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LIGHT HARVESTING ENHANCEMENT USING METAL NANOPARTICLES

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Metal nanoparticles are very important for their optical properties when they interact with light. Metal nanoparticles have the ability to confine the collective oscillation of electrons, which is called localized surface plasmon resonance (LSPR). In this work, silver nanoparticles have been proposed to enhance light harvesting, which could be useful for different applications. Metal nanoparticles such as gold and silver nanoparticles have the ability to concentrate field in a very small space. In this study, gold and silver nanoparticles optical response was investigated using frequency domain simulation. The resonance wavelength of gold and silver nanoparticles was about 550 nm and 400 nm, respectively.

Silver nanoparticles showed better LSPR performance than gold nanoparticles. Therefore, silver nanoparticles were chosen for optical field enhancement. Here silver nanoparticles were placed on a silicon substrate for optical field enhancement. To study the effect of size on the optical response of silver nanoparticles, the optical properties of this structure with different silver nanoparticles diameter values were investigated. Silver nanoparticles with 40 nm diameters showed a better optical response. To study the effect of the distance between silver nanoparticles on the optical response, different gap values were put between silver nanoparticles. The gap value of 4 nm showed a better optical response. The obtained results showed that the localized field is strongly dependent on the metal type, size, and space between nanoparticles. In addition, the optical field concentration can be controlled by tuning the size and space between silver nanoparticles. This will support localized field enhancement. The enhanced localized field will increase the field absorption near the surface, which can be beneficial for energy harvesting applications such as solar cells and detectors

Keywords: silver nanoparticles, LSPR, light harvesting, optical response, light confinement, field enhancement, gold nanoparticles, silicon substrate

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1. Introduction

Metallic nanostructures have been exploited in a wide range of applications due to their optical properties like localized surface plasmon resonance (LSPR) [1]. Metallic nanoparticles optical properties depend on the material type, size, and shape [2]. In the LSPR, light is confined on the metallic nanostructure surface within a certain area based on different factors. Based on the size and shape of the metallic nanostructures, it is possible to tune the optical response within visible light wavelengths. This notable feature of tuning is considered an important factor for many light interaction structures applications such as detectors and solar cells [3, 4].

Light confinement is very important for making high-efficiency harvesting devices. Different methods have been used to trap light on the structure surface [5, 6]. These nanostructures have been widely used to enhance light confinement. When light interacts with the structures, light reflection and absorption can be controlled by the surface morphology and arrangement, which can reduce the reflection by increasing the scattering of light inside the nanostructure, which will enhance light harvesting [7].

Various methods have been used previously for light confinement. However, they suffered from some problems. For example, the surface area and total volume of the device were increased, which affected the overall performance of the device [8]. Also, they were not very efficient for light confinement. Therefore, metallic nanostructures have become a promising alternative for light confinement for their high ability for enhancing light in the subwavelength area. The collective oscillations of electrons in metallic nanostructures show potential for near and far light confinement. The optical response can be tuned based on different factors that will enhance the field confinement for different optical devices applications [9].

Metallic nanostructures have the ability to confine light within the subwavelength area, which is very important for light harvesting enhancement. The optical properties of metallic nanostructures have been employed in many applications like sensing, imaging, and laser [10]. In addition to the size and shape of metallic nanostructures, another important factor is the gap between metallic nanostructures that can play a vital role in optical response and eventually light confinement. As a result, light confinement between metallic nanostructures in the subwavelength area has become very important for many light-related devices [10, 11].

Light enhancement using metal nanostructures is very important and can be exploited for various applications. For instance, using metal nanostructures with available light-based devices can enhance the performance of these devices such as increasing the absorption range of light to increase efficiency. Efficiency is a very important factor for energy conversion devices, which convert light into electricity. In the electronic devices, very thick layers would increase the total cost although the absorption will be high but the output current would not be high. Therefore, very thick layers could be used and combined with metal nanoparticles to improve the absorption and decrease the total cost and make the devices small in size and could be integrated with other systems [12, 13].

Metal nanoparticles as the foundation of surface plasmon could help improve the light conversion efficiency of thin layers through increasing the absorption of light in a wide range. Moreover, reducing the layer thickness would decrease the total cost. Metal nanoparticles could help light to couple to the interface materials such as semiconductor materials as hybrid devices. This would increase light trapping at the interface then increase the absorption rate inside the material. Different parameters could influence the coupling between metal nanoparticles and other materials like metal type, size, and shape. Metal nanoparticles commonly used increase the scattering near the interface. In addition, metal nanoparticles have the ability to localize the incident light and increase the localized field intensity, which would help for more interaction with light [14, 15].

Metal nanoparticles could be added to the semiconductor surface in a certain design to form an interface layer. Because of that, the light will be highly localized at the surface interface, which will lead to the field and absorption enhancement. The high density of metal nanoparticles could help enhance the field intensity. The absorption response at the interface should be fast enough to avoid energy dissipation as the heat of surface plasmon waves. Very thick layer materials would help improve the absorption response.

The recent developments in nanotechnology help improve the quality of nanostructures, which are combined with other materials for light-based devices performance enhancement. This attracted researchers to use different shapes and metals and study their effect and understand the working principles of light enhancement using metal nanoparticles to achieve and realize new devices with the ability of high field enhancement and wide wavelength operation range [16–20].

Utilizing metal nanoparticles in the local field enhancement could open the door for many practical applications such as solar cells and detector devices [17, 18]. Local field enhancement would improve the device efficiency and shrink down the size of the device.

2. Literature review and problem statement

In the localized surface plasmon resonance, conduction electrons oscillation in metal nanoparticles such as gold and silver within a short wavelength can localize the optical field in a very small space. The size and shape of these metal nanoparticles will help to localize and control the field in a very small space. The localized surface plasmon resonance could provide different optical properties in the nanoscale regime such as near field and far field enhancement. The localized surface plasmon resonance optical properties can be tuned by controlling different parameters of metal nanoparticles [18–24].

The localized surface plasmon resonance optical properties of metal nanoparticles have been employed in various practical applications such as bio-sensing, bio-imaging, and other applications. In general, these practical applications use arrays of metal nanoparticles. In [17], gold and silver nanoparticles were used to enhance energy conversion for solar cells compared to the dye-sensitized solar cells. Although, the used process was done near room temperature and without toxic materials, the glass substrate is not suitable for all practical applications. In [18], metal nanoparticles were adopted to enhance the total absorption by more than 50 % and reduce the thickness of the silicon substrate by more than 50 %. In [19], an analytical model for metal nanoparticles was used with microcavity to study radiation enhancement without the possibility for practical devices. To understand the optical properties and performance of metal nanoparticles, different studies have been conducted about the optical response of different materials and shapes of nanoparticles. For example, in [21], metal nanoparticles on an insulating substrate were deployed to study the charging effect in scanning electron microscopy but the fabrication using electron beam lithography is costly. Furthermore, in [22], a simple approach to evaluate the lifetime of a single emitter based on coupling was provided. However, separating the background photons was unsolved. In [23], a description of metal-quantum emitter nanodevices in terms of strong coupling was introduced that is limited to a single coupled mode. In [24], the strong coupling of hybrid nanostructure between semiconductor and metal surface plasmons was investigated without showing the effect of generated harmonics.

The gap between metal nanoparticles can be a very important factor in the overall optical response of metal nanoparticles. Metal nanoparticle coupled field is very sensitive to the gap between metal nanoparticles in a very small space. That is why many people become interested in investigating and studying metal nanoparticles interspacing influence on the overall optical response of the structure. In [25], the coupling between plasmonic nanocavity and monolayer materials was demonstrated for light emitting but optical nonlinearity effect was unclear. In [26], the effect of nanostructure on the overall field enhancement was studied numerically without the feasibility of real devices with similar performance.

Different metal nanostructures have been proposed for optical field enhancement such as nano-disks, nano elliptical shapes, and nanorods. In [27, 28], the influence of metal nanoparticles on infrared applications such as infrared sensing was demonstrated. Although the structure fabrication is costly to maximize the radiation power. In [29, 30], the field localization and multiresonance of twisted, closepacked and truncated nanomaterials were proposed and investigated theoretically although the structure realization will not be very simple and easy.

Strong optical localized field at a small gap between metal nanoparticles can be associated with LSPR coupled modes at nanometer gap size [31, 32]. In [31], the interference between transverse and longitudinal modes was explored toward energy transport. In [32], two layers metamaterial for resonant modes coupling was demonstrated. This can be more useful with numerical sensing ability estimation.

Understanding the optical behavior of metal nanoparticles can be done by utilizing the Lorentz-Drude model. The Lorentz-Drude model considers the effect of metal nanoparticle size and dielectric constant [15]. In [33], the multiwave interaction in the metamaterial was studied to be as a coupled resonator although not easy for fabrication. In [34], the scattering and absorption properties of nanostructures were shown theoretically that they could be controlled by incident wave polarization. However, the control and realization of the investigated structure are not simple. In [35], the metal nanocavity and field enhancement were classified in terms of the edge effect and mode transitions but the coupling effect was not considered. In [36], the field enhancement of spectroscopic measurements using metal nanostructures was demonstrated based on the nonlinear effect. In [37], the coupling between gold nanocavity and substrate was presented theoretically and experimentally. However, using different metal types like silver may give better optical performance based on optical coupling.

The localized optical field properties can be tuned by controlling the gap between metal nanoparticles in the designed structures. Different numerical analysis methods have been used to study and analyze metal nanoparticles optical response performance in the nanoscale regime such as finite element method or finite difference time domain. The distance between metal nanoparticles would influence the localized field response. The localized field within the subwavelength distance is very sensitive to the nanostructure design and environment details like the shape, size, arrangement, and dielectric contrast. Numerous kinds of nanostructures like nanorods, nanodisks, nanowires, and nanospheres have been designed to be used in various systems for their strong localized fields in the subwavelength distance. The strong localized field in the small area would enhance the collected signal. This has been deployed in many light mater interaction applications such as bio-sensing and bio-imaging applications [38–41].

During the last decade, many studies have investigated metal nanoparticles based devices for light to electrical current conversion like solar cells and electrical current conversion to light like light-emitting diodes. Therefore, quantum efficiency is a very important factor to evaluate the overall performance of the device. Using metal nanoparticles would increase the scattering near the surface, which have improved the quantum efficiency and increased the time response of interaction. This could be due to the absorption increment between two materials. Metal nanoparticles localized field could increase the interaction, which would lead to high absorption then enhance the optical response of the device. Metal nanoparticles show very good light interaction, which leads to exciting the localized surface plasmons resonance at a certain incident wavelength. The optical response strongly depends on the metal type, nanostructure design, and surrounding dielectric constant [40–42].

This would highly enhance the field at the surface of metal nanoparticles, which is very important for different optical devices and applications. The metal nanoparticles distribution and the distance between them strongly affect the overall optical response of the nanodevice. In the region of the subwavelength area, the localized field would be very sensitive to any change in the metal type, distance between nanoparticles, interface materials, nanoparticles density. To understand the mechanism of field enhancement, numerous studies have been conducted using numerical investigation and experimental exploration. Mie theory and finite element method and finite difference time domain method have been deployed to show the key factors influencing the field enhancement. For instance, silver nanoparticles have been found to provide a better optical response than gold nanoparticles in terms of field intensity and distance between nanoparticles effect [37–43].

Localized field enhancement of metal nanoparticles is very important for different practical applications such as sensing and light harvesting. Normally optoelectronic devices fabrication is based on a very thick layer to collect high electricity. However, this would degrade the device efficiency and increase the total cost. Therefore, the thickness needs to be reduced to be away smaller than the carrier diffusion length. The carriers recombination would be also decreased when the thickness is decreased. This would strongly improve the overall device efficiency. In this work, the optical response of silver nanoparticles placed on a silicon substrate was investigated. Silver nanoparticles could improve light harvesting leading to light confinement enhancement that would be useful for different applications. A strong optical field based on metal nanoparticles has been shown, which could be very beneficial for different applications such as bio-sensing, bio-imaging, and light detections and harvesting.

3. The aim and objectives of the study

The aim of the study is to investigate the optical field enhancement near the metal nanoparticles and study the influence of the metal type, size, and space between the metal nanoparticles on the overall LSPR performance. Since this investigated structure is pursuing localized field enhancement. This will allow using it for energy harvesting devices like solar cells and detectors.

To accomplish the aim of this study, the following objectives were considered:

– to investigate the optical response of gold and silver nanoparticles;

– to investigate the optical response of silver nanoparticles to find an appropriate size;

– to evaluate the optical response of silver nanoparticles at different gap values and show the influence of the distance between nanoparticles on the field enhancement.

4. Materials and methods

The investigated structure is based on using metal nanoparticles to enhance light harvesting. Gold and silver nanoparticles were deployed in the investigated structure. The investigated structure consisted of metal nanoparticles of the same radius (r) placed on a silicon substrate, as shown in Fig. 1. The optical response of each type of metal nanoparticles was investigated. The optical performance at different silver nanoparticles size was explored. A gap distance (g) was set between silver nanoparticles to study the influence of the distance between silver nanoparticles on the optical response. However, the used metal nanoparticles size was kept below 100 nm.

This research was carried out using frequency domain simulation based on the finite element method. A normal incident and linearly polarized plane wave source was deployed and applied on the investigated nanostructure to examine the optical behavior. The wavelength range of the used light source was fixed from ~300 nm to 800 nm. The optical properties of the used metal are based on Johnson. Based on that, the overall optical response for the proposed structure was evaluated. The optical response and the influence of the silver nanoparticles size and the distance between nanoparticles on the field enhancement were carefully investigated.

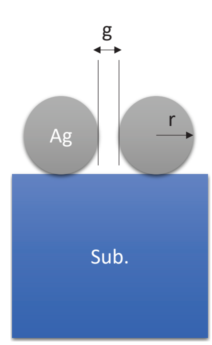

Fig. 1. Scheme of the investigated structure

The spherical shape of silver nanoparticles was chosen because it is easy to synthesize for the sake of realization of this structure.

5. Optical performance evaluation results

Metal nanoparticles have a very unique optical response when interacting with light. These efficient optical properties are due to collective oscillations of electrons, which can be excited by light. These wave oscillations enhance the scattering and absorption of metallic nanoparticles significantly.

5. 1. Optical response of gold and silver nanoparticles

In this section, the optical response of gold nanoparticles has been examined, as shown in Fig. 2, using frequency domain simulation based on the finite element method. In addition, the silver nanoparticles have been examined and shown better optical response than gold, as shown in Fig. 2, which could be due to the dielectric function of silver.

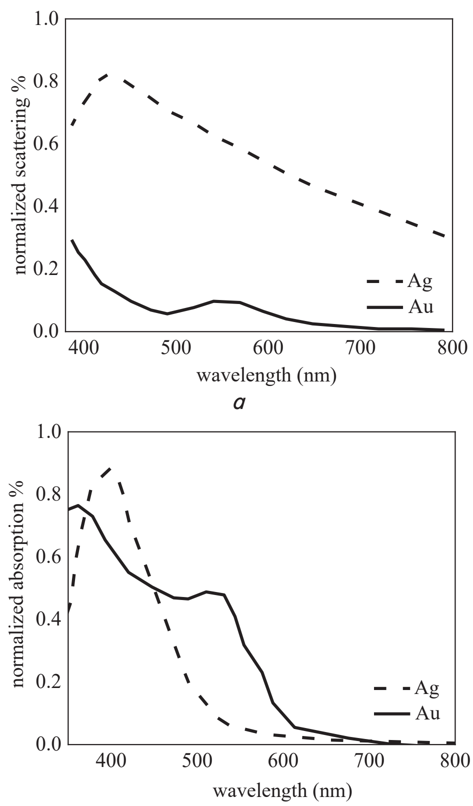

Fig. 2. Optical response of gold (Au) and silver (Ag) nanoparticles: *a* – scattering; *b* – absorption

From Fig. 2, we can see that the scattering and absorption wavelength of silver nanoparticles is about 400 nm and the scattering and absorption wavelength for the gold nanoparticles is about 550 nm.

In this investigated structure, the spherical shape of silver nanoparticles has been chosen, as shown in Fig. 1. The spherical shape metal nanoparticle was mostly chosen because it is more convenient to prepare and it is a symmetrical shape that can save time and resources during calculations. The optical response of the investigated structure depends on the nanoparticle radius. Also, it is worth mentioning that small-radius nanoparticles absorb incident light with peaks wavelength around (~400 nm). However, large radius nanoparticles show high scattering with widened response and peaks wavelength redshifted, as shown in Fig. 2.

5. 2. Optical response of silver nanoparticles

In Fig. 3, *a*, *b*, the absorption and scattering spectra are shown for silver nanoparticles. The optical response of silver nanoparticles could be adjusted through tuning the radius, shape of nanoparticles, and mesh size.

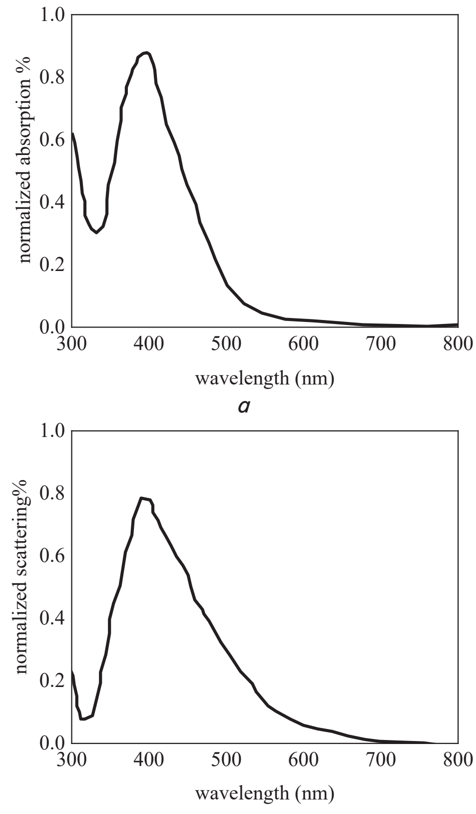

Fig. 3. Optical response of silver nanoparticles: *a* – scattering; *b* – absorption

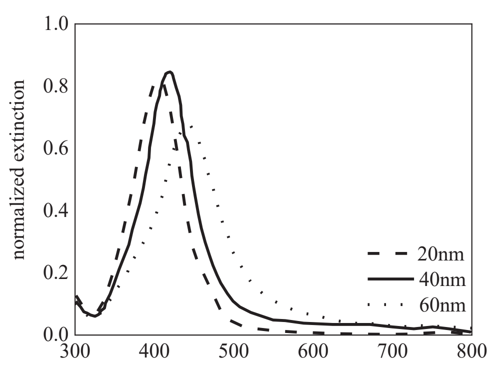

Fig. 4. Optical response of silver nanoparticles at different diameters

The metal type and shape are strongly related to the field intensity enhancement [11, 15]. The optical response is directly related to the metal nanoparticles size, i. e. diameter, based on that different diameter values have been used to find the better optical response. As shown in Fig. 4, the silver nanoparticles with 40 nm provided the best optical response.

5. 3. Optical response of silver nanoparticles at different gap values

For metal nanoparticles, when two or more nanoparticles are put together and close to each other, plasmon coupling would exist in between these metal nanoparticles. This plasmon couple would strongly enhance the optical response in the device due to the strong interaction between light and metal [22–25]. The gap between the nanoparticles could play a vital role in controlling this plasmon coupling and the overall optical response eventually.

Therefore, it is necessary to investigate the field enhancement, which is caused by deploying silver nanoparticles. In addition, it is very important to study the gap between silver nanoparticles influence on the optical response as well.

Based on that, the gap between silver nanoparticles effect was explored, as shown in Fig. 5.

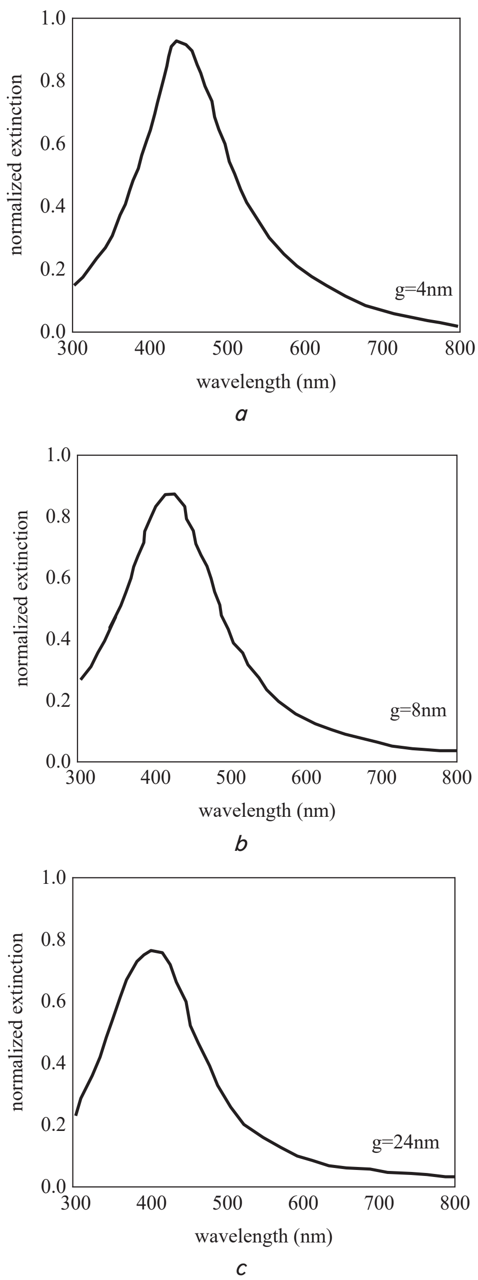

Fig. 5. Optical response of silver nanoparticles at different gap values (g): *a* – 4 nm; *b* – 8 nm; *c* – 24 nm

It was shown that the optical response is very sensitive to the gap between silver nanoparticles. Different gap values were used to study the effect on the optical response. It was noticed that there is a redshift in the optical response as the gap value decreased in addition to the amplitude value increment, as shown in Fig. 5, *a–c*. The field enhancement can be very beneficial for many applications like SERS (Surface Enhanced Raman Spectroscopy) [11, 12].

6. Discussion of the results of the optical response of metal nanoparticles

Investigating the localized optical field can provide the key parameters to design different nanostructures for different functions based on field concentration.

For metal nanoparticles like gold and silver nanoparticles, they exhibit certain localized optical field due to the type of metal or its dielectric function. The strong optical field is localized at the nanoparticles surface at a certain resonance wavelength like 550 nm for gold, as shown in Fig. 2.

The shape and size of metal nanoparticles can influence the optical response. Therefore, silver nanoparticles with different diameters were examined. The size of 40 nm provided a better optical response. Also, it was noticed that metal nanoparticles resonance wavelengths would have redshift or blue shift due to the size and index. Furthermore, the resonance wavelengths would be broadened and redshifted with increasing metal nanoparticles size. This would give an opportunity for controlling the optical response, for instance, blue shift or redshift could strongly enhance the local near field in the UV or red and near-IR spectrum as shown in Fig. 3, 4. Typically, this could be useful for many practical applications. It is worth noting that the scattering is not strong in the small metal nanoparticles. The absorption depends on the size, the physical properties of materials, and the time response of absorbed energy. These parameters need to be considered carefully to avoid the dissipation of energy.

Optical coupling between metal nanoparticles can happen in the nanoscale regime and lead to a strong optical field concentration. The influence of a small gap between nanoparticles on the field concentration within a small space was explored pursuing field enhancement. With a 4 nm gap, the field enhancement was about ~20 %. When the gap between nanoparticles increases, a blue shift of the resonance wavelength happened. The near field coupling could happen when nanoparticles are put close to each other. When the incident light is in parallel with the direction of silver nanoparticles. The coupling modes are very sensitive to the gap between nanoparticles as shown in Fig. 5. Moreover, high field scattering can happen with a large diameter and small metal nanoparticles of diameter 40 nm with a small gap between metal nanoparticles help to more enhance the local field as shown in Fig. 5.

This simple, easy, and cost-effective nanostructure with field enhancement can be an appropriate structure for energy harvesting devices like solar cells and detectors.

7. Conclusions

1. Silver nanoparticles exhibited better optical response than gold nanoparticles. However, it was shown that the resonance frequencies of both of them were different (~400 nm and 550 nm).

2. Moreover, it was shown that the silver nanoparticles size and the surrounding index play an important role to widen, narrow, and shift the optical response. In this work, the silver nanoparticles of (40 nm) diameter exhibited better optical response than other used values.

3. Furthermore, the coupling between silver nanoparticles and metal type play a vital role in light harvesting enhancement. As a result, the optical response will be red-shifted when the gap value between silver nanoparticles decreased and the peak intensity increased approximately by (~20 %).

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