

Review

Hybrid Plasmonic Materials and Architectures for Advanced Optoelectronic Systems

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Abstract

Recent developments in optoelectronics have led to the incorporation of metallic nanostructures into semiconductors and other active materials for tailoring optical confinement, carrier generation, energy transfer, and light emission. This review discusses the physical basis of these effects and their use in photovoltaic devices, light-emitting diodes, photodetectors, sensors, and flexible platforms. The mechanisms considered include localized surface plasmon resonance, near-field enhancement, light scattering, hot carrier injection, and plasmon–exciton coupling. The relative contributions of these processes often coexist within the same hybrid structure, being dependent on nanoparticle size and shape, the local dielectric environment, spectral overlap, interface properties, and device architecture. Particular attention is given to the difficulty of identifying the dominant enhancement pathways, emphasizing that similar improvements in device performance may originate from different physical mechanisms. Advances in hybrid perovskites, MXenes, metal–organic frameworks, polymeric composites, and other emerging material platforms further highlight the central role of interfacial engineering in controlling plasmonic functionality. Overall, this review highlights that understanding the interplay between plasmonic mechanisms, hybrid material design, and interfacial engineering is essential for the rational design and practical implementation of next-generation hybrid optoelectronic technologies.

Keywords: hybrid plasmonics; LSPR; interfacial engineering; hybrid optoelectronics; plasmonic nanostructures; plasmon-mediated mechanisms



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1. Introduction

The rapid evolution of modern information and energy technologies has intensified the demand for optically active platforms capable of efficiently generating, manipulating,

and detecting light at dimensions below the diffraction limit [1,2]. For decades, progress in this field has been constrained by a fundamental dichotomy between the ultrafast operational capabilities of photonic systems and the extreme miniaturization achievable in electronic circuits [1,3]. Although metallic plasmonic nanostructures offer an effective route for confining and manipulating electromagnetic fields at subwavelength dimensions, their practical implementation remains limited by competing radiative and nonradiative plasmon relaxation pathways, including intrinsic ohmic losses, whose relative contributions depend strongly on nanoparticle dimensions and the surrounding dielectric environment [1,4]. At the same time, conventional inorganic semiconductors, particularly silicon, face inherent challenges for active photonic applications because of their indirect bandgaps and inherently low light-emission efficiencies [5–7]. These complementary limitations have highlighted the need for material architectures capable of combining the optical advantages of plasmonics with the electronic functionality of semiconductors, thereby overcoming the restrictions associated with single-component systems [8,9].

To address these challenges, increasing attention has been directed toward hybrid architectures that combine organic and inorganic constituents at molecular and nanoscopic length scales through the incorporation of metallic nanoparticles (NPs) [5,10]. Rather than functioning as simple combinations of individual materials, these systems frequently exhibit interfacial interactions that generate functionalities unattainable in their isolated counterparts [10]. By integrating noble NPs with organic semiconductors, dielectric matrices, and other functional materials, hybrid platforms simultaneously combine strong optical responses with efficient carrier transport and the structural versatility required for advanced optoelectronic applications [5,8]. Consequently, research in plasmonics has progressively evolved beyond the study of isolated resonant nanostructures toward the development of multifunctional hybrid systems capable of integrating optical enhancement, charge transport, and optoelectronic functionality within a single platform [11,12]. The relative contributions of these plasmon-mediated mechanisms are not universal but depend on nanoparticle dimensions, antenna–effector coupling, interfacial electronic structure, and spectral matching between plasmonic resonance and the adjacent functional material [13–16].

A central factor governing the performance of these systems is the increasing importance of interfacial engineering. Within hybrid antenna–effector architectures, interfaces act as the primary regulators of charge transfer, electronic coupling, and energy transport between constituent materials [10]. The rational design of these interfaces is particularly important for suppressing nonradiative quenching pathways and mitigating Fermi-level pinning effects that have historically limited efficient charge-carrier injection and extraction across metal–semiconductor junctions [10,17]. Moreover, these interfacial effects frequently determine whether plasmon-mediated mechanisms contribute positively to device operation or instead promote energy dissipation within the metallic nanostructure together with carrier recombination losses within the adjacent semiconductor, ultimately governing the overall effectiveness of plasmonic enhancement at the device level [17]. Consequently, interfacial engineering not only determines the effectiveness of individual plasmonic mechanisms but also influences the ability to distinguish their relative contributions in practical optoelectronic devices.

Recent advances in optoelectronics have been driven by the emergence and integration of several hybrid material platforms, including MXenes, transition-metal dichalcogenides (TMDs), metal–organic frameworks (MOFs), and hybrid organic–inorganic perovskites (HOIPs), attracting considerable attention because of their outstanding optical absorption and charge-transport properties [18–21]. Although these material families differ substantially in composition, dimensionality, and operating principles, they share a common

objective, the engineering of interfaces capable of controlling light-matter interactions with a level of precision difficult to achieve in conventional materials [22]. Among them, MXenes are particularly attractive because their metallic conductivity and tunable work functions facilitate the formation of clean van der Waals (vdW) heterointerfaces [23]. Unlike conventional metal–semiconductor contacts, these interfaces minimize chemical disorder and reduce the formation of electronically detrimental interfacial states [17]. At the same time, polymeric and nanocomposite systems have enabled the development of mechanically flexible optoelectronic devices and wearable biosensors with intrinsic immunity to electromagnetic interference [5,24]. These materials have been incorporated into multi-functional platforms targeting next-generation communication technologies, point-of-care diagnostics, and high-efficiency solar energy conversion [11,25,26]. Although these material platforms differ in composition and dimensionality, these material platforms share a common objective: engineering plasmonic interfaces capable of balancing LSPR-mediated optical enhancement, charge transport, and operational stability. Nevertheless, despite their versatility, many hybrid systems continue to face challenges associated with long-term environmental stability, particularly under prolonged thermal stress and humid operating conditions [27,28].

Despite the significant advances reported during the last decade, several scientific and technological barriers continue to limit the large-scale implementation of hybrid plasmonic systems. Major challenges include the reproducible fabrication of ultra-small plasmonic nanostructures, the long-term stability of hybrid interfaces, and the effective management of interfacial recombination processes [18,24]. In particular, recombination pathways associated with trap states and localized electronic inhomogeneities remain an important source of efficiency loss in practical devices [18]. Furthermore, the same plasmon-mediated optical effects responsible for enhancing light harvesting can also intensify local heating and nonradiative dissipation, creating an inherent trade-off between optical enhancement and operational stability [29]. Addressing this balance remains essential for the development of high-performance hybrid plasmonic platforms [3,29]. Progress toward practical implementation therefore requires not only a deeper understanding of the nanoscale physics governing hybrid interfaces but also the development of reproducible and scalable fabrication strategies, such as inkjet printing and roll-to-roll processing [28,30,31].

This review examines recent developments in hybrid plasmonic materials and devices, with particular emphasis on how plasmon-mediated mechanisms, hybrid material design, and interfacial engineering jointly govern optoelectronic performance. Beyond summarizing recent advances, the review critically discusses the physical conditions under which different plasmon-mediated mechanisms become dominant, their implementation across hybrid material platforms, and the challenges associated with experimentally identifying the dominant mechanisms responsible for device performance. By integrating advances in plasmonic physics, materials engineering, and optoelectronic applications, this review provides a critical perspective on the opportunities and limitations shaping next-generation hybrid plasmonic systems.

2. Methods

This review was developed through a structured multi-platform literature survey that combined conventional academic practices with the support of generative artificial intelligence (AI) tools. Literature search was conducted using the Web of Science (Clarivate Plc, London, UK), Scopus (Elsevier B.V., Amsterdam, The Netherlands), Google Scholar (Google LLC, Mountain View, CA, USA), and IEEE Xplore (Institute of Electrical and Electronics Engineers, Piscataway, NJ, USA) databases. Review articles and original research were considered, with an initial emphasis on publications from the last five years while also

including seminal contributions published between 2000 and 2026. Non-peer-reviewed material was excluded. The literature search was performed using combinations of the following keywords and concepts: plasmonics; localized surface plasmon resonance; surface plasmon polaritons; hybrid materials; organic–inorganic interfaces; perovskites; MXenes; graphene; metal NPs; photovoltaics; light-emitting diodes; photodetectors; biosensors; flexible electronics; conductive hydrogel; and wearable optoelectronics. Following the initial search, publications were manually screened according to their relevance to the scope of this review, prioritizing studies addressing plasmonic mechanisms, hybrid material platforms, interfacial engineering, and optoelectronic device applications. Both experimental and theoretical studies were considered when they provided relevant insights into plasmonic mechanisms, hybrid material platforms, interfacial engineering, or device operation.

In addition to traditional databases, the AI-assisted academic search platform Consensus (Consensus NLP, Inc., San Francisco, CA, USA; <https://consensus.app>) was employed exclusively as a semantic literature discovery tool to facilitate the identification of relevant publications, accelerate the extraction of key findings, and improve the comprehensiveness of the bibliographic survey. Consensus was not used to evaluate the scientific quality of publications or determine their inclusion in the review, as all final selection decisions remained the responsibility of the authors.

To support the organization and synthesis of the collected data, Gemini 3.1 Pro (Google, Mountain View, CA, USA) was employed to improve grammatical coherence, stylistic clarity, and overall narrative organization. In addition, NotebookLM Pro (Google, Mountain View, CA, USA) was used to organize bibliographic information, prepare summary tables, and refine figure design. All AI-assisted outputs were independently verified against the original publications before being incorporated into the manuscript. References, digital object identifiers (DOIs), and all AI-generated summaries were manually cross-checked by the authors to ensure that all statements accurately reflected the findings reported in the primary literature.

3. Discussion

3.1. Fundamentals of Hybrid Plasmonic Systems

Modern hybrid plasmonic architectures are engineered through the integration of organic and inorganic components at molecular and nanoscopic length scales to overcome the intrinsic efficiency and stability limitations associated with single component materials [6,10,11]. These systems encompass a broad range of material platforms, including MXenes, graphene, semiconducting polymers, perovskites, and metal oxides, which are assembled into functional interfaces through weak vdW interactions or hydrogen bonding [6,11,32]. Their optoelectronic behavior is determined by the combined influence of hybrid interfacial properties and plasmon-mediated light-matter interactions.

To understand these interactions, it is first necessary to establish the fundamental physical mechanisms governing plasmon excitation, relaxation, and energy transfer in metallic nanostructures. From a classical electrodynamic perspective, the optical response of plasmonic metals is commonly described by the Drude free-electron model, which treats conduction electrons as a nearly free electron gas interacting collectively with an external electromagnetic field [13,33]. This framework provides the physical basis for understanding plasmon excitation, resonance, and damping in noble metals and serves as the starting point for most classical descriptions of plasmonic nanostructures. Plasmonic phenomena originate from the collective oscillation of free charge carriers in metallic materials under electromagnetic excitation. Depending on their spatial confinement and the boundary conditions imposed by the metallic geometry, plasmonic excitations can be broadly distinguished into volume and surface modes [1,15,33,34]. In an extended homogeneous

metal, ordinary bulk volume plasmons correspond to longitudinal collective oscillations of the conduction electron gas and does not directly couple to transverse electromagnetic radiation under conventional optical excitation [13,15]. However, this restriction does not generally apply to confined volume plasmon modes in finite metallic nanoparticles. At the nanoscale, spatial confinement and the breaking of translational symmetry modify the selection rules, allowing confined volume modes to become optically active depending on nanoparticle geometry and excitation conditions [15]. By contrast, surface plasmon modes are associated with metal–dielectric interfaces, and their optical coupling depends on whether the excitation is localized or propagating [13,33]. At extended interfaces, surface plasmons can couple with electromagnetic waves to form surface plasmon polaritons (SPPs), propagating modes capable of transporting electromagnetic energy along the interface [34]. Because the momentum of an SPP exceeds that of a free-space photon at the same frequency, direct optical excitation is not possible. Efficient excitation therefore requires momentum-matching strategies, including prism coupling, diffraction gratings, or periodically patterned metallic nanostructures [33,34]. Owing to their ability to confine and guide electromagnetic energy beyond the diffraction limit, SPPs have been widely exploited in waveguiding, sensing, and light-management applications [13,33,34]. Unlike localized surface plasmons, SPPs are sustained by extended metal–dielectric interfaces or periodically coupled plasmonic structures and therefore are not supported by isolated metallic nanoparticles [15]. In contrast, the optical response of subwavelength hybrid plasmonic systems is mostly governed by localized surface plasmon resonance (LSPR), arising from the coherent, collective, non-propagating oscillation of conduction electrons within metallic nanostructures at specific excitation frequencies [35–37]. Unlike propagating surface plasmon polaritons, LSPRs enable strong subwavelength optical confinement and generate intense localized electromagnetic fields, commonly referred to as hotspots near the nanoparticle surface [34,36,38]. The spectral position and intensity of these resonances are governed by the Fröhlich condition, which for idealized spherical NPs is satisfied when $\text{Re}[\epsilon_m(\omega)] = -2\epsilon_d$, where ϵ_m and ϵ_d correspond to the dielectric functions of the metal and surrounding medium, respectively. Consequently, the plasmonic response is highly sensitive to nanoparticle size, morphology, composition, and dielectric properties of the surrounding environment [13,33,36,39]. From a theoretical perspective, the optical response of isolated spherical NPs can be described using classical Mie theory, whereas realistic nanostructures and complex hybrid architectures generally require numerical approaches based on Maxwell’s equations, including discrete dipole approximation (DDA), the finite-difference time-domain (FDTD), and the finite-element method (FEM) [13,14,33]. Early experimental studies demonstrated that variations in nanoparticle geometry, particularly increased aspect ratio in anisotropic nanostructures such as nanorods and nanoplates, produce pronounced redshifts in the plasmon resonance frequency, facilitating spectral matching with semiconductor absorption bands [12,13,36,40–42]. While these classical approaches provide a useful description of many plasmonic nanostructures, their quantitative accuracy depends on the use of an appropriate size-dependent dielectric response. For metallic nanostructures with dimensions of several tens of nanometers, the Drude dielectric function must be revised to account for strong radiative damping associated with Lorentz friction, which is particularly pronounced at this scale compared with ultra-small clusters and the bulk-metal limit [16]. At ultra-small dimensions and in strongly confined systems, the quantum-mechanical descriptions become necessary when nonlocal electronic effects, quantum confinement, electron-density redistribution, electron spill-out, or tunneling significantly influence plasmon dynamics [15,43]. Moreover, classical electromagnetic models do not explicitly account for quantum-mechanical antenna–effector coupling across hybrid interfaces. Under conditions of strong near-field coupling, complementary quan-

tum descriptions are required to evaluate plasmon-mediated transition probabilities and interfacial energy-transfer processes [15,16]. In these regimes, descriptions based on the random-phase approximation (RPA) or density functional theory (DFT) can be employed to capture nonlocal screening, electron spill-out, and collective electronic excitations [15,43].

Following plasmonic excitation, the energy stored in the collective electron oscillation relaxes through competing radiative and nonradiative pathways. Radiative decay results from the emission of electromagnetic energy by the oscillating plasmon-induced dipole into the far field and is commonly described in terms of electromagnetic back-action (Lorentz friction), whose relative contribution depends strongly on nanoparticle size [16]. In contrast, nonradiative decay transfers plasmon energy into electronic excitations within the metal. Consequently, the balance between radiative damping and nonradiative pathways, including Landau damping depends on nanoparticle dimensions, geometry, and the surrounding dielectric environment, ultimately governing the relative efficiency of light scattering, photothermal conversion, and hot-carrier generation [3,13,14].

As nanoparticle dimensions decrease toward the ultra-small regime, nonradiative relaxation through Landau damping becomes increasingly important. In this regime, the collective plasmon excitation decays into highly energetic single-particle excitations, generating energetic nonequilibrium carriers on timescales of only a few femtoseconds [13,35,44]. Under favorable interfacial energy alignment, these hot carriers may be injected into the conduction band of an adjacent semiconductor, such as TiO₂, before undergoing internal thermalization [45]. Otherwise, the excited carriers redistribute their excess energy through electron–electron scattering processes occurring within approximately 500 fs to 1 ps, followed by electron–phonon scattering events on timescales of 1–5 ps that transfer thermal energy to the metallic lattice [13,29,35]. This relaxation ultimately dissipates heat into the surrounding medium over timescales ranging from 100 ps to 10 ns, giving rise to the plasmonic photothermal effect [3,29]. Consequently, the contribution of hot carrier injection strongly depends on nanoparticle size, interfacial energy alignment, and the competition with ultrafast carrier thermalization, making it one of the most challenging plasmon-mediated mechanisms to exploit efficiently in hybrid optoelectronic systems [29,35,38].

In hybrid plasmonic architectures, metallic nanostructures frequently act as optical nanoantennas that concentrate incident light and mediate energy transfer to nearby semiconductors, molecular absorbers, or emitters. In these antenna–effector architectures, the metallic nanostructure acts as the optical antenna, whereas the adjacent semiconductor, molecular absorber, or emitter functions as the effector that receives the transferred energy. From a quantum-mechanical perspective, the interaction between plasmonic nanoantennas and nearby effectors can be described as a near-field coupling process between the collective plasmon excitation and the electronic or excitonic states of the adjacent material. In this regime, the transition probability associated with plasmon-mediated antenna–effector coupling can be described within the framework of Fermi’s Golden Rule, providing a quantum-mechanical framework that complements the classical electromagnetic description [15]. A representative application of this framework is found in metallized perovskite solar cells, where a subsequent theoretical analysis interpreted the additional plasmon-mediated contribution within a quantum near-field coupling framework involving nonvertical interband transitions, with the corresponding transition probabilities evaluated using Fermi’s Golden Rule, as discussed in Section 3.3 [46,47]. Depending on the nanoparticle size, geometry, and interfacial configuration, plasmon-mediated interactions may proceed through near-field electromagnetic coupling, radiative scattering, hot-carrier injection, or plasmon–exciton interactions [13,48,49]. The relative contribution of these competing interaction mechanisms depends strongly on nanoparticle dimensions, spectral overlap, antenna–effector separation, and the electronic structure of the hybrid interface [15]. Near-field coupling

enables localized energy transfer directly at the hybrid interface, whereas far-field scattering primarily redistributes incident radiation over larger distances [16].

Beyond plasmon generation and relaxation processes, the efficient operation of hybrid plasmonic systems depends strongly on the ability to tailor charge transfer across material interfaces. Among the available materials, MXenes have emerged as particularly effective components because of their metallic conductivity and tunable work functions facilitate the formation of clean vdW interfaces with reduced interfacial disorder [23]. Unlike conventional metal–semiconductor contacts, these vdW junctions suppress the formation of metal-induced gap states (MIGS) and mitigate Fermi-level pinning, thereby preserving the intrinsic electronic properties of semiconductor surfaces and promoting more efficient charge injection and extraction processes [23]. Similar interfacial control phenomena have long been recognized as critical factors governing charge transport across hybrid optoelectronic architectures [50]. Beyond charge transport, the local interfacial environment also plays a decisive role in governing excitonic and energy transfer processes. Within organic–inorganic hybrid systems, tailoring the local dielectric constant can reduce the exciton binding energy, typically between 0.3 and 1.0 eV, thereby promoting more efficient carrier photogeneration compared with fully organic systems [8,51]. The transport properties of organic semiconductors are strongly influenced by molecular packing, energetic disorder, and intermolecular electronic coupling, factors that ultimately determine carrier mobility within hybrid structures [52]. Beyond charge transport across hybrid interfaces, efficient device operation also depends on how optical energy is transferred between plasmonic nanostructures and surrounding photoactive materials.

Furthermore, interfacial energy transfer in hybrid plasmonic systems proceeds through several competing mechanisms whose relative contributions depend on nanoparticle dimensions and interface design [48,53]. While mechanisms such as Förster resonance energy transfer (FRET) rely on long-range dipole–dipole interactions, short-range electron exchange can occur through Dexter energy transfer [8,53]. In many plasmonic hybrid systems, these processes coexist with surface energy transfer (SET), plasmon-induced resonance energy transfer (PIRET), and plasmon–exciton coupling mechanisms, resulting in complex and competing interfacial pathways [48,53]. In particular, SET has been identified as an efficient transfer pathway in systems where excitonic dipoles interact with nearby metallic surfaces, exhibiting a characteristic distance-dependent behavior [48]. A particularly important form of interfacial coupling emerges in plexcitonic systems, where strong interactions between localized plasmons and excitons generate hybridized states accompanied by spectral Rabi splitting, enabling active modulation of spontaneous emission dynamics [13,49].

Many of these plasmonic and interfacial effects directly influence device performance, particularly in thin-film architectures such as perovskite and quantum-dot solar cells, where optical confinement and light scattering processes are used to increase photon utilization [21,28,54]. In these systems, metallic nanostructures function as subwavelength scattering centers that increase the effective optical path length by redirecting incident light into the absorber at larger propagation angles [13,40,54]. Simultaneously, the near-field enhancement associated with LSPR amplifies the local electromagnetic field, thereby increasing the generation rate of electron–hole pairs in the adjacent semiconductor within the surrounding medium [28,38,41,55]. Beyond local field enhancement, nanoscale coupling between the plasmonic nanoantenna and the surrounding photoactive material can also promote efficient energy transfer across the hybrid interface, with the dominant mechanism depending on both the nanoparticle dimensions and the antenna–effector separation [15,16]. In light-emitting diodes (LEDs), these interactions can also modify spontaneous emission dynamics through the Purcell effect, where an increased local density of optical states near

the plasmonic nanostructure enhances spontaneous emission rates [1,8,56]. Nevertheless, device performance remains strongly dependent on the spatial positioning of the NPs. For example, positioning Au NPs at the interface between the electron transport layer and the absorber layer in perovskite solar cells can enhance electromagnetic coupling within the active region, thereby promoting photon absorption while facilitating charge extraction. Under appropriate interfacial conditions, this balance between optical and electrical enhancement mechanisms can contribute to improved carrier collection and reduced interfacial carrier recombination losses [28,57]. Conversely, excessive plasmonic coupling or improper nanoparticle distribution may intensify nonradiative dissipation pathways and interfacial recombination, ultimately counteracting the optical benefits introduced by plasmonic confinement.

Despite these advantages, hybrid plasmonic systems continue to face several fundamental physical limitations. Strong LSPR-mediated optical effects are frequently accompanied by increased ohmic losses within the metallic components, generating parasitic heating that can deteriorate sensitive organic materials or destabilize perovskite lattices [1,3,29]. At sufficiently small interparticle and interfacial separations, quantum size effects and the non-local dielectric response become significant [13,43,58]. Under these conditions, classical electrodynamics no longer provides an adequate description of the plasmonic response. Quantum-mechanical effects give rise to a nonlocal distribution of conduction electrons near the metal surface, ultimately limiting the degree of electromagnetic field confinement and enhancement [13,43,58]. Thus, advanced quantum approaches such as DFT and RPA are frequently employed to describe strongly confined plasmonic systems and nonlocal electronic dynamics. DFT provides an atomistic description of plasmon excitations in ultra-small metallic clusters, although its computational cost restricts its applicability to relatively small systems. By contrast, RPA offers an efficient framework for describing collective plasmon excitations and nonlocal optical response over a broader range of nanoparticle sizes and confinement regimes [43]. Collectively, these physical mechanisms demonstrate that the performance of hybrid plasmonic systems arises from the interplay between plasmon excitation, competing radiative and nonradiative relaxation pathways, and interfacial charge-transfer and energy-transfer processes. The following section examines how these principles are implemented across the principal classes of hybrid plasmonic materials currently employed in optoelectronic devices.

3.2. Hybrid Materials for Plasmonic Devices

The transition from monolithic plasmonic structures to hybrid material architectures has substantially expanded the design landscape for next-generation optoelectronic systems. Through the integration of noble-metal NPs with a broad range of organic and inorganic semiconductors, these platforms establish highly interactive interfaces where localized plasmonic effects and semiconductor properties interact to enhance optical absorption, carrier dynamics, and interfacial energy-transfer processes through mechanisms whose relative contributions depend on nanoparticle dimensions and interface design [14,39]. Within these systems, the dielectric environment provided by the host semiconductor modulates the plasmonic resonance, whereas the metallic NPs amplify localized electromagnetic fields, which can promote carrier generation through plasmon-mediated near-field coupling [14]. This design flexibility has been further expanded through the development of bimetallic, alloyed, and core-shell plasmonic nanostructures. By modifying nanoparticle composition and architecture, these systems provide additional degrees of freedom for tailoring plasmon resonance frequencies, electromagnetic field distributions, charge-transfer characteristics, and chemical stability [59]. In particular, multimetallic alloys such as AgPt, AuPt, AgAuPt, and AgAuPdPt can exhibit tunable LSPR arising from the combined contributions of differ-

ent metallic elements, where both electronic heterogeneity and nanoparticle morphology contributing to the modulation of resonance intensity and spectral position. Consequently, alloyed and multicomponent plasmonic nanostructures have emerged as versatile material platforms for the rational design of next-generation hybrid plasmonic systems [20,41,59].

Within HOIPs and lead-halide systems, the effectiveness of plasmonic enhancement is strongly governed by the spatial distribution of the constituent components [21,28]. In parallel, the development of lead-free perovskite compositions has emerged as an important research direction aimed at reducing toxicity while preserving favorable optoelectronic properties [60]. Strategically positioning plasmonic NPs at the electron-transport layer interface or within the absorber layer can enhance antenna–effector near-field coupling, potentially resulting in significant improvements in photocurrent generation and power conversion efficiency [21,28]. However, excessive proximity between metallic nanostructures and photoactive regions may also intensify nonradiative recombination within the semiconductor and local thermal dissipation, illustrating the delicate balance between optical enhancement and operational stability in plasmonic photovoltaics [3,29,57]. To address these limitations, sophisticated multiple-core–shell nanostructures, including oxide–metal–oxide configurations, are being employed because they provide the thermal robustness required during device fabrication while simultaneously enabling tunable plasmonic resonances spanning the visible and near-infrared spectral regions [41]. This strategy has proven particularly effective in practical photovoltaic systems, where balancing efficient light harvesting with charge extraction remains essential for maximizing device performance [41].

Although TiO₂ remains one of the most extensively investigated oxide semiconductors in plasmon-enhanced architectures, similar strategies have also been successfully implemented in a broader family of metal oxides, including ZnO, zirconium-doped indium oxide (IZrO), and transparent conductive oxides such as indium tin oxide (ITO) and Al-doped ZnO (AZO) [61–63]. These materials offer distinct advantages in terms of charge transport, optical transparency, and interfacial engineering. The incorporation of plasmonic nanostructures has been associated with both improved light harvesting through near-field enhancement and far-field scattering and more efficient carrier extraction, ultimately leading to enhanced device performance [62].

Beyond perovskite-based and metal-oxide systems, two-dimensional (2D) materials have emerged as powerful interfacial platforms capable of combining efficient charge transport with strong optical confinement [17,22,64]. This level of interfacial control preserves the intrinsic electronic properties of the semiconductor surface while significantly reducing the formation of MIGS and undesirable tunneling currents [17,23]. In graphene-based systems, the gapless electronic structure, together with favorable interfacial energy alignment, can facilitate hot carrier extraction [21,64,65]. Collectively, these characteristics make 2D materials particularly attractive for hybrid plasmonic architectures where efficient carrier extraction and interfacial stability are critical [26]. It is important to distinguish the plasmonic behavior of 2D materials according to their structural configuration. When patterned into confined nanostructures such as nanoribbons, nanodisks, or periodic arrays, graphene and MXenes can support LSPRs, enabling strong electromagnetic confinement and tunable optical responses [17,64]. In contrast, continuous graphene or MXene layers primarily modulate charge-transfer processes and, under appropriate conditions, can support propagating plasmonic modes [17,64]. This distinction is particularly relevant for the design of photodetectors, biosensors, and vdW heterostructures, where the plasmonic response depends strongly on whether the material functions as an active resonator or as an interfacial transport layer [22,23]. Nevertheless, despite these advantages, long-term environmental stability remains a persistent challenge for many 2D systems, particularly under humid

or oxidative operating conditions where surface degradation can progressively degrade carrier-transport properties [23,26].

Whereas 2D materials primarily optimize charge transport across atomically sharp interfaces, MOFs provide an alternative strategy based on structural organization and controlled nanoparticle distribution. Owing to their porous crystalline frameworks, MOFs allow precise spatial organization of plasmonic NPs, minimizing aggregation effects while intensifying localized electric fields through cooperative coupling phenomena [66]. In energy harvesting and sensing applications, 2D MOF films facilitate efficient interfacial charge transport through metallized porphyrin units, contributing to enhanced transient photocurrent responses [66]. These architectures frequently rely on FRET processes in guest MOF systems, facilitating efficient light harvesting and energy transfer between donor and acceptor components within the hybrid framework [20,67]. Despite these advantages, the relatively low intrinsic conductivity of many MOF systems can still limit efficient charge extraction, particularly in architectures requiring rapid carrier transport across extended interfaces [20]. The concept of highly organized hybrid assemblies is also reflected in emerging photosynthetic biohybrid systems, where biological and inorganic components cooperate to optimize light harvesting and energy conversion processes [68]. Collectively, these examples highlight the growing importance of structural organization as a tool for controlling plasmon-mediated energy conversion.

Polymeric and nanocomposite systems introduce an additional level of versatility by supporting both electrical transport and optical waveguiding within mechanically flexible platforms [6,8,31,69]. Polymeric biomaterials further provide optical transparency, biocompatibility, and mechanical adaptability, making them attractive candidates for biophotonic and wearable optoelectronic applications [70]. In these platforms, the incorporation of plasmonic NPs can modify spontaneous emission dynamics through the Purcell effect, a mechanism that has been widely exploited in blue and deep-ultraviolet (UV) LEDs to promote higher internal quantum efficiency (IQE) under appropriate emitter-plasmon coupling conditions [8,56,71]. The functionality of these systems is further enhanced in responsive polymer hydrogels, where environmental stimuli such as temperature, pH, or ionic strength actively modulates the refractive index or regulates nanoparticle separation distances [72,73]. This adaptive behavior enables reversible switching of collective plasmonic modes, thereby facilitating highly sensitive biosensing platforms and light-driven mechanical actuation processes [72,73]. At the same time, polymer-based systems frequently face limitations associated with thermal degradation, mechanical fatigue, and long-term structural instability, particularly under prolonged optical excitation or repeated deformation cycles [24]. The adoption of renewable materials and green processing approaches is becoming relevant as hybrid optoelectronic technologies move toward large-scale manufacturing [74]. Figure 1 schematically illustrates the incorporation of metallic nanostructures into semiconductor, organic, and 2D material platforms, highlighting how plasmon-mediated interactions influence charge generation, carrier transport, optical emission, and sensing performance.

Although considerable progress has been achieved in hybrid plasmonic materials, interfacial and material-related limitations remain among the principal obstacles restricting device performance. Interfacial recombination processes, predominantly governed by Shockley–Read–Hall (SRH) recombination through trap states and Langevin recombination driven by Coulombic interactions, continue to constrain the overall efficiency of these systems [21,22,25,71]. Furthermore, structural heterogeneity within organic–inorganic blends can generate localized electronic variations that negatively impact device reproducibility and operational stability [22,71]. The vdW gap between layered materials may also act as an effective tunnel barrier, increasing contact resistance and complicating charge

injection processes [17,22]. Consequently, the rational engineering of hybrid structures, particularly through grain-boundary control, precise nanoparticle incorporation, and optimized energy-level alignment, remains essential for overcoming these interfacial limitations and advancing high-performance plasmonic technologies [21,22]. Moreover, these considerations illustrate that the role of hybrid materials extends beyond simply supporting plasmonic nanostructures. Instead, each material platform provides a distinct strategy for tailoring interfacial interactions, thereby determining the relative contributions of coexisting plasmon-mediated mechanisms under specific operating conditions.

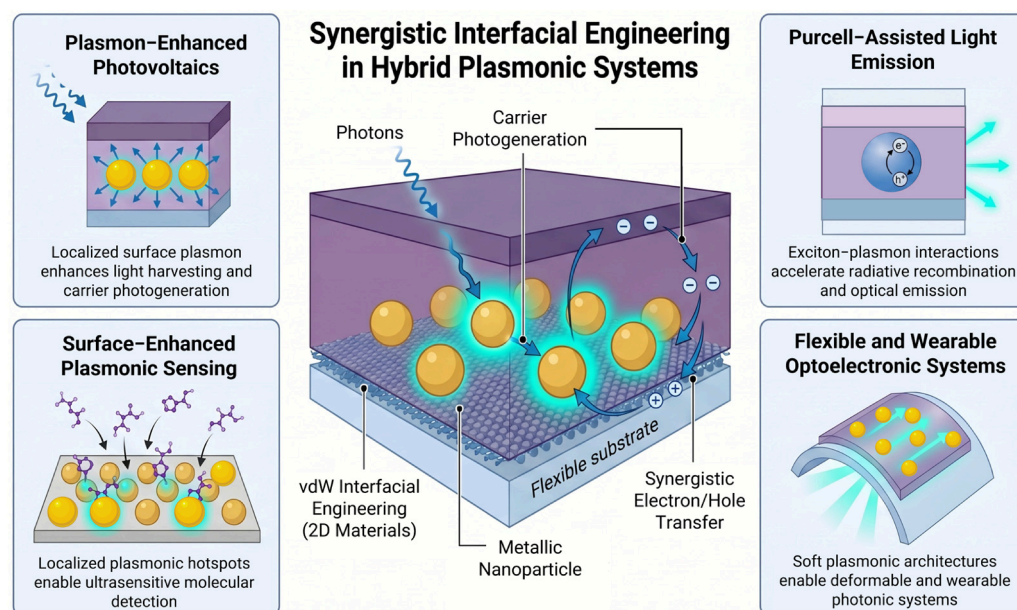


Figure 1. Schematic illustration of the main plasmon-mediated structures for enhanced optoelectronic and flexible devices. Metallic NPs integrated into hybrid material platforms enable improved light harvesting, carrier dynamics, optical emission, molecular sensing, and mechanical flexibility.

3.3. Functional Applications of Hybrid Plasmonic Devices

The implementation of plasmonic phenomena at the device level is primarily governed by the optimization of the interface between metallic NPs and active semiconductor layers. Although the plasmon-mediated mechanisms described above operate across most hybrid optoelectronic technologies, their relative contributions vary considerably depending on device architecture, material platform, and interfacial design. Consequently, each application discussed below emphasizes different mechanisms to optimize optical absorption, charge transport, radiative emission, or sensing performance. In photovoltaic systems, the incorporation of Au and Ag NPs addresses the intrinsic mismatch between optical absorption depths and minority carrier diffusion lengths by increasing short-circuit current density (J_{SC}) through localized electromagnetic field amplification [21,28,55,57,75]. Early demonstrations of plasmon-sensitized solar cells showed that ordered assemblies of Au NPs could enhance photocurrent generation through plasmon-mediated charge-transfer processes [76]. Similar improvements have been reported in organic photovoltaic systems incorporating Au nanospheres, where LSPR contributes to enhanced optical absorption and carrier generation [77]. This effect is particularly pronounced in perovskite solar cells (PSCs), where the LSPRs supported by embedded Au NPs with diameters typically below 40 nm activate complementary optical and electrical plasmon-mediated mechanisms that collectively improve light harvesting, carrier separation, and charge extraction [28,55]. Near-field enhancement increases the local electromagnetic intensity within the absorber layer, thereby promoting higher photocarrier generation rates, whereas far-field scattering and plasmon-assisted

light trapping extend the effective optical path length and improves photon utilization across a broader spectral range [21,29,55]. In addition, plasmon-induced charge-transfer processes may facilitate carrier separation and extraction at critical interfaces, ultimately contributing to enhanced J_{SC} and power conversion efficiency (PCE) [21,55]. A representative experimental example was reported for MAPbI₃ perovskite solar cells incorporating Ag@TiO₂@Pa core–bshell nanoparticles, in which the best power conversion efficiency increased from 18.37% to 20.24% accompanied by improvements in J_{SC} and fill factor [46]. The experimental study attributed the performance enhancement to synergistic optical and electrical contributions rather than to increased absorption alone [46]. A subsequent theoretical analysis discussed this system and interpreted the additional electrical and excitonic contributions within a quantum-mechanical near-field coupling framework, in which the localized plasmon near field induces nonvertical interband transitions in the adjacent semiconductor and the corresponding transition probabilities are evaluated using Fermi's Golden Rule [47]. Within the theoretical model, classical near-field focusing was found to account for only a minor fraction of the calculated plasmon-mediated absorption enhancement, indicating that an additional quantum mechanical coupling contribution must be considered [47]. Because the theoretical treatment relies on simplified nanoparticle geometries and band-structure approximations, it should be regarded as a physically motivated interpretation of the experimental behavior rather than as a direct quantitative fit to the full experimental device architecture [47]. Nevertheless, device performance remains highly dependent on the spatial positioning of these nanostructures [55,57]. While locating plasmonic NPs at the absorber interface may enhance antenna–effector near-field coupling and photocurrent generation, excessive proximity to the fluorine-doped tin oxide (FTO) layer can induce parasitic absorption and accelerate undesirable interfacial recombination processes [28]. Advanced thin-film TiO₂/Si heterojunctions and tandem photovoltaic architectures further exploit metallic back reflectors and LSPR-active Ag NPs to improve long-wavelength absorption, contributing to higher PCE through reduced reflection losses and enhanced light scattering [54,78,79]. Comparable enhancements have also been observed in silicon-based photovoltaics through LSPR excitation in Ag NPs embedded near the absorber region [80]. Collectively, these approaches illustrate how plasmonic nanostructures can simultaneously enhance optical absorption and carrier generation, although their effectiveness ultimately depends on maintaining a delicate balance between strong electromagnetic confinement, efficient charge extraction, and controlled thermal dissipation. Beyond electricity generation, hybrid perovskite systems are being explored for photoelectrochemical applications, including water splitting and carbon dioxide reduction [81].

Interfacial modulation also plays a central role in plasmon-mediated energy-transfer and charge-transfer mechanisms, including PIRET and hot carrier injection, both of which can extend spectral utilization beyond the intrinsic semiconductor band edge through different physical pathways [28,41,82–84]. Rather than relying exclusively on direct photon absorption within the semiconductor, these processes can enable the harvesting of energy that would otherwise be dissipated through nonradiative plasmon relaxation pathways [82–84]. In flexible organic solar cells (FOSCs) incorporating Ag nanowires (NWs) electrodes, coherent near-field electromagnetic coupling through PIRET can compete with dissipative plasmon relaxation pathways, enabling energy transfer toward green fluorophores and leading to reported transmittance improvements exceeding 10% and PCE values approaching 19.5% [82]. Comparable panchromatic enhancement has been demonstrated in dye-sensitized solar cells (DSSCs) utilizing multiple-core-shell TiO₂-Au-TiO₂ (TAuT) NPs, where tunable LSPR enables balanced light harvesting across the solar spectrum while simultaneously maintaining the thermal stability required during annealing processes [41]. More recently, bimetallic and core–shell configurations, including Mo@MoS₂

structures, have been employed to suppress carrier recombination within the photoactive layer and exciton quenching by preventing direct contact between the metallic component and the perovskite absorber layer [57]. In parallel, the incorporation of Pt NPs has demonstrated a cooperative interaction between LSPR and pyroelectric effects, promoting enhanced exciton generation and improved charge-transfer dynamics for efficient photoelectrocatalytic processes [85]. Although these approaches substantially improve spectral utilization and carrier dynamics, excessive plasmonic coupling may still introduce additional nonradiative decay pathways and localized heating effects that negatively impact long-term operational stability. The diversity of plasmon-mediated enhancement strategies across different hybrid optoelectronic platforms is summarized in Table 1, highlighting the relationship among the material platform, dominant plasmonic mechanism, and resulting device performance.

Table 1. Representative hybrid plasmonic architectures for optoelectronics and photonic applications highlighting plasmonic effects, functional contributions, and device performance.

Plasmonic Application	Plasmonic Component	Plasmonic Effect	Contribution to Device Performance	Device Improvement	Ref.
Plasmonic paper-based microfluidics	Au NPs (~60 nm)	Near-field enhancement	Generates plasmonic hotspots; enhanced SERS-based molecular recognition	LOD = 10 μ M EF = 10 ⁷	[86]
Flexible polymer LED	Ag NWs (~30 nm diameter) Ag NPs	LSPR-SPP; plasmon–exciton coupling	Enhanced spontaneous emission through plasmon–exciton coupling	EQE = 5.6%	[87]
Plasmonic polymer microcapsules	Au NPs (30 $\pm$ 11 nm)	Interparticle plasmon coupling	Dynamic modulation of interparticle plasmon coupling	pH range = 2–9 Response < 1 s	[88]
Flexible AgNW/polymer composite	Ag NWs (96 $\pm$ 31 nm diameter)	LSPR-mediated photothermal effect	Photothermal nanowire welding and polymer integration	Sheet resistance = 43 m Ω /sq EMI shielding 90 dB	[89]
MXene/GaN photodetector	Ti ₃ C ₂ T _x MXene nanosheets	Plasmon-enhanced interfacial charge transfer	Improved interfacial carrier extraction and low-loss charge transport	Responsivity = 44.3 mA/W On/off ratio = 11,300	[90]
Perovskite LED	Au NPs (75 nm core/5 nm shell)	Near-field enhancement, Purcell effect	Enhances photon out-coupling; accelerates spontaneous emission through the Purcell effect	EQE: 7.1 to 10.3% Lifetime: 20 $\times$ longer	[91]
High-resolution Quantum Diode LED	Au NPs (~20 nm) embedded in PMMA honeycomb barrier	LSPR, plasmon–exciton coupling	Enhances spontaneous emission via Purcell effect; suppresses nonradiative exciton decay	EQE: +42.8% Lifetime: 2.4 $\times$ longer	[92]
Organic LED	POM-coated Ag core–shell NPs embedded in PEDOT:PSS HTL	LSPR, near-field enhancement; light scattering	Improve spontaneous emission and carrier balance	Threshold voltage: 11.3 to 7.2 V Luminance: 16.113 cd/m ²	[93]
Br-based Perovskite solar cell	Mo@MoS ₂ core–shell nanospheres (13 nm core/7 nm shell)	LSPR, near-field enhancement	Improve light harvesting; promotes charge separation and hole transport	PCE = 9.62% J _{SC} : 7.91 to 8.8 mA/cm ²	[57]
InGaN/GaN MQWs solar cell	Ag NPs (~40 nm)	LSPR, near-field enhancement	More light absorption; increased photocarrier generation	J _{SC} : 8.08 to 10.17 mA/cm ² Efficiency +27%	[94]
CZTS/c-Si tandem solar cell	Ag NPs (130–180 nm)	Light scattering	Extend optical path length; enhances photon harvesting	PCE = 20.99 to 28.28% J _{SC} = 14.26 to 19.93 mA/cm ²	[54]
Lead-free FASnI ₃ perovskite	Au NPs (55 nm)	LSPR, light scattering, light trapping	Boosted IR absorption; increase carrier generation; reduces carrier recombination	PCE: 13.9 to 21.8% J _{SC} = 30.67 to 38 mA/cm ²	[55]

Table 1. Cont.

Plasmonic Application	Plasmonic Component	Plasmonic Effect	Contribution to Device Performance	Device Improvement	Ref.
SERS/LSPR aptamer biosensor	Au NPs (~37 nm)	LSPR, plasmonic coupling	Hotspots formation; Aggregation-induced coupling	LOD = 17.6 nM Linear range = 0.04–40 μ M	[95]
h-BN nanosheet photodetector	Al NPs (20–30 nm)	LSPR, near-field enhancement	Enhancement of deep UV photocarrier generation and collection	Responsivity = 11.3 μ A/W Photocurrent $+5.5\times$ at 205 nm	[96]
Hybrid ExG-OTFT/SPR sensor	Au film with periodic grating (50 nm thickness)	SPP	Surface refractive index modulation; charge distribution sensing	Reduce voltage threshold to ~40 mV	[97]
Bimetallic Au-Ag hybrid system	Au-Ag nanoslit arrays (~5 nm)	LSPR, near-field enhancement	Provides electromagnetic confinement; enhances SERS response	LOD = 1 pM EF = 2.2×10^7	[98]
MXene/GaN vdW Schottky photodetector	Ti ₃ C ₂ T _x MXene nanosheets (~1.7 nm)	High quality vdW Schottky interface	Promotes self-powered carrier extraction; improves carrier transport	Responsivity = 681.6 mA/W Detectivity = 7.65×10^{13} Jones	[99]
Ag/WO ₃ /InGaN heterostructure	Ag NPs (147 $\pm$ 1.8 nm)	LSPR, hot carrier injection	Enhances visible light absorption, Schottky-assisted charge separation	Photocurrent density $+2.72\times$ ABPE = ~1.67%	[100]
Bimetallic Au-Cu hybrid system	Au-Cu NPs (~50 to 200 nm)	Hot carrier injection	Composition-dependent hot carrier dynamics and photocatalysis	Higher photocatalytic reaction rate $> 10\times$	[101]

LOD: Limit of detection, EF: Enhancement factor, EMI: Electromagnetic interface, LE: Luminous efficiency, ABPE: Applied bias photon-to-current efficiency.

Unlike photovoltaic devices, where plasmonic interactions primarily improve light harvesting and carrier generation, light-emitting devices exploit plasmon-mediated mechanisms to tailor spontaneous emission dynamics through the Purcell effect and plasmon–exciton coupling, thereby influencing emission efficiency and operational stability [1,8,56]. Within these devices, localized electromagnetic confinement can modify the local density of optical states and thereby alter spontaneous emission rates [102,103]. In blue organic light-emitting diodes (OLEDs), exciton coupling with silver nanoclusters introduces an additional radiative decay channel capable of competing with nonradiative pathways. By accelerating spontaneous emission and shortening exciton residence times within the emissive layer, this plasmon-assisted interaction reduces energy losses associated with trap-assisted processes and ultimately leads to nearly a twofold increase in external quantum efficiency [48]. The efficiency of this LSPR-mediated emission process is highly dependent on the separation distance between the emitter and the plasmonic nanostructure, making the optimization of dielectric spacer layers, commonly based on SiO₂ shells or poly(methyl methacrylate) (PMMA) matrices, essential for suppressing luminescence quenching and minimizing tunnel-induced losses [92,103]. High-resolution quantum-dot light-emitting diodes (QLEDs) also benefit from plasmonic enhancement through honeycomb-patterned barrier layers containing AuNPs. In these architectures, the enhanced local density of optical states promotes faster spontaneous emission, reducing exciton residence times and suppressing degradation pathways associated with prolonged exciton accumulation, leading to improved emission efficiency and operational stability [92]. Additional photoluminescence enhancement has been reported in semiconductor quantum-dot/polymer composite thin films incorporating Ag layers, highlighting the versatility of plasmon-assisted emission control in hybrid light-emitting systems [104]. In deep-ultraviolet (DUV) LEDs, where optical anisotropy in AlGaIn quantum wells limits light extraction, aluminum-based plasmonic structures are incorporated to compensate for total internal reflection and improve

light extraction efficiency (LEE) [56]. While Purcell-enhanced emission primarily relies on modifications of the local density of optical states, stronger plasmon–exciton coupling can further alter exciton dynamics and spontaneous emission rates through the formation of hybridized light–matter states, providing additional pathways for controlling emission efficiency and spectral response in plasmonic light-emitting devices [102,103]. Despite these advances, maintaining stable exciton–plasmon coupling without introducing additional quenching mechanisms remains a persistent challenge, particularly in high-power and high current-density operating conditions [71,105].

The coupling between optical and electronic responses is further exploited in multifunctional sensing platforms. Recent studies emphasize the growing role of plasmonic NPs as highly versatile sensing platforms for biochemical diagnostics and medical monitoring applications [106,107]. Integrated surface plasmon resonance (SPR) and organic thin-film transistor (ExG-OTFT) systems enable the simultaneous detection of mass uptake through refractive-index shifts together with collective charge-carrier redistribution via threshold voltage modulation [97]. This dual-mode transduction strategy overcomes the baseline drift limitations commonly associated with single-mode sensors and enables highly sensitive monitoring of biomolecular interactions [97]. Beyond conventional SPR sensing, the analytical sensitivity of these platforms can be further amplified through nanoparticle-on-film (NPoF) configurations and 5 nm hybrid bimetallic nanoslit arrays, achieving high surface-enhanced Raman scattering (SERS) enhancement factors [98,107]. Additionally, chiral plasmonic metasurfaces constructed from LSPR-active NPs or DNA-directed assemblies introduce new sensing modalities by enabling the detection of variations in optical chirality for ultrasensitive cancer biomarker analysis [38,108]. However, the extreme field localization required for ultrahigh sensitivity also increases susceptibility to fabrication imperfections, nanoparticle aggregation, and signal variability, all continuing to limit large-scale reproducibility in practical sensing devices [98,107,108].

Beyond conventional rigid optoelectronic devices, hybrid plasmonic architectures are being translated into flexible and wearable platforms that impose additional requirements for mechanical stability and environmental robustness. The transition of these technologies toward wearable and mechanically flexible platforms typically requires the integration of plasmonic nanostructures into substrates such as polyethylene terephthalate (PET), polydimethylsiloxane (PDMS), hydrogels, and smart textiles [24,97,109–111]. The integration of self-powered sensing capabilities is also emerging as a key requirement for future wearable human–machine interfaces and Internet-of-Things technologies [112]. These wearable systems frequently utilize evanescent field interactions in tapered or side polished optical fibers to monitor sweat biomarkers with minimal invasiveness [111]. Periodic Ag meshes incorporating nanohole perforations have also emerged as robust transparent conductive electrodes, demonstrating high mechanical flexibility while maintaining high PCE in PSCs after repeated bending cycles [113]. Despite these advances, several operational limitations continue to hinder long-term stability, including parasitic nonradiative damping and nanoparticle agglomeration [24,103,107,114]. Environmental factors such as humidity and temperature fluctuations can destabilize hybrid interfaces, particularly in flexible architectures where mechanical strain may disrupt conductive pathways [24,97,114]. Group III-nitride semiconductor platforms are additionally gaining attention as promising building blocks for mechanically flexible and high-performance plasmonic optoelectronic devices [23,115]. Ultimately, the rational engineering of hybrid plasmonic systems through optimized energy-level alignment, precise spatial organization, controlled interfacial coupling, and stabilized hybrid interfaces continues to be essential for achieving the multifunctional photonic integration required in next-generation human body centric technologies [26,114,116–118]. Overall, the applications discussed in this sec-

tion illustrate how the same fundamental plasmon-mediated mechanisms can be exploited differently depending on device architecture, material platform, and interfacial design. Figure 2 schematically summarizes these relationships by illustrating the roles of near-field enhancement, far-field scattering, light trapping, plasmon–exciton coupling, and hot carrier injection across representative hybrid optoelectronic technologies.

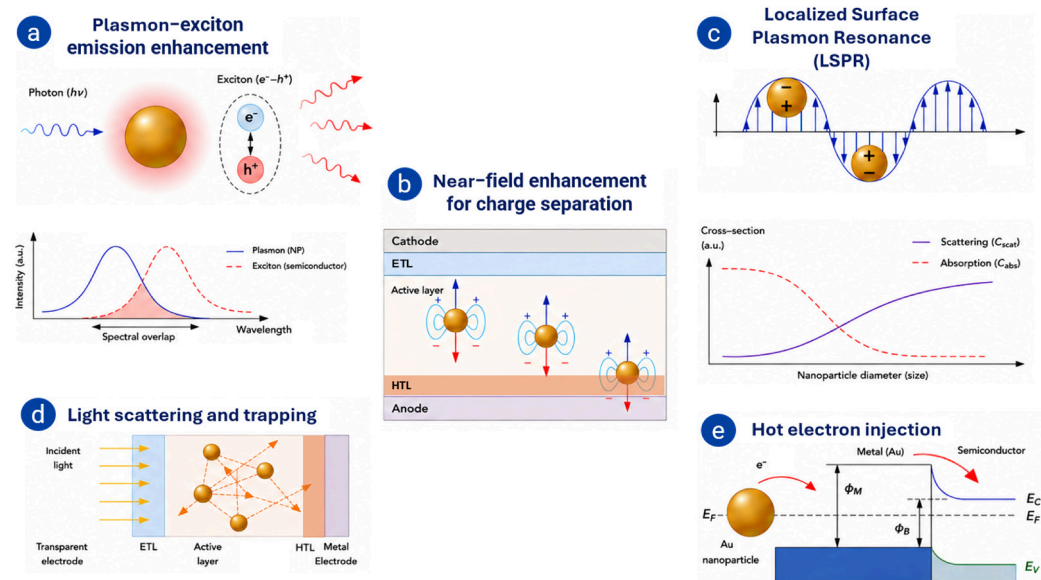


Figure 2. Schematic illustration of plasmon-mediated enhancement mechanisms employed in hybrid optoelectronics. (a) Plasmon–exciton emission enhancement, illustrating the influence of spectral overlap and coupling regimes on radiative emission. (b) Near-field enhancement, highlighting the dependence of electromagnetic field confinement on the nanoparticle position within the active layer. (c) LSPR, showing the size-dependent transition between absorption and scattering dominated optical response. (d) Light scattering and trapping, illustrating optical path-length enhancement within the active layer. (e) Hot electron injection, depicting the influence on energy-band alignment and Schottky barrier height on carrier injection into semiconductor.

3.4. Interpretative Consideration for Hybrid Plasmonic Optoelectronics

One of the most significant achievements of hybrid plasmonic optoelectronics has also become one of its greatest scientific challenges [1,3]. Although performance enhancement is now routinely demonstrated across a broad range of photovoltaic devices, light-emitting systems, photodetectors, and chemical sensors, identifying the physical mechanism responsible for these improvements has become difficult as device architectures become more complex [6]. The field has therefore evolved from demonstrating that plasmonic nanostructures can improve device performance to understanding how and under which physical conditions these enhancements occur [3,6]. Because multiple plasmon-mediated mechanisms may coexist within the same hybrid architecture, their relative contribution depends on nanoparticle dimensions, interfacial electronic structure, antenna–effector coupling, and spectral matching rather than on device performance metrics alone [15,16]. As hybrid platforms incorporate multifunctional semiconductors, charge-transport layers, and engineered interfaces, similar improvements in PCE, EQE, responsivity, or photocurrent may originate from different physical processes depending on the material system and device architecture. Consequently, demonstrating enhanced device performance has become comparatively straightforward, whereas establishing the dominant mechanism responsible for that improvement has emerged as one of the major scientific challenges in hybrid plasmonic optoelectronics [3].

One of the principal obstacles to identifying the dominant enhancement mechanism is the widespread assumption that improvements in device performance directly reflect the dominant plasmonic effect [3,18]. While correlations between LSPR and enhanced device performance are frequently reported, correlation alone does not establish the physical origin of the observed improvement [3,18]. For example, increased photocurrent in plasmonic photovoltaic devices has been associated with near-field enhancement, light scattering, or hot carrier injection [21,57], whereas comparable improvements in EQE reported for perovskite and quantum-dot LED have been interpreted in terms of the Purcell effect, plasmon–exciton coupling, or improved interfacial carrier injection [92]. Likewise, enhanced responsivity in hybrid photodetectors may result from near-field enhancement, built-in electric fields established at vdW interfaces, or improved carrier extraction across Schottky contacts [23,90]. At the same time, the incorporation of metallic NPs frequently modifies crystallization kinetics, grain growth, defect passivation, energy-level alignment, carrier transport, and charge extraction, leading to performance improvements that may closely resemble those traditionally attributed to plasmonic effects alone [18,21,119]. These observations indicate that similar improvements in device performance do not necessarily arise from the same physical mechanism, emphasizing that identifying the dominant enhancement mechanism, rather than simply demonstrating improved device performance, remains one of the major scientific challenges in hybrid plasmonic optoelectronics [3,18].

This complexity is further amplified by the unequal level of experimental evidence supporting the proposed enhancement pathways. Optical mechanisms, such as near-field enhancement and light scattering, are generally validated through direct optical characterization and electromagnetic simulations, providing relatively strong experimental evidence [14,58]. In contrast, mechanisms involving interfacial charge transfer or quantum-mechanical antenna–effector coupling are more difficult to verify experimentally. As discussed before, hot carrier injection depends on interfacial energy alignment, Schottky-barrier height, carrier transport, and ultrafast carrier dynamics, whereas PIRET, the Purcell effect, and plasmon–exciton coupling rely primarily on near-field electromagnetic coupling, the local density of optical states, or hybrid light-matter coupling [3]. Consequently, optical mechanisms are commonly supported by direct evidence of electromagnetic field confinement, whereas interfacial and nonradiative plasmon-mediated pathways are often inferred from indirect observations, including enhanced photocurrent, increased EQE, or spectral overlap with the LSPR [14,58]. Hot carrier injection represents perhaps the clearest example of this challenge, since electron–electron scattering, electron–phonon coupling, momentum mismatch, Schottky barrier limitations, and carrier back-transfer all compete with carrier extraction on femtosecond-to-picosecond timescales [75]. Similar limitations also apply to PIRET and the Purcell effect, where spectral overlap or reduced a photoluminescence lifetime alone cannot conclusively distinguish the proposed mechanism from competing relaxation pathways [3]. To facilitate the interpretation of these overlapping enhancement pathways, Table 2 compares the dominant plasmon-mediated mechanisms according to their characteristic operating conditions, principal experimental limitations, and current level of mechanistic evidence. Accordingly, future studies should place greater emphasis not only on identifying which mechanism provides the greatest improvement in device performance, but also on demonstrating which mechanism can be experimentally verified with the highest level of confidence within a given hybrid architecture.

Collectively, the studies discussed throughout this review indicate that plasmonic nanostructures should no longer be regarded merely as optical nanoantennas, but rather as multifunctional interfacial components whose optical, electronic, structural, and chemical contributions emerge from the interplay between antenna–effector coupling, interfacial electronic structure, and nanoparticle dimensions. Consequently, identifying the dominant

enhancement mechanism requires the combined analysis of device architecture, interfacial properties, and experimental evidence, since similar improvements in device performance may originate from different physical processes depending on the material system and device architecture [3,18,23]. In practice, several plasmon-mediated mechanisms frequently operate simultaneously within the same hybrid architecture, and the experimentally observed device response generally reflects their combined contributions rather than a single isolated process [15]. This perspective provides a rigorous framework for interpreting the different plasmonic enhancement mechanisms discussed throughout this review and establishes the context for the remaining challenges and future research directions.

Table 2. Critical comparison of the dominant plasmonic enhancement mechanisms, their operating conditions, and key considerations for mechanistic interpretation.

Plasmonic Mechanism	Typical Nanostructure Design	Dominant Physical Conditions	Main Limitations	Interpretation Challenge
Near-field enhancement	Metallic nanoantennas (<50 nm), nanogaps, core-shell hybrids	Strong LSPR excitation under antenna-effector near-field coupling	Rapid field decay, quantum quenching	May be confused with improvements cause by crystallization, defect passivation, or interfacial charge-transfer enhancement
Light scattering	Large metallic NPs (>50–100 nm), hemispherical structures, nanoarrays	Large radiative scattering cross-section; weak absorption losses	Parasitic absorption, back-reflection	Enhanced photocurrent may simply reflect improved optical path length
Hot carrier injection	Small metallic NPs coupled to direct metal-semiconductor (Schottky) interfaces	Ultra-small metallic NPs (<10 nm), favorable Schottky barrier, and suitable band alignment	Thermalization, back-transfer, momentum mismatch	Requires direct evidence of carrier extraction before thermalization
PIRET	Core-shell or dielectric-spaced hybrids	Spectral overlap under antenna-effector near-field electromagnetic coupling, nanometer spacing	Strong distance dependence	Often difficult to distinguish from hot carrier injection or FRET
Purcell effect	Metallic NPs and plasmonic nanocavities	Resonant emitter-plasmon coupling and optimized emitter-metal spacing	Nonradiative quenching	Reduced PL lifetime alone does not uniquely identify Purcell enhancement because quenching similitudes
Plasmon-exciton coupling	Resonant NPs-exciton Hybrids (<50 nm with optimized spectral overlap and spacing)	Strong plasmon-exciton coupling with spectral resonance	Ohmic losses, spectral mismatch	Strong coupling should be confirmed through hybridized states exhibiting Rabi splitting

3.5. Challenges and Future Perspectives

Building upon the mechanistic considerations discussed in the previous section, the continued development of hybrid plasmonic technologies requires addressing several fundamental trade-offs associated with plasmonic electron oscillations, energy dissipation, and interfacial charge transport. Although localized plasmonic fields can substantially enhance optical absorption and carrier generation, nonradiative damping within metallic nanostructures remains a major source of parasitic heating and performance degradation, particularly in organic and perovskite-based systems [27]. Device performance is also strongly influenced by interfacial phenomena, with the spatial distribution of plasmonic components

governing the balance between optical enhancement and carrier recombination losses within the semiconductor [119]. Consequently, achieving efficient plasmonic enhancement while minimizing thermal instability, nonradiative decay, and carrier recombination remains one of the principal challenges for the practical device implementation [27].

Future research efforts are centered on advanced interfacial engineering as a primary strategy for optimizing carrier transport and energy conversion dynamics [119]. In particular, strategic modulation of the work function at clean vdW interfaces, especially in systems incorporating 2D materials such as MXenes and graphene, offers an effective route for suppressing chemical disorder and mitigating Fermi-level pinning [23,26,27]. Within this framework, emerging platforms based on MXene-nitride heterostructures and carbon-derived conductive electrodes are expanding the range of available plasmonic functionalities while maintaining mechanical flexibility and chemical robustness [26,120]. These materials also provide alternative pathways for the fabrication of plasmonic architectures with a high density of electromagnetic hot spots while reducing reliance on complex lithographic processes [121]. However, translating such highly controlled nanoscale assemblies into technologically relevant devices will require overcoming persistent challenges associated with structural reproducibility, environmental stability, and large-area manufacturing. Addressing these challenges will be essential for translating advances in materials and interface engineering into scalable device technologies.

The transition toward scalable manufacturing remains equally essential for the industrial implementation of hybrid plasmonic technologies, driving the need for high-throughput fabrication strategies such as inkjet printing and roll-to-roll processing [30,119]. Recent advances in green-solvent-based inks and additive engineering have demonstrated that environmentally friendly processing routes can simultaneously improve device reproducibility and environmental stability by reducing trap-state formation within the bulk material [30]. These developments are consistent with broader efforts toward renewable materials and environmentally responsible processing routes in optoelectronics [24]. As the structural complexity and multidimensional parameter space of multifunctional hybrid systems continue to expand, conventional trial-and-error optimization becomes inefficient. Consequently, data-driven methodologies are becoming essential for accelerating materials discovery and device optimization [107]. Machine-learning approaches are particularly valuable for interpreting complex spectroscopic datasets and enabling more reliable predictions of electronic coupling strengths in heterogeneous materials, thereby supporting the rational design of robust and autonomous photonic platforms [107]. Nevertheless, the successful integration of data-driven optimization with reproducible nanofabrication workflows remains at an early stage and will require closer synergy between computational prediction, materials synthesis, and device engineering.

Recently, the development of adaptive polymer matrices and responsive hybrid architectures is opening new pathways toward multifunctional devices in which plasmonic interactions can be dynamically modulated in response to external stimuli. This capability represents an important step toward bridging the gap between passive optical manipulation and active nanophotonic control [107]. Overall, hybrid plasmonics is evolving toward sophisticated architectures that combine the structural flexibility and processability of polymers with the high carrier mobility and strong optical response of inorganic materials [119,121]. Ultimately, continued progress will depend on integrating mechanistic understanding, interface engineering, scalable manufacturing, and predictive design approaches into unified device design strategies capable of translating fundamental plasmonic phenomena into robust and commercially viable optoelectronic technologies.

4. Conclusions

Hybrid plasmonic systems have emerged as versatile platforms for tailoring light-matter interactions through the integration of metallic NPs with organic, inorganic, and low-dimensional materials. The examples discussed throughout this review illustrate how different plasmon-mediated mechanisms, including near-field enhancement, hot carrier injection, far-field scattering, and exciton–plasmon coupling, can be selectively exploited to improve optical absorption, charge transport, radiative emission, and sensing performance across a broad range of optoelectronic technologies. By integrating fundamental plasmonic mechanisms with recent advances in hybrid materials and device engineering, this review provides a unified framework for interpreting the diverse plasmon-mediated enhancement pathways reported across contemporary hybrid plasmonic optoelectronic systems.

Although plasmonic effects can significantly enhance optoelectronic performance, their effectiveness ultimately depends on how efficiently carriers and electromagnetic energy are managed at hybrid interfaces through the precise control of the location, shape, size, and chemical composition of metallic NPs. Across the material platforms discussed in this review, including vdW heterostructures, MXenes, MOFs, HOIPs, hybrid semiconductors, and polymeric systems, interfacial engineering emerges as the common framework through which LSPR-mediated interactions can be effectively translated into improved charge transport, energy conversion, and device functionality. These developments highlight that the practical implementation of plasmonic concepts depends not only on the optical functionality of metallic nanostructures, but also on the rational engineering of hybrid interfaces capable of sustaining efficient plasmonic coupling and long-term operational stability.

Further development of hybrid plasmonic devices will depend on maintaining nanoscale control along fabrication processes, especially when scalability increases due to nanoparticle distribution, compatibility with the surrounding materials, and interfacial stability. As previously discussed, small variation in these parameters can change the balance between optical enhancement, carrier extraction, recombination, and thermal losses, supporting the discussion about the limitations to obtain high reproducibility in scalable devices. For this reason, plasmonic mechanisms should be investigated alongside materials selection, interface design, and process optimization to achieve more efficient, stable and reproducible performance in photovoltaic, sensing, light-emitting, and flexible devices.

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