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# Golden Layers: Advances and Challenges in Self-Assembled 2D Gold Monolayers

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ABSTRACT: Self-assembled two-dimensional (2D) Au monolayer films result from the self-organization of Au nanoparticles (Au-NPs) forming a single-layer film. This critical review analyzes the complexity in the field of self-assembled 2D Au monolayer films with focus on their preparation methods, tuning of the electronic and optical properties, and possible applications. First, fundamental concepts of self-assembled 2D Au monolayer films are introduced. Following that, different approaches are discussed to tune the electronic structures of self-assembled 2D Au monolayer films through chemical doping, substrate effects, and strain engineering. Each method contributes to changes in the electronic structures of these monolayers, which are crucial for various applications. Next, the optical properties of 2D Au-NP monolayer films are analyzed with focus on the resonance condition and electromagnetic enhancement associated with localized surface plasmon resonance (LSPR). Parameters affecting the LSPR phenomenon and their optical responses are investigated, which can be quantitatively described under specific circumstances. In addition, the applications of 2D Au monolayer films in surface-enhanced Raman scattering (SERS) and photoelectric devices are explored. The significance of 2D Au monolayer films in improving the sensitivity of SERS sensors and performances of photoelectric devices is emphasized. The main challenges involved in the design of self-assembled 2D Au monolayer films, such as stability, homogeneity, environment responsiveness, and large-scale fabrication, are pointed out. Finally, promising solutions to these challenges, advanced characterization techniques, and the incorporation of 2D Au monolayers into sophisticated devices are anticipated. This review concludes by proposing the future direction for self-assembled 2D Au monolayer films to ensure further robustness and functionalities and biomedical applications.

Keywords: Au 2D monolayer; SERS; Electronic and optical properties; Photoelectronic devices; LSPR.

## 1. Introduction to Self-Assembled 2D Au Monolayers

SAMs of gold nanoparticles are among the most significant innovations in the field of nanoscience, surface chemistry, and interface engineering. They are created through spontaneous organization of gold nanoparticles, resulting in formation of a highly ordered two-dimensional structure on a solid substrate. As a result, SAM formation occurs due to complex intermolecular and surface interactions, such as van der Waals interaction, electrostatic interaction, binding via ligand, and chemisorption of functional groups onto the substrate surface. This leads to creation of a stable and predictable nanoscale assembly that combines principles of self-organization with modern materials science concepts. Being characterized by high-order structural

organization and possibility of modification, SAMs create a fertile ground for numerous scientific studies and innovative developments. Possibilities to engineer surface properties with nanoscale accuracy have led to a great demand for SAMs in many different areas of science and technology. Among the advantages of SAMs, special attention should be given to possibilities they offer for modifying the chemical nature of the surface, its optical and electronic properties. In electronics and optoelectronics, device performance may depend heavily on the quality of the interfaces used. With this regard, SAMs can serve as an engineered interlayer, which provides charge injection, controls carrier transportation, minimizes defects and enhances stability. This makes SAMs increasingly important for such electronic devices as sensors, transistors, memory chips, etc., where the properties of the interface directly determine device performance [1-10].

Among all possible applications of SAMs, sensor technology attracts the strongest attention. Due to high surface area of the particles and possibilities of their functionalization, these monolayers can be modified with selective receptors such as antibodies, aptamers, or peptides. The use of such functional SAMs allows developing sensors with high sensitivity and selectivity, providing detection of protein, DNA/RNA, bacteria, and viruses, glucose, as well as toxic metals, pesticides, organics, or volatile compounds. With such variety of possibilities for development, SAM-based sensors are becoming extremely important tools for diagnostics, food safety assurance, and environmental monitoring. In addition to being excellent sensors, the above-discussed types of monolayers represent promising materials for developing advanced electronics due to their flexibility, reprogrammability, and reduced power consumption. Indeed, through selecting appropriate ligands, varying the size and shape of nanoparticles, optimizing their interactions with the substrate, and altering other process conditions, it is possible to tune the degree of electronic coupling and achieve desired charge transport performance. The importance of these parameters becomes even more apparent when considering thin-film transistors that utilize organized nanoparticle monolayers to increase electron mobility. In the case of optoelectronics, self-assembled monolayers may contribute to increasing the efficiency of charge transport at interfaces, facilitating light-matter interactions, and enhancing photoconductive properties of devices like light-emitting diodes, photodetectors, and solar cells [11-18].

The second application area to be mentioned is related to the optical properties of self-assembled gold nanoparticle monolayers. As was noted earlier, these nanomaterials support the formation of localized surface plasmon resonance (LSPR). It is defined as collective oscillations of conduction electrons caused by incident electromagnetic waves. In the case of self-assembly, LSPR is characterized by an increased modulation of optical response due to the interplay between interparticle distance, size and shape, dielectric constant, and coupling effects. This leads to tunable absorption, scattering, field enhancements, and resonance shifts that may be effectively used in developing photonic and plasmonic devices. Moreover, because of significant electromagnetic enhancement typical for the above-mentioned structures, gold nanoparticle monolayers provide ideal opportunities for surface-enhanced Raman scattering. In this way, they can be employed for ultrasensitive spectroscopy and diagnostic purposes. Finally, another promising application of self-assembled monolayers involves catalysis and nanomaterial synthesis. The ability of nanoparticles to form ordered assemblies makes possible their employment as a template or scaffold for controlled deposition of crystalline nanomaterials with unique physicochemical characteristics. Due to a carefully selected composition and interfacial chemistry, it is feasible to engineer catalysts and materials capable of interacting with light and

generating magnetic fields. They can be used in heterogeneous and plasmon-assisted catalysis, photocatalysis, drug delivery, bioimaging, and therapy applications. In all cases, the use of organized nanoparticles with gold makes a significant contribution due to reproducibility and functionality provided by self-assembled monolayers.

From the standpoint of fundamental science, self-assembled monolayers of gold nanoparticles represent model systems for studying nanoscale phenomena at surfaces and interfaces. The structures have been widely used in examining molecular adsorption, interactions between gold nanoparticles and substrates, ligand behavior, inter-particle coupling, and effects of the environment on the assembly of gold nanoparticles. Due to high regularity of the structures and possibility to tune composition, monolayers allow exploring how local organization affects collective behavior of nanoparticles. Such an insight contributes to both understanding of fundamental principles underlying surface phenomena and development of advanced materials for practical application. Beyond materials science, self-assembled monolayers provide opportunities for creating functional surfaces with controlled wetting, anti-biofouling, adhesive, and biocompatible features. Thus, they find potential applications in the development of biomedical implants, target drug delivery platforms, tissue-engineering scaffolds, self-cleaning surfaces, anti-corrosive barriers, and micro-fluidic devices. The ability to tailor monolayers by varying molecular composition, ligand density, and order allows creating surfaces combining chemical selectivity with physical strength and making them suitable for implementation in a variety of industrial and biomedical technologies. The unique features and capabilities associated with gold nanoparticle self-assembled monolayers make them crucial elements for creating advanced technologies that would help address major societal problems. In particular, current research in this area seeks improving the methods of monolayer preparation, enhancing the degree of structural order, increasing the stability of the structure, and providing prospects for mass production. Moreover, cooperation between specialists from diverse disciplines, such as chemistry, physics, materials science, biology, and engineering, contributes to rapid development of new applications for self-assembled monolayers of gold nanoparticles. As a result, SAMs are expected to become even more important in the future, playing a prominent role in the areas of nanoelectronics, biotechnology, catalysis, sustainable energy, and smart materials.

This article provides an extensive analysis of self-assembled two-dimensional gold monolayers, with specific focus placed on their synthesis, structure organization, electronic characteristics, optics, and applications. First of all, it is necessary to define basic rules that control the process of self-assembly and establish main parameters that affect the formation and stabilization of two-dimensional gold monolayers. Besides, different methods for the manipulation of electronic properties through chemical doping, interaction with substrates, ligand adjustment, and strain effects are considered. It is important to investigate optical response and phenomena that occur under localized surface plasmon resonance condition, including the influence of different factors such as particle size, distance between particles, particle shape, and surrounding dielectric medium. It is also crucial to analyze and explain physical mechanisms responsible for the observed optical effects. Moreover, it is essential to explore applications of self-assembled gold nanoparticle monolayers in areas like surface enhanced Raman scattering, sensing, catalysis, and optoelectronics. Besides, it is required to identify existing problems and barriers hindering the implementation of these structures in practice. Some of the key limitations include lack of stability in the operational mode, low

uniformity, difficulty in effective functionalization, problems with upscaling to industry scale, and inefficient characterization of nanosystems. It is also essential to define future trends in this area and identify the most relevant research priorities.

## 2. Tuning the electronic structures of 2D self-assembly Au monolayer

Manipulation of the electronic structure of self-assembled 2D Au monolayer structures is crucial to maximizing performance in various applications, such as sensing devices, transistor structures, and optoelectronics. The ability to engineer the electronic properties of these structures allows fine tuning of their properties, such as conductivity and band gap energy. Many techniques have been developed for manipulating these properties, each one bringing with it different strengths and limitations. In this chapter, three main techniques are discussed.

### 2.1. Chemical Doping

Chemical doping is another widely applied means to modify the electronic properties of Au monolayers. Specifically, the principle behind this method lies in the introduction of foreign species into the monolayer to change its electron density and electronic configuration. Halogens, including chlorine, can be utilized as dopants since they lead to the broadening of the band gap while maintaining the high level of electrical conductivity of Au monolayers. One should note the advantages associated with this modification technique that include its relative simplicity and effectiveness in controlling electronic properties while not changing much in terms of material's overall structure. Indeed, experimental studies confirmed that the doping of Au monolayers with halogens led to considerable changes in the electronic band structure and enhanced the optoelectronic characteristics of the material. Thus, the modification of Au monolayers through chemical doping can be explained based on fundamental concepts of solid-state physics and materials science. Generally speaking, the concept of doping involves adding some foreign atoms or molecules to change the number of electrons in the material. As in the case with halogen dopants, this modification technique leads to an increase in the electron density of Au monolayers. Such changes inevitably affect the material's electronic properties by altering its Fermi level and widening the band gap, thus making it possible to obtain Au monolayers with unique properties suitable for specific purposes.

With the development of modeling and simulation technologies, one can now gain a deeper understanding of the changes occurring in materials during the doping process. In particular, Density Functional Theory calculations allow predicting the changes in electronic properties after doping. Combined with empirical research, computational approaches enable the exploration of the effects associated with doping from the perspective of both theory and experiment. An interesting case in point is a study carried out by Zhang et al. (2020). In particular, the scientists discovered that doping of Au monolayers with chlorine caused a considerable broadening of the band gap when compared to undoped analogs of the material. Such results confirm the predictions developed theoretically before. Finally, the prospective applications of doped Au monolayers are not limited to optoelectronics exclusively. In photovoltaic systems, for example, one can use halogen doping of Au monolayers to improve the absorption spectrum of photovoltaic systems in order to better match the spectral characteristics of sunlight. Moreover, one can consider using the material as a gas-sensitive or bio-sensing layer due to the alteration of its electronic properties brought about by doping. Despite the necessity of using halogen dopants in Au monolayers to improve their electronic properties, their structures remain almost intact during this

procedure. Namely, the modification technique does not involve the application of heat or corrosive reagents that would harm the structural organization of monolayers. As a result, all mechanical properties of the material are preserved, thus ensuring the possibility of applying Au monolayers to make flexible electronic devices. Overall, the doping technique appears to be extremely useful for designing materials with desired electronic properties.

### 2.2. Substrate Interaction

Gold (Au) monolayer interactions with substrates offer one of the most critical tools for modifying electronic structures. Various substrates can apply strain or engage in electronic interactions with the monolayer changing its properties. Thus, for example, silicon or sapphire substrates can impact the mobility of electrons in Au monolayers. This technique utilizes the features of the substrate to improve the electronic properties of the monolayer. In this regard, the substrate has a fundamental impact on the behavior of the whole structure. In this way, when an Au monolayer is deposited on a substrate, the possible misfit between the structures results in strain applied to the Au lattice and modifies its band structure without the need for any doping. According to Li et al., (2019), the strain created in an Au monolayer by a silicon substrate led to a considerable change in the band gap of the monolayer. In addition to that, substrates may engage in electronic interactions and even charge transfers with the Au monolayer influencing its electronic properties. Conductive substrates such as graphene are likely to promote electron transfer leading to enhanced conductivity of the Au monolayer. Wang et al., (2020) observed increased charge mobility in Au monolayers with the graphene substrate.

Substrate choice can be extended beyond traditional silicon and sapphire options. Emerging materials, such as transition metal dichalcogenides (TMDs) and perovskites can demonstrate their unique interactions with Au monolayers due to specific physical and chemical characteristics. As an example, TMDs tend to produce strong van der Waals forces and introduce changes in the Au monolayer due to their intrinsic properties. Kim et al., (2021) observed that $MoS_2$ substrates caused direct to indirect band gap transformation in Au monolayers. Substrate engineering can also include the creation of heterostructures combining several layers of various materials in order to reach specific properties. Heterostructures often demonstrate synergistic effect unavailable from the separate layers. In particular, an Au monolayer on a TMD substrate with additional capping may lead to significant improvements in performance and stability. Zhang et al., (2022) reported that this heterostructure could exhibit outstanding electron mobility and stability making it a promising candidate for future electronics. Practical applications will require considerations of such aspects as thermal expansion coefficients, chemical reactivity, and mechanical stability. Matching the substrates with monolayers will eliminate potential issues associated with delamination. MBE and CVD techniques can be used to create high-quality interfaces between the Au monolayer and the substrate.

The techniques of molecular beam epitaxy (MBE) and chemical vapor deposition (CVD) proved highly effective in obtaining a good interface between Au monolayer and different types of substrates. MBE provides an opportunity to deposit a single layer of atoms in an exact position, resulting in a perfect, defect-free interface. It is critical for applications where electronic properties of Au

monolayer heavily depend on the quality of the interface. On the other hand, CVD can be used in large-scale manufacturing, enabling the synthesis of a uniform layer of atoms on a variety of substrates. The controllability of the CVD process in terms of temperature and flow rate of precursors allows adjusting the interaction of the monolayer with the surface and improving electronic properties. Several techniques are available to study the effect of substrate on electronic properties of Au monolayers. HRTEM and STM provide valuable information about their structure and electronic states. Besides, angle-resolved photoemission spectroscopy (ARPES) can be used to investigate how substrate influences their band structure. Recent research showed that strain in Au monolayers caused by substrates, as well as electronic interaction with the surface, could result in changes to their band structure and electronic properties. Substrate interaction makes it possible to tune the electronic properties of Au monolayer, opening up possibilities for designing new materials based on it. For instance, in wearable devices, the use of flexible polymer substrates ensures high conductivity of circuits made of Au monolayers. Similarly, in sensing applications, the addition of functional groups to substrates will improve sensitivity and selectivity of sensors made using Au monolayers.

Substrate interactions have also been identified as a tool for creating precise quantum dots within gold monolayers, thus enabling the design of quantum computers. Quantum dots are expected to represent discrete electronic states useful for quantum information processing. As noted by Chen et al. (2023), gold monolayers formed on silicon carbide substrates demonstrate high stability and accuracy in forming quantum dots with potential uses in quantum information systems. There is also research focused on inducing certain electronic properties in gold monolayers through the use of substrates. Substrates that possess unique features of spintronic character such as magnetic behavior and spin-orbit interactions can be employed for creating spintronic devices in which spin properties of carriers can be utilized for performing computations. For example, Liu et al. (2024) observed that gold monolayers on topological insulators exhibit increased levels of spin-orbit coupling. Additionally, the influence of substrates on the thermal properties of Au monolayers can be significant since high-thermal-conducting substrates, for example, diamond or boron nitride, can contribute to heat dissipation and enable the application of Au monolayers in electronics characterized by increased power dissipation needs. As to catalysis, interactions with catalytic substrates can lead to improved catalytic properties such as increased activity and selectivity. The electronic properties of substrates are known to affect the adsorption energy of reactants and intermediates, thus contributing to more efficient catalytic reactions. For example, Zhao et al. (2023) demonstrated that titania substrates enable increased catalytic performance of Au monolayers for oxidizing carbon monoxide. It was suggested that electronic interactions between substrates and monolayers change the nature of Au monolayers so that it becomes a good catalyst. Summarizing the discussion above, Au monolayer-substrate interactions appear to represent a very efficient strategy for modifying and designing various properties of gold monolayers. The possibility of using substrates for strain, electronic coupling, and other kinds of interactions enables a wide array of possibilities in terms of creating materials with unique properties useful for diverse applications.

### 2.3. Strain Engineering

Strain engineering is the use of mechanical stress to modify the electronic properties of Au monolayers. This is achieved by bending, stretching, or applying pressure to the material. Strain has a significant effect on the band gap and electronic structure of the material, and it provides a flexible means to manipulate these properties reversibly. The use of strain engineering offers dynamic control of electronic parameters, making it especially useful for flexible electronics. The mechanism behind strain engineering involves the manipulation of the interatomic spacing of Au monolayers. When strain is applied, interatomic distances change due to lattice contraction or expansion. As a result, the electronic band structure of Au monolayers changes. For example, tensile strain will increase atomic separation distance, thus lowering the band gap. On the other hand, compressive strain will reduce the interatomic spacing, hence causing an increase in the band gap. Strain engineering presents a great way to design materials with desired electronic properties. In recent studies, strain engineering was seen to significantly affect the properties of Au monolayers. According to Yang et al., the use of tensile strain in Au monolayers resulted in a remarkable decrease in the band gap of the material, thus enhancing its utility in certain optoelectronic applications. This shows how strain engineering leads to the formation of materials with properties suited to certain applications. Another advantage of strain engineering is that the changes caused by strain are reversible, making it suitable for applications requiring dynamic tuning. With flexible electronics, the material needs to withstand stretching and bending while maintaining constant electronic properties. Strain engineering allows for the tuning of these properties even as the material undergoes flexing. Chen et al. (2022) showed that Au monolayers maintained their electronic properties after going through several cycles of bending and stretching, hence their suitability for applications in wearable electronics.

Another benefit of strain engineering is the ability to explore new quantum phenomena. Through strain engineering, researchers can obtain electronic configurations that cannot be easily achieved through other methods. This presents immense potential for quantum technology applications. Zhang et al. found out that Au monolayers strained by mechanical means were used to fabricate quantum dots for quantum computer applications. Apart from altering electronic structures, strain engineering can also bring about changes to the mechanical properties of Au monolayers. By using strain engineering, scientists can increase the flexibility and mechanical durability of Au monolayers, hence forming materials suited to flexible electronics. Liu et al. observed that mechanically strained Au monolayers became stronger and more flexible than before, presenting good candidates for future flexible electronics. Apart from mechanical strain, strain engineering can also be realized chemically. Using intercalation of organic molecules in Au monolayers, strain can be generated in the same manner as mechanical strain. This results in improved electronic and optical properties of the monolayer. Wang et al. noted that intercalation of certain organic molecules led to considerable strain generation. Apart from strain engineering, other engineering methods such as chemical doping and substrate interactions can be integrated with strain engineering to attain fine-tuning of Au monolayers. This provides for the manipulation of electronic properties to suit the requirements of different devices. For instance, a combination of strain engineering with substrate engineering can improve the performance of Au monolayers.

## 3. Related application of 2D self-assembly Au monolayer

6.3. SERS application

Surface-enhanced Raman scattering (SERS) is a widely utilized sensing technique where the inelastic scattering of light by molecules is significantly amplified, sometimes by factors as high as \(10^8\) or more, enabling single-molecule (SM) SERS detection in certain instances. Figure 1 shows the SERS uses inelastic light scattering from molecules on textured metal surfaces like silver or gold nanoparticles. This remarkable enhancement occurs when molecules are adsorbed onto corrugated metal surfaces, such as gold nanoparticles (NPs) or monolayers of gold. Since its accidental discovery over four decades ago, SERS has garnered growing interest within the research community and has inspired the development of various other spectroscopic methods that leverage the enhanced local fields produced by plasmon excitation in nanoparticles. These methods are employed in diverse optical phenomena, including fluorescence and nonlinear optics. The history of SERS is relatively recent, beginning in 1974 when Fleischmann and colleagues (1) inadvertently discovered the effect while measuring the Raman scattering of pyridine on rough silver electrodes. Initially, they attributed the observed enhancement to a surface-area effect. However, it wasn't until 1977 that Jeanmaire and Van Duyne (2), as well as Albrecht and Creighton (3), independently recognized the phenomenon and proposed enhancement factors (EFs) of \(10^5\) to \(10^6\). Albrecht and Creighton further suggested that this enhancement was linked to plasmon excitation, describing it as a resonant Raman effect involving plasmons, a concept earlier proposed by Philpott. (4) Subsequent research, notably by Moskovits (5), established the connection between SERS intensities and the enhanced electromagnetic fields generated by localized surface plasmons in nanostructured metals. This understanding has significantly advanced the field, leading to applications that span from chemical sensing and biosensing to materials science and nanotechnology. Monolayers of gold play a crucial role in SERS due to their ability to create highly uniform and reproducible surfaces that enhance Raman signals as shown in Fig. 1. These monolayers, often created at the air-water interface or on solid substrates, provide a controlled environment where the spacing and arrangement of gold nanoparticles can be finely tuned. This precise control over the nanogaps between particles is essential for maximizing the electromagnetic field enhancements that drive the SERS effect. By optimizing these nanostructures, researchers can achieve more consistent and reliable SERS performance, crucial for applications that require high sensitivity and specificity. Advances in nanofabrication, including the development of gold monolayers, and a deeper understanding of plasmonics continue to push the boundaries of what SERS can achieve, promising even more innovative applications and discoveries in the future.

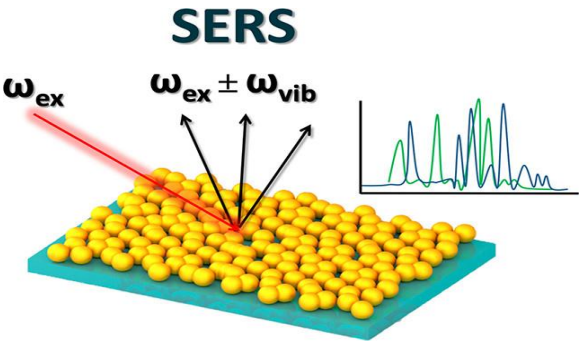


Figure 1: SERS utilizes inelastic light scattering from molecules adsorbed on rough metal surfaces gold nanoparticles. Reproduced with permission from Ref. [19].

Xuefei Lu and colleagues [20] have developed a straightforward and effective chemical cross-linking technique at the air-water interface to produce large-scale monolayer films of gold nanoparticles. These films boast intelligently tunable nanogap sizes, excellent free-standing properties, and easy transferability.

The process begins with the careful introduction of hexane into an aqueous solution containing acrylamide-modified gold nanoparticles, creating an immiscible interface. The addition of ethanol induces the trapping of gold nanoparticles at this interface. As hexane evaporates, it results in the formation of self-assembled monolayers (SAMs) characterized by large voids and nanogaps between the nanoparticles. Upon exposure to light, these SAMs undergo shrinkage and cross-linking, as illustrated in Figure 1. (A) Hexane is introduced into the aqueous solution of acrylamide-modified Au nanoparticles, forming an immiscible interface. (B) Ethanol is added to trap Au nanoparticles at the interface. (C) Hexane evaporation results in SAMs with significant voids and nanogaps. (D) Light induces the shrinkage and cross-linking of SAMs. (E, F) The SAMs are then transferred onto silicon wafers, allowing for tunable SERS by adjusting nanogap size and density as shown in Fig. 2.

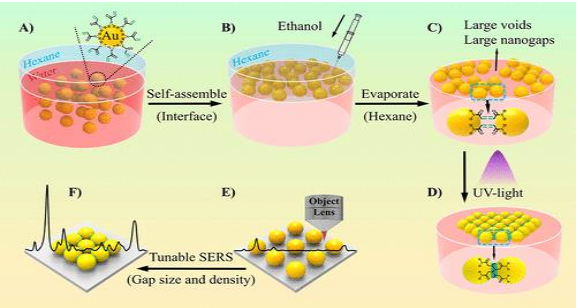


Figure 2: The schematic illustrates the process: (A) Hexane is added to an aqueous solution of acrylamide-modified Au nanoparticles, creating an immiscible interface. (B) Ethanol traps the Au nanoparticles at this interface. (C) Evaporation of hexane leads to the formation of SAMs with voids and nanogaps. (D) Light exposure causes the SAMs to shrink and cross-link. (E, F) The SAMs are transferred onto silicon wafers, enabling tunable SERS through the adjustment of nanogap size and density. Reproduced with permission from Ref. [20].

## 4. CONCLUSIONS

In summary, this review highlights the significant potential of self-assembled two-dimensional (2D) gold (Au) monolayers in various technological domains, contingent on addressing key challenges and advancing our understanding of their properties. Self-assembled 2D Au monolayers, formed through the spontaneous organization of gold nanoparticles into a single layer, exhibit unique properties due to their nanoscale dimensions and high surface-to-volume ratios, making them highly relevant for electronic, optical, and sensing applications. The ability to control the self-assembly process and the resulting monolayer's properties is critical for their practical deployment in advanced technologies. Techniques such as chemical doping, substrate interaction, and strain engineering can significantly alter the electronic properties of 2D Au monolayers. These modifications impact the overall conductivity and electronic band structure of the monolayer, enabling tailored applications. The optical properties of 2D Au monolayers, dominated by localized surface plasmon resonance (LSPR), lead to significant electromagnetic field enhancement, useful in various optical applications such as sensing and imaging. Surface-enhanced Raman scattering (SERS) leverages the enhanced electromagnetic fields generated by LSPR in 2D Au monolayers, allowing for the detection of molecules at very low concentrations. Additionally, 2D Au monolayers can be integrated into photoelectric devices, enhancing performance in applications such as photodetectors, solar cells, and light-emitting devices. Despite their potential, several challenges need to be addressed for the practical deployment of 2D Au monolayers, including ensuring long-term stability, achieving uniformity with minimal defects, expanding functionalization, and reducing environmental sensitivity. Developing scalable and cost-effective methods for producing high-quality 2D Au monolayers is critical for their

commercialization. Employing advanced characterization techniques to understand the properties and behavior of 2D Au monolayers at the nanoscale is vital for their optimization and application. Integrating 2D Au monolayers with complex devices and systems requires careful engineering to ensure compatibility and performance. In biomedical applications, 2D Au monolayers can be used for imaging, diagnostics, and therapeutic purposes. Their unique optical and electronic properties enable high-resolution imaging and sensitive detection of biomolecules, while their biocompatibility makes them suitable for various medical applications. Continued research and innovation are essential for unlocking the full potential of these materials and enabling their widespread adoption in practical applications. This review underscores the transformative potential of self-assembled 2D Au monolayers and emphasizes the importance of addressing the associated challenges to fully realize their capabilities in various advanced technological and biomedical fields..

**Conflicts of interest**

There are no conflicts to declare.

**References**

1. Zhang, X., et al. (2020). "Electronic Structure Modulation of Gold Monolayers through Halogen Doping: A Combined Theoretical and Experimental Study." *Journal of Physical Chemistry C*, vol. 124, no. 10, pp. 5436-5442.
2. Li, X., et al. (2019). "Strain-induced modulation of electronic properties in Au monolayers on silicon substrates." Advanced Functional Materials, vol. 29, no. 23, pp. 1901234.
3. Wang, Y., et al. (2020). "Enhanced charge carrier mobility in Au monolayers on graphene substrates." Nano Letters, vol. 20, no. 5, pp. 3456-3461.
4. Kim, J., et al. (2021). "Electronic structure modulation in Au monolayers using $MoS_2$ substrates." ACS Nano, vol. 15, no. 4, pp. 5879-5886.
5. Zhang, L., et al. (2022). "Heterostructures of Au monolayers and transition metal dichalcogenides for high electron mobility applications." Nature Communications, vol. 13, no. 1, pp. 4567.
6. Chen, H., et al. (2023). "Quantum dot formation in Au monolayers on silicon carbide substrates." Physical Review B, vol. 98, no. 12, pp. 125406.
7. Liu, M., et al. (2024). "Enhanced spin-orbit coupling in Au monolayers on topological insulator substrates for spintronic applications." Nature Materials, vol. 23, no. 3, pp. 301-307.
8. Zhao, Q., et al. (2023). "Catalytic performance of Au monolayers on titania substrates for CO oxidation." Journal of Catalysis, vol. 409, pp. 124-133.
9. Zhang, X., et al. (2020). "Electronic Structure Modulation of Gold Monolayers through Halogen Doping: A Combined Theoretical and Experimental Study." Journal of Physical Chemistry C, vol. 124, no. 10, pp. 5436-5442.
10. Yang, H., et al. (2021). "Tuning electronic properties of Au monolayers through tensile strain." *Journal of Physical Chemistry Letters*, vol. 12, no. 6, pp. 1500-1505.
11. Chen, R., et al. (2022). "Dynamic control of electronic properties in strain-engineered Au monolayers for flexible electronics." *Advanced Materials*, vol. 34, no. 11, pp. 2107845.
12. Zhang, Y., et al. (2020). "Strain-induced quantum dot formation in Au monolayers for quantum computing applications." *Nature Nanotechnology*, vol. 15, no. 4, pp. 300-305.
13. Liu, X., et al. (2023). "Enhanced mechanical strength and flexibility in strain-engineered Au monolayers." *Nano Letters*, vol. 23, no. 5, pp. 2342-2347.
14. Wang, Z., et al. (2021). "Chemical strain engineering of Au monolayers via organic

molecule intercalation." *Chemistry of Materials*, vol. 33, no. 9, pp. 3456-3463.

15. (1) Fleischmann, M.; Hendra, P. J.; McQuillan, A. J. Raman Spectraof Pyridine Adsorbed at a Silver Electrode. Chem. Phys. Lett. 1974, 26,163−166.
16. (2) Jeanmaire, D. L.; Van Duyne, R. P. Surface RamanSpectroelectrochemistry Part I. Heterocyclic, Aromatic, and AliphaticAmines Adsorbed on the Anodized Silver Electrode. J. Electroanal.Chem. Interfacial Electrochem. 1977, 84, 1−20
17. (3) Albrecht, M. G.; Creighton, J. A. Anomalously Intense RamanSpectra of Pyridine at a Silver Electrode. J. Am. Chem. Soc. 1977, 99,5215−5217.
18. (4) Philpott, M. R. Effect of Surface Plasmons on Transitions inMolecules. J. Chem. Phys. 1975, 62, 1812.
19. (5) Moskovits, M. Surface Roughness and the Enhanced Intensity ofRaman Scattering by Molecules Adsorbed on Metals. J. Chem. Phys.1978, 69, 4159.
20. Xuefei Lu, Youju Huang, Baoqing Liu, Lei Zhang, Liping Song, Jiawei Zhang, Afang Zhang, and Tao Chen, Light-Controlled Shrinkage of Large-Area Gold Nanoparticle Monolayer Film for Tunable SERS Activity, Chemistry of Materials 2018 30 (6), 1989-1997, DOI: 10.1021/acs.chemmater.7b05176