Transformation, reaction and organization of functional nanostructures using solution-based microreactor-assisted nanomaterial deposition for solar photovoltaics

ABSTRACT

Microreactor-Assisted Nanomaterial Deposition (MAND) process offers unique capabilities in achieving large size and shape control levels while providing a more rapid path for scaling via process intensification for nanomaterial production. This review highlights the application of continuous flow microreactors to synthesize, assemble, transform, and deposit nanostructured materials for Solar Photovoltaics, the capabilities of MAND in the field, and the potential outlook of MAND.

Microreactor-Assisted Nanomaterial Deposition (MAND) is a promising technology that synthesizes reactive fluxes and nanomaterials to deposit nanostructured materials at the point of use. MAND offers precise control over reaction, organization, and transformation processes to manufacture nanostructured materials with distinct morphologies, structures, and properties. In synthesis, microreactor technology offers large surface-area-to-volume ratios within microchannel structures to accelerate heat and mass transport. This accelerated transport allows for rapid changes in reaction temperatures and concentrations, leading to more uniform heating and mixing in the deposition process. The possibility of synthesizing nanomaterials in the required volumes at the point of application eliminates the need to store and transport potentially hazardous materials. Further, MAND provides new opportunities for tailoring novel nanostructures and nano-shaped features, opening the opportunity to assemble unique nanostructures and nanostructured thin films. MAND processes control the heat transfer, mass transfer, and reaction kinetics using well-defined microstructures of the active unit reactor cell that can be replicated at larger scales to produce higher chemical production volumes. This critical feature opens a promising avenue in developing scalable nanomanufacturing. This paper reviews advances in microreactor-assisted nanomaterial deposition of nanostructured materials for solar photovoltaics. The discussions review the use of microreactors to tailor the reacting flux, transporting to substrate surfaces via controlling process parameters such as flow rates, pH of the precursor solutions, and seed layers on the formation and/or transformation of intermediary reactive molecules, nanoclusters, nanoparticles, and structured assemblies. In the end, the review discusses the use of an industrial scale MAND to apply anti-reflective and anti-soiling coatings on the solar modules in the field and details future outlooks of MAND reactors.

Keywords: solution deposition · thin-film · nucleation & growth · nanostructure

Discussion

- Nanostructures with suitable properties for solar PV applications were fabricated by controlling the nanoparticles’ reaction, organization, and transformation using MAND.

- Using scalable nanomanufacturing techniques like MAND coatings on existing solar modules to enhance their performance will be easier and more cost-effective.
Introduction

With the world’s ever-increasing energy consumption and the fact that a significant share comes from fossil fuels, it is essential to increase sustainable energy production that is feasible and reliable for the public. Solar energy is a good choice of renewable energy source, with solar photovoltaic capacity at 500 GW in 2018. However, these solar cells lose a significant amount of energy due to light reflection, dust and/or particulate accumulation, and heating. Over the years, researchers have conducted many innovative works to improve solar photovoltaic performance using nanostructured materials, including nanostructured coatings that will enhance light absorption and minimize reflection. Superhydrophobic coatings that are self-cleaning, bandgap engineering of nanostructured films and thermal management of solar cells. Nucleate pool boiling is a widely studied method for thermal management in electronics cooling, batteries, and power plants. One of the paths to enhance heat transfer efficiency is surface engineering with nanostructured coatings. There have been few works in terms of passive heat management techniques, such as metamaterials, graphene/Ag hybrid film, and SiO$_2$ particles, to mitigate the adverse thermal effects. These nanostructures and nanostructured films (nanocrystalline, nanoporous, core–shell, nanocomposites, nanowires, nanorods, and QDs) may be artificial designs or nature-inspired designs from plants (epidermal cell of leaves of shade adapted plants), insects (moth-eye and butterfly wings) and other organisms (bacterial chlorosomes). Various fabrication methods have been exploited to study the effect of nanostructures, including physical and chemical deposition techniques, namely nanoimprint lithography, electrodeposition, soft imprinting method, rapid ion etching, magnetron sputtering, chemical vapor deposition and many other different techniques. These studies proved that these nanostructured coatings increase the overall performance of PV devices. Ma et al. fabricated micro and nano structured CaF$_2$ coatings by magnetron sputtering. The coatings demonstrated good transmittance, average reflectance below 6% at incident angles between 45° and 90° and a water contact angle of 139.4°. When 10% CaF$_2$ coatings are deposited on the solar cell, the short current density is about 17.8%, 8.8%, and 7.6% higher than uncoated glass when the incident angles were at 30°, 60°, and 90°. Nonetheless, most of these fabrication techniques require high capital cost equipment, and some require high vacuum/very high temperatures. As a next step, scalable and cost-effective nanomanufacturing processes are critical to translating these innovative nanostructured solutions into real-world applications.

Chemical solution deposition (CSD) and chemical bath deposition (CBD) are promising deposition methods due to their potential for large-area fabrication, low-temperature processing, and simplicity. CSD and CBD can deposit a wide variety of materials, including unary elements, binary, ternary, or multinary metal oxides, sulfides, selenides, tellurides, halides, and nitriles. CdS nanostructures with appropriate bandgaps (~2.5 eV) for solar cells, observe an efficiency increase from 5.67 to 9.59% when the TiO$_2$ electrode was modified by dip-coating with HfO$_2$ due to enhanced dye absorption. Other nanomaterials for solar PV applications synthesized through CSD or CBD processes include 2.5% conversion efficient ZnO nanorods based inorganic solar cells, ZnO nanorod arrays that saw a 170% increase in PV conversion efficiency when implemented in Si solar cells, and Ge-alloyed CZTS thin films with an efficiency increase from 3.82% to 4.72% corresponding to the non-alloyed absorber layer. Some of the other materials deposited by these chemical deposition methods are listed in Table 1.

However, despite their versatility, low cost, and large-area potentials, CSD and CBD have technical issues limiting their utility. A vital problem of the batch CBD process is its difficulty in controlling the reaction rate once it starts. The compound is continuously deposited from a super-saturated solution everywhere in the solution, including the container walls. The homogeneous reaction in which nanoparticles form in the solution results in a lower yield of reactant conversion to film, which is a significant problem of the batch CBD process. The depletion of reactants from the homogeneous particle formation would also limit the achievable terminal thickness by batch CBD processes. One remedy to slow down the homogeneous precipitation in the batch CBD process is to add complexing agents or a buffer reagent, but that would slow down the surface deposition reaction. Chang and Paul’s research groups at Oregon State University developed two different MAND techniques to leverage, improve and expand the CSD and CBD chemistry. Figure 1a-c show a simple schematic of a MAND reactor with different zones, pathways to final nanostructured films, and progress of various building blocks deposited, respectively. These techniques are microreactor-assisted solution deposition (MASD) and nanoparticle deposition (MANpD). In the former process, short-life reactive ions and molecules generated from the microreactor enable the heterogeneous growth of nano-crystalline thin films on the substrate surface. In the latter technique, the nanoparticle growth, size, shape, and morphology are controlled and generated by a homogeneous reaction within the microreactor before being deposited on the substrate surface. Choi et al. reviewed the MASD process for thin-film semiconductors and the potential of scaling up these processes for large-scale manufacturing of thin films and coatings. There is, however, no review article yet on the MAND processes focusing on guiding reaction, assembly, and transformation of nanomaterials to fabricate the nanostructured PV materials.

This review will first introduce the principles and crucial parameters that affect the reaction, organization, and transformation of nanostructures using the MAND systems, followed by a brief discussion on different types of PV systems and where MAND comes into the picture. This work also highlights nanostructured photovoltaic thin films synthesized by controlling reaction, organization, and transformation by adjusting the crucial experimental parameters. The application of MAND in the field is discussed. Finally, we presented the challenges and outlook of MAND at the end.
Table 1. Examples of materials deposited by CSD and CBD.

| Materials    | Deposition method | Remarks                                                                 | References |
|--------------|-------------------|-------------------------------------------------------------------------|------------|
| AgBr, AgCl, AgI | —                 | Silver halides were deposited on the glass slides using silver nitrate and halogenobalcohols | 53         |
| Ag$_2$S      | Spin coating      | Ag$_2$S nanostructured film was fabricated by high-speed rotating thermal decomposition during the sequential spin coating of precursor solutions | 63         |
| BaWO$_4$     | Microwave-CBD     | BaWO$_4$ with a dumbbell, kernel, bowknot, and cauliflower microstructures was obtained by changing the reaction time and initial concentration of the precursors used in the reaction system | 64         |
| BiI$_3$      | Spin coating      | BiI$_3$ and MAI precursors were used to synthesize MBI precursor solution and spin-coated to obtain BiI$_3$ nanofibers | 65         |
| CdSe         | CBD               | CdSe nanocrystals were synthesized from the direct reaction between Cd$^{2+}$ and Se$^{2-}$ by appropriately controlling pH and concentration | 66         |
| CdSe$_{1-x}$S$_x$ | CBD             | Cadmium chalcogenide films with a tunable bandgap of 1.86–2.15 eV were deposited by CBD by varying the sulfur content | 67         |
| CdTe         | CBD               | Cd (OH)$_2$ films were first deposited on the glass slides with Cd (NO$_3$)$_2$ as the precursor source in an H$_2$O$_2$ solution. Later, the slide was immersed in a bath with a pre-prepared telluride precursor solution to fabricate CdTe thin films | 68         |
| Cd$_x$Zn$_{1-x}$O | Spin coating  | Acetate salts of Cd and Zn with MEA stabilizer were prepared in a sol–gel solution for spin coating films | 69         |
| CdZnS        | CBD               | Sulfate salts of Cd and Zn were used to deposit CdZnS films chemically. A CIGS based solar cell (glass/Mo/CIGS/CdZnS/i-ZnO) was numerically simulated, and an increase in efficiency was observed with an increase in Zn$^{2+}$ concentration | 70         |
| CsPbI$_2$Br$_2$ | Spin coating   | The deposition solution was made by PbBr$_2$ and CsI precursors in DMSO. This perovskite solar cell achieved higher open-circuit voltages using the In$_2$S$_3$ ETL layer | 71         |
| CsPbI$_{3-x}$Br$_x$ | Spray coating | CsPbI$_3$ precursor solution was spray-coated on to CsPbI$_3$Br layer to form graded thin films and resulted in solar modules with a PCE of 13.82% | 72         |
| Cs$_2$SnI$_6$ | Spray coating     | CsI and SnI$_2$ precursors dissolved in DMF were spray-coated onto a CBD deposited CdS layer to fabricate solar cells on FTO glass substrates. Photoconductive films with an optical bandgap of 1.36 eV were obtained using this method | 73         |
| CuBiS$_2$    | CBD               | Binary metal sulfide NPs were deposited on TiO$_2$ coated FTO substrate using copper nitrate, bismuth nitrate, and sodium thiosulfate precursors | 74         |
| Materials            | Deposition method | Remarks                                                                                                                                                                                                 | References |
|----------------------|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Cu(In,Ga)Se2         | Spin coating      | A viscous paste of mixed metal nitrates was synthesized by condensing the solution mixture under reduced pressure. The mixed metal oxide film formed was sulphurized and selenized sequentially to get CIGSSe films | 75         |
| CuInTe2              | Spin coating      | Hydrazine-based precursors were synthesized using Cu2S and In2Te3.                                                                                                                                       | 76         |
| CuO                  | CBD               | CuO NPs were deposited on a Si substrate by adding the complexing agent drop-by-drop to the precursor solution at 60 °C.                                                                           | 77         |
| Cu2O QDs             | CBD               | Cu2O QDs were deposited on the ITO glass substrate using CuSO4 and Na2S2O3 precursors in this CBD process. The ITO substrate was previously coated with ZnO nanorod arrays to fabricate heterostructure PV devices | 78         |
| Cu2SnS3              | CBD               | Binary chalcogenide was fabricated by annealing stacked SnS/Cu layers deposited by CBD.                                                                                                                 | 79         |
| Cu4S                 | CBD               | Copper sulfate and thiourea precursor sources are deposited and annealed at 60 °C to form a Cu4S back contact layer.                                                                                      | 80         |
| CuTe                 | M-CBD             | p-type CuTe was fabricated using modified CBD process without oxide impurities.                                                                                                                         | 81         |
| Cu2ZnSnS4 (CZTS)     | Spray coating     | Aqueous solutions of Cu, Zn, Sn, and S precursors were spray deposited on preheated Mo substrate, and further sulfurization of the deposited film was conducted at 600 °C.                                         | 82         |
| InN                  | Spin coating      | Indium nitrate dissolved in ethanol was spin-coated on a glass substrate, and NH3 was used for nitridation.                                                                                               | 83         |
| In2S3                | Spin coating      | An inverted organic solar cell device (ITO/In2S3/P3HT: PCBM/MoO3/metal), In2S3 EIL was fabricated using a sol–gel spin coating technique at low temperatures.                                               | 84         |
| In2S3                | CBD               | The ETL for inorganic perovskite solar cells was fabricated by low-temperature CBD using thioacetamide and indium chloride precursor sources. These films resulted in a PCE of 5.59% compared to 5.02% using the TiO2 layer | 71         |
| CI-MAPbi3            | Spray and spin coating | MAI, PbI2, and MACI were dissolved in an NMP and DMF solvent mixture. The ink was deposited on FTO coated glass using both spin coating and spray coating techniques. The performance of films deposited by both these techniques is comparable | 85         |
| MAPbi3               | Dip-coating       | Sequential dipping in Pb(NO3)2 and MAI solution led to the formation of the perovskite layer on a solar cell, resulting in a PCE of 12.41%                                                                  | 86         |
| Materials                | Deposition method | Remarks                                                                                                                                                                                                 | References |
|--------------------------|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Mg-CZTS                  | Spin coating      | Mg-doped CZTS films were fabricated with different Mg concentrations using acetate salts of corresponding metals and were subsequently dissolved in 2-Me for spin coating. The produced films were used to investigate the bandgap of CZTS for solar cell applications  | 87         |
| Mn-CdO                   | Spin coating      | Acetate salts of Cd and Mn were used to deposit CdO films and Mn-doped CdO films with tunable bandgaps by changing Mn concentration                                                                              | 88         |
| MoS₂                     | CBD               | A synthesized precursor source for both Mo and S was used in the CBD bath. Hydrazine hydrate as a reducing agent and glass substrate was annealed at different temperatures under vacuum after deposition | 89         |
| Ni-Co-Mn oxide           | CBD               | Chloride salts of three metals were mixed in DI water, and aqueous NH₃ was added to the salt solution. The precursor impregnated foam was annealed at 350 °C to obtain ternary oxide | 90         |
| Nb-SnO₂                  | CBD               | Halide salts of Sn and Nb were used to deposit SnO₂ and Nb-doped SnO₂. PCE of 20.5% efficiency was achieved after doping                                                                                      | 91         |
| Pb Chalcogenide/CdS      | CBD               | PbS QDs were deposited on CdS coated FTO glass substrate to fabricate tandem solar cell (FTO/CdS/PbS QDs/PbS QDiM/PbSe QDiM/metal. The stacked PV device showed a PCE of 4.2% compared to 0.6% from an FTO/CdS/PbS/metal device | 92         |
| Pb₁₋ₓMnₓS                | CBD               | Ternary chalcogenide nanoparticle films are grown on glass substrates using CBD, and the bandgap of the films can be tuned from 1.50 to 2.50 eV by varying X                                                                 | 93         |
| PbSe                     | CBD               | This CBD used lead acetate tetrahydrate and sodium selenosulfate precursors in a bath at 70 °C for 1 h                                                                                                      | 94         |
| Sb₂S₃                    | Spin coating      | Chloride salt of Sb and NH₄CSNH₂ was used to make a complex spin-coating solution on a mesoporous TiO₂ layer to fabricate solar cells (Sb₂S₃/mp-TiO₂/TiO₂/FTO). The authors were able to show a PCE of 6.4% and a short circuit current density of 16.1 mA cm⁻² | 95         |
| Sb₂Se₃                   | CBD               | A solar cell device (TCO/CdS/Se/ Sb₂Se₃:Sb₂O₃/Sb₂Se₃) was fabricated by chemical deposition showed a Vₜₚ of 520 mV and Jₛ of 4.2 mA/cm². Sb₂Se₃ film was produced by heating the CBD generated Sb₂Se₃:Sb₂O₃ film in the presence of Se | 96         |
| Se                       | CBD               | Elemental Se was deposited using sodium selenosulphate precursor                                                                                                                                          | 49         |
| SiC-SiO₂                 | Spin coating      | TEOs, citric acid, and ethylene glycol precursors were used to make the sol–gel solution and spin-coated onto a Si solar cell, resulting in low reflectance and a PCE of 16.99%                                           | 97         |
| Materials | Deposition method | Remarks | References |
|-----------|------------------|---------|------------|
| SnS: Cu   | CBD              | Sn and Cu’s chloride and sulfate salts were used in the chemical bath to deposit p-type SnS: Cu on FTO glass substrate at 80 °C. The heterojunction solar cells (FTO/SnS: Cu/ZnS/TiO₂/Pt) fabricated showed a high photocurrent density of 1.76 mA/cm² | 98          |
| SnS₂      | CBD              | Thioacetamide and tin chloride precursors were used to deposit the nanosheet array films on glass and filter papers at 75 °C. The filter paper-based device showed the capability of detecting low-intensity broadband light of 400 and 500 nm wavelengths | 99          |
| SrSnO₃    | CBD              | The substrates were dipped in Sr (NO₃)₂ and Na₂SnO₃ precursor solution and calcined at 450° C | 100         |
| SrTiN₂    | Spin coating     | In this polymer-assisted epitaxial nitride deposition, the water-soluble polymer was used to hinder the formation of particles in the solution and any precipitation | 101         |
| TiO₂      | Dip-coating      | A sol–gel formed from mixing tetrabutyl orthotitanate, acetic acid, and butanol was dip-coated and annealed at 100 °C | 102         |
| TiO₂/TiO₂-V₂O₅ | Spin coating and Dip-coating | Oxides of Ti and Ti-V were fabricated using the chemical deposition method using titanium ethoxide and vanadium oxide powder. The fabricated films have refractive indices of 1.89–2.19 for pure oxide and 1.91–2.28 for mixed oxide | 103         |
| WO₄       | CBD              | An aqueous solution of Sodium tungstate dihydrate and diethyl sulfate precursors were used in the CBD solution and kept at 95 °C | 104         |
| WO₃       | Spin coating     | Tungsten ethoxide, acetic acid, and IPA were used to make precursor solutions and deposited as a hole transporting layer using a spin coating method | 105         |
| WSe₂      | CBD              | A WSe₂ film of the optical bandgap of 1.48 eV was fabricated using a chemical bath with sodium tungstate, hydrazine, tartaric acid, and sodium selenosulfate | 106         |
| ZnO       | Spin coating     | 1:1 ratio of zinc acetate dihydrate, 2-ME, and MEA are mixed and stirred at 60 °C and stored at room temperature for 48 h to allow gel formation | 107         |
| ZnO       | CBD              | A seed layer of nanocrystalline ZnO was fabricated by dip-coating precursor solutions of FTO substrate, and then NWs were grown on that seed layer. This process of CBD was carried out at 95 °C, and a new bath was used every 3 h to increase the length of NWs | 108         |
| ZnS       | CBD              | ZnO NWs coated glass was immersed in CBD precursor solution containing Zinc acetate, ammonia, and thiourea to deposit ZnS | 109         |
Critical parameters of MAND

The fundamental principle of MAND reactors is to provide enhanced momentum, heat, and mass transfer and impart a uniform experience for precursor molecules by process intensification like any other microreactor device. Several experimental parameters influence the reaction inside the MAND reactor from the inlet to the product deposition on the substrate. As in any chemical reaction, the reaction rate (Eq. 1) depends on temperature, the concentration of reactants, and residence time to form final products from reactive precursor molecules and is unique for each reaction. These parameters affect the concentration of reactive molecules formed inside the reactor, nucleation, growth, and size of NPs as shown in Fig. 2a. To elaborate further on these three factors,

- Firstly, the temperature of the precursor molecules flowing into the reactor will impact how fast the reaction will be and therefore influence the final nanostructured film, NP size, and size distribution. Secondly, the temperature of the substrate where the final product is being deposited will also affect the nanostructured film formation when reactive fluxes hit the surface.
- The precursors’ concentration and ratios will influence nanostructures due to difficulty initiating or suppressing nucleation and growth. This difficulty results in unwanted NP growth when they are in excess or low deposition rates/incomplete reaction when they are deficient. In addition, adding additives to the reaction mixture will affect pH and, thereby, size and shape of nanostructures.
- Optimum residence time will provide needed time to form reactive molecules in the MASD process and particle growth and assembly in the MANpD process. Flow rates of the precursor streams and reactor design will dictate the residence time inside the MAND reactors.

\[
\text{reaction rate} (r) = k(T)A^nB^m
\]

where \(k(T)\) is the temperature-dependent rate constant, and \(A\) and \(B\) are the concentration of the precursors.

Furthermore, several factors (Fig. 2b, c) such as mixing, microreactor design, the addition of additives, and flow conditioning by segmentation will influence the residence time, fluid flow, and mixing inside the microreactor and thereby the deposited nanostructured films. In addition, in any solution deposition method, the type of substrate surface and the presence of a seed layer on the substrate will also influence the film’s crystal structure, nanostructured film deposition rate, and assembly of nanomaterials.

Controlling all these parameters is easier using MAND-like process intensification devices, and scaleup by numbering approach would allow large scale fabrication at low cost while minimizing material waste. While the CBD and CSD techniques (Fig. 2d) can deposit large-scale films, they suffer from material wastage during deposition and non-uniformity. Unlike MAND, CSD requires other synthesis methods to synthesize NP inks if manipulating nanostructures’ shape and size is necessary for application. As discussed in the introduction section, it is challenging to separate homogenous nucleation from the heterogeneous deposition on the immersed substrate in the CBD method. This deficiency leads to both heterogeneous deposition and homogenous NPs sticking to the surface and adhesion and defective device issues. A clear distinction of control over Cds deposition growth on the substrate by CBD and MAND is shown in Fig. 2e and f.

Solar PV materials and MAND

What are the different parts of solar cell devices? Before answering this question, solar PV systems are classified into many categories by active materials or device structures. Based on primary active material, they have been classified into silicon (single-crystal, polycrystalline, hydrogenated Si), semiconductor compounds (GaAs, CdTe, CZTS, CIGS), and novel complex materials (DSSC, colloidal QDs, polymer, perovskites, inorganics-in-organics) as shown in Fig. 3. Depending on the type of solar cell, some or all of these layers such as primary light absorbing active material (CdTe, CIGS, CZTS, QDs, DSSC, polymer, perovskites, hybrid\textsuperscript{117,118}), metal back electrodes (Au, Ag, Cu) or carbon based electrodes\textsuperscript{119}, TCO coatings (AZO, ITO, FTO, and other mixed metal oxides\textsuperscript{120}), ETL (SnO\textsubscript{2}, TiO\textsubscript{2}, CdSe and core-shell particles such as Al\textsubscript{2}O\textsubscript{3}/ZnO, TiO\textsubscript{2}/

### Table 1. (continued)

| Materials      | Deposition method | Remarks                                                                 | References |
|----------------|-------------------|------------------------------------------------------------------------|------------|
| ZnSe           | CBD               | A chemical bath with selenourea and zinc sulfate precursors resulted in a white film on the substrates | 110        |
| Zn\textsubscript{2}SnO\textsubscript{4} | CBD               | Surface treatment of screen-printed Zn\textsubscript{2}SO\textsubscript{4} electrode was achieved through CBD of Zn\textsubscript{2}SO\textsubscript{4} film | 111        |
| ZnWO\textsubscript{4}/NiO    | CBD               | Ni foam was impregnated with a precursor solution of Zn, W, and Ni sources in a CBD bath and annealed at 100 °C for 10 h | 112        |
Figure 1. (a) Simple schematics of MAND systems. (b) different routes to nanostructured films, some parts are Adapted from 61, and some parts are reproduced with permission from 113: copyright 2010, Elsevier Ltd. (c) deposition of ARC on solar modules in fields and fabricating solar PV devices by MAND.
Figure 2. (a) Schematics of residence time, temperature, and concentration effects on particle-free reactive flux, (b) wheel of reaction parameters that require investigation for particle-free reactive flux in a microreactor, (c) different stages of reaction by controlling the wheel of parameters, (d) different solution deposition methods (Reproduced with permission from\textsuperscript{116}, copyright 2011, Royal Society of Chemistry), (e, f) SEM micrographs of CdS films deposited by CBD and MAND, respectively (reproduced with permission from\textsuperscript{115}, copyright 2007, IOP Publishing).
MgO, Nb₂O₅, HTL (PEDOT:PSS, MoO₃, WO₃, NiO), ARCs (SiO₂, TiO₂, ZnO, ZnS, ZrO₂, Si₃N₄, MgF₂), self-cleaning coatings (ZnO, SiO₂, other bio-inspired structures), nanostructures (nanocomposites, nanotubes, nanowires, nanoporous, downshifting layers (CdS QDs, Er³⁺ doped CsPbCl₃, FAPbBr₃), and work function modification (fluorinated TiOₓ) is required to fabricate highly efficient solar cells.

Where does MAND come into the picture? What types of PV materials have been successfully deposited by MAND techniques? MAND can be used to deposit many of these layers for solar cell devices with good control over reaction parameters to produce desired morphology. Table 2 lists some of the PV materials that MAND successfully synthesized. Why is the control of the critical parameters essential for the fabrication of PV materials or devices? In nanomanufacturing, the efficient management of parameters is necessary to control the morphology and properties of synthesized/deposited nanostructures. This objective can be achieved by implementing microreactors instead of large batch reactors. This capability provides the needed advantage to fabricate highly efficient solar cells.

So, how did the previous works use MAND techniques to control the experimental parameters for the deposition of these PV materials? To answer this question, in the next section, examples of PV materials deposited by MAND are discussed, classified based on well-controlled reactive flux, homogeneous generation of nanoparticles and their assembly, and finally, the transformation of nanostructures by regulating experimental parameters discussed in the previous section.

**Reaction, organization, and transformation of nanostructures by MAND**

**Reaction: Reactive flux generation**

Converting precursors to intermediary reaction molecules can be controlled using MASD. A variety of materials like Ag, Cu₂S, CuInS₂, CuInSe₂, Cu₂Se, CdS, CdTe have been successfully deposited using MASD. In this section, controlling the reaction of precursor molecules into reactive fluxes will be discussed. Kim et al. reported CuInSe₂ and CuSe thin films deposited using the MASD process. The precursors used for CuSe are copper chloride and sodium seleno-sulphite, while indium chloride is the precursor source material for indium in CuInSe₂.
In both cases, the reactant streams’ inlet concentrations, residence times, and temperatures are controlled to prevent homogeneous particle formation, and the reactant flux impinges on heated substrates maintained at 140 °C. The as-deposited CuSe films have a bandgap of 1.80 eV, and films annealed at 400 °C have a bandgap of 1.50 eV. The bandgaps of these films are ideal for solar cell applications. In addition, the observed increase in grain size of the films after annealing is also favorable for photovoltaic applications. Compared to the reported values in the literature, the slightly higher bandgap of CuInSe₂ (1.54 eV for as deposited and 1.25 eV for annealed at 400 °C) is due to quantum size effects. Cadmium Sulfide (CdS) is another critical semiconductor material with many solar cells. Many studies are associated with the reaction kinetics of CdS deposition by batch CBD processes. Chang et al. carefully investigated the deposition

| Material  | Method | Highlights | References |
|-----------|--------|-----------|------------|
| Ag        | MASD   | Morphology of Ag was controlled from nanocrystals to nanocrystalline film by varying deposition times | 140,141 |
| Ag        | MASD   | Uniform films of Ag were deposited at room temperature with electrical conductivity values of about half of the bulk conductivity | 140 |
| CdS       | MANpD  | CdS nanoparticles range from 1.13 nm to 1.26 nm obtained by varying the residence time from 0.26 s to 3.96 s | 142 |
| CdS       | MASD   | It is commonly used as a buffer layer in solar cells; it is one of the materials studied thoroughly using MAND techniques. A bandgap of 2.44 eV of CdS thin films with a deposition rate of 25.2 nm/min was obtained | 60,143–145 |
| CdTe      | MASD   | A bandgap of 1.57 eV was achieved at low temperature and non-vacuum synthesis conditions | 146 |
| Cu₂S      | MASD   | 40–100 times higher deposition rates than CBD were achieved, and deposited films on textured Si have shown an increase in photon absorption | 147 |
| CuInS₂    | MASD   | An environmentally friendly chalcopyrite film with bandgaps of about 1.5 eV was fabricated | 148 |
| CuInSe₂   | MASD   | In these two works, nanostructures were synthesized but fell short of direct deposition. One result showed that nucleation temperature and residence times could control the chalcopyrite or sphalerite phase formation, and another work used synthesized nanocrystal inks | 149,150 |
| CuInSe₂   | MASD   | The optical bandgaps of as-deposited and annealed films were found to be 1.54 eV and 1.25 eV, respectively | 151 |
| CuSe      | MASD   | Films with a bandgap of 1.5 eV were formed | 152 |
| ZnO       | MANpD  | Many investigations were conducted to fabricate ZnO using MANpD | 113,153–159 |
| ZnS       | MANpD  | A highly uniform nano ZnS film with a bandgap of 3.73 eV was obtained | 160 |
| HSNP      |        | Uniform HSNPs of 30 nm were synthesized in a CFM, and a 3.8% increase in PCE was achieved by coating them as ARCs on monocrystalline solar cells | 161 |
of CdS using the MASD process and made a comparison with the batch process.\textsuperscript{60, 143–145} Paul et al.\textsuperscript{143} developed a flow cell to enable large-scale manufacturing of CdS films on the substrate for PV applications. CFD simulations were used to study the flow behavior and velocity inside the flow cell, and the geometry and dimensions of the flow cell were guided by the simulations. Using the flow reactor, Su et al.\textsuperscript{144} manufactured dense CdS films on FTO glass with a high growth rate of 25 nm/min. Compared to the batch CBD process, this high growth rate is particularly beneficial for large-scale manufacturing of CdS thin films. CdTe, another chalcogenide of Cd with a bandgap of 1.4–1.5 eV and an absorption coefficient of $10^{15}$ cm$^{-1}$, is also a good candidate for thin-film photovoltaic applications.\textsuperscript{146,168,169} The polycrystalline CdTe films were synthesized using CFM with cadmium chloride, tellurium oxide precursors, ammonium chloride, ammonium hydroxide, and hydrazine hydrate reagents. The reactive flux is impinged on a 320 °C hot substrate and annealed at 400 °C under an inert atmosphere.\textsuperscript{146}

Park et al.\textsuperscript{92} reported a low-temperature, high-throughput deposition (1 µm thick film/5 min deposition time) of CuInS$_2$ thin films. This chalcophyre material is an environmentally friendly absorber material with a high absorption coefficient suitable for thin-film photovoltaics.\textsuperscript{170,171} In their study, the indium layer is deposited first on the substrate, followed by Cu and sulfur layers using corresponding precursor solutions made of copper sulphate and thiourea, which were then pre-mixed and heated to 80 °C to form a particle-free reactive flux before impinging on the temperature-controlled substrate. The concentration of thiourea is varied to investigate its effect on the nanostructured film formation. S and In$_2$O$_3$ impurity peaks appear in the XRD pattern as the concentration of thiourea increases above 0.04 M. These peak intensities increase with an increase in thiourea concentration. Inequality of the ionic reaction rates between In$^{3+}$–S$^{2-}$ and Cu$^{2+}$–S$^{2-}$ or the liberation rates of In$^{3+}$, Cu$^{2+}$, S$^{2-}$ ions from the precursor solutions are potential causes of these impurities. The bandgaps of both as-deposited and annealed films were measured and estimated to be between 1.52 and 1.60 eV, which are within the reported literature values.\textsuperscript{148} Silver (Ag) is one of the metals with valuable properties for a wide range of applications.\textsuperscript{172–174} One potential application of Ag for solar cells is to enhance sunlight’s absorption in the visible and IR spectrum using plasmonic nanostructured Ag films with 20% intensity of plasmonic absorption. First, a series of bath reactions were conducted to investigate the required residence time for the silver nanocrystal formation. After 30 s, the precursor mixture turned light brown, and a dark brown color emerged at 42 s. A strong absorption peak at 410 nm was detected in UV-VIS measurements, indicating plasmonic absorption for the samples with a residence time of 42 s. When the residence time increases to 62 s, the UV-VIS spectra cannot be measured, indicating the aggregation of nanocrystals. These results are well-matched with the CFM results compared with the UV-VIS spectrum at different flow rates. The SERS spectra of films deposited on glass substrate were measured by varying the deposition times from 2 to 15 min. Rhodamine B (RhB, 10$^{-7}$ M) was used as adsorbate for the measurements. Figure 4f shows that the peaks started showing up after 2 min deposition, and the intensity of peaks continues to grow with deposition time. In Fig. 4g, SERS spectral intensity at 1685 cm$^{-1}$ was displayed with different deposition times. The increase in intensity is seen with increasing deposition period. The authors attribute this to forming denser, closely connected Ag nanocrystal films.

Cu$_2$S, a p-type semiconductor material with a bandgap of 1.2–2.5 eV depending on its phase, is one of the most studied materials among various metal chalcogenides because of the wide variety of applications in solar control coatings, photothermal applications, and solar cells.\textsuperscript{147,175,176} The MASD deposition of this material is studied along with the film growth kinetics using copper sulfate (CuSO$_4$), thiourea (SC[NH$_2$$_2$]), sodium acetate (NaAc), NH$_2$OH, and TEA precursors concentrations with a ratio of 1:0.56:1:8.21:7.55. The reaction setup and mechanism are displayed in Fig. 5a. The reactant streams are mixed in a micro-mixing element and sent through a tube maintained at 40 °C followed by deposition on the substrate at different temperatures. At the initial concentrations of 0.02 M CuSO$_4$, 0.011 M SC[NH$_2$$_2$], 0.02 M NaAc, 0.168 M NH$_3$, and 0.151 M TEA and at a concentration of two factors less than this initial concentration, the homogenous particle formation is observed at different process conditions which indicates that if
Figure 4. Characterization of Ag nanocrystals via (a) TEM micrograph, (b) SAED pattern, and (c) zoomed-in Ag nanocrystal micrograph, (d) Size distribution, (e) schematics showing MAND printer set up for Ag line fabrication (Reproduced with permission from140; copyright 2015, Royal Society of Chemistry). (f) SER spectra of Ag films various deposition times, and g) SER intensity of Ag films at 1688 cm\(^{-1}\) (reproduced with permission from141; copyright 2017, Royal Society of Chemistry) with different deposition periods.
the concentration of reactants is too high, it is hard to control homogeneous nucleation even while varying the homogenous reaction temperature and residence time. Hence, the authors reduced the initial concentration by five times to generate particle-free reactive flux by flowing this reactant mixture through a tube at room temperature and impinging this reactive molecule on the substrate at 80 °C to fabricate nanostructured Cu$_2$S films.

Next, Vas-Ummuay et al. demonstrated conformal growth of these films on textured Si surface for photonic absorption. The pyramidal structures were created on the Si surface by immersing the substrate in 2 vol % IPA in 0.5 M sodium hydroxide (NaOH) solution, followed by cleaning with DI water, hydrochloric acid (HCl), and DI water. The Cu$_2$S is deposited on these substrates with a concentration five times lower than the initial concentration at a residence time of 62 s and substrate temperature of 80 °C. The SEM micrograph of textured Si surface (Fig. 5) and cross-section micrograph (Fig. 5c) of Cu$_2$S film deposited textured Si shows conformal coverage with the thickness of about 200 nm. Reflectance spectra of the film (Fig. 5d) deposited on the textured surface show a 15% decrease in reflectance when compared to polished Si measured by an integrated sphere in the wavelength range of 400–800 nm.

From these above-reported investigations, it has been shown that MASD can be used to control the reaction condition to deliver particle-free reactive fluxes on the surfaces to promote heterogeneous reaction on the surface with good conformal coverage and adhesion of the deposited films. Residence time, the concentration of precursor molecules and temperature are the critical parameters in guiding the reaction to form reactive intermediate molecular fluxes to optimize the deposition process, as illustrated in Fig. 2a–c. The influence of these parameters on some aspects of the deposition process is discussed below.

**Residence time and mixing**

Residence time in the MASD can be controlled by the reactor tubes’ length or the reactant streams’ flow rate. This process parameter will significantly affect the deposition rates, end products, and particle-free film formation for better adhesion. An advantage of MASD over CBD is that residence can be precisely controlled, in principle, for any material deposition with or without changing the reactor size. One clear example of the residence time effect on the deposition rate and particle-free flux is the CdS thin films deposited by MASD. It was found that HS$^-$ ions produced from the hydrolysis of thiourea (reactions shown below in Eqs. 3 and 4) act as the predominant sulfur source for heterogeneous CdS film formation.

Furthermore, the hydrolysis reaction also impacts the deposition rate as it is the primary sulfur source for CdS formation, and optimum residence time should be provided for the reaction. It was observed at residence times of up to 35 s, the growth rate is increased, and between 35 and 70 s, the formation of nanoparticles indicated a homogenous reaction inside the reactor. Compared to CBD, one can study the onset of homogenous particle formation and rate of depositions of products as a function of the residence time and analyze the reactants and products at different intervals with different characterization techniques such as UV-Spectroscopy and TEM to improve the deposition rate.

\[
\text{SC(NH}_2\text{)}_2 + \text{OH}^- \rightarrow \text{HS}^- + \text{CH}_3\text{N}_2 + \text{H}_2\text{O} \quad (3)
\]

\[
\text{HS}^- + \text{OH}^- \rightarrow \text{S}^{2-} + \text{H}_2\text{O} \quad (4)
\]

Another example that showed the effect of residence time on controlling the reactive flux of silver was the fabrication of nanostructured Ag to demonstrate visible to infrared plasmonic absorption. Some reactions are speedy, which makes controlling the process challenging using a batch reactor. Microreactors provide fast and uniform mixing compared to the conventional reactors which lead to excellent temporal resolution. The reaction of tollens reagent and HCHO is one of these speedy reactions. Using the MAND process, the reaction produced silver clusters in less than 30 s and Ag nanocrystals around 42 s, and aggregated nanocrystals in about 62 s, as illustrated on the right side of Fig. 4e, enabled by the continuous flow and the fast, uniform mixing of reactants in the microreactors. The generated clusters coalesce to form the nanocrystals that served as reactive building blocks in the nanostructured silver film showing a broadband plasmonic absorption. This control over residence time prevented further coalescence of nanocrystals that would precipitate Ag particles in this stabilizer-free reaction system for the uniform deposition of the nanostructured film.

**Temperature and concentration**

The temperature of the reactant streams entering the microreactor and the temperature provided inside the microreactor before impinging on the substrate are also crucial for controlling the particle-free reactive flux. Again, deposition of CdS reactive flux is an excellent example to see this thermal effect. When the preheated reactant streams entered the reactor at 80 °C, NPs formed from the homogeneous nucleation even with shorter residence times like 1 s. The temperature sped up the hydrolysis of thiourea, releasing free sulfide ions and these ions reacted with free cadmium ions to form nanoparticles.

Concentration is related to the previous parameters in the reaction aspect, as residence time and temperature are always integrated into a reaction. The concentrations of reactant species will significantly impact the control of the reaction to produce particle-free reactive molecules. If the concentration exceeds a threshold limit, substantial nucleation could lead to particle formation and be unfeasible to block the homogeneous reaction. This concentration effect is seen in the previous discussions about the fabrication of Cu$_2$S thin films. Furthermore, the concentrations of additives that could be complex with reactive ions to hinder the particle formation were shown using the MASD technique. To impede the particle formation of Cu$_2$S in MASD, TEA and NH$_3$ are used to complex with Cu ions. The heterogeneous reaction of particle-free reactive molecules is induced by equilibrium TEA and ammonia complexes with Cu ions by controlling the concentration of metal ions to prevent homogeneous nucleation. These formed copper complexes react...
Figure 5. (a) Schematics of MASD of copper sulfide, (b) SEM micrograph of pyramid textured Si surface, (c) cross-sectional micrograph of the film deposited by MASD, (d) reflectance spectra (Reproduced with permission from\textsuperscript{147}; copyright 2015, Royal Society of Chemistry).
with HS\(^-\) ions to form copper sulfide, as shown in the reactions below.\(^{147}\)

\[
\text{[Cu(TEA)}_n]^{2+} + 2\text{OH}^- + \text{site} \leftrightarrow \text{[Cu(OH)}_2(\text{TEA})_n\text{]}^{ads}, n = 1, 2
\]

\[\text{(5)}\]

\[
\text{[Cu((NH}_3)_4]^{2+} + 2\text{OH}^- + \text{site} \leftrightarrow \text{[Cu(OH)}_2((\text{NH}_3)_4\text{]}^{ads} + 2\text{NH}_3
\]

\[\text{(6)}\]

\[
\text{[Cu(OH)}_2(\text{TEA})_n\text{]}^{ads} + \text{HS}^- \leftrightarrow \text{CuS(film)} + \kappa\text{TEA} + \text{OH}^- + \text{H}_2\text{O} + \text{site}
\]

\[\text{(7)}\]

\[
\text{[Cu(OH)}_2((\text{NH}_3)_4\text{]}^{ads} + \text{HS}^- \leftrightarrow \text{CuS(film)} + 2\text{NH}_3 + \text{OH}^- + \text{H}_2\text{O} + \text{site}
\]

\[\text{(8)}\]

**Organization: Nanoparticle generation and assembly**

In the following section, how MANpD is used to control nucleation, growth, functionalization, and structured assembly of particles by controlling the homogeneous chemical reaction in the continuous flow microreactor (CFM) will be discussed. Different nanostructured materials like Ag,\(^{149}\) CdS,\(^{142}\) ZnS,\(^{160}\) CuInS\(_2\),\(^{149,150}\) ZnO\(^{113,153-159}\) have been manufactured and deposited for different applications. Su et al.\(^{142}\) studied CdS nanoparticles using cadmium nitrate, sodium polyphosphate, sodium sulfide, and other streams with cadmium chloride and thiourea by MANpD. The particle size produced by this method varied from 1.13 to 1.26 nm when the residence time changed from 0.26 to 3.96 s. Kim et al.\(^{150}\) synthesized CuInS\(_2\) nanocrystal inks followed by drop-casting to fabricate PV devices with a PCE of 1.9%. In another study, a solar microreactor is used to manufacture CuInS\(_2\) nanoparticles by Kreider et al.\(^{149}\) In this work, the premixed Cu:In:Se = 1:3:2 precursors are sent through stainless-steel tubes wound into two separate coils and coated with pyromark absorber coating. The solar light is simulated using 20 W halogen lamps, and the produced nanoparticles were cleaned and redispersed in toluene. Chalcopyrite and sphalerite phases are formed depending on the residence time and reaction temperature used during the process. Lee et al.\(^{160}\) synthesized highly uniform ZnS thin film by homogeneous particle generation using the MANpD reactor. The solution’s pH is controlled by adding ammonia to the precursor solution, and a low ammonia concentration leads to varying grain size. A very high concentration of ammonia leads to irregular film growth. The optimum volume of ammonia (8 ml) generated uniform ZnS films with a bandgap of 3.73 eV.

ZnO, which boasts a wide bandgap of 3.37 eV, is one of the widely studied materials among various metal oxides because of its wide variety of applications in solar cells, catalysis, and biosensors. Several works demonstrated synthesizing ZnO nanostructures by different techniques with tuned morphologies of ZnO nanowires, nanorods, and nanocubes.\(^{23,154,158,177}\) Furthermore, mimicking nanostructures from nature is exciting and leads to improved performances. Many researchers have studied different biomimetic structures because of their exciting properties, such as gecko’s toe for medical adhesives, butterfly wings for display surfaces, beetles back for harvesting water and the lotus leaf for repelling water, and moth’s eye for ARCs.\(^{154,178,179}\)

Because of its potential, ZnO is the most widely studied material by MAND.\(^{113,153-159}\) Han et al.\(^{154}\) manufactured nanostructured ZnO ARCs using CFM that mimic structures of the surface of the eye of the night-flying moth.

The Si substrate is treated in NaOH solution to create a textured surface to fabricate the ZnO nanostructures. The Ag seed layer is prepared using AgNO\(_3\), PVP, and ethylene glycol. The ZnO nanostructures are created using zine acetate, ammonium acetate, and sodium hydroxide precursors. The precursor solutions passed through a 1 m length tube maintained at 70 °C for 6.2 s. Later, the solution impinges on the textured surface with an Ag seed layer maintained at 70 °C, promoting heterogeneous nucleation of ZnO nanorods. On the other hand, the solution impinged on the textured surface without the Ag seed layer led to homogenous nucleates on the valleys of the textured surface. The moth’s eye (Fig. 6a) is fabricated on a textured Si surface using CFM by controlling the residence time, temperature, and concentration of precursors. The cross-sectional SEM micrographs of the well-assembled ZnO nanostructures formed on the pyramidal surface of Si are displayed in Fig. 6b–d. Lastly, the reflection of this surface and coated surface is characterized using UV-VIS spectroscopy (Fig. 6e). The reflectance of the polished surface, textured surface, and textured surface with moth’s eye structure are 30.8%, 10.6%, and 3.4%, respectively. This shows that these mimicked structures significantly reduce reflectance, which is beneficial when acting as ARCs for solar cells and other PV applications.

Furthermore, Choi et al.\(^{158}\) explored the assembly and organization of ZnO nanostructures using a helical microreactor (Fig. 7a) by exploiting fluid forces in dean vortices in a winding tube. By constructing the speciation diagram at different pH values using the MINTEQ program, as shown in Fig. 7b, starting precursors for forming nanocrystals’ nucleation could be determined. An irregular network of nanocrystals and stable dispersion of nanocrystals was formed when the pH was 9.5 and 13, respectively. In addition, dean vortices formed in a helical microreactor, and electrostatic repulsive forces (Fig. 7c) were used to study the assembly of nanocrystals. Different flow rates such as 6.8, 14.7, 28.1 mL min\(^{-1}\) were used in the study. Figure 7d shows that simulated velocity profile with maximum velocity moves towards the outlet wall with the increase in dean number (K = Re \(\sqrt{d/R}\), where d is the hydraulic radius and R is the mean radius of curvature of the channel). Different 3D nanostructures were generated depending on the dean number, showing the promise of microreactors to control morphology and properties of films. Building on this work, without changing experimental conditions such as chemical precursors, surfactants, and temperatures, different distinct morphologies, and assemblies of ZnO nanostructures
were obtained by varying the flow rates and the rotating speed of deposition. Individual nanocrystals (6.8 mL min\(^{-1}\)), rectangular assemblies (14.7 mL min\(^{-1}\)), and spherical assemblies (28.1 mL min\(^{-1}\)) of ZnO are found from TEM micrographs as shown in Fig. 7e–g, respectively. Flower-like ZnO nanofilms were fabricated at a flow rate of 14.7 and 28.1 mL min\(^{-1}\) with more petals in case of higher flow rates (Fig. 7h, i).

Moreover, when the substrate is rotated at a speed of 1500 rpm, and a flow rate of 28.1 mL min\(^{-1}\) precursor molecules impinging on the substrate created an amorphous ZnO film, as displayed in Fig. 8a. Later, different ZnO nanostructures were organized using this amorphous seed layer. ZnO nanowires and a crystalline thin film were organized by deposition with flow rates of 6.8 mL min\(^{-1}\) and 28.1 mL min\(^{-1}\) on the amorphous layer, respectively.

This structural organization of ZnO is further investigated by controlling the reaction kinetics in the microreactor. The process is improved to fabricate the seed layer and NWs in a continuous one-step process. Figure 8b–e show HRTEM micrographs of the seed layer and ZnO NWs. The work revealed that both polycrystalline (Fig. 8b) and single-crystalline NWs (Fig. 8c) could be fabricated using the MANP process by controlling the seed layer and nucleation of ZnO nanocrystals. It is also revealed that the NWs cannot be formed without an amorphous seed layer.

The above paragraphs summarize the progress of the organization and assembly of nanostructures using MANP for sustainable energy applications. Residence time, mixing, temperature, the concentration of reactants and additives influence the growth and assembly of the nanostructured materials inside the reactor as they would for particle-free reactive molecules. The factors included in Fig. 2a–c apply for the assembly of nanostructures, but the tuning of the parameters will be different. However, the goal of MANP is to provide reaction conditions that would allow homogenous nucleation to synthesize nanomaterials, and these factors will come into play in terms of nanoparticles size, shape, and distribution. Furthermore, reactor design and fluid flow inside the microreactor are important contributors. Next, a few examples of synthesis in the continuous flow microreactor and MANP that would explain the effect of the aspects mentioned above on nanostructured materials will be discussed. Even though some of these reported works are not directly related to solar PV applications, they explain experimental parameters and reactor designs that could help direct the microreactor-assisted nanomaterial deposition of materials for sustainable energy applications.

**Residence time, temperature, and concentration**

In general, it is essential to have uniform, monodisperse nanoparticle deposition to preserve their properties for the required application. This could be achieved by a supersaturated solution that allows fast nucleation followed by growth of the particles with the aid of rapid mixing and heat transfer provided by process intensification at the microscale. To delineate the effect of
The reactor used in this study is termed as a K-M mixer, constitutes an inlet plate composed of seven 100 µm wide channels, a mixing plate-where all these streams form inlet plate mix with each other. This mixed solution then flows out of the outer plate with a channel size of 360 µm. The particles obtained by the microreactor were found to be chamfered cubic shape with a narrow size distribution at a concentration ratio of [2-MIM]/[Zn^2+] is 60. When concentration increases, the solution becomes supersaturated and allows increased nucleation and thereby smaller nanoparticles. This is observed when ZIF-8 nanoparticle size reduced from 1.8 µm to 51 nm when the R value rose from 40 to 200. The particle’s growth rate and shape can also be influenced by the temperature of the microreactor system. In this study, when the nanoparticles are synthesized at room temperature, the particles formed at 184 s, 600 s, and 1 h are cubes, cubes with truncated edges, and chamfered cubes, respectively. However, when the reaction temperature is 60 °C, diamond faces result at 184 s, and dodecahedron-shaped particles are synthesized at 600 s. This is due to kinetically controlled growth rates at different reaction temperatures. The same can be achieved by adding surfactant additives to promote the reaction. Indeed, by changing NaOH precipitator concentrations, different shapes such as flower and chrysanthemum and morphologies of ZnO nanostructures were obtained using MAND. As discussed earlier, the residence time is always an essential contributor in optimizing the particle size distribution. UiO-66 nanoparticles synthesized in the CFM are an instance to show how residence time (0.44 min to 2 min) could be used to manipulate the particles from hundreds of nm to a few nm. Beyond 3 min, the microreactor was blocked because of the excessive growth of particles allowed by longer residence time in the reactor. This control of nucleation and growth rate of particles could be exploited to tune and manipulate nanostructures by the experimental parameters.

**Reactor design, fluid flow, and mixing**

Reactor designs and fluid flow inside the microreactors can enhance and regulate the mixing that would allow controlled synthesis and assembly of nanomaterials. Gao et al. extensively investigated tuning the size of silver particles by holding the mixing of precursors in different reactor designs and presented a detailed comparison of these reactive designs. The mixing efficiencies of reactors are enhanced by curvature, segmentation by Taylor flow, or static mixers. Diffusion-limited mixing in single-phase flow reactors is enhanced by 3D reactor designs by creating dean vortices inside the reactor or with another mixing condition depending on the application. For example, helical, planar serpentine, alternating axis, and straight tube reactors (Fig. 9a) are examined to control the size of the Ag nanoparticles. The mixing in straight tube reactors is by diffusion, and in the 3D configurations, it is by both diffusion and advection. The reported results from this work confirm that the mixing efficiency across the length of these reactors significantly increases with distance, whereas it stays almost constant while the straight reactor. At a low Reynolds number (Re = 10), periodically (184°) changing dean vortices cancel each other in a planar serpentine reactor while the mixing efficiency of the helical reactor is slightly higher than that of the alternating axis reactor. As the Reynolds number increases from 40 to 200, fluid rotation effects in a planar serpentine reactor are augmented and the mixing efficiencies of all the curved reactor designs are comparable, while the alternating axis reactor is slightly ahead in terms of mixing efficiency as the directional change of dean vortices are by 90° in this design. This design disrupted dean vortices improved mixing efficiency, and eventually led to improved nucleation rate and thereby, smaller particles.

Simulated results of mixing in four reactor designs at different locations with varying Re are shown in Fig. 9b. This concept of enhanced mixing and growth rate by varying the flow rates to achieve different degrees of dean vortices formation has been utilized to assemble rectangular and spherical ZnO assemblies by MAND. Mass transfer and mixing in microreactors can also be modified and improved by introducing fluid into the microreactors to control flow patterns. Segmented flow is where the gas/liquid is introduced into the microreactor systems to enhance the mass transfer and mixing. The gas–liquid segment resulted in smaller particles sizes than liquid–liquid segments when air and kerosene are used as inert phases in Ag NPs synthesis, indicating that mass transfer is significantly affected by choice of inert fluid. The change of the inert phase can also influence the shape and growth of the particles. This was demonstrated by manufacturing different Pd and Pt nanostructures shapes using a single microreactor design (Fig. 9c–e) with different dispersive fluids to implement the segmented flow. Figure 9f shows different nanostructures obtained in the spiral microreactor with N2, O2, and CO. When Oxygen gas is used as the dispersive phase, anisotropic growth of Pd nanocrystals is promoted by oxidative etching. This anisotropic growth is influenced by the concentration of reductants, flow rates of gas and liquid, and temperature of the reaction system. Thereafter, CO is employed as the dispersed gas phase, allowing the formation of nanosheets at a temperature of 35 °C instead of the above 110 °C temperature when other gases are used. This indicates that CO also acted as a reducing agent while promoting anisotropic growth by the selective chemisorption on the metal nanoparticles.

As MANpD involves the synthesis and possibly organization of nanoparticles inside the microfluidic system before deposition, it utilizes individual particles as building blocks upon deposition, making it easier to organize and construct patterned or porous films or structures and making it possible to create core-shell
Figure 8. (a) Schematics of ZnO morphologies deposited by MAND (Reproduced with permission from155: copyright 2014, American Chemical Society). HRTEM micrographs, (b) seed layer and polycrystalline ZnO, (c) amorphous ZnO seed layer with FFT, (d) polycrystalline ZnO layer, (e) ZnO NWs with FFT (reproduced with permission from156: copyright 2016, Royal Society of Chemistry).
Figure 9. (a) Different reactor designs, (b) effect of mixing at different Re at different positions when different reactor designs used (Reproduced with permission from 182; copyright 2021, Elsevier). (c) Schematics of the reactor, (d) spiral microfluidic reactor used to produce nanocrystals, (e) segments of precursors at a residence time of 150 s, (f) Different shapes of nanocrystals produced using spiral microfluidic reactor (reproduced with permission from 192; copyright 2016, The Royal Society of Chemistry).
particles. However, MANpD’s use of the supersaturated solution is more susceptible to clogging of the tube due to heterogeneous nucleation and growth along the capillary walls and high size dispersities due to wide residence time distributions (RTD) of the particles. Aside from the previously mentioned conditions to aid rapid mixing and heating, to further address these issues, reactor designs can be improved to increase the mixing of reagents while avoiding contact between the reagents and the capillary tubes. To date, continuous flow microreactors have mainly been employed in MANpD due to their simplicity, adaptability, and ease of operation, and several options towards this enhancement are available. If the continuous flow setup is to be kept, then coaxial flow microreactors could be used. As shown in Fig. 10a, in a coaxial flow microreactor, two co-current
capillaries are used. The smaller inner capillary tapers into the larger capillary, and the inner fluid is composed of the synthesis solution, while the outer fluid is an inert solution, preventing contact between the capillary wall and the synthesis solution. It is observed that all synthesis and growth occur in the inner dispersed solution and thus, there is no adhesion of the product to the capillary wall.\textsuperscript{193, 194}

Another possible avenue to enhance mixing and avoid blockage is through segmented microfluidic reactors, which employ either gas–liquid (bubble) or liquid–liquid (droplet) segmented flows. Segmented flow microreactors employs active mixing, which employs the segmentation between the two distinct phases to enhance mixing. In continuous flow microreactors, sub-millimeter sized capillary dimensions lead to low Reynolds numbers and laminar flows. This leads to a parabolic velocity profile, which causes wide RTDs in which flow velocity in the center of the capillary is much larger and particles synthesized near the center are thus smaller (Fig. 10b). Compared to continuous flow microreactors, segmented flow systems promote recirculation of the synthesis solution within each individual segment. In gas–liquid segmented flow, liquid slugs are separated by gas plugs which create segments that have improved mixing relative to single phase flows (Fig. 10c).\textsuperscript{195} These systems also maintain simplicity due to the easy separation between gas and liquid phases. However, although gas–liquid segmented flows address the issue of nanoparticle polydispersity, there is still contact between the precursor solution and the tube walls, so clogging can still occur. Even so, the risk of fouling is much lower relative to the CFM systems, as there is increased mixing and movement of the precursor solution leading to less contact of reagents with the wall. Introducing a gas phase also leads to noncontinuous contact between the capillaries and synthesis solution, further reducing the risk of clogging. Liquid–liquid segmented flows create emulsions that encapsulate individual segments of the synthesis solution (Fig. 10d). The segmented droplets lead to self-recirculation flows, increasing mixing and narrowing RTDs. In addition, as the reactions are encapsulated within the emulsions, there is no interaction between the synthesis solution and capillary walls.\textsuperscript{194, 196} However, employing both aqueous and oil-based solutions introduce complications in the deposition and post-deposition processes as it is tricky to make the deposited particles stick on the surface and requires extra steps to remove unwanted oil or aqueous phases.

Transformation: Modification of generated nanostructures

Nanostructures are transformed to achieve tailored properties by manipulating their composition, atomic structure, morphology, and size. These could be partially transformed core–shell particles, hollow nanostructures, or core-sheath NWs, as shown in Fig. 11a.\textsuperscript{197, 198} He et al.\textsuperscript{165} fabricated hollow silica nanoparticles (HSNPs) using CFM. The CFM process consisted of a hydrodynamic focusing micromixer (HFM) and an HPLC pump to send precursor solutions through the HFM. As elucidated in Fig. 11b, solution stream A (PAA in NH\textsubscript{3}OH) and solution stream B (1% TEOS in ethanol) are introduced into the HFM, and a pH of 10 was maintained to allow deprotonation of PAA. The outlet stream from the microreactor was collected in a flask aged for 3 h with vigorous stirring. The solution was centrifuged and washed to collect HSNPs and redispersed in ethanol. For comparison, HSNPs are also synthesized using a batch reactor system with the same chemical precursors. The particle size and morphology were determined by TEM. Figures 11c–k present the TEM micrographs of manufactured HSNPs at different experimental conditions by varying PAA/NH\textsubscript{3}OH ratios, TEOS/EtOH ratios, and Flow rate ratios of streams. Figure 11c–e show the effect of the total flow rate, while Fig. 11f, g, and i display the impact of the flow rate ratio. Smaller size HSNPs and narrower size distributions emerged as the flow ratio increased up to 2.58 mL/min, and a further increase in flow rate didn’t show any change. The increase in flow rate ratio indicates that broader size distribution particles will result from uncharged PAA molecules. Figures 11c, j and k exhibit the outcomes of the varying PAA concentrations. The TEM micrographs show that the HSNPs have a necklace configuration at lower PAA concentrations, likely due to the drifting of counterions from PAA because of osmotic pressure created by dilute concentrations.

These produced HSNPs and YVO\textsubscript{4}:Eu are used to create optically graded thin-films to achieve downshifting and ARC for solar module power enhancement.\textsuperscript{199} In this work, an FDTD model (Fig. 12a) was first solved to optimize the parameters by the sweeping thickness of films (thereby refractive indices) for graded thin films interacting with UV and visible light (depicted in Fig. 12b) over the wavelength range of 400–800 nm. The simulated results showed that the down-shifting films could be created without sacrificing the transmittance in the wavelength region. The YVO\textsubscript{4}: Eu nanoparticles are synthesized using a hydrothermal batch reaction process with yttrium nitrate, sodium orthovanadate, and europium nitrate as precursors for YVO\textsubscript{4} and Eu doping, respectively. Later, the inks were formulated for spin coating based on the data presented in Table 3 for each layer with different refractive indices. Figure 12c and d show the optical images under daylight and UV light (254 nm) for different cycles of spin coating on glass substrates. They show that the intensity of illuminated red light increased with an increase in the number of cycles of the coating. The graded thin films were fabricated by spin coating on the glass substrate with ink E deposited on the glass substrate, followed by ink D, A, and C. The fifth and topmost layer was again ink E based on simulation results. The cross-sectional SEM micrograph (Fig. 12e) shows the intermingled layers of graded thin films instead of stacked multilayers. The authors explain that the previous dried layer might have been dissolved by the ink for the following layer during spin coating, and then resettling particles created an intermediate zone between two adjacent layers. However, more studies are required to clearly understand how sensitively the intermediate layer affects the optical properties of the thin films. Using the spin-coating method, it would be hard to replicate the same layer characteristics each time. The use of multi-head MAND deposition heads would be an alternative for large-scale production
with better control over the interface between each layer. Figure 12f shows an SEM micrograph of the surface morphology of HSNPs, and the compacted silica particles can be seen from the magnified micrograph. The measured transmittance shows (Fig. 12g) that five layers of the graded thin film have higher transmittance than ten layers of just ink A and bare glass.

Figure 11. (a) Schematics showing chemical transformation of nanostructures (Reproduced with permission from197: copyright 2011, Elsevier Ltd), (b) pathway of PAA spherical templates for HSNPs, TEM micrographs synthesized by CFM and bath reactor, (c) PAA/NH$_3$OH = 0.08; PAA concentration in stream A/mixed stream-1.0/0.03, (d) PAA/ NH$_3$OH = -0.17; PAA concentration in stream A/mixed stream-4.0/0.25, (e) PAA/ NH$_3$OH = -0.08; PAA concentration in stream A/mixed stream-4.3/0.12, (f) PAA/ NH$_3$OH = -0.06; PAA concentration in stream A/mixed stream-4.0/0.09, (g) PAA/ NH$_3$OH = -0.04; PAA concentration in stream A/mixed stream-4.0/0.07, (h) bath reaction, (i) PAA/ NH$_3$OH = -0.08; PAA concentration in stream A/mixed stream-4.0/0.25, (For all samples TEOS/EtOH is 2.5 otherwise mentioned), (j) PAA/ NH$_3$OH = -0.05; TEOS/EtOH-1.5; PAA concentration in stream A/mixed stream-4.0/0.12, (k) PAA/ NH$_3$OH = -0.02; TEOS/EtOH-0.5; PAA concentration in stream A/mixed stream-3.8/0.12 (reproduced with permission from161: copyright 2017, IOP Publishing Ltd).
substrate. The effect of this graded RI on PVs is measured by placing the coated glass substrate on a p-Si PV cell. The current density of the setup is measured, and the PV cell with coated glass has a higher current density (Fig. 12h). It is found that the solar conversion efficiency can be enhanced by 4.12% when compared with PV cells covered with bare glass.
Impact of experimental conditions

As discussed in the previous sections, reaction temperature, concentration, mixing, and residence time are the factors that influence the transformation of nanostructures in the microreactors. Before looking at these, progress on the investigations of transformations of nanostructures in the continuous flow microreactors that are not directly related to the solar PV materials will be discussed briefly. Song et al. synthesized core–shell MnO2-PPy nanoparticles for supercapacitor applications. The oxide NPs synthesized in the first stage of the reactor transformed into core–shell particles by modifying with the PPy shell in the second stage. Figure 13a shows the formation mechanism of these core–shell nanostructures. Abou-Hassan et al. synthesized γ-Fe2O3/silica core–shell nanoparticles using a multi-stage continuous micro-flow system as depicted in Fig. 13b. Kikkeri et al. synthesized carbohydrate functionalized pyridine coated CdTe/ZnS nanostructures using a three-stage continuous flow microreactor as shown in Fig. 13c.

From the results obtained from CFM, the authors proposed a reaction mechanism (Fig. 14a) to form HSNPs with HFM. The aggregation of PAA-TML is very low in CFM systems due to quick mixing compared to the batch reactor system. After charging PAA, the TEOS (positively charged Si) is attracted to the PAA because of its negative charge, allowing for the formation of the Si shell. Narrow size distributions of NPs are formed with short mixing times compared to broader size distributions at the longer mixing times shows the importance of mixing and residence times in the reactor. The size distribution of transformed HSNPs is also strongly dependent on the concentration of PAA templates in the reactor. Strings of templates formed because of the absence of counterions due to high osmotic pressure at lower PAA concentrations. While at higher concentrations, the initially developed nano templates aggregated and resulted in a broader distribution of transformed HSNPs. Figure 14b–g show the morphology and size distribution of transformed core–shell MnO2-PPy NPs from MnO2 NPs at different ratios of KMnO4 to MnSO4. The wide range distribution of produced NPs attributed to the race between reaction and mixing. Efficient and rapid micro-mixing is necessary to generate uniform nuclei to generate uniform size distribution. Nucleation induction time is also less in this work than mixing time, resulting in inefficient mixing and thus wider size distribution of NPs.

MAND has not been used to deposit transformed nanostructures directly onto the surface of interest. However, the progress of using CFM to generate transformed NPs discussed above shows

| Table 3. Ink formulations for five layers (reproduced with permission from199: copyright 2021, Elsevier Ltd). |

| Ink | A | B | C | D | E |
|-----|---|---|---|---|---|
| YVO4: Eu (mg) | 3.0 | 2.7 | 2.4 | 2.1 | 0 |
| HSNPs (µL)a | 0 | 6.5 | 13.0 | 19.5 | 65.0 |
| EtOH (mL) | 0.4 | 0.3994 | 0.3987 | 0.3981 | 0.3935 |
| Refractive Index | 1.81 | 1.79 | 1.76 | 1.73 | 1.36 |

a0.136 g HSNPs were redispersed in 10 mL EtOH.

Figure 13. Schematics of different transformations of nanostructures (a) MnO2/PPy (Reproduced with permission from201: copyright 2020, Elsevier Ltd). (b) γ-Fe2O3/silica Core/Shell particles (reproduced with permission from203: copyright 2009, Wiley–VCH Verlag GmbH & Co). (c) carbohydrate functionalized CdTe/ZnS nanostructures (reproduced with permission from202: copyright 2010, Wiley–VCH Verlag GmbH & Co).
the promise of using MAND to synthesize, transform and deposit nanostructures. For instance, functionalization of generated nanostructures in one stage of a microreactor can be achieved in a downstream microreactor connected in series, similar to the multi-stage reactor used by Kikkeri’s research group for functionalization of QDs. Few other aspects of transformation that could be realized using MAND is briefly discussed in the outlook section.

**MAND for solar modules in the field**

The loss of light due to the reflection and accumulated mass (soils, dust, air particulates, pollutants) hindering light in the field leads to lower efficiency of installed solar modules. The accumulated mass (i.e., dirt, dust, pollutants, and air particles) on a cover can significantly reduce the power output of a solar PV module, ranging from 1% to as much as 70% in some areas without cleaning. Another study estimates that these annual soiling losses were up to 2.8%, and seasonal soiling losses are as high as 20%. One way to mitigate the soiling effect is to regularly clean the solar arrays, which increase the LCOE and requires water. Even in optimized cleaning scenarios, soiling reduces the current global solar power production by at least 3–4%, with at least 3–6 billion US dollar annual revenue losses, which could rise to 4–7%, and more than 4–8 billion US dollar losses, in 2023 according to Ilse et al.

Ilse’s team performed a techno-economic assessment of soiling mitigation strategies. These strategies include automated cleaning machines, anti-soiling coatings, PV module design, tracking system modifications, improved soiling monitoring, site adaption, electrodynamic screens, wind cleaning, and dew mitigation. Their analysis shows that anti-soiling coatings are the most cost-effective strategies and can be combined with other mitigation strategies such as fully automated cleaning, PV module design modification, and tracking system modification.
The ARCs developed using MAND by the team at Oregon State University led to a start-up venture, Pellucere Technologies (formerly CSD Nano), to commercialize the technologies. Pellucere Technologies is applying MoreSun® (refractive index of 1.28 and reflection losses less than 0.5%) and Talus DRT™ (prevents dirt from adhering to the surface) onto solar modules in the field to improve energy gains. MoreSun® ARC is a nanoporous silica-based thin film whose design is inspired by sub-wavelength structures in a moth’s eye. An early example is a 100 KW demo at Thessaloniki, Greece, a ground installation at an agricultural land area (Fig. 15a). Figure 15b shows a 3.8% gain on an average after coatings.

Another problem for solar modules in the field is the accumulation of dirt, affecting the modules’ light absorption and power efficiency. The Talus DRT™, with its distinctive nanostructures, rejects the dirt, as shown in Fig. 16. Recent results of antisoiling coatings developed by Pellucere Technologies are presented in Fig. 17. Figure 17 shows the antisoiling coating performance on solar panels at a southern California location over an 8-month duration. The results show that about 4% power gains by minimizing the reflection and about an average of 9.4% power gain by minimizing the soiling, which totals up to 13.4% power gains as of February 2022. Dust conditions significantly influence the power gains resulting from the antisoiling, and the fluctuations can be clearly seen in the figure.

Challenges and outlook

MAND processes have shown the capability to deposit various functional nanostructured materials relevant to solar photovoltaics. However, the development of MAND processes is still at an early stage; significant efforts are necessary for MAND processes to reach their full potential. They are expanding the material space of their applications, understanding the fundamentals of reaction kinetics and transport phenomena, and making more complex nanostructured materials via advanced reactor designs with increased complexity.

Despite the recent progress, there remain challenges in fabricating solar cell devices and directly writing nanomaterials using a MAND reactor. One crucial area is controlling mixing to generate reactive fluxes with improved temporal resolution. Micromixer is an essential component in using continuous flow microreactors to control nanoparticle size and shape and their distributions. In contrast, fundamental studies using micromixing to generate and transport intermediate reactive molecules and ions to the surface for depositing nanostructured films are limited.

MAND process has the potential to fabricate nanostructured thin films for various emergent new materials. For example, nanostructured perovskites have been widely studied due to their interesting electrical and optical properties that allow PV applications. Controlled nucleation and crystallization are essential to achieve uniform crystal size and coverage; MAND has good potential to meet these requirements. In addition, the manufacturing and depositing of ligand-free perovskite nanostructures can be realized by MAND to avoid the washing and redispersing steps of most of the current synthesis techniques.

The transformation of nanomaterials has not been thoroughly investigated using MAND. There are also limitations in directly depositing the partially transformed nanoparticles (e.g., hollow nanostructures with templates) on the substrate—investigations into developing continuous post-synthesis processes such as functionalization, template removal, and chemical activation before surface reaction are needed. Moreover, the sequential transformation of single nanoparticles into nanostructures with a more complex structure, such as core–shell particles core/sheath wires, are areas for future studies.
Furthermore, MAND printing was demonstrated previously by Choi et al.\textsuperscript{140} to print conductive Ag lines. However, a microchannel applicator was used instead of direct writing from a nozzle. Controlling reaction is a significant issue in the direct printing of nanostructured materials. The precursor molecules should not experience different reaction conditions as this might lead to undesired reactive fluxes, the mixture of intermediate molecules and nanoclusters, non-uniform nanoparticles size distribution as time progresses. A few possible approaches to mitigate this issue are listed below:

- One can use a moving stage underneath the substrate. However, the controlling flow rate and the stage movement would be challenging. Furthermore, there will be no stop mechanism when the writing is finished at a particular location.
- Drop-on demand releasing precursor streams into the CFM can be another way to achieve MAND writing. One can use a porous tip at the end of the MAND stream to print the nanostructured materials on the substrate surfaces.
- In another design, one can exploit the microfluid flow confinement by infusing and withdrawing the ink generated by the microreactor. The fluid flow will be uncertain mainly because the other immiscible liquid is often necessary to confine the flow movement. Hence, modeling and simulation of fluid flow on the surface will guide the designing of new generations of MAND reactor systems.

We are investigating some of these approaches in our laboratories.

**Summary**

Solution-based processes for fabricating nanostructured thin films have several advantages, including low processing temperature, inexpensive capital cost, and large-area deposition capability. MAND technology offers large surface-area-to-volume ratios within microchannel structures to accelerate heat and mass transport, which enable rapid changes in reaction temperatures and concentrations that enhance the capability and control of chemical solution-based deposition processes. This review presents exemplary MAND processes that make nanostructured photovoltaics materials, including metal contacts, absorber layers, window layers, and ARCs. MAND produces tailored reactive fluxes by controlling reactant concentrations, residence times, temperatures, mixing, fluid flow, and other external fields (e.g., photons). It can also transform intermediate templates into different shapes via micromixing and capture by \textit{in situ} reactions to form various hollow silica nanostructures. The ARC coatings and dirt rejection technology, a commercial success enabled by MAND, increases power gains by 4 to 10% by reducing dirt’s reflection and accumulation on solar modules. In the end, the challenges and future outlook of MAND, such as ligand-free nanomaterial deposition and 3D printing, are presented.
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Data availability
Not applicable.

Code availability
Not applicable.

Declarations

Conflict of interest
Chih-Hung Chang, Brian K. Paul, and Seung-Yeol Han hold a financial interest in Pellucere Technologies.

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REFERENCES
1. N. Soudi, S. Nanayakkara, N.M.S. Jahed, S. Naahidi, Rise of nature-inspired solar photovoltaic energy converters. Sol. Energy 208, 31–45 (2020). https://doi.org/10.1016/j.solener.2020.07.048
2. M. Jeffery, Accelerating the transition to sustainable energy systems. Energy Policy 36, 4116–4125 (2008). https://doi.org/10.1016/j.enpol.2008.06.020
3. N. Ali, R. Ahmed, J.T. Luo, A. Kalam, A.G. Al-Sehemi, Y.Q. Fu, Advances in nanostructured homojunction solar cells and photovoltaic materials. Mater. Sci. Semicond. Process. 107, 104810 (2020). https://doi.org/10.1016/j.mssp.2019.104810
4. R. Yu, Q. Lin, S.-F. Leung, Z. Fan, Nanomaterials and nanostructures for efficient light absorption and photovoltaics. Nano Energy 1, 57–72 (2012). https://doi.org/10.1016/j.nanoen.2011.10.002
5. Q. Huang, J. Zhao, Y. Chen, J. Wang, Y. Zhao, X. Zhang, G. Hou, Plasmonic modulated back reflector for thin film photovoltaics. Sol. Energy Mater. Sol. Cells 225, 110997 (2021). https://doi.org/10.1016/j.solmat.2021.110997
6. A. Gok, Reliability and Ecological Aspects of Photovoltaic Modules (IntechOpen, London, 2020)
7. G. Conibeer, M. Green, R. Corkish, Y. Cho, E.-C. Cho, C.-W. Jiang, T. Fangsuwannarak, E. Pink, Y. Huang, T. Puzzer, T. Trupke, B. Richards, A. Shalav, K. Lin, Silicon nanostructures for third generation photovoltaic solar cells. Thin Solid Films 511–512, 654–662 (2006). https://doi.org/10.1016/j.tsf.2005.12.119
8. W. Charfi, M. Chaabane, H. Mhiri, P. Bournot, Performance evaluation of a solar photovoltaic system. Energy Rep. 4, 400–406 (2016). https://doi.org/10.1016/j.egyr.2018.06.004
9. V.V. Tyagi, N.A.A. Rahim, N.A. Rahim, J.A.L. Selvaraj, Progress in solar PV technology; research and achievement. Renew. Sustain. Energy Rev. 20, 443–461 (2013). https://doi.org/10.1016/j.rser.2012.09.020
10. A.S. Sarkun, N. Ekren, Ş. Sağlam, A review of anti-reflection and self-cleaning coatings on photovoltaic panels. Sol. Energy 199, 63–73 (2020). https://doi.org/10.1016/j.solener.2020.01.004
11. K.K. Ilse, B.W. Figgis, V. Naumann, C. Hagendorf, J. Bagdahn, Fundamentals of soiling processes on photovoltaic modules. Renew. Sustain. Energy Rev. 98, 239–254 (2018). https://doi.org/10.1016/j.rser.2018.09.015
12. S.M. Hubbard, Nanostructured photovoltaics for space power. J. Nanophotonics 3, 031830 (2009). https://doi.org/10.1117/1.3266502
13. G. Zhang, S. Finefrock, D. Liang, G.G. Yadav, H. Yang, H. Fang, Y. Wu, Semiconductor nanostructure-based photovoltaic solar cells. Nanoscale 3, 2430–2443 (2011). https://doi.org/10.1039/c1nr10152b
14. P.P. Boix, Y.H. Lee, F. Fabregat-Santiago, S.H. Im, I. Mora-Sero, J. Bisquert, S.S. II, From flat to nanostructured photovoltaics: balance between thickness of the absorber and charge screening in sensitized solar cells. ACS Nano 6, 873–880 (2012). https://doi.org/10.1021/nn204382k
15. M.L. Broersma, Y. Cui, S. Fan, Light management for photovoltaics using high-index nanostructures. Nat. Mater. 13, 451–460 (2014). https://doi.org/10.1038/nmat3921
16. L. Tsakalakos, Nanostructures for photovoltaics. Mater. Sci. Eng. R 62, 175–189 (2008). https://doi.org/10.1016/j.mser.2008.06.002
17. F. Priolo, T. Gregorkiewicz, M. Galli, T.F. Krauss, Silicon nanostructures for photonics and photovoltaics. Nat. Nanotechnol. 9, 19–32 (2014). https://doi.org/10.1038/nnano.2013.271
18. K. Nikolaidou, S. Sarang, S. Ghosh, Nanostructured photovoltaics. Nano Futur. 3, 012002 (2019). https://doi.org/10.1039/c9np00200k
19. R. Ramadan, M. Manso-Silván, R.J. Martin-Palma, Hybrid porous silicon/silver nanostructures for the development of enhanced photovoltaic devices. J. Mater. Sci. 55, 5456–5470 (2020). https://doi.org/10.1007/s10853-020-04394-z
20. G.I. Buyuk, S. Ilican, Electrical and photovoltaic properties of p-n heterojunctions obtained using sol-gel derived nanostructured ZnO: La films onto p-Si. Superlatt. Microstruct. 145, 106605 (2020). https://doi.org/10.1016/j.spmi.2020.106605
21. C. Wu, K. Wang, M. Batmunkh, A.S.R. Bati, D. Yang, Y. Jiang, Y. Hou, J.G. Shapter, S. Priya, Multifunctional nanostructured materials for next generation photovoltaics. Nano Energy 70, 104480 (2020). https://doi.org/10.1016/j.nanoen.2020.104480
22. X. Luo, L. Lu, M. Yin, X. Fang, X. Chen, D. Li, L. Yang, G. Li, J. Ma, Antireflective and self-cleaning glass with robust moth-eye surface nanostructures for photovoltaic utilization. Mater. Res. Bull. 109, 183–189 (2019). https://doi.org/10.1016/j.materresbull.2018.09.029
23. K. Davis, R. Yarbrough, M. Froeschle, J. White, H. Rathnayake, Band gap engineered zinc oxide nanostructures via a sol-gel synthesis of solvent driven shape-controlled crystal growth. JSC Adv. 9, 14638–14648 (2019). https://doi.org/10.3390/JSCRA2091H
24. S. Thangavel, S. Ganesan, S. Chandramohan, P. Sudhagar, Y.S. Kang, C.-H. Hong, Band gap engineering in PbS nanostructured thin films from near-infrared down to visible range by in situ Cd-doping. J. Alloys Compd. 495, 254–267 (2010). https://doi.org/10.1016/j.jallcom.2009.03.135
25. U. Sajjad, I. Hussain, M. Sultan, S. Mehdi, C.C. Wang, K. Rasool, S.M. Saleh, A.Y. Elnaggar, E.E. Hussein, Determining the factors affecting the boiling heat transfer coefficient of sintered coated porous surfaces. Sustain. Growth Futur. 13, 12631 (2021). https://doi.org/10.3390/sgf13012631
26. U. Sajjad, I. Hussain, M. Imran, M. Sultan, C.-C. Wang, A.S. Alsulbabi, K.H. Mahmoud, Boiling heat transfer evaluation in nanoporous surface coatings. Nanomaterials 11, 3383 (2021). https://doi.org/10.3390/ nanomaterials11123363
61. C. Chang, B.K. Paul, S.-O. Ryu, Fabrication of Nanostructured Thin Films Using Microreactors Graphene, Carbon Nanotubes, and Nanostructures, 1st edn. (CRC Press, Boca Raton, 2017), pp. 321–338

62. C.-H. Choi, B. Paul, C.-H. Chang, Microreactor-assisted solution deposition for compound semiconductor thin films. Processes 2, 441–465 (2014). https://doi.org/10.3390/pr20200441

63. C. Chen, Y. Zhai, F. Li, G. Yue, Fabrication of silver sulfide thin films for efficient organic solar cells with high short-circuit currents based on double heterojunctions. J. Power Sources 290, 259–268 (2015). https://doi.org/10.1016/j.jpowsour.2015.08.066

64. E. Wang, C. Liu, J. Zeng, K.W. Li, H. Wang, Fabrication and morphology control of BaWO4 thin films by microwave assisted chemical bath deposition. J. Solid State Chem. 182, 677–684 (2009). https://doi.org/10.1016/j.jssc.2008.12.014

65. M.F. Achoi, M.A.A. Noman, S. Kato, N. Kishi, T. Soga, Synthesis of bismuth triiodide nanofibers by spin-coating at room temperature. Materiala 16, 101077 (2021). https://doi.org/10.1016/j.matla.2021.101077

66. Y. Yochelis, G. Hodes, Nanocrystalline CdSe formation by direct reaction between Cd Ions and selenosulfate solution. Chem. Mater. Phys. 101077 (2021). https://doi.org/10.1016/j.mtla.2021.101077

67. J.I. Contreras-Rascón, J. Díaz-Reyes, J.E. Flores-Mena, M. Galvan-Arellano, C. Chang, B.K. Paul, S.-O. Ryu, Preparation of CdTe coatings using CdTe nanofibers by spin-coating at room temperature. Materialia 623, 61–66 (2001). https://doi.org/10.1016/S0169-4332(03)00623-8

68. M. Sotelo-Lerma, R.A. Zingaro, S.J. Castillo, J. Heo, F. Zhang, C. Xiao, S.J. Heo, J.K. Park, J.J. Berry, K. Zhu, S.H. Im, Efficient and stable graded CsPbI3−xBrx perovskite solar cells and subcell CsPbIBr 2 perovskite solar cells via low-temperature processed In2S3 as electron-transport-layer. Nano Energy 108, 230–237 (2014). https://doi.org/10.1016/j.solener.2014.07.011

69. Z. Lei, L. Feng, G. Zeng, W. Li, J. Zhang, L. Wu, W. Wang, Influence of CuSb back contact on CdTe thin film solar cells. J. Semicond. 34, 014006 (2013). https://doi.org/10.1088/1674-4926/34/1/014006

70. H.M. Pathan, C.D. Lokhaner, D.P. Amankear, T. Seth, Preparation and characterization of copper telluride thin films by modified chemical bath deposition (M-CBD) method. Appl. Surf. Sci. 219, 291–297 (2003). https://doi.org/10.1016/S0169-4332(03)00623-8

71. D. Huang, K. Wang, L. Yu, T.H. Nguyen, S. Ikeda, F. Jiang, Over 1% efficient unbiased stable solar water splitting based on a sprayed Cu2ZnSnS4 photocathode protected by a H2O2 photocorrosion-resistant film. ACS Energy Lett. 3, 1875–1881 (2018). https://doi.org/10.1021/acsenergylett.8b01005

72. Z.Y. Lee, S.S. Ng, F.K. Yam, Growth mechanism of indium nitride via sol–gel spin coating method and nitridation process. Surf. Coat. Technol. 310, 38–42 (2017). https://doi.org/10.1016/j.surfcoat.2016.12.066

73. F. Aslan, G. Adam, P. Stadler, A. Goktas, I.H. Mutlu, N.S. Sariciftci, Sol-gel derived In2S3 buffer layers for inverted organic photo voltaic cells. Sol. Energy 100, 230–237 (2014). https://doi.org/10.1016/j.solener.2014.07.011

74. S. Ulica, B. Dou, D.H. Kim, K. Zhu, J.M. Wallis, J.W. Bowers, M.F.A. Van Heest, Scalable deposition of high-efficiency perovskite solar cells by spray-coating. ACS Appl. Energy Mater. 1, 1853–1857 (2018). https://doi.org/10.1021/acsenergymat.8b00328

75. M. Adnan, J.K. Lee, All sequential dip-coating processed perovskite layers from an aqueous lead precursor for high-efficiency perovskite solar cells. Sci. Rep. 8, 1–10 (2018). https://doi.org/10.1038/s41598-018-20296-2

76. Y. Sui, Y. Zhang, D. Jiang, W. He, Z. Wang, F. Wang, B. Yao, L. Yang, Investigation of optimum mg doping content and annealing parameters of Cu2MgxSn1−xSnS4 thin films for solar cells. Nanomaterials 9, 1–13 (2019). https://doi.org/10.3390/nano9070955

77. Z.A. AlAhmed, H.A. Albritthen, A.A. Al-Ghamdi, F. Yakuphanoglu, Optical band gap controlling of nanostructure Mn doped CdO thin films prepared by sol-gel spin coating method. Optik 126, 547–557 (2017). https://doi.org/10.1016/j.ijleo.2015.01.005

78. P. Roy, S.K. Srivastava, Chemical bath deposition of MoS2 thin film using ammonium tetrathiomolybdate as a single source for molybdenum and sulphur. Thin Solid Films 496, 293–298 (2006). https://doi.org/10.1016/j.tsf.2005.06.368

79. S. Chen, G. Yang, H. Zheng, Aligned Ni-Co-Mn oxide nanosheets grown on conductive substrates as hinder-free electrodes for high capacity electrochemical energy storage devices. Electrochim. Acta 220, 296–303 (2016). https://doi.org/10.1016/j.electacta.2016.10.119

80. E. Halvani Anaraki, A. Kermanpur, M.T. Mayer, L. Steier, Turren-Cruz, J. Seo, J. Luo, S.M. Zakeeruddin, W.R. Tress, M.F.A.M. Edvinsson, C. Turren-Cruz, J. Seo, J. Luo, S.M. Zakeeruddin, W.R. Tress, M. Edvinsson, M. Grätzl, A. Hagfeldt, J.P. Correa-Baena, Low-temperature Nb-doped SnO2 electron-selective contact yields over 20% efficiency in planar perovskite solar cells. ACS Energy Lett. 3, 773–778 (2018). https://doi.org/10.1021/acsenergylett.8b00055

81. J. Qiu, B. Weng, W. Ge, L.L. McDowell, Z. Cai, Z. Shi, A broadband Pb white light-emitting diode (WLED) solar cells with tandem quantum-dots embedded in the bulk matrix (QDM) absorption layers by using chemical bath deposition. Sol. Energy Mater. Sol. Cells 172, 117–123 (2017). https://doi.org/10.1016/j.solmat.2017.07.025

82. R.K. Joshi, P. Kumar, H.K. Sehgal, A. Kanjilal, Study of solution grown Cu2O nanostructures for solar cells. RSC Adv. 5, 3929–3936 (2015). https://doi.org/10.1039/c5ra13776k

83. X. Xue, Y. Wang, G. Jiang, W. Liu, C. Zhu, Cu2SnS3 solar cells fabricated by chemical bath deposition-annealing of SnS/Cu stacked layers. Sol. Energy Mater. Sol. Cells 144, 281–288 (2016). https://doi.org/10.1016/j.solmat.2015.09.017

84. Z. Lei, L. Feng, G. Zeng, W. Li, J. Zhang, L. Wu, W. Wang, Influence of CuSb back contact on CdTe thin film solar cells. J. Semicond. 34, 014006 (2013). https://doi.org/10.1088/1674-4926/34/1/014006
166. A. Ashok, C. Regmi, A. Romero-Nuñez, M. Solis-López, S. Velumani, H. Castaneda, Comparative studies of CdS thin films by chemical bath deposition techniques as a buffer layer for solar cell applications. J. Mater. Sci. Mater. Electron. 31, 7499-7518 (2020). https://doi.org/10.1007/s10584-020-03024-3

167. M. Kostoglou, N. Andritsos, A.J. Karabelas, Modeling thin film CdS developmental in a chemical bath deposition process. Ind. Eng. Chem. Res. 39, 3272-3283 (2000). https://doi.org/10.1021/ie990472q

168. X. Mathew, J.R. Arizmendi, J. Campos, P.J. Sebastian, N.B. Mathews, C.R. Jiménez, M.G. Jiménez, R. Silva-González, M.E. Hernández-Torres, R. Dhore, Shallow levels in the band gap of CdTe films deposited on metallic substrates. Sol. Energy Mater. Sol. Cells 70, 379-393 (2001). https://doi.org/10.1016/S0927-049X(00)00179-4

169. V. Fthenakis, C. Athias, A. Blumenthal, A. Kulur, J. Magliozzo, D. Ng, Sustainability evaluation of CdTe PV: an update. Renew. Sustain. Energy Rev. 123, 109776 (2020). https://doi.org/10.1016/j.rser.2020.109776

170. S.-Y. Han, C. Pan, D.-H. Kim, C. Chang, Low-cost & low-temperature curable solution-processed silica-based nanostructured antireflective coatings on CuInS$_2$/Ga$_2$Se$_3$ thin film solar cells. RSC Adv. 5, 24712-24717 (2015). https://doi.org/10.1039/C5RA15602A

171. H. Li, W. Li, W. Li, M. Chen, R. Snyders, C. Bittencourt, Z. Yuan, Engineering crystal phase of polytypic CuInS$_2$ nanosheets for enhanced photocatalytic and photoelectrochemical performance. Nano Res. 13, 585-590 (2020). https://doi.org/10.1007/s12274-020-2665-4

172. B. Sanbergen, T.L. Temple, R. Liang, A.H.M. Smets, R.A.C.M.M. Van Swaaij, M. Zeman, Application of plasmonic silver island films in thin-film silicon solar cells. J. Opt. 14, 024010 (2012). https://doi.org/10.1088/0963-9714/14/2/024010

173. C. Zhang, N. Kinsey, L. Chen, C. Ji, M. Xu, M. Ferrera, X. Pan, V.M. Shalaev, A. Boltasseva, L.J. Guo, High-performance doped silver films: overcoming fundamental material limits for nanophotonic applications. Adv. Mater. 29, 5117 (2017). https://doi.org/10.1002/adma.201605177

174. Y. Yang, S. Matsubara, L. Xiong, T. Hayakawa, M. Nogami, Solvothermal synthesis of multiple shapes of silver nanoparticle films and their SERS properties. J. Phys. Chem. C 111, 9095-9104 (2007). https://doi.org/10.1021/jp068539b

175. L. Reijnens, B. Meester, A. Goossens, J. Schoonman, Atomic layer deposition of CuSx for solar energy conversion. Chem. Vap. Depos. 131e, 7534–7543 (2016). https://doi.org/10.1021/jp410329f

176. V.K. Parashar, M. Gijs, Matsubara, J. Chen, C. Ji, M. Xu, M. Ferrera, X. Pan, V.M. Shalaev, A. Boltasseva, L.J. Guo, High-performance doped silver films: overcoming fundamental material limits for nanophotonic applications. Adv. Mater. 29, 5117 (2017). https://doi.org/10.1002/adma.201605177

177. J. Yoshida, H. Kim, A. Nakai, Green and sustainable chemical synthesis using flow microreactors. Chemuschem 4, 331–340 (2011). https://doi.org/10.1002/cssc.201000271

178. C. Petschacher, A. Eitzlmayr, M. Besenhard, J. Wagner, J. Barthelmes, A. Bemrskop-Schnürig, J.G. Khinast, A. Zimmer, Thinking continuously: a microreactor for the production and scale-up of biodegradable, self-assembled nanoparticles, Polym. Chem. 4, 2342-2352 (2013). https://doi.org/10.1039/c3py30979e

179. N. Aoki, S. Hasebe, K. Mae, Mixing in microreactors: Effectiveness of lamination segments as a form of feed on product distribution for multiple reactions. Chem. Eng. J. 140, 323-331 (2004). https://doi.org/10.1016/j.cej.2003.10.015

180. Y. Yang, S. Matsubara, L. Xiong, T. Hayakawa, M. Nogami, Solvothermal synthesis of multiple shapes of silver nanoparticle films and their SERS properties. J. Phys. Chem. C 111, 9095-9104 (2007). https://doi.org/10.1021/jp068539b

181. N. Assmann, P.R. von Rohr, Extraction in microreactors: Intensification by adding an inert gas phase. Chem. Eng. Process. Process. Intensif. 50, 822–827 (2011). https://doi.org/10.1016/j.cep.2011.05.009

182. Z. Peng, G. Wang, B. Moghaddasi, E. Doroudchi, A review of microreactors based on slurry Taylor (segmented) flow. Chem. Eng. Sci. 247, 117040 (2022). https://doi.org/10.1016/j.ces.2021.117040

183. D.V. Ravì Kumar, B.L.V. Prasad, A.A. Kulkarni, Segregated flow synthesis of Ag nanoparticles in spiral microreactor: role of continuous and dispersed phase. Chem. Eng. J. 192, 357–360 (2012). https://doi.org/10.1016/j.cej.2012.02.084

184. V. Sebastian Cabeza, S. Kuhn, A.A. Kulkarni, K.F. Jensen, Size-controlled flow synthesis of gold nanoparticles using a segmented flow microfluidic platform. Langmuir 28, 7007–7013 (2012). https://doi.org/10.1021/la205131e

185. V. Sebastian, C.D. Smith, K.F. Jensen, Shape-controlled continuous synthesis of metal nanostructures. Nanoscale 8, 7534-7543 (2016). https://doi.org/10.1039/c5nr05313d

186. Z. Liu, Y. Lu, B. Yang, G. Luo, Controllable preparation of poly(butyl acrylate) by suspension polymerization in a coaxial capillary microreactor. Ind. Eng. Chem. Res. 50, 11853–11862 (2011). https://doi.org/10.1021/ie201497b

187. C.-X. Zhao, L. He, S.Z. Qiao, A.P.J. Middelberg, Nanoparticle synthesis in microreactors. Chem. Eng. Sci. 66, 1463–1479 (2011). https://doi.org/10.1016/j.ces.2010.08.039

188. S.A. Khan, A. Günther, M.A. Schmidt, K.F. Jensen, Microfluidic Synthesis of Colloidal Silica. Langmuir 26, 8604–8611 (2010). https://doi.org/10.1021/la9049902

189. K. Amreen, S. Goel, Review–miniaturized and microfluidic devices for automated nanoparticle synthesis. ECS J. Solid State Sci. Technol. 10, 017002 (2021). https://doi.org/10.1149/2162-8777/abd19

190. G.D. Moon, S. Ko, Y. Min, J. Zeng, Y. Xia, U. Jeong, Chemical transformations of nanomaterials for solar module power enhancement. Mater. Des. 185, 109454 (2021). https://doi.org/10.1016/j.matdes.2021.109454

191. D. Mattey, R.D. Robinson, Chemical transformations of nanomaterials for energy applications. J. Mater. Chem. A 2, 5965-5978 (2014). https://doi.org/10.1039/C3TA13982D

192. Y. He, J. Liu, S.-J. Sung, C. Chang, Downshifting and antireflective thin films for solar module power enhancement. Mater. Des. 201, 109454 (2021). https://doi.org/10.1016/j.matdes.2021.109454

193. L. Gomez, M. Arruebo, V. Sebastian, L. Gutierrez, J. Santamaria, Facile synthesis of SiO$_2$/Au nanoshells in a three-stage microfluidic system. J. Mater. Chem. B 22, 21420–21425 (2012). https://doi.org/10.1039/c2jm32406e

194. Y. Song, M. Shang, J. Li, Y. Su, Continuous and controllable synthesis of MnO2/Pt composites with core-shell structures for supercapacitors. Chem. Eng. J. 165, 127059 (2021). https://doi.org/10.1016/j.cej.2020.127059
R. Kikkeri, P. Laurino, A. Odedra, P.H. Seeberger, Synthesis of carboxydrate-functionalized quantum dots in microreactors. Angew. Chem. Int. Ed. 49, 2054–2057 (2010). https://doi.org/10.1002/anie.200905053

A. Abou-Hassan, R. Bazzi, A. Odedra, P.H. Seeberger, Synthesis of carboxydrate-functionalized quantum dots in microreactors. Angew. Chem. Int. Ed. 49, 2054–2057 (2010). https://doi.org/10.1002/anie.200905053

L. Gomez, V. Sebastian, S. Irusta, A. Ibarra, M. Arruebo, J. Santamaria, Scaled-up production of plasmonic nanoparticles using microfluidics: from metal precursors to functionalized and sterilized nanoparticles. Lab Chip 14, 325–332 (2014). https://doi.org/10.1039/c3lc50999k

L. Micheli, E.F. Fernández, J.T. Aguilera, F. Almonacid, Economics of seasonal photovoltaic soiling and cleaning optimization scenarios. Energy 215, 119018 (2021). https://doi.org/10.1016/j.energy.2020.119018

A. Sayyah, M.N. Horenstein, M.K. Mazumder, Energy yield loss caused by dust deposition on photovoltaic panels. Sol. Energy 107, 567–604 (2014). https://doi.org/10.1016/j.solener.2014.05.030

K. Ilse, L. Micheli, B.W. Figgis, K. Lange, D. Dafler, H. Hamifi, F. Wolfertstetter, V. Naumann, C. Hagendorf, R. Gottschalch, J. Bagdahn, Techno-economic assessment of soiling losses and mitigation strategies for solar power generation. Joule 3, 2303–2321 (2019). https://doi.org/10.1016/j.joule.2019.08.019

A.K. Mondal, K. Bansal, A brief history and future aspects in automatic cleaning systems for solar photovoltaic panels. Adv. Robot 29, 515–524 (2015). https://doi.org/10.1080/01691864.2014.996692

M.K. Swain, M. Mishra, R.C. Bansal, S. Hasan, A self-powered solar panel automated cleaning system: design and testing analysis. Electr. Power Components Syst. 49, 308–320 (2021). https://doi.org/10.1080/15325088.2021.1937440

B. Figgis, B. Guo, W. Javed, S. Ahzi, Y. Rémond, Dominant environmental parameters for dust deposition and resuspension in desert climates. Aerosol Sci. Technol. 52, 788–798 (2018). https://doi.org/10.1080/02786826.2018.1462473

B. Figgis, A. Nouviaire, Y. Wubulikasimu, A. Ait-Mokhtar, R. Belbari, S. Ahzi, Y. Rémond, A. Ennaoui, Investigation of factors affecting condensation on soiled PV modules. Sol. Energy 159, 486–500 (2018). https://doi.org/10.1016/j.solener.2017.10.089

K. Ilse, M.Z. Khan, N. Voicu, V. Naumann, C. Hagendorf, J. Bagdahn, Advanced performance testing of anti-soiling coatings—Part I: sequential laboratory test methodology covering the physics of natural soiling processes. Sol. Energy Mater. Sol. Cells 202, 110048 (2019). https://doi.org/10.1016/j.solmat.2019.110048

K. Ilse, M.Z. Khan, N. Voicu, V. Naumann, C. Hagendorf, J. Bagdahn, Advanced performance testing of anti-soiling coatings—Part II: particle-size dependent analysis for physical understanding of dust removal processes and determination of adhesion forces. Sol. Energy Mater. Sol. Cells 202, 110049 (2019). https://doi.org/10.1016/j.solmat.2019.110049

T. Sarver, A. Al-Qaraghulti, L.L. Kazmerski, A comprehensive review of the impact of dust on the use of solar energy: history, investigations, results, literature, and mitigation approaches. Renew. Sustain. Energy Rev. 22, 698–733 (2013). https://doi.org/10.1016/j.rser.2012.12.065

F. Lu, S. Guo, T.M. Walsh, A.G. Aberle, Improved PV module performance under partial shading conditions. Energy Procedia 33, 248–255 (2013). https://doi.org/10.1016/j.egypro.2013.05.065

B. Conceição, H.G. Silva, L. Fialho, F.M. Lopes, M. Collares-Pereira, PV system design with the effect of soiling on the optimum tilt angle. Renew. Energy 133, 787–796 (2019). https://doi.org/10.1016/j.renene.2016.10.080

A. Fernández-García, F. Sutter, L. Martínez-Arcos, C. Sansom, F. Wolfertstetter, C. Delord, Equipment and methods for measuring reflectance of concentrating solar reflector materials. Sol. Energy Mater. Sol. Cells 167, 28–52 (2017). https://doi.org/10.1016/j.solmat.2017.03.036

B. Conceição, H.G. Silva, M. Collares-Pereira, CSP mirror soiling characterization and modeling. Sol. Energy Mater. Sol. Cells 185, 233–239 (2018). https://doi.org/10.1016/j.solmat.2018.05.035

B. Guo, W. Javed, V.S. Khoo, B. Figgis, Solar PV soiling mitigation by electrodynamic dust shield in field conditions. Sol. Energy 188, 271–277 (2019). https://doi.org/10.1016/j.solener.2019.05.071

B. Guo, B. Figgis, W. Javed, Measurement of electrodynamic dust shield efficiency in field conditions, J. Electrostat. 97, 26–30 (2019). https://doi.org/10.1016/j.jelecstat.2018.11.007

B. Figgis, A. Ennaoui, S. Ahzi, Y. Rémond, Review of PV soiling particle mechanics in desert environments. Renew. Sustain. Energy Rev. 76, 872–881 (2017). https://doi.org/10.1016/j.rser.2017.03.100

N. Ahmad, A. Khandakar, A. El-Tayeb, K. Benhmed, A. Iqbal, F. Tonati, Novel design for thermal management of PV cells in harsh environmental conditions. Energies 11, 13231 (2018). https://doi.org/10.3390/en11113231

S. Preet, Water and phase change material based photovoltaic thermal management systems: a review. Renew. Sustain. Energy Rev. 82, 791–807 (2018). https://doi.org/10.1016/j.rser.2017.09.021

(2021) UNMATCHED AR PERFORMANCE—Pellucere Technologies. https://www.more-sun.com/antireflective. Accessed 20 Nov 2021

(2021) ANTI-SOILING REDEFINED—Pellucere Technologies. https://www.more-sun.com/antisoiling. Accessed 20 Nov 2021

K. Han, C.H. Chang, Numerical modeling of sub-wavelength anti-reflective structures for solar module applications. Nanomaterials 4, 67–120 (2014). https://doi.org/10.3390/nano4110011

M. Fievez, P.J. Singh Rana, T.M. Koh, M. Manceau, J.H. Lew, N.F. Jamaludin, B. Ghosh, A. Bruno, S. Cros, S. Berson, S.G. Mhaisalkar, W.L. Leong, Slot-die coated methylammonium-free perovskite solar cells with 18% efficiency. Sol. Energy Mater. Sol. Cells 230, 111189 (2021). https://doi.org/10.1016/j.solmat.2021.111189

J. Shamsh, A.S. Urban, M. Imran, L. De Trizio, L. Mannu, Metal halide perovskite nanocrystals: synthesis, post-synthesis modifications, and their optical properties. Chem. Rev. 119, 3296–3348 (2019). https://doi.org/10.1021/acs.chemrev.8b00644

Y.-A. Lu, T.-H. Chang, S.-H. Wu, C.-C. Liu, K.-W. Lai, Y.-C. Chang, Y.-C. Chang, H.-C. Lu, C.-W. Chu, K.-C. Ho, Coral-like perovskite nanostructures for enhanced light-harvesting and accelerated charge extraction in perovskite solar cells. Nano Energy 38, 138–146 (2019). https://doi.org/10.1016/j.nanoen.2019.01.014