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The research path to commercialization: A perspective on plasmonic nanoparticles in organic and perovskite optoelectronics

Rachith Shanivarasanthe Nithyananda Kumar [a,b,*], Alessandro Martulli [c], Sebastien Lizin [c], Wim Deferme [a,b,*]

[a] Hasselt University, Institute for Material Research (IMO), Martelarenlaan 42, 3500 Hasselt, Belgium
[b] IMEC, division IMOMEC, Wetenschapspark 1, 3590 Diepenbeek, Belgium
[c] Hasselt University, Environmental Economics, Centre for Environmental Sciences, Faculty of Business Economics, 3590 Diepenbeek, Belgium

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ABSTRACT

The emergence of plasmonic nanoparticles in organic and perovskite optoelectronics has evolved beyond its role as a mere light emission and absorption enhancer, by delving into the exotic properties of semiconductor thin films. These properties include stimulated emission (lasing), coherent emission (superradiance), reversible spontaneous emission, and spontaneous synchronization leading to coherent emission. Despite the wealth of available fundamental knowledge, the commercialization of plasmonic nanoparticles in organic and perovskite optoelectronics such as light emitting diodes, photovoltaics and photodetectors, has yet to reach fruition. This paper reviews the technical challenges acting as barriers to commercialization and highlights how their solutions are influenced by economic, sustainability, and regulatory hurdles. A focused examination of technological challenges, including deposition, material compatibility, scalability, and reproducibility of the device performance, is presented. This perspective article concludes by proposing potential solutions and offering a future outlook for the field, emphasizing sustainability, the circular economy, and responsible electronics, alongside the continued advancement of fundamental knowledge.

1. Introduction

The aggregated market valuation of organic and perovskite optoelectronic devices is poised to ascend to approximately half a trillion dollars by the outset of the next decade[1,2]. This surge is predominantly propelled by the key applications—ranging from light emission[3] to photovoltaics[4–6] and flexible electronics. Such unprecedented growth is underpinned by meticulous research endeavours delving into novel materials, avant-garde device architectures, and diverse fabrication strategies[7], all aimed at augmenting device performance and establishing them as formidable contenders vis-à-vis their inorganic counterparts.

Among the earliest strategies employed to augment organic device performance was the integration of metal nanoclusters[8,9]. This move was intended to enhance absorbance across various spectra. It was inspired by a nuanced understanding of localized surface plasmon resonance exhibited by metal nanoparticles[10]. Despite advancements in novel organic semiconductors, integrating plasmonic nanoparticles (PNPs) has remained pivotal. PNPs are not only valued for their multifaceted functionality but also for their

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* Corresponding authors at: NREL, Golden, Colorado (Nithyananda Kumar). Hasselt University, Institute for Material Research (IMO), Martelarenlaan 42, 3500 Hasselt, Belgium (Wim Deferme).

E-mail addresses: rachith.shanivarasanthe@uhasselt.be (R.S. Nithyananda Kumar), wim.deferme@uhasselt.be (W. Deferme).

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potential to unlock novel physics that is not achievable with organic semiconductors alone. These include but are not limited to, stimulated emission (lasing)[11], coherent emission (superradiance)[12], and reversible spontaneous emission[13]. PNPs in the field of perovskites[14] also follow the same trend as their organic semiconductor counterpart due to their similar fabrication strategies and optoelectronic properties.

Since the 1990s, the role of PNPs in organic electronics has expanded to encompass a myriad of plasmon-enhanced optical properties[15], spanning absorption for photovoltaics[16], emission for fluroscence[17,18] and light emission[19], resonance energy transfer[20] (e.g., Förster and Dexter mechanisms), and nonlinear optical phenomena such as multi-photon absorption[21], photon upconversion[22], and unexplored magneto-optic Kerr and Faraday effects[23] in organic materials. Plasmon-assisted phenomena like heating and catalysis[24], and charge transfer[25], alongside a possible stimulated emission and processes induced by plasmons such as hot carrier generation[26] and hybridized electronic states, continue to contribute to the diverse array of explored properties. For perovskite (2009 s)[14], plasmon-enhanced emission[14], absorption[14,27], laser[28], and sensor[29] functionalities have been investigated, enriching the landscape of possibilities.

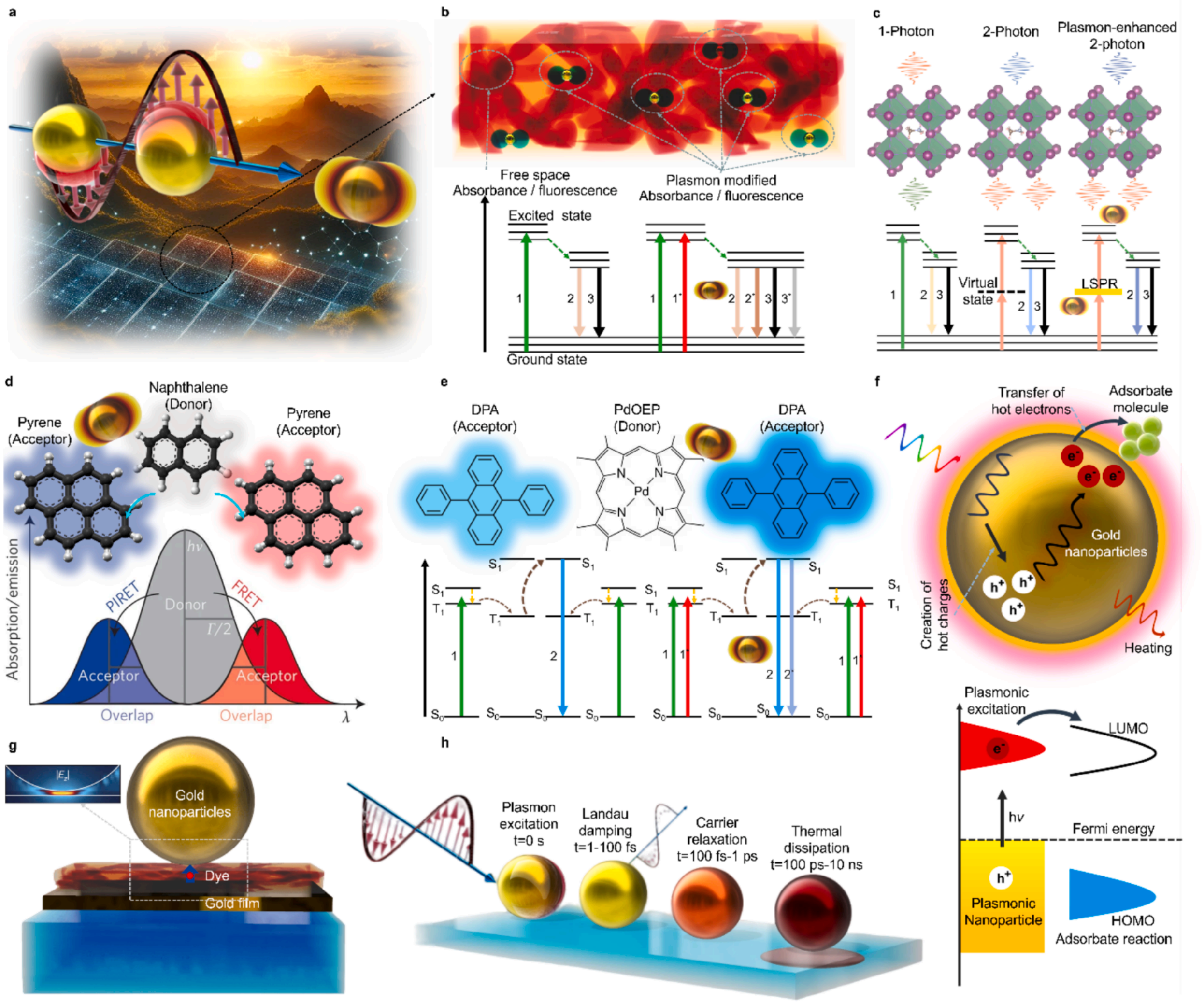


Fig. 1. (a) Graphical representation of electron clouds oscillating in the direction opposite to the electric field around nanoparticles that are much smaller than the incident wavelength, in a photovoltaic plate. (b) Illustration of plasmon-enhanced absorption and fluorescence with a Jablonski diagram for the free-space condition and the modified form in the presence of PNPs in an organic semiconductor matrix. (c) Schematic of plasmon-enhanced multi-photon absorption and fluorescence in a perovskite matrix with the Jablonski diagram. (d) Representation of plasmon-induced resonance energy transfer between donor and acceptor, Adopted with permission[20]. (e) Representation of plasmon-enhanced photon upconversion between donor and acceptor along with their respective Jablonski diagram. Adopted with permission[22]. (f) Plasmon-enhanced hot electron generation and the respective schematic for the transfer of hot electrons from the PNPs to the LUMO of the adsorbate, Ref. with permission from the Royal Society of Chemistry. (g) Schematic diagram of plasmon-exciton coupling at the hot spots, Adopted with permission. (h) Representation of effects induced by the photoexcitation of hot electrons and their relaxation times, adopted with permission
Reproduced from [38][39][40].

Despite the wealth of theoretical and experimental knowledge at the disposal of the scientific community, the integration of PNPs into organic and perovskite optoelectronic devices like light emitting diodes, photo voltaic and photodetectors, has encountered impediments on the road to commercialization, large scale deployment and industrial uptake. Challenges encompass expensive fabrication processes, material compatibility concerns, inefficiencies leading to wastage, lack of scalability in deposition techniques from laboratory to industry, absence of standardized fabrication processes, inconsistent device performance, and regulatory, environmental, and sustainability considerations. Seminal review articles by M. Z. Pakhuruddin et al[16], M. Saliba et al[30], D. D. Zhang et al[31], and b. Ai et al[32] extensively discuss the fundamental science and applications of plasmonic nanoparticles (NPs) in organic and perovskite electronic devices, particularly their role in enhancing the power conversion efficiencies (PCE) of solar cells and the efficiency of OLEDs. These studies highlight the potential of metallic nanostructures to achieve optical enhancements, including near- and far-field effects, tailored by NP shape, size, and positioning. However, despite these advancements, they primarily focus on scientific understanding without detailing pathways to commercialization, a critical gap for bringing these innovations into widespread use.

This perspective provides an integrated approach to advancing the commercialization of plasmonic nanoparticles (PNPs) within organic and perovskite optoelectronics, addressing the technical, economic, and environmental considerations critical to scaling this technology. The objective of this article is to present a comprehensive framework to bridge the gap between fundamental plasmonic insights—such as plasmon-exciton interactions—and scalable production strategies, ultimately facilitating the integration of PNPs into scalable, market-ready devices. By analysing the essential performance improvements required to offset the additional costs of PNPs, this article provides detailed recommendations for materials and fabrication processes tailored to applications across displays, lighting, photothermal therapies, photovoltaics, and photodetectors. These insights emphasize sustainable deployment strategies that align with industry needs and regulatory frameworks. This perspective thus serves as a comprehensive resource for researchers, industry stakeholders, and policymakers, offering actionable guidance essential for the future of flexible, hybrid, and plasmonic-enabled electronics. This work offers a concise exploration of PNPs and their profound impact on the optical properties of thin films in section 2. It focuses on the roadblocks such as cost and environmental considerations that limit the integration of PNPs into consumer products. Efforts that explore less critical[33] plasmonic nanomaterials compatible with organic or perovskite semiconductors to meet environmental and sustainability regulations are discussed in section 3.

Furthermore, in the context of fabricating these PNPs incorporated devices (see section 4), suggestions are focused on minimizing material waste and fabrication costs through substantial efforts. This includes implementing high-transfer-efficiency, roll-to-roll-compatible upscaling techniques, which herald a promising path towards market integration. Additionally, diverse strategies are explored aimed at enhancing device reproducibility in section 5. Moreover, a brief discussion is undertaken regarding the future trajectory of PNPs-incorporated optoelectronics, specifically in the realms of plasmon and exciton coupling.

2. Plasmon-enhanced/assisted/mediated optical properties

Plasmons, derived from the collective oscillation of conduction electrons in metals, play a crucial role in manipulating electromagnetic radiation at the nanoscale. In noble metal nanoparticles like gold and silver, plasmons are generated through Localized Surface Plasmon Resonance (LSPR), initiated by the surface-confined oscillation of free electrons when exposed to incident light, Fig. 1a. The nuanced characteristics of LSPR, such as frequency and decay time, intricately depend on factors like metal type, nanoparticle geometry, and environmental conditions. The interaction of incident light with metallic nanoparticles induces near-field and far-field enhancements in plasmonics. In the near field, the coherent oscillation of surface charges creates highly intensified electric fields in close proximity to the nanoparticle surface (Fig. 3i and m), establishing a precise interaction zone. Simultaneously, plasmons contribute to far-field enhancement through the scattering of electromagnetic fields, releasing photons that extend the interaction range. These near- and far-field enhancements are foundational properties in plasmonics. Within the forthcoming section, a brief exposition on the enhanced properties guided by plasmons is presented. Table 1 summarizes the photon energy requirements for various plasmon-enhanced properties and the corresponding plasmonic nanomaterials. For a more exhaustive elucidation of discrete plasmon-enhanced properties and their mechanisms, readers are encouraged to pursue specialized articles tailored to each facet.[18,20,21,25,27,34–37] These scholarly resources meticulously scrutinize the intricate interplay of plasmons with various phenomena, illuminating their myriad applications and unravelling the underlying complexities.

2.1. Absorbance

The plasmon enhanced absorption in an organic or inorganic thin film is a basic yet groundbreaking approach involving the plasmonic metallic nanostructures where the intricate engineering of metal dielectric configurations facilitates the concentration and manipulation of light within a thin film, resulting in heightened absorption capabilities[4,41], Fig. 1a. This is done in three ways[42], *At first*, in their role as subwavelength antennas, they take leverage of strong local field enhancements to increase absorption in the surrounding semiconductor material. They do so by facilitating the efficient coupling of plasmonic near-fields to the semiconductor, augmenting the effective absorption cross-section[43], Fig. 1b and 3 k. *Secondly*, PNPs showcase their efficacy as subwavelength scattering entities. Positioned strategically, they intricately manipulate incident plane waves into the semiconductor thin film, optimizing the efficiency of light trapping. This controlled scattering process assumes a pivotal role in navigating dielectric interfaces, ingeniously extending the optical path length, Fig. 3j. *Finally*, in plasmonic light-trapping, light transforms into Surface Plasmon Polaritons (SPPs), tiny waves along the plasmonic metal–semiconductor interface, Fig. 3n. At the plasmon resonance frequency, SPPs efficiently capture and guide light within the semiconductor layer, causing a 90-degree redirection of incident solar flux. This results in

Table 1
Overview of Plasmonic Nanomaterials: Key Properties and Applications.

Property	Basic Process	Plasmonic Enhancement mechanism	Photon Energy	End Result	Application
Absorbance	Light absorption occurs when photons with sufficient energy excite electrons from the valence band to the conduction band, creating electron-hole pairs.	Enhance local electromagnetic fields via surface plasmon resonance (SPR), which amplifies light intensity around the PNPs, increasing photon absorption and thus boosting photogenerated carrier generation	UV to Visible, varies with LSPR peak	Heightened absorption capabilities.	Advanced semiconductor devices, solar cells.
Fluorescence	Fluorescence is the emission of light by a substance that has absorbed light or other electromagnetic radiation. After absorbing photons, the substance re-emits light at a longer wavelength due to energy loss through non-radiative processes.	Increase excitation efficiency of the semiconductor as the higher radiative recombination rate of excitons leads to stronger fluorescence emission, whereas the enhanced field favors radiative decay, minimizing non-radiative losses	Visible to NIR, based on material's fluorescence spectrum	Altered quantum yield and fluorescence lifetime.	Biosensing, imaging, fluorescence spectroscopy, light emitting diodes.
Multi-Photon Absorption	Involves enhancement in the simultaneous absorption of multiple photons by a molecule, leading to a transition to a higher energy state.	The strong and localized electric fields over PNPs enhances the probability of multiple photon absorption.	NIR to Mid-IR, higher photon energies for multi-photon processes	Intensified absorption in specific areas.	Biomedical imaging, materials research.
Resonance Energy Transfer	Excess energy from an excited donor molecule is transferred to an acceptor molecule without light emission, mediated by dipole–dipole interactions.	Enhance energy transfer between donor and acceptor molecules via dipole–dipole coupling. The energy absorbed is transferred to the semiconductor, creating electron-hole pairs. Proper allignment of the plasmon resonance maximizes the energy transfer effiiency	Visible to NIR, related to LSPR peaks and spectral overlap	Enhanced energy transfer efficiency.	Nanoscale energy transfer, bioimaging.
Photon Upconversion/Downconversion	Conversion of photons from one energy level to another, such as converting low-energy photons to high-energy ones.	PNPs concentrate light into a small volume, increasing the interaction between photons and the semiconductor. Therefore, two-photon absorption and energy transfer upconversion are improved.	NIR to Visible, requires energy input to upconvert lower energy photons (Upconversion).Visible to NIR, converting higher energy photons to lower energies(downconversion).	Improved upconversion/ downconversion efficiency.	Solar cell efficiency, non-invasive imaging, quantum cryptography.
Hot Carrier Generation	Absorption of photons in metallic structures generates energetic hot carriers (electrons and holes) which can participate in chemical reactions or create a photodetector current.	Absorbing photons and produce hot electrons and holes via Landau damping. The high-energy carriers can be used in chemical reactions or transferred to nearby materials; whereas the hot electrons specifically have longer lifetimes for collection.	UV to Visible, dependent on catalytic processes(catalysis) Visible to NIR, depends on material's electronic properties (charge transfer)	Catalysis, photothermal effects, and current generation.	Cancer therapy, photodetectors, Solar cells, photochemistry.

(*continued on next page*)

Table 1 (*continued*)

Property	Basic Process	Plasmonic Enhancement mechanism	Photon Energy	End Result	Application
Exciton Coupling	Interaction between plasmons and excitons leads to hybrid states (plexcitons) that modify the optical properties of the coupled system.	Interaction between plasmons in PNPs and excitons in semiconductors enhances local density of states and alters the optical properties of the semiconductor, resulting in altered spontaneous emission rates, energy transfer and absorption.	Visible to NIR, dependent on material's exciton properties	Modified optical properties, enhanced emission.	Light harvesting, Light emitting diodes, plasmonic lasers, biosensing.
Exotic Plasmonic Properties	In magnetoplasmonics, a magnetic field influences the behavior of surface plasmon polaritons (SPPs) on metallic surfaces, causing changes in their propagation and interaction with light. Faraday Rotation: Rotation of the plane of polarization of light in a magnetic field due to the material's magneto-optical properties. Circular Dichroism: Differential absorption of left and right circularly polarized light by chiral materials, revealing molecular chiral characteristics.	Plasmonic effects combined with magneto-optical phenomena manipulate surface plasmon polaritons using magnetic fields, resulting in increased rotation of polarized light or in selective absorption of circularly polarized light.	Visible to NIR, dependent on material's exciton properties	Advanced control of optical effects.	Optical devices, chiral sensing, magnetoplasmonics.

lateral light absorption within the material, surpassing typical optical absorption lengths.

Hence, plasmonic metallic nanostructures play a crucial role in orchestrating nano-antennas, scattering techniques, and Surface Plasmon Polariton (SPP) dynamics, acting as precise architects of light manipulation. Their nuanced functions mark a pivotal chapter in plasmonic light-trapping for advanced semiconductor devices, paving the way for strategic advancements in achieving heightened light absorption.

2.2. Fluorescence

Fluorescence is the luminescent phenomenon observed when a fluorescent chemical compound re-emits light upon excitation by single-colour electromagnetic radiation or broad-spectrum light[44]. The fluorescence is characterized by quantum yield and lifetime. Here, quantum yield represents the ratio of the number of photons emitted by the fluorophore to the number of photons absorbed, providing a measure of the efficiency of fluorescence conversion. The lifetime is defined as the average time taken by the excited state of the fluorophore to return to its electronic ground state, encompassing both radiative (emission of a photon) and non-radiative (other relaxation processes) contributions. The quantum yield (Q) of a fluorophore is given by[44]:$Q = k_r/(k_r + k_{nr})$ where: k_r is the radiative decay rate, k_{nr} is the non-radiative decay rate. The measured lifetime (t) of the fluorophore[45,46] is given by: $t\ (s^{-1}) = 1/k_r + k_{nr}$.

Plasmon-enhanced fluorescence (PEF) involves the interaction between fluorophores and plasmonic nanostructures (metal nanoparticles)[18]. This effect is notably characterized by the observation of dramatic changes in fluorescent lifetime and quantum yield. The underlying mechanism involves the electromagnetic interaction between the molecules and the localized surface plasmon resonances (near field) present in the metal nanoparticles, Fig. 1b. The coupling between the molecules and the near field over the metal nanoparticles (a) modifies the decay pathways through the generated near field, which alters the quantum yield of the materials, and (b) is highly sensitive to the distance between them, resulting in a distribution of decay rates.

The impact of the near field, E, on the transition rate of the quantum state is given by the Fermi golden rule. $\gamma_{e\chi} = (4\pi^2)/h|\langle e|E.p|g\rangle|^2\rho_e$, where $\gamma_{e\chi}$ is the excitation rate, e and g represent the wavefunction of excited and ground state, h is the Planck's constant, p is the absorption transition dipole moment and ρ_e is the density of the excited state. In PEF, in addition to the near field, the excitation power (P_0) is a crucial factor. This power is absorbed by both the fluorophore and the nanoparticle, and it significantly influences the strength of the coupling between the molecule and the plasmons.

With the plasmon-enhanced fluorescence, the quantum yield becomes[44,47], $Q_p = (k_r + k_p)/(k_r + k_{nr} + k_p + k_{p,nr})$ where, Q_p, k_p, and $k_{p,nr}$ represent the plasmon enhanced; quantum yield, radiative and non-radiative decay rate respectively. Here the plasmon enhanced radiative decay contributes positively to quantum yield whereas the plasmon enhanced non-radiative decay rates give rise to plasmon enhanced quenching of the fluorophores.

The scattering profile of the nanostructure and its LSPR wavelength, dependent on the refractive index of the medium, also play essential roles in tuning PEF for maximum enhancement. The interaction involves increased radiative decay, and elastic scattering of emitter frequencies by the metal nanoparticle. The elastic scattering contribution is observed in the form of spectral profile modification, where the shape of the fluorescence spectrum is influenced by the scattering profile of the nanostructure. Overall, PEF[47] is a complex interplay of factors involving quantum yield, nanostructure properties, and the environment.

2.3. Multi-photon absorption

Multi-photon absorption refers to the simultaneous absorption of multiple photons by a molecule, causing its transition from a lower energy state to a higher one[44]. The mechanism is elucidated through quantum processes, exemplified by two-photon absorption (2PA) where a molecule, immersed in a nonlinear absorbing medium, absorbs two photons in distinct steps[44,48], Fig. 1c. In the first step, a photon propels the molecule from its initial state to an intermediate state, marked by a brief, uncertain residence time. The second step involves the absorption of another photon while the molecule resides in the intermediate state, completing the transition to the final real state. This simultaneous two-step event distinguishes true multi-photon absorption from cascaded one-photon processes, emphasizing the critical role of intermediate states and the uncertainty principle in governing these quantum interactions.

The concept extends seamlessly to three-photon absorption (3PA) and beyond, where additional photons and intermediate states are introduced. In 3PA, three photons are absorbed in three steps involving two intermediate states. Each step contributes to the molecule's progression from its initial state through intermediate states to the final real state. The simultaneous occurrence of these steps, dictated by the uncertainty principle, characterizes multi-photon absorption as a single elementary process. The framework can be applied to describe multi-photon absorption involving more than three photons, highlighting the quantized nature of the interaction between radiation and matter.

Plasmon-enhanced multi-photon absorption[49] involves the utilization of PNPs, to amplify the multi-photon absorption (MPA) process in molecules. The mechanism of plasmon-enhanced multi-photon absorption involves the creation of localized electric fields by PNPs, particularly in hotspots (spaces where strong localized electric fields are generated). Molecules strategically positioned within these hotspots experience a significant boost in the local electric field strength due to plasmonic effects. This intensified electric field enhances the multi-photon absorption process in nearby molecules, increasing the probability of simultaneous absorption of two photons. Importantly, the plasmonic effects are highly localized, concentrating the enhanced absorption in specific regions (hotspots) around the nanostructures. This localization is crucial for achieving precise and intensified absorption in targeted areas, making plasmon-enhanced two-photon absorption a valuable tool in applications such as biomedical imaging and materials research.

Interestingly, the photon upconversion often involves similar multi photon interactions, where two lower-energy photons are absorbed by a material, and their energies are combined to emit a higher-energy photon[50,51], Fig. 1e. This process allows for the conversion of low-energy photons, such as infrared light, into higher-energy photons, like visible or ultraviolet light.

Apart from multi photon interactions, various mechanisms also contribute to photon upconversion: Excited State Absorption (ESA) [52], and Energy Transfer Upconversion (ETU)[53], with a specific type called Triplet-Triplet Annihilation (TTA) falling under ETU [51]. In TTA, donor and acceptor molecules work together to sequentially absorb and transfer energy, resulting in the emission of a higher-energy photon. Photon upconversion finds diverse applications, such as enhancing solar cell efficiency, enabling non-invasive cancer treatment, improving microscope resolution, and contributing to technologies like micro-fabrication and quantum cryptography.

Plasmon-enhanced photon upconversion[22,54] is again a strategic process designed to augment the efficiency of upconversion, where lower-energy photons transform into higher-energy counterparts. Plasmon-enhanced upconversion integrates PNPs as nano-antennas, to tailor electromagnetic fields. Unlike normal upconversion, plasmon-enhanced upconversion may result in substantial spectral shifts, emphasizing the importance of maximizing spectral overlap between plasmon resonance and emitter absorption/ emission frequencies. The process also differs due to its multistep nature, with plasmon resonances influencing decay rates from long-lived intermediate states, impacting overall upconversion efficiency. Mechanistically, plasmon-enhanced upconversion concentrates incident fields, elevates radiative decay rates, controls field overlap through nanoantenna properties, and exhibits a power dependence in emitted power[55]. In summary, plasmon-enhanced photon upconversion represents a sophisticated strategy utilizing plasmonic structures to optimize absorption, emission, and field interactions, holding promise for diverse applications in sensing, imaging, and photovoltaics.

While both multi photon absorption and photon up convertors leverage plasmonic hotspots for enhancement, their fundamental differences lie in the energy pathways and photon interactions involved. Multi photon absorption operates primarily as a simultaneous photon absorption process in high-field regions, suited for localized imaging applications. In contrast, photon up converters utilizes plasmon resonances for multi-step photon interactions, optimizing spectral overlap and enabling applications that require photon frequency conversion. Both approaches illustrate the versatile role of PNPs in controlling and enhancing photonic processes for advanced technological applications.

Similar to photon up convertors, photon down upconvertors[56,57] involve a nonlinear optical process, but unlike photon upconvertors here a single high-energy photon is converted into two or more lower-energy photons. This mechanism finds applications in areas such as bioimaging, quantum information, and solar energy, where it enables efficient photon management for enhanced energy capture or information processing. In solar energy, for instance, downconversion can shift ultraviolet light to the visible spectrum, improving the photovoltaic cell efficiency by making better use of high-energy photons. Plasmon-enhanced downconversion

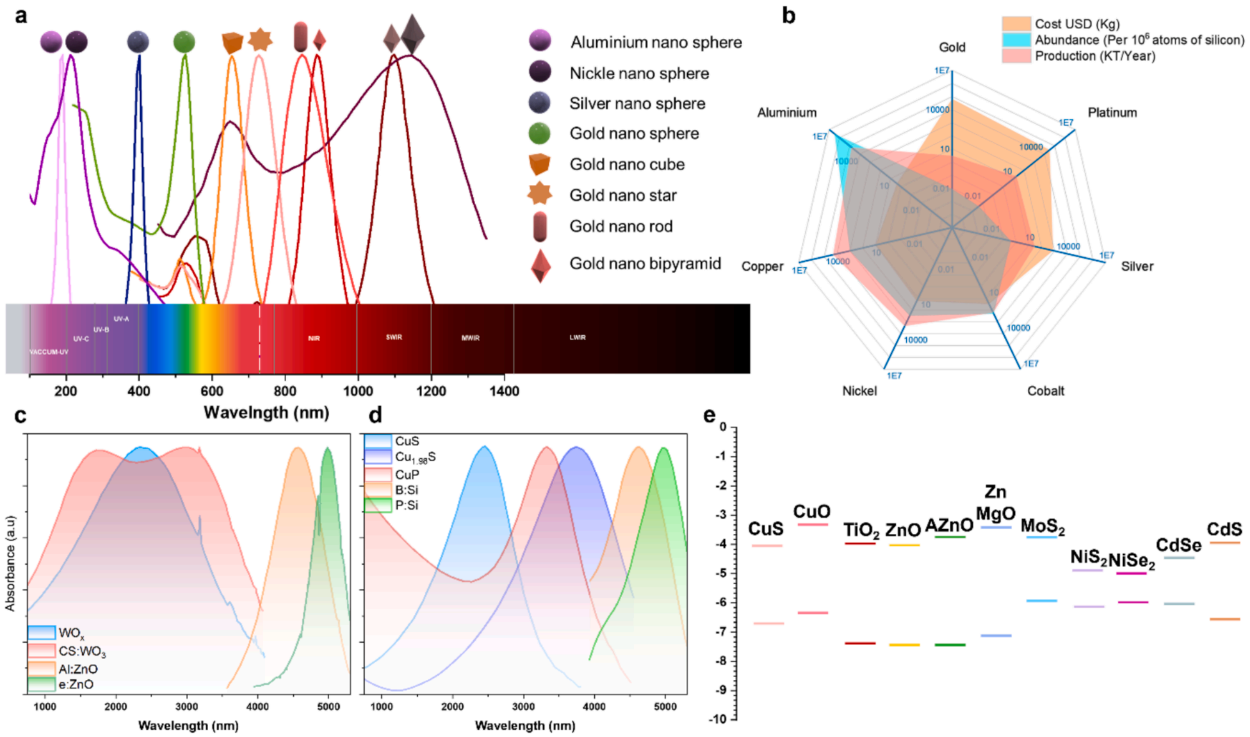


Fig. 2. (a) The LSPR spectrum for various noble nanoparticles and different shapes of gold nanoparticles[88] calculation based on Mie theory implementation. (b) Radar chart representing the cost per kg, abundance on Earth, and annual production of various noble PNPs. (c and d) The LSPR spectrum of semiconducting and 2D PNPs and metal chalcogenides exhibiting LSPR in the mid-infrared spectrum respectively, adopted with permission [89]. (e) The energy level diagram for plasmonic 2D and semiconducting nanoparticles, illustrating their functionalities.

enhancement relies on localized surface plasmon resonance (LSPR), where resonant oscillations of conduction electrons in the metal nanoparticles amplify the local field, leading to greater photon absorption and emission rates in adjacent downconverting materials. While this technique holds promise for applications in photovoltaics by boosting light conversion efficiency, optimization is needed to balance enhancement and potential quenching due to losses in the metal particles. Future work is needed to practically avail the benefits of photon downconversion in efficient solar panels, bioimaging with heightened sensitivity, and also in advanced lighting technologies.

2.4. Resonance energy transfer

Resonance Energy Transfer (RET) is a process where the excess energy of an excited donor molecule is efficiently transferred to an acceptor molecule without emitting light[20,49]. This transfer involves electronic energy moving between molecules through dipole–dipole couplings, resembling a molecular energy relay. It plays a crucial role in various biological and chemical processes.

Plasmon-induced/mediated or controlled Resonance Energy Transfer (PI/C/M−RET)[49] is a specific directional transfer of energy from PNPs to a semiconductor through dipole–dipole coupling, distinguishing it from general Fluorescence Resonance Energy Transfer (FRET), Fig. 1d. The sequence initiates with light absorption by PNPs, leading to plasmonic oscillations (plasmons). This absorbed energy transfers to a semiconductor, generating electron–hole pairs near its band edge. PIRET modifies the excitation and de-excitation pathways of a FRET pair with the introduction of PNPs. These nanoparticles influence the excitation rates of both donor and acceptor molecules, altering various decay channels, including energy transfer, radiative decay, and nonradiative decay. The tunability of PIRET is achieved by adjusting the plasmon resonance of proximal PNPs. When the plasmon peak aligns with the donor's emission peak, there is a notable reduction in energy transfer efficiency. Conversely, positioning the plasmon peak between the donor's intrinsic emission and the acceptor's absorption peak significantly enhances energy transfer, evidenced by distinct peaks in fluorescence spectra. Further, red-shifting the plasmon peak to align with the acceptor's intrinsic emission peak demonstrates increased energy transfer efficiency. This synthetic control over the FRET process provides valuable insights into the nuanced dynamics of PIRET, with implications for nanoscale energy transfer applications. Experimentally, PIRET extends the energy transfer distance up to ~120 nm,

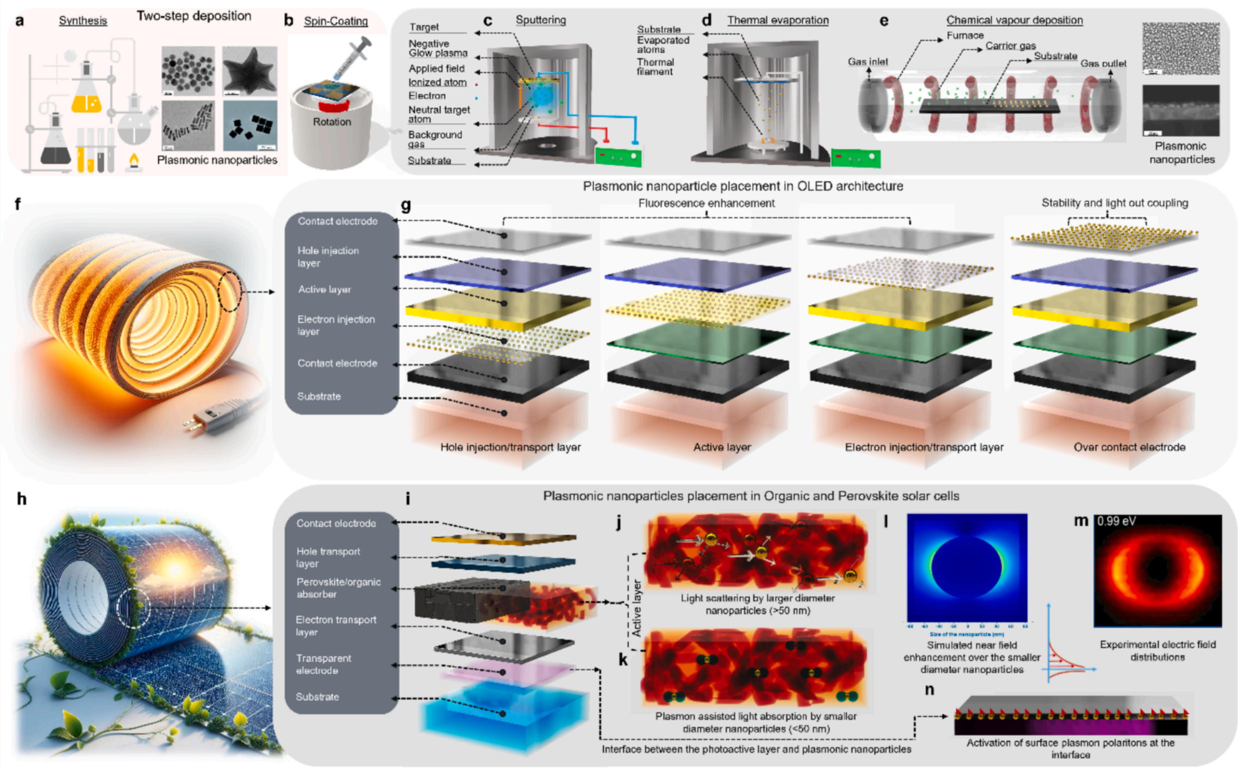


Fig. 3. (a) Illustration of the synthesis of PNPs for solution processing and the various shapes of synthesized nanoparticles, Adopted with permission [90,91] (b) Graphical representation of various lab-scale deposition techniques: (b) spin coating, (c) sputtering, (d) thermal evaporation, and (e) chemical vapour deposition, including an SEM example of gold nanoparticles deposited via thermal evaporation and annealing. (f) Futuristic illustration of flexible OLEDs. (g) Representation of possible locations for PNPs in OLEDs. (h) Futuristic representation of flexible solar cells. (i) Possible locations for plasmonic nanoparticle deposition. Graphical representation of plasmon-enhanced absorption by (j) using far-field scattering, (k) near-field enhancement inside the active layer of a solar cell, (l) numerical simulation showing near-field enhancement over PNPs, (m) experimental results of electric field distribution (near field) via electron energy loss spectroscopy over PNPs, adopted with permission[41], and (n) representation of plasmon-enhanced absorption using surface plasmon polaritons.

surpassing traditional Förster radii between organic dyes (1–10 nm)[58]. This underscores the notable potential of plasmon-mediated processes.

2.5. Hot carrier generation-Catalysis-Chemical reaction-charge transfer

Plasmon-assisted hot carrier generation[40,59] is a fascinating phenomenon initiated by the illumination of metallic structures, unleashing a cascade of complex processes with varied outcomes. In the process of hot carrier generation and relaxation within metallic structures, the absorption of photons initiates a cascade of events. Plasmon resonances, particularly in metallic nanostructures, enhance light absorption, leading to Landau damping and the creation of hot electron–hole pairs[40]. The subsequent distribution of carriers is influenced by factors such as plasmon energy, particle size, and electronic structure. On extended metal surfaces, relaxation occurs with timescales around 100 fs to 1 ps, resulting in a Fermi–Dirac-like distribution, Fig. 1h. In contrast, PNPs exhibit longer lifetimes for non-thermal hot electrons, allowing a state-selective population of adsorbate resonances. The generated hot electrons and holes can catalyze chemical reactions on adsorbates[36], offering potential applications in surface-enhanced processes and photochemistry. Additionally, the internal decay of hot electrons in PNPs contributes to significant heating[60], leading to diverse applications such as photothermal cancer therapy and nano fluidics. Photodetectors based on the photo ejection of hot electrons from metals show promise[61–63], with efforts focused on optimizing interfaces and employing nanostructured surfaces or optical antennas to enhance efficiency. The dynamics involve a complex interplay of processes with distinct timescales, from ultrafast electron–phonon interactions to longer heat transfer times to the surroundings. In the context of hot carrier devices, a critical aspect is the efficient collection of excited hot electrons. Again here, plasmon-assisted hot carrier generation[64] plays a pivotal role, where the absorption of a photon in a metal generates energetic hot electrons that are lifted from states below the Fermi level. These hot electrons can move

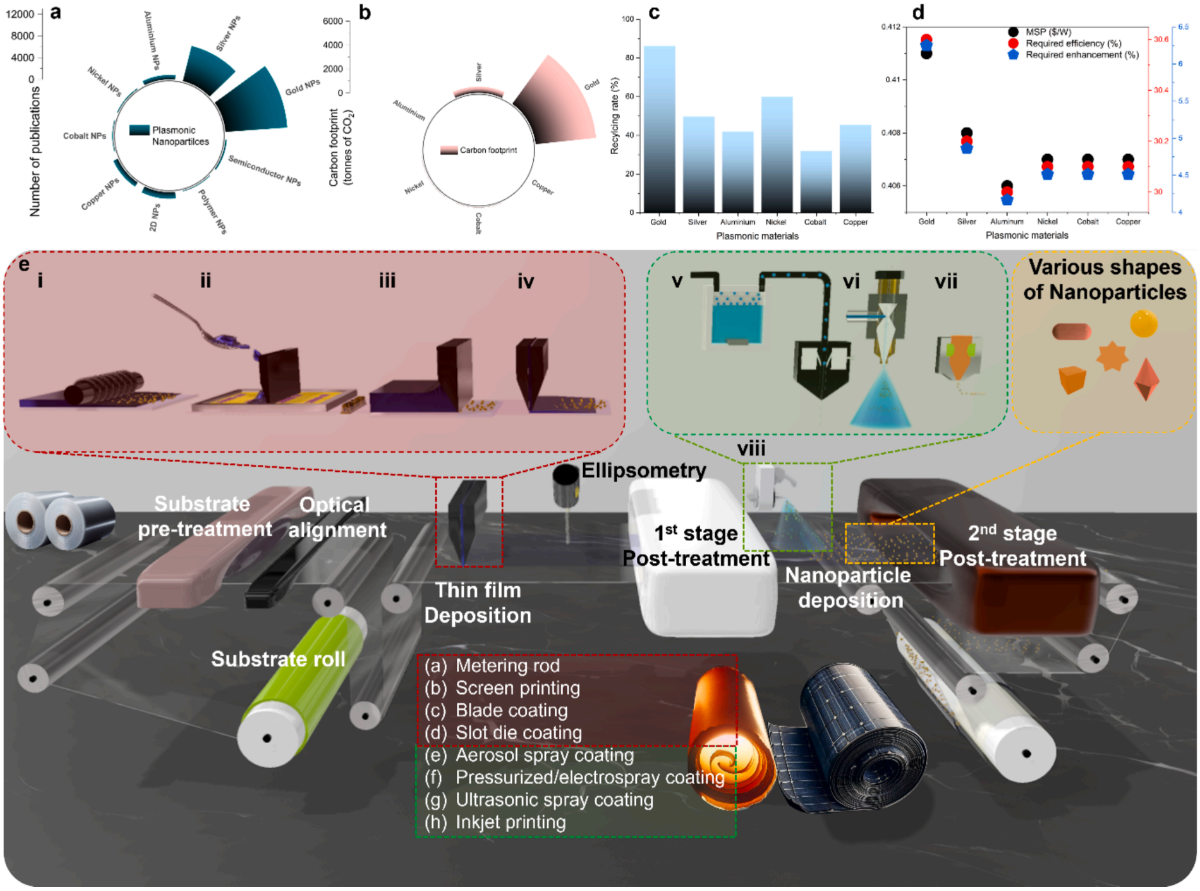


Fig. 4. (a) Statistics on the number of publications over the years on various PNPs(data from Scopus). (b) The carbon footprint of various plasmonic noble nanoparticles[119]. (c) Current recycling percentage of various plasmonic noble nanoparticles(data from IEA[120]). (d) Techno-economic analysis of MEP and efficiency requirements after incorporating the plasmonic noble nanoparticles. (e) Graphical representation of the proposed processing line for incorporating PNPs into a solar cell using various deposition techniques: (e.i) Mayer rod, (e.ii) screen printing, (e.iii) doctor blade coating, and (e.iv) slot die coating for the plasmonic nanoparticle and functional layer mixture deposition; and deposition techniques like spray coating, including (v) pressurized, (vi) electrostatic, (vii) ultrasonic, and (viii) inkjet printing for the deposition of PNPs at specific locations with specific surface coverage.

towards the metal/oxide interface, contributing to a current when emitted over a Schottky barrier. Moreover, plasmon-induced charge transfer[35] (PICT) represents a promising avenue in harnessing the potential of surface plasmons for various applications, particularly in the realm of solar energy conversion and photocatalysis. The conventional limitations of surface plasmons, characterized by rapid damping and short-lived excitations on plasmonic nanostructures, have spurred the exploration of PICT as a means to extract hot carriers before their thermalization with the metal lattice. This process offers a route to utilize the energetic charge carriers for practical purposes, such as generating electric currents or driving chemical reactions.

Plasmon-induced chemical reactions and catalysts have emerged from femtochemistry studies[38,65], Fig. 1f, revealing distinct pathways under femtosecond laser excitation. Extended metal surfaces and nanoparticles facilitate distinct pathways for hot-electron dynamics, influencing the state-selective population of adsorbate resonances through rapid equilibration and prolonged non-thermal lifetimes. This facilitates chemical transformations, such as plasmon-induced dissociation of molecules, showcasing potential applications in selective desorption, dissociation, or translational motion of adsorbates on a metal nanoparticle surface. Simultaneously, plasmon-induced localized heating[40] in metallic nanoparticles finds applications in diverse fields, including cancer therapy, photothermal nanotherapeutics, and chemical separation. Resonant nanoparticles efficiently convert light into heat, enabling precise control and energy-efficient processes with applications in areas like steam generation, heterogeneous catalysis, and drug delivery.

2.6. Exciton coupling

Plasmon-exciton coupling, commonly referred to as a plexciton[39,66–68], is a phenomenon arising from the interaction or coupling of plasmons and excitons, Fig. 1g. Excitons, involve the bound state of an electron and a hole, forming quasi-particles with distinct characteristics in various materials. Plasmon and exciton coupling delves into the intricate interaction between metal interfaces and fluorescence. This coupling is pivotal for manipulating the spontaneous emission of fluorophores near metallic surfaces. The coupling arises from the interplay between the high-density conduction electron states in the metal and the low-density electromagnetic modes in free space, resulting in a hybrid resonance with a large local density of states of the molecules. However, the inherent weak coupling due to the mismatch in the length scale between photons and fluorophores limits the potential applications. To address this, PNPs come into play, elevating the coupling strength by localizing electromagnetic radiation in their vicinity. The strength of the coupling, measured by the Rabi splitting energy, determines the optical properties of the coupled molecules, offering control over spontaneous emission, absorption, energy transfer at the nanoscale, and nonlinear optical behaviours. Plexcitons have gained attention in molecular plasmonics, finding applications in light harvesting, plasmonic lasers, biosensors, and spectroscopy. Understanding and manipulating plasmon-exciton coupling requires the integration of PNPs with excitonic materials, and the development of hybrid structures with tunable plasmon resonance wavelengths and large Rabi splitting energies.

Integrating PNPs with fluorophores within thin films creates nanocavities, presenting a viable alternative to traditional microcavities. This integration, facilitated by the versatility of nanoparticles, enables organic optoelectronic device architectures without compromising electronic and optical properties resulting in exotic characteristics like polariton lasing. In contrast to conventional photon lasers, polariton lasing exhibits a significantly lower threshold, allowing ultralow-threshold or electrically pumped coherent light sources. Recent advancements in organic semiconductor microcavities have demonstrated room-temperature polariton lasing [69], showcasing its potential for practical applications. However, challenges such as continuous-wave operation and lower thresholds persist. Integration with PNPs in organic materials systems holds promise for addressing these challenges. The plexciton could enhance polariton properties. The combination of organic polariton lasers with plasmonic nanostructures may offer tunable and efficient coherent light sources with applications in various fields, including light harvesting, sensing, and optoelectronic devices. Ongoing research aims to explore and optimize these hybrid systems for improved performance and versatility.

Plexciton exerts notable effects on various optical phenomena, notably influencing stimulated emission, coherent emission, and reversible spontaneous emission. In the realm of stimulated emission, wherein photons are emitted due to the induced decay of excited states, the robust interaction between plasmonic modes[69] and excitons facilitates heightened emission rates. This heightened efficiency is pivotal for applications like lasers and light-emitting devices, where amplified light emission is crucial. Coherent emission, characterized by the generation of light waves with a consistent phase relationship, is significantly impacted by plexciton[70]. The hybrid states formed due to the interplay between plasmons and excitons influences the coherence properties of the emitted light. This effect is of paramount importance in applications necessitating controlled and coherent light sources, exemplified by plasmonic lasers. Furthermore, plexciton's influence extends to reversible spontaneous emission, a phenomenon wherein emitted photons can be reabsorbed by the quantum system. The strong coupling between plasmonic modes and excitons could induce noteworthy modifications to the characteristics of spontaneous emission, offering avenues for manipulating the reversibility of the emission process. This feature holds particular relevance in quantum optics applications, providing a means to exercise control over the quantum states of emitted light.

2.7. Exotic plasmonic properties

Plasmonics has not only enhanced the properties of thin films, as elucidated in the previous discussion on plasmon-enhanced features, but has also extended its influence into fields like magnetoplasmonics[71], Faraday rotation[72], and circular dichroism [73]. In magnetoplasmonics, the amalgamation of plasmonics and magneto-optics enables the manipulation of surface plasmon polaritons (SPPs) using magnetic materials. The synergistic effects of coherent oscillations and magneto-optical phenomena, such as the Faraday and Kerr effects, offer new avenues for controlling electromagnetic energy on the nanoscale. Nanostructures with tiny slits in a metal layer on a ferromagnetic material can achieve significant Faraday rotation with low optical losses. In the realm of Faraday rotation, integrating plasmonics with magneto-optics in a plasmonic photonic crystal greatly enhances the Faraday effect across a wide range of frequencies. Plasmonic nanowire arrays on magneto-optical films can increase Faraday rotation by up to 8.9 times while remaining transparent[74], enabling advanced applications in optical devices, antennas, and circulators. Circular dichroism, another key plasmonic effect, arises from the selective absorption of left and right circularly polarized light by chiral structures. Recent advances have extended circular dichroism studies to plasmonic nanostructures, including noble metal nanoparticles, chiral metamaterials, and photonic crystals, showing intriguing responses. Even achiral plasmonic nanostructures can generate circular dichroism signals under specific conditions, enhancing optical activity. This field has potential applications in chiral catalysis, sensing, and polarization-sensitive optical devices.

Despite significant progress in magnetoplasmonics, Faraday rotation, and circular dichroism within inorganic materials, these phenomena are relatively unexplored in organic materials. The unique electronic and optical properties of organic materials, along with their tunability, make them promising candidates for future research. Incorporating plasmonic and magneto-optical effects in organic and perovskite systems could lead to new possibilities in organic and perovskite electronics, bio-sensing, and optoelectronic devices, presenting exciting challenges and opportunities for a wide range of applications.

3. Plasmonic nanomaterials

The selection of which PNPs to integrate into organic/perovskite electronic devices, aimed at harnessing their plasmonic properties to enhance device performance, and their large-scale production requires a thorough examination of multiple factors besides those related to their technical performance. Important considerations are: resource scarcity, the environmental impact of rare metals' mining (carbon foot print), the availability of suitable recycling methods, and human and ecosystem toxicity risks. Addressing these issues is crucial to incentivize industries to adopt plasmonic nanostructures in organic/perovskite devices on a widespread scale.

In this section, we will first review materials that have been extensively studied and then explore innovative materials currently under consideration. A major factor driving industry interest is the ease of depositing these nanoparticles using existing roll-to-roll fabrication methods. This aspect, is discussed in more detail in Section 4, "Techniques to Deposit PNPs." This article does not cover the synthesis of nanoparticles in detail. However, readers are encouraged to consult the most authoritative [75–86] for a thorough exploration of synthesis methods for various types of nanoparticles.

3.1. Noble metal nanoparticles

The family of noble metal nanoparticles which were extensively investigated in the organic/ perovskite electronics includes gold (Au), silver(Ag), platinum(Pt), aluminium(Al), nickel (Ni), cobalt(Co), copper(Cu). For a 20 nm spherical nanoparticle, the plasmon peak or localized surface plasmon resonance (LSPR) peak for the above said materials is shown in Fig. 2a. The LSPR of Al, Ni, Pt, Co, and Ag lies in the UV region and the LSPR of Cu and Au lies in the visible spectrum. However, it should be noted that the LSPR is dependent on the dielectric medium surrounding the nanoparticles and also the size and shape of the nanoparticles. For example, the Au with different shapes exhibits LSPR in the infrared and near-infrared regions. The shapes of gold nanoparticles with respect to the LSPR are shown in Fig. 2a, including, nanocube, nanostar, nanorods and nanobipyramid. The presence of the dielectric medium can also redshift the LSPR. Within the category of noble metals Al, Au, Ag, Co and Pt are recognized as critical raw materials[87] and hence it is advisable to exercise caution and explore alternative options when considering the use of these materials.

Au is nevertheless currently favoured over other materials for electronics applications due to its unique combination of properties that make it highly suitable for various electronic components. One key attribute is Au's exceptional resistance to corrosion, attributed to its noble character, ensuring the longevity and reliability of electronic devices. Also, the selective tunability of its LSPR over a wide range from visible to NIR spectrum eases its usage in various organic/perovskite electronics devices. While other metals like silver may offer lower cost and enhanced absorption, Au's stability and enduring performance in the face of oxidation effects make it a preferred choice in electronics, where longevity and reliability are paramount. Despite its extreme scarcity[92] (0.005 ppm crustal abundance), gold has historically held a prominent position in luxury and aesthetics, particularly jewellery. However, the rise of organic and perovskite electronics challenges this narrative. The exploration of novel materials and advancements in electronics demands a precise recalibration of Au's position within this dynamic landscape. The growing importance of Au recycling offers a crucial pathway towards mitigating its scarcity and environmental impact. In 2023[93], an estimated 90 tons of new and old scrap was recycled, equivalent to about 36 % of reported consumption. This highlights the significant potential for reducing the reliance on virgin Au mining and its associated environmental footprint. Furthermore, research on the recycling of Au from e-waste[94] is gaining traction. Notably, a study by Maria Clara Costa et al.[95] demonstrates the effectiveness of using biogenic sulfide generated by sulfate-reducing bacteria to recover gold from low-concentration solutions making the recycling cost effective and sustainable. This innovative approach further strengthens the circular economy and sustainability of using gold in organic and perovskite electronics. The toxicity of Au nanoparticles[96] is a topic of increasing debate in the field. While some studies argue that Au nanoparticles are not toxic[97–99], others contradict these claims[100–102]. To reach a universal understanding of their toxicity, it's essential to conduct a thorough investigation into the physical and chemical changes that Au nanoparticles undergo at each stage of interaction with biological media.

Ag, the second most studied precious metal after Au, also boasts a rich history and diverse range of applications[103]. The LSPR of Ag lies in the ultraviolet region and has limitations due to its stability concerns. However, employing a dielectric spacer of a few nanometers enhances their stability, and also red shifts the LSPR while the utilization of various shapes allows for selective tuning. However, the escalating demand for Ag in the electronics industry poses a potential challenge to the sustained use of Ag NPs in the distant future. As the global shift towards non-fossil energy production gains momentum, Ag's importance amplifies, especially in the burgeoning electric vehicle (EV) market. The International Energy Agency predicts 125 million EVs on the road by 2030, driving the demand for Ag in critical safety and environmental applications within EVs. Additionally, the surge in renewable energy aspirations fuels the demand for Ag in solar infrastructure, with global Ag photovoltaic demand exceeding 4000 tons in 2023[104]. Projections indicate an 85 % growth in Ag demand, reaching 7400 tons in the next decade, driven by the rising growth of electricity demand and the decreasing costs of photovoltaic technology production. Similar to Au, there has been an immense amount of research focussed on recycling [105,106]. The green synthesis of Ag NPs [107] from waste streams offers significant potential for sustainable and circular economy integration within organic and perovskite electronics. However, caution is necessary when considering the toxicity of Ag nanoparticles. Despite their well-known antibacterial properties and widespread use in cosmetics, sunscreen, and sensors, in vitro studies indicate that Ag nanoparticles can have toxic effects on human health[108,109].

Exploring the viability of utilizing abundant, low carbon footprint and cost-effective materials such as aluminium[110], copper [111], nickel[112] and cobalt[113] offer a promising avenue, for selectively tuning LSPR across various sizes and shapes to cater to diverse applications. Despite being classified by the EU as strategic raw materials, these elements still present valuable opportunities for innovation in this field. Due to the inherent abundance and relative ease of scalable production and low carbon footprint (Fig. 4b) compared to gold and silver, Al, Cu, Co and Ni nanoparticles are poised to dominate the future of plasmonics in organic and perovskite optoelectronic devices, Fig. 2b. Since the LSPR of these materials can be spectrally tuned for various applications simply by adjusting their size, shape, and the refractive index of the surrounding medium, Eg: encapsulating them in core–shell geometries, enables their use across a wide spectral range from UV to NIR. Recycling of these materials[114–116] is a well-established process, in particular Cu, which is theoretically 100 % recyclable. Recycling of the PNPs is gaining traction[95,117,118], with an emphasys on biorecovery[95]. Furthermore, the low energy consumption associated with recycling these materials (particularly Al, where recycling requires only about 5 % of the energy consumed during production through ore) significantly enhances their environmental sustainability and cost-effectiveness compared to other plasmonic materials. However, this approach necessitates a rigorous examination of the toxicity [39,66–68] associated with nanoparticles. To address potential health and environmental concerns, it becomes imperative to conduct comprehensive studies on toxicity profiles. Furthermore, the development of surface modifications or coatings assumes paramount importance in order to curtail the release of toxic ions and enhance overall biocompatibility. Employing advanced surface engineering techniques, coupled with the utilization of stabilizing agents, emerges as a strategic avenue to minimize reactivity at the nanoscale, thereby mitigating the risk of oxidative stress. This nuanced approach could ensure the responsible and safe deployment of these nanoparticles in various applications by industry.

3.2. *Semiconductor nanoparticles*

Plasmonic semiconductors[85,89,121–123] constitute an emerging frontier in nanoscale optics, unravelling innovative avenues to transcend the intrinsic diffraction limit of light through the exploitation of distinctive material properties. As seen previously, metals like gold (Au) and silver (Ag) have been pivotal for their pronounced plasmon resonance, conductivity, and ease of synthesis. However, contemporary advances spotlight plasmonic semiconductors including oxides[124], chalcogenides[85], nitrides[125], and III–V semiconductors[126] as compelling alternatives, offering a broader spectral range and increased adaptability and exhibiting plasmonic bands in the NIR-to-THz frequencies as shown in Fig. 2c and d, complementing the spectral regions covered by metals. The LSPR spectrum strategically aligns with crucial spectral regions, including telecommunications bands (1260–1625 nm), solar energy spectrum (295–2500 nm), and the biological transparency window (650–1350 nm)[121]. The diverse material composition within the semiconductor family, coupled with the tunability afforded by in-situ factors and post-synthetic methodologies, confers exceptional versatility.

Plasmonic semiconductors have evolved into a frontier for nanoscale light manipulation, highly doped semiconductors, in particular, offer unparalleled flexibility in plasmon dynamics, supporting near-field amplification, hot carrier injection, and thermalization. Hybrid structures, such as metasurfaces and heterostructures, provide additional dimensions for regulating plasmonic response, enabling collective plasmonic modes and extended plasmon propagation.

The field of degenerately doped semiconductor nanocrystals (NCs) has witnessed rapid growth since the pioneering report by Zhao et al. in 2009[127], showcasing localized surface plasmon resonances (LSPRs) in copper sulfide ($Cu_2 - xS$) nanocrystals in the near-infrared (NIR) range. Luther et al.[128] later demonstrated that a broad range of semiconductor NCs, with appreciable free carrier concentrations, can sustain LSPRs spanning from visible to terahertz frequencies. Doped semiconductor NCs, such as phosphorous and boron-doped silicon[129], aluminium-doped zinc oxide[129], and indium-doped tin oxide[130], exhibit intense resonances in the mid to near-IR due to plasmonic absorption. The exceptional characteristic of degenerately doped semiconductor NCs lies in the high levels of doping, leading to carrier densities around 10^{21} cm^{-3} and LSPRs in the NIR. The carrier density variation and defect states influence the LSPR position, making these materials attractive for controlled plasmon tuning over a wide spectral range. Despite the promise, the field of plasmonic semiconductors is nascent, with challenges pertaining to understanding intricate plasmon dynamics and translating theoretical insights into real-world applications.

An intriguing and pivotal facet with significant promise for the industry lies in the versatile functionality of plasmonic semiconductors. The capability of these nanoparticles to exhibit p-type or n-type characteristics, contingent upon the doping employed, renders them highly adaptable for functions such as charge transport, injection, or extraction layers, Fig. 2e. This multifunctionality, coupled with their inherent plasmonic enhancement in photon absorption, emission, or detection, augments their utility across a spectrum of applications. Moreover, the utilization of earth-abundant and non-critical materials in these nanoparticles addresses concerns related to resource availability and environmental impact.

For instance, copper-based materials, such as copper oxide (CuO) or copper sulfide (Cu_2S), exemplify the move towards sustainable semiconducting PNPs. Their plasmonic behaviour, coupled with the abundance and recycling of copper[115], makes them a candidate for being an environmentally friendly alternative. Another avenue involves the use of semiconductors like zinc-oxide (ZnO) in plasmonic nanoparticle formulations[131]. These materials, with tunable plasmonic resonances, offer versatility in the optical spectrum for various applications, including solution-processed organic/perovskite electronics. ZnO, known for its low toxicity and biocompatibility[132], underscores the potential for these nanoparticles in eco-friendly electronic applications. The emphasis on non-critical materials and sustainable processes positions plasmonic semiconductors as not only technologically advantageous but also environmentally conscious choices for the future.

3.3. 2D materials

2D nanomaterials have emerged as superior alternatives to conventional metallic nanoparticles in the realm of plasmonic sensing. Unlike metallic nanoparticles, 2D nanomaterials, such as graphene[133], transition metal dichalcogenides[134], black phosphorene (BP)[135], transition metal carbides, nitrides and carbonitrides (MXene)[136], hexagonal boron nitride (h-BN)[137], and metal–organic frameworks (MOFs)[138] boast unique crystal structures with van der Waals stacking, providing distinct frameworks for plasmon-polaritons. Their exceptional properties include large optical densities, high exciton binding energies, and extreme surface-to-volume ratios. These materials allow for unprecedented high-level doping through various methods, fostering unique plasmonic phenomena like hyperbolic plasmons and anisotropic responses. Despite facing challenges such as weak signals, the integration of 2D materials in plasmonics holds great promise, enabling active control of light-matter interactions and paving the way for innovative applications in optoelectronics.

Graphene, a single or few layers of sp^2-bonded carbon atoms, exhibits extraordinary physiochemical properties such as ultrahigh electrical and thermal conductivity, mechanical strength, specific surface area, and stability. Thanks to these interesting properties, graphene is the most studied 2D material. Graphene's unique layered honeycomb crystalline structure provides high plasmon flexibility, making it an excellent plasmonic medium in the MIR-THz range.

Hexagonal boron nitride (h-BN), sharing a similar hexagonal and atomically thin structure with graphene, exhibits comparable properties such as high thermal conductivity and mechanical strength. However, a significant distinction lies in their electron structures. Due to the heteroatom bonding nature of h-BN, electron distribution in the B–N bond is less homogeneous compared to the C–C bond in graphene, with electrons more centralized around the N atom. This results in a substantial electric bandgap of 5.97 eV in h-BN nanosheets, contributing to its high insulating and optically transparent properties. Additionally, h-BN demonstrates superior thermal and chemical stability compared to graphene, making it an ideal shielding material to protect active metal nanostructures employed in plasmonic sensors.

In contrast to the zero-gap graphene and wide-gap h-BN, transition metal dichalcogenides (TMDs), a class of semiconductive materials, offer a narrow and tunable bandgap, making them valuable in optoelectronic and electronic applications. The chemical formula for TMDs is MX2, where M represents a transition metal atom, and X denotes a chalcogen atom. These materials exhibit hexagonal structures with distinct stacking phases, such as the 2H phase with ABA stacking and the 1 T phase with ABC stacking. TMDs [139], including MoS_2, $MoSe_2$, $MoTe_2$, WS_2, WSe_2, and WTe_2, undergo a transition from an indirect to a direct bandgap as the material is thinned to a monolayer. Monolayer TMDs exhibit unique electron structures characterized by a lack of inversion symmetry, leading to spin splitting of electronic bands driven by spin–orbit interaction. This spin splitting, coupled with tunable bandgaps and high exciton binding energies, results in strong absorption coefficients for visible and near-infrared light in TMDs. Despite weak plasmon resonance, plasmonic TMDs display unique behaviour, sustaining hyperbolic plasmon polaritons, spin–orbit coupling, and surface polaritons in topological insulators.

Among 2D group VA nanomaterials[140], phosphorene is the foremost and most extensively explored. This material typically refers to monolayer or few-layer black phosphorene, derived from bulk black phosphorus. BP exhibits a tunable bandgap ranging from approximately 0.3 to 2 eV. Plasmons in BP are tunable through potassium doping, introducing external strain and an out-of-plane electric field. Expanding beyond phosphorene, other 2D group VA nanomaterials, such as arsenene, antimonene, and bismuthene, have garnered increasing attention[141]. Antimonene stabilized in the b-phase showcasing semiconductive properties with an indirect bandgap of approximately 2.28 eV. Monolayer Antimonene exhibits high carrier mobility, superior thermal conductivity, strain-induced band transitions, and promising spintronic properties. To address the environmental concerns associated with arsenene and antimonene, ongoing research is focused on developing innovative recovery methods[118,142].

MXene[143] represents a novel class of 2D nanomaterials, comprising transition metal carbides, nitrides, and carbonitrides, characterized by the universal formula Mn + 1XnTx. In this formula, M denotes an early d-transition metal atom, X indicates nitrogen and/or carbon atoms, and T represents surface-terminated functional groups such as –OH, O, and −F. Recent studies have unveiled impressive optical properties in some MXenes, including tunable broadband absorption and intense surface plasmon resonance, suggesting their potential for applications in optoelectronics and plasmonics. The first synthesized MXene, Ti_3C_2Tx, has been identified as a plasmonic material[144] with the potential to replace traditional plasmonic metal nanomaterials. Notably, Ti_3C_2Tx exhibits layer-dependent plasmonic behaviour, despite its bulk plasmon energy being thickness-independent due to weak interlayer coupling. Additionally, research by El-Demellawi and colleagues[145] has demonstrated that the multipolar surface plasmons of Ti_3C_2Tx nanosheets can be finely tuned in the visible and mid-infrared (MIR) range by controlling the amounts and types of surface radicals. This insight opens avenues for leveraging MXenes, particularly Ti_3C_2Tx, in the development of advanced plasmonic applications with tailored optical properties.

3.4. Polymer nanocomposites

Polymer plasmonics is a burgeoning field that leverages the unique properties of conducting polymers to support localized surface plasmon resonances[146,147]. These resonances arise from the collective oscillations of mobile charge carriers within the polymer network. The resonance behaviour of these polymers is tunable through chemical redox reactions, allowing the material to switch between metallic and dielectric states. This tunability is a significant advancement, as it provides control over the optical properties of the material. In highly doped states, polymers like PEDOT:PSS exhibit negative real permittivity, characteristic of metals, for wavelengths above 2700 nm[148]. This metallic behaviour is crucial for their plasmonic functionality. Recent advancements in the field have shown that polymers such as PEDOT:Sulfate nanodisks[149] can undergo reversible redox reactions, maintaining their plasmonic properties over multiple cycles. Additionally, other semiconducting polymers like poly[2,5-bis(3-tetradecylthiophen-2-yl)thieno[3,2-b]thiophene] (PBTTT)[150] and poly[3-hexylthiophene-2,5-diyl] (P3HT)[151,152] have been explored for their negative permittivity in the near-infrared (NIR) range. These materials demonstrate the potential for broadening the spectrum of plasmonic polymers available for various applications. In the field of polymer plasmonics, there is also a section where PNPs are embedded in a polymer matrix creating polymer plasmonic nanocomposites[147]. These nanocomposites offer several advantages: (a) the inherent ability of polymers to prevent the aggregation of PNPs addresses a common issue in solution-based technologies, (b) they demonstrate versatility, operating under harsh conditions such as elevated temperatures or pressures, (c) biocompatibility[153]. Additionally, polymer-based plasmonic sensors can respond to mechanical stresses, including shear and compressive forces, adding another layer of functionality to their application.

The ability to dynamically tune the optical properties of conducting polymers opens new avenues in organic and perovskite electronics. Their mechanical flexibility and tunable properties make them suitable for flexible electronics, enhancing the functionality and durability of devices, and expanding their utility across various industries. The biocompatibility[154,155] of polymer plasmonic materials ensures that materials interact safely with biological systems, reducing their toxicity, promoting biodegradability, and minimizing pollution, thereby contributing to a more environmentally friendly approach.

4. Techniques to deposit PNPs

As discussed in the plasmonic nanoparticle section, depending on functionality and requirements, PNPs can be strategically placed in various locations within organic and perovskite electronic devices. These nanoparticles can be incorporated into transparent electrodes, hole injection/transport/extraction layers, electron injection/transport/ extraction layers, and also in the active layer. They can be deposited as nanocomposites with the base material or independently at the desired position. For example, a mixture of Au nanoparticles (NPs) and PEDOT:PSS can be deposited together, or Au NPs can be deposited solely over PEDOT:PSS. This flexibility in nanoparticle placement and incorporation necessitates a variety of deposition techniques. A versatile deposition technique that can handle all these requirements would greatly facilitate the commercialization of large-area organic and perovskite electronics.

In the following section, we will briefly discuss the deposition techniques currently used in academic research. We will also provide overview for industry-specific deposition techniques suitable for fabricating large-area organic and perovskite electronics. This structured approach aims to bridge the gap between research methodologies and industrial-scale applications, ensuring efficient and scalable production processes.

4.1. Spin coating

Spin coating, Fig. 3b, a ubiquitous deposition technique in thin film laboratories, utilizes centrifugal forces to deposit materials onto substrates. Due to its widespread adoption, the spin coating has emerged as a crucial tool in substantiating the efficacy of solution-processed organic/perovskite devices incorporating PNPs, showcasing enhanced performance. The strategic positioning of these nanoparticles, dictated by the desired functionalities, is crucial for optimizing device performance. For instance, embedding PNPs in a hole injection/transport/extraction layer facilitates increased plasmonic light scattering, while incorporating them at random surface coverage within the active materials of organic/perovskite solar cells overshadows light absorption. This is because, at high surface coverage, localized heating (hot spots from closely spaced nanoparticles) leads to increased recombination and enhances the thermal degradation and increased surface roughness leads to shunt current and metal-enhanced quenching of excitons, whereas low surface coverage results in only minimal enhancement of light absorption. Spin coating, despite its common usage, presents a two-stage process for incorporating PNPs into a device. The initial synthesis of nanoparticles in a solution phase[156–158], Fig. 3a, often dispersed in solvents, including those marketed as “green[159],” is followed by deposition and optional annealing to remove the surfactants used to stabilize the nanoparticles.

Spin coating, with its simplicity and efficacy, is well-suited for studying the proof of concept when nanoparticles are randomly distributed in thin films. However, challenges arise when precise control over the vertical distance or surface coverage of nanoparticles is necessary, as spin coating lacks the requisite control over nanoparticle mobility during centrifugal force exertion. Varying nanoparticle concentrations in the deposition solution become the primary means of influencing distribution. Yet, the technique suffers from a significant drawback – more than 90 % of the deposited solution is wasted[[160], raising environmental concerns in alignment with UN and EU policies. Spin coating’s inability to scale up, particularly for roll-to-roll fabrication, limits its industrial applicability. The excessive material consumption in the spin coating, coupled with challenges in coating large or irregularly shaped substrates, poses economic and environmental considerations that hinder its broader implementation in the industry.

4.2. Vapour deposition

The vapour deposition techniques (Fig. 3c-e) such as sputtering[161], thermal evaporation[162] chemical vapour deposition [163,164] and atomic layer deposition[165], streamline the process of nanoparticle deposition into two stages and these are the commonly used techniques adopted by the industry to deposit thin films. Here, nanostructures/thin films are directly deposited onto a substrate, and subsequent annealing at a specific temperature, along with the wetting characteristics of the substrate, determines their final size. The annealing process[166] involves the initial nucleation phase, where atoms or molecules adhere to the substrate, forming nanoislands with irregular shapes. The Volmer-Weber mode typifies this early stage, leading to non-uniform island formation before achieving a continuous film. Further annealing results in Ostwald ripening where the small nanostructures merge into big nanostructures and form a single structure. They inherently contribute to the prevalence of spheroid nanoparticles due to isotropic growth dynamics. Nonetheless, the controlled application of heat or other post-deposition techniques can influence the ultimate nanoparticle size, shape, and distribution within the thin film.

However, this method lacks versatility in achieving diverse nanoparticle geometries, as most deposited nanoparticles tend to assume a spheroid shape. The vertical position of the nanoparticle with respect to the active layer (excitons) can be easily controlled in the vapour deposition, but there are some issues pertaining to depositing the nanoparticles over the soft substrate and low surface energy substrates like organic semiconductors. Energetic particles employed during deposition pose a risk of damaging soft organic semiconductors. Furthermore, the majority of organic semiconductors employed, exhibit lower glass transition temperatures, making the annealing process for achieving the desired nanoparticle size a challenging endeavour. The employment of a low surface energy substrate in thin film deposition poses challenges throughout the process: (a) Weak nucleation, arising from limited adhesion of atoms or molecules, results in sparse initial clusters and non-uniform growth; (b) Coarsening is hindered by poor interparticle forces due to inadequate adhesion; (c) Annealing effectiveness diminishes, impacting nanoparticle size, shape, and crystallinity optimization; (d) Surface diffusion processes are impeded by limited substrate interaction. The inherent isotropic growth dynamics in vacuum deposition methods are exacerbated on low surface energy substrates, promoting the formation of predominantly spherical nanoparticles. Overcoming these challenges requires surface treatments to enhance adhesion and improve the overall quality of the deposited thin film.

Implementing conductive thermal annealing to transform thin films into nanoparticles involves placing the substrate on a hot plate for an extended period. However, its application in a roll-to-roll setup is challenging due to the necessity for direct contact between the substrate and the heating element. In the context of roll-to-roll manufacturing, a more feasible annealing technique involves the use of a convective oven. But, if we consider a roll-to-roll web line moving at a speed of 30 m/min with a moderate dwell time of 10 min, the required oven length for a single layer would be around 300 m[167]. This poses a significant infrastructure challenge, as processes requiring longer annealing times—such as the 120 min needed for nanoparticle formation—become impractical due to the excessive oven length required. This calculation does not account for additional layers of depositions. The implications of such an extensive web length extend beyond the spatial footprint and associated costs; they also introduce challenges related to heightened web tension requirements and potential registration mismatches, impacting overall yield. Vacuum deposition techniques are also associated with higher material wastage up to 60 %.[168,169].

4.3. Printing and coating techniques

Similar to spin coating, various printing and coating techniques utilize a two-step process. These methods leverage pre-synthesized nanoparticles and deposit them using roll-to-roll compatible techniques and optional annealing to remove surfactants. Unlike vapour deposition, printing and coating offer a significant advantage: high-throughput roll-to-roll systems capable of achieving speeds exceeding 100 m per minute[170,171]. This efficiency makes it highly attractive to industries, reducing production costs significantly. Roll-to-roll (R2R) processing, which involves utilizing solutions and dispersions of functional materials such as inks and pastes through wet deposition methods, has become a well-established and extensively utilized manufacturing approach within the printing and coating industries. Here it offers a key advantage of being simple, facilitating continuous production—an essential requirement for mass production during commercialization. Additionally, the deposition techniques used exhibit high materials utilization ratios, reaching up to 90 %[172]. This feature significantly reduces production costs by minimizing the use of expensive charge transporting materials and concurrently curbing environmental waste. Its current applications span a broad spectrum, encompassing areas ranging from packaging and paper production to functional membranes, photographic films, thin-film batteries, and textiles. In the field of electronics and optoelectronics, the Roll-to-Roll (R2R) processing phase is presently immersed in research and development for various applications, including intricate devices like solar cells[173,174], transistors[171], and light-emitting devices[175]. The prospect of R2R printed and coated electronics primarily lies in the market for budget-friendly, entry-level, and potentially disposable devices, deviating from a prominent presence in high-end consumer electronics. However, the introduction of PNPs has the potential to reshape perceptions of R2R technologies, challenging the notion of inferior quality and positioning them as contenders theoretically capable of rivalling vacuum-deposited technologies known for their fabricated device efficiency.

Within the dynamic landscape of roll-to-roll manufacturing of organic/perovskite electronics devices, a diverse array of around thirty compatible coating methods, featuring an extensive array of variations, is actively employed. This comprehensive collection comprises a wide spectrum of advanced techniques, encompassing slot die, doctor blade, screen printing, Mayer rod, and cutting-edge droplet-based methods such as inkjet printing, spray coating, and ultrasonic spray coating. Readers are encouraged to refer to “Roll-to-Roll Manufacturing” by Jehuda Greener et al[176] and “Printing of flexible light emitting devices” by Inge Verboven et al[177] for in-depth information on the roll-to-roll manufacturing of functional materials tailored for diverse applications including OLEDs. The slot die coating[178], doctor blade coating[179], screen printing[180], Mayer rod[181], inkjet printing[182] and spray coating[183–185] emerge as a versatile technique for the creation of thin, consistent films and are extensively explored as a large-scale coating method by academia and industry due to its simplicity, versatility, and scalability.

As of august 2024, the R2R compatible techniques, employed by organic photovoltaics technology (Heliatek, 0.9 m^2 area)[186] and perovskite photovoltaics technology (solliance, 30-cm wide)[187] over a large scale, have achieved a power conversion efficiency of 8–9 % and 12.6 % respectively and have successfully achieved a remarkable carbon footprint of less than 10 g of CO_2 equivalent per kilowatt-hour. This achievement surpasses traditional silicon solar cells by four to five times, with a carbon payback time of less than 9 months. Consequently, the energy generated through roll-to-roll fabricated organic and perovskite solar cells is not only 100 times more environmentally friendly than coal-powered electricity generation but also represents a significant advancement in sustainable energy production. Therefore, the R2R compatible printing and coating technologies hold immense potential in the mass production of organic and perovskite electronics at low cost and this technology paves the way for environmentally friendly affordable energy solutions. Coupled with the PNPs, the efficiency of the devices could be enhanced further making the affordable, efficient, environmentally friendly organic and perovskite device a reality. As shown in Fig. 3g, i, j and k, the PNPs could be deposited at a different location depending on the functionality expected out of PNPs. This corresponds to choosing different deposition techniques. For achieving strong light absorption, industry-standard methods like slot-die coating or screen printing can efficiently deposit both PNPs and active layer materials, Fig. 4e (i,ii,iii and iV). However, if precise control over nanoparticle positioning and optimized surface coverage are crucial, then droplet based techniques like ultrasonic spray coating, electrospray coating and inkjet printing (Fig. 4e (V, Vi,Vii and Viii)) become the preferred technique[188]. This method offers meticulous control over both the vertical and horizontal distribution of the materials.

5. Device performance and reproducibility

In plasmonic nanostructured materials, noble metal nanoparticles such as gold, silver, and aluminium are leading research due to their unique optical properties and light interactions. This field is seeing a surge in activity, driven by the potential advancements and applications these materials offer. A Scopus search revealed a surge in research on PNPs in organic and perovskite electronics, with 1,880 articles published between 2000 and 2024. This highlights the rapidly growing interest and significant advancements in this captivating field. This remarkable proliferation of research underscores the pivotal role that plasmonic semiconducting nanoparticles, 2D materials, and polymer nanoparticles can play in enhancing the performance of organic and perovskite electronic devices. The sheer volume of literature is indicative of the transformative potential of these nanomaterials, urging industry stakeholders to redirect their focus towards the promising intersection of nanotechnology and electronics.

As the number of publications continues to climb, it becomes increasingly evident that the infusion of PNPs is not just an academic pursuit but a technology with potential commercial viability. To encourage the industry to adopt devices incorporating plasmonic nanoparticles (PNPs), it is essential to demonstrate significant benefits in several key areas. These include the ease and cost-effectiveness of integrating PNPs, measurable improvements in device efficiency compared to standard benchmarks, and consistent reproducibility of results. Additionally, adherence to environmental regulations, as previously discussed, is crucial. In the next section, we will explore the observed performance enhancements, reproducibility concerns, and potential strategies to address these issues. The ever growing knowledge urges the industry to heed this call and actively engage in translating these advancements from laboratory breakthroughs to market-ready solutions.

5.1. Photovoltaics

PNPs have emerged as promising components in the optimization of solar cell performance. By leveraging the phenomenon of localized surface plasmon resonance (LSPR) and surface plasmon polaritons (SPPs), these nanoparticles can substantially enhance both the optical absorption and electrical characteristics of solar cells. In the context of organic and Perovskite photovoltaic (O-Pe PV) cells, metal NPs incorporated within the device architecture improve light trapping via LSPR excitation, leading to enhanced optical absorption. Additionally, the presence of plasmonic NPs enhances exciton dissociation, charge transport, and collection, thereby improving overall device performance. Optimization strategies involve adjusting the materials, geometric shapes, size distributions, and topological arrangements of plasmonic NPs within the device architecture, often guided by theoretical simulations such as finite-difference time-domain (FDTD) modelling. Understanding the mechanisms underlying enhanced performance, including LSPR scattering, exciton dissociation, resistance reduction, and charge transport enhancement, is crucial for the design and development of efficient plasmon-incorporated solar cells. Building on this foundation, the brief review explores recent advancements in plasmon-enhanced photovoltaics. It highlights how integrating plasmonic nanoparticles (PNPs) into organic solar cells (OSCs) can significantly improve performance by enhancing light absorption and optimizing charge transport. The discussion focuses on various configurations where PNPs are strategically placed in the hole transport layer (HTL), electron transport layer (ETL), and active layer. These placements have shown promising results, showcasing the effectiveness and versatility of plasmonic enhancement in photovoltaic technology. For a deeper understanding of this rapidly evolving field, readers are encouraged to consult the existing literature. [14,16,27,30,189–191].

In the field of organic photovoltaics, studies have demonstrated substantial efficiency improvements by embedding plasmonic NPs in the HTL mostly in PEDOT:PSS. For instance, decahedral-shaped Au NPs [192] in the PEDOT:PSS layer significantly enhance performance by improving light absorption without increasing the photoactive layer's thickness, achieving power conversion efficiencies (PCE) up to 10.29 % (∼28 % enhancement). Similarly, hollow and spectrally tunable Au nanorattles[193] incorporated into organic photovoltaics (OPVs) have shown up to a 15 % increase in PCE, attributed to plasmon resonance energy transfer and near-field enhancements. Additionally, metal nanodot (MND) arrays fabricated via laser interference lithography (LIL)[194] have demonstrated a 34.4 % PCE enhancement, reaching over 10 % efficiency through surface plasmon resonance (SPR) effects. Gold nanostars[195] integrated between the HTL and the active layer further enhance absorption across a wide spectrum, achieving a PCE of 10.5 % (~14 % enhancement) by facilitating balanced carrier collection and improved electrical properties.

Just as there have been significant advancements in incorporating PNPs into the HTL, substantial research has also focused on their integration into the ETL, mostly PEDOT:PSS, ZnO and TiO_2. Zhishan Bo et al.[196] demonstrated that integrating heterostructured Au $-$ $Cu_2{-}xS$ nanocrystals (NCs) leads to significant enhancements in light absorption and power conversion efficiency (PCE) in polymer solar cells (PSCs), with PCE increasing notably from 7.45 % to 9.00 %, primarily attributed to enhanced short-circuit current density (Jsc). Similarly, the incorporation of Au NPs into ZnO films, as elucidated by Ashish Garg[197], offers a promising avenue for improving the performance of inverted PTB7-Th organic solar cells (OSCs), resulting in a substantial increase in device PCE from approximately 9.0 % to 11.8 %. Optical and electrical studies suggest that the observed PCE enhancements stem not only from localized surface plasmon resonance (LSPR) effects but also from interfacial effects that enhance charge transport and collection.

Incorporating PNPs in the active layer, like in the HTL and ETL, significantly impacts organic solar cells' performance. We'll briefly review the two best devices. The first study by Yan et al.[198] introduces Au@Ag core–shell nanocuboids, achieving a remarkable 22.8 % relative enhancement in power conversion efficiency (PCE), reaching PCE exceeding 10 %. This approach relies on precisely controlling the Ag shell thickness (optimal at 20 nm) to achieve broadband light absorption that complements the organic material's absorption profile. The second study by Jen et al.[199] explores core-bishell Ag@TiO_2@Pa nanoparticles, demonstrating a significant enhancement of 12.3 − 20.7 % with a maximum power conversion efficiency of 13.0 %.

Similar to organic photovoltaic, incorporating PNPs into perovskite photovoltaic (PePVs) necessitates meticulous attention to their placement, material integration, and geometric configuration[32]. NPs can be positioned in various layers of PSCs, including ETLs like PCBM, TiO_2, Al_2O_3, and SnO_2, HTLs like spiro-OMeTAD, PEDOT:PSS, and VOx and in the perovskite itself. The geometry of NPs varies, with forms like spheres, nanostars, core–shell structures, nanorods, nanocubes, triangles, and more being used. Materials for NPs include Ag, Au, Au@SiO_2, Ag@TiO_2, SiO_2@Ag@TiO_2, Au@Ag, Au–Ag alloy, Au@Pt@Au, and Cu–Ag alloy. These strategically placed NPs have been shown to significantly enhance PCE. Notably, incorporating NPs within the HTL led to a PCE range of 12.5 % to 21.38 %[200], with some cases achieving up to 60 % enhancement[201]. Similarly, incorporating NPs in the ETL resulted in a PCE range of 16.3 % to 20.5 %[202] with a maximum enhancement of 61.64 %[42]. Finally, placing NPs directly within the perovskite layer achieved a PCE of up to 20.29 %[42]. It's worth noting that the percentage enhancement tends to be higher for architectures where the initial reference PCEs were relatively lower, and conversely, lower for those with higher initial PCEs.

The size and concentration of NPs, as well as the mechanisms and associated effects, play a crucial role in their performance in solar cells. The majority of the studies utilize NPs in the 10–50 nm range. The deposition technique dictates material loading. Solution processing uses 0–5 wt% for desired surface coverage, while vacuum deposition focuses on deposition rate, film thickness control and annealing to achieve the required surface coverage. Mechanisms include localized surface plasmon resonance (LSPR), field enhancement, electron-hole separation, scattering, charge separation, light absorption, hot electron injection, and carrier transport. However, bare NPs and NP agglomeration can create charge recombination centres[203,204] through both interface induced and trap assisted recombination mechanisms, leading to performance degradation[205]. It is also observed that NPs act as nucleation sites for perovskite film formation, improving crystal quality and coverage[14].

Despite the performance enhancements and clear advantages of incorporating PNPs in organic or perovskite solar cells, several reproducibility challenges persist that must be addressed to incentivize the industry to adopt plasmon-incorporated organic/perovskite solar cell technology. Efficiency reduction is a primary concern. While PNPs can enhance the absorption of light, they can also cause parasitic absorption and scattering losses. This means that some of the light that is absorbed by the nanoparticles is not converted into electricity but is instead lost as heat. This can reduce the overall efficiency of the solar cell. Also, there can be issues related to the interface between the nanoparticles and the organic or perovskite materials. Interface-induced recombination occurs when PNPs disrupt the energy level alignment between layers, causing a mismatch that interferes with balanced electron and hole injection. This imbalance can be exacerbated by interfacial defects introduced by the PNPs, which may lead to poor film morphology or discontinuities at the interfaces. These interfacial defects then act as centres for non-radiative recombination, reducing device efficiency. Additionally, trap-assisted recombination, or Shockley–Read–Hall (SRH) recombination, can be triggered if PNPs introduce or exacerbate bulk or surface defects within the perovskite lattice, especially in polycrystalline films. PNPs can create deep traps by inducing structural stress or vacancies in the crystal lattice, leading to charge carrier losses through trap states in the bandgap. Managing these recombination pathways is key to maximizing device performance, often achieved through interfacial engineering like using core shell nanoparticles and chemical passivation techniques around PNPs to minimize defect-related recombination. This can affect the charge transfer and overall performance of the solar cell. Along with reproducibility concerns, challenges like stability also play a significant role in the performance and longevity of plasmonic-enhanced OPV or Pe-PV. The high energy of plasmons can interact with the organic or perovskite materials, leading to their degradation over time. This breakdown can result from both direct interactions and localized heating effects caused by the plasmons. Localized heating leading to thermal degradation, in particular, can reduce the lifespan and performance of these devices. Stability in particular with perovskite devices is of concern while using the noble metal nanoaprticles for plasmonic application. It is because in the electrode engineering strategy of perovskite PV it has been found that metal ions generated from interfacial redox reactions can diffuse into perovskite layers after overcoming kinetic diffusion barriers, potentially leading to device degradation[206]. Common metal electrodes, such as Au[207], Ag[208], and Cu[209], are monovalent and thus migrate relatively easily in $MAPbI_3$. The effects of these metal ions on the perovskite structure depend on the nature of the trap states they create. For example, Au ions can interact with Pb vacancies to form deep trap states, which significantly reduce perovskite performance, while Ag and Cu tend to create shallower trap states due to their milder crystal field effects. This may explain why Cu contacts do not notably degrade power conversion efficiency, as demonstrated in studies[209] where perovskite solar cells (PSCs) incorporating a Cu electrode maintained efficiencies above 20 % even with direct Cu-perovskite contact. In contrast, the diffusion of metals like Au can produce harmful deep-level defects, making it crucial to minimize such ions to maintain efficient charge transport in perovskite materials.

Further research is needed to fully understand how plasmon-induced degradation affects organic and perovskite solar cells and to develop strategies to mitigate these issues. Translating these technologies to large-scale manufacturing encounters hurdles such as achieving precise control over the size, shape, and distribution of the particles, scalability of synthesis methods, and seamless integration with existing fabrication processes.

Along with the reproducibility of the performance, environmental factors must also be considered. The use of rare earth elements (mostly Au and Ag) has environmental implications, and strategies for recovering and reusing these materials at the end of the device lifespan are not yet addressed. Sustainability concerns surrounding material toxicity and energy-intensive processes underscore the imperative for alternative materials and optimized production techniques. Furthermore, ensuring reproducibility in device performance poses technical challenges, including consistent NP incorporation, long-term stability assessment, and mitigation of potential electrical effects.

Strategies for mitigating these obstacles include developing new fabrication techniques that allow for more precise control over the size and distribution of the nanoparticles. Additionally, materials could be developed that are more resistant to the high energy of the plasmons, improving the stability of the solar cells. Research is also being conducted into ways to reduce parasitic absorption and scattering losses, such as by optimizing the shape and arrangement of the nanoparticles[210,211] particularly for the large sized nanoparticles where a balance between scattering and absorption must be maintained. For Eg[211], Al nano-cubes with edges around 100 nm and a periodic spacing of 320 nm, as well as Ag nano-cubes with 80 nm edges and a period of 280 nm, offer an ideal balance between scattering and absorption. These dimensions maximize the near-field enhancement, allowing more effective light trapping within the active perovskite layer while minimizing parasitic absorption in the nanoparticles themselves. By directing photon absorption improvements within the absorber layer instead of the nanoparticles, this optimization enhances photocurrent output, ultimately improving the cell’s overall performance without the excess energy loss that larger or less strategically spaced nanoparticles might incur. Finally, improving the interface between the nanoparticles and the organic or perovskite materials could enhance charge transfer and overall performance[199].

5.2. Photodetectors

Photodetectors, akin to photovoltaics, leverage PNPs to enhance performance by bolstering light absorption and enhancing charge carrier generation and collection. Integration of PNPs enriches photodetectors with heightened sensitivity, faster response times, and improved functionality under low-light conditions, rendering them well-suited for advanced technological applications[212]. Research findings and technological advancements in plasmon-enhanced photodetectors underscore innovative methodologies and practical implementations that have substantially elevated device performance. The incorporation of gold nanoparticles (Au NPs) onto organic phototransistors[212] has emerged as a promising strategy, functioning as both electron transport channels and plasmonic excitation centres, potentially leading to enhanced device performance. The Au NPs enhance photo absorption and exciton dissociation, generate additional hot carriers[37], and facilitate plasmon-induced resonance energy transfer (PIRET)[20], resulting in ultrahigh photoresponsivity and effective amplification of ultraweak light signals. Guodan Wei et al. [213] presented a novel approach to enhancing near-infrared (NIR) organic photodetectors (OPDs) through LSPR, achieving 25-fold enhancement compared to pristine devices while achieving improvements in responsivity and detectivity values of 2200 mA W^{-1} and 2.8×10^{12} Jones, respectively in stretchable broadband plasmonic photodetectors. Nae-Eung Lee and colleagues[214] continued the work on Stretchable Broadband Plasmonic Photodetector (SBPPDs) utilizing hybrid metal nanoparticles and an organic semiconductor, showcasing robust performance under stretching conditions. Lee’s team employed two distinct approaches for the sensing layers: a hybrid configuration comprising silver nanoparticles (Ag NPs)/ PEDOT:PSS thin film, and a thin film of nanocomposite mixture of Ag NPs and PEDOT:PSS. These layers are directly integrated into the substrate, enabling them to withstand tensile strain. Their SBPPDs capitalize on hot-carrier injection from Ag NPs to PEDOT under both visible and near-infrared illumination. Remarkably, both configurations of the SBPPDs exhibit impressive responsivity across various wavelengths while maintaining robust electrical performance even under stretching. This integration of plasmonic photodetectors with a stress-adaptable substrate through conventional fabrication methods represents a significant advancement, surmounting previous limitations and paving the way for the realization of stretchable wearable optoelectronics. Tao Xu’s team[215] enhanced the performance of narrowband organic photodetectors (OPDs) in the NIR range through a combination of solution-processable gold NanoRings-copper thiocyanate (CuSCN) hybrid hole transport layers (HTLs) and an optical microcavity, achieving highly tunable NIR selectivity and a specific detectivity exceeding 10^{13} Jones at 820 nm, along with a finely selective photoresponse and a 3-fold increase in photocurrent intensity. Additionally, ongoing research in plasmonic OPDs explores novel strategies for improving performance, with investigations into alternative materials, device architectures, and fabrication techniques aiming to enhance responsivity, selectivity, and operational stability. These advancements pave the way for innovations in applications such as wireless optical communication and imaging systems.

Next, we shift focus to plasmonic perovskite photodetectors as we continue exploring photodetection. Recent developments in combining perovskite materials with PNPs show promise for further enhancing the efficiency and functionality of photodetection devices. Haibo Zeng’s team[216] presented a novel approach to improving the performance of all-inorganic perovskite photodetectors (PDs) through the synergistic effects of preferred film orientation and plasmonic enhancement, achieving exceptional performance characteristics and a significant plasmonic enhancement factor. By utilizing CsPbBr3 nanocrystals (NCs) and gold nanocrystals (Au NCs) in solution-processable films, they demonstrate PDs with exceptional performance characteristics, including a 238 % plasmonic enhancement factor and a remarkable on/off ratio of 10^6 and enhanced charge carrier transport, leading to increased photocurrent. Zhuoying Chen et al.[63] integrated Au NPs into graphene/methylammonium lead iodide perovskite (CH3NH3PbI3) hybrid photodetectors to exploit the surface plasmonic effect for performance enhancement. The unique device configuration, with Au NPs physically separated from the perovskite layer by graphene, enables efficient near-field enhancement of perovskite light harvesting, facilitating improved photoresponsivity and response speed. Zheyu Fang's team[[62] introduced a novel approach to enhancing the performance of organic–inorganic hybrid perovskite photodetectors across visible and NIR spectra by fabricating photodetectors on arrays of Au nanostructures, extending the optical response into the NIR range. Indicating a significant enhancement in photocurrent, achieving a maximum external quantum efficiency (EQE) of approximately 65 %. Moreover, the use of the plasmonic-functionalized substrate extends the optical response of the photodetector beyond the perovskite absorption edge into the NIR range, offering a wide range of applications in photodetection and potentially enhancing solar cell efficiency by capturing near-infrared sunlight. Jiang Wu et al.[217] presented a novel approach to enhancing the performance of inorganic perovskite $CsPbBr_3$ quantum dot (QD) photodetectors through metallic nanoparticles decorated on anodic aluminium oxide (AAO) hybrid plasmonic nanostructures, achieving a significant increase in photocurrent by approximately 43 times. Also, by manipulating the pore sizes, light loss is effectively diminished, resulting in improved spatial light utilization. Dangyuan Lei et al. [218] presented a pioneering approach to enhancing the performance of lead-free $CsSnBr_3$ perovskite quantum dots (QDs) in a flexible broadband photodetector. By precisely controlling the thickness of an Al_2O_3 spacer between the $CsSnBr_3$ QDs and a silver nanoparticle membrane, the photodetector achieves a remarkable broadband spectral response from 300 to 630 nm. With a 5 nm thick Al_2O_3 film, the device exhibits a maximum photocurrent enhancement of 6.5-fold at 410 nm, along with a responsivity of 62.3 mA/W and detectivity of 4.27×10^{11} Jones. Importantly, the flexible photodetector maintains its performance even after 100 bending cycles, attributed to the tension offset induced by the self-assembled nanoparticle membrane.

Chunlei Guo's team[219] demonstrated a groundbreaking approach to enhancing the performance of triple-cation mixed metal halide perovskite photodetectors in the NIR range utilizing plasmonic bowtie nanoantenna (BNA) arrays, achieving a remarkable enhancement in photoresponse. The fabricated plasmonic Perovskite photodetectors exhibit an astonishing ≈2962 % enhancement in photoresponse under 785 nm laser illumination compared to conventional Si/SiO_2-based photodetectors. The plasmonic PD demonstrates a high external quantum efficiency (EQE) of 188.8 %, over 30 times higher than normal PDs, and a detectivity of 1.5×10^{12} Jones, showcasing its potential for high-frequency photoswitching and stable operation under NIR radiation. Wei Lei's team[220] introduced a novel approach to enhancing the performance of perovskite-based UV photodetectors through in-situ fabrication of $MACsPbBr_3$ perovskite crystals embedded in a polymer matrix, achieving impressive performance characteristics and further enhancement through plasmonic enhancement using Au NPs and structured ZnO layers. By this architecture, the photodetector's performance is improved, with a photocurrent enhancement of 10^{-5}, responsivity of 55.91 AW^{-1}, and detectivity of 7.91×10^{14} Jones. Huan Lou and their team[221] presented a novel approach for enhancing the performance of $CH_3NH_3PbI_3$ perovskite photodetectors through integration of triangular silver (T-Ag) optical nanostructures fabricated using a gas–liquid interface self-assembled polystyrene (PS) mask layer, this modified strategy leads to a remarkable increase in photogenerated current (481.25 %) and response speed (26.30 %). Overall, these studies represent significant advancements in plasmonic-enhanced photodetectors and hold promise for a wide range of applications in optoelectronic devices, communication systems, and beyond.

As mentioned in the photovoltaics section, incorporating PNPs in photodetectors also presents several reproducibility challenges. These include (i) heightened dark current and noise resulting from hot carrier generation under different illumination conditions, (ii) inconsistencies in responsivity and external quantum efficiency due to the uneven enhancement of the electric field caused by nanoparticle distribution and size, (iii) complex fabrication processes requiring precise nanoparticle control, (iv) and the risk of local

Table 2
Input data for the cost analysis for R2R fabrication of perovskite/CIGS solar cells with PNPs.

Parameter	Value	Unit
Deposition Method	Inline spray coater with 5 nozzles	–
Nozzle Cost	€10,000	per nozzle
Additional Equipment	Ultrasonic generators, ink pump regulating units, mounting equipment	–
Energy Consumption	1	kW
Nanoparticle Consumption	1	gram per 80 sqm
Surface Coverage	5 %	–
Material Cost		
* Gold	€60	per gram
* Silver	€0.67	per gram
* Aluminum	€0.0024	per gram
* Nickel	€0.0167	per gram
* Cobalt	€0.0271	per gram
* Copper	€0.01	per gram
Solvent	Isopropyl Alcohol (IPA)	–
Solvent Cost	€5.48	per litre
Solvent Consumption	20.4	litres per 80 sqm
Material Utilization Efficiency	98 %	–

heating effects that could degrade organic and perovskite materials.“.

Addressing these issues is crucial for optimizing the performance and reliability of plasmon-enhanced photodetectors. To address the challenges associated with incorporating PNPs in photodetectors, several solutions can be considered. For reducing dark current and noise, optimizing the size, shape, and material of the nanoparticles can minimize hot electron generation. Ensuring a uniform distribution of nanoparticles through advanced fabrication techniques like ultrasonic spray coating can address inconsistencies in responsivity and EQE. Developing precise and scalable fabrication methods, such as nanoimprint lithography or self-assembly, can simplify the integration process. Additionally, employing thermal management strategies, such as heat sinks or thermal interface materials, can mitigate local heating effects and enhance the stability of organic and perovskite photodetectors.

5.3. Light emission devices

Unlike photovoltaics and photodetectors, where incorporation of the PNPs results in enhanced light absorption and charge carrier generation, their main role in light emitting devices is to enhance light emission efficiency and control spectral properties. They help improve the colour purity, brightness, and directionality of emitted light. In the integration of PNPs in OLEDs, two crucial effects[19] garner industry interest—the Localized Surface Plasmon Resonance (LSPR) effect and light scattering (LS). The effectiveness of the Localized Surface Plasmon Resonance (LSPR) effect in influencing the radiative recombination of excitons hinges on the size, shape, composition, interparticle distance, and spatial relationship between PNPs and excitons, necessitating the optimization of NP properties for maximal radiative enhancement through efficient coupling with surface plasmons.

For effective LS, a high refractive index contrast between scattering centres and the surrounding medium is crucial, achievable by introducing high refractive index nanoparticles and a low index surrounding medium with suitable sizes comparable to the light wavelength. Both the LSPR and LS effects in OLEDs depend on the strategic positioning of PNPs whether over the anode, embedded in the hole (electron) injection/transport layer/active layer, or over the cathode (Fig. 3g). Notably, when incorporating PNPs into the active layer, precaution is crucial to prevent exciton quenching[222]. This quenching results from enhanced non-radiative recombination contributions caused by the electric field generated by the LSPR. To mitigate this effect, encapsulating the nanoparticles in a spacer material is recommended, ensuring optimized performance and efficiency in OLED devices.

Several studies in the literature highlight enhanced performance through the incorporation of PNPs. Detailed information on these advancements can be found elsewhere[19,223]. Here, we highlight a few examples of top-performing devices within each architecture, showcasing their maximum achieved performance in terms of relative efficiency. In the case of LSPR induced light emission enhancement, a silica coated silver nanocube[224] embedded in the hole injection/transport layer of an OLED, such as PEDOT:PSS, demonstrated a remarkable performance enhancement of 400 % compared to devices without nanocubes. Silver coated gold nanostars with a silica spacer embedded[225] in a Poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene]- end capped with Polysilsesquioxane (MEH-PPV, orange emitter) and Poly(9,9-dioctylfluorene-alt-benzothiadiazole) (F8BT, green emitter), active layers in OLED architectures resulted in remarkable 50 % enhancement in the electroluminescence. A silver nanoparticle embedded in the ZnO electron injection layer exhibited a remarkable ∼ 180 % increase in the external quantum efficiency of the OLEDs [226].Recently[3], silver nanocubes over the contact electrode of silver and separated by an organic spacer have exhibited a four-fold improvement in plasmon enhanced stability through an intentional far-field coupling of the nanocubes to the surface plasmon mode of the silver cathode with excitons followed with 40 % increase in the light emission performance.

When examining light enhancement induced by light scattering (LS), our focus will be solely on PNPs. This choice is motivated by existing studies, which have explored various strategies for optical light outcoupling[227–229], including the use of particles with a size of 0.8 μm. While these larger particles are part of the broader landscape of optical light outcoupling techniques, our analysis will concentrate specifically on the role of PNPs in enhancing light emission. Additionally, nanoparticles placed outside the OLED architecture[230] are not considered here as they are also considered as light outcoupling strategies rather than plasmonic enhancement of light emission.

Various studies have proposed innovative approaches to enhance the efficiency of organic light-emitting diodes (OLEDs) by optimizing internal light extraction mechanisms. Karl Leo and team[231] introduced a novel internal light extraction system for white OLEDs, integrating spontaneously formed plasmonic tin oxide nanostructures with a highly conductive, low refractive index polymer electrode. This system effectively addressed the poor light extraction efficiency typical of conventional planar OLEDs, achieving a significant enhancement in external quantum efficiency (EQE) by factors of 1.7 to 2.9, particularly when employing a hemispherical lens. Additionally, Jung-Yong Lee and team[232] investigated the impact of size-controlled Au and Ag NPs on OLED performance enhancement through scattering effects. Their findings revealed synergistic effects of tailored Au and Ag NPs, resulting in a remarkable 63.9 % enhancement in EQE when combined, with Ag NPs notably improving light extraction efficiency by over 4.2 %. Meanwhile, Qibing Pei and team[233] introduced a flexible, nanocomposite substrate designed to maximize light outcoupling efficiencies of

Table 3
Cost Analysis for R2R Fabrication of perovskite/CIGS solar cells with PNPs.

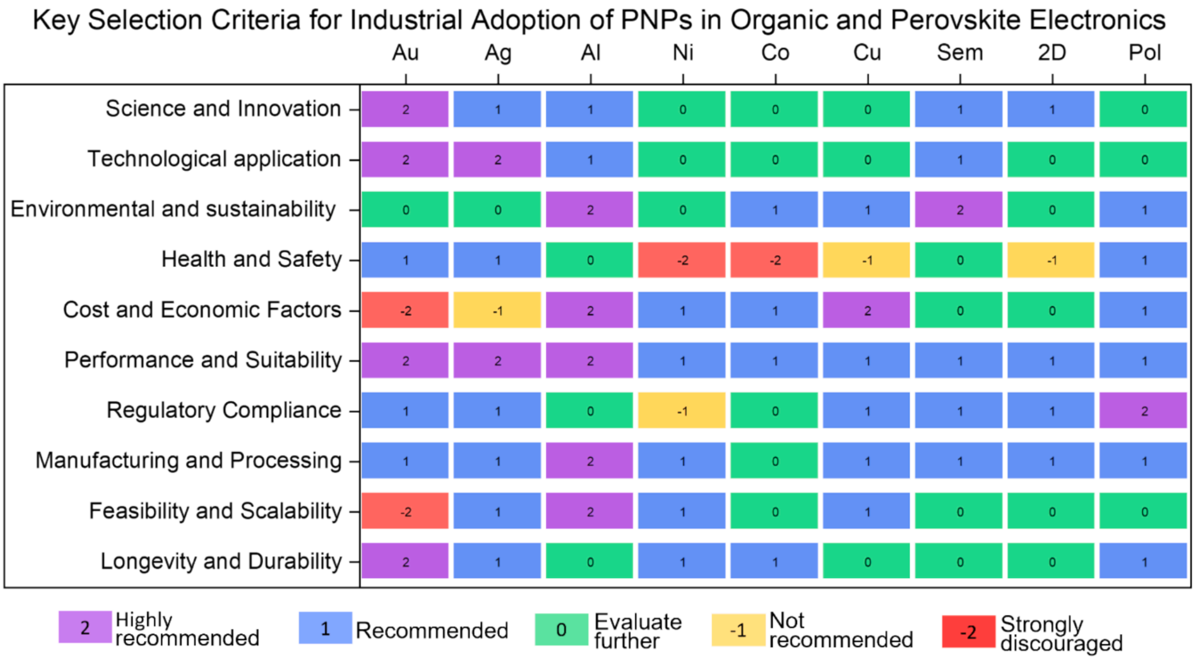
	Gold	Silver	Aluminium	Nickel	Cobalt	Copper
Minimum Sustainable Price (W^{-1})	€0.411	€0.408	€0.406	€0.407	€0.407	€0.407
Required Efficiency (%)	30.60	30.2	30	30.1	30.1	30.1
Required percentage enhancement	6.25	4.86	4.16	4.51	4.51	4.51

* Baseline Perovskite/CIGS Efficiency 28.80 % and Minimum Sustainable Price (Baseline) €0.416 $^{-1}$W.

OLEDs. By integrating silver nanowires, a high-index polymer layer, and a light-scattering layer, they achieved impressive metrics of 107 lm W^{-1} power efficiency and 49 % external quantum efficiency. Sung Min Cho and team[234] investigated the efficacy of mesoporous titanium dioxide (TiO_2) nanoparticles as a light scattering layer in OLEDs, demonstrating a 30 % improvement in efficiency compared to amorphous TiO_2. Additionally, Byeong-Kwon Ju and team[235] presented a novel approach using low-temperature annealed silver nanoparticles to enhance light extraction efficiency in flexible OLEDs, resulting in a 24 % improvement in EQE. Lastly, Changhee Lee and team[236] introduced thermally-assisted, self-aggregated silver nanoparticles as a scattering layer, achieving an 11 % improvement in EQE without compromising viewing angle characteristics. Jun Yeob Lee and team[237] also developed a light-scattering hole transport layer embedded with in-situ generated silver nanoparticles, offering a straightforward solution to increase OLED EQE without complex fabrication processes. These studies collectively highlight diverse strategies for improving OLED efficiency through internal light extraction mechanisms, promising advancements in practical lighting applications.

Like the advances in the plasmon enhanced OLEDs, the incorporation of the plasmonic nanoparticles demonstrated a significant improvement in the performance of the perovskite light emitting diodes(PeLEDs). Studies involving Au, Ag and Au-AG alloy nanoparticles have shown that, the PNPs are capable of dramatically boosting both luminescence and the efficacy curtesy of the near field and far field enhancement. For instance, incorporating Au NPs into the PEDOT:PSS in a $CH_3NH_3PbBr_3$ PeLEDs resulted in a 109 % increase in luminance and a 97 % improvement in EQE to 1.83 %[238]. Similarly, in $CsPbBr_3$ PeLEDs, the addition of Au NPs with a MgZnO spacer achieved a 1.55-fold enhancement in luminance, with EQE improving by 52.9 % and current efficiency by 56.5 %[239]. Ag nanorods have also shown great promise, increasing luminance by 42 % and current efficiency by 43.4 % in $CsPbBr_3$ PeLEDs[240]. Moreover, Au-Ag alloy nanoparticles[241] proved effective by tuning the LSPR wavelength to match the perovskite emission, resulting in a 25 % enhancement in luminescence. Despite these challenges, these advances highlight the transformative potential of plasmon-enhanced PeLEDs, with substantial improvements in efficiency and stability across various material systems.

Incorporating PNPs into organic and perovskite light-emitting diodes (LEDs) poses several challenges, including those related to charge injection, material compatibility, and device stability. One significant issue is the potential disruption of charge injection due to the presence of PNPs, which may hinder the efficient transfer of electrons and holes at the electrode/organic interface. This can lead to increased leakage current and reduced device performance. Additionally, the introduction of PNPs may alter the electrical properties of the organic or perovskite materials, affecting their charge transport characteristics and leading to non-uniform device operation. Moreover, the incorporation of nanoparticles can result in compatibility issues with the device fabrication process, such as aggregation or uneven dispersion—excessive concentrations can lead to poor film morphology, which can lead to variations in device performance and reliability. Furthermore, PNPs may introduce optical losses or quenching effects, diminishing the emission efficiency of the OLEDs or perovskite LEDs. To address these challenges, researchers are exploring various strategies, including surface modification techniques to improve the compatibility between nanoparticles and organic/perovskite materials[242,243], optimizing the nanoparticle concentration[188] and distribution to minimize aggregation and ensure uniform dispersion, and engineering the device structure to mitigate charge injection limitations and optimize optical properties. Additionally, the development of novel materials and fabrication



Key Selection Criteria for Industrial Adoption of PNPs in Organic and Perovskite Electronics

	Au	Ag	Al	Ni	Co	Cu	Sem	2D	Pol
Science and Innovation	2	1	1	0	0	0	1	1	0
Technological application	2	2	1	0	0	0	1	0	0
Environmental and sustainability	0	0	2	0	1	1	2	0	1
Health and Safety	1	1	0	-2	-2	-1	0	-1	1
Cost and Economic Factors	-2	-1	2	1	1	2	0	0	1
Performance and Suitability	2	2	2	1	1	1	1	1	1
Regulatory Compliance	1	1	0	-1	0	1	1	1	2
Manufacturing and Processing	1	1	2	1	0	1	1	1	1
Feasibility and Scalability	-2	1	2	1	0	1	0	0	0
Longevity and Durability	2	1	0	1	1	0	0	0	1

2 Highly recommended
1 Recommended
0 Evaluate further
-1 Not recommended
-2 Strongly discouraged

Fig. 5. Overview for material selection in R2R fabrication are presented, considering the diverse needs of global organizations, scientific communities, and end-users. These suggestions are informed by a thorough TEA and comprehensive studies on the toxicity, recyclability, and waste management implications of gold, silver, aluminium, nickel, cobalt, copper, semiconductor, 2D, and polymer nanoparticles.

methods, such as hybrid nanocomposites or solution processing techniques, may offer alternative approaches to integrate PNPs into organic and perovskite LEDs while minimizing adverse effects on device performance and stability. Ultimately, a comprehensive understanding of the interactions between PNPs and organic/perovskite materials, coupled with careful design and optimization of device architectures, is essential to harness the full potential of plasmonic-enhanced light-emitting diodes for next-generation optoelectronic applications.

6. Techno-economic analysis

Bridging the gap between promising material science and scalable manufacturing, this techno-economic analysis explores the integration of roll-to-roll compatible deposition techniques for PNPs in organic and perovskite solar cells. We begin by establishing a baseline cost comparison for organic/perovskite solar cells and organic light-emitting diodes (OLEDs) fabricated using various deposition techniques, excluding PNPs. In the context of the cost analysis for the solution-processed R2R fabricated devices, organic photovoltaics[244] with 10 % Power Conversion Efficiency (PCE) and a 20-year lifespan, featuring annual degradation at 0.05 % and a 70 % fill factor, are estimated to cost \$0.47 per watt. Additionally, the manufacturing expenses for these modules are projected to be \$57.24 m^{-2}. In a comparable context, perovskite Photovoltaics[7] with a 10 % PCE with a shorter 3-year lifetime, and annual degradation of 0.3 %, have an estimated module cost of \$0.18 W^{-1}. This provides a cost comparison with traditional crystalline silicon (c-Si) modules[7,167], which range from \$0.15 to \$0.27 W^{-1}. Forecasts suggest a promising future for R2R solution-processed perovskite photovoltaic devices, anticipating a decrease in manufacturing costs[173] to approximately \$5m^{-2}(excluding encapsulation). In both the Organic and Perovskite Photovoltaics, the materials cost significantly influences the overall module cost. As manufacturing throughput increases, there is a corresponding reduction in manufacturing costs, with materials accounting for around 90 % of the total PV module manufacturing cost[167]. Notably, the substrates, the contact electrodes and the active layer are identified as the most expensive components, and the cost is significantly impacted by the synthesis and fabrication steps. The same holds for R2R fabricated devices. Anticipating advancements in power conversion efficiency, and consequently changes in both retail prices per watt of generated electricity and power generated per unit are expected. For instance, the projected perovskite retail price of \$1 to \$1.5 (at 10 % PCE) is expected to decrease to \$0.5 to \$0.7 W^{-1} with a 15.5 % PCE[173].

In the case of organic light-emitting diodes (OLEDs) which have successfully transitioned from the lab to the commercial market, the forecasts from the Department of Energy (DOE) predict that white OLEDs will achieve a panel efficiency of 190 lmW^{-1} by 2025 [245], with the goal to reduce the fabrication cost to \$100 m^{-2} from the current \$290 m^{-2}. The cost of illumination for white OLEDs currently ranges from \$50 to \$300$(klm)^{-1}$, dependent on panel efficiencies[246,247].

The main cost components in OLED production are substrates, materials, capital equipment, and miscellaneous operational expenses[248]. Larger throughput in high-volume manufacturing has the potential to reduce capital and operational costs. However, these projections are based on the sheet-to-sheet vacuum deposition process and not the more cost-effective roll-to-roll (R2R) production method. The prediction for R2R fabrication, with a vacuum deposition capability[248] of $> 6 \times 10^6$ m^2yr^{-1}, is anticipated to significantly lower illumination costs to \$12.5 $(klm)^{-1}$. Implementing light extraction strategies and cost-cutting measures could further reduce the cost to \$6.3 $(klm)^{-1}$, aiming for a manufacturing cost of \$53.6 m^{-2} in the near future. Despite the benefits, the installation of new R2R-capable vacuum deposition systems demands a substantial capital investment of \$293 million, and the cost of illuminance remains 60 % higher than conventional LEDs. The adaptation of solution-processed roll-to-roll fabrication technology presents an alternative with minimal capital investment, reduced material waste, and low maintenance and depreciation costs. This method can seamlessly integrate with existing roll-to-roll technology for organic and perovskite photovoltaics without extensive equipment overhauls. Despite the potential advantages of solution-processed materials in OLED displays and lighting, their widespread adoption has faced obstacles due to inferior performance when compared to traditional methods. To address this efficiency gap, the integration of PNPs is considered. However, it is essential to note that the synthesis and deposition cost of these PNPs must be offset by the enhanced efficiency of the devices.

By leveraging insights from previous research, we aim to evaluate whether the integration of PNPs can bridge the performance gap and justify their inclusion in the fabrication process. Building upon the techno-economic analysis based on single-junction perovskite and single junction CIGS by Martulli et al.,[249] this work extends the analysis to plasmonic nanoparticle incorporated perovskite-CIGS tandem solar cells and predicts the efficiency required compared to the reference device efficiency to successfully incorporate the PNPs into the organic and perovskite solar cells.

The parameters used in the model are given in Table 2 and the fabrication sequence is shown in Fig. 4. Table 3 provides the estimates for the Minimum Sustainable Price (MSP, the price that covers the costs of production) for the perovskite/CIS configuration without nanoparticles was €0.416 W^{-1}. Integrating the nanoparticle, gold, silver, aluminium, nickel, cobalt and copper including its deposition process, material, energy, and capital costs, changed the MSP to €0.411, €0.408, €0.406, €0.407, €0.407and €0.407 per Watt respectively.

To ensure cost competitiveness upon the integration of PNPs, the efficiency must exceed specific thresholds depending on the type of nanoparticle used. Specifically, the required efficiencies for plasmon enhanced perovskite/CIGS solar cells are as follows: 30.60 % for gold, 30.20 % for silver, 30.00 % for aluminium, and 30.10 % for nickel, cobalt, and copper, Fig. 4d. This suggests a promising future for the commercialization of PNP-incorporated organic and perovskite electronics. As outlined in the previous sections of this article, achieving an efficiency improvement of at least 30 % is attainable when incorporating plasmonic nanoparticles (PNPs) into the solar cells, compared to the reference samples. Further research into optimizing nanoparticle material selection, surface coverage, and potential efficiency enhancements is recommended. This analysis highlights the potential trade-off between material costs, additional deposition steps and efficiency gains when incorporating PNPs into the R2R fabrication process.

7. Outlook

The potential of PNPs to enhance optical and electrical properties has driven significant growth in the commercial interest of plasmon-enhanced sensors, as well as applications in medicine. This commercial interest is mirrored by a notable increase in research publications (Fig. 4a) on PNPs over the years, reflecting their expanding role in various fields.

However, despite this academic interest, the widespread commercial adoption of PNPs in fields such as large-area organic and perovskite electronics remains a challenge. Despite the promising applications of PNPs, questions about their exact functionalities and environmental concerns, such as the usage of harmful solvents, carbon footprint and recycling of the noble metals used in these applications (see Fig. 4b), continue to hinder their widespread adoption. However, there is increasing interest from both academia and industry in using green solvents for the synthesis and deposition of PNPs and in developing methods for the recycling of these materials. As illustrated by the current recycling rates for various noble metals (Fig. 4c), increasing these rates not only has the potential to significantly mitigate the carbon footprint associated with the production of noble metal nanoparticles but also contributes to closing the loop and ensuring that valuable metals remain within the economy at the end of their lifespan. In addition, there is an ongoing interest in alternative nanomaterials such as semiconductors, polymers, and 2D materials. These materials hold the potential to either replace or complement noble metals, reducing both fabrication and material costs without compromising environmental sustainability. Such advancements could help industries meet environmental regulations (Critical Raw Materials Act), such as recycling more effectively.

Furthermore, encapsulating low-cost materials like aluminium, copper, and cobalt nanoparticles can selectively tune the LSPR, enabling their use across various wavelengths, and also aiding in reducing the safety concerns with respect to the toxicity of these base materials. These materials, with their significantly lower carbon footprints compared to gold and silver, present promising candidates for large-scale applications in photovoltaics, light emission, and photodetectors. Innovations in the functionality of plasmonic materials, combined with environmentally friendly deposition methods using green solvents and solution processing, could greatly benefit the environment. And since solution processing technologies are scalable through roll-to-roll (R2R) fabrication technologies, they offer more flexibility for the current industry infrastructure to adopt them, as existing deposition techniques, which have already proven to be R2R-compatible, can be readily utilized. For example, an illustration for a R2R compatible processing line for plasmonic incorporated organic or perovskite solar cells is shown in Fig. 4e. Existing R2R techniques, such as Mayerrod coating (Fig. 4e.i), screen printing (Fig. 4e.ii), doctor blade coating (Fig. 4e.iii), and slot-die coating (Fig. 4e.iv), can effectively deposit plasmonic nanoparticle/polymer perovskite nanocomposites. Additionally, deposition techniques like spray coating (pressurized (Fig. 4e.v), electrostatic (Fig. 4e.vi), and ultrasonic (Fig. 4e.viii)), and inkjet printing (Fig. 4e.vii) can precisely deposit PNPs at desired vertical distances and surface coverage in various functional layers (ETL/EIL/AL/HTL/HIL).

A techno-economic analysis of the aforementioned fabrication sequence for perovskite tandem photovoltaic cells indicates that incorporating PNPs raises the minimum sustainable price (MSP) marginally from a baseline MSP of \$0.416 W^{-1} without nanoparticles, Fig. 4d. To match the baseline MSP with an efficiency of 28 %, an efficiency enhancement between 4.15 % to 6.25 % would be required, depending on the specific PNPs used. Encouragingly, achieving a 30 % enhancement in device performance with PNPs is feasible, which would further reduce the MSP. The use of low-cost plasmonic materials such as aluminium, copper, cobalt, and advanced functional materials like 2D semiconducting polymers could lower the MSP even further, presenting a viable alternative to traditional silicon electronics.

Given these findings, overview for material selection in R2R fabrication are presented, Fig. 5, considering the diverse needs of global organizations, scientific communities, and end-users. These suggestions are informed by a techno-economic analysis (TEA) and comprehensive studies on the toxicity, recyclability, and waste management implications of gold, silver, aluminium, nickel, cobalt, copper, semiconductor, 2D, and polymer nanoparticles. By carefully selecting materials that balance performance, cost, and environmental impact, industries can more effectively incorporate PNPs into commercial applications while addressing sustainability concerns.

Author information

Rachith Shanivarasanthe Nithyananda Kumar (R.S.N), Wim Deferme (W.D), Alessandro Martulli (A.M) and Sebastien Lizin (S.L).

Contribution

The conceptualization and methodology for the project were led by R.S.N and W.D. Software usage was carried out by R.S.N, while formal analysis and data curation were collaboratively undertaken by R.S.N and A.M. Investigation efforts were shared among the team members. Resources were provided by W.D, and writing of the original draft was a collaborative effort involving R.S.N, A.M, S.L, and W.D. Additionally, all four contributed to the review and editing process. Visualization tasks were handled by R.S.N, with S.L and W.D providing supervision and overseeing project administration. Funding acquisition was managed by W.D.

Summary

This article dwells into the challenges in taking the plasmonic nanoparticle blended organic and perovskite optoelectronics in to commercialization. This is very crucial since both theoretically and experimentally (on lab scale) it is observed that the device performance increases noteworthily upon incorporating plasmonic nanoparticles. The increase in performance would inevitably results in more power generation as in case of photovoltaics and consumes less power in the case of light emitting devices and photodetectors. Of paramount importance is the potential for stimulated and coherent emission in excitonic systems, unlocking the doors to organic and perovskite lasing dreams and opening avenues in quantum communication, sensing, and metrology. Furthermore, the seamless integration of plasmonic nanoparticles into flexible electronics not only enhances efficiency but also aligns with environmental friendliness, contributing to the global pursuit of the Paris Climate Accord. In essence, the marriage of plasmonic nanoparticles with organic and perovskite optoelectronics holds the promise of ushering in a new era of technological understanding and environmental responsibility.

Physics Unveiled: Our perspective starts by exploring the physics behind various processes where plasmons enhance or assist, leading to an eloquent description of the unique properties that emerge when plasmons and excitons interact.

Materials Symphony: Next up, we look into the different materials used for plasmonic nanoparticles. We not only check out the ones already in use but also look at new materials being tried out to meet global and environmental rules, making sure they work well with organic and perovskite materials. It's a mix of being innovative and following the rules.

Crafting the Future: Moving on, we meticulously detail the varied fabrication techniques employed for depositing plasmonic nanoparticles. A critical examination ensues, uncovering bottlenecks that impede the seamless commercialization of plasmonic-incorporated organic and perovskite optoelectronic devices. This section concludes with thoughtful recommendations poised to refine and elevate fabrication techniques, paving the way for smoother integration.

Navigating Challenges: We then dive deep into the problems that come up when using devices with plasmonic nanoparticles. This also include techno-economic analysis where we evaluated he economic feasibility of integrating plasmonic nanoparticles (PNPs) into organic and perovskite solar cells through a detailed cost analysis of R2R manufacturing processes. By comparing the cost structure of these technologies with established benchmarks like OLEDs and crystalline silicon, the study identifies key cost drivers and assesses the potential impact of PNPs on overall device economics. The analysis aims to provide crucial insights for industry stakeholders to make informed decisions regarding technology adoption and investment. This closer look helps us understand the challenges better and the possible solution, acting as a guide for future improvements and a deeper mastery of these exciting technologies.

Outlook on the Horizon: Concluding our perspective, we cast our gaze towards the future, envisioning the evolution of plasmonic nanoparticle-infused organic and perovskite optoelectronics into a reliable and efficient technological cornerstone. This journey, in time, holds the potential to unravel solutions to both technological and fundamental societal challenges, forging a path towards a brighter, sustainable tomorrow.

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CRediT authorship contribution statement

Rachith Shanivarasanthe Nithyananda Kumar: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alessandro Martulli:** Writing – review & editing, Investigation, Formal analysis. **Sebastien Lizin:** Writing – review & editing, Project administration, Funding acquisition. **Wim Deferme:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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