

RESEARCH ARTICLE

Fano Resonance in Plasmon–Exciton Coupling in Au/Ag–Si Nanoparticles Coupled with WS₂ Monoatomic Layer

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ABSTRACT: We present a comprehensive numerical modeling of Fano resonance induced by plasmon-exciton coupling (PEC) in hybrid nanostructures composed of a Ag/Au core and a monolayer WS₂ shell. The study is based on Maxwell-Garnett effective-medium to homogenize a concentric core of metal and silicon and Mie theory. We are aimed to examine the impacts of the core radius and shell thickness on the absorption efficiency, PEC strength, and generated Fano resonance, including resonance tuning, cavity dissipation, and hybrid-mode formation near the WS₂ A-exciton around 2.005618 eV. The study compares the efficiency of gold and silver in the proposed metal–Si-WS₂ core-bishell architectures. The results are used to distinguish strong PEC from mere spectral splitting by evaluating the exciton linewidth, cavity decay rate, coupling strength, and Rabi splitting. We show that Ag-Si-WS₂ nanoshells achieve the most favorable balance between tunability and low dissipation, which produces clear Fano resonance with hybrid splitting. The smallest Ag-Si and Au-Si structures are shown to achieve the highest PEC strength. Au-Si-WS₂ nanoshells exhibits clear Fano resonance appearance but in the weak regime of PEC due to larger cavity dissipation. These findings identify AgSi- WS₂ as practical design guidelines for future plexcitonic nanodevices.

Keywords: Nanophotonics, Fano Resonance, Surface Plasmonics, Excitons, Hybrid Nanostructures.

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1. INTRODUCTION

Plasmon–exciton coupling (PEC) is a central topic in modern nanophotonics because they enable control of light–matter interactions at subwavelength scales. The localized surface plasmon of a metal nanoparticle (NP) can interact with an excitonic transition in a semiconductor or molecular emitter to form new hybrid states. The properties of these hybrid states differ fundamentally from those of the uncoupled constituents [1–4]. The PEC, including asymmetric Fano-

type line shapes, is attractive for next-generation nanophotonic devices, such as ultrafast optical switches, low-threshold nanolasers, sensitive biosensors, nonlinear platforms, and quantum light sources [5–8]. Monolayer WS₂ is a prominent excitonic material due to its direct band gaps and strong A-exciton resonance in the visible (~619 nm), which makes it an appealing quantum emitter for coupling to plasmonic nanocavities [9–14]. The atomic-scale thickness allows efficient interaction with tightly confined electromagnetic fields near metallic or dielectric nanostructures. Therefore, WS₂ provides a versatile platform for engineering coherent light–matter coupling and Fano-resonant spectral features.

The cavity design is crucial for PEC. Achieving spectral overlap of the plasmonic field of bare metallic NPs (Ag, Au) with the WS₂ exciton requires relatively large particles with broadened linewidths and higher-order multipolar

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contributions [15-20]. These factors can mask strong PEC signatures and distort Fano line shapes in absorption spectra. Core-shell and core-bishell architectures have emerged as a powerful solution to optimize this trade-off [21-26]. Introducing a Si interlayer between the metal core and the WS₂ monolayer can simultaneously redshift the plasmon resonance, act as a spacer that suppresses nonradiative quenching and enhance environmental stability. Also, the Si layer preserves a confined optical mode that couples efficiently to the WS₂ exciton, making metal-Si-WS₂ hybrids core-bishell NPs promising candidates for realizing pronounced Fano-resonance features. The research challenge is then how to engineer Ag- and Au-based core-bi-shell architectures to exhibit clear and quantifiable Fano-type spectral signatures.

In this paper, we perform a systematic theoretical investigation of PEC in Ag-Si-WS₂ and Au-Si-WS₂ hybrid nanostructures. The main aim is to determine which platform is more favorable for achieving coherent hybridization with well-resolved Fano-resonance line shapes. The analysis is based on Mie theory for multilayer spheres [27] and effective-medium description of the metal-silicon nanoshell [28-30]. Because exciton generation in the WS₂ monolayer is fundamentally an absorptive process, and photoluminescence measurements correlate with the absorption efficiency at the pump wavelength [31, 32], we investigate the appearance of Fano-resonance in the spectra of the absorption efficiency. By scanning the core radius and silicon shell thickness, the study identifies the geometries that bring the plasmonic resonance into coincidence with the WS₂ A-exciton. The results demonstrate that the Ag-Si nanoshell can support a sufficiently narrow and spectrally tunable plasmon resonance to produce clear hybrid splitting with Rabi splittings on the order of 113 meV. In small-size NPs, the two hybrid structures satisfy the strong PEC condition [7], confirming coherent plasmon-exciton exchange rather than a merely dissipative resonance enhancement. In large-size NPs, Au-Si-WS₂ hybrids remain less effective despite exhibiting spectral doublets due to their higher cavity losses. The present analysis provides a clear theoretical basis for understanding why Ag-Si-WS₂ outperforms the corresponding Au-based and all-dielectric alternatives in the pursuit of strong plasmon-exciton coupling.

The next section introduces the simulation model of the hybrid core-shell nanostructures for PEC including Mie theory and effective-medium method of the metal-silicon nanoshell. In Section 3, we present the results of absorption efficiency of Ag/Au-Si and PEC in hybrid nanostructures of Ag-Si-WS₂ and Au-Si-WS₂. Finally, the conclusions appear in Section 4.

2. METHODOLOGY

Figure 1 is a schematic of the proposed hybrid nanostructure Ag-Si or Au-Si nanoshell enveloped by a WS₂ monolayer with thickness of $t=0.7$ nm. The Ag/Au-Si nanoshell consists

of a spherical Ag/Au core with core radius R_c and Si shell of thickness d , with a total radius of $R = R_c + d$. The host medium is assumed to be air. We investigate the absorption response of the hybrid system of concentric isotropic spheres by employing the approach developed by Aden and Kerker [33,34] based on Mie theory for core-single shell structures. For the Ag-Si-WS₂ and Au-Si-WS₂ structures, we employ the effective medium method [28-30] to simplify the Ag/Au-Si nano-shell into a homogeneous particle with an effective dielectric function. Consequently, the entire hybrid system can be represented as a core-shell configuration, with the core being the equivalent Ag/Au-Si particle and the shell being the WS₂ layer. The Si shell, which minimizes photothermal heating in the WS₂ layer [35], provides an effective free parameter to tune the plasmon resonance while maintaining desirable spectral characteristics of the resonance peak.

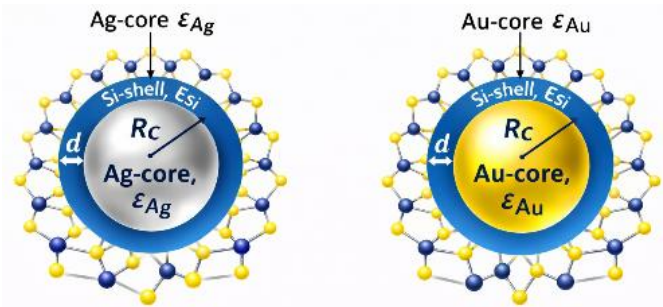


Fig. 1. A schematic of a simple experimental setup with a single Ag-Si and Au-Si nanoshell enveloped by a WS₂ monolayer.

The Maxwell-Garnett (M-G) approach [28-30] describes the extinction spectra of Ag-Si and Au-Si nanoshells when treated as a homogenous particle with equivalent or effective optical permittivity. The effective permittivity, ϵ_{eff} , of the equivalent particle of the Ag-Si or Au-Si nanoshell is given by [36]

$$\epsilon_{eff}^m = \epsilon_{Si} \frac{(\epsilon_m + 2\epsilon_{Si}) + 2f_{corr}(R_c)(\epsilon_m - \epsilon_{Si})}{(\epsilon_m + 2\epsilon_{Si}) - f_{corr}(R_c)(\epsilon_m - \epsilon_{Si})} \quad (1)$$

where ϵ_{eff}^m is the effective permittivity of the equivalent solid particle, $m = (\text{Ag or Au})$ denotes the metallic core material, ϵ_m is the dielectric function of the metallic core, and ϵ_{Si} is the dielectric function of the Si shell. The function $f(R_c) = R_c^3/R^3$ is the filling factor of the metal-Si nanoshell. Mie theory is then applied to evaluate the optical response of the simplified hybrid system of a spherical Ag/Au-Si NP coated by a WS₂ monolayer. The extinction and scattering efficiencies are expressed as follows [37]:

$$Q_{ext} = \frac{2}{\alpha^2} \sum_{n=1}^{\infty} (2n+1) \text{Re}(a_n + b_n) \quad (2)$$

$$Q_{sca} = \left(\frac{2}{\alpha^2}\right) \sum_{n=1}^{\infty} (2n+1) \text{Re}(|a_n|^2 + |b_n|^2) \quad (3)$$

$$Q_{abs} = Q_{ext} - Q_{sca} \quad (4)$$

where a_n and b_n are the electric and magnetic Mie-like coefficients for spherical nanoshells, $\alpha = 2\pi R_s/\lambda$ is a size parameter where $R_s = R + t$ is the total radius of the reduced structure, and λ is the wavelength of light. We applied the precise algorithms developed by Toon and Ackerman to calculate the Mie-like coefficients a_n and b_n , as reported in Ref. [37].

The Lorentz–Drude model is applied to describe the dielectric function of the metallic core of radius R_c [38] taking into account the size-dependent damping related to electron–surface scattering [37],

$$\varepsilon_m(R_c, \omega) = \varepsilon(\omega)_{exp} + \frac{\omega_p^2}{\omega^2 + i\omega\Gamma_0} - \frac{\omega_p^2}{\omega^2 + i\omega\Gamma} \quad (5)$$

with $m = Ag, Au$. $\varepsilon(\omega)_{exp}$ is the experimental bulk dielectric function, ω_p is the bulk plasma frequency, and Γ_0 is the bulk collisional frequency. $\Gamma = \Gamma_0 + \frac{Av_f}{2R_c}$ represents the modified bulk collisional frequency that takes into account the size-dependent electron scattering effect. v_f is the Fermi velocity, and $A \sim 1$ is a theory-dependent parameter [38]. The function $\varepsilon(\omega)_{exp}$ is given by [39]:

$$\varepsilon(\omega)_{exp} = 1 - \frac{\Omega_p^2}{\omega^2 + i\omega\Gamma_0} + \sum_{j=1}^p \frac{f_j \omega_p^2}{(\omega_j^2 - \omega^2) - i\omega\Gamma_j} \quad (6)$$

where $\Omega_p = \sqrt{f_0} \omega_p$ with oscillator strength f_0 and damping constant Γ_0 . The contribution of interband transitions to the dielectric constant is determined by the third term. In this study, we employ the values for Ω_p , ω_j , Γ_j , and f_j reported by Johnson and Christy [40]. The permittivity of Si and WS₂ are extracted from the experimental data reported in Refs. [41] and [42], respectively.

3. RESULTS AND DISCUSSION

The excitons are generated by a monoatomic WS₂ shell with thickness of 0.7 nm. Figure 2 displays the absorption spectrum of a WS₂ monolayer surrounding an air core, which is dominated by the A exciton. This appears as resonant enhancement with a linewidth that reflects the excitonic dissipation rate γ_{ex} . The absorption data show a clear, highly systematic radius dependence. As the air-core radius

increases from 10 to 100 nm, the absorption response strengthens strongly; the spectral maximum shifts slightly to lower energy, and the excitonic feature becomes much more pronounced. Numerically, the peak value of Q_{abs} rises from about 0.148 at $R = 10$ nm to about 0.532 at $R = 100$ nm, which is roughly a 3.6 times enhancement. At the same time, the energy of the maximum shifts from about 2.008 eV to about 2.024 eV. That is, the resonance position is comparatively stable within the excitonic region while the amplitude changes strongly.

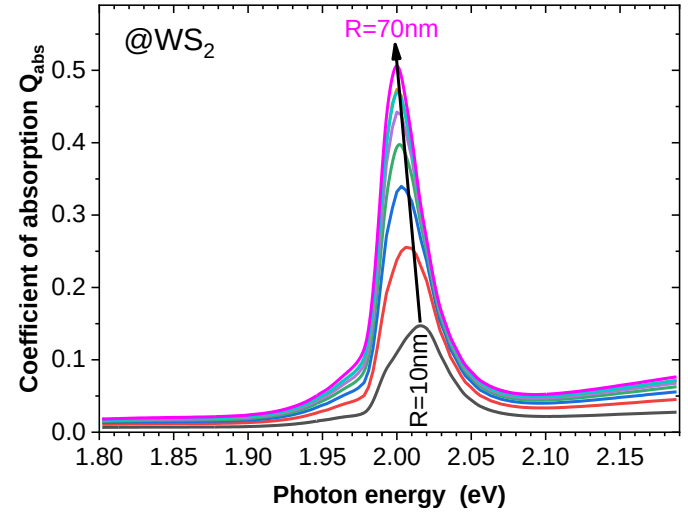


Fig. 2. Absorption efficiency spectra Q_{abs} of WS₂ nanoshell with thickness of 0.7 nm enclosing an air-core of radii ranging between $R_c = 20$ and 100 nm.

The broadening of Q_{abs} contains contributions from intrinsic exciton damping, radiative broadening, and geometry-dependent electromagnetic coupling. The baseline-corrected full width at half maximum (FWHM) decreases from approximately 43 meV at $R = 10$ nm to approximately 30 meV at $R \geq 50$ nm. This behavior indicates reduced effective damping of the excitonic mode and improved spectral definition at larger core radii. FWHM measures twice the excitonic (quantum emitter) dissipation rate γ_{QE} , whose extracted values are $\gamma_{QE} = 21.5, 20.5, 18.5, 17.4$, and 16.5 meV when $R = 10, 20, 30, 40$ and ≥ 50 nm.

In Figures 3(a) and (b), we characterize examples of the absorption efficiency of Ag-Si and Au-Si, respectively, combined nanosphere with core radius $R_c = 30$ nm. The Si-shell thickness ranges between $d = 2$ and 14 nm. Figure 3(a) of the Ag-Si shows a progressive redshift of the dominant dipolar absorption peak as the thickness d increases. The observed tunability is governed by the interplay between the Ag core and dielectric Si shell as captured by the Maxwell–Garnett effective-medium description. Changing the thickness d modifies the metal filling factor $f(R_c) = R_c^3/R^3$ and the effective permittivity ε_{eff}^m of the equivalent homogeneous NP, which control the spectral position of the dipole plasmon supported by the core–shell structure. From

the Mie-theory standpoint, the symmetric dipole-like mode in the Ag-Si nanoshell corresponds to the lowest-order electric multipole ($n = 1$) of the equivalent sphere, whose resonance condition can be approximated by $\text{Re}[\varepsilon_{\text{eff}}^m(\omega)] \approx -2\varepsilon_{\text{med}}$. Increasing the thickness d increases the effective refractive index seen by this mode and shifts the resonance to lower energies, while modifying its radiative damping and hence its linewidth [43]. In a nanoscience sense, the Ag-Si NP behaves like a compact resonant cavity whose frequency can be tuned through the excitonic window without destroying the mode quality. Figure 3(b) shows the analogous tuning behavior for Au-Si NP, but with the increase of the Si shell thickness increases, the absorption efficiency remains lower and the lines are more damped than in the Ag NP. This is consistent with the larger intrinsic optical dissipation of Au in the visible due to interband absorption [43], which makes Au less favorable than Ag for achieving strong PEC.

Table 1 lists the numerical values of the resonance energy $\hbar\omega_{\text{cav}}$, absorption peak $Q_{\text{abs(max)}}$ and decay rate γ_{cav} of the plasmonic cavities Ag-Si and Au-Si as functions of the Si shell thickness d . The table indicates that a single dipolar plasmon peak can be continuously swept across the 1.957 –

2.248 eV window for the Ag-Si NP and the 1.765 – 2.311 eV range for the Au-Si window by adjusting the Si coating while keeping the metal core fixed. Also, the table shows a monotonic redshift of the symmetric mode with increasing the shell thickness d . Ag-Si nanoshells offer a broad and controllable design to align the plasmon resonance with the WS₂ exciton energy around $\hbar\omega_{\text{ex}} = 2.005$ eV, whereas the Au-Si nanoshells show a similar trend. The values of the plasmon cavity decay rate $\gamma_{\text{cav}} = \text{FWHM} / 2$ are shown to decrease with the increase of d , which is seen in Fig. 3 as narrowing of the absorption spectrum. The values of γ_{cav} of the Au-Si NP are larger than those of the Ag-Si NPs, which is attributed to the larger intrinsic optical dissipation of Au in the visible-light regime due to interband absorption.

From here, we are concerned with the main findings of this study, presenting PEC in the proposed hybrid Ag-Si-WS₂ and Au-Si-WS₂ to the larger intrinsic optical dissipation of Au in the visible-light regime due to interband absorption systems. First, we adopt the pairs of metal core radius R_c and Si-shell thickness d of the Ag-Si and Au-Si NPs that yield absorption spectra with a peak energy $\hbar\omega_{\text{res}}$ coincident with the excitonic resonance $\hbar\omega_{\text{res}}$ of the monolayer WS₂ shell.

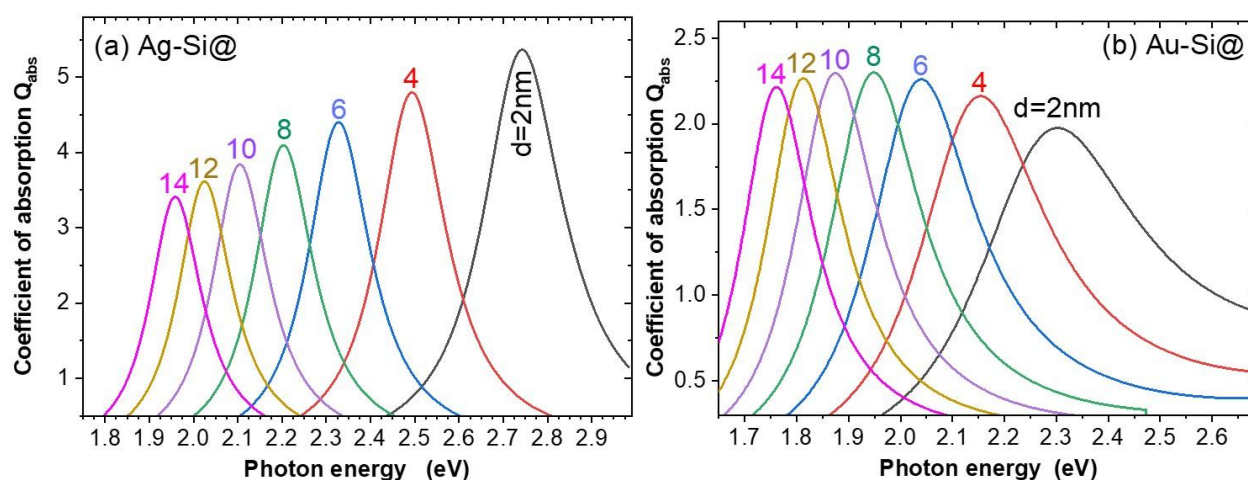


Fig. 3. Energy spectra of the absorption coefficient Q_{abs} of (a) Ag-Si NP and (b) Au-Si NP with metallic core radius $R_c = 30\text{nm}$ and Ag/Au-shell thicknesses of $d = 8 \sim 14\text{nm}$ that result in plasmon resonance (λ_{cav}) in the regime of the excitonic resonance energy in Fig. 2.

Table 1. Values of resonance energy $\hbar\omega_{\text{cav}}$, absorption peak value $Q_{\text{abs(max)}}$ and decay rate γ_{cav} of the Ag-Si and Au-Si combined NPs as functions of the Si shell thickness d .

Ag-Si NP				Au-Si NP		
d (nm)	$\hbar\omega_{\text{cav}}$ (eV)	$Q_{\text{abs(max)}}$	γ_{cav} (meV)	$\hbar\omega_{\text{cav}}$ (eV)	$Q_{\text{abs(max)}}$	γ_{cav} (meV)
2	2.746	5.36	113	2.311	1.98	243
4	2.492	4.80	95	2.162	2.16	166
6	2.328	4.40	88	2.048	2.26	135
8	2.204	4.10	83	1.957	2.30	116
10	2.103	3.84	80	1.883	2.30	103
12	2.025	3.62	76	1.820	2.27	94
14	1.957	3.41	75	1.765	2.22	87

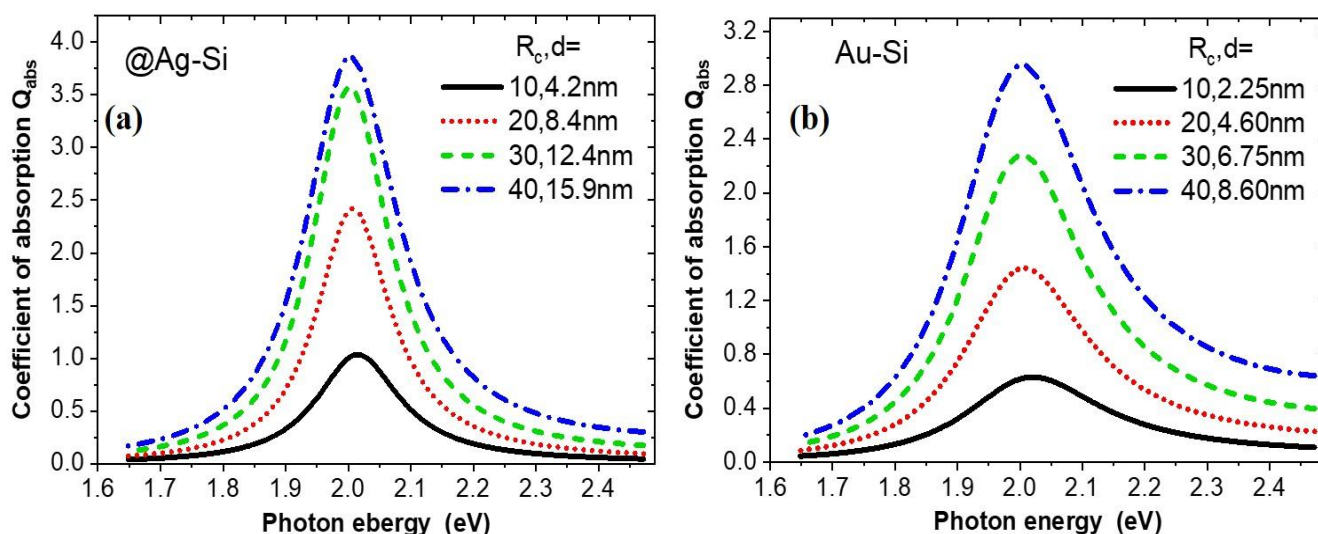


Fig. 4. Absorption efficiency Q_{abs} of (a) Ag-Si with $(R_c, d) = (10, 4.2), (20, 8.4), (30, 12.4), (40, 15.9)$ -nm, and (b) Au-Si NP with $(R_c, d) = (10, 2.25), (20, 4.60), (30, 6.75), (40, 8.60)$ -nm, with peak plasmonic resonance energy $\hbar\omega_{\text{res}}$ coincident with the exciton-resonance energy $\hbar\omega_{\text{res}}$ of the WS₂ shell.

Table 2. Plasmonic decay rates in Ag-Si and Au-Si NPs, as extracted from Figures 4(a) and (b).

R_c (nm)	Ag-Si core shell		Ag-Si core shell	
	d (nm)	γ_{cav} (meV)	d (nm)	γ_{cav} (meV)
10	4.20	81	2.25	105
20	8.40	72	4.60	127
30	12.40	75	6.75	125
40	15.90	90	8.60	137
50	4.20	81	2.25	105

Figure 4(a) shows the absorption spectra $Q_{\text{abs}}(\lambda)$ of the bare Ag-Si nanoshells using geometrical sets as $(R_c, d) = (10, 4.2), (20, 8.4), (30, 12.4),$ and $(40, 15.9)$ nm. The figure shows that the Ag-Si cavity can be tuned into spectral coincidence with the WS₂ exciton with resonances sufficiently narrow to preserve cavity quality. The extracted cavity decay rates are $\gamma_{\text{cav}} = 94.209, 81.169, 99.105,$ and 95.841 meV for the core-radii $R_c = 10, 20, 30$ and 40 nm, respectively. That is, resonances are achieved without the severe broadening accompanied with large bare Ag particles, which indicates that the Si shell effectively compensates for the mismatch between the metal plasmon and the exciton energy, which represents the key physical prerequisite for the later hybrid splitting demonstrated in Figure 5(a).

Figure 5(b) gives analogous absorption spectra for Au-Si nanoshells, tuned also to approach the WS₂ exciton energy. The selected geometries bring the plasmonic resonance near λ_{ex} , but the peaks are broader and more damped than in the Si-Ag NP. The decay rate γ_{cav} reaches 015 meV for the smallest core and remains high at 127–131 meV for the larger particles due to the intrinsic optical loss of Au in the visible light that penalizes the resonance quality even when spectral alignment is achieved. Table 2 compares the cavity

dissipation rates γ_{cav} for the Ag-Si and Au-Si nanoshells selected to resonate in the regime of the WS₂ exciton. The Ag-Si geometries exhibit substantially smaller losses, with γ_{cav} ranging from 81 to 90 meV, whereas the corresponding Au-Si resonances are much broader, reaching 105 meV for the smallest core. This contrast highlights the advantage of Ag as a low-loss plasmonic core for plexcitonic design. Table 2 is then a guide to stronger PEC in the Ag-Si-WS₂ system than the Au-Si-WS₂ counterpart.

The absorption efficiency spectra of the full Ag-Si-WS₂ and Au-Si-WS₂ hybrid structures are characterized in Figs. 5(a) and (b), respectively. The magnetic Mie resonance of metal-Si compound NP is tuned to the WS₂ exciton energy $\hbar\omega_{\text{ex}}$. This spectral overlap leads to a pronounced modification of the absorption line shape; the observed peak broadening and asymmetric Fano-interference profile indicate PEC. The strong coupling regime can be observed when the Rabi-splitting energy Ω_R exceeds the sum of γ_{QE} and γ_{cav} :

$$\text{Condition} \quad : \quad \frac{\Omega_R}{(\gamma_{\text{QE}} + \gamma_{\text{cav}})} > 1 \quad (7)$$

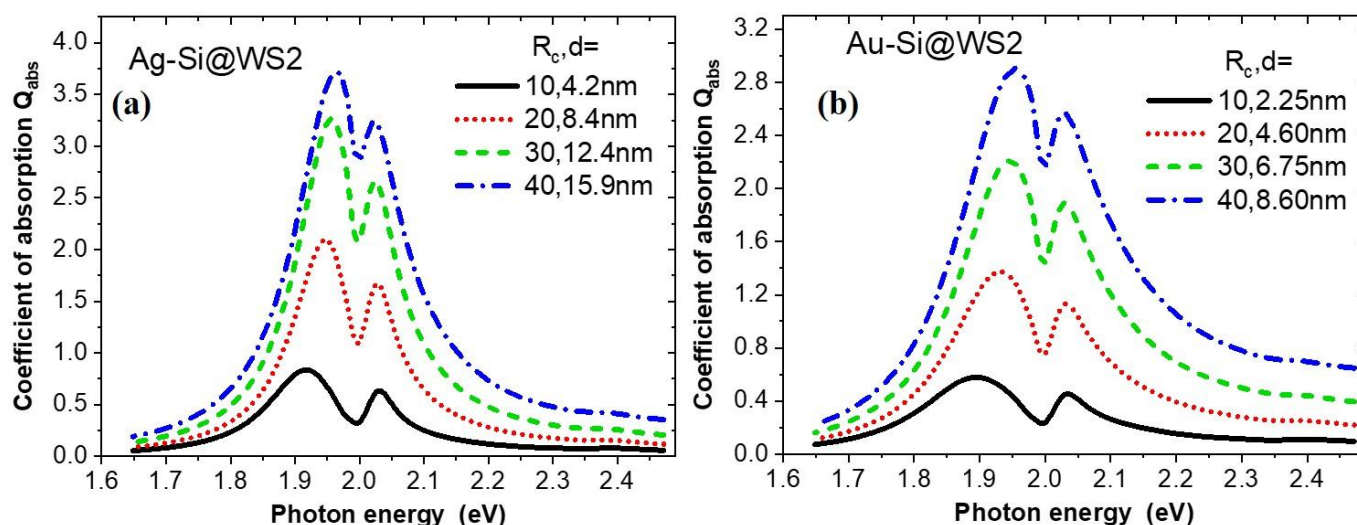


Fig. 5. The doublet absorption spectrum of the coupled (a) Ag-Si-WS₂ with $(R_c, d) = (10, 4.2), (20, 8.4), (30, 12.4), (40, 15.9)$ -nm, and (b) Au-Si-WS₂ with $(R_c, d) = (10, 2.25), (20, 4.60), (30, 6.75), (40, 8.60)$ -nm at plasmon–exciton resonance in air. The Rabi-splitting energy decreases from 113 to 58 meV with the increase of R_c from 10 to 40 nm for the Ag-Si-WS₂ system, while the corresponding decrease in the Au-Si-WS₂ system is from 137 to 76 meV.

Figure 5(a) clearly presents Fano-resonance like spectra of the Ag–Si–WS hybrid system, where the coupled system develops two distinct hybrid modes and a clear dip at the excitonic resonance energy $\hbar\omega_{ex}$. The appearance of a split absorption profile along with Fano-like asymmetry indicates either coherent plasmon–exciton hybridization or simple spectral superposition depending on the ratio of Ω_R to $(\gamma_{QE} + \gamma_{cav})$, as given in condition eq. (7). The extracted Rabi energy-splitting decrease from 113 meV for $(R_c, d) = (10, 4.20)$ nm to 58 meV for $(40, 15.90)$ nm, which points out that the PEC strength is geometry dependent and weakens as the cavity becomes larger and more dissipative. The Ag–Si–WS₂ system gives favorable balance between resonance alignment, linewidth, and splitting amplitude. The hybrid eigenmodes are born from the coherent exchange of energy between the excitonic transition and the plasmonic cavity mode [44, 45]. The lower-energy and higher-energy branches are no longer purely excitonic or purely plasmonic.

Figure 5(b) shows the corresponding coupled spectra for Au–Si–WS₂, where doublet-Fano line shapes are also observed around the exciton energy. The extracted splittings, from 137 meV down to 76 meV as R_c increases from 10 to 40 nm, are sizable but smaller than those in the Ag-based system; they occur on top of much larger cavity losses. This means that the spectral splitting is partly masked by dissipation, so the hybridization is less coherent even though the spectral signature may look similar. This distinction is important because a split spectrum alone is not enough to claim strong coupling.

Figure 6 presents the dependence of the plasmon–exciton interaction on the core radius R_c for the Ag-Si-WS₂ and Au-Si-WS₂ hybrid nanostructures. The figure plots the ratio of Rabi splitting Ω_R to the total decay rate $\gamma_{cav} + \gamma_{QE}$,

which serves as a practical indicator of whether the system approaches the strong-coupling threshold. The figure indicates that the coupling ratio is highest at $R_c = 10$ nm in both Ag-Si-WS₂ (1.10) and Au-Si-WS₂ (1.08) and then falls below unity for larger cores, showing that strong PEC is only retained in the most favorable geometry of smaller-size NPs.

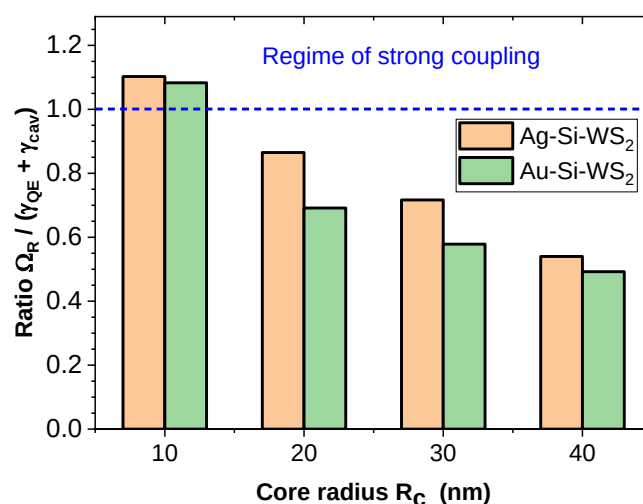


Fig. 6. Histogram of the ratio of Rabi-splitting to total decay rate $\Omega_R/(\gamma_{QE} + \gamma_{cav})$ versus the core radius R_c of the two-hybrid systems Ag-Si-WS₂ and Au-Si-WS₂ extracted from the spectra of PEC in Fig. 6.

Table 3 presents a quantitative summary of the Ag-Si-WS₂ hybrid parameters. It shows that the smallest Ag-Si geometry

$d, R_c = 10, 4.20$ nm is the only clearly strong-coupled case with the largest normalized splitting of 1.10. The larger radii move the system into Fano-interference with nearly strong or weak coupling, which is not enough for preserving coherent energy exchange. Table 4 corresponds to the parameter map for Au-Si-WS₂. Although the smallest geometry $d, R_c = 10, 2.25$ nm lies within the strong-coupling regime, all larger sizes fall into the weak-coupling region; the coupling ratio remains well below unity. These tables therefore support the conclusion that Ag-Si-WS₂ is the more promising platform, but only within a narrow geometric window.

Table 3. Physical Parameters for the Ag-Si-WS₂ System.

R_c, d (nm)	$\gamma_{cav} + \gamma_{QE}$ (meV)	Ω_R (meV)	$\frac{\Omega_R}{\gamma_{cav} + \gamma_{QE}}$	Coupling regime
10, 4.20	102.5	113	1.10	Strong
20, 8.40	92.5	80	0.87	Nearly strong
30, 12.40	93.5	67	0.72	Weak
40, 15.90	107.4	58	0.54	Weak

Table 4. Physical Parameters for the Au-Si-WS₂ System.

R_c, d (nm)	$\gamma_{cav} + \gamma_{QE}$ (meV)	Ω_R (meV)	$\frac{\Omega_R}{\gamma_{cav} + \gamma_{QE}}$	Coupling regime
10, 2.25	126.5	137	1.08	Strong
20, 4.60	147.5	102	0.69	Weak
30, 6.75	143.5	83	0.58	Weak
40, 8.60	154.4	76	0.49	Weak

4. CONCLUSIONS

This study demonstrated that dielectric-engineered plasmonic nanoshells provide an effective route for controlling PEC in WS₂-based hybrid nanostructures. By combining effective-medium homogenization with Mie theory, the work establishes how the resonance of Ag-Si and Au-Si nanoshells can be tuned into spectral overlap with the WS₂ A-exciton, revealing doublet absorption spectra with Fano-resonance. The results show that by appropriately choosing core radius and Si-shell thickness, smaller Ag-Si and Au-Si nanoshells support a sufficiently narrow and spectrally tunable plasmon resonance to produce hybrid splitting. The range of the Rabi energy splitting is 58–113 meV for Ag-Si-WS₂ system and 76–137 meV for Au-Si-WS₂ system. As the NP size increases, the coupling weakens, indicating that the strong-coupling regime is confined to a relatively narrow geometric window. For larger-size NPs, the Au-Si-WS₂ hybrids are less effective despite exhibiting apparent Fano-spectral doublets, which roots to the higher cavity losses. This distinction is essential, because a split

absorption spectrum alone does not constitute evidence of strong coupling; the criterion is whether the hybrid splitting surpasses the total linewidth of the interacting modes. The present analysis provides a clear theoretical basis for understanding why Ag-Si-WS₂ outperforms the corresponding Au-based and all-dielectric alternatives in the pursuit of strong PEC.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

All of the data obtained or analyzed during this study is included in this paper.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for the content and writing of this article.

Author's contribution statement

All authors have contributed equally to the research and preparation of this work.

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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