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Recent Advancements in Solar Cell Technology: An Overview

Abstract:-Since the Industrial Revolution, the global need for electricity has expanded in a variety of industries. The balance of demand and supply for electricity necessitated the use of both traditional and nontraditional energy sources. Traditional sources of energy, like coal, gas, and oil (fossil fuels), have finite quantities; they are depleted as a result of ongoing use and will run out in the near future. Fossil fuels emit greenhouse gases, which hurt the ecosystem. An affordable substitute for fossil fuels is solar energy, which can satisfy the world's massive energy demand. It is the most sought after and preferred renewable energy source due to its sustainability, trustworthiness, longevity, never running out, being environmentally pure, free of charge, noise-free, ubiquitous, affordable maintenance over decades, and no recurring expenses after installation. This article analyzes the evolution of solar power technology in various generations, with a focus on the use of diverse materials and architectures, power conversion efficiency, obstacles, future prospects, and current advances.

Keywords: Solar Cell Technology; Crystalline Solar Cell; Passivated Contact; Transition Metal Oxides (TMO); Carrier Selectivity; Heterojunction Intrinsic Thin Layer (HIT)

I. INTRODUCTION

Energy is a basic human need, along with food, clothing, and accommodation. Coal, oil, and gas (fossil fuels) are used to generate power around the world. Fossil fuels are continuously utilized, their reserves are decreasing, they will run out in the near future, and harm the environment by releasing green house gases[1,2]. Demand for energy cannot be met solely by traditional energy sources; it also requires nontraditional sources like biomass, wind, solar, tidal, and so on[3,4]. Solar power is popular, trustworthy, and sustainable source of power and it can meet the need for energy as a substitute for fossil fuels. The sun energy never runs out, is ecologically friendly, free of charge, noiseless, ubiquitous, requires little maintenance over decades, and has no ongoing costs once installed[5,6]. Photovoltaic and photothermal technologies both use solar energy. In photovoltaic technology, a solar cell turns solar energy directly into electrical energy, whereas in photothermal technology, light is transformed into heat by focusing reflected light on a target using mirrors, and a turbine and generator produce electricity by converting water into steam[7,8,9]. Solar cells (or photovoltaic cells) is a semiconductor devices based on photovoltaic effect that convert sunlight directly into electricity[10,11]. Silicon is widely used in solar cells because it is abundant, non-toxic, easily accessible, and inexpensive. PN junctions are essential in silicon solar cells, which are created by combining P- and N-type doped semiconductors through the diffusion technique, and large-area PN junctions are generated from silicon wafers[12,13]. The greatest theoretical efficiency of PV solar cells is 29.43% for silicon, featuring a 1.1eV band gap known as the Shockley-Queisser limit. Solar cells come in many different varieties developed in different eras, such as crystalline solar cells (c-Si) and their subdivisions, monocrystalline and polycrystalline, that employ wafer technology[14,15]. Thin film technology is used in a-Si, cadmium telluride (CdTe), and copper-indium-gallium-selenide (CIGS) solar cells; emerging solar cells include quantum dot (QD), polymer and organic, dye-sensitized, perovskites, kesterite, and tandem solar cells[16,17]. In photovoltaic (PV) technology, c-Si solar cells reigned with a 95% market share. In HIT solar cell technology undoped hudrogenated a-Si thin layer employs as surface passivation which lower the recombination losses, and doped hudrogenated amorphous silicon thin layer used as carrier selective contact with interdigitated base contact (IBC) achieved the efficiency of 26.7%[17,18]. Hazardous and combustible gases are generated during the synthesis of doped hydrogenated amorphous silicon. An alternative to hydrogenated doped amorphous silicon selective contact, transition metal oxide (TMO) contacts of titanium oxide and molybdenum oxide can be used, which minimize the parasitic losses, environmentally friendly, and cost effective[19-21]. Currently, TMOs have an efficiency of about 24%, have more potential up to 28.4%, and employ SHJ-IBC (HBC) structure technology; further efficiency can be improved[22-24]. This article discusses multiple manufacturing technologies for enhancing solar cell efficiency,

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with a focus on the use of various materials, power conversion efficiency, commercial obstacles, future issues, and current advances in solar cell structure technology (HIT) with TMO contacts[25, 26]. The key challenge with solar cells is increasing their efficiency and lowering their production costs, which can provide a levelized cost of electricity to our society [27-29].

II. WORKING OF SOLAR CELLS

A solar cell is made up of PN junctions, which are created by incorporating two layers of P and N semiconductors through the diffusion technique[30,31]. This electron fills holes, and holes as well as electrons combine to become neutral near the junction, forming a depletion region there. The P-side has negative ions (anions), while the N-side contains positive ions (cations) across the junction, resulting in an internal electric field (or potential barrier of 0.5 to 0.7 volts) across the junction[32,33].

The block diagram of solar cells exhibited in Fig.1

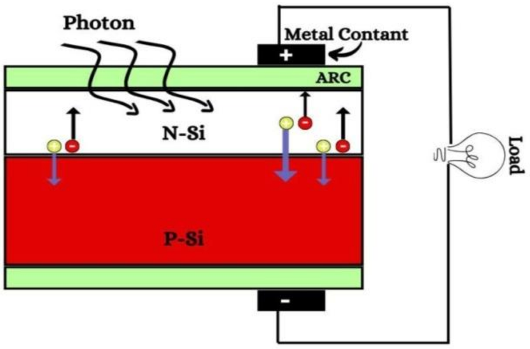

Fig.1-Block diagram of solar cells

A photovoltaic (PV) cell has three components that operate together. Light absorption leads to the production of electron-hole (e-h) pairs, the division of opposite-type charge carriers, and the extraction of the carrier in the external circuit. When photons from the sun hit the silicon atom in the solar cell, the silicon releases its electrons, leaving holes where the outgoing electrons belonged. Electron-hole pairs are then produced[34-36].The holes in the depletion region travel towards the P-section when an internal electric field is present, and the electrons in the depletion region move towards the P-section because the opposing polarity of the electric field attracts them. The holes and electrons flow in the direction of their corresponding terminals[37,38]. An electric current flow when these devices are connected by a metal wire or load. The potential between the terminals is referred to as open circuit voltage (V_{oc}) when no current is drawn, while short circuit current (I_{sc}) is the maximum current that may be carried over a zero-resistance wire[39-41].

The I-V characteristics curve is exhibited in figure-2.

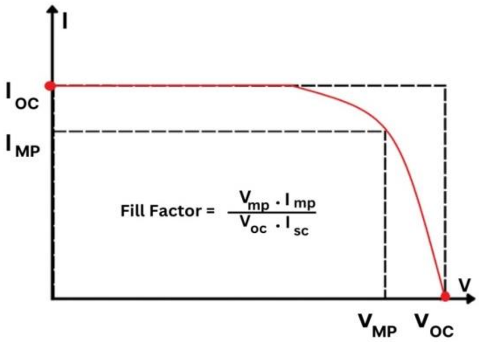

Fig.2- I-V Characteristics curve of solar cells

The ratio of P_{max} to the product of I_{sc} and V_{oc} provides the fill factor, which we determine together with the V_{max} and I_{max} points[42,43].

$$FF = \frac{Vmax.Imax}{Voc.Isc}$$

$$PCE = \frac{Pout}{Pin} \times 100\%$$

$$PCE = J_{sc}.V_{oc}.FF$$

$$J_{sc} = \frac{Isc}{A}$$

Where J_{sc} short circuit current density and A is surface area

III. SOLAR CELLTYPES :

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-3.

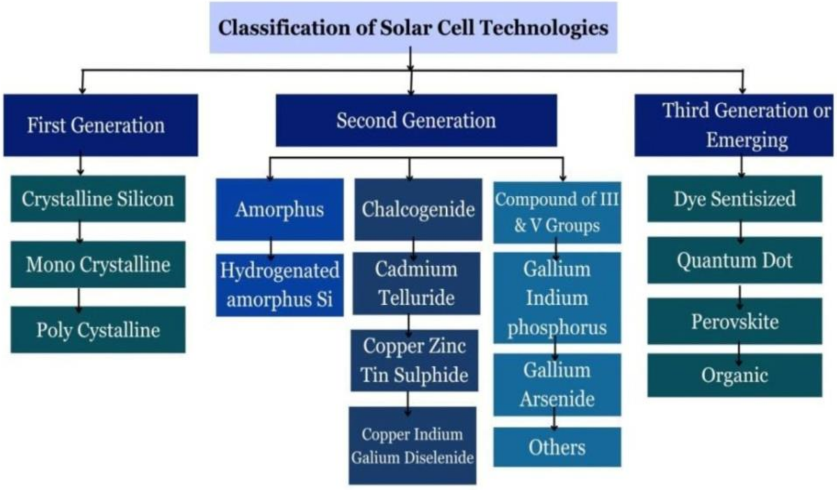

Fig. 3- Classification of solar cells technology.

Wafer technology (first generation) solar cells are found in mono-crystalline and poly-crystalline wafers, while thin-film technology (second generation) includes amorphous silicon, CdTe, and C.I.G.S., emerging technologies (third generation) include D.S.S.C., quantum dots, organics, perovskytes,tandemsolarcells,etc.[44-46].~~The.~~The solar cell technologies are categorized as follows:

3.1 Wafer Technology (First Generation)

Initially in photovoltaic (PV) technology c-Si used to make solar cells in first generation of solar cells.In this generation, silicon wafers are used for fabrication, the oldest and most popular technology because silicon is abundant and non-toxic, around 95% of the world's solar power produced by using (c-Si) wafers[47,48]. When ingots take in the form of single crystals is monocrystalline and contain multiple crystals is called polycrystalline are the subgroups of c-Si solar cells ~~(AcharyyaSetal.,2022)~~[49,50].

Monoorsingle-crystalline solar cells are produced usingthe Czochralski process,a precise and expensive re-crystallization process with efficiency ranging from17% to 24%, requiring precise processing from large ingots. Polycrystalline solar cells are composed of multiple crystals in a single cell,created by chilling a graphite mould that has silicon molten inside of it[51,52].They are the most popular solar cells but less efficient than single- c-Si ones,although they are slightly less expensive to manufacture,accounting for12.1% to14% of the total.Monocrystalline and polycrystalline Silicon are used for commercial modules and dominated in PVmarket[53,54].

Table1- Mono-crystalline & poly-crystalline solar cells and their efficiency and properties.

Sub group of wafer technology	η%	Properties
Single c-Si solar cells	17 to 24	High efficient, expensive, and complex manufacturing process than Multi c-Si solar cells.
Multi c-Si solar cells	12.1to14	Cheaper but less efficient than mono-crystalline solar cells.

3.2 Thin-Film Technology

Thin film solar cells are made of a-Si, CdTe, & C.I.G.S.; they are less expensive and *100 times* thinner than silicon wafer cells. Thin-film solar cells degrade in the environment, achieving an efficiency of 5–7 % . Thin-film cells based on a-Si:H have acquired commercial traction due to the high cost of c-Si, which can be manufactured in large sizes and placed on curved surfaces[55,56]. Thin layer solar cells are as follows:

3.2.1 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[57,58].

3.2.2 Cadmium-Telluride Solar Cells

CdTe is a cost-effective photovoltaic material witha1.5 electronvolt band gap, excellent stability and absorption of light, the direct bandgap semiconductor characteristics of which make it perfect for thin-film solar cells. Cadmium sulphide (CdS) layers are sandwiched to provide PN junction diodes in CdTe solar cells, synthesized from polycrystalline materials and coated with multiple layers on the substrate, making them flexible and available on polymer substrates. Cadmium telluride, a hazardous heavy metal, causes severe environmental damage ~~(SharmaSetal.,2015)~~.Cadmium-telluride is a thin-layer PV technology have an efficiency of 22.1%. CdTe has same band gap as GaAs so it have identical properties like good absorption of light and low photon energy losses. Commercial cadmium solar panels are cost-effective and offer shorter energy payback times, but their long-term viability is uncertain due to the fact that cadmium is highly toxic and tellurium is very rare[59,60].

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

C.I.G.S. has a narrow band gap that ranges from1 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 2 3.4% [61,62].

3.2.4 Ga-As Thin Film Solar Cells

The straight band gap of GaAs is 1.43 eV which is an analogous with visible light, leading to thinner and better absorption layers and reduced energy loss, and GaAs has superior electron-transport properties. Compound semiconductors from group III and the periodic table's V elements have demonstrated greatly improved efficiencies. However, their manufacturing is expensive. Gallium arsenide (GaAs) possesses the best performance of all photovoltaic material, reaching 29.1%, but very expensive, used in space applications[63,64].

Table2-Second generation solar cells and their efficiency and properties

Name of Thin film solar cell	Efficiency	Properties
a-Si	05-12%	Light in weight, cheaper, absorbs more energy than c-Si but less efficiency

Cadmium telluride	15-16%	Good performance at high temperature, cheaper but toxic.
CIGS	20.0%	Good performance at high temperature, cheaper but toxic, low stability and have complex structure.
Gallium arsenide thin film	28.7%	Ga expensive, low abundance and As is highly toxic.

3.3 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:

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

The D.S.S.C. is a low-cost, flexible solar cell technology that operates similarly to photosynthesis. A conductive support system, a semiconductor sheet, dye, electrolyte, and counter electrode are its five constituent parts. Efficiency can be increased by fine-tuning components. DSSCs are designed considering optoelectronic properties like absorption coefficient, band alignment, dye morphology, and assembly mode on the TiO_2 photo-anode, and conversion efficiencies of over 11% and 15% have been achieved in laboratory studies. However, challenges like dye degradation and stability issues persist [65,66].

3.3.2 Kesterite Solar Cells

Kesterite solar cells, made from copper(Cu)-zinc(Zn)–tin(Sn)-sulphide(S) [CZTS] & copper(Cu)-zinc(Zn)-tin(Sn)-selenide(Se) [CZTSe], have similar optical and electronic properties to CdTe and CIGS but lack toxic elements Cd and In. They have an efficiency around 8% with CZTS cells and around 10% with CZTSe cells, but face limitations like dominant interface recombination & less minority carrier life time[67,68].

3.3.3 Polymer Organic Solar Cells

Flexible solar cells made of thin layers coated on a polymer sheet are known as polymer solar cells. They function as a combination of a polymer and fullerene and can be made from various materials for sunlight absorption. Organic solar cells, thin film cells using organic semiconductors, offer advantages like affordability, flexibility, and light weight but have low efficiency. Organic solar cell belongs to the excitonic solar cells category. When sunlight falls on a cell, it produces electron-hole pairs, with absorbent materials like poly(3-hexylthiophene) (P3HT),phthalocyanine,and6,6]-phenyl-C_{61}-butyricacidmethylester (PCBM).When a photon is absorbed in an organic semiconductor, it excites one electron to valence band & and creates a hole in the conduction band. These holes and electrons remain bound due to columbic forces. If the junction is composed of two distinct organic materials, efficient charge separation of excitons and free carrier production may take place. The bulk hetero-junction increases the donor-acceptor interface area, allowing each to be thinner around the junction. The bi-continuous phase separated network at the donor-acceptor interface separates excitons generated in donor material due to photon absorption. In commercial organic solar cells, a mix of P3HT (Donor) and PCBM (acceptor) is used to achieve an efficiency of about 5%. Metals like Al, Ag, and Au are also used for the back electrode[69-71].

3.3.4 Perovskite Solar Cells

The light-absorbing layer of perovskite solar cells is made up of organometallichalides, which have the same crystal structure as $CaSiO_3$, namelyABX_3 (A-organic/ inorganic cation, B-metal cation, & X-halide, peak efficiency has risen to 25.5%,with exceptional qualities such as bipolar charge transfer and robust tuneable absorption characteristics[42,43]. It is anticipated that perovskites, a kind of chemical with the formula ABX_3,will be important for electric car batteries due to their efficiency of up to 31%. $CaSiO_3$ or $MgSiO_3$, abundant, offers lower combination losses, low material cost, and a longer charge carrier diffusion length. $CH_3NH_3PbI_3$ used for high-efficiency perovskite solar cells. However, perovskite degrades over time, with a best life time of 10,000 hours but low stability, much shorter than the 25 years expected from commercialized PV technologies[24,25]. The most rapidly developing technology, perovskite solar cells have the potential for increased efficiency and reduced manufacturing costs. Commercialization of perovskite cells faces obstacle like stability in environment, mechanical fragility and toxicity of lead halides[15,16].

3.3.4 Quantum-Dot Solar Cells

Quantum dots (QD) solar devices, introduced by Burnhamand Duggan in 1989, area technology with a flexible band gap that is modifiable through manipulation of artificial atom sizes, with an efficiency of 18.1%. QDs are composed of semiconductors from transition metal groups, such as porous Si or TiO_2. Advancements in nanotechnology have led to their use as an alternative to bulk materials like Si, CdTe, or CIGS. Colloidal CdX (X= Se, S or Te) is the most investigated QD, known for its excellent optical and electrochemical properties. QDs are ideal absorber materials in third-generation photovoltaic cells, with a maximum efficiency of 16% using hot photo-generated carriers[47,48].

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

Tandem solar cells are composed of multiple semiconductor-based p-n junctions connected sequentially from top to bottom. The p-n junction's varied band gap allows it to absorb different wavelengths of sunlight and create more electric current, which is short circuit current, increasing its efficiency[20-22]. It offers a high PCE of up to36% and is reasonably priced. The top-to-bottom p-n junction has a decreasing band gap, therefore the higher cell generates more photocurrent than the lower cell. Tandem cells have an efficiency greater than 36%, which exceeds the Schockley-Quisser limit. The combination of groups III and IV, such as Ga-As and In-Ph, can enhance efficiency but is costly[52,53]. High-efficiency GaAs are employed in multijunction cells for space applications and solar concentrators. GaAs solar cells can found in thin film,single crystal, polycrystalline, and tandem forms.The efficiency of polycrystalline GaAs single junction solar cells is 28.8%, 18.4%, that of thin-film GaAs solar cell is 18.4%,and that of multijunction GaAs solar cells is 31.6%[29-31].

Table 3-Third generation solar cell,their efficiency and properties

Name of Solar cells	Efficiency	Properties
D.S.S.C	05 to 20%	Semi-flexible, Low cost but low stability.
Organic/Polymer solar cells	09 to 11%	Light, flexible, less lifetime, low efficiency.
Perovskite solar cells	21.0%	Cheaper, good thermal stability but toxic
Quantum-dots solar cells	11 to 17%	Have ability to tune band gap but less efficient.
Multi-junction solar cells	36.0%	Highly efficient but more expensive.

IV. HETEROJUNCTION WITH INTRINSICTHIN LAYER (HIT) ARCHITECTURE TECHNOLOGY.

The silicon heterojunction SHJ/HIT structure solar cell is exhibited in figure 4.

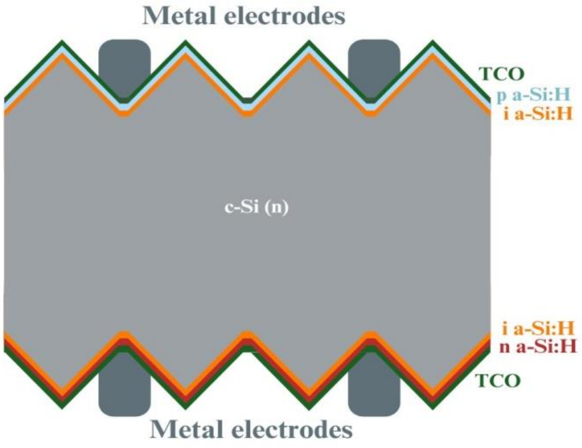

Fig.4- HIT solar cells structure

It is a hybrid technology that combines c-Si cells and thin film of a-Si, heterojunctions formed between c-Si, and doped a-Si contacts with dissimilar bandgaps[41,42]. A front junction of a silicon p-i-n-i-n doped stack makes up a HIT solar cell; the central portion is a c-Si(n) wafer where an inherent a-Si:H layer and P- & N- type doped hydrogenated a-Si contacts are deposited symmetrically on both sides of it. The over layers are transparent conducting oxide; ITO is employed as an ARC, and metal grids are employed to gather charges and provide sunlight. HIT is 90% bifacially constructed, the front side's sheet resistance is reduced, and lateral electron transport can occur in the absorber rather than the front TCO due to the same rear-junction design, leading to efficiency and cost benefits[5-8].

HIT solar cells consist of N-type c-Si as substrate, a pure a-Si thin layer for surface-passivation, which decreased surface defects and reduced recombination, and hydrogenated doped a-Si layers as passivated contacts deposited using plasma-enhanced chemical vapour deposition (PECVD) on both sides of the a-Si layer[29-31]. PN junction created by n-type c-Si and P-doped a-Si layer for power generation; ITO coating on both the passivated contacts is done for good propagation of light and enhance conductivity; silver electrodes are deposited on top and bottom surfaces. N-type c-Si has higher mobility, and degradation by sun light is less. When sunlight falls on solar cells, photons are captured up by atoms of silicon (c-Si) and produce pairs of electrons and holes.

These electrons and holes divide apart by an electric field developed across the PN junction in the depletion layer and move to the opposite terminal by carrier-selective contacts of solar cells[44-46]. The charge carrier recombination is suppressed by carrier-selective contacts as well as surface passivation by the thin a-Si layer, which stops the capture of the carrier by surface defects. Before sunlight reaches the c-Si layer, it is pass through the the top layer of i-a-Si:H, and most of the sunlight is converted into electricity by them idle c-Si layer. Doped a-Si selective contacts & undoped hydrogenated a-Si layers are used in the HIT silicon solar cell which has a wider band gap passivating interface for high efficiency and carrier selectivity[38-41].Utilizing a thin hydrogenated a-Si passivation layer, KANEKA Corporation and LONGI produced broad-area HBC solar cells with efficiencies of 26.81% and 27.09%, respectively[3,5].For regions with abundant light, HIT solar panels provide steady and effective power generation[3,5].Their low temperature coefficient of - 0.24% /°C, processing at 200°C to 300°C,and HIT double design that boosts efficiency by 20 to 30% make them perfect[47-49]. Passivated contacts of hydrogenated doped a-Si replaced by TMOs heterocontacts achieved efficiency more than 23.5% and have a further potential up to 28.4% with HBC structure technology[9,10].

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

TMOs exhibit a variety of electrical, catalytic, structural, optical, and non toxic characteristics.TMOs feature a wide band gap, a diverse variety of work functions, high transparency,low temperature deposition using simpler procedures, and are low cost.TMOs' work functions are dependent on partially filling 2p-orbitals of O_2 and partially filled d-orbitals, modifying cation oxidation states,and oxygen or metal cation deficits. These defects change the oxidation state,the electronegativity associated with the material's work function,and the carrier concentration and Fermi levels[15-17]. The energy level is influenced by oxygen vacancies at the interface of metal oxide. Si oxygen-deficient MoO_3 can be denoted as MoO_{3-x} or MoO_x, where x is the degree of oxygen. After depositing aTMOs layer on Si,oxygen releases free electrons, causing a defect in the forbidden energy band near the conduction band (CB) & occupying d-orbital states.TMOs with oxygen vacancies are classed as n-type semiconductors, whilst those with metallic vacancies are categorized as p-type semiconductors[11,12].

In doped a-Si are as ,HIT solar cells exhibit parasitic absorption and recombination losses and doping-free concepts like molybdenum oxide are being explored to reduce Auger recombination in carrier-selective regions..TMO passivated contacts decreased parasitic absorption losses due to the greater band gap in the emitter zone, recombination loss due to the lack of a strongly doped layer, and functioned as carrier selectivity contacts.The maximum efficiency of 22.1% is achieved when MoO_{3-x} is utilized in the hole-contact stack, and 21.1% when TiO_{2-x} is used as an electron-selective contact[34-38].TMOs with double heterocontact achieved efficiencies of over 23.5%, work functions of 6.9 eV for MoO_x and~4.0 eV for TiOx, and a η of 24.83% through modeling[9-11]. It is possible to create TMOs that have dopant-free carrier-selective contacts utilizing a simple process at low temperatures without the emission of hazardous and flammable gases. TMO connections in solar cells minimize parasitic light absorption while increasing Jsc, with a high efficiency potential of up to 28.4%[10-12].

Transition metal oxides (TMOs) like TiO_2 and MoO_3 work as carrier-selective or passivated contacts. Contacts and interfaces perform both carrier-selectivity and passivation, enabling one type of charge carrier to pass while damming up the other. It's called passivating contacts. Pssivating contact reduces the conductivity of one carrier, preventing it from travelling across interfaces, while boosting the conductivity of the other carrier, allowing it to flow freely away from the interface[30-32]. Passivated contacts regulate them mobility of charge carrier sowing to conductivity asymmetry. Selectivity is obtained by regulating the charge carrier concentration on the surface and generating a symmetric conductivity by passivating contact, which is made feasible by negative fixed charges and metal oxide's high work function. Passivated contacts reduce contact resistance and recombination current density, which improves solar cell performance[58-60]. Carrier selectivity as exhibited in figure-5.

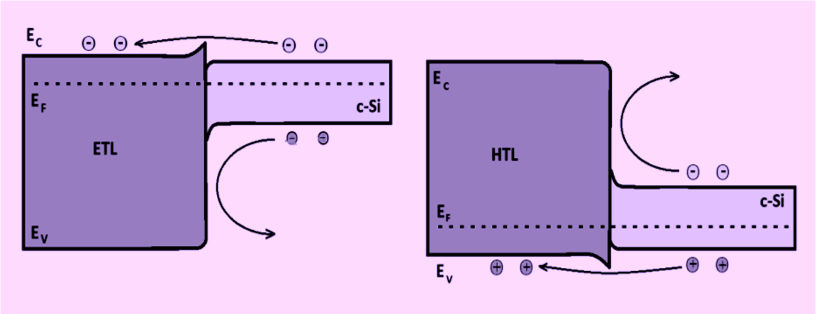

Fig.5-TMOs hole-selective & electron-selective passivating contacts

TiO_2 is an electron-selective contact due to its smaller conduction band offset and larger valence band offset with silicon, while MoO_3 are hole-selective contacts due to their wide conduction band offset and smaller valence band offset[24-26]. When the TMO's conduction band energy is higher than the Si layer's valence band energy, surplus holes undergo band-to-band tunnelling. Charge carriers flows asymmetrically within the solar cell in the direction of the contact are as due to the charge-carrier selectivity at the terminals. The open circuit voltage (V_{oc}) significantly indicates the suppression of non-collected charge carriers towards the opposite polarity contact[13-15].

4.2 Novel Design of TMO Passivated Contacts based HIT Structure Solar Cells

The novel design and configuration of a solar cell are shown in figure 6. The novel solar cell utilizes titanium oxide as an electron-selective contact and MoO_3 as a hole-selective contact. Silicon wafers of n-type, Czochralski, or floating zone are used, and R.C.A.I and R.C.A.II solutions in 2% HF are used for cleaning the wafer. Thermal evaporation, or atomic layer deposition (ALD) or pulse laser deposition (PLD),is used to grow the MoO_3 film on one side while the TiO_2 film is grown on the other. SiO_2 is deposited on both sides of a thickness around 1.2nm, or the SiO_2 layer is inherently present on a silicon wafer of thickness 1to 2 nm after cleaning by RCAI and RCA II when not dipping in HF. ITO serves as an anti-reflection coating on the front surface of the MoO_3 layer, with Ag deposited at the front and Al deposited at the rear surface[9,19,31].

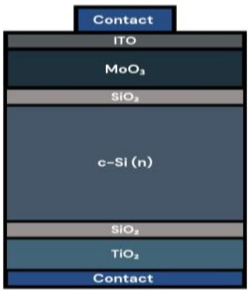

Fig.6-Novel Design of TMO Contact c-Si Solar Cell.

The Si wafer is kept within the chamber during thermal evaporation for TiO_2 deposition. Tetrakis di-methyle amido titanium and water steam are employed as precursors for titanium and oxygen,respectively,at temperatures <200°C.Ozone and $Mo(CO)_6$ are used as precursors for Mo and oxygen deposition of MoO_3 films on Si wafers.The pressure in the chamber remained constant at 1Torr throughout the experiment.MoO_3 films are grown to a thickness of 7nm, TiO2 is 5nm,and ITO is RF sputtered to a thickness of 80 nm at~200°C. 300 nm Ag is evaporated to metalize the device's front using a shadow mask with a bus-bar and finger pattern. Solar devices utilize silver and aluminium contacts for anode and cathode electrodes respectively, with a single ITO anti reflection coating at the top interface for efficient solar energy production)[1-3,19].

V. .CHALLENGES AND FUTURE ASPECTS

challenges of solar industry are high manufacturing cost and have low efficiency. Most of the solar modules and raw material like silicon wafers and Ag and Al pastes are still imported from China. Lack of The waste management to dispose of waste from solar industry, lack of innovative financing options for the construction of large-scale solar PV parks, and Lack of space for installation of large ground to mount solar panel[50,51]. Polymer-based solar cells are still a viable choice, but they deteriorate with time. The disadvantages of solar cell, solar power plant is seasonal than other renewable energy sources, Once installed, it is challenging to remove and re-install the solar cell to another location; Low rate of energy conversion about 25%, require a large area for installation and heavy weight of panel on rooftop[52,53].

Theoretically, nano-crystal quantum dot solar cells can convert almost 60% of the solar spectrum into electrical power, but practically, research is required in this field. Future advances include floating solar farms that save land by using panels that float on water, building integrated photovoltaic in building structures with roofs and canopies providing natural light, and photovoltaic glasses. Through industry-specific investment, incentives, and support for entrepreneurs, India needs to address the research and development and manufacturing gaps in the solar sector[50-52]. It should create industrial-style hubs for specific technological domains, generating raw materials such as silicon wafer, aluminium and silver paste, and solar panel components. Due to seasonal and latitudinal changes, there is less sunlight available throughout the night and during rainy seasons. New materials that improve solar energy harvesting are being made possible by research and development in solar photovoltaics, with product design and materials being essential elements in the commercialization process[31,42.49]. , and due to the variation of solar energy with time, the solar cell sector has difficulties with energy storage[15-17].Current storage technologies are costly and have limited lifespans. Potential options for storing solar energy include rechargeable lithium-oxygen batteries and quinone, an organic battery.

VI. CONCLUSION

Solar power is a sustainable, reliable, noiseless, cost-free,clean,and environmentally friendly technology that is used in a variety of applications, including road traffic signals, artificial satellites, space shuttles, photo-detectors, road lighting, medical research, battery charging, supplying electricity to isolated and pathless areas, and detecting electromagnetic radiation in the visible spectrum. Solar energy is a sustainable alternative to fossil fuels since the sun will likely persist for billions of years, but fossil fuel resources are fast dwindling. Solar PV systems have a 25-year lifespan, low greenhouse gas emissions, and lower operating and maintenance expenses than other renewable energy sources. Solar power is a sustainable alternative to traditional electric power that meets global energy demands and is necessary for now and tomorrow's world. Enhancing the efficiency of solar cells and cutting production costs are the main goals of research. Doped hydrogenated a-Si selective contacts, which lower the recombination, allowed HIT-IBC architectural technology to achieve 26.7% efficiency.

In solar cells, TMO connections stake the place of doped a-Si selective contacts. This reduces parasitic losses and achieves efficiencies more than 23.5% for MoO_3 and TiO_2 contacts. Inc-Si solar cells, TMO double- asymmetric hetero-contact / passivated contacts have an efficiency of about 25% and a potential of over 28.4%,which can be further increased with HBC technology. This review discusses various manufacturing technologies for improving solar cell efficiency, focusing on material property optimization, TMO connections,and optimizing the TMO contact energy band with c-Si, commercial obstacles, future issues, and current advances in solar cell structure technology (HIT)with TMO contacts. The main challenge is to increase efficiency and lower production cost, with solar technology aiming to surpass 23% module efficiency at less than US$ 0.2/W within five years as c-Si dominates the market, enabling levelized electricity cost for society.

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