

Solar Cells: In Research and Applications—A Review

Shruti Sharma¹, Kamlesh Kumar Jain¹, Ashutosh Sharma^{2*}

¹CMD College, Bilaspur, India

²Materials Science and Engineering, University of Seoul, Seoul, South Korea

Email: ^{*}stannum.ashu@gmail.com

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Abstract

The light from the Sun is a non-vanishing renewable source of energy which is free from environmental pollution and noise. It can easily compensate the energy drawn from the non-renewable sources of energy such as fossil fuels and petroleum deposits inside the earth. The fabrication of solar cells has passed through a large number of improvement steps from one generation to another. Silicon based solar cells were the first generation solar cells grown on Si wafers, mainly single crystals. Further development to thin films, dye sensitized solar cells and organic solar cells enhanced the cell efficiency. The development is basically hindered by the cost and efficiency. In order to choose the right solar cell for a specific geographic location, we are required to understand fundamental mechanisms and functions of several solar technologies that are widely studied. In this article, we have reviewed a progressive development in the solar cell research from one generation to other, and discussed about their future trends and aspects. The article also tries to emphasize the various practices and methods to promote the benefits of solar energy.

Keywords

Solar Energy, Fossils, Power, Pollution, Renewable

1. Introduction

Everyday sun sends out tremendous amount of energy in the form of heat and radiations called solar energy. Solar energy is a limitless source of energy which is available at no cost [1] [2]. The major benefit of solar energy over other conventional power generators is that the sunlight can be directly harvested into solar energy with the use of small and tiny photovoltaic (PV) solar cells [3] [4]. The Sun is assumed as a big spherical ga-

*Corresponding author.

seous cloud made up of hydrogen and helium atoms. This big spherical gaseous cloud is mainly composed of several hydrogen nuclei combining to form helium energy with the emission of energy from the fusion of the hydrogen nuclei in inner core of the Sun via nuclear fusion (**Figure 1**) [5].



During this process of fusion, four hydrogen atoms combine to form one helium atom with a loss of mass which is radiated as thermal energy [1] [4]-[5]. This radiant energy produced by fusion reactions is free from any pollutant, gases, or other reaction by-product. This is why it is the major driving force of all the clean energy technology, in view of the climatic disturbance caused by the emission of carbon from the fossil fuels deposits. One of the biggest advantages of solar energy is that it is free reachable to common people and available in abundant supply compared to that of the price of various fossil fuels and oils in the past decade [1]-[7]. Moreover, solar energy requires considerably lower manpower expenses over conventional energy production technology.

Though the solar energy is freely available everywhere, there is still an initial expenditure on the equipments for harvesting this radiant energy by developing solar cells, panels and modules [8]. These small and tiny solar cells produce no noise during their operation. On the other hand, the big power pumping devices produce unbearable sound pollution, and therefore they are very disturbing to the society [6]-[8]. Nowadays, due to the decreasing amount of renewable energy resources, the per watt cost of solar energy device has become more important in the last decade, and is definitely set to become economical in the coming years and grow as better technology in terms of both cost and applications [9] [10].

In spite of numerous advantages, this energy has few limitations too. Firstly, solar energy doesn't radiate at night. Secondly, the solar energy is almost not constant all the time. There must be plenty of sunlight available to generate electrical energy from a solar PV device [7] [10] [11]. Moreover, apart from daily fluctuations in the intensity of radiant energy, the solar energy is hindered to reach the earth during bad climatic conditions. For example, the amount of sunlight reaching the earth's surface depends on location, time as well as weather as it falls during winter season as compared to the summer, and the Sun's radiation is less intense [10] [11]. To overcome these demerits of this technology, solar energy must be stored elsewhere at night and the highly efficient solar cells and modules needs to be developed.

There have been an enormous amount of research activities to harvest the Sun's energy effectively by developing solar cells/panels with high conversion efficiencies. The photovoltaic conversion efficiency is referred to the efficiency of solar PV modules, and is defined as the fraction of Sun's energy that can be converted into electricity. Solar panels are a huge collection of tiny solar cells arranged in a definite geometrical shape to produce a given amount of power supply. The storage of solar power is still has not been achieved successfully. Currently the radiation efficiency of solar panel is up to 22% [11]. There are many solar photovoltaic batteries available which are usually more expensive and bulky. These are more suitable for small scale or household solar needs compared to large solar plants [12] [13].

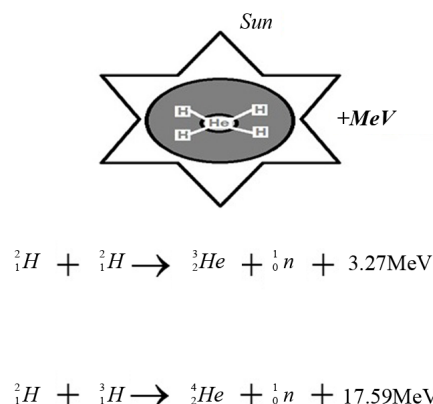


Figure 1. Nuclear fusion reaction: source of solar energy [5].

The working mechanism of solar cells is based on the three factors: (1) Adsorption of light in order to generate the charge carriers, holes (p-type) and electrons (n-type) (2) Separation of charge carriers, and (2) the collection of charge carriers at the respective electrodes establishing the potential difference across the p-n junction. The generation of voltage difference noticed at the p-n junction of the cell in response to visible radiation is utilized to do the work.

In the past, various kinds of semiconductor materials and technologies are devised to design solar cells with low cost as well as high conversion efficiency. Traditional solar panels made from silicon crystalline wafer modules are heavier which makes the transportation difficult. These are generally the large sized solar panels covered with glass sheets. A heavier and bulky solar panel requires a lot of space and sometime big roofs to fit these bulky and large solar panels in case of high power applications [11]-[13]. Therefore, in this article keeping in mind the efficient use of solar energy by solar cells research and development, we will study the different types of solar cells.

2. Solar Cells

The photovoltaic (PV) effect was first observed by Alexandre-Edmond Becquerel in 1839 [14]. Subsequently, in 1946 the first modern solar cell made of silicon was invented by Russel Ohl [14] [15]. Earlier photovoltaic solar cells are thin silicon wafers that transform sunlight energy into electrical power. The modern photovoltaic technology is based on the principle of electron hole creation in each cell composed of two different layers (p-type and n-type materials) of a semiconductor material, as shown in **Figure 2**. In this arrangement of the structure, when a photon of sufficient energy impinges on the p-type and n-type junction, an electron is ejected by gaining energy from the striking photon and moves from one layer to another. This creates an electron and a hole in the process and by this process electrical power is generated [16]. The various types of materials applied for photovoltaic solar cells includes mainly in the form of silicon (single crystal, multi-crystalline, amorphous silicon) [3]-[6], cadmium-telluride [3] [4], copper-indium-gallium-selenide [3] [4] [8], and copper-indium-gallium-sulfide [10] [16]. On the basis of these materials, the photovoltaic solar cells are categorized into various classes as discussed in the following sections (also shown in **Figure 3**).

2.1. First Generation Solar Cell—Wafer Based

As it is already mentioned, the first generation solar cells are produced on silicon wafers. It is the oldest and the most popular technology due to high power efficiencies. The silicon wafer based technology is further categorized into two subgroups named as [2]-[4] [10] [16].

- Single/ Mono-crystalline silicon solar cell.
- Poly/Multi-crystalline silicon solar cell.

2.1.1. Single/Mono-Crystalline Silicon Solar Cell

Mono crystalline solar cell, as the name indicates, is manufactured from single crystals of silicon by a process called Czochralski process [16]-[18]. During the manufacturing process, Si crystals are sliced from the big sized ingots. These large single crystal productions require precise processing as the process of “recrystallizing” the cell is more expensive and multi process. The efficiency of mono-crystalline single-crystalline silicon solar cells lies between 17% - 18% [8].

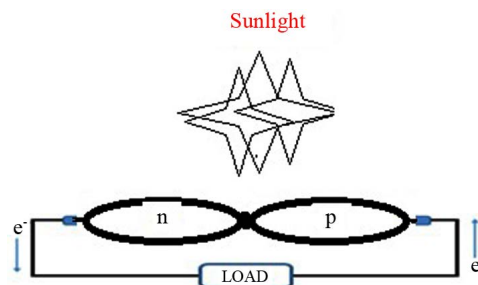


Figure 2. The semiconductor p-n junction solar cell under load.

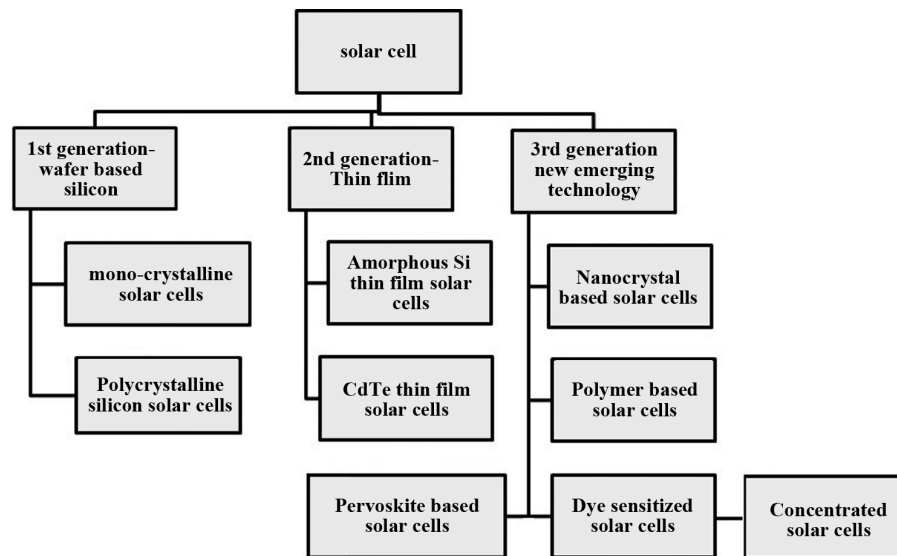


Figure 3. Various types of solar cell technologies and current trends of development [2] [16].

2.1.2. Polycrystalline Silicon Solar Cell (Poly-Si or Mc-Si)

Polycrystalline PV modules are generally composed of a number of different crystals, coupled to one another in a single cell. The processing of polycrystalline Si solar cells is more economical, which are produced by cooling a graphite mold filled containing molten silicon. Polycrystalline Si solar cells are currently the most popular solar cells. They are believed to occupy most up to 48% of the solar cell production worldwide during 2008 [19]. During solidification of the molten silicon, various crystal structures are formed. Though they are slightly cheaper to fabricate compared to monocrystalline silicon solar panels, yet are less efficient ~12% - 14% [20].

2.2. Second Generation Solar Cells—Thin Film Solar Cells

Most of the thin film solar cells and a-Si are second generation solar cells, and are more economical as compared to the first generation silicon wafer solar cells. Silicon-wafer cells have light absorbing layers up to 350 μm thick, while thin-film solar cells have a very thin light absorbing layers, generally of the order of 1 μm thickness [21]. Thin film solar cells are classified as;

- a-Si.
- CdTe.
- CIGS (copper indium gallium di-selenide).

2.2.1 Amorphous Silicon Thin Film (a-Si) Solar Cell

Amorphous Si (a-Si) PV modules are the primitive solar cells that are first to be manufactured industrially. Amorphous (a-Si) solar cells can be manufactured at a low processing temperature, thereby permitting the use of various low cost, polymer and other flexible substrates. These substrates require a smaller amount of energy for processing [22]. Therefore, a-Si amorphous solar cell is comparatively cheaper and widely available. The “amorphous” word with respect to solar cell means that the comprising silicon material of the cell lacks a definite arrangement of atoms in the lattice, non-crystalline structure, or not highly structured. These are fabricated by coating the doped silicon material to the backside of the substrate/glass plate. These solar cells generally are dark brown in color on the reflecting side while silverish on the conducting side [23].

The main issue of a-Si solar cell is the poor and almost unstable efficiency. The cell efficiency automatically falls at PV module level. Currently, the efficiencies of commercial PV modules vary in the range of 4% - 8%. They can be easily operated at elevated temperatures, and are suitable for the changing climatic conditions where sun shines for few hours [24].

2.2.2 Cadmium Telluride (CdTe) Thin Film Solar Cell

Among thin-film solar cells, cadmium telluride (CdTe) is one of the leading candidate for the development of

cheaper, economically viable photovoltaic (PV) devices, and it is also the first PV technology at a low cost [8] [25] [26]. CdTe has a band gap of ~ 1.5 eV as well as high optical absorption coefficient and chemical stability. These properties make CdTe most attractive material for designing of thin-film solar cells.

CdTe is an excellent direct band gap crystalline compound semiconductor which makes the absorption of light easier and improves the efficiency. It is generally constructed by sandwiching between cadmium sulfide layers to form a p-n junction diode. The manufacturing process involves three steps: Firstly, the CdTe based solar cells are synthesized from polycrystalline materials and glass is chosen a substrate. Second process involves deposition, *i.e.*, the multiple layers of CdTe solar cells are coated on to substrate using different economical methods. It is already mentioned that CdTe has a direct optimum band gap (~ 1.45 eV) with high absorption coefficient over $5 \times 10^{15}/\text{cm}$ [27]. Therefore, its efficiency usually operates in the range 9% - 11% [8] [28]. CdTe solar cells can be made on polymer substrates and flexible. However, there are various environmental issues with cadmium component of solar cell. Cadmium is regarded as a heavy metal and potential toxic agent that can accumulate in human bodies, animals and plants. The disposal of the toxic Cd based materials as well as their recycling can be highly expensive and damaging too to our environment and society [10] [24]. Therefore, a limited supply of cadmium and environmental hazard associated with its use are the main issues with this CdTe technology [26]-[29].

2.2.3 Copper Indium Gallium Di-Selenide (CIGS) Solar Cells

CIGS is a quaternary compound semiconductor comprising of the four elements, namely: Copper, Indium, Gallium and Selenium [10] [30]. CIGS are also direct band gap type semiconductors. Compared to the CdTe thin film solar cell, CIGS hold a higher efficiency $\sim 10\%$ - 12% . Due to their significantly high efficiency and economy, CIGS based solar cell technology forms one of the most likely thin film technologies. The processing of CIGS are done by the following techniques: sputtering, evaporation, electrochemical coating technique, printing and electron beam deposition [16] [31]. In addition, the sputtering can be a two or multi-step process involving with deposition and subsequent interaction with selenium later, or can be a one-step reactive process. However, evaporation is similar to the sputtering in the sense that it can be used in a single step, two-step or multiple processing steps. The substrates for CIGS material can be chosen from glass plate, polymers substrates, steel, aluminum etc. The advantages of CIGS thin film solar cells include its prolonged life without a considerable degradation. These properties of CIGS indicate an easy solution to enhance the efficiency [8] [22] [28]. **Table 1** shows a comparison of popular wafer based solar cell and thin film solar cell [16] [17].

2.3. Third Generation Solar Cells

Third generation cells are the new promising technologies but are not commercially investigated in detail. Most of the developed 3rd generation solar cell types are [2]:

- 1) Nano crystal based solar cells.
- 2) Polymer based solar cells.
- 3) Dye sensitized solar cells.
- 4) Concentrated solar cells.

2.3.1. Nano Crystal Based Solar Cells

Nanocrystal based solar cells are generally also known as Quantum dots (QD) solar cells. These solar cells are composed of a semiconductor, generally from transition metal groups which are in the size of nanocrystal range made of semiconducting materials. QD is just a name of the crystal size ranging typically within a few nanometers in size, for example, materials like porous Si or porous TiO_2 , which are frequently used in QD [32]. The structure of the QD solar cells are shown in **Figure 4** [10]. With the advance of nanotechnology, these nanocrystals of semiconducting material are targeted to replace the semiconducting material in bulk state such as Si, CdTe or CIGS. This idea of the QD based solar cell with a theoretical formulation were employed for the design of a p-i-n solar cell over the self-organized in As/GaAs system [32]. Generally, the nanocrystals are mixed into a bath and coated onto the Si substrate. These crystals rotate very fast and flow away due to the centrifugal force. In conventional compound semiconductor solar cells, generally a photon will excite an electron there by creating one electron-hole pair [33]. However, when a photon strikes a QD made of the similar semiconductor material, numerous electron-hole pairs can be formed, usually 2 or 3, also 7 has been observed in few cases [2] [29].

Table 1. A comparison of various types of solar cells [16] [17].

Cell type	Crystalline silicon		Thin Film		Third Generation			Perovskites	
	Monocrystalline	Polycrystalline	CdTe	CIGS	Amorphous Silicon	Nanocrystal	Dye Sensitized	Polymer	Concentrated
Efficiency	14% - 17.5%	12% - 14%	9% - 11%	10% - 12%	4% - 8%	7% - 8%	≈10%	≈3% - 10%	≈40%
High temperature performance	Not good at high temperatures	Not good at high temperatures	Good in cool as well as high temperature conditions	Good in cool as well as high temperature conditions	Good in cool as well as high temperature conditions	Excellent thermal stability	Not good in high temperature conditions	Not good in high temperature conditions	Excellent thermal stability
Size	Significantly less volume to produce the same amount of power	Significantly less volume to produce the same amount of power	Offering a wide range of product design from flexible, light durable	Offering a wide range of product design from flexible, light durable	Offering a wide range of product design from flexible, light durable	Offering a wide range of product design from flexible, light durable	Offering a wide range of product design from flexible, light durable	Offering a wide range of product design from flexible, light durable	Offering a wide range of product design from flexible, light durable
Cost	Two times more expensive compared to thin-film.	Two times more expensive compared to thin-film.	50 percent less expensive than conventional silicon cells	50 percent less expensive than conventional silicon cells	50 percent less expensive than conventional silicon cells	50 percent less expensive than conventional silicon cells	50 percent less expensive than conventional silicon cells	50 percent less expensive than conventional silicon cells	50 percent less expensive than conventional silicon cells
Additional detail	Oldest PV technology	Economical choice	Toxic due to Cd	Some CIGS have impressive 20% efficiency	Needs long installation time and large space	Needs short installation time and large space	Needs short installation time and large space	Needs short installation time and small space	Needs short installation time and minimum space

Substrate	
Electron injection	e^-
QD	
Hole	p^+
Anode (Transparent)	

Figure 4. A schematic of Quantum dot (QD) layer [32].

2.3.2. Polymer Solar Cells

Polymer solar cells (PSC) are generally flexible solar cells due to the polymer substrate. The first PSC were invented by the research group of Tang *et al.* at Kodak Research Lab. [2]. A PSC is composed of a serially connected thin functional layers coated on a polymer foil or ribbon. It works usually as a combination of donor (polymer) and a acceptor (fullerene). There are various types of materials for the absorption of sunlight, including organic material like a conjugate/conducting polyme [2] [34]. In 2000, Heeger, MacDiarmid, and Shirakawa fetched the Nobel Prize in Chemistry for the discovering a new category of polymer materials known as conducting polymers [35] [36]. The PSC and other organic solar cells operate on same principle known as the photovoltaic effect, *i.e.*, where the transformation of the energy occurs in the form of electromagnetic radiations into electrical current [37]. Yu *et al.* mixedpoly [2-methoxy-5-(2'-ethylhexyloxy)-p-phenylene vinylene] (PPV), C60 and its other derivatives to develop the first polymer solar cell and obtained a high power conversion efficiency [38]. This process triggered the development of a new age in the polymer materials for capturing the solar power. After significantly optimizing the parameters, researchers achieved efficiency over 3.0% for PPV type PSCs [38]-[40]. These unique properties of PSCs opened a new gateway for new applications in the formation of stretchable solar devices including textiles and fabrics [39]. A modern recycling concept known as polarizing organic photovoltaics (ZOPVs) was also developed for increasing the function of liquid crystal displays utilizing the same polarizer, a photovoltaic device and proper light conditions/solar panel [39]-[41].

2.3.3. Dye Sensitized Solar Cells (DSSC)

Recent research has been focused on improving solar efficiency by molecular manipulation, use of nanotechnology for harvesting light energy [42]-[45]. The first DSSC solar cell was introduced by Michel Gratzel in Swiss federal institute of technology [10] [16]. DSSCs based solar cells generally employ dye molecules between the different electrodes. The DSSC device consists of four components: semiconductor electrode (n-type TiO_2 and p-type NiO), a dye sensitizer, redox mediator, and a counter electrode (carbon or Pt) [46]. The DSSCs attractive due to the simple conventional processing methods like printing techniques, are highly flexible, transparent and low cost as well [10]. The novelty in the DSSC solar cells arise due to the photosensitization of nano grained TiO_2 coatings coupled with the visible optically active dyes, thus increasing the efficiencies greater than 10% [42]-[44] [46] [47]. However, there are certain challenges like degradation of dye molecules and hence stability issues [10]. This is due to poor optical absorption of sensitizers which results in poor conversion efficiency. The dye molecules generally degrade after exposure to ultraviolet and infrared radiations leading to a decrease in the lifetime and stability of the cells. Moreover, coating with a barrier layer may also increase the manufacturing more expensive and lower the efficiency [8].

2.3.4. Concentrated Solar Cells

Concentrating photovoltaic (CPV) has been established since the 1970s [45] [48] [49]. It is the newest technology in the solar cell research and development. The main principle of concentrated cells is to collect a large amount of solar energy onto a tiny region over the PV solar cell, as shown in **Figure 5**. The principle of this technology is based on optics, by using large mirrors and lens arrangement to focus sunlight rays onto a small region on the solar cell [8]. The converging of the sunlight radiations thus produces a large amount of heat energy. This heat energy is further driven by a heat engine controlled by a power generator with integrated. CPVs have shown their promising nature in solar world [49] [50]. It can be classified into low, medium, and high concentrated solar cells depending on the power of the lens systems [49]. Concentrating photovoltaic technology have the following merits, such as solar cell efficiencies >40%, absence of any moving parts, no thermal mass, speedy response time and can be scalable to a range of sizes.

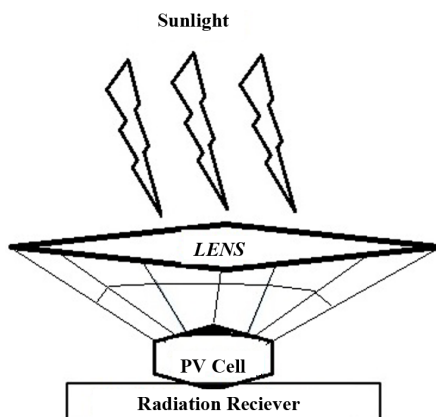


Figure 5. Schematic of concentrated solar cell [48] [49].

2.4. Perovskite Based Solar Cell

Perovskites are a class of compounds defined by the formula ABX_3 where X represents a halogen such as I^- , Br^- , Cl^- , and A and B are cations of different size. Perovskite solar cells are recent discovery among the solar cell research community and possess several advantages over conventional silicon and thin film based solar cells. Conventional Si based solar cells need expensive, multiple processing steps and require high temperatures ($>1000^\circ C$) and vacuums facilities [51] [52]. The perovskites based solar cells can have efficiency up to 31% [53]. It can be predicted that these perovskites may also play an important role in next-generation electric automobiles batteries, according to an interesting investigation recently performed by Volkswagen [52] [53]. However, current issues with perovskite solar cells are their stability and durability. The material degrades over time, and hence a drop in overall efficiency. Therefore more research is needed to bring these cells into the market place.

3. Advances in Energy Storage

Since the sunlight is not always available, all these businesses of PV solar cells may not work at night and a lot of electricity will go unused [54]. Therefore energy storage is an important factor in solar cell market. A comparison and summary of various types of solar cells is summarized in Table 1.

Several energy storage devices are available in the market but those are highly expensive and a short life span. Recently, in 2014, Harvard University researchers developed a new type of battery based on organic molecules called Quinone. It is found in plants and is economical in a sense that it can store sunlight energy for a couple of days [55].

The world's first solar cell energy storage is introduced by Wu and his co-workers at Ohio State University. This device not only can store energy but can also reduce the costs of renewable energy by 25%, relying on a new aqueous, rechargeable lithium-oxygen battery used in sunlight [56].

4. Conclusion

Solar power generation has been developed as one of the most demanding renewable sources of electricity. It has several advantages compared to other forms of energy like fossils fuels and petroleum deposits. It is an alternative which is promising and consistent to meet the high energy demand. Though the methods of utilizing solar energy are simple, yet need an efficient and durable solar material. Technology based on nano-crystal QD of semiconductors based solar cell can theoretically convert more than sixty percent of the whole solar spectrum into electric power. The polymer base solar cells are also a viable option. However, their degradation over time is a serious concern. There are various challenges for this industry, including lowering the cost of production, public awareness and best infrastructure. Solar energy is the need of the day and research on the solar cells has a promising future worldwide.

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