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Evolution of Photovoltaic Cells: From Silicon to Graphene - A Review of Generations, Technologies, and Future Directions

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ABSTRACT :

The purpose of this paper examines the evolution of photovoltaic (PV) cells, with a focus on the technological advancements, efficiency improvements, and manufacturing innovations across various generations of solar cells. It begins by highlighting the critical role of photovoltaics in advancing renewable energy solutions and reducing dependence on fossil fuels. The discussion then delves into the key developments in PV cell technology, from the first generation of silicon-based cells to the more recent advancements in third-generation solar technologies. This includes innovations such as multi-junction cells, which enhance light absorption by combining multiple materials with varying band gaps, and the use of intermediate energy levels in the silicon bandgap to improve efficiency. The paper also reviews the emerging potential of fourth-generation graphene-based photovoltaic cells, which offer new possibilities in efficiency and sustainability due to graphene's unique properties, such as high electron mobility and transparency. Through an extensive literature review, the study concludes that despite the introduction of these new technologies, silicon-based photovoltaic cells still hold the largest market share. Ongoing research into enhancing the efficiency and reducing the costs of silicon-based cells remains a priority in the field of photovoltaic technology.

Keywords: photovoltaic; solar cells; renewable energy; photovoltaic cell manufacturing technologies; efficiency; photovoltaic generations.

Introduction :

Throughout the past few decades, clean and renewable energy needs have increased at an accelerated pace around the world [1]. Prominent reasons for such exponential growth include fighting climate change and reducing dependence on fossil fuel. Among these, the most promising technology is photovoltaic cell that converts sunlight into electricity. This has been characterized by advancement of PV technology over the last decades, and due to its consequence, by more efficient, cost-effective and diversified solar panels. Evolution of photovoltaic cells has been categorized into different generations; each one is material, architecture, and manufacturing technique different from the others [2]. A first generation, mainly crystalline silicon (Si)-based, market-dominated mechanism developed through established performance and reliability and scaled for many decades. However, with rapidly growing demands for solar energy, efficient, light, and flexible alternatives for silicon-based PV cells are in great demand. Recently, it was two-dimensional materials, especially graphene and other carbon-based nanomaterials, that marked the new front in photovoltaic technology and promised to open up new possibilities in pushing the limits of PV efficiency and flexibility while offering new solutions for alternative energy storage and conversion techniques. Thin-film and organic solar cells are the second and third generations of PV technology, respectively, offering extreme improvements in performance at low material costs. Both the second and third generations also make possible lightweight, flexible panels with new integration opportunities from building-integrated photovoltaics to portable power sources[3].

Evolution of PV cells

The PVC-related research work has been very clear-cut with the passage of generations-overcoming weaknesses of their predecessors, finding ways to improve efficacy, scalability, and costs[4]. The first generation PVCs are crystalline silicon-based technology. Although well established for high efficiencies and robustness of solar cells, they have remained relatively expensive to install and manufacture at a large scale. Although the silicon dependence is efficient, yet in economics and scaling up, it needs to be improvised for competition with non-fossil fuels at the international level. To bridge this gap, second generation of PVCs have developed thin-film technologies based on amorphous silicon, polycrystalline silicon, cadmium telluride, and copper indium gallium selenide (CIGS), respectively. Such materials are capable of offering rather cheap substitutes for single-crystal silicon at some loss in performance but, compared to any other material, economic feasibility of the thin films has made solar technology available to common usage, weighing performance against price.

This leads to an entirely new paradigm based on bio-mimicked and nanomaterial-based designs that have remained immune to the S-Q limit that has created a bottleneck of sorts in theory, impeding the development of single-bandgap semiconductor-based solar cells. As the discussion approaches the improvements in the energy conversion efficiency, the possibility of twin-cells and tandem-cells harnessing materials with different bandgaps comes across as very promising to reach through a larger chunk of the Sun's spectrum. This approach, improved with enhanced semiconductor applications places solar energy closer to the upper limits of theoretical efficiency. Fourth generation PVCs incorporate a large degree of bio-inspired technologies and novel nanomaterials like carbon quantum dots (CQDs)[5], which can make cells features wherein some biological processes can be simulated or biological components (like photosynthetic) can be incorporated to enhance charge separation and electron evolution. Near-quantum efficiency solar energy harvesting based photostable complexes construction examples from nature that can be used as well-defined models for the parsing of solar energy with high fidelity. Collectively, these advancements underscore the transformative journey of PVC technology toward higher efficiency, sustainability, and practical deployment.[Fig.1]

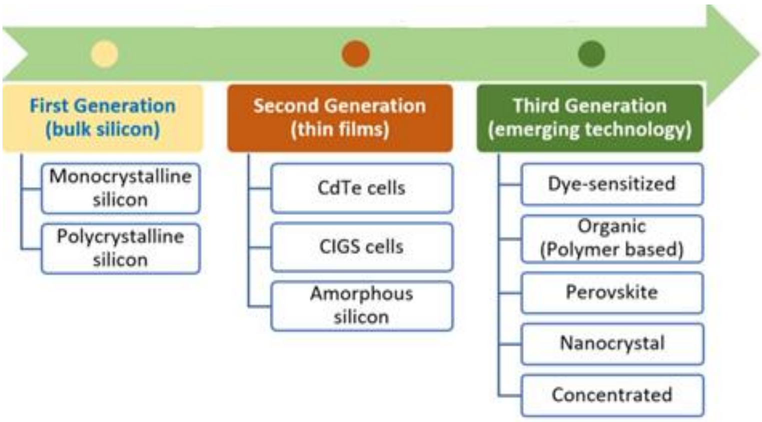

Fig 1. Photovoltaic Technology Generations

Historical Background and Evolution of Photovoltaic Cells :

Photovoltaic technologies require material to follow a path of increasing efficiency, decreasing the cost, and scaling up well. Among perovskite materials, with lead or tin-halide composition, they have drawn considerable attention due to high efficiencies and the potential for inexpensive production. The flexibility to adjust the band gap confers on the perovskite material's tenability for absorption from the ultraviolet region through the visible into the infrared spectrum; energy conversion rates rise by many orders of magnitude. However, this is limited to widespread uses due to stability and lead toxicity issues; lead-free alternatives and lifespan improvements are actively pursued. These materials are applied mainly as high-power stand-alone cells or in conjunction with silicon cells to achieve superior performance.

OPVs are organic photovoltaic materials based on polymers or small molecules that can carry electrical currents upon illumination[6]. As a result, the advantages of lightness and flexibility of design and minimal environmental degradation due to recyclability characterize them. Being easily manufactured and versatile, OPVs are limited by lower efficiency and stability, limiting their lifespan. OPVs best applications in portable electronics, wearable solar devices, and building integrated photovoltaics (BIPV) due to their requirements for flexibility and transparency.

Thin-film technologies, such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) solar cells, are placing solar manufacturing on the affordable solution map. CdTe cells have a very minimalistic environment impact, and CIGS cells offer higher efficiencies and flexibility. However, they both use rare materials, and the CIGS requires complexity in production that makes it tough for mass application. CdTe is the preferred option at the utility scale, while CIGS has excellent applications in flexible electronics and small-scale solar panels[7].

New frontier in photovoltaic innovation: Emerging carbon-based nanomaterials, such as graphene and carbon nanotubes. These add features including high flexibility and lightweight as well as electrical and thermal conductivity, and environment friendliness as well as nontoxicity. Graphene can be used as a transparent conductive layer or electrode in solar cells and is an integral part of hybrid structures that enhance performance. Yet, there are problems with scaling up to mass-production while keeping manufacturing costs low.

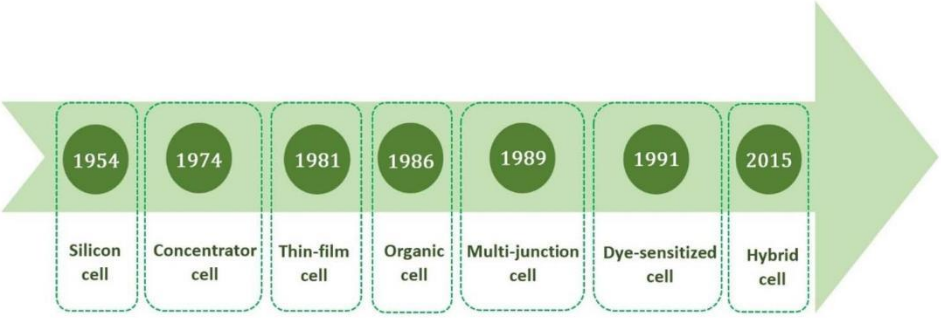

Fig 2. Evolution of PV cells

- 1954 - Silicon Cell: The first silicon-based solar cell is developed, which introduces the modern technology of photovoltaics into the world. Of these types, silicon cells are the primary choice for conversion into solar energy, particularly monocrystalline silicon, because of their potential efficiency and stability.

- 1974 - Concentrator Cell: Concentrator photovoltaic (CPV) cells concentrate sunlight with lenses or mirrors onto smaller, high-efficiency solar cells to achieve greater efficiency. They are usually used in solar farms.

- 1981 - Thin-film Cell: Thin-film solar cells have appeared as a flexible and lightweight alternative to conventional silicon-based cells. They are made by depositing one or more thin layers of photovoltaic material on a substrate. Common materials include cadmium telluride (CdTe) and amorphous silicon (a-Si).
- 1986-Organic Cell: Organic photovoltaic cells (OPVs) are based on organic material, either polymer or a small molecule, to convert light into electricity. Such cells have great prospects as far as low-cost, flexible, and light solar technologies go; however, the efficiency is inferior to that of silicon-based cells.

- 1989 - Multi-junction Cell: Multi-junction solar cells have an architecture of multiple layers of semiconductor materials, each tuned to capture distinct wavelengths. This improves the efficiencies compared to a single-junction solar cell.

- 1991 - Dye-sensitized Cell: Dye-sensitized solar cells (DSSCs) convert sunlight into electricity using the absorbing properties of a photo-sensitized dye. These are relatively simple to manufacture and are often used in small scale, low-cost applications.

- 2015 - Hybrid Cell: Hybrid cells combine different photovoltaic technologies, such as organic materials with inorganic semiconductors, to improve efficiency and stability. These are typically seen as a step toward more advanced and versatile solar cell technologies.[Fig.2]

Basic working Principle of photovoltaic cell

The working principle of photovoltaic (PV) cells is based on the photovoltaic effect, where light energy is converted directly into electrical energy. Here's a breakdown of how it works:

1. Absorption of Light: PV cells are made of semiconductor materials (commonly silicon) that absorb photons (light particles) from sunlight.
2. Creation of Electron-Hole Pairs: When photons hit the surface of the PV cell, their energy is transferred to electrons in the semiconductor material. This energy excites the electrons, freeing them from their atomic bonds and creating electron-hole pairs (where a "hole" is the absence of an electron).
3. Separation of Charges: The PV cell has a built-in electric field due to a p-n junction (an interface between p-type and n-type semiconductors). This electric field drives the free electrons towards the n-type side and the holes towards the p-type side, creating a potential difference.
4. Continuous Process: As long as the PV cell receives light, it continues to generate electron-hole pairs, sustaining a flow of current through the external circuit.[Fig.3]

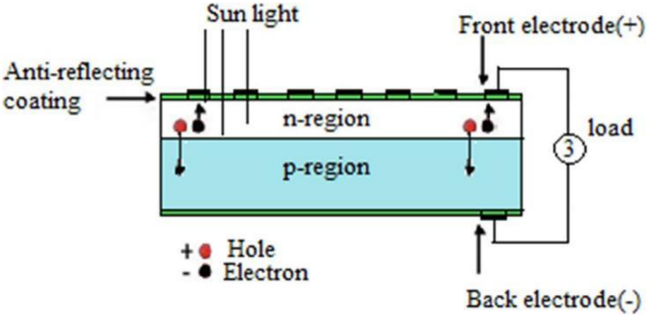

Fig 3.Construction details of PV cell

Current Technologies in Photovoltaic Cells :

PV technologies have been greatly improved over many generations but now focus on efficiency, cost, and sustainability. The generations of photovoltaic cells are divided into first-generation, which is mainly composed of crystalline silicon (c-Si), that predominates the market because of their high efficiency up to 26 percent in laboratory conditions and durability. Second-generation photovoltaic cells, based on materials such as cadmium telluride and copper indium gallium selenide, are cheaper to produce, flexible, but less efficient as a class. Next generation brings near-horizon new technologies in perovskite cells and tandems, that might break the limits of efficiency a single junction can be with innovative materials and geometries of stacks. Organic PV cells and quantum dot technologies promise lightweight, flexible, and lower-cost alternatives; stability and scalability are barriers to their application. Advanced materials like graphene have also been developed toward improving charge transport and increasing the energy conversion efficiency, hence a step forward toward advanced solar cells.

- **Monocrystalline and Polycrystalline Silicon**

Till date, the pillars of the solar industry include monocrystalline and polycrystalline silicon cells because they have tried and tested reliability and vast acceptance. Monocrystalline cells, that are made up of single-crystal silicon, have an efficiency between 20–25% and last for a very long time. The process produces monocrystalline cells, using the Czochralski method-an energy-intensive process in which uniform crystal structures ideal for optimal electron flow are created; however the above precision comes at a cost. Polycrystalline silicon cells are less efficient than these-they derive from several silicon crystals and are 15-20% efficient-compared with above-with simpler manufacturing processes, hence cheaper. Both have challenges, like each having a point of diminishing returns on their efficiency improvements and silicon production having an enormous negative impact on the environment, which prompts researchers to look for other materials and methods.

- **Thin-Film Technologies**

Thin-film photovoltaic technologies, including cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si), have been some of the leading new technologies pushing traditional silicon-based cells[8]. For instance, such CdTe cells are highly efficient at low illumination and are much cheaper to manufacture, as CdTe is freely available raw material. CIGS cells have a slightly better efficiency compared with the ones of CdTe, but it has a drawback in its availability because of indium. Amorphous silicon is extremely cheap and highly adaptable, but its efficiencies tend to be pretty low, so it seems fit for only small electronics. Not only toxicity, as in the case of cadmium in CdTe, challenges the thin-film technologies but also stability if exposed to extended sunlight exposure to overcome the crystalline silicon cells.

- **Organic Photovoltaics**

Organic photovoltaics represent a fast-emerging area in solar energy innovation using carbon-based polymers or molecules to absorb sunlight and convert it into electricity. Key strengths include their flexibility and lightweight with ultra-low-cost production prospects via roll-to-roll printing processes. However, they have a long way to go for efficiency, as OPVs generally range between 10–15%. Stability and degradation in environmental conditions are also critical issues. OPVs have big potential for wearable technology, building-integrated photovoltaics, and portable energy solutions, and novel material research and encapsulation techniques are continually being developed.

- **Perovskite Solar Cells**

Perovskite solar cells represent a "game changer" in the photovoltaic industry: this emerging class of materials consists of perovskite-structured members that are, primarily, hybrid organic-inorganic lead halides, with characteristics such as high light absorption, tunable band gaps, and long-lived charge carrier lifetimes. Shortly after their discovery, perovskite cells have reached efficiencies above 25%, rivaling the best monocrystalline silicon. This material also provides an excellent potential opportunity for low-cost solution-based processing. Still, challenges to the commercialization front face their instability in materials, lead toxicity, and scale-up manufacturing. Lead-free perovskites and enhanced stability mechanisms will potentially unleash these cells.

- **Graphene-Based Solar Cells**

Graphene is a single sheet of carbon arranged in a hexagonal lattice that has recently been found to be the world's most promising material for photovoltaic applications. This is due to its higher electrical conductivity and flexibility, along with the wide range of light absorption. In a few research works, it has been determined that graphene-based elements can be utilized for the conception of dye-sensitized and perovskite cells, and these would lead to higher charge transport along with overall efficiency. Commercialization of solar cells based on graphene will have very serious issues with high cost of production, the scale-up problem, and necessity for highly advanced fabrication techniques. Still, cells based on graphene will be able to reshape solar technologies in terms of efficiency, duration, and flexibility in near future with further advances in synthesis and integration.

Together, these are exciting developments for the solar industry; each of them brings about differently diversified benefits and challenges. Advancements in these emerging technologies perovskite and graphene-based cells indicate promising futures for solar power and its fulfillment of the earth's energy needs while driving closer to sustainable and affordable solutions.

Advancements in Materials and Technologies

Recent technological advancements in PV technology have significantly increased efficiency, as well as durability and cost-effectiveness, pointing to a more sustainable future for energy. In terms of materials, perovskite and multi-junction cells have seen impressive improvements, with perovskite cells surpassing 25% and multi-junction cells achieving more than 40% in laboratory conditions. Quantum dots and nanostructures further improve light absorption and subsequent energy conversion efficiencies. Manufacturing processes, such as roll-to-roll printing and thin-film technologies, make it possible to produce low-cost flexible and lightweight solar panels, opening new fields in wearables and building-integrated photovoltaics.

Graphene and 2D Materials: Graphene and other two-dimensional (2D) materials are close to a new revolution in solar cells due to excellent electrical, optical, and mechanical properties. Graphene with unmatched electrical conductivity, flexibility, and transparency plays a highly significant role in improving the transport of charge and reducing energy loss in photovoltaic systems. Other 2D materials, such as transition metal dichalcogenides (MoS_2 and WS_2, to name a few), support graphene with tunable electronic properties, as well as strong photogathering capabilities. The hybrids that contain the graphene-graphite layer coated with organic or perovskite layers show some hope for increasing efficiency by several orders, as the graphene increases charge carrier mobility, whereas the other material maximizes light absorption and energy conversion capabilities. These advancements pave the way toward much more efficient, lightweight, and flexible solar cells that overcome some of the conventional hindrances of silicon-based technologies.

Tandem Solar Cells: Tandem solar cells break new efficiency grounds by stacking multiple layers of optimized photovoltaics for distinct ranges in the solar spectrum[9]. Band gap is a complement for most of the materials, with the perovskite paired with silicon or CIGS material for making tandem cells, which break the efficiency limit imposed by Shockley–Queisser on single-junction cells. Recent advancements in the efficiency of silicon-perovskite tandems have crossed 30%, opening avenues to future photovoltaics. While still presenting challenges in the form of manufacturing complexity and cost, materials integration and scaling have, for the first time, brought tandem cells close to commercial viability, making it an extremely important part of the solar industry's future[10].

Quantum Dot Solar Cells: Quantum dot (QD) solar cells benefit from nanoscale semiconductor particles with tunable band gaps to achieve better light absorption and energy conversion. This enables the nanoparticles to be engineered to have a broad absorption of infrared and ultraviolet light, traditionally underutilized by conventional cells. Solution-based processes offer promise for low-cost manufacture. Current QD cells do not approach the efficiency levels of silicon or perovskite counterparts but research is unlocking the considerable promise of these very lightweight, flexible solar technologies. Advances in stability and surface passivation are particularly critical in pushing quantum dot cells toward commercial applications[11].

Transparent Solar Cells: Transparent solar cells mark a groundbreaking step in building-integrated photovoltaics (BIPVs) as these cells enable the fully integrated nature of solar technologies into windows, facades, and other surfaces that are transparent[12]. These cells use materials that selectively harvest non-visible light while visible light can pass through, still generating electricity. Organic and perovskite-based transparent cells are the most relevant systems involved in this developing field, with efficiencies now above 10% for semi-transparent designs. Emerging applications in architectural design and urban environments highlight their potential in two-way functionality: integration of energy generation with aesthetic and functional transparency. The overriding challenges are to optimize the transparency-efficiency trade-offs and improve the durability of these novel cell architectures over the long term. Such developments in materials and technologies demonstrate an endless quest for more efficient, cost-effective, and versatile photovoltaic cells. Future breakthroughs in graphene-based hybrids and tandems as well as optically transparent photovoltaics are exected to transform solar power into something that could revolutionize the role of solar energy in solving the global energy challenges. A key point in this advancement is the central theme of the paper: how new materials and technologies can shape the future of photovoltaics, beyond the limits dictated by silicon-based approaches.

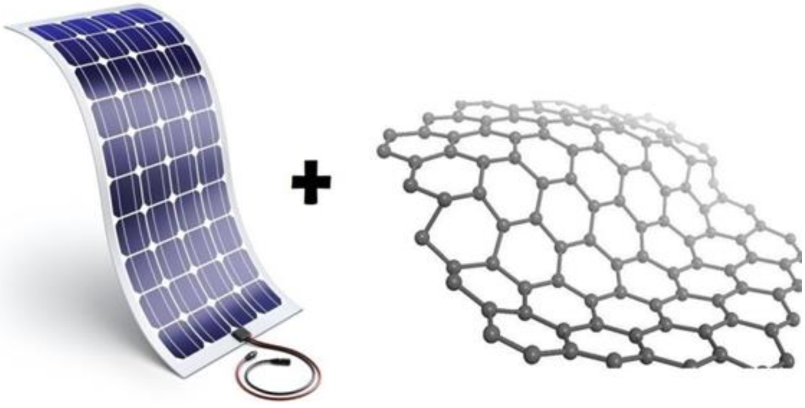

Fig 4. Structure of graphene used in PV cells

Graphene, a two-dimensional material consisting of a single layer of carbon atoms that constitute a hexagonal honeycomb lattice, has gained great significance as a transformative material in PV technology because of its excellent properties. Its structure, characterized by hybridization, allows it to have high electrical conductivity and remarkable mechanical strength. Graphene's delocalized π-electrons facilitate ultrafast charge transport that makes it an excellent candidate for improving charge carrier dynamics in PV cells. Graphene is optically transparent with a transparency of almost 97.7% for visible light, qualifying it for applications as a transparent conductive electrode, which presently utilizes indium tin oxide as a traditional material.[Fig.4]

Challenges in Photovoltaic Technologies :

Despite many advances, PV technology still confronts several problems preventing its widespread use and long-term sustainability. One of the key issues is efficiency limitations, particularly under conditions of real-world operation. Shading, temperature fluctuations, and suboptimal illumination all reduce performance, whereas several material sources, from perovskites to tandem cells, are known for their very high efficiencies but have scalability and stability issues. For example, perovskite solar cells degrade if exposed to moist and ultraviolet light during their lifetime of operation. Silicon PV cells, dominating the market, also reach saturation at a certain level of efficiency, because of material properties[13].

Durability and Stability

The lifetime and reliability of photovoltaic material are directly proportional to its durability and stability. For example, while silicon cells have shown such a long lifetime for decades, new materials and perovskites and organics are prone to degradation by environmental factors like moisture, heat, and UV. Instability in chemical properties and phase degradation practically hinders the deployment of perovskite cells. Thus, enormous research is now going on in improving encapsulation techniques, stabilization of material formulations, and hybrid designs to achieve a longer lifetime. Further reduction in LCOE with a lifecycle of 20–30 years is yet to be proven, but more so in terms of acceptance and deployment.

Environmental Impact

The photovoltaic technology itself is said to be friendly to the environment. The challenge may lie afterward when dealing with materials after they have reached the end of their product life. Methods of obtaining silicon are also energy-intensive and emit greenhouse gases. The chemistry of CdTe and CIGS is toxic, rare materials: they contain compounds made from cadmium and indium. Recycling solar panels has proven to be most problematic by the sheer amount of material that has turned out to be very hard to separate and recover at cost. Closing the loop recycling systems, in addition to greater availability and environmental acceptability of the material, are of substantial value in reducing the ecological footprint of solar energy systems. There are increasingly more applications of LCAs in assessing and reducing the environmental impacts linked with new photovoltaic technologies[14].

The overcoming of these challenges will take photovoltaic technologies further. The paper does very well into the theme of how developments in material science and manufacturing, alongside sustainability, can overcome what is now a barrier to progress and take solar energy where it should go. Knowing and resolving these challenges will push photovoltaic closer to the widespread deployment with a sustainable basis for the world's energy portfolio.

Future Development and New Directions Graphene and Beyond Graphene :

Graphene has many wonderful properties: electrically conductive, flexible, and see-through. Thus, it could form the basis for future generations of solar photovoltaic technology and future studies will, most probably target increasing yields of high-quality, defect-free graphene for combining with other high-end materials such as perovskites and organic photovoltaics to make hybrid solar cells with better performance and greater resistance. Apart from graphene, other 2D materials such as borophene and phosphorene possess complementary optoelectronic properties; among such materials, scientists are extending the toolbox for the innovations photovoltaics[15]. Another great advancement in AI and machine learning has been generated through achievements in the pursuit of and optimization of materials; such technologies accelerate novel compound discovery, predict behavior of material, and cut years off timelines pertaining to research and development. AI-powered models of solar cell design are also making fine-tuning of the architectures of the devices possible, with greater precision at the edges in terms of efficiency and scalability.

Large Area Perovskite Solar Cells

As perovskite solar cells have culminated from amazing laboratory records for efficiency, it is rather obvious that there are considerable barriers in scaling up a technology for large-area production. Stability still remains as the biggest issue since these cells are sensitive to degradation by environmental stressors such as water and heat. Future work down this road will be toward making tougher perovskite compositions, better encapsulation processes, and removal of issues related to lead toxicity by alternative materials. Roll-to-roll processing and inkjet printing will push perovskite technologies out of the research lab and into commercial markets at scales that will differ fundamentally from what they are today. Even though innovation often begins in academia, industry and governments have to collaborate speedily on the journey from discovery to market.

Interconnection to Energy Storage

Beyond the integration, synergetic integration of photovoltaic applications with energy storage systems ensures energy in a seamless, efficient, and self-sustaining manner. Eventually, combinations of solar cells with advanced batteries and supercapacitors will overcome the contentious aspect of solar power about the intermittence of solar energy in supplying electricity, which is both virtually and sufficiently all the time. Newer trends tend towards the tandem system where photovoltaic panels feed directly into energy storage devices, thereby eliminating most losses in conversion. Next-generation areas such as that of solar flow battery have lots of promise wherein it can conserve excess daylight energy produced during the day and distribute it at night. Technologies adopted will be pushing off-grid applications, electrical vehicle charging, smart grid systems.

Solar Cell Recycling and Sustainability

The photovoltaic industry dimension is ever larger in dimension and therefore sustainability in their manufacturing and recycling turns essential in their case. Recyclable solar panels have the very least expensive, not to say ineffective, recycling processes applied today and actually can reclaim but a few percent at best. Current research work in this field has focused on environmentally benign manufacturing techniques, the design of easily dismantled photovoltaic modules, and further improvement of recycling processes for silicon, silver, and other rare metals. Employment of nontoxic, readily available materials for future solar cells will bring further improvements in sustainability. With time, life cycle assessments are becoming increasingly used to evaluate the footprint of the photovoltaic technology environment, innovating further in alternative greener directions.

Among the sustainability advantages of this practice is that this not only reduces waste but also responds to increasing concerns over industry's long-term impact on resource supplies and ecosystems.

These new trends express the dynamic development of photovoltaic technologies. Fulfilling the promise of solar energy will demand material improvements, integration with energy systems, and sustainable practices to make photovoltaics a central component in a renewable energy strategy worldwide.

Left column: Structure of the Graphene-Based PV Cell

Graphene: Here, in this PV cell, graphene is the material used in the electrodes. Graphene is actually one atom thick layer of carbon atoms arranged in a hexagonal lattice structure with outstanding electrical conductivity, mechanical strength and flexure. In solar cells, graphene may improve charge collection efficiency and curb losses between the recombination electrons and holes.

MoS_2 (Molybdenum Disulfide): In the current device, the semiconductor is MoS_2. MoS_2 is a layered material classified under transition metal dichalcogenides, which family possesses a few unique electronic and optical properties within its monolayer counterpart, where it bears a direct bandgap, thus classifying it as one of the materials that could potentially absorb light efficiently enough to specifically manifest an energy conversion event within photovoltaic applications.

SiO_2/n-Si (Silicon Dioxide / n-type Silicon): It comprises the bottom layer of SiO_2 (Silicon Dioxide) and n-Si (n-type Silicon). Silicon is the most dominant material in the conventional photovoltaic technology. In this case, due to semiconductor n-type silicon, the photovoltaic device's charge carrier-generation capability under illumination. SiO_2 is an insulating layer[16].

Right Side: I-V Curve

Current Density (mA/cm²) vs. Voltage (V This is an I-V curve obtained to describe the electrical characteristics of the solar cell in test. The curve plots current density with applied voltage varied to a cell[17].

Efficiency (η = 11.1%): The efficiency of the reported PV cell is 11.1%. It is the percentage of solar power consumed by the device to form electrical energy. In short, better efficiency means better conversion. Though the number is significantly low compared to the conventional silicon-based cells, this definitely allows one to predict the future feasibility of using 2D materials like graphene and MoS_2 for future solar technologies.

Voltage and Current Density Points: The graph is typical of saturation current which corresponds to where the saturation current has occurred and open circuit voltage where the current is zero therefore it provides good performance metrics for the PV cell. [Fig.5]

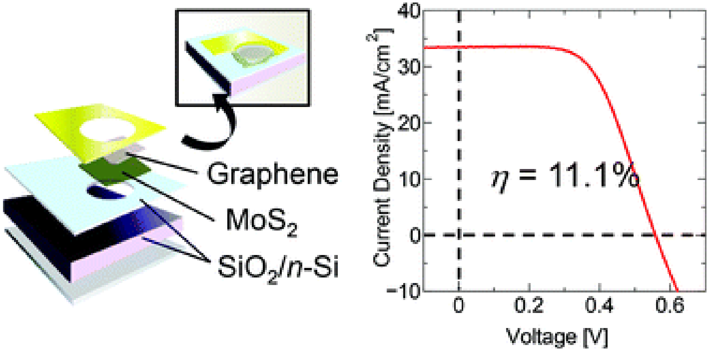

Fig 5.Effect of graphene materials on efficiency

Schematic representation of a graphene/MoS_2/SiO_2/n-Si heterojunction photovoltaic device and its corresponding current density-voltage (J-V) characteristic curve under illumination, showing a power conversion efficiency η of 11.1%. Introducing graphene and MoS_2 into the structure will enhance light absorption and charge transport within the structure.

Conclusion :

Silicon to graphene probably represents the paradigm shift in renewable energy science, since photovoltaic (PV) technology relies on the transition from the established silicon-based PV cells, though widespread and still so effective. Among other factors-they are reaching now their theoretical performance limits and have some serious problems related to cost, scalability, and the environment-fundamental and technological challenges call for graphene in this context as a two-dimensional material with extraordinary electrical, thermal, and mechanical properties. These applications include acting as an optically transparent electrode, charge carrier layer, and even as a thermal dissipation material in the next generation of solar cells. Graphene, with its tunable properties over regular silicon, promises better absorption of light, quicker charge transport, and minimum losses in terms of energy. Such effects are particularly conspicuous in hybrid and tandem cells, in which graphene is interposed between emerging materials such as perovskites and organic photovoltaics, thereby resulting in much better power conversion efficiencies and operative lifetimes. This revolutionary contribution of graphene shows it can play a very critical role in thermal management. It overcomes the inefficiency caused by overheating in conventional PV systems by bringing cooling materials, like TIMs, PCMs, and nano fluids, into optimal operating temperatures for extended functional life of solar panels and for energy yield increase. Furthermore, due to its eco-friendliness and very low weight, graphene is more fit for the developing flexible solar cells not only in wearable, robotics, but also in space exploration. Where graphene promises revolutionary PV technology, challenges still remain concerning scaled production, cost integration, and long-term stability. For the applications to become all-pervasive, breakthrough concerning fabrication techniques via CVD and doping methods will be necessary to unlock the potential power of graphene, while also making it commercially viable so that graphene-enhanced solar cells are efficient without making them inaccessible. From silicon to graphene, all these are crucial steps toward finding sustainable energy solutions. Leverage on those or even more excellent properties of graphene for photovoltaic technology can create more highly efficient and a broad area of application closer to the goals of global sustainability.

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