Efficiency Improvement of Solar Cells

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***Abstract*—Solar cells are an integral part of the switch from conventional to renewable energy sources. Started with an efficiency of under 10% solar cells meanwhile are reaching over 40% with a potential of further enhancements. With this development they are a promising technology to massively decentralize our energy supply in the future. Especially mobile gadgets like mobile phones, tablets but also autonomous vehicles can benefit from this progression.**
This paper gives an insight into the functional mechanism, a comparison between different technologies, methods and techniques been used for efficiency enhancement of solar cells.

***Index Terms*—Solar cells, efficiency, ARC, multi-layer, perovskite, radiation bundling**

I. Introduction

Mobility is a keyword in our society. No other renewable energy source is providing such a high degree of mobility as solar cells do. Started as an experiment by Edmond Becquerel in 1839 solar cells are used for example as energy source for satellites, generating power in buildings and are a fundamental part of future smart grid concepts for energy harvesting to increase the share of renewable energies.

With increasing efficiency and decreasing costs solar cells find their way in evermore markets and products. In the last couple of years products like powerbanks to recharge mobile phones became suitable for the mass. In other concepts solar cells serve as an additional energy supply for a wide spectrum of vehicles and autonomous systems like the NASA Helios Prototype.

As the sun is an inexhaustible energy source researchers try to raise the efficiency of solar cells in order to use as much as possible of the provided energy. With its radiation power of $P_{sun} = 3.845 \cdot 10^{26} W$ and an irradiation of annually $W_{Earth} = 1.119 \cdot 10^{18} kWh$ it fits the annual world energy consumption multiple times [1].

Though photovoltaics made a big progress over the last decade the potential is not yet exhausted. High-tech solar cells are on the verge to reach an efficiency of 50% in the next few years. In addition new materials and methods accelerate further developments.

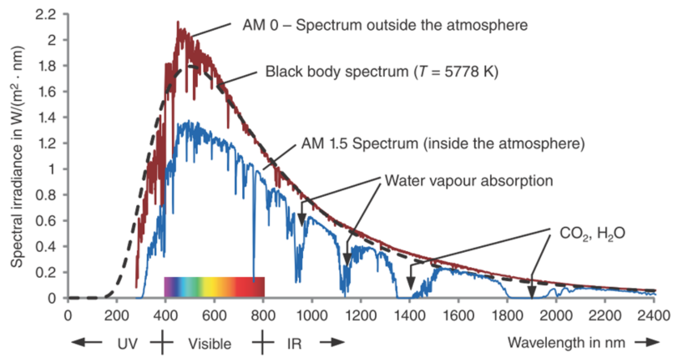

Fig. 1. Solar spectrum with AM 0 spectrum outside the atmosphere (red), idealized black body spectrum (black dashed line), AM 1.5 spectrum inside the atmosphere (blue) [1]

II. Sun Radiation

According to Planck's Law of Radiation the surface temperature of a body determines the spectrum of radiation it gives off to its surroundings. The radiation of the sun is the result of fusion of hydrogen to helium. With a surface temperature of 5778 Kelvin the spectrum of the sun is nearly a *Black Body Spectrum* at this temperature represented as the black dashed line in fig. 1, with its peak at a wavelength of around 500 nm [1].

Outside earth's atmosphere the radiation equals $1367 W/m^2$, which is referred to as the *solar constant* and is the integral sum of the individual parts of the *Air Mass 0 (AM 0)* spectrum. Air Mass defines the path the radiation took

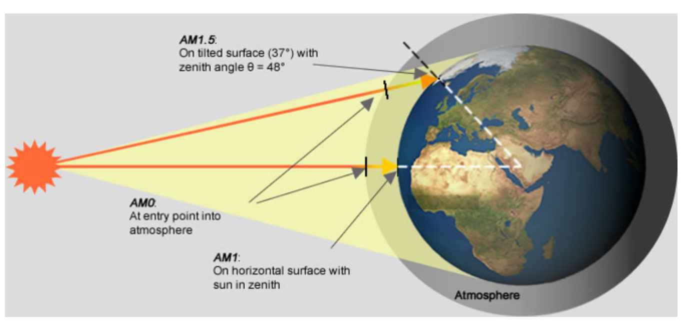

Fig. 2. Air Mass: AM 0 outside the atmosphere; AM 1 inside the atmosphere vertically to the sun; AM 1.5 inside the atmosphere with a path length 1.5 times compared to AM 1 [2]

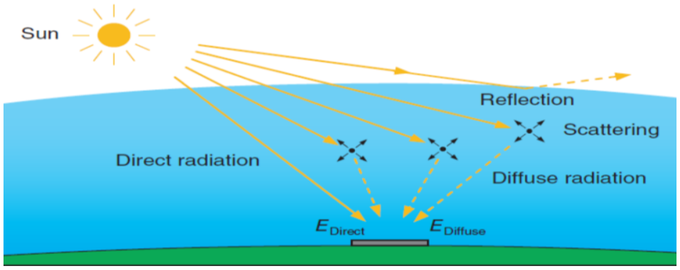

Fig. 3. Losses and radiation types [1]

through earth's atmosphere. AM 0 defines the spectrum outside earth's atmosphere. On passing the atmosphere the spectrum weakens due to different processes: reflections at earth's atmosphere, absorption and scattering. As a result the global radiation is separated into two radiation types: *direct* and *diffuse* radiation (fig. 3).

As a result a new Air Mass spectrum is generated according to the sun position. AM 1 defines the spectrum inside the atmosphere if the path of radiation is vertical (sun in zenith). An important spectrum is AM 1.5 which is the average year's spectrum, as it occurs in autumn and fall.

III. Semiconductor Physics

In order to understand the working principle of a solar cell a closer look at semiconductors is required. *Bohr's Atomic Model* describes one atom as a combination of one nucleus (enclose neutrons and protons) and a specific number electrons orbiting circular its nucleus. These circular orbits are so-called shells which represent an specific energy level.

In a semiconductor atoms are coupled to a crystalline structure in which the energy levels are spread. The result of this are energy bands. Two bands are important for solar cell operation: the valence band W_V, highest energy level occupied by electrons and the conduction band W_L, energy level above the valence band unoccupied by electrons (fig. 7). In between these two energy levels the bandgap ΔW_G is located. The amount of energy needed to separate an electron from the valence band, create an electron-hole pair and move the electron to the higher leveled conduction band is defined by the width of the bandgap. Also the bandgap defines the wavelength needed for absorption of light.

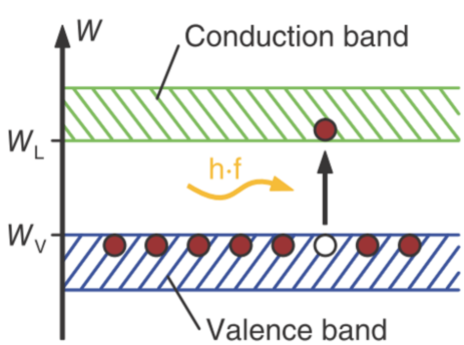

Fig. 4. Band model [1]

In equ. 1 the required energy of a photon to lift an electron from the valence band to the conduction band is described as the product of the Planck's constant h and the frequency f. According to equ. 2 the required wavelength is a result of a division of the speed of light c_0 by the frequency.

$$\Delta W_G = W_L - W_V = h \cdot f \tag{1}$$

$$\lambda = \frac{c_0}{f} \tag{2}$$

Light incidence on a semiconductors surface leads to the following three cases (fig. 5):

- wavelength is smaller than bandgap wavelength
- wavelength equal to bandgap wavelength
- wavelength is bigger than bandgap wavelength.

In the first case the energy of photons is higher than needed to lift the electron. The additional energy generate thermalization losses. In the last case the energy of photons is to low to lift the electron; so it gets lifted but recombines with the hole short after. This case generates so-called transmission losses. Photons are efficiently absorbed in case the energy of the photons corresponds to the bandgap energy.

The *Shockley Queisser Efficiency Limit (SQ Limit)* (fig. 6) describes the maximum theoretical efficiency for single p-n junction-semiconductors at AM 1.5. As shown in fig. 6 the efficiency is dependent on the used base-material and its provided band gap [3].

Still there is a difference between the theoretical efficiency and the efficiency of production cells. The reason for this are losses described earlier as thermalization and transmission and additional losses like reflections on the cell surface.

IV. Function of Solar Cells

As presented in fig. 7 a typical silicon solar cell works like a photo diode. The p-n junction is asymmetrically doped. On light incidence electron-hole pairs are generated by the absorbed photons. Separated from the space charge region

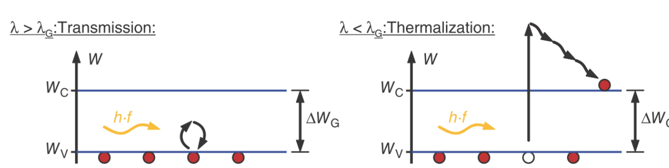

Fig. 5. Losses depending on the energy of photons: energy is lower than bandgap energy (left), energy is higher than bandgap energy (right) [1]

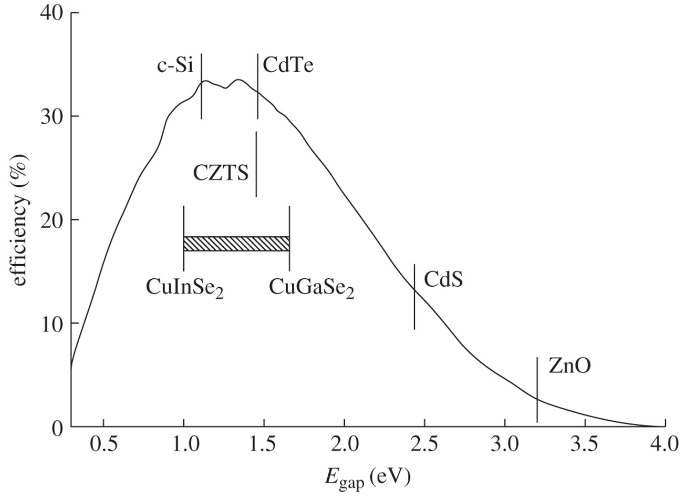

Fig. 6. The Shockley Queisser Efficiency Limit and efficiency depending on the semiconductor band gap in electron volts. Efficiency of solar cell materials are displayed as colored dots in the diagram [3]

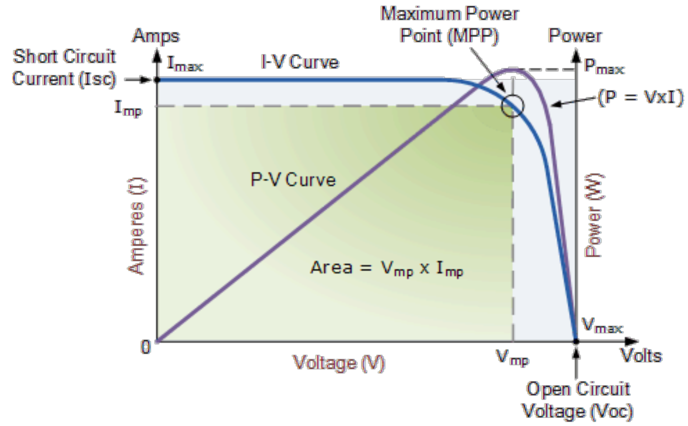

Fig. 8. Characteristic curve of a solar cell: characteristic curve (blue) and corresponding power curve (purple); area (green) at Maximum Power Point (MPP) represents point with highest power output [7]

electrons move through the n^+-emitter to the front contact, which is connected with a negative contact by the busbar. Holes moves in the opposite direction through the p-base to the back contact, which is connected to the positive contact. On connecting a load to both contacts electrical energy is generated. Finally electrons and holes recombine in the p-n junction.

Depending on the connected load resistance the generated power varies. Based on equ. 3 two extreme cases can occur: For an infinite load resistance the current becomes zero. This case is referred to as Open Circuit Voltage V_{OC}. Short Circuit Current I_{SC} is the result of the opposite case, in which the load resistance equals zero. For this case the voltage becomes zero. In both cases no power is generated according to equ. 3.

$$P = U \cdot I \tag{3}$$

Usually solar cells operate between these two extremes represented as the blue curve in fig. 8. Maximum power is generated at the *Maximum Power Point (MPP)*, in which the area is at its maximum. In this case current and voltage is referred to as I_{MPP} and V_{MPP}.

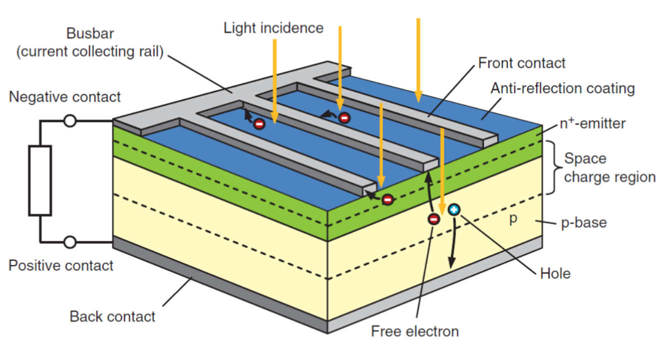

Fig. 7. Method of function of a solar cell [1]

Theoretically the mathematical product of I_{SC} and V_{OC} represents the maximum power of a solar cell. However, only a part of the solar cells area can be used to convert light into electrical power; the rest is covered by e.g. front contacts. The relationship between the theoretical maximum area and the MPP area is called *Fill Factor (FF)* (equ. 4), which is a measure of quality for a solar cell.

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}} \tag{4}$$

The characteristic curve is influenced by temperature and the intensity of light incidence. With decreasing intensity the short circuit current get reduced and redefines the curve. As a result of a rising temperature the open circuit voltage is being reduced. Both effects have a negative influence on the efficiency.

Depending on the solar cell technology its value is between 0.75 and 0.85 (Si-cells) [1] [4] respectively 0.5 and 0.7 [4] [5] or 0.6 and 0.75 [1] (thin film cells).

V. Cell technologies

Basically solar cells are divided into three generations. Solar cells of the first generation are mainly silicon-based and have an efficiency upto 15% (Polycristalline) respectively 20% (Monocristalline). These cells are stable and have a good performance but require a high energy input in production, as they are silicon-based. With an market share of about 90% first generation cells dominate the market [16] [12].

Second generation solar cells aim at a decent performance at lower material consumption to decrease manufacturing costs. As the base-material these cells use amorphous silicon, CIGS (Copper-Indium-Gallium-Selenide) or CdTe (Cadmium-Telluride). Depending on the used base-material these cells

TABLE I
CELL TECHNOLOGY COMPARISON [6]

	Mono	Poly	Thin	CIGS
	1st Gen		2nd Gen	
Efficiency	14 - 20%	12 - 15%	6 - 10%	13 - 15%
Low light performance	losses(diffuse)	losses(diffuse)	low losses	low losses
Thermal behavior	high temp losses	high temp losses	low losses	low losses
Cost (1 = lowest)	3	2	1	4
Long-term test	very high performance, stable	high performance, stable	average performance	low performance
Durability	high	high	lower	not tested yet
Weight	higher	higher	lower	lower
Failure vulnerability	very low	very low	low	low

(also called thin film cells) provide an efficiency of upto 10% (amorphous silicon, CdTe) respectively 15% (CIGS) [6].

Third generation solar cells are not available as commercial products yet. This category includes solar cells based on new materials like perovskite or multi-junction cells.

VI. POTENTIAL OF EFFICIENCY IMPROVEMENT

Efficiency improvement is a driving factor in the solar cell industry as it:

- enhances efficiency to gain higher yields
- decrease material/manufacturing costs.

Besides the improvement techniques and methods to enhance the efficiency of solar cells new promising materials are emerging.

A. Anti-Reflection Coating (ARC)

As efficiency of solar cells is dependent on the ability to absorb photons, it's important to reduce reflection on the cells surface and therefore the number of photons reflected [9]. Reflection is the result of light incidence at the interface of two materials with different *refractive indices n*, which indicates the reduction of the speed of light when travels through the material compared to its speed in vacuum (equ. 5).

$$n = \frac{c_0}{v} \tag{5}$$

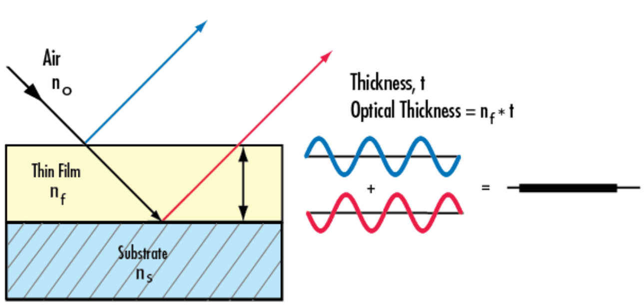

Fig. 9. Destructive interference depending on thickness of ARC and the refractive indices of ARC and the cell base-material [8]

According to equ. 6 the *refractive index* of the ARC is depending on n_0 (index of refraction of air) and n_{bm} (index of refraction of base-material).

$$n_{arc}^2 = n_0 n_{bm} \tag{6}$$

Other important parameters for ARC are the wavelength, thickness and angle of light incidence. To achieve a destructive interference of the reflected light on the upper and lower boundary (fig. 9) the thickness of ARC has to calculated according to equ. 7, where λ_d is the wavelength fitting the band gap [9].

$$d = \frac{\lambda_d}{4 n_{arc}} \tag{7}$$

As a result the *Reflection factor R* is calculated with the Fresnel equations (equ. 8) [1].

$$R = (\frac{n_{arc}^2 - n_1 \cdot n_2}{n_{arc}^2 + n_1 \cdot n_2})^2 \tag{8}$$

As shown in fig. 10 depending on the coating and its thickness a *Reflection factor R* of nearly zero can be achieved for a specific range of the spectrum. A new trend are multi-layer ARCs to spread the effect on a broader range of the spectrum for single- and multi-junction cells. An theoretical efficiency of 16.97% could be reached for a single-junction GaAs solar cell compared to 16.36% for the same cell with a single-layer ARC and 12.01% without ARC. The main reasons for the slightly higher efficiency with double-layer ARC is the ratio between both layers [10].

B. Multi-Junction Cells

Multi-Junction cells (also called Multi-Layer cells) can be described as a stack of layers based on different semiconductor materials. The used semiconductor materials differ in their p-n junction with varying band gaps. An example of the multi-junction principle is shown in fig. 11. Solar cells with multiple layers are arranged in a top level layer for lower wavelength. The layer below the top level layer is meant to absorb a higher level of wavelength and so on.

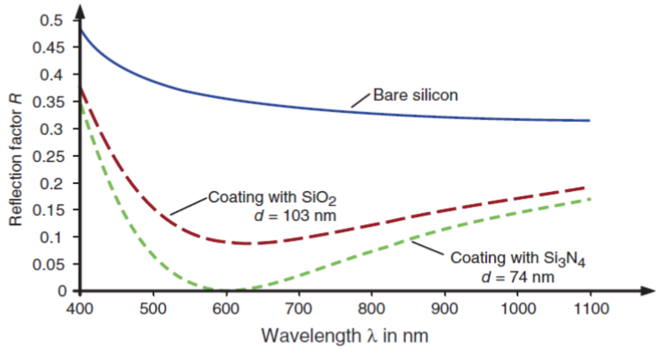

Fig. 10. Reflection factors depending on wavelength: Base silicon without ARC; ARC silicon oxide SiO_2 reduces reflection factor to 0.1 at a wavelength of around 600 nm; ARC silicon nitride Si_3N_4 reduces reflection factor to nearly 0 at a wavelength of 600 nm [1]

By using several junctions with varying band gaps these cells absorb a broader range of the spectrum to enhance efficiency of the whole stack. A record efficiency of 46.0% could be reached with multi-layer cells (at laboratory conditions) [12].

C. Radiation Bundling

Radiation bundling aims at a reduction of solar cell area at an enhanced performance. Solar cells using this technique are also called concentrator cells achieving a higher performance by using a solar cell with a smaller area in combination with a cheap technology like parabolic mirror or a Fresnel lens. Either way the radiation is concentrated and a higher current is achieved which enhances the characteristic curve. Concentrator cells are classified by the *sun* factor, which indicates the intensity of radiation incidence [13].

As the reduction of solar cell area is the driving motivation for radiation bundling the solar cells efficiency is a ratio of

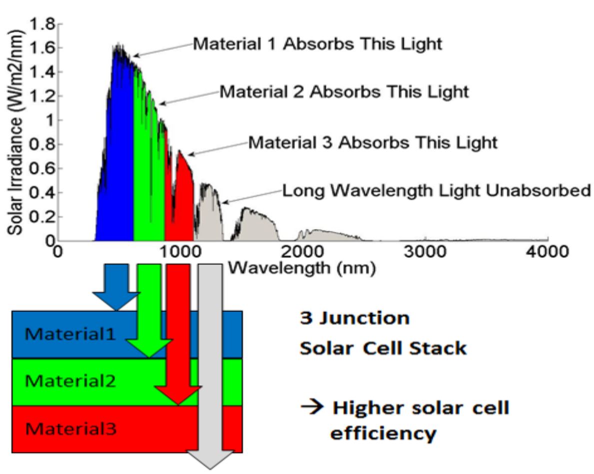

Fig. 11. Multi-Junction cell principle [11]

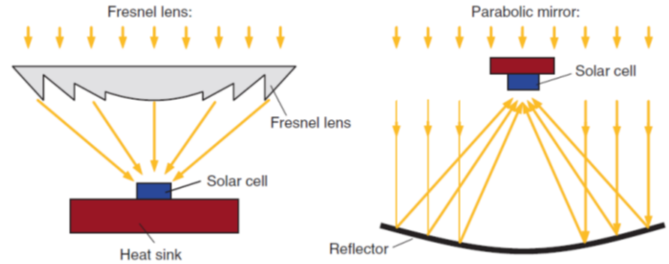

Fig. 12. Radiation Bundling: Fresnel lens method (left) and parabolic mirror method (right) [1]

generated Power P and the product of the radiation on the surface of the cell E_x and the cell area A_{sc} (9).

$$\eta_{cs} = \frac{P}{E_x \cdot A_{sc}} \tag{9}$$

However, the efficiency enhancement by radiation bundling has a price: as the efficiency electrical losses increase as well and the resistance of the solar cell rises with square of the operating current. With rising temperature the efficiency suffers which makes a heat sink indispensable. As a result of this the efficiency rises not continuously (fig. 13) [1] [13].

In 2009 an efficiency of 41.6% could be reached by Spectrolab, Inc. by using radiation bundling in combination with a multi-junction cell [14]. According to the National Renewable Energy Laboratory (NREL) a new record of 46% was achieved [15].

D. Perovskite Cells

Perovskite cells is a new emerging material in the evolution in photovoltaics which could lead to the third generation of solar cells: low in material and manufacturing costs but highly efficient. Discovered 1839 by Gustav Rose in the

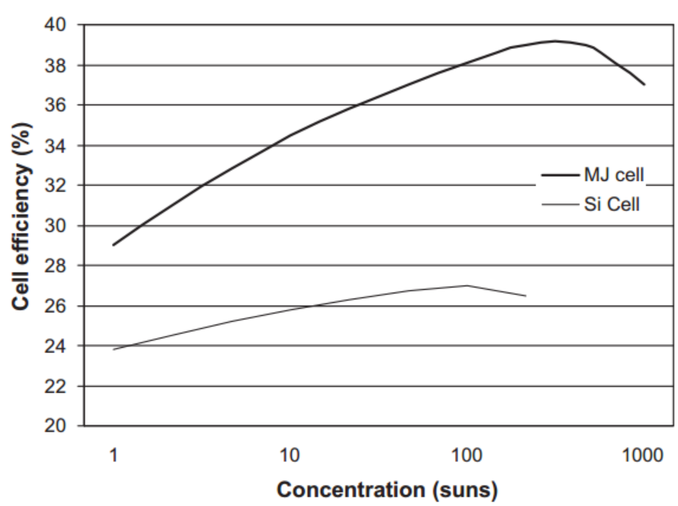

Fig. 13. Solar cell efficiency evolution of a typical silicon cell (Si cell) compared to a multi-junction cell (MJ cell) in dependence of the concentration factor [13]

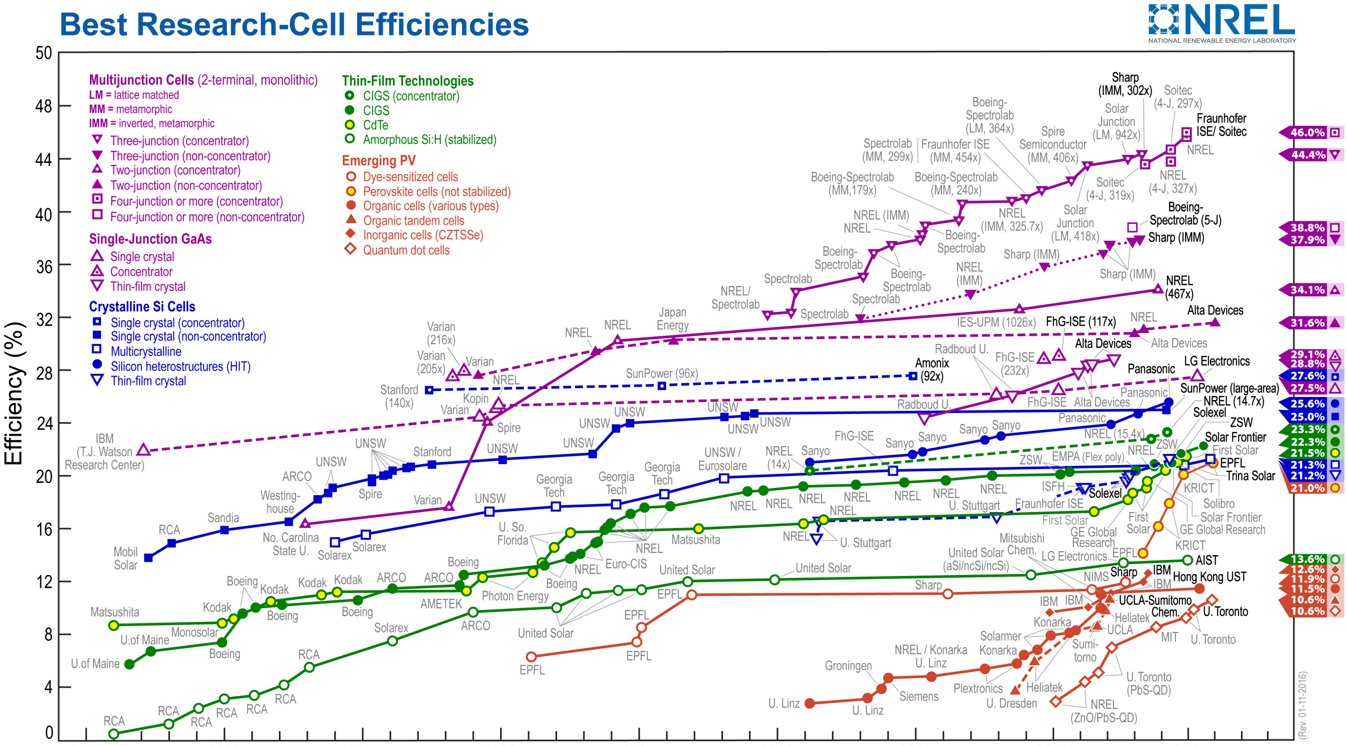

Fig. 14. Best Research-Cell Efficiencies recorded by the NREL [15]

Ural Mountains of Russia and named after mineralogist Lev Perovski perovskite is a highly promising material to be used for thin film cells.

The band gap is defined by the element which is used for the anodes and cathodes. This way it is not tuned to one specific wavelength. Perovskite can be used as an additional layer in other thin film cells or stand-alone. A stand-alone cell could be designed out of several perovskite single cells with differing combination of elements to absorb a wide spectrum of light [16].

Started at 2.2% in 2006 perovskite-based solar cells could reach an efficiency of 20.1% by 2014 with a promising potential for future development. Additional properties like flexibility, low weight and semi-transparency make a wider application spectrum possible compared with conventional solar cells [17].

However, perovskite solar cells are not stable yet. Their short lifespan and moisture sensitivity are problems to solve before commercial products can be released. Also a substitute for the toxic lead is being searched [16].

VII. Conclusion

In this paper, several methods where presented to enhance the efficiency of solar cells. Also new materials like perovskite have the potential to lift solar cells on a new level.

The National Renewable Energy Laboratory (NREL) is recording the best research-cell efficiencies for every type of cell [15]. According to their chart for 2015 (fig. 14) the highest recorded efficiency of 46% was reached by Fraunhofer ISE and Soitec with a four-junction concentrator cell with no intensity information provided. The highest reached efficiency in Crystalline Si Cells is 27.6% with a single crystal concentrator cell at an intensity of 92. CIGS cells are reaching the highest performance in the category of thin-film technologies at 23.3%. Among the emerging solar cells perovskite is reaching the highest performance with 21.0%, though not stabilized yet.

As shown in fig. 14 the most promising solar cells are cells using multiple of the presented methods for efficiency improvement. Multi-junction concentrators cells offer the possibility to use a wider spectrum of light and at the same time keep the cell area as small as possible which leads to lower costs in future commercial products.

Another possibility is offered by emerging solar cell materials like perovskite. With its low weight, flexibility, and potential in higher performance at a decent costs it prepare the ground for new solar-based products reaching from wearable solar cells integrated in gadgets like smartphones, tablets to autonomous systems and all kinds of vehicles.

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