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Advanced Development of Sustainable PECVD Semitransparent Photovoltaics: A Review

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Energy is the driving force behind the upcoming industrial revolution, characterized by connected devices and objects that will be perpetually supplied with energy. Moreover, the global massive energy consumption increase requires appropriate measures, such as the development of novel and improved renewable energy technologies for connecting remote areas to the grid. Considering the current prominent market share of unsustainable energy generation sources, inexhaustible and clean solar energy resources offer tremendous opportunities that, if optimally exploited, might considerably help to lessen the ever-growing pressure experienced on the grid nowadays. The R&D drive to develop and produce socio-economically viable solar cell technologies is currently realigning itself to manufacture advanced thin films deposition techniques for Photovoltaic solar cells. Typically, the quest for the wide space needed to deploy PV systems has driven scientists to design multifunctional nanostructured materials for semitransparent solar cells (STSCs) technologies that can fit in available household environmental and architectural spaces. Specifically, Plasma Enhanced Chemical Vapor Deposition (PECVD) technique demonstrated the ability to produce highly transparent coatings with the desired charge carrier mobility. The aim of the present article is to review the latest semi-transparent PV technologies that were impactful during the past decade with special emphasis on PECVD-related technologies. We finally draw some key recommendations for further technological improvements and sustainability.

Keywords: nanostructred materials, semitransparent solar cells, renewable energy, PECVD, energy conversion

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INTRODUCTION

In recent decades, thousands of research reports related to green renewable energy have attracted the attention of scientists worldwide. One of the inexhaustible energy generation sources that can successfully suit mankind's need for sustainable socio-economic growth in an interconnected world is the sun (IEA, 2020; Jacobson et al., 2017; IRENA, 2020; Brinkerink et al., 2018; Kim et al., 2020; Huang and Luscombe, 2019; Burke and Lipomi, 2013). The direct conversion of sunlight to electricity, well known as photovoltaic energy conversion, has been successfully demonstrated using various photonic materials with high photon absorption capabilities classified in two main categories, organic and inorganic semiconductors (Nakamura et al., 2019; Kim et al., 2020). The successfully converted solar energy is used in daily life activities such as water heating, solar cooking, deep water pumping, household device PV powering, and clean hydrogen generation, out of a total annual provision of 18 TW solar energy available on the earth's surface (Smyth et al., 2005; Kalyanasundaram and Grätzel, 2012; Chandel et al., 2015; Aramesh et al., 2019; Kuang et al., 2019).

Sunlight to electrical energy conversion without the interference of any intermediary thermal generator leads to photovoltaic (PV) conversion. The PV conversion process takes place in an electron device, known as a solar cell, which is a component from which the power output is the conjunction of mechanical, electrical, and photophysical properties, mainly (Green, 2020). For decades, scientists have been working on the enhancement of key technical characteristics such as efficiency, which is expressed as a fractional relationship of the output generated current over the incoming absorbed photons under specific irradiance conditions (Green, 2020). Interestingly, several approaches were found to considerably enhance the efficiency of PV solar cells; these include intrinsic and extrinsic factors, both related to the thin films' deposition techniques (Kemell et al., 2005). Generally, thin film solar cell components are fabricated using various vacuum and non-vacuum deposition techniques such as sol-gel spin coating, spray coating, doctor blade, drop casting, dip coating, ink-jet evaporation, Pulsed Laser Deposition, Chemical Vapor Deposition (MOCVD), Molecular Beam Epitaxy (MBE), Electron-Beam Physical Vapor Deposition (EBPVD), magnetron sputtering, and Plasma Enhanced Chemical Vapor Deposition (PECVD) (Steirer et al., 2009; Eslamian, 2014; Eslamian and Zabihi, 2015; Lu et al., 2015; Leyden et al., 2016; Farrag and Balboul, 2017; Matur and Baydogan, 2017; Hodgkinson et al., 2018; Abzieher et al., 2019; Ji et al., 2019; Lim et al., 2021a; Smirnov et al., 2021; Sun et al., 2021).

An extensive survey by solar PV specialists established that there exist three generations of PV solar technology that have been reported so far (Khatibi et al., 2019; Green et al., 2020), among which semi-transparent photovoltaic solar cells (STPSCs) is one of the most promising for the next generation of environmentally friendly renewable energy sources (Lim et al., 2021b). STPSCs have been recently manufactured via thin films' deposition techniques such as Inkjet printing, Pulsed laser deposition (PLD), and PECVD as reported in recent studies. This includes perovskite solar cells which reached a record high efficiency of over 25% (Cheng et al., 2014; Xie et al., 2018; Corzo et al., 2020; Lim et al., 2021b). In addition, recent studies have demonstrated that the use of various protective and antireflective coatings, such as intrinsic a-Si:H layers, among others, can considerably enhance the performance of future generations of thin film solar cells (Uzum et al., 2017; Zhao et al., 2017; Li et al., 2020a; Bacal et al., 2020; Qu et al., 2021). The scientific community devoted to semitransparent solar cell technology research may consider the recent advent of monolithic Perovskite/Si tandem solar cells as a unique opportunity to reshape the current knowledge in the field, allowing the possibility to reach the Shockley-Queisser theoretical efficiency limit of 33% (Ail-Ashouri et al., 2020; Lu et al., 2020). The present review is mainly devoted to Semi-transparent solar cells technology with special focus on Plasma Enhanced Chemical deposition (PECVD)-based devices.

BACKGROUND OF BUILDING-INTEGRATED PHOTOVOLTAICS TECHNOLOGY

Building-integrated photovoltaics (BIPVs) are considered as the most promising option that will boost renewable energy among all PVs currently available in the market (IEA et al., 1996). Global reports from well-established renewable energy institutions ascertain that in the entire PV solar technology market, approximately USD 14.4 billion was attributed to BIPVs technology in 2020 (EMR, 2021). Considering that semitransparent solar cells are among the major components in BIPVs, this technology will obviously benefit from the net market growth estimated at about 20% for the next 6 years (see **Figure 1A**); (EMR, 2021). Prospective actors in the renewable energy sector have to consider two major categories of BIPV technologies depending on their architectural need, namely roof-based and façade-based BIPVs. Moreover, these categories are mainly shared among crystalline silicon and thin films solar technologies (see **Figure 1B**). Notwithstanding the perceived bright future of BIPV, stakeholders are constantly driven by the predominant circular economy vision of national governments, which are mostly eagerly engaged in the successful greener fourth industrial revolution. In a recent report by the Becquerel Institute, three BIPV products were defined. Among these, glazed semi-transparent BIPV offers flexibility for effective integration in both building roofs and façades (Curti et al., 2020); (see **Figure 1C**).

PV CELL WORKING PRINCIPLE

Put simply, a photovoltaic solar cell is an electron device characterized by three main parts, amongst which the photoactive layer, the electrons and holes transport layers, and the electrical contact layers are deposited on a transparent substrate (**Figure 2**).

The photoactive central layer is preferably a direct band gap semiconductor material that is highly sensitive to photon absorption throughout the entire electromagnetic solar spectrum. Moreover, the photoactive layer forms a PN junction with the electron transport layer, similar to a diode where electron-hole pairs "excitons" are generated after photon absorption (Gray et al., 2011). Consecutively, the generated charge carriers are dissociated due to the presence of an electric field at the PN junction as to allow electrons and holes to migrate at the negative and positive electrode terminal, respectively (**Figure 3**); (Markvart and Castaner, 2003). The resulting direct current flow throughout the device PN junction follows a single direction from the negative to the positive terminal. It is worth mentioning that among factors that affect the PV solar cell efficiency, the diffusion length is the most prominent which requires detailed time resolved fluorescence analysis for better understanding.

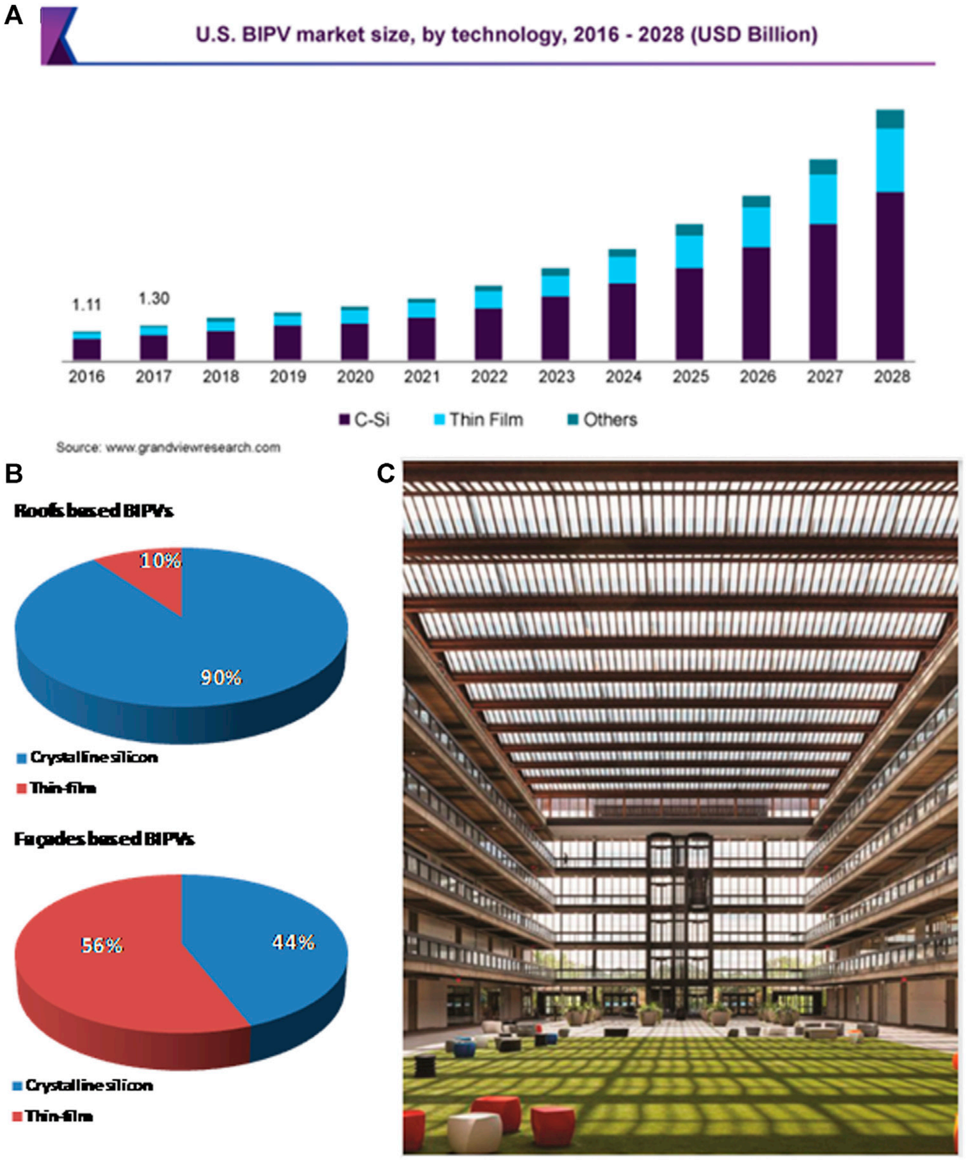

FIGURE 1 | (A) US forecast of BIPV market, © (2021) Grand View Research (EMR, 2021). **(B)** BIPV technologies split for **(top)** roof and **(bottom)** façade applications, respectively. Redrawn from (Zanetti et al., 2017). **(C)** Photograph of semitransparent BIPVs BellWorks, skylight, United States. Reprinted with permission © Onyx Solar (Curti et al., 2020).

PECVD DEPOSITION TECHNIQUE

Background

Plasma Enhanced Chemical Vapor Deposition (PECVD) was first demonstrated in the fifties and sixties at various laboratories. Their research outputs are among the most seminal traceable proofs known to date (Poole, 1953; Ennos, 1954; Christy, 1960; Baker and Morris, 1961; Christy, 1962; Alt et al., 1963; Ing and Davern, 1964). Since its discovery almost 6 decades ago, PECVD has successfully overcome the major drawbacks encountered in the use of other deposition techniques as well as conventional wet chemistry. Moreover, PECVD is one of the main processes used in the nanofabrication of electron devices in order to deposit high quality thin film semiconductors (Jeong et al., 2020). Generally, in nanofabrictation, PECVD of a thin film immediately follows the doping of silicon compound film pre-grown on Si wafer with either Arsenic, phosphorous, or boron via Ion Implantation which aims to tune the conductivity, relative to a particular technology application of the semiconductor industry (Skorupa et al., 1987; Yokota et al., 1994). Consecutively to PECVD process, a lithography process is used to apply a pattern on the thin film semiconductor via a pre-coated photoresist film using either

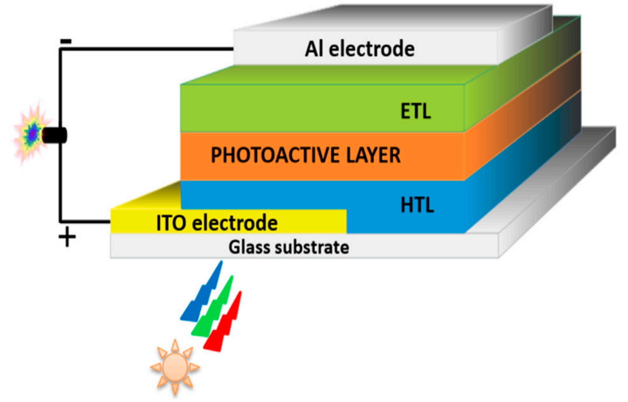

FIGURE 2 | Structure of organic PV solar cell device (ETL and HTL denote electron and hole transport layer, respectively).

EUV light or electron beam (Desai et al., 2016; Shamma et al., 2016; Van de Kerkhof et al., 2021).

Fundamental Principles

The PECVD thin films deposition technique is a complex process deriving from the conventional chemical vapor deposition (CVD) which can operate either in open or closed reactor configurations, the latter being the most convenient for industrial usage (Martinu et al., 2010). Generally, the operation of CVD systems consists of filling the reaction chamber with reactants via a supply section designed to allow easy delivery of solid, liquid, or gaseous reactants for substrate coating under vacuum (**Figure 4**). However, due to the drawbacks resulting from solids and liquids reactants management, gaseous reactants are used in PECVD processes in which the reactant is delivered in the reaction chamber via gas-flowing elements, coupled to computer-controlled pressure controllers. The chemical reaction is activated by a low-temperature inductively/capacitively-coupled plasma produced by DC or RF power source, which, in contrast to other CVD techniques, uses the plasma as a source of activation energy instead of high temperatures, allowing much larger flexibility in substrates and samples diversity (Bera et al., 2002). It is worth mentioning that the produced plasma has the characteristics of the "inert" carrier gas, such as Ammonia, Argon, Helium, Nitrogen, and Oxygen, used in the process, including their derived forming gasses. PECVD-deposited thin films' high quality and superior properties are governed by various parameters including RF power, plasma temperature, reactor pressure, gas phase diffusion, and gas flow rate in addition to the types of carriers and reacting gases. Typically, the neutrally charged and highly energetic plasma used during PECVD thin films deposition is a partially or totally ionized gas composed of charged particles, electrons, and neutral atoms constituents (Hamedani et al., 2016). The main PECVD setups are presented in the next sections.

Over the years, tremendous advancements have resulted in the development of several plasma technologies to fit scientific research needs. This has led to the identification of two major plasma classifications: thermal and non-thermal plasma. The class of thermal plasma techniques includes inductively coupled plasma (ICP) (Jatta et al., 2019), electron cyclotron resonance chemical vapor deposition (ECR-CVD) (Hu et al., 2015), direct-current plasma (DCP) (Wahyudiono et al., 2020), direct current-inductively coupled (DC-ICP) hybrid (Kambara et al., 2014), and plasma spraying (Navidpour et al., 2017). On the other hand, capacitively coupled plasma (CCP) (Fang et al., 2016), Dielectric barrier discharge (DBD) (Tsai et al., 2020), Glow discharge (GD) (Schmitt et al., 1988), Plasma Enhanced Atomic Layer Deposition (PEALD) (Jin et al., 2013), and DC Magnetron sputtering (Kim et al., 2012) are non-thermal plasma deposition techniques. Despite the progress made in the Plasma technologies, there is still hot debate on the constituent of the deposited film mass because the ions and neutral species present in the plasma behave differently depending on the dynamic physical and chemical conditions (Michelmore et al., 2015).

Inductively Coupled Plasma

In the inductively coupled plasma (ICP) deposition, the ionized gas is obtained by coupling the electromagnetic field produced by a coil within the reaction chamber without the need for paired electrodes (Cuxart et al., 2017). The radiofrequency (RF)-ICP is a thermal plasma system which can perform thin films deposition in a wide variety of environments, such as oxidizing, reducing, inert, and many more reactive atmospheres (Cuxart et al., 2017). It is worth noting that ICP-PECVD configuration allows an extremely high purified environment appropriate for the synthesis of nanomaterials requiring accurate control of morphology and chemistries (Cuxart et al., 2017). The ICP configuration is advantageous as compared to its counterpart due to its higher energy density capabilities; its setup is presented below in **Figure 4**.

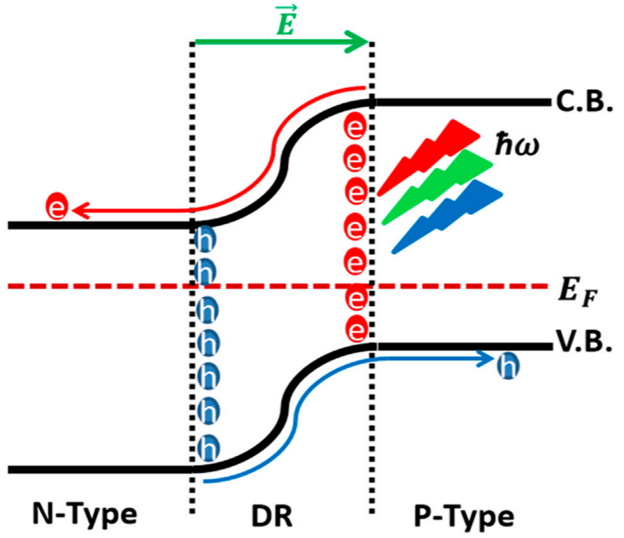

FIGURE 3 | Schematic band diagram of a solar cell device as a PN junction.

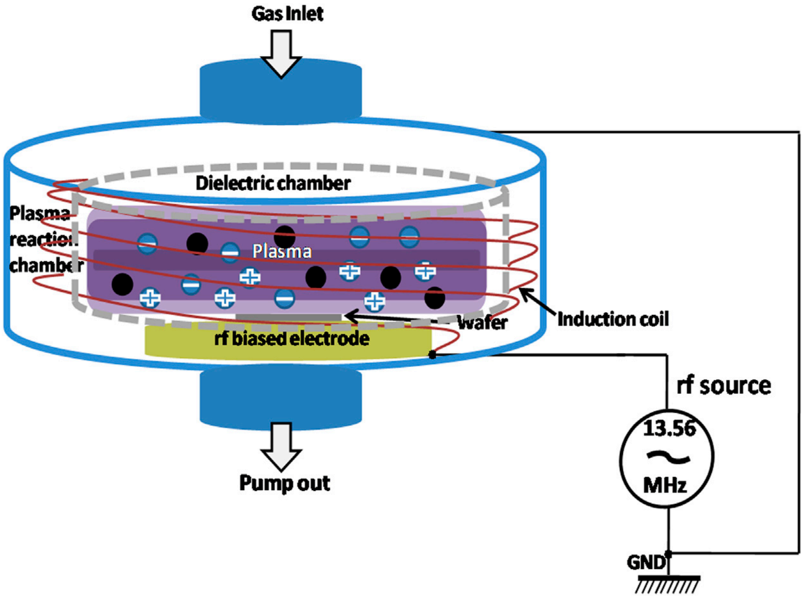

FIGURE 4 | Schematic configuration setup of Inductively Coupled Plasma.

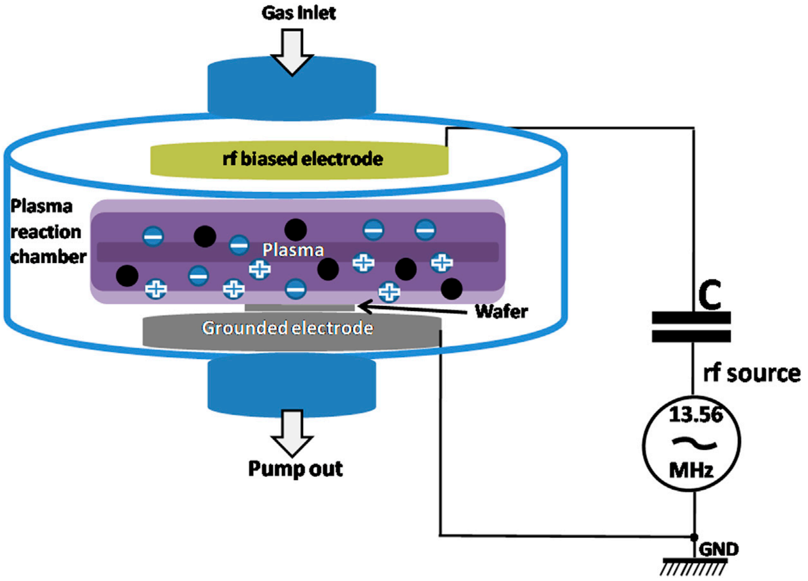

FIGURE 5 | Basic schematic principle of Capacitively Coupled Plasma.

Capacitively Coupled Plasma

In the plasma deposition system industry, most non-thermal radio frequency plasma are generated by capacitively coupling two metal electrodes short-distanced placed in the reaction chamber, one of which is connected to a single frequency microwave RF power source (13.56 MHz) and the other of which is grounded (Ohtsu, 2018). Upon electric field appearance in between the electrodes, atoms are ionized in order to release electrons which are accelerated by the RF electric field to produce secondary electrons leading to electron-avalanche due to the exponential field increase (Ohtsu, 2018). Consecutively, an electron-avalanche breakdown will make the gas electrically conductive due to its large number of bind-free electrons and allow perfect surface coating (Ohtsu, 2018). The schematic principle of CCP, which is similar to a conventional capacitor, is presented in **Figure 5**.

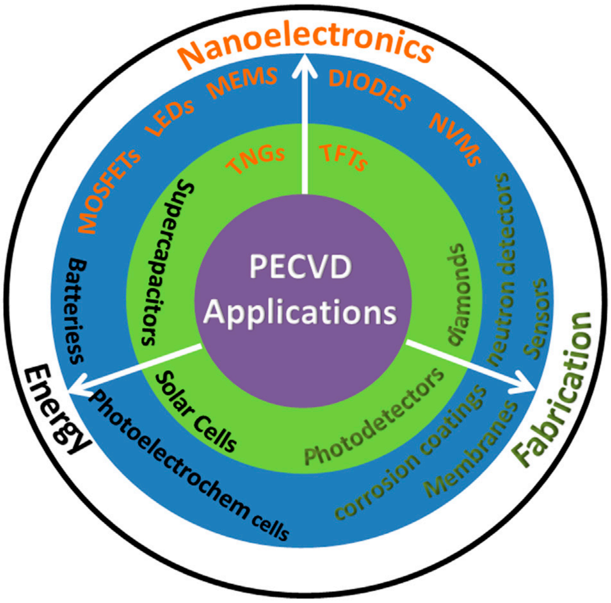

FIGURE 6 | Various applications of PECVD.

Technology Application

PECVD is promising in the entire nanofabrication of semiconductor-based devices (see **Figure 6**), however, there is still room for improvement when real device commercialization comes in to play. It is worth noticing that notable results such as in Solar cells (Gabriel et al., 2014), Light emitting diodes (LEDs) display (Park et al., 2019), Sensors (Forleo et al., 2009), photocatalysis (Nada et al., 2017), triboelectric nanogenerators (TNGs) (Wang et al., 2016), Thin Film Transistors (TFTs) (Park et al., 2008), non-Volatile Memories (NVMs) (Choi et al., 2007), integrated circuits (Zhang et al., 2013), neutron detection (Bute et al., 2021), diamond growth (Mankelevich and May 2008), photonic waveguides (Neutens et al., 2019), energy storage (Quesnel et al., 2016), and UV photodetectors (Chao and Wei, 2015) are essential to the successful development of the next generation of commercially viable electronic devices.

SEMITRANSPARENT PECVD SOLAR TECHNOLOGY

The concept of semitransparent electron devices dates back to the early 2000s when Forrest's group first successfully demonstrated semitransparent cathodes for organic light emitting devices prior to its solar cells application 6 years later (Burrows et al., 2000; Bailey-Salzman et al., 2006). Moreover, the promise of the concept was successfully followed by the so-called inverted solar cell configuration which was initially applied to organic photovoltaic solar cells (OPVSCs) in Yang's group (Li et al., 2006). In his seminal work on semitransparent OPVSCs, Bailey-Salzman et al. (Bailey-Salzman et al., 2006) astoundingly envisioned the use of multiple paints in the form of thin films coated on building walls and windows to generate power (Chae et al., 2014). Fifteen years later, tremendous progress (see **table 1**) was made on the use of this architectural-friendly concept which has been successfully integrated in other solar cell technologies, among which the most prominent based on PECVD are discussed in the following subsections.

Silicon Solar Cells

Recently, a group of scientists developed a semitransparent non-stoichiometric photovoltaic solar cell based on Si-rich $\mathrm{Si_xC_{1\text{-}x}}$ p-i-n grown by hydrogen-free PECVD at low plasma power (Cheng et al., 2014). During the fabrication process using RF plasma power ranging from 20–100 W (40W step) at a power density of 560 mW cm^{-2}, the optical bandgap of Si-rich $\mathrm{Si_xC_{1\text{-}x}}$ absorbing layer was effectively controlled by varying the Si/C ratio. Moreover, the device absorbing layer was sandwiched in between a $\mathrm{Si_xC_{1\text{-}x}}$:P and $\mathrm{Si_xC_{1\text{-}x}}$:B which were doped at various fluences to accurately define their conductivity for ensuring optimal charge mobility across the device. Furthermore, the charge collection process was realized using ITO and Al electrode which were connected to P-type SiC and N-type SiC films respectively (see **Figure 7**). Ultimately, the optimized device fabricated with an absorbing layer of 25 nm exhibited the highest power conversion efficiency (Cheng et al., 2014). The optimization of deposition parameters remains a key challenge for better performance of the devices (see **table 2**).

In 2014, Chae and colleagues (Chae et al., 2014) successfully integrated semitransparent solar cells in building windows via building integrated photovoltaic (BIPV). In the study, two parameters were considered to evaluate the performance of the devices: the thickness of a-Si:H absorbing layer and the applied texture. The p-i-n absorbing layer was deposited via PECVD at 250°C on glass substrate pre-coated with ZnO:Al film. Moreover, the tuning of parameters revealed enhanced power conversion efficiency (PCE) in the device with 180 nm thicker absorbing layer, the performance of which was further improved with texturing to reach 6.3% PCE.

Elsewhere, Kang et al. (Kang et al., 2019) applied engineering light absorption to fabricate a transparent solar cell with a 70 nm thick SiN AR coating deposited via PECVD on the SiMW tips. The resulting J_{SC} considerably increased from 17.07 to 18.94 mA cm^{-2} while the other key parameters did not undergo the expected changes due to the decrease of V_{OC} and ideality factor FF relative to the device without SiN AR layer. The authors attributed the V_{OC} decrease to the localization of the n-Si and p-PEDOT heterojunctions which formed only on the side surface and not on the top surface of SiMWs, resulting in hampering electron-hole pairs' generation.

Perovskite Solar Cells

Nowadays, perovskite solar cells are recording unprecedented momentum across the scientific community worldwide due to their versatile properties and easy and sustainable processing (Leyden et al., 2016; Jain et al., 2019; Tavakoli et al., 2019; Zhu

TABLE 1 | Summary performances of the representative semitransparent PV solar cells.

Cell type	Cell structure	Device layers	Avt (%)	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF (%)	PCE (%)	Ref. (Year)
Perovskite	Single	ITO/Glass/NiO//$(C_sFAMA)Pb(IBr)_3$//PMMA:PCBM/ZnO/IZTO	12.89	19.02	1070	76.88	15.72	Lim et al. (2021a)
Perovskite	Single	ITO/Glass/SnO_2//Perovskite//spiro-MeOTAD/MoO_x/AZO/Ag	–	20.6	1200	68.4	16.6	Li et al. (2020b)
Polymer	Single	ITO/Glass/ZnO//PBDB-T:PTAA:Y1//MoO_3/Au/Ag	20.1	19.7	860	69.1	12.1	Cheng et al. (2020)
n-Silicon	Single	n-Si/SiO_2//SiMPF//IZO/PEDOT:PSS	10	22.54	537	66.7	8.07	Kang et al. (2019)
Perovskite	Single	FTO/Glass/p-SnO_2//Perovskite//spiro-MeOTAD/Ag/ITO	–	21.52	1060	77.5	17.7	Dewi, (2019)
Perovskite	Single	ITO/Glass/PTAA//$MAPbI_3$//PCBM/C_{60}/BCP/Cu/Au	–	20.6	1080	74.1	16.5	Chen et al. (2016a)
Perovskite	single	FTO/glass/bl-TiO_2 //$MAPbI_3$//spiro-OMeTAD/Li-TFSi/Au	36.6	19.2	950	64	11.7	Chen et al. (2016b)
Perovskite	Single	MgF_2/ITO/glass/cp-TiO_2//Perovskite//Spiro-MeOTAD/MoO_x/ITO/Au/Pt	–	–	–	–	12.2	Duong et al. (2016)
Perovskite	Single	FTO/Glass/ZnO/PCBM //$CH_3NH_3PbI_3$//Spiro-OMeTA/MoO_3/In_2O_3:H	–	17.4	1104	73.6	14.2	Fu et al. (2015)
Perovskite	Single	FTO/Glass/TiO_2 //Perovskite//Spiro-OMeTAD/PEDOT:PSS/PDMS/PMMA/Graphene	–	19.17	960	67.22	12.37	You et al. (2015)
Polymer	Single	PTB7-th:ATT-2	37	18.53	712	59	7.74	Liu et al. (2017)
i-SiC	Tandem	Al/a-SiH://i-SiC//N-type SiC/a-SiH://i-SiC//N-type SiC/ITO	–	19.1	780	35	5.24	Cheng et al. (2014)
a-Si:H	Single	Glass/ZnO:Al//a-Si:H	–	10.1	904.6	68.6	6.3	Chae et al. (2014)
Polymer	Single	ITO/Glass/ZnO //PCDTBT/PCBM/ITIC//Ag/MoO_3	39	8.65	895	51.9	4.02	Sano et al. (2019)
Polymer	Single	PET/Ag/FPI-PEIE //PBDTT-F-TT:PCBM//MoO_3/UTMF-Ag/TeO_2	–	18.25	810	0.70	10.4	Huang et al. (2015)
Polymer	Single	ITO/glass/ZnO-NPs/SAM //P3HT/PCBM/PEDOT:PSS//Ag	–	10.25	620	66.6	4.20	Hau et al. (2009)

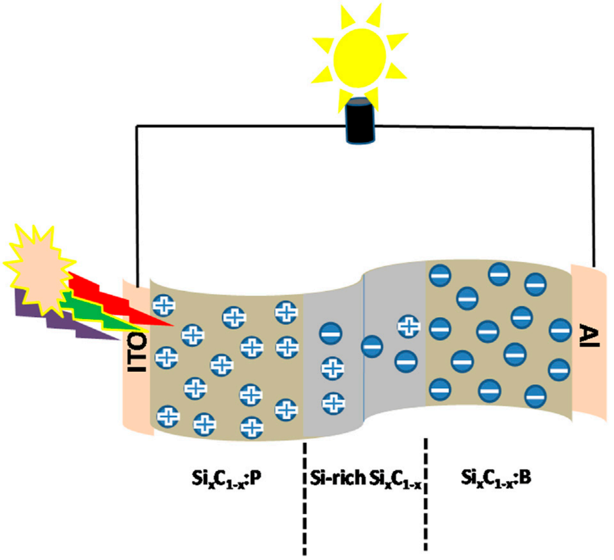

FIGURE 7 | Schematic drawing of the device structure.

et al., 2019; Elseman et al., 2020a; Asuo et al., 2020; Elseman et al., 2020b; Rahmany and Etgar, 2020; Selim and ElsemanHao, 2020; Xu et al., 2020; Chen et al., 2021; Cui et al., 2021; Heshmati et al., 2021; Jeong et al., 2021; Tong et al., 2021). In 2018, a research group innovatively demonstrated that the application of atmospheric pressure plasma enhanced chemical vapor deposition (AP PECVD) can contribute to improving the efficiency of a perovskite solar cell. Technically, the roll-to-roll plasma system used Argon gas flow and an audio frequency power supply (3.4 kHz) which activated the plasma under a potential of 4 and 8 kV to achieve 10.68 m hr^{-1} line speed for the deposition of mesoporous TiO_2 film (Hodgkinson et al., 2018). The deposited film served as the hole blocking layer coated on top of the TCO of the solar cell; afterward, the performance of the device was compared to a reference cell with the TiO_{2-x} electron transport layer sputtered using an RF source at 60$\underline{\text{o}}$C in argon along with oxygen at a pressure of 7.5 x 10^{-6} mbar (Hodgkinson et al., 2018). It is worth mentioning that this strategy consisting in the tuning of the electronic properties of the Electron transport layer and/or hole transport layer was found to be beneficial in the decline of their parasitic absorption (Li et al., 2020b).

In a completely different study, the optimized use of Aluminum-doped ZnO (AZO) as a transparent electrode (TE) of a semitransparent perovskite solar cell (ST-PSCs) in a tandem perovskite/Si device contributed to reaching power conversion efficiency (PCE) of 23.1% (Li et al., 2020b). The authors particularly stressed the crucial role of the transparency and conductivity of the TE in the high performance of ST-PSCs which constituted the top part of the tandem device. Interestingly, the AZO layer was found to bring more stability in the device relative to devices without an AZO layer (Li et al., 2020b). Moreover, in this tandem solar cell device, the PECVD technique was successfully used to deposit the lower silicon bi-layer TOPCon structure, including the hydrogenated silicon nitride (SiN_x:H) which served as anti-reflection coating and front passivation layer. Finally, the tandem semitransparent concept demonstrated to perform better with PCE reaching over 20% (Chen et al., 2016a; Dewi, 2019).

TABLE 2 | Summary of PECVD parameters used in semitransparent PV solar cells thin films' growth.

Gas	Temperature (°C)	Layer	Gas flow rate	RF power (W)	Voltage (kV)	Pressure (Torr)	Ref
Ar-SiH_4, CH_4	550	i-SiC	–	20–100	–	0.08	Cheng et al. (2014)
–	250	a-Si:H	–	–	–	–	Chae et al. (2014)
–	–	SiMPF	–	100	–	0.04	Kang et al. (2019)
Ar	60	TiO_{2-x}	14.6 L min^{-1}	–	4, 8, 10	–	Hodgkinson et al. (2018)
–	–	AlO_x/SiN_x	–	–	–	–	Dewi, (2019)
TMD, PH3, SiH4	–	a-Si:H	–	–	–	–	Chen et al. (2016a)

CONCLUDING REMARKS AND FUTURE PROSPECTS

The present review highlighted the recent advances in the development of semitransparent solar cells, which offers a promising future in building integrated photovoltaic applications. The review shows that the emergence of semitransparent solar cell technologies is mainly driven by research undertaken in polymer solar cells, perovskite solar cells, and Si-based solar cells. To be more concise, we focused our effort on semitransparent technologies that used the versatile advantages offered by PECVD technique owing to its applicability in matured industrial manufacturing processes. We surprisingly realized that, despite the unique strengths of PECVD thin film deposition, very limited numbers of reports on semitransparent solar cells are available to date. Nonetheless, PECVD demonstrated its efficacy in several semitransparent solar cells including monolithic perovskite/Si tandem solar cells, which are currently exhibiting the highest power conversion efficiency in the entire field.

Considering factors that hamper the optimal performance of semitransparent solar cells, mainly polymers and perovskites-based PV, some recommendations are necessary to contribute to improving the manufacturing processes of future generations of semitransparent solar cells:

1) Encapsulation of the device using a thin dielectric layer with higher resistance to UV degradation and thermal oxidation in addition to a good light transmission aiming to combat oxygen infiltration and moisture. Particular care will be required to ensure that the encapsulating layer exhibits higher oxygen transmission rate (OTR) and water vapor transmission (WPTR), which are governed by Fick's law (Uddin et al., 2019).
2) Reinforced PECVD is one of the most adapted solutions to perform encapsulation at low temperatures. However, stringent precautions are recommended, especially the passivation of intrinsic defects which persist to single layer encapsulation.

Looking ahead, great effort is still required to innovatively design and fabricate industrially viable high quality and colorless semitransparent photovoltaic solar cells that meet the requirement for building and window integration. This includes the stringent control of PECVD parameters/factors such as gas flow rate, pressure, voltage, gas mixture, rf power, platen temperature, and plasma chemistry during the formation of the various layers and the application of tunnel oxide passivating contacts (Yoon et al., 2020).

AUTHOR CONTRIBUTIONS

GK: Data acquisition, investigation, analysis, writing-original draft manuscript; MD: Supervision, resources, project administration, writing-draft review, funding acquisition. BM: supervision, administration and technical support.

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