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Photovoltaic Cell Generation and Recent Advancements in its Development

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Abstract
Solar cells, with their ability to use solar energy, have the potential to tackle both the energy crisis and environmental damage in an energy-driven future. Photovoltaic technology is a promising option for environmental conservation and the elimination of fossil fuels, as existing energy sources contribute to pollution and the greenhouse effect. Solar technology, a renewable energy source, has helped to address environmental problems by developing efficient and improved solar cell designs. Large installation areas, expensive prices, and associated losses that result in lower operating efficiency preclude large-scale commercialization. Generations of breakthroughs in this subject have stemmed from researchers' hard work. Recent advancements in photovoltaic cells include multi-junction and intermediate energy levels in silicon's forbidden band, as well as advanced state-of-the-art solar cells such as quantum dots, perovskite, organic, dye-sensitized, nanotubes, and graphene-based photovoltaic cells. This study investigates the most recent innovations and manufacturing procedures, as well as the efficiency attained in several generations of photovoltaic cells. Although new types of solar cells have emerged, silicon cells continue to dominate the market and require further research to enhance efficiency.

Keywords: Photovoltaic Cell, Advancements, Generation, Development, Silicon Cells, Photovoltaic Technology

1. Introduction

Fossil fuels are the world's primary energy source, yet their scarcity and damaging carbon dioxide emissions contribute to global warming, the greenhouse effect, climate change, and ozone depletion (Zeng Y et al., 2022). With rising population and economic expansion, there is a greater need for alternate energy sources. Solar energy is the ideal option because of its general accessibility, universality, and eco-friendliness, making it a more sustainable and environmentally beneficial alternative to conventional energy generation (Melskens J., et al., 2018 ; Chowdhury S et al., 2019; Wang Y. et al., 2023) .French physicist Edmond Becquerel made the discovery of the photovoltaic phenomenon, which generates an electric current when exposed to light, in 1839. photovoltaic is turning photon energy into electricity so used the term photoelectric. By applying a gold coating to selenium in 1884, Charles Fritts created the first solar cell, which produced a steady, continuous current with an energy conversion rate of 1% to 2%, using the photoelectric effect, Russian scientist Alexander Stoletov created the first solar cell that same year (Ballif et al., 2022). In the 1950s, Bell Laboratories found that silicon was more efficient than selenium, which helped them create a solar cell with an efficiency of 6%.Chapin, Fuller, and Pearson created the silicon solar cell at Bell Labs, which was the first useful device for harnessing solar thermal and photovoltaic power to transform solar energy into electricity (Zeng Y et al., 2022). In 1960, GaAS solar cells with efficiency around 14% were used in space applications. In the 1970s, the United States experienced an energy crisis, which prompted the development of solar cells as a feasible and economical energy source. American rooftop solar panels that incorporate modern technologies such as building-applied photovoltaic (BAPV) solar cells give environmental benefits while being neither subtle nor physically appealing (Liu et al., 2020; Wang Y et al., 2023).

The Shockley-Queisser (SQ) limit of 29.43% sets an upper efficiency limit for silicon, taking into account the balance of photogeneration and radiative recombination (Shockley W. et al., 2018). Silicon solar panels have a efficiency of 22% to 25%, but they can only convert about one-fifth of the sun's energy into electricity due to limited wavelength absorbance, optical, quantum, recombination losses and electrical losses, and inability to absorb photons below and above the band gap energy (Wang Y. et al., 2023 ; Masmitja G. et al., 2018).The band gap, or the minimum energy required for photons to participate in photovoltaic conversion, is strongly related to cell efficiency and is heavily influenced by the material employed in the cell (Messmer C. et al., 2018).The cells are predicted to have a direct band structure, be conveniently accessible, non-toxic, and high in photovoltaic efficiency(Rehman F. et al., 2023). Silicon, which has a band gap of 1.12 eV, can be modified to alter its physical properties, specifically the band gap width (Sharma S. et al., 2015). Improved silicon solar cell power generation efficiency requires an intermediate band in the forbidden band gap, which allows photon absorption below the energy gap, resulting in improved quantum efficiency. This can be accomplished using high-concentration doping and high-dose metal ion implantation (Yu C. et al., 2018 ; Wilson G.M.; et al., 2020).

Short-circuit current, open-circuit voltage, and fill factor, which are influenced by material properties and manufacturing techniques, all contribute to solar cell efficiency. The efficiency and cost-effectiveness of constructing a photovoltaic cell are largely determined by the material used. Cell efficiency data is supplied for a variety of semiconductor families, including multi-junction, gallium arsenide, crystalline silicon, thin film technologies, and upcoming photovoltaic technologies, which are classified as first, second, third, and next generation (Pastuszak J. et al., 2022). Third-generation solar cell designs seek to improve performance by addressing loss processes and using the complete spectrum through novel mechanisms for forming new electron-hole pairs (Yoshikawa K, et al., 2017). Although new types of solar cells have emerged, silicon cells continue to dominate the market and require further research to enhance efficiency (Plakhotnyuk MM et al., 2017 ; Patwardhan S. et al., 2018). Hterojunction intrinsic thin layer(HIT/SHJ), passivated emitter and rare contact(PERC), interdigitated back contact (IBC), tunnel oxide poly- crystalline(TOPCon), Poly-Si ions oxide (POLO), and heterojunction back contact(HBC) are solar cell structure innovations that reduce energy losses, increase efficiency, and have practical applications (Liu et al., 2020; Wang Y et al., 2023). HIT solar cell architecture when doped a-Si:H selective contact replaced by transition metal oxides and i-a-Si:H thin layer by SiO_2 then achieve efficiency around 25% and have more potential up to 28.4 % by HBC structure technology (Cao Y.et al., 2018; Mehmood H. et al., 2020; Masmitja G. et al., 2022). The paper addresses contemporary advances, manufacturing techniques, and efficiency in photovoltaic cell generations, focusing on the emergence of new types of solar cells.

2. Solar Cell Types:

There are three generations of solar cells: wafer technology, thin-film technology, and emerging technology/next generation, which are also known as the first, second, and third generations as shown in figure-1.

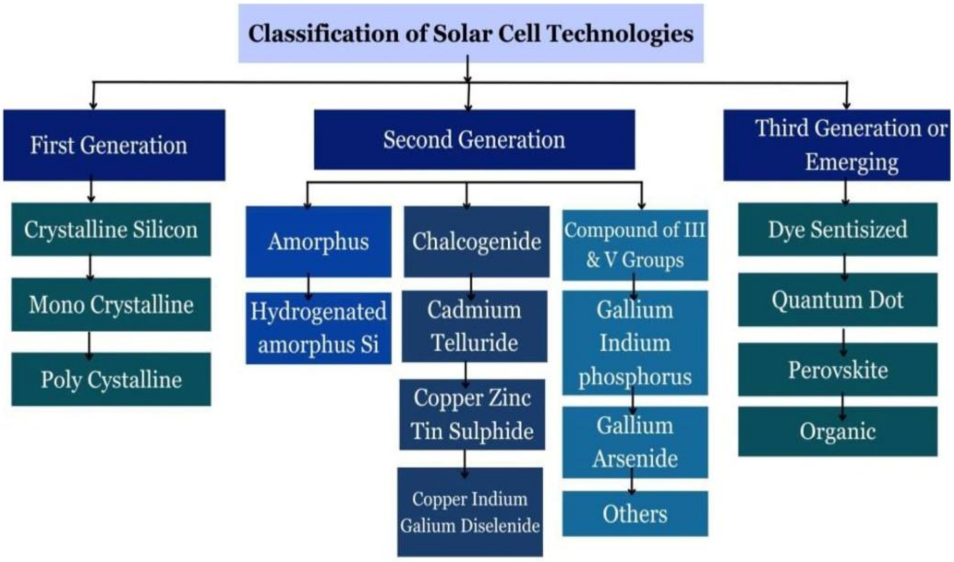

Figure:1- Classification of solar cells technology.

First-generation solar cells built of mono- and poly-crystalline silicon have attained great efficiency, but they are expensive to manufacture, restricting their widespread use.Amorphous silicon, copper indium gallium arsenide, and cadmium telluride are used in second-generation solar cells, commonly known as thin-film solar cells, due to their wide band gap for photon absorption. However, these cells have disadvantages like as toxicity, instability, and limited efficiency, rendering them unsuitable for large-scale applications (Richter A. et al., 2021; Rehman F. et al., 2023). Third-generation solar cells emerged in a variety of designs, including dye-sensitized solar cells (DSSCs), quantum dot solar cells (QDSCs), organic solar cells (OSCs), and perovskite solar cells (PSCs). A DSSC, a device that functions in low light, contains an organic electrolyte that is volatile and can evaporate if not properly packed (Singh, B.P. et al., 2021).

PSCs are inexpensive, simple construction processes with high power conversion efficiency (PCE), however they are prone to environmental degradation due to their sensitivity to heat and humidity. OSCs are environmentally clean, lightweight, and cost-effective electrical sources; but, they lack stability and have a limited lifespan. OSCs are environmentally clean, lightweight, and cost-effective electrical sources; but, they lack stability and have a limited lifespan (Battaglia C. et al., 2016 ; Wilson G.M. et al., 2020).The effort to develop more efficient and stable solar cells resulted in the creation of fourth-generation solar cells. Fourth-generation solar cells, also known as hybrid solar cells, combine previous-generation advantages such as affordability, flexibility, and high nanomaterial stability by combining both inorganic and organic components. These materials are often made up of metal oxides, metal nanoparticles, carbon nanotubes, graphene, and its derivatives (Mahmoudi T. et al., 2022 ; Rehman F. et al., 2023).

2.1 Wafer Technology (First Generation)

The initial generation of photovoltaic (PV) technology employed c-Si for solar cell production. In this generation, silicon wafers are the oldest and most widely used technology, accounting for around 95% of global solar power production. Polycrystalline solar cells, which are made up of both single and multiple crystals, are subgroups of c-Si solar cells(Singh, B.P.; et al., 2021). The Czochralski technique produces mono or single-crystalline solar cells with efficiencies ranging from 17% to 24%. Polycrystalline solar cells, which combine many crystals in a single cell, are the most common but less effective than single-c-Si cells. They are commonly utilized in commercial modules and account for the majority of the PV market. Single c-Si solar cells have efficiencies ranging from 17 to 24 percent, whereas multi-c-Si cells have efficiencies ranging from 12.1 to 14% (Pastuszak J. et al., 2022).

2.2 Thin-Film Technology

Thin film solar cells, made of a-Si, CdTe, and C.I.G.S., are less expensive and 100 times thinner than silicon wafer cells. They degrade in the environment and achieve 5-7% efficiency (Perez E et al., 2015). Despite the high cost of c-Si, they can be manufactured in large sizes and placed on curved surfaces. Thin layer solar cells are as follows:

2.2.1 Amorphous Silicon (a-Si) Thin Layer Solar Cells

a-Si thin layer solar cells, fabricated by doping silicon material on a substrate or glass plate, are inexpensive and widely available due to their non-crystalline structure and lack of fixed atom arrangements. However, their efficiency is poor and unstable, falling short of that of commercial PV modules. Amorphous silicon solar cells, with a doped silicon material on the back side, are ideal for varying climatic conditions and can operate at high temperatures, enhancing light absorption (Almosni S., et al., 2018).

2.2.2 Cadmium-Telluride Solar Cells

CdTe is an inexpensive photovoltaic material with a 1.5 electron volt band gap and high light absorption, making it ideal for thin-film solar cells. Its straight band gap semiconductor properties make it ideal for thin-film solar cells (Wu X. et al., 2004; Pastuszak J. et al., 2022). CdS layers are sandwiched to form PN junction diodes in CdTe solar cells, which are flexible and can be mounted on polymer substrate. Cadmium telluride, a dangerous heavy metal, is a thin-layer PV technology that has a 22.1% efficiency. CdTe has the same band gap as GaAs, resulting in high light absorption and little photon energy losses. However, their long-term viability is unknown due to cadmium's severe toxicity and tellurium's scarcity (Wu X. et al., 2004; Fthenakis V. et al., 2020).

2.2.3 Copper-Indium- Gallium- Di-selenide (C.I.G.S.)

C.I.G.S. has a narrow band gap that ranges from 1 to 1.7 electron volts and is composed of copper (Cu), indium (In), gallium (Ga), and selenium(Se). It is deposited through thermal evaporation, an electron evaporator, or sputtering With a five-layer structure with substrates like glass plates, polymers, steel, and aluminium and a higher efficiency of 10% to 12%, CIGS is a popular thin film technology for solar cells .It has same performance like CdTe have a with a efficiency peak of 23.4% (Stamford, L. et al., 2019 ; Salhi, B. et al., 2022; Rehman F. et al., 2023).

2.2.4 Ga-As Thin Film Solar Cells

GaAs has excellent electron transport capabilities and thinner absorption layers, thanks to its 1.43 eV straight band gap. Its efficiency are equivalent to visible light compound semiconductors, but production is costly (Hayat M.B et al., 2020). GaAs has the highest performance of any photovoltaic material, reaching 29.1%, although it is costly for space applications. Other materials, such as a-Si, cadmium telluride, CIGS, and GaAs thin film, have varying efficiency levels (Ballif C. et al., 2022).

2.3 Emerging Technology/Next Generation (Third Generation)

The most effective aspects of first- and second-generation cells are combined in emerging technologies, however first-generation cells exhibit greater efficiency than second-generation cells.

Emerging technology solar cells include quantum dot (QD), polymer & organic, dye-sensitized, perovskites, kesterite, and tandem solar cells. These cells are introduced to boost power conversion efficiency (PCE) and reduce manufacturing cost as follows:

2.3.1 Dye Sensitized (D.S.S.C.) Solar Cell

The D.S.S.C. is a low-cost, flexible solar cell technology that works similarly to photosynthesis. It consists of five parts: a conductive support system, a semiconductor sheet, a dye, an electrolyte, and a counter electrode. Fine-tuning components can lead to higher efficiency (Sancun Hao. et al., 2006 ; Saga T. et al., 2010). DSSCs are developed with optoelectronic features such as absorbance coefficient, band alignment, dye morphology, and assembly mode on the TiO2 photoanode in mind, and laboratory experiments have yielded conversion efficiencies of more than 11% and 15%. However, obstacles such as dye degradation and stability issues continue (Goetzberger A.et al., 2003; Wilson G.M., et al., 2020).

2.3.2 Kesterite Solar Cells

Kesterite solar cells, manufactured from copper(Cu)-zinc(Zn)-tin(Sn)-sulphide (S) [CZTS] and copper(Cu)-zinc(Zn)-tin(Sn)-selenide (Se) [CZTSe], have optical and electrical properties similar to CdTe and CIGS, but without the hazardous metals Cd and In. They have an efficiency of roughly 8% with CZTS cells and about 10% with CZTSe cells, but they have drawbacks such as dominant interface recombination and a shorter minority carrier lifespan(Almosni S., et al., 2018; Wang, W. et al., 2018).

2.3.3 Polymer/ Organic Solar Cells

Polymer solar cells are flexible solar cells that consist of thin layers deposited on a polymer sheet. They combine a polymer and a fullerene and can be manufactured from a variety of materials to absorb sunlight. Organic solar cells, or thin film cells made with organic semiconductors, have advantages such as affordability, flexibility, and light weight, however they are inefficient. Organic solar cells fall under the excitonic solar cell category. When sunlight strikes a cell, it generates electron-hole pairs through absorbent materials such as poly (3-hexylthiophene) (P3HT), phthalocyanine, and 6,6]-phenyl-C61-butyric acid methyl ester (PCBM) (Perez E et al., 2015). When a photon is absorbed by an organic semiconductor, it excites one electron in the valence band and forms a hole in the conduction band. These holes and electrons are still linked due to columbic forces.If the junction is made up of two different organic materials, efficient charge separation of excitons and free carrier generation may occur. The bulk hetero-junction expands the donor-acceptor interface area, allowing each to be thinner near the junction. The donor-acceptor interface has a bi-continuous phase separated network that separates excitons produced by photon absorption in the donor material. To attain an efficiency of approximately 5%, commercial organic solar cells use a combination of P3HT (donor) and PCBM (acceptor). Metals such as Al, Ag, and Au are also utilized as back electrodes (Green M.A. et al., 2016; Fthenakis V et al., 2020).

2.3.4 Perovskite Solar Cells

The light-absorbing layer of perovskite solar cells is composed of organometallic halides with the same crystal structure as CaSiO3, namely ABX3 (A-organic/inorganic cation, B-metal cation, & X-halide).

Peak efficiency has increased to 25.5%, with exceptional properties such as bipolar charge transfer and robust tuneable absorption characteristics. Perovskites, a type of chemical with the formula ABX3, are expected to be useful for electric vehicle batteries due to their up to 31% efficiency. CaSiO3 or MgSiO3 is plentiful, has low recombination losses, low material costs, and a longer charge carrier diffusion length (Sharma P. et al., 2020).CH3NH3PbI3 is used to make high-efficiency perovskite solar cells. However, perovskite degrades over time, with a best lifetime of 10,000 hours but poor stability, far short of the 25 years expected from marketed PV technologies. Perovskite solar cells, the most quickly emerging technology, offer the potential to improve efficiency while lowering production costs. The commercialization of perovskite cells faces obstacles such as environmental stability, mechanical fragility, and lead halide toxicity(Chowdhury S et al., 2019).

2.3.5 Quantum - Dot Solar Cells

Burnham and Duggan introduced quantum dots (QD) solar cells in 1989, which had an adjustable band gap that can be changed by adjusting the size of artificial atoms and have an efficiency of 18.1%(Wilson G.M. et al., 2020 ; Sharma P. et al., 2020). QDs are made up of semiconductors from transition metal groups, like porous Si or TiO2 (Nozik AJ. et al., 2010). Nanotechnology advancements have enabled their usage as an alternative to bulk materials such as Si, CdTe, and CIGS. Colloidal CdX is the most studied QD, with good optical and electrochemical characteristics. QDs are appropriate absorber materials for third-generation photovoltaic cells, with a maximum efficiency of 16% when using hot photo-generated carriers (Hayat M.B et al., 2020 ; Chowdhury S et al., 2019).

2.3.6 Tandem Solar Cells (or multi-junction solar cells)

Tandem solar cells are made up of numerous semiconductor-based p-n junctions connected sequentially from top to bottom. The p-n junction's variable band gap allows it to absorb different wavelengths of sunlight and generate more electric current, known as short circuit current, so boosting its efficiency. It has a high PCE of up to 36% and a reasonable price (Geoffrey S et al., 2009). The top-to-bottom p-n junction has a decreasing band gap, therefore the upper cell generates more photocurrent than the lower cell. Tandem cells have an efficiency greater than 36%, above the Schockley-Quisser limit. The use of groups III and IV, such as Ga-As and In-Ph, can improve efficiency but is expensive(Wilson G.M. et al., 2020 ; Liu Y.; et al., 2022).

High-efficiency GaAs are used in multijunction cells for space applications and solar concentrators. GaAs solar cells come in a variety of morphologies, including thin film, single crystal, polycrystalline, and tandem(Almosni S., et al., 2018; Sharma P. et al., 2020). Polycrystalline GaAs single junction solar cells have an efficiency of 28.8%, 18.4% for thin-film GaAs solar cells, and 31.6% for multijunction GaAs solar cells. D.S.S.C. have an efficiency range of 05 to 20%, Organic/Polymer solar cells have an efficiency range of 09 to 11%, Perovskite solar cells have an efficiency range of 21.0%, Quantum-dots solar cells have an efficiency range of 11 to 17%, and multi-junction solar cells have an efficiency range of 36.0%(Chowdhury S et al., 2019).

3. Heterojunction with Intrinsic Thin Layer (HIT) Architecture Technology

The silicon heterojunction SHJ/HIT structure solar cell is exhibited in Figure 2.

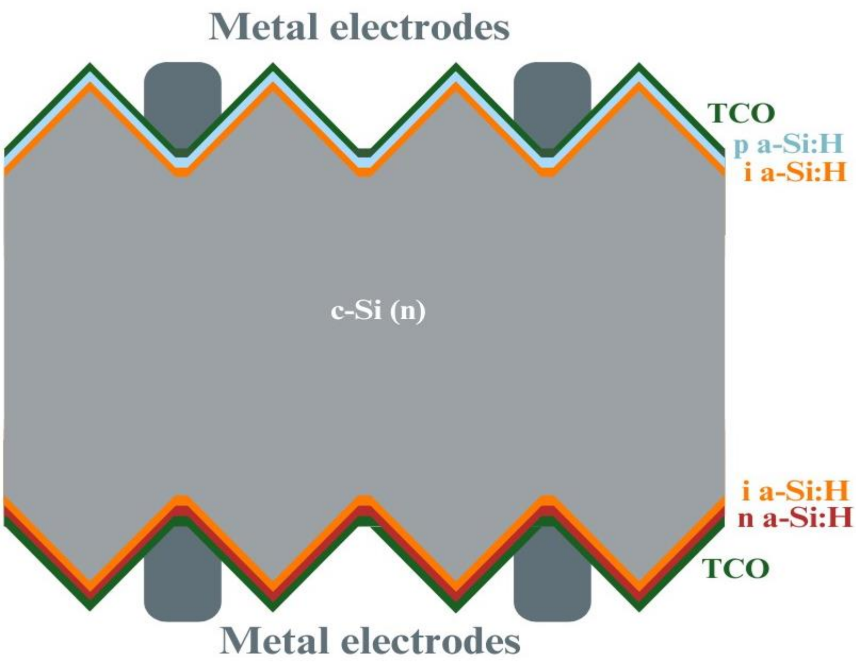

Figure: 2- HIT solar cells structure

The HIT solar cell is a hybrid design that combines c-Si cells with a thin layer of a-Si, heterojunctions, and doped a-Si contacts. It is made up of a front junction comprising a silicon p-i-n-i-n doped stack, a c-Si(n) wafer with an inherent a-Si:H layer, P- and N-type doped hydrogenated a-Si contacts, transparent conducting oxide overlayers, ITO as an ARC, and metal grids for charging and sunlight (Green M.A. et al., 2016; Allen TG. et al., 2019). HIT is 90% biologically formed, minimizes sheet resistance, and enables lateral electron movement in the absorber, resulting in increased efficiency and cost savings.HIT solar cells have an N-type C-Si substrate, a pure a-Si thin layer for surface passivation, and hydrogenated doped a-Si layers as passivated contacts. A PN junction is formed for power generation, and an ITO coating is used for light propagation and conductivity. Silver electrodes are placed on both top and bottom surfaces (Singh, B.P.; et al., 2021). N-type c-Si has more mobility and is less affected by sunshine. When sunlight strikes solar cells, photons are caught by silicon atoms, resulting in pairs of electrons and holes (Garcia-Barrientos, A. et al., 2021).

Solar cells use an electric field to separate electrons and holes, which then move to the other terminal via carrier-selective contacts. The thin a-Si layer inhibits charge carrier recombination and surface passivation, therefore preventing surface defects. The top layer of i-a-Si:H filters sunlight, while the intermediate c-Si layer converts the majority of it into energy (Cao Y.et al., 2018; Chowdhury S et al., 2019). The HIT silicon solar cell uses doped a-Si selective contacts and undoped hydrogenated a-Si layers to achieve high efficiency and carrier selectivity. KANEKA Corporation and LONGI developed broad-area HBC solar cells with efficiency of 26.81% and 27.09%, respectively (Lin H. et al., 2023 ; Michel J. Ibarra et al., 2023) . In areas with plenty of sunlight, HIT solar panels generate consistent electricity. Their low temperature coefficient and the HIT double design boost efficiency by 20-30%. Passivated contacts of hydrogenated doped a-Si are replaced (Chowdhury S et al., 2019).

3.1 Transition Metal Oxides (TMO) Selective Contacts and Carrier Selectivity

Transition metal oxides (TMOs) exhibit a variety of electrical, catalytic, structural, optical, and nontoxic properties. They have a large band gap, a variety of job functions, high transparency, low temperature deposition employing simpler techniques, and are affordable in cost(Greiner MT et al., 20112). TMOs work by partially filling 2p-orbitals of O2 and partially filling d-orbitals, altering cation oxidation states, and addressing oxygen or metal cation deficiencies. These flaws affect the oxidation state, electronegativity, carrier concentration, and Fermi levels. The energy level is affected by the presence of oxygen vacancies at the metal oxide contact (Greiner MT et al., 2013). MoO3-x, often known as MoOx, refers to Si oxygen-deficient MoO3 (Khokhar MQ. et al., 2022 ; Bullock J et al., 2019). After forming a TMO layer on Si, oxygen liberates free electrons, creating a defect in the forbidden energy band near the conduction band (CB) and occupying d-orbital states. TMOs with oxygen vacancies are classed as n-type semiconductors, whilst those with metallic vacancies are classified as p-type semiconductors (Taguchi, M. et al., 2013, Sanyal S.et al., 2019). Doping-free approaches such as molybdenum oxide are being investigated to reduce Auger recombination in carrier-selective zones in doped a-Si areas (Nayak M. et al., 2018) TMO passivated contacts reduce parasitic absorption losses due to the larger band gap in the emitter zone, recombination losses due to the absence of a highly doped layer, and serve as carrier selectivity contacts (Gao P. et al., 2017 ; Hermle M. et al., 2022) TMOs with double heterocontact achieved efficiencies of more than 23.5% (Yan D. et al., 2018), reduced parasitic light absorption while improving Jsc, and had an efficiency potential of up to 28.4% (Dréon J. et al., 2020 ; Bullock J et al., 2019). Carrier selectivity as exhibited in figure-3.

TiO2 is an electron-selective contact due to its smaller conduction band offset and larger valence band offset with silicon, while MoO3 are hole-selective contacts due to their wide conduction band offset and smaller valence band offset as exhibited in figure 5 (Wang Z. et al., 2019 ; Kumar M.et al., 2021). When the TMO's conduction band energy is higher than the Si layer's valence band energy, surplus holes undergo band-to-band tunneling (Goetzberger A.et al., 2003; Gerling LG. et al., 2017). Charge carriers flow asymmetrically within the solar cell in the direction of the contact areas due to the charge-carrier selectivity at the terminals. The open circuit voltage (Voc) significantly indicates the suppression of non-collected charge carriers towards the opposite polarity contact (Nagamatsu K.A. et al., 2015 ; Chee KW. Et al., 2022).

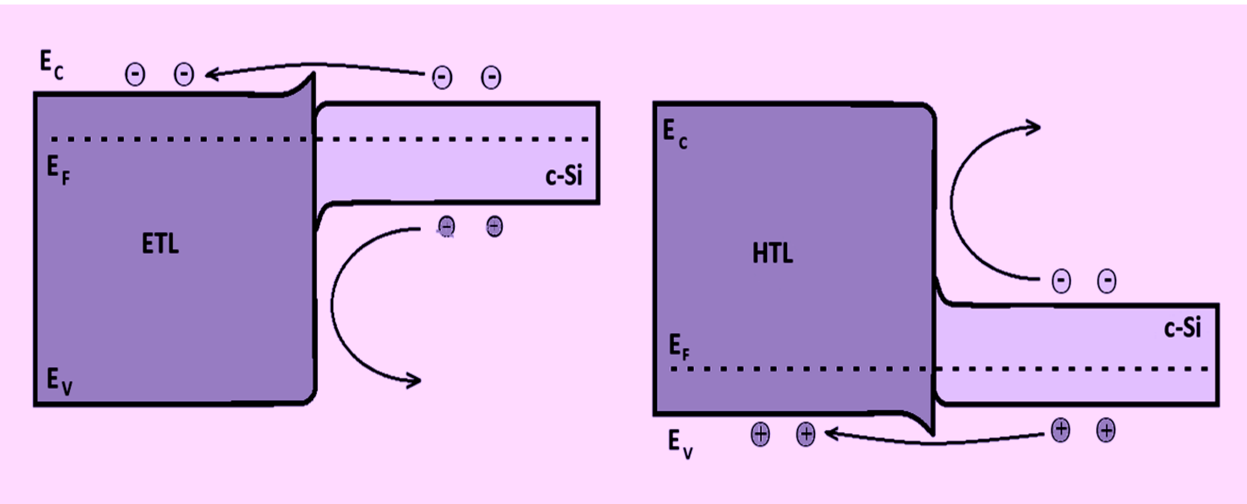

Figure: 3 TMOs hole-selective & electron-selective passivating contacts

4. Result and discussion

SHJ structure with an IBC structure called heterojunction back contact (HBC) acquired 26.7% efficiency (Kodati, R.B et al., 2020). KANEKA Corporation and LONGI produced broad-area HBC solar cells with efficiencies of 26.81% in 2022 and 27.09% in 2023, respectively (Lin H. et al., 2023; Ibarra Michel et al., 2023). The HBC structure is one of the most promising solutions for enhancing performance in c-Si-based solar cells. It possesses the advantages of both the heterojunction and IBC structures with a high quality passivation produces high open-circuit voltage (Voc) and high short-circuit current density (Jsc); the front-side electrodes do not produce a shading effect (Green M. et al., 2021 ; Battaglia C. et al., 2019). HIT-based transition metal oxides carrier selective contacts made of titanium oxide and molybdenum trioxide, making passivation a cost-effective, low-temperature, and environmentally friendly, straightforward fabrication process that suppresses recombination loss, achieves an efficiency exceeding 23.5%, and has potential above 28.4% (Lin H.et al., 2023, Schmidt et al., 2022).

We have successfully created a solar cell on a wafer of c-Si(n) by deposition of TiO2 and MoO3 as electron and hole selective contacts by pulse laser deposition (using a KrF exciter laser at 248 nm for 20 ns) of 5 nm and 7 nm, ITO coating of 70 nm, SiO2 passivation layer of 1.2 nm, and 200 nm coating of silver and aluminum on the front and back surface of wafer in UGC-DAE consortium, Indore. Thickness is measured by the profilometer attached to the PLD. The I-V characteristic curve from the Keithley four probe with a solar simulator found Jsc 41 mA/cm2, FF 77%, and Voc 0.784 and finds efficiency 24.75 %, I-V and P-V curves with data shown in figure 4. HIT solar cell have a further potential above 28.4% in HBC configuration (Zhao Y. et al., 2023; Mehmood H.et al., 2020). When transition metal oxide passivated contact-based HIT solar cell, employs HBC structure technology, efficiency can be improved up to the theoretical maximum limit while remaining cost-effective and without causing any damage to the environment (Kang D. et al., 2023; Lin H. et al., 2023).

Date: 2024/5/09
Type: H-BSS-1403
Repeat time: 3
Isc : 41.0 [mA]
Voc : 0.784 [V]
Pmax : 24.75 [mW]
Ipmax: 36.08 [mA]
Vpmax : 0.686[V]
FF: 77%
Eff: 24.75[%]
Jsc : 41.0 [mA/cm^2]
M.Temp : 25°C
Irr. : 1000/m^2
Ref. D No: JETp-C01W
Cal. Val. of Ref: 122.91[mA at 1000/m^2
Scan mode Isc to Voc

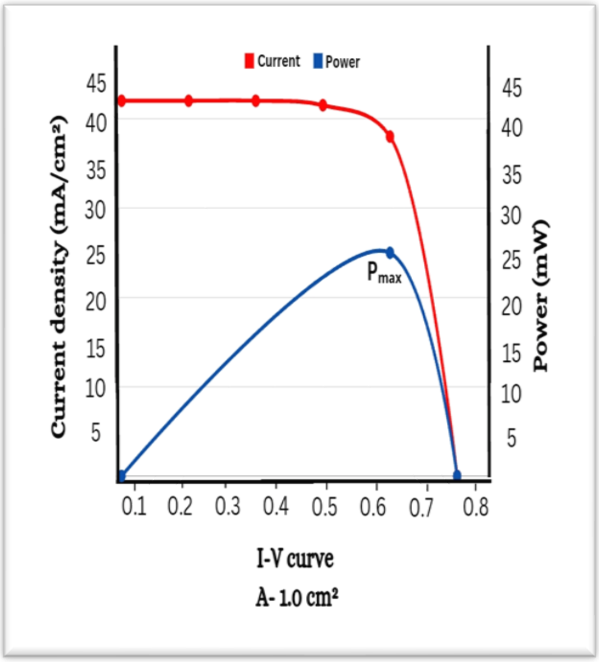

Figure: 5 I-V and P-V characteristic curve of solar cell and its data

5. Challenges and Future Aspects

When stacked on top of conventional silicon cells, perovskite cells increase efficiency by more than 50%, providing a financially viable option for converting solar power (Mozaffari S. et al., 2017). It is difficult to deposit the semiconductor onto glass plates, though. Large glass pieces currently need to be coated using a nitrogen-filled box, but this gets harder and harder. After 25 years, silicon panels can still function at 80%, with stable tandem perovskites losing 1% of their efficiency (Yuan J et al., 2020). In order to potentially dominate the industry and pave the way for next-generation solar technology, the objective is to build more durable and efficient tandem solar panels for use in applications like as electric vehicles, drones, and sailboats (Liu Y. et al., 2020; Wong T.K.S. et al., 2022) Solar modules and raw components are mostly sourced from China, and waste management difficulties remain, huge-scale solar PV parks lack innovative financing solutions, and there is limited space for huge ground-mount solar panels (Green M.A. et al., 2016 ; Sagar et al., 2020). Polymer-based solar cells are viable, however they deteriorate over time. Solar power plants are expensive to install at first, seasonal, and difficult to reinstall. The solar power plant has a low energy conversion rate of 25%, needs a big installation area, and is heavy (Taguchi, M. et al., 2000; Billewicz P., et al., 2017). Nano-crystal quantum dot solar cells have the potential to convert 60% of the sun spectrum into electricity, but further practical research is required (Vijayan R.A., et al., 2019). Future developments include floating solar farms, integrated photovoltaic and photovoltaic glasses. India must address research and development deficits through industry-specific investment, incentives, and assistance for entrepreneurs (Sharma, D. et al., 2009). Industrial-style hubs should produce raw materials such as silicon wafers, aluminum, and silver paste. Energy storage is difficult due to seasonal and latitudinal variations, and present solutions are expensive and have short lifespans (Yamaguchi, M. et al., 2005; Wu C., et al., 2020). New materials are being developed to improve solar energy harvesting, with product design and materials critical to commercialization. Future technological breakthroughs will include the creation of multi-junction solar cells built of various materials, which could lead to increased photovoltaic capabilities(Chowdhury S. et al., 2019; Liu Y. et al., 2020).

6. Conclusion

Solar power is a renewable, reliable, and ecologically benign technology utilized in a variety of applications, including road traffic signals, artificial satellites, photo-detectors, medical research, and electromagnetic radiation detection. Solar energy is a sustainable alternative to fossil fuels because the sun's lifespan is predicted to last billions of years, but fossil fuel reserves are fast depleting.

Solar cell research is moving forward with quantum dots-based, perovskite, organic, and dye-sensitized solar cells that provide high efficiency, tiny designs, flexibility, and reliability. Climate change and the instability of fossil fuels have raised the importance of photovoltaics, resulting in better performance and efficiency. First-generation solar cells have long-term stability and efficiency of 15-20%, whilst second-generation cells are less expensive and have an efficiency of 10-15%. Third-generation cells are promising because to their high efficiency, low cost, and ease of manufacturing. Nanotechnology and multifunctional nanomaterials are enabling the development of next-generation solar cells, with monocrystalline silicon cells dominating the market.

Doped hydrogenated a-Si selective contacts, which reduce recombination, enabled HIT-IBC architectural technique to attain 26.7% efficiencies. In solar cells, TMO connections replace doped a-Si selective contacts. This minimizes parasitic losses and results in efficiencies around 25% for MoO3 and

TiO_2 contacts. In c-Si solar cells, TMO double-asymmetric hetero-contact/passivated contacts have a potential of more than 28.4%, which can be enhanced further with HBC technology.

This article addresses different manufacturing technologies for increasing the efficiency of solar cells, with particular emphasis on TMO connections, material property optimization, and optimizing the TMO contact energy band with c-Si. It also covers commercial challenges, issues for the future, and recent developments in solar cell structure technology (HIT) with TMO contacts. As c-Si dominates the industry, the primary task is to raise efficiency and reduce production costs. Solar technology aims to reach 23% module efficiency at less than US$0.2/W within five years, enabling a levelized cost of power for society.

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