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Emerging Role of Semiconductor Nano-Photocatalysts in Strengthening Surface Enhanced Raman Scattering Applicability for Sustainable Multifunctional Applications

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Abstract

Surface-enhanced Raman scattering (SERS) has emerged as a powerful analytical technique for the ultrasensitive detection of organic, inorganic, and biological molecules, with promising applications in environmental monitoring, biomedical diagnostics, and chemical analysis. Traditionally, noble metal nanostructures have served as key SERS substrates due to their localized surface plasmon resonance driven electromagnetic enhancement. However, evolving application requirements including operational durability, sustainability considerations, and economic factors have driven the exploration of complementary materials to expand and diversify SERS platform capabilities. In response, semiconductor-based nano-photocatalysts have attracted growing interest as complementary materials in SERS substrate design. These materials offer distinct advantages, including photocatalytic activity, efficient surface adsorption and self-cleaning as well as charge transfer capabilities—enhancing SERS sensitivity, reproducibility, and structural robustness. Furthermore, they enable real-time monitoring of photocatalytic molecular transformations and reaction intermediates, contributing valuable insights into surface chemistry and charge-transfer mechanisms. Hybrid SERS substrates, combining semiconductor photocatalysts with noble metal nanostructures, provide synergistic SERS enhancement effects through the integration of electromagnetic and chemical (or charge transfer) mechanisms, while also improving optoelectronic properties and expanding functionality in other directions. The incorporation of emerging photocatalytic materials such as UV and visible-light-active semiconducting materials, semiconducting polymeric and two-dimensional semiconducting materials with special features/characteristics like thermoelectric, magnetic and self-cleaning properties-further strengthens SERS applicability by offering greater flexibility, multifunctionality, and sustainability. This minireview highlights the emerging role of such semiconductor nano-photocatalysts in advancing SERS technology toward sustainable multifunctional applications. It discusses recent advances, current challenges, and future strategies aimed at enhancing SERS efficiency and broadening its utility in environmental, biomedical, and catalytic domains.

Keywords: Photocatalysts; SERS ultra-detection; Synergetic SERS effect; Noble metal hybrid SERS substrates; Environmental sensing and remediation; Multifunctional applications

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1. Introduction

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The year 2024 was celebrated as the 50th anniversary of the discovery of surface-enhanced Raman spectroscopy (SERS) [1-3]. SERS is a kind of surface sensitive scientific tool measuring the enhanced Raman signals from an analyte molecule adsorbed on the surface of a nanostructured material under the influence of laser irradiation constituting the Raman spectrophotometer (**Figure 1**). SERS has been found to be a popular ultra-detection method for the variety of molecular species in environmental monitoring and wastewater treatment as well as in biomedical research[4, 5]. In recent years, there has been a growing interest of the scientific community on developing and designing SERS materials/substrates with higher sensitivity, durability/stability and recyclability for long-term applications[6-10]. A great deal of research has been conducted with excellent results as reported in the literature[4-6, 9-15]. Generally, noble metals nanostructures (NMNs) are known to be the best SERS substrates because of their localized surface plasmon resonance (LSPR) properties[13, 16]. SERS is primarily reported as contribution from electromagnetic (EM) enhancement attributed to the LSPR properties of NMNs, which amplifies the Raman signals. This model does not rely on specific chemical bonding between the adsorbate and the NMNs. It accounts for phenomena such as enhanced signals occurring at a distance from the metal surface and the angular dependence of the enhancement relative to the direction of the incoming radiation. This mechanism can explain realistic EM enhancement factors of up to 10^4. However, noble metals also present certain practical limitations, such as poor thermal and chemical stability in harsh environments, susceptibility to surface fouling, limited recyclability, and high cost, which have been documented in previous studies.[17] These challenges restrict their long-term use in sustainable or regenerative SERS platforms. The another mechanism that contributes to the SERS signals is the chemical (CM) enhancement attributed to the charge transfer (CT) mechanism, particularly shown by semiconductor nanostructures [18, 19]. It involves various CT interactions between the semiconductor surface and adsorbed molecules particularly through vibronic coupling as proposed by Herzberg-Teller and further elaborated by Lombardi[20-24]. In 1983, Yamada et al.[25] made a significant contribution to SERS research reporting on first SERS activity by a semiconductor material with a remarkable enhancement of pyridine's Raman signal when adsorbed on a NiO substrate[25]. This work expanded the scope of SERS to include semiconductor materials, which was traditionally associated only with NMNs such as Au and Ag nanostructures. Later, SERS research on semiconductor materials flourished with a focus on a variety of metal oxides and other semiconductor photocatalysts including ZnO[6], TiO_2[26, 27], Fe_2O_3[28], CuO[29],Ta_2O_5 [12],CdS [30], ZnSe [31] etc. in addition to two dimensional (2D) emerging nanomaterials such as graphene oxide (GO) [32, 33], MoS_2 [34, 35] etc.

The development of semiconductor-based SERS substrates also encouraged the modification of semiconductor materials through surface activation/defects and doping with metals/non-metals as well as integration with NMNs which further improve the Raman signal enhancement [6, 27, 36]. However, SERS sensitivity, stability and particularly recyclability for long-term practical applications still remain challenging specially in case of NMNs based SERS substrates which have been investigated very seriously in last a few decades [10, 15]. In this context, various strategies have been implemented for achieving higher sensitivity and stability as well as

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recyclability by engineering of shape, size, dimensions (0-3D) of NMNs and semiconductors or coupling these nanomaterials together or further with other functional nanomaterials. Particularly, nano-photocatalyst semiconductors are found to be more interesting in view of their sole SERS functionality as well as their emerging role in strengthening SERS ultra-detection applicability of NMNs towards multifunctionality. Semiconductor nano-photocatalysts, with their inherent ability to interact with light, charge carriers, and molecular adsorbates as well as their self-cleaning ability (i.e. through photodegradation of adsorbed molecules on its surface), offer an innovative approach to design noble metal free nano-photocatalyst based SERS substrate with improved SERS sensitivity while addressing the long-standing issues of recyclability and stability in case of NMNs. Semiconductor nano-photocatalysts offer unique advantages for SERS applications due to their high surface area, which enhances both analyte adsorption and charge separation, as illustrated in **Figure 1(a)**. When exposed to light excitation, these materials generate electron-hole pairs that enable a dual functionality: simultaneous photodegradation of contaminants and SERS sensing through charge-transfer interactions.[37] [38, 39] This dual mechanism is further enhanced by the combination of chemical and electromagnetic effects, resulting in sensors with high sensitivity, excellent stability, and recyclability.[20, 40-42] The integration of nano-photocatalysts and metal components in hybrid nanostructures represents a significant advancement in SERS technology, as shown in **Figure 1(b)**. The nano photocatalyst-metal hybrids synergistically combine photocatalytic activity with plasmonic effects, creating platforms capable of both efficient analyte detection and environmental remediation.[43, 44] These hybrid systems offer several key advantages that strengthen SERS performance. First, they exhibit enhanced photocatalytic activity through the Schottky effect at metal-semiconductor interfaces and localized surface plasmon resonance properties. Second, their synergistic SERS and photocatalysis capabilities enable real-time monitoring of chemical reactions and in-situ molecular interaction studies. Additionally, their light-induced self-cleaning ability provides recyclable substrates through photodegradation of adsorbed molecules, while semiconductor coatings improve noble metal nanostructure stability, as shown in **Figure 1(b)**. In addition to these characteristics, diverse semiconductor nano-photocatalysts (i.e. polymeric, 2D, magnetic etc.) with special features like magnetic, thermoelectric, and mechanical properties provide more flexible and sustainable SERS substrates with multifunctional applications are reported in this minireview which have rarely been reviewed previously.

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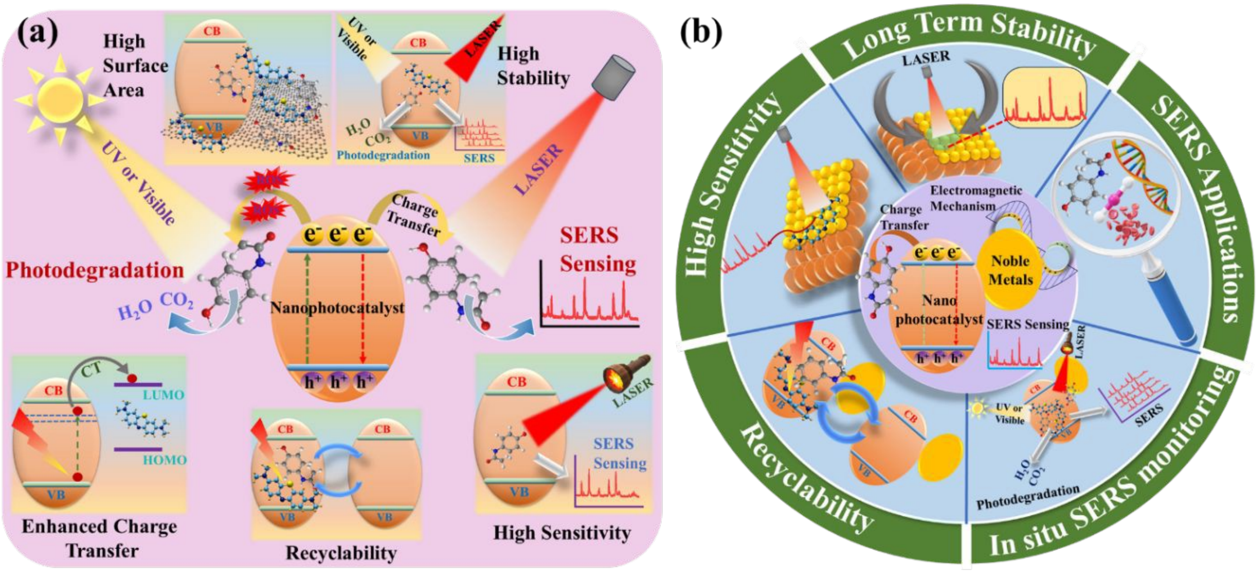

Figure 1: Schematic: (a) Role of novel semiconductor sole nano-photocatalysts in strengthening SERS detection activity (b) Improved SERS and multifunctional activities of nano-photocatalyst when combined with noble metals.

2. SERS Mechanisms and Monitoring Strategies

SERS achieves its extraordinary sensitivity through a combination of electromagnetic and chemical enhancement mechanisms. Electromagnetic enhancement is the dominant mechanism and is attributed to the excitation of LSPRs in noble metal nanostructures, such as gold or silver[3]. When these nanostructures are illuminated, collective oscillations of conduction electrons generate intense localized electromagnetic fields, particularly at "hot spots"—nanoscale junctions or gaps between particles. When incident light (E_i) excites the LSPR of NMNs, it induces strong local fields ($E_{i,s}$), enhancing the total field to ($E_i + E_{i,s}$). This intensified field excites nearby adsorbed molecules, boosting the Raman signal to $(E_i + E_{i,s})^2$. Similarly, the emitted Raman field (E_R) is enhanced to $(E_R + E_{R,s})^2$. Thus, the overall Raman intensity increases by a factor of E^4, as illustrated in **Figure 2(a)**[3, 45, 46]. When the energy difference between incident and scattered light is small, EM enhancement is often described using a near-field model that assumes a uniform field across the molecule[3]. However, for nanoparticles with atomic-scale growth, field gradient effects become significant, contributing additional enhancement from the inhomogeneous field. EM enhancement on metallic substrates can range from 10^4 to 10^{10}, and because it arises from plasmon resonance, it is generally considered independent of the molecule's electronic structure[47].

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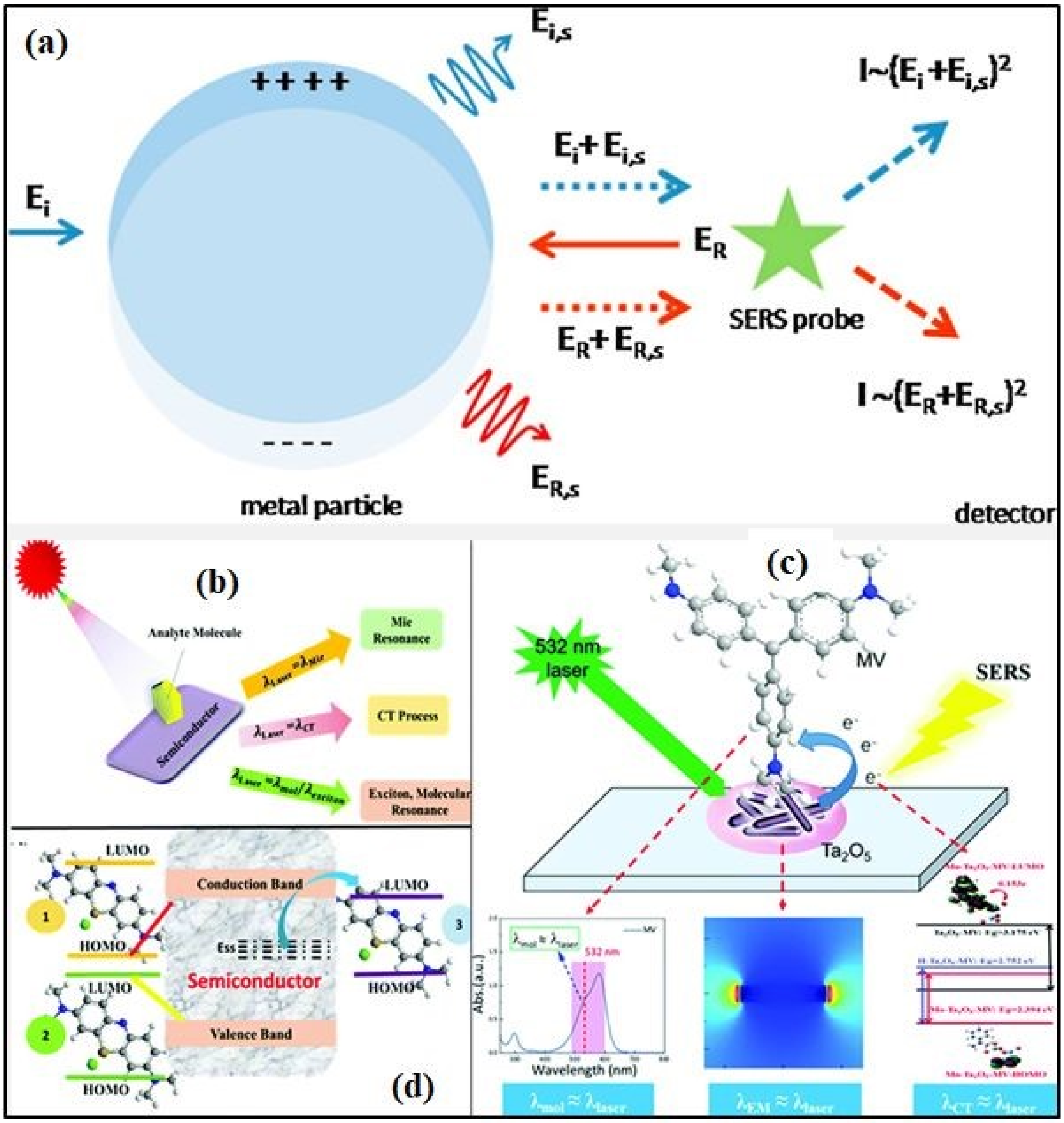

Figure 2: **(a)** Schematic diagram depicting the electromagnetic enhancement process in SERS. Reprinted from open source access ref.[46] **(b)** Schematic illustrating tunable SERS enhancement in semiconductor systems. (Reprinted with permission from ref.[18] Copyright 2022, Royal society of chemistry) **(c)** Mechanism of the "coupled resonance" strategy on Ta_2O_5-based SERS substrates. (Reprinted from open source access ref.[48]). **(d)** Possible CT pathways: (1) HOMO to CB, (2) VB to molecular LUMO, and (3) surface state to molecular LUMO. (Reprinted with permission from ref. [18] Copyright 2022, Royal society of chemistry)

Unlike the EM, the CM is directly related to the electronic structure of the molecule on the surface. The CM SERS enhancement is achieved when multiple resonance conditions overlap: (i) the laser wavelength matches the molecular electronic transition ($\lambda_{\text{laser}} = \lambda_{\text{mol}}$), (ii) Mie-type resonances occur due to nanoparticle morphology ($\lambda_{\text{laser}} = \lambda_{\text{Mie}}$), and (iii) the laser also aligns with the CT resonance energy ($\lambda_{\text{laser}} = \lambda_{\text{CT}}$) **(Figure 2(b-c))**. This phenomenon, known as coupled resonance, is supported by Herzberg–Teller vibronic coupling, where vibrational modes gain intensity through electronic transitions[49].Even when the laser is slightly off-resonance, intensity

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borrowing can occur from nearby excitonic or molecular resonances, still resulting in significant enhancement[18]. The choice of laser is a critical factor in SERS experiment design. The laser wavelength should ideally match the plasmon resonance of the SERS substrate, typically composed of gold or silver nanoparticles, to maximize electromagnetic enhancement. It is also important to select a wavelength that avoids fluorescence from the sample, which can obscure the Raman signal; near-infrared lasers, such as those operating at 785 nm, are often preferred for biological samples for this reason. For studies focused on charge transfer or resonance Raman effects, the laser should be chosen to match the electronic transition of the molecule or the charge transfer complex[18].

Mie resonance, seen in dielectric particles and noble metal nanoparticles, boosts the local electromagnetic field when particle size matches the light's wavelength, enhancing the Raman signal. For noble metal-free substrates, the enhancement scales with the square of the scattering efficiency[50].In molecular resonance, no substrate is required. When the excitation laser wavelength matches the energy gap between the molecule's HOMO and LUMO, a resonant Raman spectrum is produced, increasing the Raman intensity by 3–4 times[49]. In the CT mechanism, the analyte chemically adsorbs on the substrate, changing its polarizability and modifying its Raman spectra. SERS enhancement in semiconductors mainly comes from direct CT between the analyte and substrate, which requires matching energy levels. CT can occur via electrons moving from the analyte's HOMO to the semiconductor's conduction band, from the semiconductor's valence band to the analyte's LUMO, or through sub-band gap states. Other less common paths involve electron transfer between CT complexes and the semiconductor's conduction band[51] **(Figure 2(d))**.

The ability to monitor chemical reactions on nanoparticle surfaces or within confined environments is of growing importance, both for advancing fundamental physicochemical knowledge and for enabling practical technological applications. Monitoring reactions with SERS relies on detecting changes in the vibrational spectra of molecules adsorbed on or near the substrate surface[50]. As a reaction unfolds, SERS can reveal shifts in Raman peak positions, which indicate changes in bonding or electron density, as well as intensity variations that may result from resonance effects or altered charge transfer efficiency. The appearance or disappearance of specific peaks can also be correlated with the formation or consumption of transient intermediates or products[52]. CT processes at interfaces can also be effectively probed using SERS. These processes are often evidenced by spectral shifts reflecting changes in the electronic structure of the molecule due to electron movement between the molecule and the substrate[53].

Several analytical tools are available for studying CT with SERS. Electrochemical SERS (EC-SERS), for instance, involves applying an external potential to drive and monitor redox or CT reactions at electrode surfaces, enabling direct observation of electron transfer processes[54].Computational modeling, particularly density functional theory (DFT), is also commonly used to predict possible charge transfer pathways and to interpret observed spectral changes based on molecular orbital energies and substrate band structure[55].A range of experimental tools and tests further enhance the ability of SERS to monitor dynamic processes.

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Dynamic or time-resolved SERS enables real-time tracking of reaction kinetics and the identification of transient species, even down to the single-molecule level[56]. Multimodal SERS platforms, which combine SERS with complementary techniques such as electrochemistry or microscopy, provide a more comprehensive analysis of reaction mechanisms and charge transfer dynamics. Additionally, flow systems allow for the continuous monitoring of reactions under controlled conditions, improving reproducibility and enabling detailed kinetic studies[57].

In summary, SERS provides a versatile and sensitive platform for monitoring chemical reactions and charge transfer at surfaces. By thoughtfully selecting the substrate, laser wavelength, and experimental approach, researchers can obtain real-time, molecular-level insights into dynamic processes that are often inaccessible by other analytical methods. This makes SERS an indispensable tool for advancing our understanding of interfacial chemistry and reaction mechanisms.

3. The Role of Nano-Photocatalyst in Strengthening SERS Applicability for sustainable multifunctional applications

In recent years, semiconductor nano-photocatalysts have garnered attention as promising materials in diverse fields including environmental remediation, energy conversion, chemical sensing etc. [58, 59]. As discussed above, semiconductor materials offer notable self-cleaning ability, allowing for multiple uses which contributes to the sustainable long-term applications. The ability to engineer semiconductor band structures through doping, heterojunction formation, and surface modifications enables optimization of SERS performance of these materials tailored to specific needs. These innovations are essential for ensuring the long-term durability, structural stability, and sustainable recyclability of SERS substrates across diverse sensing and photocatalytic applications which have been discussed here.

3.1 Through Surface/Doping Engineering of Sole Semiconductor Photocatalysts for Enhanced CT SERS Activity

Doping engineering in semiconductor nano-photocatalyst optimizes their energy band gap and enhances CT between the semiconductor substrates and target molecules. Recent advancements highlight the role of surface/doping engineering in improving optical, electrical, structural, and surface properties for applications such as photocatalysis and SERS ultra-detection. By introducing foreign elements, doping transforms non-SERS active semiconductors into efficient SERS substrates by generating defects that increase charge carrier density, modify lattice constants, bond energies, and tailor energy band gaps along with surface area and defect content[6, 60]. These modifications/changes collectively enhance CT efficiency enabling superior SERS performance in particular semiconductor molecule systems[20]. For instance, recently, our group reported hydrothermal synthesis of TiO_2 nanorods (NRs) and Ta-doped TiO_2 NRs (**Figure 3(a-b))** with enhanced optical and CT properties. Optimized TiO_2 NRs (band gap: 2.95 eV) and Ta-doped TiO_2 NRs (band gap: 2.58 eV) exhibited improved SERS activity for methylene blue (MB) detection **(Figure 3(c))** attributed to synergistic effects of soaking treatment and Ta doping, which induced surface/lattice defects and additional energy levels in TiO_2[61]. The improved performance

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resulted from enhanced CT processes that were facilitated by surface defects and Ta-induced energy levels that acted as mediator states. Ta doping introduced defect states below the conduction band, which enabled efficient electron transfer and stabilized molecule interactions. This synergistic defect engineering and doping strategy significantly enhanced optical and electronic properties of TiO_2, establishing it as a cost-effective platform for sensitive molecular detection in environmental and biomedical applications.

Li et al. [62] studied that Sr doping in TiO_2 introduced surface oxygen vacancies and energy level defects which significantly enhanced SERS activity with a detection limit of 1×10^{-9} M and enhancement factor (EF) of 9.3×10^{6} for 4-mercaptobenzoic acid, comparable to NMNs based SERS substrates. The enhanced SERS activity resulted from a double-defect mechanism introduced by Sr doping, involving surface oxygen vacancies and Ti^{3+} defect energy levels. These defects worked synergistically to create a multichannel CT pathway that significantly amplified SERS performance. XPS analysis confirmed Ti^{3+} states and oxygen vacancies, while EIS measurements demonstrated improved charge transfer in Sr-doped samples, directly correlating with enhanced SERS activity. Interestingly, Jiang et al.[63] investigated SERS activity of Nd-doped MoS_2 nanoflowers (NFs) and found that 2% Nd-doped MoS_2 exhibited remarkable SERS activity with an EF of approximately 1.29×10^{6} towards MB analyte attributed to the energy level transition and CT mechanism. The effectiveness of this SERS substrate was again demonstrated through its ability to detect various compounds at extremely low concentrations, achieving limits of detection of 10^{-8} M for bilirubin and 10^{-9} M for both dipterex and bisphenol A. Their XPS and PL studies confirmed the chemical enhancement mechanism through charge transfer, with XPS detecting binding energy changes and PL verifying Nd^{3+}-associated energy level transitions. Similarly, Adesoye et al.[64] investigated SERS enhancement using 5,5-dithiobis-2-nitrobenzoic acid (DTNB) as a model compound with ZnO and Mg-doped ZnO substrates. It was found that 2% Mg-doped ZnO showed the highest SERS enhancement, producing a signal approximately three times stronger than pure DTNB, while pure ZnO showed less than twice the SERS enhancement. The improved performance was attributed to bandgap suppression and the creation of new surface-state energy levels through Mg doping, which facilitated CT between VB of ZnO and LUMO of DTNB. Furthermore, Zhao et al.[65] and Ji et al.[44] investigated the enhancement of SERS performance by Nd-doping in TiO_2 and Zn-ion doping in ZrO_2 nanoparticles (NPs), respectively, achieving excellent sensitivity.

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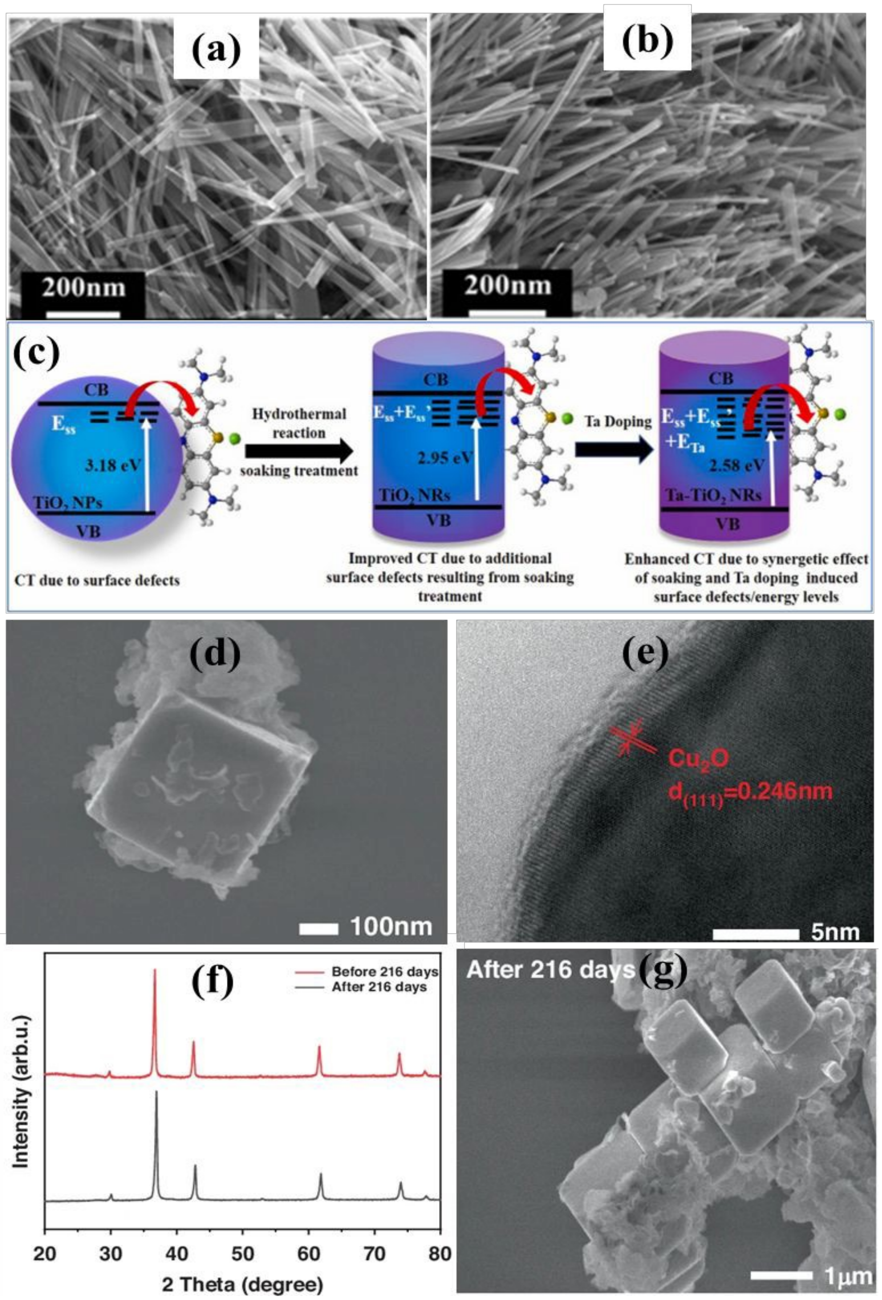

Figure 3: **(a-b)** SEM images of TiO_2 and Ta-doped-TiO_2 NRs. **(c)** Schematic of various CT processes for enhanced SERS activities attributed to the hydrothermal synthesis process of TiO_2 NRs followed by soaking treatment and Ta doping indicating generation of various defects/energy levels. (Reprinted with permission from ref.[27] Copyright 2022, Elsevier) **(d-e)** SEM and HRTEM images of Cu_2O/g-C_3N_4 MPH. **(f-g)** XRD and SEM images of Cu_2O/g-C_3N_4-0.2 MPH post photocatalysis after 216 days. (Reprinted from open source access ref.[9])

Similarly, doped semiconductor are also shown to enhance SERS detection capabilities through multiple mechanisms[66, 67] i.e. through heterojunctions and interface formation between two different semiconductors resulting in improved charge separation. In SERS, such heterojunctions/interfaces are responsible for amplifying the Raman signals for detecting low-concentration of molecules, while in photocatalysis, reduction in charge recombination is

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promoted along with light absorption, boosting efficiency in pollutant degradation and energy conversion. These properties make heterojunctions ideal for high-performance SERS sensors and photocatalysts. Recently, Yang et al.[9] fabricated a Cu_2O/g-C_3N_4 based p–n heterojunctions (MPH) device, integrating SERS detection with photocatalytic degradation as shown in scanning electron microscopy (SEM) micrographs (**Figure 3d)** demonstrating that Cu_2O microspheres successfully couple with g-C_3N_4 while retaining their original structure. The high-resolution transmission electron microscopy (HRTEM) image (**Figure 3e)** shows the lattice fringes with an interplanar spacing of 0.24 nm, corresponding to the (111) plane of Cu_2O microspheres. The Cu_2O/g-C_3N_4-0.2 MPH device (with 20% g-C_3N_4) exhibited enhanced charge separation, high SERS sensitivity with EF of 2.43×10^6, and 98.3% methyl orange (MO) degradation efficiency under visible light. The device maintained over 93% photocatalytic efficiency after 216 days, with stable structural performance, as further confirmed by XRD and SEM results as shown in **Figures 3(f–g)**. The Z-type mechanism of the device contributed to its high self-cleaning capability and efficient pollutant detection[9].

Recent studies have shown that 2D materials like MoS_2, GO, and reduced GO (rGO) can serve as effective SERS substrates and photocatalysts without the need for EM enhancement or heterojunction formation. These materials offer tunable band structures, abundant surface-active sites, and strong light–matter interactions, enabling efficient CT-induced Raman enhancement and visible-light-driven photocatalysis. Our group has demonstrated that GO[68] and doped GO[69], synthesized via a modified Hummers method, exhibits high photocatalytic activity and excellent adsorption capacity, while 1T/2H phase-engineered MoS_2 nanosheets show improved photocatalysis due to enhanced charge separation[70]. In one study, MoS_2 nanosheets with tunable defects exhibited a low detection limit for SERS[35], while in another, 3D hollow-structured MoS_2 achieved significant enhancement for rhodamine 6G detection[71]. These findings highlight the potential of metal-free 2D materials as sustainable, multifunctional platforms for both SERS sensing and pollutant removal.

Thus, the introduction of dopants and formation of heterojunctions in sole/hybrid semiconductors can improve the CT efficiency, modify band structures, and creates beneficial defect states that contribute to SERS enhancement. These advances suggest that doped and heterojunctions/hybrid semiconductor SERS substrates could provide a cost-effective and efficient alternative to noble metal-based systems, while offering additional advantages such as tunable optical and electronic properties for potential applications.

3.2 Through Interface Coupling of Semiconductor Nano-Photocatalysts with NMNs

The development of SERS substrates through the interface coupling of nano-photocatalysts with NMNs represents a significant breakthrough, improving the sensitivity, stability, and multifunctionality such hybrid SERSB substrates. At the heart of this innovation lies in the unique optical property of NMNs, specifically LSPR [51, 72] responsible for EM SERS enhancement. NMNs generate strong LSPR when exposed to specific wavelengths of light, which create intense localized EM fields around the NMNs resulting in the formation of "hotspots," between the NMNs

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where the EM field is dramatically amplified [73]. This amplification plays a critical role in enhancing the Raman signals of molecules adsorbed within the 'hot spot' or close to the NMNs surface, enabling the detection of low-concentration analytes [74]. Interestingly, when NMNs are coupled with semiconductor nano-photocatalysts, the resulting composite materials can simultaneously leverage both the EM and CT SERS enhancement provided by NMNs and photocatalysts respectively. This coupling not only amplifies the Raman signals from the target molecules but also facilitates the generation of energetic hot electrons through plasmon decay. These hot electrons can drive chemical reactions, boosting the efficiency of the SERS process [75]. Additionally, the surface functionalities such as surface area or surface defects of the substrate enhances the adsorption of analytes on its surface increasing their effective concentration near the hotspots due to NMNs and thereby further enhancing the SERS signals[27]. This synergy between plasmonic (i.e. NMNs) and semiconductor photocatalyst with enhanced surface area/properties also increases the selectivity of the substrate for specific analytes[76].

Moreover, the interface coupling enables CT processes between the NMNs and the nano-photocatalyst. The tunability of plasmonic resonance through structural modifications allows the substrate to be optimized for specific wavelengths of excitation light, offering enhanced flexibility for different applications [77]. The combined EM and CT SERS enhancement mechanisms significantly boost the overall efficiency of the SERS process, providing a robust platform for advanced analytical applications. Pramanick et al.[78] studied Cu and Ag NPs and their $CuAg_2$ nanocomposites at varying ratios for photocatalytic degradation of pollutants under visible light. The Ag-rich nanocomposite ($CuAg_2$) exhibited the highest photocatalytic activity, primarily due to its enhanced light-harvesting ability and synergistic CT between Cu and Ag. $CuAg_2$ effectively mineralized pharmaceutical pollutants, including sulfamethoxazole (SMX) and norfloxacin (NOR). In addition, $CuAg_2$ also served as a SERS substrate for detecting these pollutants. An Operando catalytic activity study and liquid chromatography-mass spectrometry (LC-MS) were employed to investigate the degradation pathways for SMX and NOR using SERS mechanism, further elucidating the photocatalytic process discussed in Section 2.3 [78].

Thermoelectric materials, like gallium nitride (GaN), are gaining attention for their dual role as photocatalysts and SERS enhancers. For example, Tan et al.[79] designed an electric-field-induced SERS (E-SERS) substrate by combining GaN with Ag NPs, achieving a tenfold enhancement in SERS signals over conventional noble metal substrates. The thermoelectric potential of GaN modulates CT by shifting Fermi level of Ag, increasing electron transition rates especially for low-Raman-scattering molecules. This platform also enables plasmon-driven redox reaction monitoring. Finite element analysis clarified the mechanisms: in n-type GaN, CT from GaN to Ag forms a Schottky barrier **(Figure 4(a-c)).** Heating generates a negative thermoelectric potential, raising GaN's bands and enhancing electron flow to Ag, activating O_2 and oxidizing p-aminothiophenol (PATP) to dimethylaminoborane (DMAB) Cooling reverses this with a positive potential, lowering the barrier and allowing hot electrons to flow from Ag to GaN, enabling resonant back-conversion of DMAB to PATP. [79]

Similarly, combination of 2D materials with NMNs has garnered significant attention for SERS applications, as these materials can offer unique properties such as large surface areas,

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tunable electronic structures, and strong plasmonic effects. For example, Rahim et al.[7] presents an ultrasensitive SERS platform based on an 2,3,5,6-tetrafluorotetracyanoquinodimethane (F4TCNQ)/MoS_2 heterostructure grown on anodic aluminum oxide (AAO) templates and flat Al_2O_3. The optimized heterostructure showed highest SERS enhancement due to the strong coupling between EM and CT mechanisms. This dual enhancement operates via two complementary pathways: charge transfer between probe molecules and the heterostructure amplifies Raman signals through chemical mechanisms, while intense localized electric fields within V-shaped nanocavities enhance light-matter interactions through electromagnetic effects. Comprehensive characterization employed ultraviolet photoelectron spectroscopy to probe electronic structures and confirm charge transfer processes, while COMSOL simulations mapped electric field distributions within nanocavities to identify regions of electromagnetic enhancement. These analytical approaches provided thorough mechanistic understanding of the SERS processes. The heterostructure enhanced photo-induced CT, achieving an ultralow limit of detection (LOD) of 9.0×10^{-16} M and a high EF, rivaling noble metal substrates. The SERS stability up to 3 months with rapid SERS response were observed. Additionally, the platform demonstrated effective photodegradation of MB, with hydrophilic Al_2O_3 surfaces showing faster degradation (84%) than AAO (79%). The substrate also enabled sensitive detection of Hg^{2+} ions in water with a LOD of 10^{-11} M. Overall, the combination of nanoarchitecture templates and organic/inorganic heterostructures offers high sensitivity, stability, and versatility for SERS sensing[7].

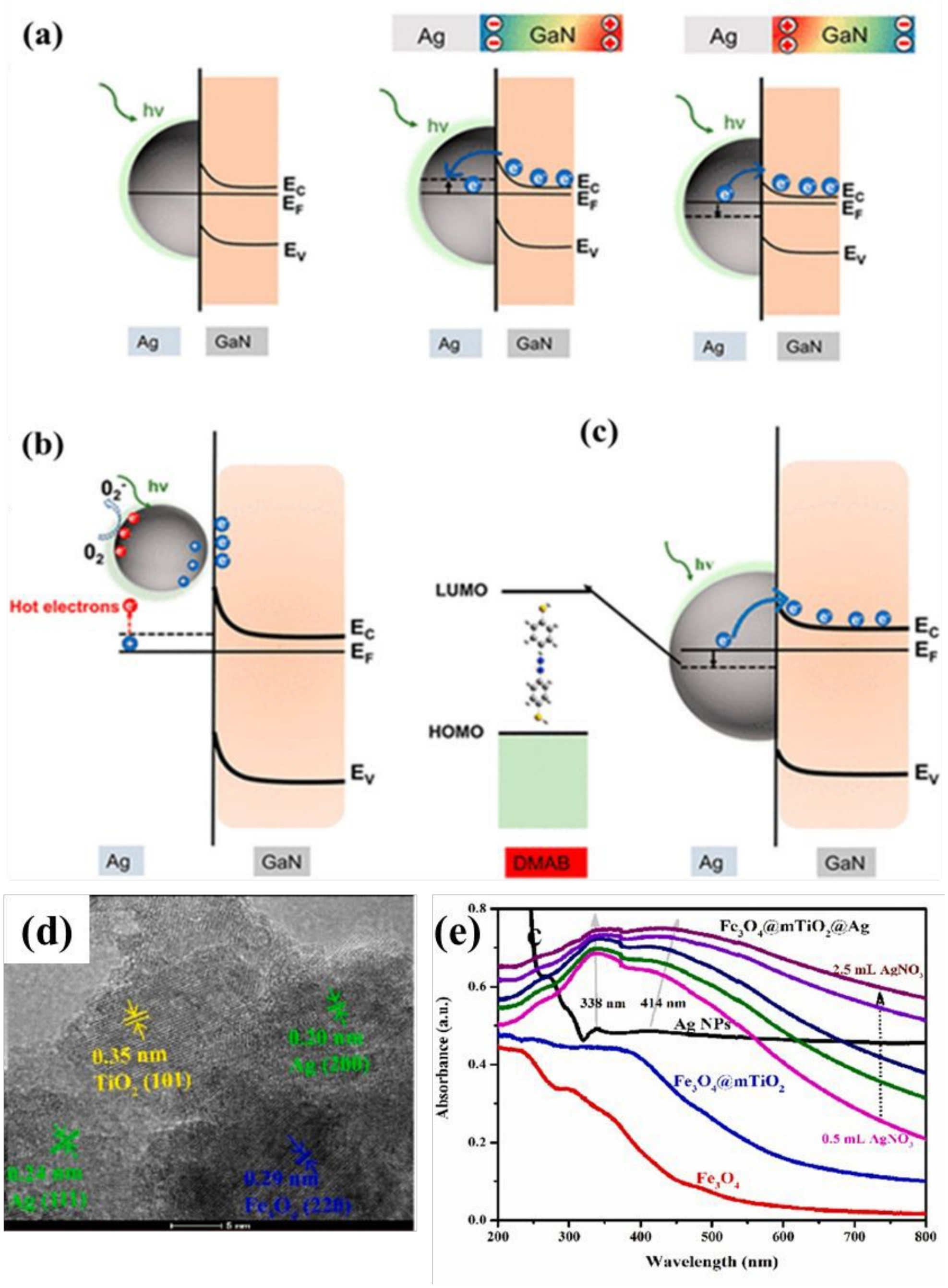

Figure 4: (a-c) The energy band diagram and the direction of CT in the Ag-GaN structure at room temperature, as well as during the heating and cooling processes. (Reprinted with permission from ref.[79] Copyright 2023, American Chemical Society) **(d)** HRTEM image and **(e)** absorption spectra of Fe_3O_4@$mTiO_2$@Ag@GO. (Reprinted with permission from ref.[80] Copyright 2025, Elsevier)

Similarly, magnetic plasmonic photocatalysts are advanced materials that combine the unique properties of magnetic, plasmonic, and photocatalytic components to create SERS platforms for various environmental applications. For example, Liao et al. [80] developed Fe_3O_4@$mTiO_2$@Ag@GO through a green, microwave-assisted hydrothermal process as shown by HRTEM image in **Figure 4(d).** UV–vis spectra as shown in **Figure 4(e)** further verified the

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successful formation of Ag NPs in the composite resulting in characteristic LSPR peaks at 338 and 414 nm and exhibited enhanced light absorption in the 350–450 nm range. This is due to the combined LSPR effect of Ag NPs and intrinsic absorption of the TiO_2 shell. The resulting material was investigated for SERS detection and photocatalytic degradation of fluoroquinolone- NOR, ciprofloxacin (CIP), and enrofloxacin (ENR) with LOD as low as 0.1 μg/mL, supported by density functional theory (DFT) calculations. The photocatalytic degradation of NOR was 4.6 and 1.4 times faster on Fe_3O_4@mTiO_2@Ag@GO than on Fe_3O_4@mTiO_2 and Fe_3O_4@mTiO_2@Ag, respectively. The composite material was also recyclable for at least five cycles.[80]

Overall, interface coupling of photocatalysts with NMNs creates a powerful platform for SERS applications, merging the analytical capabilities of SERS with the reactive versatility of photocatalysis. This innovative approach not only addresses the limitations of traditional SERS substrates but also opens up new avenues for the detection and degradation of hazardous chemicals, making these hybrid systems highly suitable for long-term use in diverse fields.

3.3 Through In-Situ SERS Monitoring of Photocatalysis Reactions Mechanisms

In-situ SERS monitoring of photocatalysis reactions has emerged as a pivotal technique for understanding reaction mechanisms at the molecular level. This approach supports the unique properties of SERS substrates, particularly those that are also effective photocatalysts, to provide real-time insights how materials behave under working conditions in photocatalytic processes[81]. As discussed earlier, these materials primarily fall into two categories: hybrid nanostructures composed of semiconductors, either with or without NMNs.

Various SERS substrates, including NMNs and metal-organic frameworks, have been utilized to monitor photocatalytic reactions, allowing for the observation of charge carrier dynamics and reaction pathways. In-situ SERS enables the tracking of dynamic changes during photocatalytic reactions, providing direct evidence of intermediate states and electron transfer mechanisms as shown in **Figure 5(a)** [82] . For example, Zhang et al.[82] explored in situ photocatalytic degradation of 4-chlorophenol (4-CP) using TiO_2@Ag/cellulose microfiber as both a photocatalyst and a SERS substrate as depicted in **Figure 5(b)**.The study provided insights into the degradation pathway through time-resolved SERS analysis. Time-resolved SERS spectra during the photodegradation process are shown in **Figure 5(c)**, with several snapshot spectra at different stages highlighted in **Figure 5(d)**. In the first minute of the photocatalytic reaction, the SERS peak at 1048 cm⁻¹ (C–Cl stretching) disappeared, while peaks for O–H and C–O stretching shifted, indicating the formation of hydroquinone (HQ) via dichlorination and hydroxylation. Over time, HQ was further oxidized to 1, 4-benzoquinone (BQ), evidenced by the appearance of SERS peaks for C–O stretching (1605 cm^{-1}) and C–H in-plane bending (1163 cm^{-1}). After 4 minutes, the SERS intensities of multiple peaks related to aromatic compounds were enhanced, suggesting the formation of quinhydrone. By 8 minutes, a sharp decrease in SERS peak intensities indicated the cleavage of the aromatic ring. The intensity ratio between 1605 cm^{-1} and 1575 cm^{-1} was used to track the generation and conversion of quinhydrone, revealing that it was the final aromatic intermediate before ring cleavage shown in **Figure 5(e)**. This work demonstrated the power of

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time-resolved SERS as a sensitive and molecular fingerprinting tool for monitoring photocatalytic molecular transformations and intermediate species in real time.

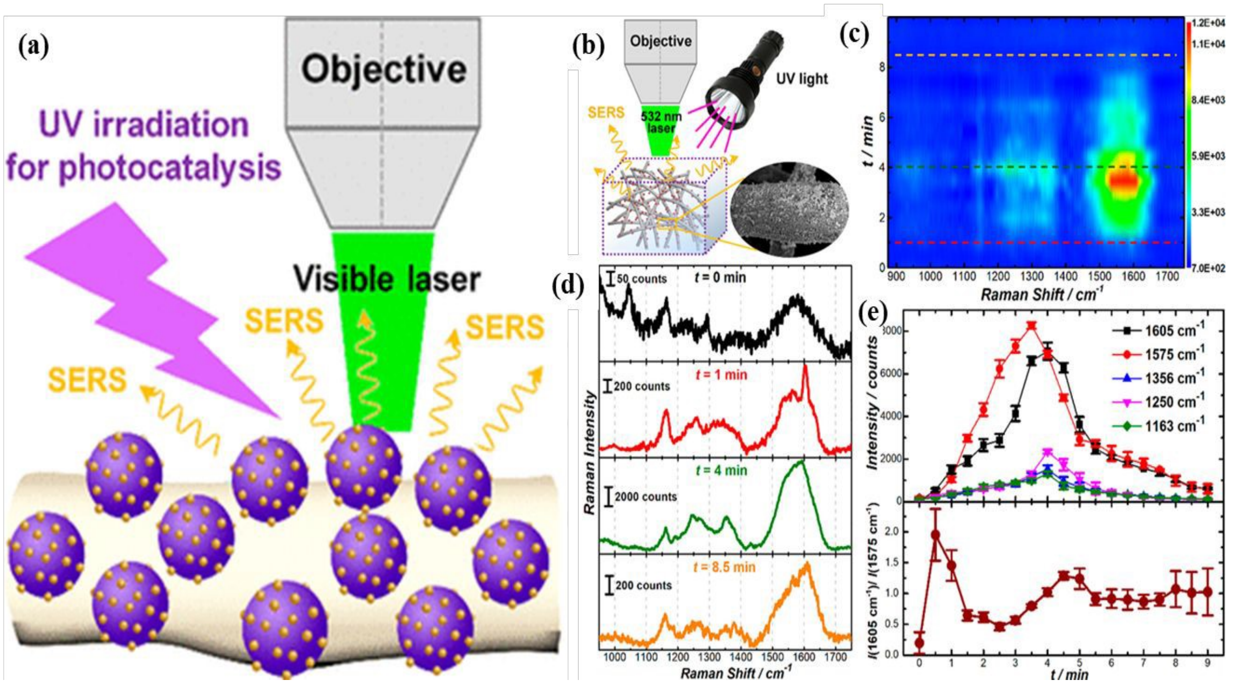

Figure 5: (a) Schematic showing in-situ SERS detection and on-site photocatalytic degradation. **(b)** A schematic diagram illustrating the in-situ reaction monitoring using SERS. **(c)** The temporal progression of SERS spectra during the photocatalytic degradation of 4-CP on TiO_2@Ag/CMFs. **(d)** Snapshot SERS spectra captured at reaction times of 0, 1, 4, and 8.5 minutes. **(e)** Temporal changes in the (upper panel) SERS peak intensities of Raman modes at 1605, 1575, 1356, 1250, and 1163 cm^{-1}, and (bottom panel) the intensity ratio between the 1605 cm^{-1} and 1575 cm^{-1} modes throughout the photocatalytic reaction. (Reprinted with permission from ref. [82] Copyright 2018, American Chemical Society)

As discussed in Section 2.2, $CuAg_2$ exhibited dual functionality as a photocatalyst and SERS-active material. Operando SERS monitoring revealed real-time degradation of p-nitrophenol, with the $–NO_2$ peak at 1290 cm^{-1} decreasing over time, indicating its conversion to aminophenol. SMX showed complete loss of Raman signals within 45 minutes, while NOR exhibited a gradual decline of the 1380 cm^{-1} band, confirming its degradation. These results demonstrate the effectiveness of operando SERS in tracking photocatalytic reactions and intermediate species[78]. In addition, Jiang et al.[83] introduced a flexible cotton fabric (Cot) Cot/3%Ca-TiO_2 substrate exhibiting high SERS activity and stability which was used for the rapid in situ detection of quinolone antibiotics (like enrofloxacin) in aquatic products and natural water systems. The detection process involved wiping samples from surfaces (e.g., fish) and analyzing those using SERS, achieving low LODs of 10^{-9} M. The minimum detectable concentrations of the three antibiotic residues in real water samples reached as low as 1×10^{-8} M. The calculated LODs

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for the three antibiotics were 8.41×10^{-9} M, 9.89×10^{-9} M, and 9.54×10^{-9} M, respectively. Interestingly, Ag triangular nanoplates (AgTNPs) based AgTNP@TiO_2@Ag core-satellite composites represented a significant advancement in sensitive sensing and in-situ SERS monitoring of organic dye photodegradation using portable Raman spectroscopy. These composites capitalized on the unique properties of AgTNPs and TiO_2 to generate abundant hot spots, significantly enhancing SERS sensitivity. This advancement enabled the precise detection of MB dyes at extremely low concentrations, with a remarkable sensitivity reaching 10^{-10}M [84]. Similarly, Fe_3O_4@TiO_2–Au NPs have demonstrated superior photocatalytic performance due to their reduced bandgap energy and LSPR from Au NPs. Compared to Fe_3O_4@TiO_2, which showed minimal changes in MO SERS spectra, Fe_3O_4@TiO_2–Au NPs achieved a significant higher degradation rate, reducing MO concentration by 88.4% in just 32 minutes, compared to 3.7% for Fe_3O_4@TiO_2 [85]. Similarly, Ag@AgX on a polyaniline (PANI) surface enabled strong SERS detection. The Fe_3O_4@C/1D PANI/Ag@AgCl photocatalyst effectively detected rhodamine B and monitored its degradation in real time serving as both a photocatalyst and a SERS substrate[86].

Theoretical studies on SERS have been performed to understand the EM and CM mechanisms. Additionally, the finite-difference time-domain (FDTD) simulations and DFT models help in optimizing nanostructure designs and predicting their SERS performances. Similarly, 2D correlation spectroscopy (2D-COS) combined with SERS provides insights into CT mechanisms, improving understanding of hybrid materials for enhanced SERS and photocatalysis. For example, Chu et al.[87] fabricated a 3D Ag@ZnSe(x) structure by sputtering Ag and ZnSe onto a polystyrene template which introduced a CT effect within the system as was validated through 2D-COS-SERS. The photodegradation of malachite green (MG) was catalyzed by CT effect and it was successfully monitored by in-situ using SERS. Notably, the degree of catalytic degradation by Ag@ZnSe(x) was proportional to the extent of CT (ρCT). Both the SERS and catalytic mechanisms were thoroughly analyzed using the 2D-COS-SERS technique. This study highlights the synergistic effects of EM and CT mechanisms offering new insights into photocatalysis with dye molecules and real-time monitoring of catalytic processes.

Such advancements in synergetic nanomaterials combining photocatalytic and SERS activity have revolutionized in situ monitoring of photocatalytic processes and understanding of the proper mechanisms. These innovative SERS materials/substrates not only provide unparalleled sensitivity and real-time insights into reaction mechanisms but also hold immense potential for environmental monitoring and pollution control, making them invaluable tools for addressing global environmental challenges.

3.4 Through Designing Recyclable SERS Substrate and Protective Coating for Long Term Sustainable Applications

Designing recyclable SERS substrates and protective coatings for long-term applications involves innovative materials and fabrication strategies aimed at enhancing both Raman signal performance, structural stability of the materials and operational durability. Recent research has

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focused on the development of metal-semiconductor based hybrid nanostructures that not only deliver strong Raman signal enhancement but also offer recyclability and robustness under varying environmental conditions. In this context, our group recently developed ZnO/Ag nanohybrid substrates that exhibit outstanding sensitivity, stability, and recyclability, using MB as a model pollutant. These substrates achieved a high EF of 3.7×10^7 and an ultralow detection limit of 10^{-12} M, underscoring their suitability for environmental monitoring and analytical applications. The synergistic combination of Ag nanocrystals (which generate intense LSPR) and the chemically stable ZnO matrix, contribute to the long-term functional integrity of the hybrid system. Impressively, the substrates retained over 89% of their initial SERS performance after four cycles of UV-induced self-cleaning, confirming their efficient photodegradation capability and excellent reusability.

Similarly, Korcoban et al.[88] developed a recyclable SERS sensor using colloidal lithography, forming TiO_2 hollow-shell structures decorated with Ag NPs. Optimal Ag NPs deposition achieved high SERS sensitivity, supported at least three detect/clean cycles, and maintained reproducibility across 30 tests. Excessive Ag reduced photocatalytic efficiency, highlighting the importance of precise metal loading. This approach offers a tunable platform for integrating SERS and self-cleaning in environmental applications. Building on this, another study presented a simple and green method for preparing Au NRs based Au NRs@TiO_2 nanocomposites, where the TiO_2 shell was formed via in situ reduction at room temperature. These nanocomposites demonstrated superior SERS activity compared to pure Au NRs, offering enhanced sensitivity and reproducibility for pollutant detection. The Au NRs@TiO_2 substrates also exhibited notable recyclability, with the ability to self-clean via UV light, maintaining their SERS performance after multiple cycles[89]. This combination of high sensitivity, reusability, and portability underscores the potential for using these materials in real-world environmental monitoring, where complex samples and rapid detection are often required. In addition, several other studies on noble metal/metal oxide hybrids have explored similar structures and approaches, further advancing the development of recyclable and high-performance SERS substrates [11, 90-92].

To further enhance both sensitivity and recyclability in SERS applications, researchers have explored composites that integrate traditional metal oxides photocatalysts and emerging functional nanomaterials with excellent features including photocatalytic properties like 2D materials and NMNs etc. These multifunctional platforms harness the plasmonic effects of NMNs i.e. Ag or Au, the CT capabilities of 2D materials, and the photocatalytic/self-cleaning functions of metal oxides photocatalysts, making them highly adaptable for real-world sensing challenges. A notable example is the hybrid SERS substrate composed of carbon cloth (CC), MoS_2, Ag NPs, and polydimethylsiloxane (PDMS) i.e. CC/MoS_2@Ag@PDMS to create a highly stable and flexible material as produced by Song et al.[93] **(Figure 6(a))**. It maintained performance over 100 deformation cycles and showed a high EF ~10^7 with a detection limit of 10^{-12} M for 4-ATP (R^2 = 0.997). The substrate benefits from both EM and CM effects and features MoS_2-based self-cleaning, enabling easy reuse-ideal for point-of-care testing and field applications **(Figure 6(b-c))**. Similarly, Barveen et al. [94] developed a reusable, flexible SERS substrate by anchoring Au NPs onto MoS_2 grown on CC via photoreduction. It achieved a detection limit of 10^{-11} M for

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nitrofurantoin, combining EM enhancement from Au and CT from MoS_2. The substrate remained stable after 50 bends, enabled swab-based detection on irregular surfaces, and featured UVC-assisted self-cleaning for multiple reuse cycles-highlighting its potential in food safety applications. Additionally, Fang et al.[95] of a self-cleaning, recyclable SERS substrate based on $AuNPs/TiO_2/Ti_3C_2$ heterostructures for MG pollutant detection. The substrate demonstrated excellent photocatalytic activity, enabling effective self-cleaning under light irradiation. It retained its SERS performance over five reuse cycles, even in complex food matrices, displaying strong potential for sustainable and practical applications in food safety monitoring.

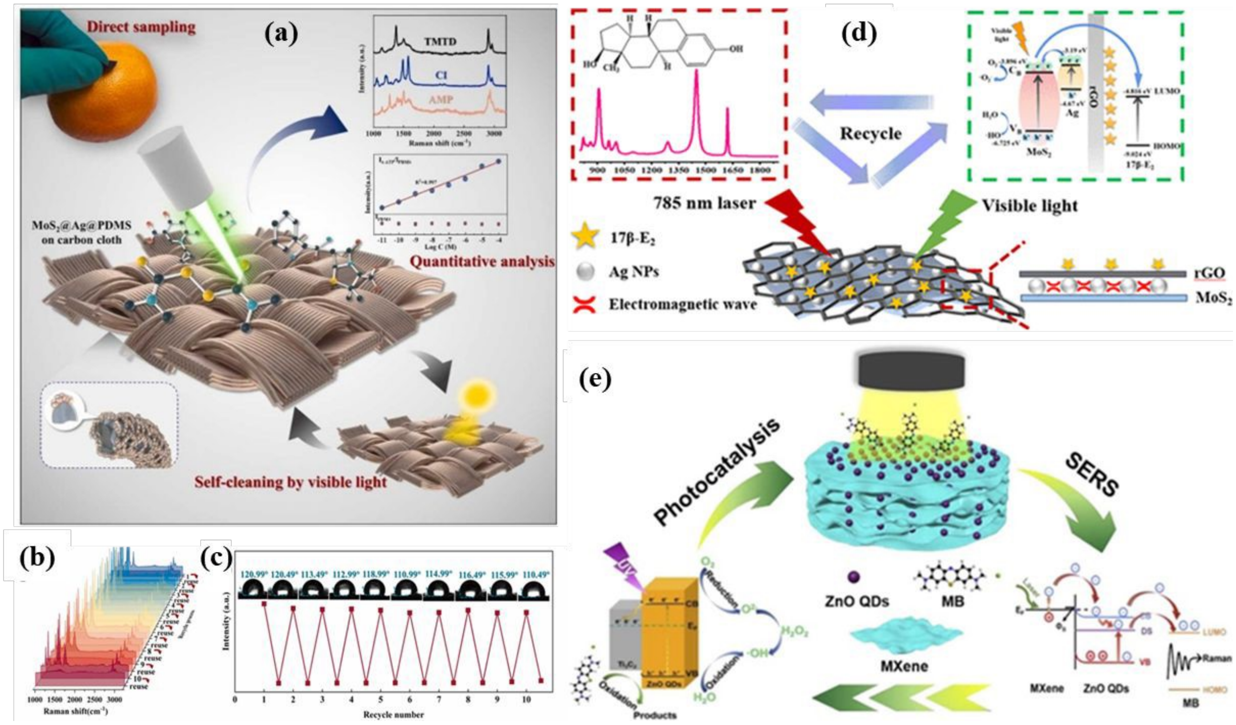

Figure 6: (a) Flexible $CC/MoS_2@Ag@PDMS$ substrate designed for self-cleaning and highly sensitive quantitative point-of-care testing of antibiotics and pesticides. **(b)** SERS spectra of 1.0×10^{-6} M 4-ATP collected during cyclic photocatalysis on $CC/MoS_2@Ag@PDMS$ substrates. **(c)** The intensity of the 4-ATP characteristic peak at 1428 cm^{-1} and the variation in the contact angle on the surface of the composite flexible substrate after multiple detection cycles. (Reprinted with permission from ref.[93] Copyright 2023, Elsevier) **(d)** SERS detection and the photocatalytic degradation of 17β-E2 by $MoS_2/Ag@rGO$. (Reprinted with permission.[96] Copyright 2024, American Chemical Society) **(e)** Schematic illustration of the recyclable SERS mechanism of Ti_3C_2/ZnO-80 film. (Reprinted with permission from ref. [97] Copyright 2025, Elsevier)

Expanding the range of analytes detected using SERS, a composite based on Ag NPs, MoS_2, and reduced rGO was developed by Liu et al.[96] for the trace detection of 17β-Estradiol (17β-E2) in environmental water. 17β-E2 is a common steroid estrogen used in animal husbandry that can contaminate water sources due to its widespread abuse. This composite material exhibited a high SERS, EF = 1.95×10^7 and a low LOD = 5×10^{-12} M, providing excellent sensitivity for 17β-E2 detection. The rGO layer not only provided a protective coating for the Ag NPs, preventing

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oxidation, but also facilitated the adsorption of the target molecule, thus enhancing the SERS signal **(Figure 6(d))**. The material demonstrated a strong linear relationship ($R^2 = 0.994$), good stability (RSD = 4.74%), and excellent anti-interference ability, with recovery rates of 100.15–108.00% for 17β-E2 in farm wastewater samples. These results suggest the composite is potential for detecting endocrine-disrupting chemicals in environmental monitoring applications.

Table 1. List of most promising semiconductor-based SERS substrates reported over the past 2–3 years.

Sr. No.	Material	Synthesis Method	SERS Mechanism	Enhancement Factor	Analyte detected	Ref.
1	WO_{3-X} / TiO_2 nanocomposite	Solvothermal + thermal reduction	CM-dominant	1.2×10^5	R6G	98
2	TiO_2 aerogels	Sol–gel + supercritical drying	CM-dominant	10^5	4-Mercaptobenzoic acid	99
3	TiO_2 multi-leg nanotubes	Electrochemical anodization	CM + weak EM	10^4	MB	100
4	MXene films	chemical etching method	CM dominant	3.27×10^{12}	R6G	101
5	Au/ZnO	Hydrothermal method + microwave radiation + Photodeposition	EM	10^6	R6G	102
6	Ag/TiO_2	Chemical vapour deposition	EM	-	RhB	88
7	Au/TiO_2	Binary surfactant-assisted seed-mediated method	EM+CM	-	R6G, malachite green (MG) and crystal violet (CV)	103
8	MoS_2	Hydrothermal method	EM+CM	10^9	Nitrofurantoin	94
9	AuNPs/TiO_2/Ti_3C_2	Oxidation of Ti_3C_2 + alkali phase transformation + AuNPs deposition (chemical reduction)	EM+CM	6.51×10^5 (MG) 2.67×10^6 (CV)	MG and CV	95
10	g-C_3N_4/Au/Ag	E-beam evaporation (Ag NRs) + organic interface self-assembly (Au NPs) + g-C_3N_4 drop coating	EM dominant	10^7	Bisphenol	104

Table 1 presents recent semiconductor-based SERS substrates with their synthesis methods, SERS mechanisms and enhancement factors, demonstrating their effectiveness in sensitive molecular detection. In addition, several other studies have reported similar hybrid systems that leverage the synergistic effects of metal oxides, 2D materials, and noble metals, further confirming the broad potential of these composites in enhancing SERS performance and ensuring reusability across various applications [8, 92, 104-108]. Recent advancements in SERS have led to the development of noble metal-free substrates for recyclable and flexible SERS sensors. Liu et al. [97] introduced a Ti_3C_2 MXene/ZnO quantum dots (Ti_3C_2/ZnO) heterostructure film, fabricated using a vacuum-assisted filtration technique, offering remarkable flexibility and high

sensitivity. The sensor exhibited excellent CT efficiency due to oxygen vacancies in the ZnO quantum dots and the Schottky barrier between Ti_3C_2 and ZnO, resulting in a low detection limit of 1×10^{-7} M for 4-mercaptopyridine (4-MPY) molecules. It demonstrated uniform and stable signals, maintaining performance for 60 days at room temperature with an RSD of 10.7%. Moreover, the substrate showed photocatalytic self-cleaning abilities, successfully degrading MB residues and achieving high reusability as shown in **Figure 6(e)**. This noble metal-free, flexible, and recyclable SERS sensor holds significant potential for in-situ molecular detection in food safety and environmental monitoring due to its high performance, sustainability, and low cost. These developments demonstrate the promising potential of recyclable and self-cleaning SERS substrates for real-world applications in food safety, environmental protection, and surface contaminant detection.

5. Outlook and Summary

Semiconductor-based nano-photocatalysts are rapidly transforming the design of SERS substrates by overcoming key limitations of traditional noble metal (i.e. NMNs) systems. Their unique properties-including CT, photocatalytic self-cleaning, and efficient surface adsorption-enhance the SERS sensitivity as well as durability and reusability of SERS materials/substrates. The hybrid architectures that integrate various semiconductors with plasmonic metals offer synergistic EM and CM enhancement mechanisms, making them particularly valuable for real-time monitoring of photocatalytic reactions, intermediate species, and surface dynamics. These platforms have shown tremendous promise in environmental sensing, biomedical diagnostics, and energy-related applications.

The future of SERS in catalysis and energy conversion holds vast potential, with several emerging directions shaping its evolution:

Operando and In Situ SERS: The shift from model systems to complex, real-world catalytic environments under true operando conditions-including gas-phase and high-temperature reactions-is a major milestone. Real-time tracking of chemical transformations will deepen our understanding of active sites, kinetics, and mechanistic pathways.

Smart and Multifunctional Hybrid Substrates: Advances in combining plasmonic nanostructures with 2D materials, magnetic/thermoelectric semiconductors, and flexible supports are enhancing both SERS response and photocatalytic efficiency. Self-cleaning, recyclable designs offer sustainability and longevity for repeated use.

Integration with Machine Learning and Spectral Analysis: The inherent complexity and high sensitivity of SERS data can lead to challenges in interpreting spectra. Emerging AI-powered tools are showing promise in spectral deconvolution, and accurate identification of molecular species, helping translate SERS into robust, automated sensing platforms.

Single-Molecule and Single-Atom Catalysis: The use of SERS for probing single-molecule reactivity and single-atom catalysts is opening new frontiers in nanoscale catalysis and energy research, allowing unprecedented insights into catalytic behavior at the atomic level.

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Transitioning from Research to Industry: To make SERS viable for industrial catalysis, systems must be operable under practical conditions, beyond ideal lab setups. Scalable fabrication methods, stability under harsh environments, and robust substrate reusability will be critical in bridging this gap.

In summary, SERS is no longer just a common analytical technique—it is evolving into a multifunctional, operando-compatible tool with broad relevance across sustainable catalysis, energy conversion, and smart sensing. Continued innovation in hybrid material design, data-driven interpretation, and scalable device fabrication will be pivotal in realizing the full industrial and environmental potential of SERS in the decades ahead.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

Conflict of Interest

There are no conflicts to declare.

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References:

1. Brolo, A. G.; Lindquist, N. C., Celebrating 50 Years of Surface Enhanced Spectroscopy. ACS Publications: 2024; Vol. 9, pp 48867-48869.
2. Fleischmann, M.; Hendra, P. J.; McQuillan, A. J., Raman spectra of pyridine adsorbed at a silver electrode. *Chemical physics letters* **1974,** *26* (2), 163-166.
3. Langer, J.; Jimenez de Aberasturi, D.; Aizpurua, J.; Alvarez-Puebla, R. A.; Auguié, B.; Baumberg, J. J.; Bazan, G. C.; Bell, S. E.; Boisen, A.; Brolo, A. G., Present and future of surface-enhanced Raman scattering. *ACS nano* **2019,** *14* (1), 28-117.
4. Sun, Z.; Ji, X.; Lu, S.; Du, J., Shining a light on environmental science: Recent advances in SERS technology for rapid detection of persistent toxic substances. *Journal of Environmental Sciences* **2024**.
5. Prakash, J., Ultrasensitive detection of emerging water contaminants using surface enhanced Raman scattering technique: Recent advancement, challenges and future prospects. *Current Opinion in Environmental Science Health* **2024**, 100552.
6. Samriti; Kumar, P.; Kuznetsov, A. Y.; Swart, H.; Prakash, J., Sensitive, stable, and recyclable ZnO/Ag nanohybrid substrates for surface-enhanced Raman scattering metrology. *ACS Materials Au* **2024,** *4* (4), 413-423.

View Article Online
DOI: 10.1039/D5NA00597C

7. Rahim, A.; Ma, L.; Saleem, M.; Lyu, B.; Shafi, M.; You, Y.; Li, M.; Zhang, X.; Liu, M., V-Shaped Heterostructure Nanocavities Array with CM and EM Coupled Enhancement for Ultra-Sensitive SERS Substrate. *Advanced Science* **2024,** *11* (48), 2409838.
8. Zheng, Y.; Yin, L.; Jayan, H.; Jiang, S.; El-Seedi, H. R.; Zou, X.; Guo, Z., In situ self-cleaning PAN/Cu2O@ Ag/Au@ Ag flexible SERS sensor coupled with chemometrics for quantitative detection of thiram residues on apples. *Food Chemistry* **2025**, 143032.
9. Yang, S.; Li, K.; Huang, P.; Liu, K.; Li, W.; Zhuo, Y.; Yang, Z.; Han, D., Dual-functional Cu2O/g-C3N4 heterojunctions: a high-performance SERS sensor and photocatalytic self-cleaning system for water pollution detection and remediation. *Microsystems & Nanoengineering* **2024,** *10* (1), 198.
10. Wang, J.; Liu, D.; Yu, N.; Cheng, P.; Cheng, L.; Liu, Y.; Zhang, Y.; Li, C.; Li, L.; Xia, C., Low-cost Ag/ZnO nanosheets arrays as sensitive and recyclable surface-enhanced Raman scattering substrates. *Optical Materials* **2024,** *157*, 116187.
11. Malik, U.; Mazur, M.; Mandaliya, D. D.; Gudi, R. D.; Periasamy, S.; Bhargava, S. K., Self-Cleaning Ag-TiO2 Heterojunction Grafted on a 3D-Printed Metal Substrate: Photocatalytic Degradation of Rhodamine B and Surface-Enhanced Raman Spectroscopic Monitoring of Kinetics. *ACS Omega* **2025**.
12. Mingjin, L.; Cheng, S.; Du, X.; Li, J.; Peng, Q.; Zhao, C.; Wang, Y.; Xiu, X., Preparation and SERS applications of Ta2O5 composite nanostructures. *Optics Express* **2023,** *31* (23), 38699-38714.
13. Tada, H.; Fujishima, M.; Naya, S.-i., Fundamentals and Applications of Gold Nanoparticle-Based Plasmonic Photocatalysts for Water Purification. *ACS EST Engineering*

2024, *4* (3), 506-524.
14. Vázquez-Iglesias, L.; Casagrande, G. M. S.; García-Lojo, D.; Leal, L. F.; Ngo, T. A.; Pérez-Juste, J.; Reis, R. M.; Kant, K.; Pastoriza-Santos, I., SERS sensing for cancer biomarker: Approaches and directions. *Bioactive materials* **2024,** *34*, 248-268.
15. Yavuz, E.; Sakir, M.; Onses, M. S.; Salem, S.; Yilmaz, E., Advancements in reusable SERS substrates for trace analysis applications. *Talanta*

2024, 126640.
16. Putri, L. A.; Prabowo, Y. D.; Dewi, D. M. M.; Mumtazah, Z.; Adila, F. P.; Fadillah, G.; Amrillah, T.; Triyana, K.; Nugroho, F. A. A.; Wasisto, H. S., Review of noble metal nanoparticle-based colorimetric sensors for food safety monitoring. *ACS Applied Nano Materials*

2024, *7* (17), 19821-19853.
17. Zhang, Q.; Li, X.; Yi, W.; Li, W.; Bai, H.; Liu, J.; Xi, G., Plasmonic MoO2 nanospheres as a highly sensitive and stable non-noble metal substrate for multicomponent surface-enhanced raman analysis. *Analytical Chemistry* **2017,** *89* (21), 11765-11771.
18. Samriti, R., Vishal; Gupta, R. K.; Prakash, J., Engineering metal oxide semiconductor nanostructures for enhanced charge transfer: fundamentals and emerging SERS applications. *Journal of Materials Chemistry C*

2022, *10* (1), 73-95.
19. Ding, S.-Y.; You, E.-M.; Tian, Z.-Q.; Moskovits, M., Electromagnetic theories of surface-enhanced Raman spectroscopy. *Chemical Society Reviews* **2017,** *46* (13), 4042-4076.
20. Rajput, V.; Gupta, R. K.; Prakash, J., Engineering metal oxide semiconductor nanostructures for enhanced charge transfer: fundamentals and emerging SERS applications. *Journal of Materials Chemistry C* **2022,** *10* (1), 73-95.
21. Lombardi, J. R., The theory of surface-enhanced Raman scattering on semiconductor nanoparticles; toward the optimization of SERS sensors. *Faraday discussions* **2017,** *205*, 105-120.

View Article Online
DOI: 10.1039/D5NA00597C

22. Lombardi, J. R.; Birke, R. L., Theory of surface-enhanced Raman scattering in semiconductors. *The Journal of Physical Chemistry C* **2014,** *118* (20), 11120-11130.

23. Yang, L.; Jiang, X.; Ruan, W.; Yang, J.; Zhao, B.; Xu, W.; Lombardi, J. R., Charge-transfer-induced surface-enhanced Raman scattering on Ag− TiO2 nanocomposites. *The Journal of Physical Chemistry C* **2009,** *113* (36), 16226-16231.

24. Lombardi, J. R.; Birke, R. L.; Lu, T.; Xu, J., Charge-transfer theory of surface enhanced Raman spectroscopy: Herzberg–Teller contributions. *The Journal of chemical physics* **1986,** *84* (8), 4174-4180.

25. Yamada, H.; Yamamoto, Y.; Tani, N., Surface-enhanced raman scattering (SERS) of adsorbed molecules on smooth surfaces of metals and a metal oxide. *Chemical Physics Letters* **1982,** *86* (4), 397-400.

26. Wang, W.; Sang, Q.; Yang, M.; Du, J.; Yang, L.; Jiang, X.; Han, X.; Zhao, B., Detection of several quinolone antibiotic residues in water based on Ag-TiO2 SERS strategy. *Science of the Total Environment* **2020,** *702*, 134956.

27. Samriti, J., Manish Chandra; Gupta, R. K.; Prakash, J., Hydrothermal synthesis and Ta doping of TiO2 nanorods: Effect of soaking time and doping on optical and charge transfer properties for enhanced SERS activity. *Materials Chemistry and Physics* **2022,** *278*, 125642.

28. Fan, Z.; Yuan, L.; Xia, T.; Zhao, C.; Guo, W.; Ibrahim, A. A.; Ansari, S. A.; Umar, A., Enhanced Alzheimer's biomarker detection using a ternary composite electrochemical aptasensor. *Microchimica Acta* **2025,** *192* (3), 167.

29. Sai, C. D.; Nguyen, Q. H.; Tran, T. N. A.; Pham, V. T.; Nguyen, T. B.; Do, H. H.; Vu, T. D., CuO nanorods decorated gold nanostructures as an ultra-sensitive and recyclable SERS substrate. *Materials Chemistry and Physics* **2023,** *293*, 126962.

30. Yang, C.; Qing, C.; Wang, Q.; Zhang, X.; Lou, J.; Liu, Y., Synthesis of the hybrid CdS/Au flower-like nanomaterials and their SERS application. *Sensors and Actuators B: Chemical* **2020,** *304*, 127218.

31. Shafi, M.; Zhou, M.; Duan, P.; Liu, W.; Zhang, W.; Zha, Z.; Gao, J.; Wali, S.; Jiang, S.; Man, B., Highly sensitive and recyclable surface-enhanced Raman scattering (SERS) substrates based on photocatalytic activity of ZnSe nanowires. *Sensors and Actuators B: Chemical* **2022,** *356*, 131360.

32. He, T.; Xiong, S.; Han, H.; Wang, D.; Wang, Y.; Dai, C.; Liu, W., Facile synthesis of Ag/GO SERS composite with highly sensitive and stable performance. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **2023,** *662*, 131008.

33. Long, Y.; Wang, W.; Xiong, W.; Li, H., Hybrid structure design, preparation of Ag-GO SERS optical fiber probe and its chemical, electromagnetic enhancement mechanism. *Journal of Alloys and Compounds* **2022,** *901*, 163660.

34. Pan, H.; Dong, Y.; Gong, L.; Zhai, J.; Song, C.; Ge, Z.; Su, Y.; Zhu, D.; Chao, J.; Su, S., Sensing gastric cancer exosomes with MoS2-based SERS aptasensor. *Biosensors and Bioelectronics* **2022,** *215*, 114553.

35. Fu, X.; Wu, H.; Liu, Z.; Wang, P.; Rong, J.; Fu, F.; Lin, Z.; Dong, Y., MoS2 nanosheets as substrates for SERS-based sensing. *ACS Applied Nano Materials* **2024,** *7* (4), 3988-3996.

36. Prakash, J.; Kumar, P.; Harris, R.; Swart, C.; Neethling, J.; van Vuuren, A. J.; Swart, H., Synthesis, characterization and multifunctional properties of plasmonic Ag–TiO2 nanocomposites. *Nanotechnology* **2016,** *27* (35), 355707.

37. Wang, Y.; Ma, S.; Yu, H.; Liu, Y.; Gao, J.; Yang, L.; Zhang, M.; He, G.; Sun, Z., Effect of TiO2 arrays on surface enhanced Raman scattering (SERS) performance for Ag/TiO2 substrates. *Nanotechnology* **2020,** *32* (7), 075708.

38. Jain, A.; Vaya, D., Photocatalytic activity of TiO2 nanomaterial. *Journal of the Chilean Chemical Society* **2017,** *62* (4), 3683-3690.

View Article Online
DOI: 10.1039/D5NA00597C

39. Pujara, A.; Sharma, R.; Sharma, S.; Bechelany, M.; Mishra, Y. K.; Prakash, J., Novel zinc oxide 3D tetrapod nano-microstructures: recent progress in synthesis, modification and tailoring of optical properties for photocatalytic applications. *Materials Advances* **2025**.
40. Tan, X.; Melkersson, J.; Wu, S.; Wang, L.; Zhang, J., Noble-Metal-Free Materials for Surface-Enhanced Raman Spectroscopy Detection. *ChemPhysChem* **2016,** *17* (17), 2630-2639.
41. Demirel, G.; Usta, H.; Yilmaz, M.; Celik, M.; Alidagi, H. A.; Buyukserin, F., Surface-enhanced Raman spectroscopy (SERS): an adventure from plasmonic metals to organic semiconductors as SERS platforms. *Journal of Materials Chemistry C* **2018,** *6* (20), 5314-5335.
42. Yang, L.; Yang, Y.; Ma, Y.; Li, S.; Wei, Y.; Huang, Z.; Long, N. V., Fabrication of semiconductor ZnO nanostructures for versatile SERS application. *Nanomaterials* **2017,** *7* (11), 398.
43. Jiang, X.; Chen, Y.; Du, J.; Li, X.; Shen, Y.; Yang, M.; Han, X.; Yang, L.; Zhao, B., Comparative study of semiconductor TiO2 and noble metal Ag substrates: The differences between chemical enhancement and electromagnetic enhancement in SERS. *Journal of Raman Spectroscopy* **2018,** *49* (8), 1257-1264.
44. Sharma, V.; Balaji, R.; Kumari, N.; Krishnan, V., SERS Application of Noble Metal–Metal Oxide Hybrid Nanoparticles. In *Noble Metal-Metal Oxide Hybrid Nanoparticles*, Elsevier: 2019; pp 457-486.
45. Prakash, J.; Sun, S.; Swart, H. C.; Gupta, R. K., Noble metals-TiO2 nanocomposites: from fundamental mechanisms to photocatalysis, surface enhanced Raman scattering and antibacterial applications. *Applied Materials Today* **2018,** *11*, 82-135.
46. Contreras-Cáceres, R.; Sierra-Martín, B.; Fernández-Barbero, A., Surface-enhanced Raman scattering sensors based on hybrid nanoparticles. In *Microsensors*, IntechOpen: 2011.
47. Wu, Y.; Weng, S.; Wang, T.; Kong, K. V.; Lin, D., Research progress on regulation strategy for surface-enhanced Raman spectroscopy. *Analytical Methods*

2025.
48. Yang, L.; Peng, Y.; Yang, Y.; Liu, J.; Huang, H.; Yu, B.; Zhao, J.; Lu, Y.; Huang, Z.; Li, Z., A novel ultra-sensitive semiconductor SERS substrate boosted by the coupled resonance effect. *Advanced Science* **2019,** *6* (12), 1900310.
49. Lombardi, J. R.; Birke, R. L., A unified approach to surface-enhanced Raman spectroscopy. *The Journal of Physical Chemistry C*

2008, *112* (14), 5605-5617.
50. Han, X. X.; Rodriguez, R. S.; Haynes, C. L.; Ozaki, Y.; Zhao, B., Surface-enhanced Raman spectroscopy. *Nature Reviews Methods Primers*

2021, *1* (1), 87.
51. Sharma, B.; Frontiera, R. R.; Henry, A.-I.; Ringe, E.; Van Duyne, R. P., SERS: Materials, applications, and the future. *Materials today* **2012,** *15* (1-2), 16-25.
52. De Albuquerque, C. D. L.; Zoltowski, C. M.; Scarpitti, B. T.; Shoup, D. N.; Schultz, Z. D., Spectrally resolved surface-enhanced Raman scattering imaging reveals plasmon-mediated chemical transformations. *ACS Nanoscience Au*

2021, *1* (1), 38-46.
53. Zhan, C.; Chen, X.-J.; Huang, Y.-F.; Wu, D.-Y.; Tian, Z.-Q., Plasmon-mediated chemical reactions on nanostructures unveiled by surface-enhanced Raman spectroscopy. *Accounts of chemical research*

2019, *52* (10), 2784-2792.
54. Murgida, D. H.; Hildebrandt, P., Disentangling interfacial redox processes of proteins by SERR spectroscopy. *Chemical Society Reviews*

View Article Online
DOI: 10.1039/D5NA00597C

2008, *37* (5), 937-945.
55. Lian, S.; Fan, Z.; Li, H.; Li, X.; Lv, X., DFT-Based Theoretical Study on Label-Free SERS Detection of Type B Fumonisins: New Insights into Molecular–Substrate Interactions and Quantification Strategies. *Langmuir*

2025, *41* (11), 7779-7789.
56. Zou, Y.; Ma, Q.; Zheng, Z.; Weng, S.; Acuna, G.; Bald, I.; Garoli, D., Advances and applications of dynamic surface-enhanced Raman spectroscopy (SERS) for single molecule studies. *Nanoscale* **2025**.
57. Tan, E. X.; Zhong, Q.-Z.; Ting Chen, J. R.; Leong, Y. X.; Leon, G. K.; Tran, C. T.; Phang, I. Y.; Ling, X. Y., Surface-Enhanced Raman Scattering-Based Multimodal Techniques: Advances and Perspectives. *ACS nano* **2024,** *18* (47), 32315-32334.
58. Li, J.; Zhang, J. Z., Optical properties and applications of hybrid semiconductor nanomaterials. *Coordination Chemistry Reviews* **2009,** *253* (23), 3015-3041.
59. Wang, X.; Zhang, E.; Shi, H.; Tao, Y.; Ren, X., Semiconductor-based surface enhanced Raman scattering (SERS): from active materials to performance improvement. *Analyst* **2022,** *147* (7), 1257-1272.
60. Wei, Y.; Wang, C.; Lei, F.; Liu, C.; Li, J.; Li, Z.; Zhang, C.; Gao, Y.; Yu, J., Precise real-time quantification for photocatalytic reaction: integration of the sensitive in-situ SERS sensor and high-efficiency photocatalyst. *Nanotechnology* **2022,** *33* (22), 225701.
61. Joshi, M. C.; Gupta, R. K.; Prakash, J., Hydrothermal synthesis and Ta doping of TiO2 nanorods: Effect of soaking time and doping on optical and charge transfer properties for enhanced SERS activity. *Materials Chemistry Physics*

2022, *278*, 125642.
62. Li, J.; Tang, Y.; Wang, X.; Kan, W.; Yang, L.; Jiang, X.; Ozaki, Y.; Han, X.; Zhao, B., Sr-Doped TiO2 with Positive Double Defects for a Highly Sensitive and Stable Surface-Enhanced Raman Substrate. *The Journal of Physical Chemistry C*

2023, *128* (1), 296-303.
63. Jiang, L.; Xiong, S.; Yang, S.; Han, D.; Liu, Y.; Yang, J.; Gao, M., Neodymium doping MoS2 nanostructures with remarkable surface-enhanced Raman scattering activity. *Ceramics International*

2023, *49* (11), 19328-19337.
64. Adesoye, S.; Al Abdullah, S.; Nowlin, K.; Dellinger, K., Mg-doped ZnO nanoparticles with tunable band gaps for surface-enhanced raman scattering (SERS)-based sensing. *Nanomaterials*

2022, *12* (20), 3564.
65. Zhao, Z.; Zhao, X.; Zhang, M.; Sun, X., Charge-transfer process in surface-enhanced Raman scattering based on energy level locations of rare-earth Nd3+-doped TiO2 nanoparticles. *Nanomaterials*

2021, *11* (8), 2063.
66. Wang, Y.; Zhang, M.; Ma, H.; Su, H.; Li, A.; Ruan, W.; Zhao, B., Surface plasmon resonance from Gallium-doped Zinc oxide nanoparticles and their electromagnetic enhancement contribution to surface-enhanced Raman scattering. *ACS Applied Materials Interfaces*

2021, *13* (29), 35038-35045.
67. Zhou, X.; Zhao, X.; Gu, S.; Xie, F.; Wang, X.; Tang, Z., Sulfur doped MoO 2 hollow nanospheres as a highly sensitive SERS substrate for multiple detections of organic pollutants. *Analytical Methods*

2021, *13* (24), 2679-2687.
68. Thakur, S.; Badoni, A.; Samriti; Sharma, P.; Ojha, A.; Swart, H. C.; Kuznetsov, A. Y.; Prakash, J., Standalone Highly Efficient Graphene Oxide as an Emerging Visible Light-Driven Photocatalyst and

View Article Online
DOI: 10.1039/D5NA00597C

Recyclable Adsorbent for the Sustainable Removal of Organic Pollutants. *Langmuir* **2024,** *40* (35), 18486-18502.
69. Samriti; Thakur, S.; Ojha, A.; Gupta, R.; Bechelany, M.; Kuznetsov, A. Y.; Swart, H. C.; Prakash, J., Graphene Oxide as Novel Visible Light Active Photocatalyst: Synthesis, Modification by Nitrogen and Boron Doping, and Photocatalytic Application. *physica status solidi (a) n/a* (n/a), 2400169.
70. Thakur, S.; Badoni, A.; Sharma, S.; Savoyant, A.; Swart, H. C.; Bechelany, M.; Kuznetsov, A.; Prakash, J., Facile Synthesis of Mixed Phase 1T/2H-MoS2 Heterostructured Nanosheets with Highly Efficient Solar Light-Driven Photocatalyst and Recyclable Adsorbent. *Chemical Communications* **2025**.
71. Gao, C.; Yang, Y.; Chen, H.; Gao, X.; Zhang, X.; Song, Z.; Zhang, T.; Chen, K.; Wang, X.; Han, Y., 3D Hollow MoS2 Architecture Enabled Highly Sensitive SERS Detection. *Advanced Materials Interfaces* **2025,** *12* (8), 2400734.
72. Demirel, G.; Usta, H.; Yilmaz, M.; Celik, M.; Alidagi, H. A.; Buyukserin, F., Surface-enhanced Raman spectroscopy (SERS): an adventure from plasmonic metals to organic semiconductors as SERS platforms. *Journal of Materials Chemistry C*

2018, *6* (20), 5314-5335.
73. Seo, S.; Chang, T.-W.; Liu, G. L., 3D plasmon coupling assisted sers on nanoparticle-nanocup array hybrids. *Scientific Reports*

2018, *8* (1), 3002.
74. Ding, S.-Y.; You, E.-M.; Tian, Z.-Q.; Moskovits, M., Electromagnetic theories of surface-enhanced Raman spectroscopy. *Chemical Society Reviews*

2017, *46* (13), 4042-4076.
75. Ma, L.; Chen, Y.-L.; Song, X.-P.; Yang, D.-J.; Li, H.-X.; Ding, S.-J.; Xiong, L.; Qin, P.-L.; Chen, X.-B., Structure-adjustable gold nanoingots with strong plasmon coupling and magnetic resonance for improved photocatalytic activity and SERS. *ACS applied materials interfaces*

2020, *12* (34), 38554-38562.
76. Pu, H.; Fang, T.; Wu, Z.; Sun, D.-W., Advancements in recyclable photocatalytic semiconductor substrates for SERS detection in food safety applications. *Trends in Food Science Technology*

2023.
77. Tan, F.; Wang, N.; Cao, S.; Liang, Q.; Yu, W.; Zhang, X. In *Visible-light photocatalysis using plasmonic coupling effect for optofluidic microreactors*, 2015 Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS (DTIP), IEEE: 2015; pp 1-4.
78. Pramanick, B.; Chawla, M.; Siril, P. F., Photocatalytic degradation of aromatic pollutants using plasmonic Cu–Ag nanocomposites. *Optical Materials* **2023,** *137*, 113553.
79. Tan, J.; Du, B.; Ji, C.; Shao, M.; Zhao, X.; Yu, J.; Xu, S.; Man, B.; Zhang, C.; Li, Z., Thermoelectric field-assisted Raman scattering and photocatalysis with GaN-plasmonic metal composites. *ACS Photonics* **2022,** *10* (7), 2216-2225.
80. Liao, W.; Zheng, L.; Hao, J.; Huang, L.; Wang, Q.; Yin, Z.; Qi, T.; Jia, L.; Liu, K., Eco-friendly fabrication of multifunctional magnetic plasmonic photocatalyst for adsorption, SERS monitoring and photodegradation of residual fluoroquinolone antibiotics in water. *Chemosphere* **2023,** *331*, 138842.
81. Singh, N.; Prakash, J.; Misra, M.; Sharma, A.; Gupta, R. K., Dual functional Ta-doped electrospun TiO2 nanofibers with enhanced photocatalysis and SERS detection for organic compounds. *ACS applied materials & interfaces* **2017,** *9* (34), 28495-28507.
82. Zhang, G.; Chen, L.; Fu, X.; Wang, H., Cellulose Microfiber-Supported TiO2@Ag Nanocomposites: A Dual-Functional Platform for Photocatalysis and in Situ Reaction Monitoring. *Industrial & Engineering Chemistry Research* **2018,** *57* (12), 4277-4286.

View Article Online
DOI: 10.1039/D5NA00597C

83. Jiang, X.; Li, K.; Tang, Y.; Wang, X.; Kan, W.; Yang, L.; Zhao, B., A double defects-dominated flexible TiO2 matrix for in-situ SERS sensing of antibiotic residues in aquatic ecosystem (fish & fishpond water) and their on-site degradation in flowing water. *Science of The Total Environment* **2024,** *921*, 171154.

84. Cheng, H.; Luo, K.; Wen, X.; Yang, J.; Li, J., AgTNP@ TiO2@ Ag core-satellite composites for sensitive sensing and in situ monitoring photodegradation of organic dyes by portable Raman spectrometer. *Spectrochimica Acta Part A: Molecular Biomolecular Spectroscopy*

2024, *306*, 123562.

85. Jin, S.; Park, E.; Guo, S.; Park, Y.; Chen, L.; Jung, Y. M., In situ SERS monitoring of photocatalysts by Au-decorated Fe 3 O 4@ TiO 2 nanocomposites: novel perspectives and insights. *CrystEngComm*

2021, *23* (47), 8443-8450.

86. Chen, Q.; Liang, W.; Shi, X.; Yang, M.; Qin, X.; Jiang, L.; Jia, C.; Chen, F.; Luo, D., Photodegradation and in-Situ SERS Monitoring Properties of Ag@ AgCl Anchored on Sea Urchin-shaped Fe3O4@ C/1D PANI Nanoparticles. *ChemistrySelect*

2022, *7* (9), e202104495.

87. Chu, Q.; Wang, W.; Guo, S.; Park, E.; Jin, S.; Park, Y.; Chen, L.; Liu, Y.; Jung, Y. M., Interface design of 3D flower-like Ag@ ZnSe composites: SERS and photocatalytic performance. *ACS Applied Materials & Interfaces* **2023,** *15* (8), 11304-11313.

88. Korcoban, D.; Kandjani, A. E.; Coyle, V. E.; Alenezy, E. K.; Bhargava, S. K.; Sabri, Y., Recyclable SERS substrate: Optimised by reducing masking effect through colloidal lithography. *Applied Surface Science* **2022,** *578*, 151852.

89. Fu, H.; Ding, N.; Ma, D.; Xu, Q.; Lin, B.; Qiu, B.; Lin, Z.; Guo, L., Green Synthesis of Three-Dimensional Au Nanorods@TiO2 Nanocomposites as Self-Cleaning SERS Substrate for Sensitive, Recyclable, and In Situ Sensing Environmental Pollutants. *Biosensors* **2023,** *13* (1), 7.

90. Chen, Z.; Sun, Y.; Zhang, X.; Shen, Y.; Khalifa, S. A. M.; Huang, X.; Shi, J.; Li, Z.; Zou, X., Green and sustainable self-cleaning flexible SERS base: Utilized for cyclic-detection of residues on apple surface. *Food Chemistry* **2024,** *441*, 138345.

91. Zheng, J.; Liu, D.; Liu, X.; Wang, Z.; Li, J.; Wang, X.; Wang, J.; Fu, Q.; Cao, Y.; Jiang, L., Ag/ZnO microcavities with high sensitivity and self-cleaning properties for fast repetitive SERS detection. *Physical Chemistry Chemical Physics* **2024,** *26* (24), 17083-17089.

92. Liao, H.; Chen, Q.; Shaoguo, Y.; Feng, Z.; Li, Z.; Lin, L.; Ren, Y.; Chen, G.; Wang, Z., Highly ordered Si-based ZnO/Ag bilayer structure for recyclable SERS substrates with ultra-sensitivity. *Ceramics International* **2024,** *50* (6), 9344-9353.

93. Song, X.; Zhang, Y.; Ren, X.; Zhang, X.; Tang, D.; Wu, J.; Li, X., Fabrication of flexible multidimensional CC/MoS2@Ag@PDMS hybrids as stable and self-cleaning SERS substrate for sensitive and quantitative point-of-care testing. *Sensors and Actuators B: Chemical* **2023,** *394*, 134439.

94. Barveen, N. R.; Chinnapaiyan, S.; Wang, T.-J.; Huang, C.-H., Photochemical decoration of gold nanoparticles on MoS2 nanoflowers grafted onto the flexible carbon cloth as a recyclable SERS sensor for the detection of antibiotic residues on curved surfaces. *Chemosphere* **2024,** *346*, 140677.

95. Fang, T.; Wei, Q.; Wu, E.; Pu, H., Elevating electron transfer of recyclable SERS sensor using AuNPs/TiO2/Ti3C2 heterostructures for detection of malachite green in sunfish. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* **2025,** *325*, 125047.

96. Liu, J.; Pan, M.; Jin, J.; Lu, Y.; Feng, Z.; Sun, T., Prepared Three-Dimensional Flowerlike MoS2/Ag@rGO Nanocomposite as a Self-Cleaning SERS Substrate for the Trace Detection of 17β-Estradiol in Environmental Water. *ACS Sustainable Chemistry & Engineering* **2024,** *12* (2), 893-903.

View Article Online
DOI: 10.1039/D5NA00597C

97. Liu, Y.; Dang, A.; Liu, X.; Wang, X.; Zada, A.; Chen, J.; Fan, X.; Zhao, T.; Li, J.; Li, T., Recyclable MXene film as SERS sensor with high sensitivity and flexibility adjusted with ZnO quantum dots. *Sensors and Actuators B: Chemical* **2025,** *422*, 136685.

98. He, X.; Gong, Y.; Niu, L.; Li, C., Development of Defect-Rich WO3-x/TiO2 Heterojunction Toward Dual-Functional Enhancement: Boosting SERS and Photocatalytic Performance. *Nanomaterials* **2025,** *15* (7), 521.

99. Liu, W.; Zhao, Z.; Yuan, M.; Wang, Z.; Shang, S.; Ye, X.; Song, Z.; Huang, L.; You, Q.; Cui, S., Theory and experiment on SERS sensitivity tuning of TiO2 aerogels based on surface oxygen vacancy engineering. *Applied Surface Science* **2024,** *655*, 159561.

100. Harini, S.; Gupta, G.; Roy, S. C.; Yalavarthi, R., TiO2 multi-leg nanotubes for surface-enhanced Raman scattering. *Journal of Physics D: Applied Physics* **2024,** *57* (32), 325106.

101. He, Z.; Rong, T.; Li, Y.; Ma, J.; Li, Q.; Wu, F.; Wang, Y.; Wang, F., Two-dimensional TiVC solid-solution MXene as surface-enhanced Raman scattering substrate. *ACS nano* **2022,** *16* (3), 4072-4083.

102. Chantaraklud, A.; Rattanabut, C.; Bamrungsap, S.; Bora, T., Light-driven in situ deposited Au nanoparticles on ZnO substrate with ultrasensitive SERS enhancement for molecular detection. *Microchimica Acta* **2025,** *192* (5), 277.

103. Fu, H.; Ding, N.; Ma, D.; Xu, Q.; Lin, B.; Qiu, B.; Lin, Z.; Guo, L., Green synthesis of three-dimensional Au nanorods@ TiO2 nanocomposites as self-cleaning SERS substrate for sensitive, recyclable, and in situ sensing environmental pollutants. *Biosensors* **2022,** *13* (1), 7.

104. Liu, X.; Yu, Y.; Xie, T.; Cao, Z.; Li, Z.; Li, Y.; Gu, Y.; Han, C.; Yang, G.; Qu, L., Fabrication of multifunctional g-C3N4-modified Au/Ag NRs arrays for ultrasensitive and recyclable SERS detection of bisphenol A residues. *Microchimica Acta* **2024,** *191* (1), 51.

105. Yang, J.; Chen, S.; Pan, M.; Ding, Y.; Wang, S., Plasmon AgNPs/MoS2/ZnO nanorods array ternary heterojunctions enabling high-efficiency solar-light energy utilization for photocatalysis and recyclable SERS detection. *Analytica Chimica Acta* **2024,** *1309*, 342668.

106. Zhang, X.; Shang, Y.; Xie, Q.; Hu, X.; Wu, K.; Qu, L.-L.; Gu, Y., Recyclable Au@ R–Fe3O4/g-C3N4 substrates for rapid SERS detection and degradation of multiple pollutants. *Talanta* **2024,** *276*, 126291.

107. Ma, X.; Wang, H.; Chen, Y.; Fu, L.; Zhou, J.; Zhang, L.; Xing, Z.; Zhang, Q.; Xia, L., Application of Ag@ g-C3N4/TiO2 cotton fabric flexible substrate with dual functionality: Photocatalytic reusability and SERS signal amplification for food safety detection. *Applied Surface Science* **2024,** *661*, 160068.

108. Chen, Y.; Liu, H.; Li, X.; Tang, S.; Gu, C.; Wei, G.; Jiang, T.; Zhou, X., Development of RGO@MoS2@Ag ternary nanocomposites with tunable geometry structure for recyclable SERS detection. *Sensors and Actuators B: Chemical* **2021,** *339*, 129856.

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DOI: 10.1039/D5NA00597C

Data availability statement

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.