Application of nanomaterial for optical sensors design

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Abstract. Nanomaterials are considered to be materials whose design construction requires at least one of their dimensions to be comprising of components that are sized within 1 to 100 nanometers. Nanosize can endow nanomaterials with new functions such as new physical, chemical and optical properties that their larger counterparts do not possess. These properties of nanoparticles have thus, become a subject of huge interest as research in them have flourished in the past decades and revealed myriads of new applications that can make this technology indispensable in our lives and in future research. Their various different physical and chemical properties, and their application in some of the most advanced technology-based research of the current decades have been discussed in this research. And also, this research will allow future researchers to exploit the existing gaps in knowledge and research to advance the field further and design newer different applications for the nanomaterials.

Keywords: Nanomaterials, Application, Sensors.

1. Introduction

Nanomaterial are materials designed with structured components with at least one dimension sized from 1 to 100 nanometres. This nanoscale dimensionality imparts to these materials' unique chemical, physical as well as optical properties which is not observed in their bulk counterparts. Especially in the realm of optical sensing, these properties have proven transformative [1]. Nanomaterial possess unique characteristics due to their increased surface area and small size. This includes improved properties like strength and flexibility well as unique electrical and thermal conductivities. Moreover, their quantum effects grant them optical, electronic and magnetic behaviors [2].

Nanomaterial have found applications across various domains, ranging from electronics, medicine, energy storage, and environmental remediation. One application that deserves special mention, given our context, is in the field of optics. The optical properties of nanomaterial can be exceptionally intriguing. Quantum dots, for instance, can emit or absorb specific wavelengths of light based on their size, a property not seen in their larger counterparts [3]. This property stems from quantum confinement effects, which play a significant role at the nanoscale.

The properties of nanomaterial can be remarkably fascinating. Quantum dots are an example; they can. Absorb specific wavelengths of light depending on their size—a characteristic absent, in their larger counterparts [3]. These optical properties of nanomaterial are influenced by phenomena, such as quantum confinement, surface Plasmon resonance and enhanced interactions between light and matter at the nanoscale. For instance, quantum dots can be precisely adjusted in terms of their fluorescence characteristics based on their size enabling detection and imaging applications. Metallic nanoparticles

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like gold and silver exhibit distinct surface plasmon resonances that're highly responsive to their surrounding environment. This makes them ideal for optical sensing applications in the detection of chemical and biological agents [3]. Optical sensors have greatly benefited from the integration of nanomaterial as they enhance sensitivity and specificity. Graphene, known for its optical properties has been effectively utilized in optical sensors [4]. Additionally, gold and silver nanoparticles with their surface Plasmon resonances have significantly improved the performance of sensors by enabling the detection of even single molecules [3].

The incorporation of nanomaterials into sensors has brought about an era with remarkable advancements, in ultra-sensitive detection capabilities. Enhanced sensors, capable of detecting the changes, in environmental factors or single molecules have a wide range of practical applications. These applications include diagnostics and environmental monitoring. This research will analyze a diverse of different optical sensors based on nanomaterials.

2. Application of nanomaterial optical sensors

Nanomaterial, with their unique optical and physical properties have opened up new vistas in the realm of optical sensing. This surge in research has led to advances that span from environmental monitoring to cutting-edge biomedical applications. Here, this research will delve into the research findings that underscore the application of nanomaterial-based optical sensors.

2.1. Gold nanoparticles

Among the most widely studied nanoparticles, gold nanoparticles (AuNPs) exhibit surface plasmon resonance (SPR), a phenomenon where conduction electrons on the metal surface oscillate coherently, leading to intense absorption and scattering of light. This SPR is highly sensitive to changes in the refractive index of the surrounding medium, allowing AuNPs to be used as sensors for detecting various molecules, including proteins, DNA, and even pollutants [5].

AuNPs have emerged as a revolutionary component in the world of nanotechnology, and their potential to enhance SPR sensitivity forms a focal point of many ground-breaking research endeavours. The Larson et al. study serves as a beacon in this arena, unravelling the intricate dance of conduction electrons on the surface of gold nanoparticles and its implications for SPR. SPR, a phenomenon hinging on the interaction between incident light and the electron clouds in thin metal layers, offers a potent method to detect molecular interactions. A significant factor that governs this resonance is the refractive index of the medium neighbouring the metal layer. Any change in this index, such as the binding of a biomolecule, can be detected with high sensitivity through SPR. The introduction of AuNPs amplifies this sensitivity multifold.

Larson et al. discovery revolved around leveraging the unique oscillations of conduction electrons on the surface of gold nanoparticles [5]. In simpler terms, AuNPs, when subjected to specific wavelengths of light, result in collective oscillations of their free electrons. This oscillation, termed as 'plasmon resonance', is particularly sensitive to the surrounding environment. By capitalizing on this heightened sensitivity, the team was able to detect extremely subtle changes in the refractive index of the neighbouring medium [5]. The most profound revelation from this study was the ability of enhanced SPR to detect a diverse range of molecules. From the intricate winding ladders of DNA sequences to the complex choreography of protein interactions, the enhanced SPR enabled by gold nanoparticles could sense them all [5]. What set this apart was the detection threshold; these interactions could be discerned at concentrations that were previously thought to be below the limits of detection. This breakthrough not only spotlighted the exceptional potential of AuNPs in SPR sensing but also paved the way for a future where molecular interactions, vital for myriad research, diagnostic, and therapeutic applications, could be detected with an accuracy and sensitivity hitherto unmatched.

2.2. Quantum dots and bioimaging

These semiconductor nanocrystals are characterized by size-tunable fluorescence. Due to their brightness and stability, quantum dots (QDs) are ideal for long-term sensing and imaging applications,

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especially in biomedicine for tracking cells and molecules [4]. QDs have long been on the radar of scientists, but it was the transformative work of Michalet et al. that catapulted them to the forefront of bioimaging research. These semiconductor nanocrystals, with their unique size-dependent fluorescence properties, promise a revolution in the realm of in vivo imaging, offering unparalleled insights into the microscopic intricacies of life. The quintessential attribute of quantum dots lies in their fluorescence. Unlike traditional dyes or fluorescent proteins, the emission wavelength of QDs can be finely tuned based on their size. This means that by merely adjusting the size of these nanocrystals, scientists can choose the exact color of light they emit upon excitation. This unique trait is a boon for researchers, enabling them to tag different biomolecules with quantum dots of varied sizes, resulting in a spectrum of fluorescent signals, all discernible from one another.

Michalet et al. delved deep into these properties, unearthing the remarkable potential of quantum dots in tracking biological processes in living organisms. Their findings illuminated three major strengths of QDs in bioimaging. For unparalleled brightness, QDs are inherently brighter than conventional fluorophores. Their unique crystalline structure and the physics governing their fluorescence ensure that when illuminated, they emit light with an intensity that is unmatched [4]. This brilliance ensures that even minute quantities of tagged biomolecules can be easily detected. For robust photo-stability, one of the major challenges with traditional fluorescent markers is their propensity to degrade or 'bleach' under prolonged exposure to light. QDs, however, showcased a tenacious resistance to this photobleaching, making them ideal for long-term imaging studies where constant illumination is a prerequisite [4]. For potential for multiplexing, the tunable nature of quantum dot fluorescence opens the door to multiplexing, a method where multiple biomolecules can be simultaneously tracked in real-time. By tagging each molecule (or group of molecules) with QDs of a specific size (and thus a specific emission color), researchers can monitor multiple cellular processes in tandem [4].

The revelations from Michalet et al.'s study underscored the transformative role of QDs in bioimaging. From tracking the frenzied dance of proteins inside a cell to monitoring the real-time spread of a signalling molecule, quantum dots have reshaped our understanding of cellular and molecular dynamics, offering a window into the very essence of life.

2.3. Magnetic nanoparticles in optical sensing

Magnetic nanoparticles (MNPs) have long captivated researchers due to their fascinating magnetic properties at the nanoscale. While their application in magnetic storage, drug delivery, and even hyperthermia treatment for cancer is well-chronicled, their role in optical sensing represents a ground-breaking new dimension. Sun et al. stood at the helm of this novel exploration, unveiling the intriguing synergies between MNPs and optical sensing platforms [6]. At the heart of this study is the marriage of two distinct principles: the magnetic characteristics of MNPs and the precision of optical detection methods. By integrating MNPs into optical platforms, the researchers crafted a system where magnetic and optical functionalities could bolster each other.

For magnetic enrichment, one of the stellar attributes of MNPs is their ability to be manipulated using external magnetic fields. This magnetic responsiveness allows MNPs to be concentrated or directed to specific locations. In the context of sensing, this translates to "magnetic enrichment." By attaching target biomolecules to these nanoparticles, researchers can use an external magnet to accumulate these targets at a specific detection site. Such a concentrated presence significantly amplifies the signal, aiding in better detection [6]. For optical detection, once the target molecules are concentrated using MNPs the optical component comes into play. Optical sensing techniques have the ability to detect the changes, in light intensity, polarization or wavelength when a target interacts with a sensor surface. By incorporating MNPs we can achieve a concentration of the target resulting in a more easily detectable optical signal [6].

The ground-breaking work by Sun et al. highlighted the potential of combining these two technologies. With the help of MNPs optical sensors have become highly sensitive thereby drastically reducing the detection threshold. This unprecedented level of sensitivity is particularly advantageous, in disease diagnostics since early stage diseases often exhibit concentrations of biomarkers. Through MNP

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enhanced sensing we can now identify these biomarkers at an early stage enabling earlier detection and subsequently more effective treatments. The journey of MNPs from mere magnetic wonders to pivotal components in ultra-sensitive optical sensing, as illustrated by Sun and colleagues, marks a transformative chapter in the annals of nanotechnology, heralding a brighter future for precision diagnostics.

2.4. Application in authenticity discrimination

According to various studies, the confirmation of food product authenticity has gained significant attention, particularly in discerning adulteration, identifying markers, and non-targeted detection. Adulteration, as highlighted by Gao et al., involves the illegal addition of substances to foods for purposes such as cost reduction, product enhancement, or profiteering. Milk adulteration with melamine is another serious concern [7]. As described by Gao et al., milk processing companies often determine protein levels in powdered infant formulas by analyzing total nitrogen content. The introduction of nitrogen-rich melamine falsely increases this content, presenting serious health risks including kidney failure. To address this, functionalized AuNPs have been used, where functionalization stabilizes the AuNPs suspension against the destabilizing presence of melamine. Additionally, Gao et al. employed AuNPs to detect melamine in milk by monitoring color changes during AuNPs biosynthesis, a change attributed to melamine's interference with AuNPs formation, as shown in Figure 1.

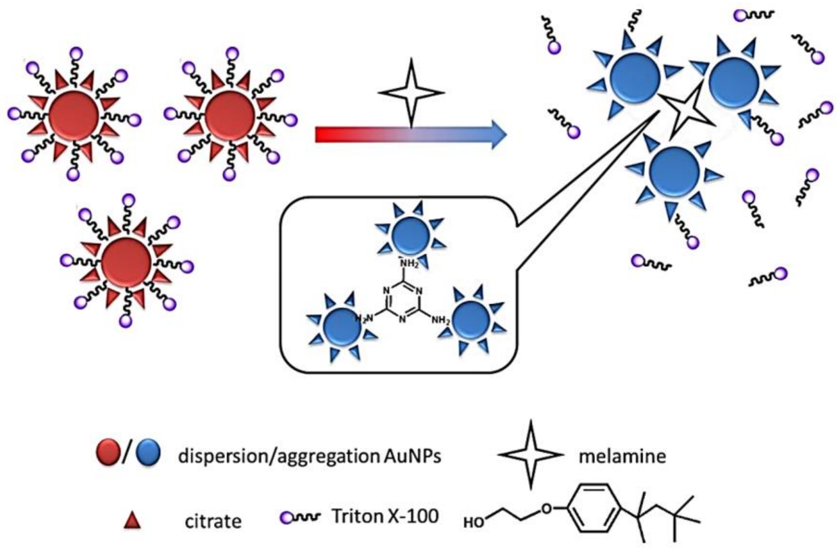

Figure 1. Scheme for colorimetric detection of melamine by using AuNPs [7].

Regarding food authenticity markers, ferulic acid, which constitutes 95% of the total phenolic acid in virgin argan oil, was identified as a crucial marker to gauge the oil's purity, as presented in a study using sensors based on AuNPs. Another interesting study focused on nucleotide fragments as markers, utilizing a specific fragment to detect pork adulteration in beef meatballs. However, as markers can also be illegally added, the emphasis is gradually shifting to non-targeted detection methods. A promising study revealed that adulterated vegetable oils could be rapidly detected using an optical sensor based on the fluorescence quenching technique, highlighting its efficiency and speed in detecting foreign components in foods.

2.5. Nanomaterial in rapid detection of food contaminants

According to the study by Chen et al., the presence of heavy metals in our environment has severe implications on human health due to their accumulation and non-biodegradability [8]. Mercury (Hg), for instance, can lead to motion disorders and heart issues, while elevated copper (Cu) levels can cause liver and metabolic disorders. The research emphasized the urgent need for robust detection methods for these contaminants, particularly in food sources.

The paper highlighted the innovative use of nanomaterials, such as QDs, for optical sensing. These nanomaterial's exhibit fluorescence quenching when interacting with heavy metal ions, which can be utilized to quantitatively detect the metals. The researchers elaborated on the Stern-Volmer (S-V) equation as a foundation for this quantitative detection and introduced radiometric fluorescence as a more sensitive detection method. Additionally, the visual representation provided by fluorescence quenching offers a quicker detection method. Chen and colleagues elaborated on specific interactions. For instance, mercury reacts with various carbon dots (CDs) causing fluorescence quenching, which can be used to measure its concentration in a sample [8]. The paper also detailed a radiometric fluorescence method which displayed heightened sensitivity compared to traditional fluorescence quenching. Furthermore, the team investigated sensor arrays, which capitalize on the synergy between various materials to enhance detection. They introduced unique systems that could simultaneously detect multiple heavy metals with heightened specificity, especially when combined with masking agents.

In conclusion, the work by Chen et al. shed light on the promising role of nanomaterial in rapidly detecting food contaminants. With a focus on heavy metals, the study underscored the potential of optical sensors, based on nanotechnology, to ensure food safety, quality, and authenticity.

2.6. Silicon nanowires in photodetection

Silicon, with its foundational role in the electronics industry, has witnessed a continual evolution in its applications. Silicon, an element, in the electronics industry has experienced advancements in its applications over time. However, it was the ground-breaking research conducted by Cui et al. that introduced an era for silicon not in its bulky form but in the innovative nanowire morphology known as silicon nanowires (SiNWs) [9]. These have been explored for their photonic properties and are used in nanoscale photodetectors, harnessing their high refractive index and light confinement capabilities [9]. This study showcased the potential of SiNWs in sensing surpassing traditional photo detectors. The appeal of silicon nanowires lies in their characteristics – their high refractive index allows them to efficiently bend and trap light within their structures surpassing materials. Moreover, their nanoscale dimensions further enhance this ability to confine light. These exceptional light confinement properties enable SiNWs to interact with light in ways paving the way for photo detection applications. In the realm of sensing detecting subtle changes or variations in light is crucial. Compared to bulk silicon counterparts SiNWs exhibited enhanced sensitivity due to their nanoscale dimensions and larger surface to volume ratio. This unique characteristic makes them highly responsive even to minute fluctuations, in incident light or environmental factors surrounding them.

SiNWs acute sensitivity makes them promising leaders, in photo detection applications that prioritize precision. Another significant advantage of SiNWs is their small device footprint. As the world moves towards miniaturization SiNWs offer a pathway to develop highly efficient photo detectors [9]. Their small size, combined with properties makes them ideal candidates for integration into dense multifunctional devices ranging from wearable technology to lab on a chip system. The ground-breaking research conducted by Cui et al. highlighted silicon nanowires as not another player but a potential frontrunner, in the future of photodetection. As researchers and industries continue to explore the potential of SiNWs it becomes evident that these tiny wires could shape the chapter in dynamic optical sensing.

2.7. Nanomaterial optical sensors in virus detection

In the field of virus detection, it is crucial to have effective methods. A recent study explored the use of sensors highlighting their advantages such, as response time, high sensitivity, and simplicity and cost effectiveness [10]. These sensors can detect viruses by observing a change in color in solutions. The research focuses primarily on two categories: nanomaterial and biomolecule modified nanomaterial.

Unmodified nanomaterial, AuNPs have been widely used in virus detection. AuNPs exhibit a color when dispersed due to their surface plasmon absorption. Wang et al. Took advantage of this principle

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by using salt induced color changes to detect the maize mottle virus (MCMV) and the cucumber green mottle mosaic virus (CGMMV) with AuNPs. This method is incredibly precise. Can even detect amounts of viral RNA. Similarly, Saleh et al. developed a technique that identifies the spring viraemia of carp virus (SVCV) using unmodified AuNPs delivering results in 15 minutes [11]. Nanomaterials modified with antibodies or peptides—provide high specificity, for virus detection. Liu et al. utilized AuNPs coated with antibodies to accurately detect the influenza A virus (IAV) [12]. These modified nanoparticles have a level of precision allowing them to effectively recognize the virus antigen and detect it with sensitivity. Additionally, Liu et al. successfully used DNA modified silver nanoparticles in a one-step method, for detecting HIV DNA [12]. In summary Shi's study in 2021 highlights the potential of both functionalized nanomaterials in developing efficient colorimetric sensors for virus detection. This presents a path, for viral diagnostics.

3. Conclusion

The current study has compiled information from a myriad of sources to uncover a wide gamut of applications that nanomaterials can be considered to be useful in. This compilation will not only help researchers into furthering their studies in this field by pointing out the remaining gaps in the existing research and indicating potential directions for further research, but it will also allow future visionaries and students to understand the beginning of this incredible journey into the world of nanoparticle applications. Clearly, as technology progresses, with time, their use and application seem to cross many different disciplines. Not only have they been used in optical sensors, in authenticity discriminations and bioimaging, they have been also heralded as the new solutions to quick diagnostics in the field of medicine. It is expected that future research in the field of medicine will definitely bring forth more incredible findings and applications.

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