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High-performance plasmonics nanostructures in gas sensing: a comprehensive review

Sajid Farooq[1, *], Allan Bereczki[1], Muhammad Habib[2], Isolda Costa[1], Olavo Cardozo[3]

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Abstract

Plasmonic nanostructures have emerged as indispensable components in the construction of high-performance gas sensors, playing a pivotal role across diverse applications, including industrial safety, medical diagnostics, and environmental monitoring. This review paper critically examines seminal research that underscores the remarkable efficacy of plasmonic materials in achieving superior attributes such as heightened sensitivity, selectivity, and rapid response times in gas detection. Offering a synthesis of pivotal studies, this review aims to furnish a comprehensive discourse on the contemporary advancements within the burgeoning domain of plasmonic gas sensing. The featured investigations meticulously scrutinize various plasmonic structures and their applications in detecting gases like carbon monoxide, carbon dioxide, hydrogen and nitrogen dioxide. The discussed frameworks encompass cutting-edge approaches, spanning ideal absorbers, surface plasmon resonance sensors, and nanostructured materials, thereby elucidating the diverse strategies employed for advancing plasmonic gas sensing technologies.

Key Words: gas; localized resonance; metamolecules; near field; plasmonics; sensor

Introduction

The domain of plasmonics has emerged as a pioneering force in advancement of gas sensing technologies, revolutionizing the landscape of detection capabilities. In the dynamic landscape of plasmonics, where groundbreaking applications in imaging, sensing, energy conversion, and beyond are envisioned, this rapidly evolving field is poised to unleash the revolutionary potential of plasmonic structures and materials.[1-3] To harness the full power of high-performance plasmonics, a commitment to rigorous quantitative analysis becomes paramount. By employing precise measurements, insightful analysis, and a comprehensive understanding of plasmonic phenomena, this scientific endeavor aspires to establish the foundation for realizing the vital potential embedded within this field.

Demonstrating their prowess, plasmonic materials have depicted exceptional capabilities in detecting gases such as nitrogen dioxide (NO_2), carbon monoxide (CO), and hydrogen (H_2), thereby making substantial contributions to critical domains like industrial safety, medical diagnostics, and environmental monitoring.[4-6] The spectrum of applications spans from ultra-sensitive ideal absorbers to innovative spectrometer-free optical sensors, presenting the versatility and effectiveness of plasmonic technologies in the realm of gas sensing.

Fundamentally, plasmonics introduces the intricate interplay between electromagnetic radiation and the collective oscillations of free electrons within nanoscale conductive materials.[7,8] This dynamic interaction gives rise to plasmon resonances, unlocking a plethora of engineered applications. Within the realm of plasmon resonances, two primary categories take center stage: surface plasmon resonance (SPR) and localized SPR (LSPR).[8-10] These distinct variants exhibit unique characteristics, finding diverse utility across various applications.

Noble metals, such as gold (Au) and silver (Ag), play a pivotal role in high-performance plasmonic systems, often in conjunction with an array of nanostructures like nanoparticles (NPs), nanowires, and nanoantennas.[8,11,12] Serving as the fundamental building blocks, these elements enable the creation of cutting-edge materials and practical systems, thereby unleashing transformative potential across industries.[13-15]

Another application of plasmonic NPs is the detection of gases such as carbon dioxide (CO_2), the primary contributor to the greenhouse effect and directly linked to the warming of the Earth's surface, as demonstrated since the 19th century by Svante Arrhenius.[16] In this regard, studies utilizing plasmonic nanostructures for CO_2 detection can be highlighted, such as Elrashidi et al.[17] where Au NPs are employed for CO_2 detection through an ultra-thin optical sensor. Carbon nanotubes have also been widely used in optical CO_2 sensors. The main reason for this is that the high selectivity of carbon nanotubes to CO_2 at room temperature among other gases was ascribed to the high affinity of carbon nanotubes to CO_2 causing high electron density and hole depletion, as described by Rezk et al.[18]

Su et al.[19] described the fabrication of room temperature ammonia (NH_3) gas sensors using noble metal (Au, Ag, or

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[1]Nuclear and Energy Research Institute, São Paulo, Brazil; [2]Department of Physics, COMSAT University, Lahore, Pakistan; [3]Post graduate program on material sciences, CCEN, Federal University of Pernambuco, Recife, Brazil
***Correspondence to:** Sajid Farooq, PhD, sajid@zjnu.edu.cn.
https://orcid.org/0000-0001-9914-5987 (Sajid Farooq); 0000-0003-0813-5527 (Allan Bereczki); 0000-0001-6280-6606 (Muhammad Habib); 0000-0002-8708-8580 (Olavo Carodozo)

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platinum (Pt))/polythiophene/reduced graphene oxide (Au, Ag, or Pt/PTh/rGO) ternary nanocomposite films through a simple one-pot redox reaction. Gas sensing tests revealed that the Au/PTh/rGO film exhibited the highest response, especially at NH_3 gas concentrations below 5 ppm, along with fast response time and good reproducibility.

Zhu et al.[20] presented the progress in designing and applying highly sensitive gas sensors with low detection limits, focusing on noble metal-decorated semiconducting metal oxides. These sensors are effective for environmental monitoring, breath analysis, and food freshness applications. Various nanostructures, such as Pt, palladium (Pd), and Au, as well as bimetallic combinations with semiconducting metal oxides like zinc oxide (ZnO) and SnO_2, have been explored to enhance sensor performance, including response, recovery speed, operating temperature, and detection limits. Innovative applications such as photo-assisted room temperature sensors and flexible wearable devices are also discussed.[20]

Wang et al.[21] depicted gas (toluene) sensing characterization that revealed significant enhancement properties after noble metal decoration with Au, Pd, and AuPd NPs, respectively. The AuPd NPs functionalized Co_3O_4/ZnO@ZnO gas sensor demonstrated optimal sensing performance. The detection limit of AuPd functionalized Co_3O_4/ZnO@ZnO was as low as 100 ppb. The enhanced sensing mechanism was primarily attributed to the synergistic effect of Au and Pd.[21]

A study in 2021 fabricated pristine tungsten oxide (WO_3) and Au-WO_3 sensors for detecting 19 important gases, including trimethylamine, formaldehyde, and carbon disulfide. Results indicate that the Au-WO_3 sensor exhibits superior selectivity and higher response to trimethylamine. Moreover, the sensor demonstrated excellent response capabilities and stability. These enhanced sensing performances are primarily attributed to the electronic and chemical sensitization effects of the noble metal Au, along with the high specific surface area supported by the mesoporous structure. Thus, Au-doped mesoporous WO_3 holds promise as a high-performance trimethylamine gas sensor material.[22]

Furthermore, in a study by Zhang et al.'s team,[23] the Cu_2O-Au chemo-resistive gas sensor showed 5-fold higher outcomes than Cu_2O sensors at room temperature, with a low detection limit of 10 ppb. This superior performance was associated to the spillover effect and catalytic activity of Au NPs, along with the enhanced H_2S adsorption facilitated by Au loading.[23]

Surface enhanced Raman scattering with Au plasmonic NPs can also be employed for the detection of gases such as CO and N_2O.[24]

Furthermore, various advancements in plasmonic sensing technologies highlight innovative approaches and structures for high-performance gas detection applications. Notable examples include the development of all-metal plasmonic perfect absorbers with ultra-sharp spectral absorption and exceptional sensing performance,[25] magneto-optical SPR utilizing nanoporous Au/cobalt bilayers,[26] and the use of computational optimization for tailoring plasmonic metasurfaces in optical MOSPR sensing system. Spatial intensity-based optical sensing, such as spectrometer-free sensing platforms,[25] and the exploration of acoustic frequency combs in plasmonics are also discussed.[27] Additionally, multifunctional fiber sensors, doped silicon nanospheres for Mie resonance-based sensing,[6] and on-chip plasmonic-catalytic H sensing with metal-insulator-semiconductor nanojunctions[28] are presented as cutting-edge contributions to the field. These diverse approaches collectively support to advancing the capabilities of plasmonic gas sensing technologies.

Quantitative analysis plays an important role in propelling the field of high-performance plasmonics nanostructures forward. Our objective is to provide a thorough and accessible review of this dynamic and ever-evolving discipline and their applications in gas sensing. This study provides a review of the latest strides in high-performance plasmonics tailored for gas sensing applications, amalgamating insights gleaned from diverse research endeavors delving into various plasmonic structures. We will introduce the numerous approaches, ongoing developments, challenges, innovative directions, and potential future avenues within the realm of quantitative analysis in high-performance plasmonics.

Data Selection

This comprehensive review involved the retrieval and assessment of articles pertaining to plasmonic-based sensors for gas analysis. In 2023, we conducted two distinct searches on electronic databases, namely Google Scholar and Web of Science, utilizing keywords such as "plasmonic sensors," "gas," and "plasmonic structures" to identify relevant studies for in-depth analysis. Our focus was on articles published in 2019–2023, and we performed a preliminary screening with an emphasis on experimental studies. We specifically sought original articles in English, excluding review articles, conference proceedings, book chapters, and reports, while including method and protocol articles. The selected articles for our review addressed aspects such as signaling in plasmonic sensing-based nanostructures, sensitivity, limit of detection, and their correlation with gases, irrespective of their methodological approaches.

Plasmonics Fundamentals

Plasmonics, a scientific field exploring plasmon resonances and uncovering phenomena like LSPR and SPR, serves as the foundation for high-performance plasmonic systems. The design and construction of these systems rely on employing plasmonic materials and structures as essential building blocks.[29,30]

There are two distinct plasmonic resonance phenomena: SPR and LSPR. SPR occurs at the interface between plasmonic nanomaterials films and a dielectric medium, typically an analyte. On the other hand, LSPR is localized within individual plasmonic NPs (P-NPs). The primary source of variation lies in the range of the electric field, which decays more rapidly in LSPR, leading to diverse applications for each phenomenon.[31] SPR finds widespread use in biosensing applications, where changes in the refractive index (RI) at the metal-dielectric interface result in shifts in resonance angle or wavelength.[32] Meanwhile, LSRP is frequently applied in sensing, imaging, and enhancing local electromagnetic fields around the NPs.[8]

Surface plasmon polaritons

When investigating the energy transfer mechanism between incident electron beams and conduction electrons within thick metallic foils, the term "surface plasmon polaritons" (SPP) was coined. This study revealed an inverse relationship between energy loss and film thickness, suggesting that SPP excitation is the primary driver of the observed energy loss behavior. Noble metals, such as Au, Ag, and copper, have garnered significant attention in SPP research due to their distinctive dielectric characteristics, characterized by high negative real components and low positive imaginary components.[8] Thanks to their strong propensity for SPP coupling, primarily occurring in the visible region of the electromagnetic spectrum, these materials simplify practical applications. Hence, materials such as highly doped metal oxides, graphene, and other 2D materials depict the ability to facilitate SPP at changeable frequencies within the infrared range, exploring the diversity of SPP-based technologies.[33]

There are several ways to activate SPPs in metallic thin films (**Figure 1**), including using prisms, diffraction gratings, or intensely focused light beams. Prism-based methods such as the Kretschmann and Otto configurations make it easier to precisely control the coupling conditions necessary for successful SPP excitation.[33,34] The opposite surface of the metallic film, which is frequently exposed to air or an analyte solution, experiences SPP when the metal film is brought into contact with the prism in the Kretschmann configuration.

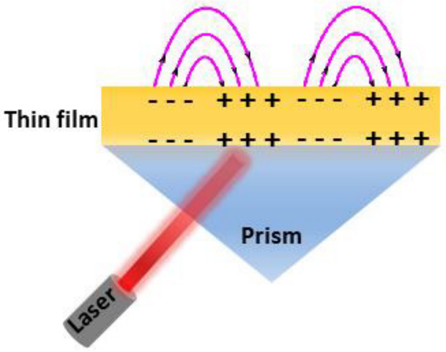

Figure 1 | The schematic diagram of fundamental phenomenon of surface plasmon resonance.
Created with Microsoft PowerPoint.

The incident light angle is then carefully adjusted to achieve this effect.

On the other hand, the Otto configuration assists SPP phenomenon in a gap between the metallic film and the prism, notably occupied by air or a dielectric's materials. However, the Kretschmann devices are often supported for its experimental simplicity as well as facile functionalization, enabling for the quantification of specific analytes through the precise monitoring of SPP coupling angles.[33,34]

These methods for exciting SPP are crucial in the realm of surface plasmon studies as they offer a nuanced understanding of the intricate interplay between light and metallic NPs. As a result, these findings hold wide-ranging significance across diverse scientific fields, encompassing applications in plasmonic sensing and advanced spectroscopy techniques. A monochromatic beam (usually a red laser, which works well with Au films) is used to excite the SPP in both prism-coupling configurations. Thus, the SPP's wave number in prism K is provided by:

$$K = \left(\frac{\omega_0}{c}\right)\eta_0 \tag{1}$$

where c indicates the speed of light in a vacuum, η_0 is the RI of prism, and ω_0 denotes the frequency of the illuminated light. The wave number of the surface polaritons in the adjacent medium k_{sp} is:

$$k_{sp} = \left(\frac{\omega_0}{c}\right)\sqrt{(\varepsilon_1 n_2^2)(\varepsilon_1 + n_2^2)} \tag{2}$$

where RI of the medium next to the metallic film (the analyte in sensor gas applications) is attributed as $n^2 = \sqrt{\varepsilon^2}$. Additionally, the dielectric function of this adjacent medium is symbolized as ε_2, while the metal's dielectric function is assigned as ε_1.

LSPR

Mie's pioneering theoretical exploration of LSPR in 1908 laid the foundation for the field of plasmonics.[35] His study delved into solving Maxwell's equations for an electromagnetic wave interacting with a sphere whose radius, denoted as "r," is less than $\lambda/2\pi$, a critical parameter relative to the wavelength of light. Through his computations, Mie derived an expression for the particle's polarizability and, consequently, its extinction cross-section (**Figure 2**). The definition of polarizability (α) is as follows:

$$\alpha = 4\pi r^3 \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} \tag{3}$$

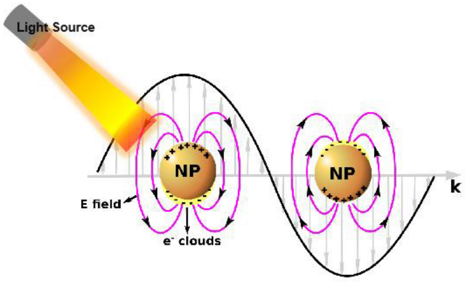

Figure 2 | The schematic diagram of fundamental phenomenon of LSPR phenomenon.
Created with Microsoft PowerPoint. e⁻: Electrons; E field: electric filed; k: wave vector; LSPR: localized surface plasmon resonance; NP: nanoparticle.

where ε_1 denotes the NP dielectric function. The resonance enhancement of α happens when the real part of ε_1 reaches a value of $-2\varepsilon_2$, a condition termed "Fröhlich" condition. This resonance phenomenon is basic to understanding LSPR. The LSPR is dependent on shape, size and material composition, as shown in **Figure 3**.

Furthermore, the feature of LSPR the extinction cross-section (σ_{ext}) of NPs, demonstrated as the sum of cross-sections of absorption (σ_{abs}) and scattering (σ_{sca}), is closely related to its polarizability. The σ_{sca} can be measured as:

$$\sigma_{sca} = \frac{k^4}{6\pi}|\alpha|^2 \quad (4)$$

where k indicates the wavenumber of the illuminated light. Additionally, the σ_{abs} is evaluated as:

$$\sigma_{|abs|=k.Im[\alpha]} \quad (5)$$

Notably, size, shape and material composition of NPs play a pivotal role in exploring its LSPR characteristics (e.g., σ_{abs} and σ_{sca}). *Im* represents imaginary value.

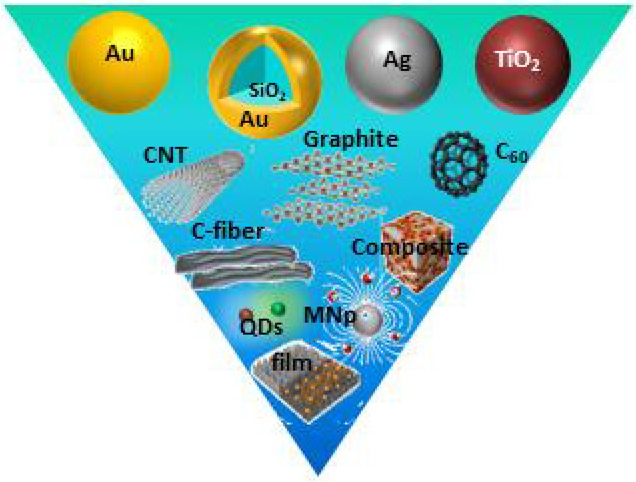

Figure 3 | The schematic diagram of diverse types, of shapes and material composition of plasmonic nanostructures.
Created with Microsoft PowerPoint. Ag: Silver; Au: gold; CNT: carbon nanotube; C_{60}: buckminsterfullerene; C-fiber: carbon fiber; MNPs: magnectic nanoparticles; QDs: quantum dots; SiO_2: silicon dioxide; TiO_2: titanium dioxide.

Features of plasmonic sensors

RI sensing

The connection between the LSPR extinction spectrum and the permittivity of the surrounding medium has been extensively explored in sensing applications. An increase in the dielectric permittivity of the surrounding medium results in a red-shift in the plasmon resonance peak. Assessing the performance of an LSPR sensor typically includes the evaluation of bulk sensitivity, defined as the change in LSPR peak wavelength per unit alteration in the RI.[7]

$$\eta_{RIS} = \left(\frac{\Delta\lambda}{\Delta n}\right) \quad (6)$$

where $\Delta\lambda$ presents the shift in the wavelength of the LSPR peak, and Δn depicts the change in the RI of the surrounding medium (**Figure 4A** and **B**).

Figure of merit

Accurate identification of precise shifts within the resonance peak can be challenging, particularly within a broad LSPR spectrum. To comprehensively evaluate the sensor's effectiveness, researchers use figure of merit as an additional parameter. Consequently, an optimal sensor must excel in both aspects, demonstrating substantial bulk sensitivity while maintaining a narrow LSPR spectrum. Therefore, figure of merit is presented as:

$$FoM = \left(\frac{\eta_{RIS}}{FWHM}\right) \quad (7)$$

where *FWHM* indicates full width half maximum of the plasmonic spectrum (**Figure 4C**).

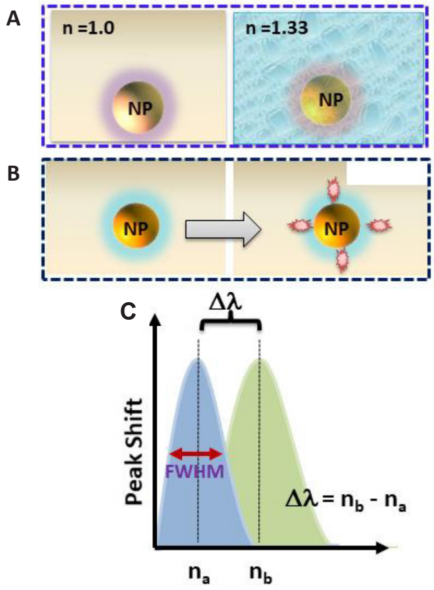

Figure 4 | Schematic diagram of plasmonic sensing mechanism.
(A) RI sensing; (B) molecular sensing; (C) figure of merit (FoM). Reprinted from Farooq and Zezell.[7] RI: Refractive index.

Molecular/gas sensing

The text discusses the advantageous features of LSPR sensors, particularly their suitability for biomedical and biological assays. A key strength lies in their label-free nature, allowing the detection of molecular attachments to NP surfaces. The sensitivity of LSPR sensors increases with the volume of the analyte. The underlying phenomenon involves the formation of self-assembled monolayers on NP surfaces. A mathematical model developed by Campbell's team[36] is highlighted, offering insights into plasmon resonance signals resulting from adsorbed molecular layers on nanostructures. This model, applicable to both SPR and LSPR techniques, focuses on the interplay between the electric field intensity and the distance from the surface. The effectiveness of Campbell's model is emphasized in explaining the shift in the LSPR peak caused by the adsorption of a molecular monolayer onto a metallic NP surface.

$$\Delta\lambda = \eta_{RIS}(n_{ad} - n_m)(1 - e^{2d/l_d}) \quad (8)$$

where l_d signifies the electromagnetic field decay length surrounding the NP. The parameter d corresponds to the thickness of the adsorbate layer, and n_{ad} and n_m denote the RI of the adsorbate layer and the surrounding medium, respectively.

Some of the published work related to the plasmonic nanostructure for gas sensing applications is epitomized in **Table 1**.[37-48]

Table 1 | Selected nanostructure for gas sensing application found in literature

Nanostructure	Synthesis methodology	Detected gas	Reference
SnO_2 monolayer	Hydrothermal	NO_2	37
Porphyrin/TiO_2 composite	Physical vapor deposition	Ammonia and Amines	38
CuO matrix dispersed (Au, Ag) nanoparticles thin film	DC magnetron sputtering	O_2	39
Silver nanoparticles decorated TiO_2 thin film	RF magnetron sputtering	CO_2	40
Au:CuO Nanocomposite	DC magnetron sputtering	Ar, N_2, O_2	41
Au-ZnO nanostructures	Photoreduction	NO, UV	42
APTES functionalized Au:CuO thin film	DC magnetron sputtering	CO	43
Gold nanoislands embedded H-glass	Thermal dewetting process	NO_2	44
Ag coated nanowire structure	AAO template assisted	Benzene	45
Au@MoS_2 core-shell nanoparticles	Solvothermal	NO_2	44
Au/gallium oxide nanostructure	Microwave assisted	CO	46
Graphene-encased gold nanorod		Cadaverine	47
Ag-plated Na-doped CuO thin films	Successive ionic layer adsorption and reaction method	CO_2	48

AAO: Anodic aluminium oxide; Ag: silver; Ar: argon; Au: gold; CO: carbon monoxide; CO_2: carbon dioxide; CuO: copper oxide; DC: direct current; MoS_2: molybdenum disulfide; N_2: nitrogen; Na: natrium; NO: nitric oxide; NO_2: nitrogen dioxide; O_2: oxygen; RF: radio-frequency; SiO_2: silicon dioxide; TiO_2: titanium dioxide; UV: ultra-violet.

Quantitative analysis techniques

Techniques for quantitative analysis are essential to the development of high-performance plasmonics nanostructures in gas sensing applications. Notably, spectroscopic techniques have been used by researchers to accurately describe plasmonic materials and their interactions with various gases. The identification of particular molecules or analytes is made possible by methods like Raman, ultraviolet-visible, and Fourier-transform infrared spectroscopy, which provide invaluable insights into variations in plasmon resonance. For instance, atomistic insights into the behavior of metal oxide semiconductor heterojunction materials have been obtained by using Fourier-transform infrared spectroscopy to investigate the structural defects and charge transport characteristics of these materials.[49] Moreover, discrete dipole approximation, finite element method, and finite-difference time-domain numerical simulations provide computational capabilities for modeling and forecasting complex plasmonic phenomena within intricate systems.[50] Such quantitative techniques not only improve our understanding of plasmonic materials but also facilitate in the optimization of sensor performance.

Specifically, the high-resolution imaging techniques such as transmission electron microscopy and scanning electron microscopy, in addition to spectroscopic methods and computational simulations, offer important visual insights into the dynamic realm of plasmonic structures and processes. Transmission electron microscopy and scanning electron microscopy are employed to investigate the structure morphology and composition of plasmonic nanostructures, providing a comprehensive view of their properties.[51] By combining these quantitative methods, it is possible to gain a thorough understanding of the optical and structural characteristics of plasmonic nanoscale structures, which facilitates in the creation of highly selective and sensitive gas sensors.

Table 2 summarizes the sensing mechanism and properties regarding gas sensing found in literature.[29,49,50,52-54] These studies exhibit the remarkable versatility of plasmonic nanostructures across diverse applications, particularly in the field of gas sensing technologies. The findings of these investigations underscore the innovative approaches aimed at improving sensitivity, selectivity, and real-world applicability. For instance, the exploration of Au nanoisland-anchored ZnO heterojunction nanofibers for NO_2 sensing stands out, demonstrating an impressive sensor response of 196% even at a reduced operating temperature of 200°C.[49] The inclusion of operando studies further enriches our understanding, offering atomistic insights into the intricate charge transfer phenomena. These studies unravel the nuanced roles played by structural defects and the plasmonic effect induced by metallic Au, providing a comprehensive perspective on the underlying mechanisms at play in these plasmonic gas sensing systems. Similarly, a plasmonic sensor, gaining the highest detectivity (1.2×10^{18} Jones) among gallium nitride-based techniques at 355 nm, leads as an outstanding ultraviolet photodetector by employing a heterogeneous array of aluminium nanocaps on gallium nitride truncated nanocones.[51] Additionally, it shows outstanding multifunctionality as a highly sensitive gas sensor for NO_2, presenting an impressive 28% response and a low detection limit of 500 ppb in ultraviolet photodetection and air-quality-index gas sensing.[51]

In the realm of CO detection, a noteworthy plasmonic CO sensor designed for room-temperature operation has been introduced. This sensor features a hole array within Ag film, ingeniously filled with Pd chloride.[29] Employing finite-difference time-domain methods, the calculated absorption spectra revealed a substantial 40% difference, underscoring the efficiency of the sensor in CO detection. Another groundbreaking plasmonic sensor, designed for high sensitivity to CO_2 concentration (303 pm/ppm), distinguished itself with its simplicity and ease of fabrication. This sensor operates on the principle of multi Fano resonance within an inverse T-shaped structure, highlighting its potential for practical and efficient gas detection applications.[29] Addressing the critical need for high-performance NO_2 gas sensors, Noh et al.[55] explore the utilization of titanium dioxide (TiO_2) nanorods and Pt NPs under ultraviolet light emitting diode for room

Table 2 | **A summary of sensing mechanism and properties regarding gas sensing**

Nanostructure	Detected gas	Sensing mechanism and properties	Reference
Aligned zinc oxide-Au nanoisland heterojunction nanofibers	NO_2	Investigating operando photoluminescence through Plasmon-mediated sensing. Excellent sensor response (196%) at 200°C operating temperature and 500 ppb NO_2. Charge transfer in nanofibers is improved by additional active sites.	49
Palladium chloride hole array in Ag film	CO	A room-temperature plasmonic CO detector. Strong interaction is provided for CO sensing by surface plasmon polaritons. Efficiency is affected by hole array dimensions	52
Inverse T-shape structure	CO_2	Multi Fano resonance observed in transmission spectrum. PHMB-filled structure serves as a high sensitivity CO_2 detector (303 pm/ppm). Simple, compact, and easy fabrication.	29
Plasmonic plastic nanocomposite	H_2	Bulk-processed materials based on plasmonic plastics for optical hydrogen detection. Plasmonic H_2-sensitive colloidal nanoparticles in polymer matrix. Allows cost-effective and scalable sensor production.	50
Lasing-enhanced surface plasmon resonance	N_2	Numerous, biomolecules and chemicals, lasing-enhanced surface plasmon resonance sensors with improved sensing performance. Employing lasing effects to compensate for ohmic loss. Applications in chemical and biological sensing.	53
Liquid hydrogenation of plasmonic nanoantennas	H_2	Hydrogenation of yttrium nanoantennas in ethanol bath. Plasmonic resonance shift (> 300 nm) in the near-infrared range. Serves as a local nanooptical indicator for deprotonation	54

Ag: Silver; Au: gold; CO: carbon monoxide; CO_2: carbon dioxide; H_2: hydrogen; N_2: nitrogen; NO_2: nitrogen dioxide; PHMB: polyhexamethylene biguanide.

temperature sensor operation. The approach leverages TiO_2 photocatalytic ability, with Pt NPs forming a Schottky barrier to capture photoactivated electrons, potentially enhanced by plasmonic effects. The study indicated the beneficial impact of annealing TiO_2 nanorods on NO_2 sensing performance, explaining through improved crystallinity revealed in X-ray diffraction patterns.[55]

Advanced monolithic photoactivated gas sensor featuring a nanowatt-level, ultra-low-power blue micro light emitting diode platform with plasmonic Ag NPs uniformly coated on porous indium oxide thin films, exhibiting high external quantum efficiency and sensor response to 1 ppm NO_2 gas with low power consumption, allowing robust applications in mobile gas sensors for personal environmental monitoring, smart factories, farms, and home appliances.[56]

In another in-depth study, exploring optical techniques such as a reliable alternative to conventional chemi-resistive gas sensing approaches for NH_3 gas detection, exhibited optical waveguides and the most conceivable optical NH_3 sensing mechanism at room temperature.[57] Further, composite nano-sensor tested for selectivity with CO_2, oxygen, and liquified petroleum gas, exhibiting significant sensor responses, appropriate for building a wireless gas detector with an Arduino module.[58] Lee et al.[59] developed a highly selective e-nose system integrated with artificial intelligence with 99.32% gas classification accuracy and 13.82% concentration regression error for five different gases in real-time.

Plasmonic plastic nanocomposites emerge as a promising and cost-effective choice for H_2 sensors, boasting impressive features such as low detection limits and rapid response times within the range of two seconds.[50] In the domain of biological and chemical molecular detection, the integration of lasing-enhanced SPR spectroscopy has proven instrumental in enhancing sensing performance.[51] Introducing a novel approach, liquid hydrogenation of plasmonic nanoantennas through alcohol deprotonation provides a unique method for tuning the optical properties of yttrium. This method results in a discernible shift in plasmonic resonance, showcasing the versatility and potential of plasmonic nanostructures in modulating their properties for specific applications.[54]

Plasmonics innovations have transcended traditional gas sensing applications, with notable contributions in diverse areas. For instance, bulk-processed plasmonic plastic nanocomposites have been introduced for optical H detection, providing a novel avenue for advancements in sensing technologies.[50] Plasmonic sensors utilizing multi Fano resonance have demonstrated their capabilities in detecting CO_2 with high sensitivity,[29] while ultrasensitive CO detectors mark another achievement in the expanding reserve of plasmonic applications.[60] Moreover, the integration of artificial intelligence into the design and optimization of plasmonic structures holds the promise of revolutionary advancements in gas sensing, and electronics, pointing towards a future where intelligent design significantly impacts plasmonics technology.[61]

In the quest for highly sensitive gas sensors, the development of all-metal plasmonic perfect absorbers has emerged as a significant milestone.[62] Additionally, the magneto-optical SPR technique indicated an enhanced transverse magneto-optical Kerr effect, achieved through a sub-wavelength periodic nanoporous Au/cobalt bilayer.[26] For optical hydrogen sensing, innovative inverse design methodologies, coupled with computational optimization, were employed to craft tailored plasmonic metasurfaces, emphasizing the power of computational techniques in sensor development.[27] Furthermore, a novel spectrometer-free H sensing platform, based on the Fano-like spatial distribution of transmission, was introduced through spatial intensity-based optical sensing.[63]

Expanding the horizons of plasmonics, the exploration of acoustic frequency combs has shown promise in precision measurements, presenting an alternative to conventional optical frequency combs.[27] Plasmonic micro-fibers, which seamlessly integrate Fano resonances and LSPR, have demonstrated capabilities in surface-enhanced Raman spectroscopy, nano-distance detection, and RI sensing.[63] Investigating the sensing potential of doped silicon nanospheres, Mie resonance structures were explored, shedding light on their application in various sensing scenarios.[30] Furthermore, the concept of on-chip plasmonic-catalytic H sensing introduced a pioneering approach that operates at room temperature and zero bias, presenting the continuous evolution of plasmonic sensor technologies.[28]

Despite the considerable strides made in plasmonic nanostructures, several challenges persist, including the need for consistency in research and development, potential risks associated with plasmonic nanomaterials in biological and environmental contexts, and issues related to cost-effectiveness and scalability in manufacturing.[64] Addressing these challenges is crucial to unlock the full potential of plasmonic nanostructures and ensure their safe and effective utilization in practical applications. The translation of these advancements into sustainable long-term solutions necessitates collaborative efforts among scientists, engineers, and policymakers.

Challenges and Future Directions

The applications of P-NPs have witnessed significant advancements, yet challenges and limitations persist. Foremost among these concerns is the potential hazards posed by P-NPs in biological and environmental contexts, despite attempts to enhance safety through surface modifications.[65] Ensuring long-term biocompatibility and safety regarding gas sensing is crucial and necessitates the establishment of regulatory standards for clinical translation. Overcoming these limitations requires the development of economically viable and environmentally sustainable synthesis techniques to facilitate widespread use of gas sensors.[66] Furthermore, the field grapples with issues of consistency and repeatability in research and development, given the diverse synthesis and characterization processes of plasmonic based gas sensors. Standardized methodologies and reporting protocols are essential to ensure credibility, replicability of findings, and promote collaboration between industry stakeholders and researchers. Moreover, the integration of nanomaterials into gas sensing platforms has significantly enhanced their applicability and performance. However, challenges persist in developing simple, cost-effective, reproducible, and scalable fabrication techniques for incorporating nanostructures into sensing interfaces. The direct electrocrystallization of nanostructures on patterned substrates presents a promising solution to address these challenges. It is essential to focus efforts on upscaling laboratory nanosensor production, guided by innovative science and engineering principles. This approach is vital for advancing scientific discoveries towards commercialization and widespread adoption across industries.[66]

The field of P-NPs holds vast potential for significant advancements across various applications in the future. A noteworthy development involves the integration of artificial intelligence and machine learning techniques in designing and optimizing plasmonic structures. This artificial intelligence-driven approach accelerates the exploration of new configurations and NP geometries, promising to revolutionize energy conversion, sensing, and electronics.[67] Simultaneously, multifunctional P-NPs are gaining prominence for personalized medicine and diagnostics, facilitating targeted cancer therapy and real-time treatment monitoring.[65] Plasmonic materials are also finding application in environmental pollutant remediation, water purification, and solar energy harvesting, addressing global challenges in sustainable energy and the environment.[68] Collaboration among scientists, engineers, and policymakers is essential to translate these trends into viable solutions for a sustainable future. Plasmonics, therefore, plays a pivotal role in reshaping industries and enhancing global living standards.

Conclusion

In summary, this review paper emphasizes the immense potential of plasmonics in advancing sensing technologies. Through comprehensive exploration and synthesis of various plasmonic materials dedicated to gas sensing applications, the versatility and adaptability of plasmonic structures become evident. Creative designs and applications, such as plasmonic micro-fibers, magneto-optical SPR, spatial intensity-based optical sensors, and all-metal plasmonic perfect absorbers, showcase the breadth of possibilities. The integration of computational optimization techniques, inverse design approaches, and unconventional concepts like acoustic frequency combs enables ultra-sensitive and targeted gas detection. This collective progress heralds a promising future for the field, promising more sophisticated and application-specific gas sensing platforms that bring precision and efficiency to sensing technologies.

These advancements not only contribute to deepening our fundamental understanding but also offer practical solutions to real-world challenges in industrial safety, medical diagnostics, and environmental monitoring. As high-performance plasmonics continues to progress, the future appears promising for the development of increasingly sophisticated and application-specific gas sensing platforms. This trajectory marks the onset of a new era characterized by enhanced precision and efficiency in sensing technologies.

Despite our rigorous approach to data selection, it's important to acknowledge several limitations of our review. Firstly, our search was confined to articles published in English between 2019 and 2023, potentially excluding relevant studies in other languages or older publications. Additionally, our focus on experimental studies may have overlooked valuable insights from theoretical or computational works. These limitations should be considered when interpreting the findings and implications of our review.

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