INVESTIGATION OF PLASMONIC Ag-Au ALLOY NANOPARTICLES

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ABSTRACT

The investigation of plasmonic Ag-Au alloy nanoparticles stands at the forefront of nanomaterial research, combining the unique optical properties of silver (Ag) and gold (Au) in a singular nanoscale entity. This abstract encapsulates the key aspects of ongoing research and the potential implications of understanding the properties of Ag-Au alloy nanoparticles. Researchers delve into the synthesis methods, exploring chemical reduction, seed-mediated growth, and advanced techniques like sonochemistry and microwave-assisted methods. Tailoring the size, composition, and morphology of Ag-Au alloy nanoparticles through precise control of reaction conditions is a focal point, allowing for the customization of their optical and catalytic characteristics. The investigation encompasses an array of characterization techniques, including transmission electron microscopy (TEM), X-ray diffraction (XRD), and UV-visible spectroscopy. These methods offer insights into the structural and optical features, enabling a comprehensive understanding of the alloy nanoparticles. Plasmonic resonance phenomena, resulting from the combination of Ag and Au components, are of particular interest due to their impact on the nanoparticles' optical responses. The applications of Ag-Au alloy nanoparticles span diverse domains, from catalysis and sensing to biomedical imaging and environmental remediation. The unique combination of properties, including tunable surface plasmon resonances and enhanced catalytic activity, positions these nanoparticles as versatile tools for addressing complex challenges in science and technology. As the investigation unfolds, the potential for Ag-Au alloy nanoparticles to catalyse innovations across various disciplines becomes increasingly evident, underscoring their significance in the nanomaterial landscape.

Keywords: Ag-Au alloy, Plasmonic, plasmonic properties, SPR

1. INTRODUCTION

The investigation of plasmonic Ag-Au alloy nanoparticles represents a compelling frontier in nanoscience and materials research, driven by the synergistic combination of silver (Ag) and gold (Au) in nanoscale structures (Han et al., 2016). This introduction provides an overview of the motivations, methodologies, and potential implications associated with the exploration of these unique nanomaterials(Olaru, Bala, Jaffrezic-Renault, & Aboul-Enein, 2015; Yamamoto, 2002).

Ag-Au alloy nanoparticles have captivated researchers due to their intriguing optical, electronic, and catalytic properties arising from the synergistic effects of incorporating both silver and gold. The amalgamation of these two noble metals results in tunable surface plasmon resonances, making Ag-Au alloy nanoparticles highly attractive for applications in catalysis, sensing, imaging, and beyond. Understanding the underlying principles governing the synthesis, characterization, and applications of these alloy nanoparticles is crucial for unlocking their full potential in various scientific and technological domains (Borah & Verbruggen, 2020; Coviello, Forrer, & Amendola, 2022).

Researchers employ a spectrum of synthesis methodologies to fabricate Ag-Au alloy nanoparticles, each offering unique advantages and control over specific nanoparticle properties. Chemical reduction methods, including traditional approaches and advanced techniques such as sonochemistry and microwave-assisted methods, enable the precise control of size, composition, and morphology (Blosi et al., 2010). Seed-mediated growth techniques provide a pathway for achieving uniform alloy nanoparticles with tailored characteristics, further expanding the versatility of Ag-Au systems.

The investigation of Ag-Au alloy nanoparticles involves a comprehensive suite of characterization techniques to unravel their structural and optical intricacies. Transmission electron microscopy (TEM), X-ray diffraction (XRD), and UV-Visible spectroscopy play pivotal roles in elucidating nanoparticle morphology, crystallinity, and plasmonic resonance features. The fine-tuning of these characteristics through controlled synthesis underscores the importance of advanced characterization techniques in guiding the investigation (Kushwaha, Kumar, Kumar, & Srivastava, 2018; Piliarik & Homola, 2009).

The multifaceted properties of Ag-Au alloy nanoparticles hold vast implications for numerous applications. Their catalytic activity is explored in diverse chemical reactions, while their tunable plasmonic resonances find utility in sensing platforms, biomedical imaging, and environmental remediation. As the investigation progresses, the potential for Ag-Au alloy nanoparticles to revolutionize fields such as medicine, energy, and materials science becomes increasingly apparent (Jiří Homola, 2003).

The investigation of plasmonic Ag-Au alloy nanoparticles is a dynamic and interdisciplinary pursuit, promising to unveil new frontiers in nanoscience. The interplay of synthesis methodologies, characterization techniques, and diverse applications underscores the versatility and potential impact of these alloy nanoparticles. As researchers delve deeper into their properties, the implications for technology and scientific understanding are poised to extend far beyond the confines of the laboratory, shaping the future of nanomaterials and their myriad applications (Nguyen, Yonezawa, Wang, & Tokunaga, 2016; Sharma & Gupta, 2005).

Plasmonic nanoparticles are a class of nanomaterials that exhibit surface plasmon resonance (SPR), a phenomenon arising from the collective oscillations of free electrons at their surfaces when exposed to electromagnetic radiation, particularly visible and near-infrared light. The optical properties of plasmonic nanoparticles are highly dependent on their size, shape, composition, and the surrounding environment. Silver (Ag) and gold (Au) nanoparticles are among the most widely studied plasmonic materials, known for their distinctive optical behaviour (Jiří Homola, Yee, & Gauglitz, 1999; Nguyen et al., 2016). The alloying of Ag and Au offers an exciting avenue for manipulating and fine-tuning the optical properties of nanoparticles(Li, Wang, Han, Wu, & Zheng, 2017; Sharma & Gupta, 2005). In this study, we will examine the optical properties of plasmonic Ag-Au alloy nanoparticles.

2. SYNTHESIS OF Ag-Au ALLOY NANOPARTICLES

The synthesis of Ag-Au alloy nanoparticles has emerged as a dynamic and intriguing field of research, driven by the desire to harness the unique properties arising from the combination of silver (Ag) and gold (Au) in nanoscale structures. These alloy nanoparticles exhibit exceptional characteristics, such as tunable optical, electronic, and catalytic properties, making them highly sought after for applications ranging from catalysis to biomedicine (Cortie & McDonagh, 2011; Sharma & Gupta, 2005).

One of the widely employed methods for synthesizing Ag-Au alloy nanoparticles is the chemical reduction approach. In this method, silver and gold salts, typically in the form of silver nitrate ($AgNO_3$) and chloroauric acid ($HAuCl_4$), serve as the precursor materials (Shaikh, Batool, Yameen, & Waseem, 2018). These precursors are dissolved in a suitable solvent, forming a solution that becomes the reaction medium. The reduction of these metal salts is initiated by the introduction of a reducing agent, which can be a mild agent like sodium citrate or a more potent one such as sodium borohydride.

The controlled reduction process results in the formation of Ag and Au atoms, which then nucleate and grow into alloy nanoparticles. The reaction conditions play a pivotal role in determining the size, composition, and morphology of the nanoparticles. Factors such as temperature, pH, and the concentration of reactants must be precisely adjusted to achieve the desired alloy nanoparticle characteristics (Gao, Hu, Wang, Chi, & Yin, 2014). Researchers have fine-tuned these parameters to create Ag-Au alloy nanoparticles with tailored properties for specific applications.

An alternative method in synthesizing Ag-Au alloy nanoparticles involves the seed-mediated growth approach (Coviello et al., 2022). In this technique, seed nanoparticles of one metal, typically silver, are first synthesized. These seed nanoparticles then act as templates for the deposition of the second metal, in this case, gold. This sequential growth ensures a controlled and uniform distribution of both metals in the resulting alloy nanoparticles. The seed-mediated growth method provides a high degree of control over particle size and composition.

Sonochemical and microwave-assisted methods represent cutting-edge approaches for the synthesis of Ag-Au alloy nanoparticles (Major, De, & Obare, 2009). Sonochemical synthesis employs ultrasonic waves to induce cavitation in the reaction mixture, leading to rapid nucleation and growth of nanoparticles. This technique is advantageous for its ability to produce nanoparticles with enhanced efficiency and controlled morphology. Microwave-assisted methods, on the other hand, utilize microwave irradiation to heat the reaction mixture quickly, resulting in reduced reaction times and improved uniformity of alloy nanoparticle formation.

The resulting Ag-Au alloy nanoparticles exhibit a remarkable array of properties. Their optical characteristics, particularly the tunable surface plasmon resonances arising from the combination of silver and gold components, make them highly attractive for applications in sensing and imaging technologies. Furthermore, the synergistic effects of combining silver and gold contribute to enhanced catalytic activity, positioning Ag-Au alloy nanoparticles as promising candidates for catalysis in various chemical reactions.

In conclusion, the synthesis of Ag-Au alloy nanoparticles involves sophisticated control of reaction conditions through chemical reduction, seed-mediated growth, and advanced methods such as sonochemistry and microwave-assisted techniques. These versatile synthesis strategies empower researchers to engineer Ag-Au alloy nanoparticles with tailored properties, paving the way for innovative applications across diverse scientific and technological domains.

3. OPTICAL PROPERTIES OF AG-AU ALLOY NANOPARTICLES

The optical properties of Ag-Au alloy nanoparticles are central to their utility. Key aspects of these properties include(Bansal, Sekhon, & Verma, 2014; Bhatia, Verma, & Sinha, 2020; Rahaghi, Poursalehi, & Miresmaeili, 2015):

Plasmon Resonance Tunability

One of the most intriguing features of Ag-Au alloy nanoparticles is their tunable plasmon resonance. By varying the Ag-to-Au ratio, researchers can precisely control the plasmon resonance wavelength, allowing for the customization of optical properties for specific applications.

Enhanced Light Absorption and Scattering

Ag-Au alloy nanoparticles exhibit enhanced absorption and scattering cross-sections compared to pure Ag or Au nanoparticles. This property is highly advantageous in applications that require efficient light-matter interactions.

Localized Surface Plasmon Resonance (LSPR)

The LSPR of Ag-Au alloy nanoparticles can be fine-tuned to match specific wavelengths of light. This capability has led to applications in colorimetric sensing, where changes in the LSPR result in measurable color shifts (Bansal et al., 2014; Kunwar, Pandey, Pandit, Sui, & Lee, 2020).

4. CHARACTERIZATION TECHNIQUES

Plasmonic Au-Ag alloy nanoparticles exhibit unique optical properties due to their surface plasmon resonance (SPR), making their thorough characterization essential for understanding their behavior and tailoring their applications. A combination of advanced techniques is employed to unravel the structural, optical, and chemical characteristics of these fascinating nanomaterials (Chinh & Trung, 2015; Cortie & McDonagh, 2011; Csapó et al., 2012; Kunwar, Pandey, Sui, Bastola, & Lee, 2018).

UV-Visible Spectroscopy

UV-Visible spectroscopy is a primary tool for characterizing plasmonic nanoparticles. The distinctive feature of Au-Ag alloy nanoparticles is the tunability of their SPR peak. By varying the alloy composition, researchers can precisely control the absorption bands, providing insights into the alloy composition and nanoparticle size distribution.

Transmission Electron Microscopy (TEM)

TEM is instrumental in visualizing the morphology and structure of Au-Ag alloy nanoparticles at the nanoscale. It allows for the determination of particle size, shape, and distribution. The bimetallic nature of Au-Ag alloys can be observed, and alloying effects on the crystal lattice can be examined.

Energy-Dispersive X-ray Spectroscopy (EDS)

EDS, often coupled with TEM, enables elemental analysis of Au-Ag alloy nanoparticles. This technique provides quantitative information about the relative concentrations of gold and silver in the alloy, confirming the desired composition and helping understand alloying effects on the plasmonic properties.

X-ray Photoelectron Spectroscopy (XPS)

XPS is employed for surface analysis, providing information about the oxidation states and chemical environments of the elements present in Au-Ag alloy nanoparticles. This is crucial for understanding the surface composition and potential modifications that may occur during synthesis or in different environments.

Scanning Electron Microscopy (SEM)

SEM complements TEM by offering insights into the surface morphology and topography of Au-Ag alloy nanoparticles. The three-dimensional images obtained help in visualizing the overall shape and arrangement of the nanoparticles.

Dynamic Light Scattering (DLS)

DLS is utilized to measure the hydrodynamic size distribution of nanoparticles in solution. For Au-Ag alloy nanoparticles, DLS provides information on their stability, aggregation behavior, and size distribution under various conditions, aiding in optimizing colloidal stability.

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR is employed to study the surface functionalization and interactions of Au-Ag alloy nanoparticles with stabilizing agents or ligands. It provides information about the chemical groups present on the nanoparticle surface, influencing their stability and compatibility in different environments.

Surface Plasmon Resonance (SPR)

SPR spectroscopy is specifically valuable for studying the interactions between Au-Ag alloy nanoparticles and their surrounding environment. Changes in the SPR signal can be correlated with binding events, making SPR a powerful technique for biosensing applications of these plasmonic nanomaterials.

In conclusion, the characterization of plasmonic Au-Ag alloy nanoparticles necessitates a multi-faceted approach, combining techniques that probe their optical, structural, and chemical properties. UV-Visible spectroscopy, TEM, EDS, XPS, SEM, DLS, FTIR, and SPR collectively provide a comprehensive understanding of these nanomaterials. This knowledge not only aids in optimizing synthesis methods but also opens avenues for tailoring the properties of Au-Ag alloy nanoparticles for diverse applications, including sensors, imaging, and catalysis.

5. APPLICATIONS OF Ag-Au ALLOY NANOPARTICLES

Ag-Au alloy nanoparticles, combining the unique properties of silver (Ag) and gold (Au), have emerged as versatile nanomaterials with a wide range of applications across various scientific and technological domains. The synergistic effects resulting from the combination of these two metals make Ag-Au alloy nanoparticles highly sought after for their distinct optical, catalytic, and biocompatible properties (Csapó et al., 2012; Han et al., 2016; Mandal, Das, & Moirangthem, 2023; Mondal et al., 2011; Saad, Gazzah, Mougin, Selmi, & Belmabrouk, 2022; Thota, Wang, & Zhao, 2018).

Catalysis

The catalytic activity of Ag-Au alloy nanoparticles is of significant interest in various chemical reactions. These nanoparticles, with their bimetallic composition, exhibit enhanced catalytic performance compared to individual silver or gold nanoparticles. They find applications in catalyzing reactions such as hydrogenation, oxidation, and reduction, opening avenues for sustainable and efficient catalytic processes.

Sensing and Detection

The unique optical properties of Ag-Au alloy nanoparticles, arising from their surface plasmon resonance, make them excellent candidates for sensing and detection applications. They are employed in various sensing platforms, including surface-enhanced Raman spectroscopy (SERS), where their enhanced electromagnetic fields enable sensitive and selective detection of molecules. This makes Ag-Au alloy nanoparticles valuable in biosensing, environmental monitoring, and medical diagnostics.

Biomedical Imaging

Ag-Au alloy nanoparticles exhibit strong absorption and scattering in the visible and near-infrared regions, making them suitable for biomedical imaging applications. These nanoparticles are employed as contrast agents in techniques such as photoacoustic imaging and computed tomography (CT) imaging. Their biocompatibility and tunable optical properties contribute to their use in improving imaging resolution and sensitivity in medical diagnostics.

Antimicrobial Applications

The antimicrobial properties of silver are well-known, and incorporating silver into Au-Ag alloy nanoparticles enhances these properties. These nanoparticles are utilized in antimicrobial coatings for medical devices, textiles, and surfaces. The controlled release of silver ions from the alloy nanoparticles provides long-lasting antimicrobial effects, reducing the risk of infections.

Photothermal Therapy

Ag-Au alloy nanoparticles are employed in photothermal therapy, a cancer treatment strategy where the nanoparticles convert absorbed light into heat, selectively targeting and destroying cancer cells. The tunability of their plasmonic properties allows for optimal absorption in the near-infrared region, where light penetration in biological tissues is maximized.

Electrocatalysis

In the field of energy conversion and storage, Ag-Au alloy nanoparticles are explored for electrocatalytic applications. They show promise in electrochemical reactions, including oxygen reduction and hydrogen evolution reactions, contributing to the development of efficient and sustainable energy storage systems.

Optoelectronics and Plasmonic Devices

The plasmonic properties of Ag-Au alloy nanoparticles make them valuable in optoelectronic devices. They are incorporated into sensors, light-emitting diodes (LEDs), and solar cells to enhance light absorption and emission properties. The ability to engineer their plasmonic resonances allows for tailored device functionalities.

Environmental Remediation

Ag-Au alloy nanoparticles are utilized in environmental applications, particularly for the removal of pollutants. Their catalytic properties play a role in the degradation of organic pollutants, and their enhanced optical properties aid in the detection and remediation of environmental contaminants.

In conclusion, the applications of Ag-Au alloy nanoparticles span a diverse range of fields, highlighting their versatility and potential impact. From catalysis and sensing to biomedical imaging and environmental remediation, these nanoparticles continue to contribute to advancements in science and technology, offering solutions to pressing challenges in various industries. The ongoing research and development in this area further underscore the promising future of Ag-Au alloy nanoparticles in addressing complex and multidisciplinary problems.

6. FUTURE DIRECTIONS OF PLASMONIC AU-AG ALLOY NANOPARTICLES

The field of plasmonic Au-Ag alloy nanoparticles is poised for exciting advancements and diverse applications in the coming years. Several future directions are anticipated to shape the research landscape (Khurana & Jaggi, 2021; Kim, Kim, Park, & Nam, 2018; Pasparakis, 2022):

Multifunctional Nanomaterials

The integration of additional functionalities into Au-Ag alloy nanoparticles is a promising avenue. Researchers are exploring ways to incorporate other materials or functional groups onto the surface of these nanoparticles, creating multifunctional nanosystems with enhanced properties for applications ranging from drug delivery to smart sensing platforms.

Theranostic Applications

Au-Ag alloy nanoparticles hold immense potential for theranostic applications, where diagnostics and therapeutic capabilities are combined in a single platform. Their unique optical properties make them suitable for simultaneous imaging and therapy, offering personalized and targeted treatment options in medicine.

Advanced Nanofabrication Techniques

Advances in nanofabrication techniques, such as bottom-up and top-down approaches, will play a crucial role in tailoring the size, shape, and composition of Au-Ag alloy nanoparticles. Precise control over these parameters will enable the design of nanomaterials with enhanced and tunable properties for specific applications.

Biocompatibility and Toxicity Studies

As Au-Ag alloy nanoparticles find increasing use in biomedical applications, there is a growing need for comprehensive biocompatibility and toxicity studies. Understanding the interactions of these nanoparticles with biological systems will guide their safe implementation in areas such as drug delivery and medical imaging.

Environmental Remediation Strategies

The application of Au-Ag alloy nanoparticles in environmental remediation is likely to expand. Future research may focus on developing efficient and scalable methods for the removal of pollutants from air, water, and soil, addressing pressing environmental challenges.

7. CONCLUSION

Plasmonic Au-Ag alloy nanoparticles represent a cutting-edge class of nanomaterials with diverse applications and immense potential for future advancements. Their synergistic properties, stemming from the combination of silver and gold, have paved the way for innovations in catalysis, sensing, biomedical imaging, and beyond. The tunability of their plasmonic resonances allows for precise engineering of optical properties, enabling applications in areas such as imaging and therapy. As research progresses, the versatility of Au-Ag alloy nanoparticles is likely to lead to breakthroughs in multifunctional nanomaterials, offering solutions to complex challenges in medicine and technology. The field's future directions are characterized by a multidisciplinary approach, combining materials science, chemistry, physics, and biology. Researchers will continue to explore novel synthesis methods, advanced characterization techniques, and innovative applications to unlock the full potential of these nanomaterials. As Au-Ag alloy nanoparticles transition from the laboratory to practical applications, it is crucial to address challenges related to biocompatibility, toxicity, and scalability. Collaborative efforts between scientists, engineers, and clinicians will be essential to harness the unique properties of Au-Ag alloy nanoparticles for real-world impact. In summary, the journey of plasmonic Au-Ag alloy nanoparticles is marked by exploration, discovery, and the promise of transformative applications. The ongoing research in this field is a testament to the dynamic nature of nanoscience and nanotechnology, offering a glimpse into a future where these nanoparticles contribute significantly to advancements in medicine, environmental sustainability, and beyond.

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