- [36] R. Venkatasubramanian, B. O'Quinn, J. Hills, P. Sharps, M. Timmons, J. Hutchby, H. Field, R. Ahrenkiel, B. Keyes. 18.2% (AM1. 5) efficient GaAs solar cell on optical-grade polycrystalline Ge substrate in conference record of the twenty fifth IEEE photovoltaic specialists conference. 25 (1996) 31-36. <https://doi.org/10.1109/PVSC.1996.563940>
- [37] M.A. Green, Commercial progress and challenges for photovoltaics. *Nat Energy.* 1 (2016) 1-4. <https://doi.org/10.1038/nenergy.2015.15>
- [38] K. Sun, C. Yan, F. Liu, J. Huang, F. Zhou, J.A. Stride, M. Green, X. Hao, Over 9% efficient kesterite $\text{Cu}_2\text{ZnSnS}_4$ solar cell fabricated by using $\text{Zn}_{1-x}\text{Cd}_x\text{S}$ buffer layer. *Adv. Energy Mater.* 6 (2016) 160-46. <https://doi.org/10.1002/aenm.201600046>
- [39] M.A. Green, Y. Hishikawa, W. Warta, E.D. Dunlop, D.H. Levi, J. Hohl Ebinger, A.W. HoBaillie, Solar cell efficiency tables (version 50). *Prog Photovolt.* 25 (2017) 668-676. <https://doi.org/10.1002/pip.2909>

- [40] M. Alves, A. Pérez-Rodríguez, P.J. Dale, C.D. Domínguez, S. Sadewasser, Thin-film micro-concentrator solar cells. *J. Phys. Energy*. 02 (2019) 76-55.
<https://doi.org/10.1088/2515-7655/ab4289>
- [41] C. Yan, C., J. Huang, K. Sun, S. Johnston, Y. Zhang, H. Sun, A. Pu, M. He, F. Liu, K. Eder, $\text{Cu}_2\text{ZnSnS}_4$ solar cells with over 10% power conversion efficiency enabled by heterojunction heat treatment. *Nat. Energy*. 3 (2018) 764–772.
<https://doi.org/10.1038/s41560-018-0206-0>
- [42] H. Sugimoto, High efficiency and large volume production of CIS-based modules. in 2014 IEEE 40th Photovoltaic specialist conference (PVSC). 40 (2014) 2767-2770.
<https://doi.org/10.1109/PVSC.2014.6925503>.
- [43] M.P. Van der Laan, S.J. Andersen, P. J.E. Réthoré, Brief communication: Wind speed independent actuator disk control for faster AEP calculations of wind farms using CFD. *Wind energy science discussions*, 2019.
- [44] A.W. Bett, S.P. Philipps, S. Essig, S. Heckelmann, R. Kellenbenz, V. Klinger, M. Niemeyer, D. Lackner, F. Dimroth. Overview about technology perspectives for high efficiency solar cells for space and terrestrial applications. in 28th European photovoltaic solar energy conference and exhibition. 2013.
- [45] S. Essig, C. Allebé, T. Remo, J.F. Geisz, M.A. Steiner, K. Horowitz, L. Barraud, J.S. Ward, M. Schnabel, A. Descoeudres, Raising the one-sun conversion efficiency of III–V/Si solar cells to 32.8% for two junctions and 35.9% for three junctions. *Nat. Energy*. 2 (2017) 1-8. <https://doi.org/10.1038/nenergy.2017.144>
- [46] H. Sai, T. Matsui, K. Matsubara, Stabilized 14.0%-efficient triple-junction thin-film silicon solar cell. *App. Phys. Lett.* 109 (2016) 183-506.
<https://doi.org/10.1063/1.4966996>
- [47] R. Cariou, J. Benick, F. Feldmann, O. Höhn, H. Hauser, P. Beutel, N. Razek, M. Wimplinger, B. Bläsi, D. Lackner, III–V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration. *Nat. Energy*. 3 (2018) 326–333. <https://doi.org/10.1038/s41560-018-0125-0>
- [48] M. Feifel, J. Ohlmann, J. Benick, M. Hermle, J. Belz, A. Beyer, K. Volz, T. Hannappel, A.W. Bett, D. Lackner, Direct growth of III–V/silicon triple-junction solar cells with 19.7% efficiency. *IEEE J. Photovolt.* 8 (2018) 1590-1595.
<https://doi.org/10.1109/JPHOTOV.2018.2868015>
- [49] T.J. Grassman, D.J. Chmielewski, S.D. Carnevale, J.A. Carlin, S.A. Ringel. GaAsP/Si dual-junction solar cells grown by MBE and MOCVD. in 2015 IEEE 42nd

- Photovoltaic specialist conference (PVSC). (2015) 1-5.
<https://doi.org/10.1109/PVSC.2015.7356384>.
- [50] T. Takamoto, H. Washio, H. Juso. Application of InGaP/GaAs/InGaAs triple junction solar cells to space use and concentrator photovoltaic. in 2014 IEEE 40th photovoltaic specialist conference (PVSC). (2014) 0001-0005.
<https://doi.org/10.1109/PVSC.2014.6924936>.
- [51] J.F. Geisz, M.A. Steiner, N. Jain, K.L. Schulte, R.M. France, W.E. McMahon, E.E. Perl, D.J. Friedman, Building a six-junction inverted metamorphic concentrator solar cell. *IEEE J. Photovolt.* 8 (2017) 626-632.
<https://doi.org/10.1109/JPHOTOV.2017.2778567>
- [52] T. Matsui, K. Maejima, A. Bidiville, H. Sai, T. Koida, T. Suezaki, M. Matsumoto, K. Saito, I. Yoshida, M. Kondo, High-efficiency thin-film silicon solar cells realized by integrating stable a-Si: H absorbers into improved device design. *Japanese J. Appl. Phys.* 54 (2015)1-5. <https://doi.org/10.7567/JJAP.54.08KB10>
- [53] Lin,Chu-Jian Investigation of Gallium Arsenide Thin Films deposited by RF Sputtering, NCU Institutional Repository.
- [54] H. Lv, F. Sheng, J. Dai, W. Liu, C. Cheng, and J. Zhang, Temperature-dependent model of concentrator photovoltaic modules combining optical elements and III–V multi-junction solar cells. *Sol. Energy.* 112 (2015) 351-360.
<https://doi.org/10.1016/j.solener.2014.12.005>
- [55] N. Jain, K.L. Schulte, J.F. Geisz, D.J. Friedman, R.M. France, E.E. Perl, A.G. Norman, H.L. Guthrey, M.A. Steiner, High-efficiency inverted metamorphic 1.7/1.1 eV GaInAsP/GaInAs dual-junction solar cells. *App. Phys. Lett.* 112 (2018) 0539051-0539055. <https://doi.org/10.1063/1.5008517>
- [56] S. Ananthakumar, J.R. Kumar, S.M. Babu, Third-generation solar cells: concept, materials and performance-an overview, in emerging nanostructured materials for energy, *Environ. Sci.* (2019) 305-339. https://doi.org/10.1007/978-3-030-04474-9_7
- [57] I. Dharmadasa, *Advances in thin-film solar cells*: Jenny Stanford Publishing. (2013).
<https://doi.org/10.1201/9780429020841>
- [58] G. Adolf, H. Christopher, Photovoltaic materials, past, present, future. *Sol. Energy Mater. Sol.* 62 (2000) 1-19. <https://doi.org/10.1016/B978-185617390-2/50006-4>
- [59] K.H. Yoon, Beard trimmer: Google Patents,2014.

- [60] L.R. Weiss, S.L. Bayliss, F. Kraffert, K.J. Thorley, J.E. Anthony, R. Bittl, R.H. Friend, A. Rao, N.C. Greenham, J. Behrends, Strongly exchange-coupled triplet pairs in an organic semiconductor. *Nat Phys.* 13 (2017) 1-5.
<https://doi.org/10.1038/nphys3908>
- [61] F.W. Low C.W. Lai, Recent developments of graphene-TiO₂ composite nanomaterials as efficient photoelectrodes in dye-sensitized solar cells: A review. *Renew. Sust. Energ. Rev.* 82 (2018) 103-125.
<https://doi.org/10.1016/j.rser.2017.09.024>
- [62] Drevets, W.C. Q.S. Li, Method for the treatment of depression: Google Patents. 2018.
- [63] A. Goetzberger C. Hebling, Photovoltaic materials, past, present, future. *Sol. Energy Mater. Sol.* 62 (2000) 1-19. [https://doi.org/10.1016/S0927-0248\(99\)00131-2](https://doi.org/10.1016/S0927-0248(99)00131-2)
- [64] M.A.V. Green, E.D. Dunlop, D.H. Levi, J. Hohl Ebinger, M. Yoshita, A.W. Ho Baillie, Solar cell efficiency tables (version 54). *Prog Photovolt.* 27(2019) 565-575.
<https://doi.org/10.1002/pip.3171>
- [65] S. Günes, H. Neugebauer, N.S. Sariciftci, Conjugated polymer-based organic solar cells. *Chem Rev.* 107 (2007) 1324-1338. <https://doi.org/10.1021/cr050149z>
- [66] C.W. Tang, Two layer organic photovoltaic cell. *App. Phys. Lett.* 48 (1986) 183-185. <https://doi.org/10.1063/1.96937>
- [67] M. Westphalen, U. Kreibig, J. Rostalski, H. Lüth, D. Meissner, Metal cluster enhanced organic solar cells. *Sol. Energy. Mater. Sol.* 61(2000) 97-105.
[https://doi.org/10.1016/S0927-0248\(99\)00100-2](https://doi.org/10.1016/S0927-0248(99)00100-2)
- [68] N. Sariciftci, D. Braun, C. Zhang, V. Srdanov, A. Heeger, G. Stucky, F. Wudl, Semiconducting polymer buckminsterfullerene heterojunctions: Diodes, photodiodes, and photovoltaic cells. *App. Phys. Lett.* 62 (1993) 585-587.
<https://doi.org/10.1063/1.108863>
- [69] B. Kraabel, D. McBranch, N. Sariciftci, D. Moses, A. Heeger, Ultrafast spectroscopic studies of photoinduced electron transfer from semiconducting polymers to C₆₀. *Phys. Rev. B.* 50 (1994) 18543. <https://doi.org/10.1103/PhysRevB.50.18543>
- [70] N. Sariciftci, F. Wudl, A. Heeger, M. Maggini, G. Scorrano, M. Prato, J. Bourassa, P. Ford, Photoinduced electron transfer and long lived charge separation in a donor-bridge-acceptor supramolecular ‘diad’ consisting of ruthenium (II) tris (bipyridine) functionalized C₆₀. *Chem. Phys. Lett.* 247 (1995) 510-514.
[https://doi.org/10.1016/S0009-2614\(95\)01276-1](https://doi.org/10.1016/S0009-2614(95)01276-1)

- [71] J.Y. Kim, K. Lee, N.E. Coates, D. Moses, T.Q. Nguyen, M. Dante, A.J. Heeger, Efficient tandem polymer solar cells fabricated by all-solution processing. *Science* 317 (2007) 222-225. <https://doi.org/10.1126/science.1141711>
- [72] T. Chang, *Real analysis 2* (2018) 1-5.
- [73] E.J. Benjamin, S.S. Virani, C.W. Callaway, A.M. Chamberlain, A.R. Chang, S. Cheng, S.E. Chiuev, M. Cushman, F.N. Delling, R. Deo, Heart disease and stroke statistics-2018 update: a report from the Circ. Res. 137 (2018) 67-426 <https://doi.org/10.1161/CIR.0000000000000558>
- [74] M.C. Scharber N.S. Sariciftci, Efficiency of bulk-heterojunction organic solar cells. *Prog Polym. Sci.* 38 (2013) 1929-1940. <https://doi.org/10.1016/j.progpolymsci.2013.05.001>
- [75] M. Gratzel B. O'Regan, A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films. *Nat.* 353 (1991) 737-740. <https://doi.org/10.1021/nl400286w>
- [76] S. Ito, M.K. Nazeeruddin, P. Liska, P. Comte, R. Charvet, P. Péchy, M. Jirousek, A. Kay, S.M. Zakeeruddin, M. Grätzel, Photovoltaic characterization of dye sensitized solar cells: effect of device masking on conversion efficiency. *Prog. photovolt.* 14 (2006) 589-601 <https://doi.org/10.1002/pip.683>
- [77] G. Redmond, D. Fitzmaurice, M. Graetzel, Visible light sensitization by cis-bis (thiocyanato) bis (2, 2'-bipyridyl-4, 4'-dicarboxylato) ruthenium (II) of a transparent nanocrystalline ZnO film prepared by sol-gel techniques. *Chem Mater.* 6 (1994) 686-691. <https://doi.org/10.1021/cm00041a020>
- [78] Y. Tachibana, K. Hara, K. Sayama, H. Arakawa, Quantitative analysis of light-harvesting efficiency and electron-transfer yield in ruthenium-dye-sensitized nanocrystalline TiO₂ solar cells. *Chem. Mater.* 14 (2002) 2527-2535. <https://doi.org/10.1021/cm 011563s>
- [79] K. Eguchi, H. Koga, K. Sekizawa, K. Sasaki, Nb₂O₅-based composite electrodes for dye-sensitized solar cells. *J. Ceram. Soc. Japan.* 108 (2000) 1067-1071. https://doi.org/10.2109/jcersj.108.1264_1067
- [80] H. Rensmo, K. Keis, H. Lindström, S. Södergren, A. Solbrand, A. Hagfeldt, S.-E. Lindquist, L. Wang, M. Muhammed, High light-to-energy conversion efficiencies for solar cells based on nanostructured ZnO electrodes. *J. Phys. Chem. B.* 101 (1997) 2598-2601. <https://doi.org/10.1021/jp962918b>

- [81] K. Hara, T. Horiguchi, T. Kinoshita, K. Sayama, H. Sugihara, H. Arakawa, Highly efficient photon-to-electron conversion with mercurochrome-sensitized nanoporous oxide semiconductor solar cells. *Sol. Energy Mater. Sol.* 64 (2000) 115-134
[https://doi.org/10.16/S0927-0248\(00\)00065-9](https://doi.org/10.16/S0927-0248(00)00065-9)
- [82] N.N. Dinh, M.-C. Bernard, A. Hugot-Le Goff, T. Stergiopoulos, P. Falaras, Photoelectrochemical solar cells based on SnO₂ nanocrystalline films. *Cr. Chim.* 9 (2006) 676-683. <https://doi.org/10.1016/j.crci.2005.02.042>
- [83] S.Gholamrezaei, M.S. Niasari, M. Dadkhah, B. Sarkhosh, New modified sol-gel method for preparation SrTiO₃ nanostructures and their application in dye-sensitized solar cells. *J. Mater. Sci. Mater.* 27 (2016) pp. 118-125.
<https://doi.org/10.1007/s10854-015-3726-4>
- [84] S.Burnside, J.-E. Moser, K. Brooks, M. Grätzel, D. Cahen, Nanocrystalline mesoporous strontium titanate as photoelectrode material for photosensitized solar devices: increasing photovoltage through flatband potential engineering. *J. Phys. Chem. B.* 103 (1999) 9328-9332. <https://doi.org/10.1021/jp9913867>
- [85] J. He, H. Lindström, A. Hagfeldt, S.-E. Lindquist, Dye-sensitized nanostructured p-type nickel oxide film as a photocathode for a solar cell. *J. Phys Chem. B.* 103 (1999) 8940-8943 <https://doi.org/10.1021/jp991681r>.
- [86] K. Sayama, H. Sugihara, H. Arakawa, Photoelectrochemical properties of a porous Nb₂O₅ electrode sensitized by a ruthenium dye. *Chem. Mater.* 10 (1998) 3825-3832.
<https://doi.org/10.1021/cm980111l>.
- [87] T.N. Rao, L. Bahadur, Photoelectrochemical studies on dye sensitized particulate ZnO thin film photoelectrodes in nonaqueous media. *J. Electrochem. Soc.* 144 (1997) 179-185. <https://doi.org/10.1149/1.1837382>
- [88] A. Zaban, S. Chen, S. Chappel, B. Gregg, Bilayer nanoporous electrodes for dye sensitized solar cells. *Chem. Comm.* 22 (2000) 2231-2232.
<https://doi.org/10.1039/B005921H>
- [89] A. Kay, M. Graetzel, Artificial photosynthesis. 1. Photosensitization of titania solar cells with chlorophyll derivatives and related natural porphyrins. *J. Phys. Chem.* 97 (1993) 6272-6277. <https://doi.org/10.1021/j100125a029>
- [90] V.A.S. Perera, An efficient dye-sensitized photoelectrochemical solar cell made from oxides of tin and zinc. *Chem. Comm.* (1999) 15-16
<https://doi.org/10.1039/A806801A>

- [91] K. Tennakone, G. Senadeera, V. Perera, I. Kottegoda, L. De Silva, Dye-sensitized photoelectrochemical cells based on porous SnO_2/ZnO composite and TiO_2 films with a polymer electrolyte. *Chem Mater.* 11 (1999) 2474-2477. <https://doi.org/10.1021/cm990165a>
- [92] S. Ferrere, A. Zaban, B.A. Gregg, Dye sensitization of nanocrystalline tin oxide by perylene derivatives. *J. Phys. Chem. B.* 101 (1997) 4490-4493 <https://doi.org/10.1021/jp970683d>
- [93] K. Sayama, M. Sugino, H. Sugihara, Y. Abe, H. Arakawa, Photosensitization of porous TiO_2 semiconductor electrode with xanthene dyes. *Chem Lett.* 27 (1998) 753-754. <https://doi.org/10.1246/cl.1998.753>
- [94] A.C. Khazraji, S. Hotchandani, S. Das, P.V. Kamat, Controlling dye (Merocyanine-540) aggregation on nanostructured TiO_2 films. An organized assembly approach for enhancing the efficiency of photosensitization. *J. Phys. Chem B.* 103 (1999) 4693-4700. <https://doi.org/10.1021/jp9903110>.
- [95] Z.S. Wang, F.Y. Li, C.H. Huang, Highly efficient sensitization of nanocrystalline TiO_2 films with styryl benzothiazolium propylsulfonate. *Chem. Comm.* 20 (2000) 2063-2064. <https://doi.org/10.1039/b006427k>.
- [96] Z.S. Wang, F.Y. Li, C.H. Huang, L. Wang, M. Wei, L.P. Jin, N.Q. Li, Photoelectric conversion properties of nanocrystalline TiO_2 electrodes sensitized with hemicyanine derivatives. *J. Phys. Chem. B.* 104 (2000) 9676-9682. <https://doi.org/10.1021/jp001580p>.
- [97] K. Sayama, K. Hara, N. Mori, M. Satsuki, S. Suga, S. Tsukagoshi, Y. Abe, H. Sugihara, H. Arakawa, Photosensitization of a porous TiO_2 electrode with merocyanine dyes containing a carboxyl group and a long alkyl chain. *Chem. Comm.* 13 (2000) 1173-1174. <https://doi.org/10.1039/b001517m>.
- [98] K. Hara, K. Sayama, Y. Ohga, A. Shinpo, S. Suga, H. Arakawa, A coumarin-derivative dye sensitized nanocrystalline TiO_2 solar cell having a high solar-energy conversion efficiency up to 5.6%. *Chem. Comm.* 06 (2001) 569-570. <https://doi.org/10.1039/b010058g>
- [99] K. Hara, T. Sato, R. Katoh, A. Furube, Y. Ohga, A. Shinpo, S. Suga, K. Sayama, H. Sugihara, H. Arakawa, Molecular design of coumarin dyes for efficient dye-sensitized solar cells. *J. Phys. Chem. B.* 107 (2003) 597-606. <https://doi.org/10.1021/jp026963x>
- [100] Z. Wu, T. Kinnunen, N. Evans, J. Yamagishi, C. Hanilçi, M. Sahidullah, A. Sizov. ASVspoof 2015: the first automatic speaker verification spoofing and countermeasures

- challenge. in sixteenth annual conference of the international speech communication association. 16 (2015) 1-5. <https://doi.org/10.7488/ds/252>
- [101] M.S. Faber S. Jin, Earth-abundant inorganic electrocatalysts and their nanostructures for energy conversion applications. *Energy Environ. Sci.* 7(2014)3519-3542. <https://doi.org/10.1039/c4ee01760a>
- [102] J. Wu, Z. Lan, J. Lin, M. Huang, Y. Huang, L. Fan, G. Luo, Y. Lin, Y. Xie, Y. Wei, Counter electrodes in dye-sensitized solar cells. *Chem. Soc. Rev.* 46 (2017) 5975-6023. <https://doi.org/10.1039/C6CS00752J>
- [103] J. Theerthagiri, A.R. Senthil, J. Madhavan, T. Maiyalagan, Recent progress in non platinum counter electrode materials for dye sensitized solar cells. *Chem. Electro. Chem.* 2 (2015) 928-945. <https://doi.org/10.1002/celec.201402406>.
- [104] S. Yun, H. Pu, J. Chen, A. Hagfeldt, T. Ma, Enhanced performance of supported HfO₂ counter electrodes for redox couples used in dye sensitized solar cells. *ChemSusChem.* 7 (2014) 442-450. doi. 10.1002/cssc.201301140
- [105] K. Kakiage, Y. Aoyama, T. Yano, K. Oya, J.-i. Fujisawa, M. Hanaya, Highly-efficient dye-sensitized solar cells with collaborative sensitization by silyl-anchor and carboxy-anchor dyes. *Chem. Commun.* 51 (2015)15894-15897. <https://doi.org/10.1039/c5cc06759f>
- [106] S.Y. Myong, Recent progress in inorganic solar cells using quantum structures. *Recent patents on nanotechnology.* 01 (2007) 67-73. <https://doi.org/10.2174/187221007779814763>
- [107] K. Barnham, P. Abbott, I. Ballsrød, D. Bushnell, A. Chatten, M. Mazzer, G. Hills, J. Roberts, M. Malik, P. O'Brien, Future applications of low dimensional structures in photovoltaics. *Proc. Photovoltaics for the 21st Century*,(2005) 30 - 45.
- [108] R.Morf, Unexplored opportunities for nanostructures in photovoltaics. *Physica E Low Dimens. Syst. Nanostruct.* 14 (2002) 78-83. [https://doi.org/10.1016/s1386-9477\(02\)00360-0](https://doi.org/10.1016/s1386-9477(02)00360-0)
- [109] C.B. Honsberg, A.M. Barnett, D. Kirkpatrick. Nanostructured solar cells for high efficiency photovoltaics. in 2006 IEEE 4th world conference on photovoltaic energy conference. 2006. <https://doi.org/10.1109/WCPEC.2006.279769>
- [110] Bailey, S., S. Castro, R. Raffaele, S. Fahey, T. Gennett, P. Tin. Nanostructured materials for solar cells. in 3rd World conference on photovoltaic energy conversion. 2003.2690-2693

- [111] K. Zhao, Z. Pan, I.n. Mora-Seró, E. Cánovas, H. Wang, Y. Song, X. Gong, J. Wang, M. Bonn, J. Bisquert, Boosting power conversion efficiencies of quantum-dot-sensitized solar cells beyond 8% by recombination control. *J. Am. Chem. Soc.* 137 (2015) 5602-5609. <https://doi.org/10.1021/jacs.5b01946>
- [112] R.K. Goyal, *Nanomaterials and nanocomposites: synthesis, properties, characterization techniques, and applications*: CRC Press, 2017.
- [113] A. Kojima, K. Teshima, Y. Shirai, T. Miyasaka, Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. *J. Am. Chem. Soc.* 131 (2009) 6050-6051. <https://doi.org/10.1021/ja809598r>
- [114] J.H. Im, C.R. Lee, J.W. Lee, S.W. Park, N.G. Park, 6.5% efficient perovskite quantum-dot-sensitized solar cell. *Nanoscale*. 3 (2011) 4088-4093 <https://doi.org/10.1039/C1NR10867K>
- [115] C.W. Chen, H.W. Kang, S.Y. Hsiao, P.F. Yang, K.M. Chiang, H.W. Lin, Efficient and uniform planar-type perovskite solar cells by simple sequential vacuum deposition. *Advanced Materials*, 26 (2014) 6647-6652. <https://doi.org/10.1002/adma.201402461>
- [116] M. Bag, Z. Jiang, L.A. Renna, S.P. Jeong, V.M. Rotello, D. Venkataraman, Rapid combinatorial screening of inkjet-printed alkyl-ammonium cations in perovskite solar cells. *Mater Lett.* 164 (2016) 472-475. <https://doi.org/10.1016/j.matlet.2015.11.058>
- [117] J. Calbo, Dye sensitized solar cells: past, present and future. photoenergy and thin film materials, in: X Yu Yang (Eds) *Photoenergy and thin film materials*, Scrivener Publishing LLC. (2019) 49-119.