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Enhancement of light absorption in a quantum well by surface plasmon polariton

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We investigate analytically the degree to which the absorption of light in a single quantum well can be enhanced in the proximity of a structured metallic surface and show that the wavelength at which the maximum enhancement of about one order of magnitude is attained depends on metal loss and the initial absorption in a quantum well. © *2009 American Institute of Physics*.
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The phenomenon of electromagnetic wave propagation near the interface between a metal and a dielectric, commonly referred to as the surface plasmon polariton (SPP), was first thoroughly explored around the middle of last century,[1,2] when the technical community had keen interest in understanding and exploiting microwaves of progressively higher frequencies. However, as the frequencies increased beyond 100 GHz, the propagation losses of the SPPs became too much of an impediment. Hence as communication networks expanded into the optical range, the metallic guiding structures that utilized the propagation of SPPs have been replaced by the low-loss dielectric waveguides and optical fibers with orders of magnitude lesser loss. Still lately the interest in SPPs has experienced a resurgence with significant developments in using SPPs in enhancing the efficiency of various optical processes. The dramatic increase in the efficiency of spontaneous Raman processes has been known for years, but more recently even more basic optical properties have shown SPP enhancement. The first definite sign of improvement has been attained in GaN photoluminescence by placing a thin Ag film on the active area.[3,4] Since then, SPP enhancement in spontaneous emission has been shown in a large number of different light-emitting media. To generalize these results and reveal the ultimate potential of SPPs by establishing realistic enhancement limits, we developed a simple yet rigorous analytical model that unambiguously answered the question of how much efficiency enhancement in spontaneous emission one can obtain for a given combination of metal and dielectric, and for a given scheme of emission collection.[5,6]

In this work, we switch our attention to the use of SPPs in enhancing light absorption, which has important applications in photodetectors and solar panels.[7–9] Although the fact that increase in emissivity is always accompanied by the commensurate increase in absorbance had been noted as early as 19th century by Kirchhoff,[10] when it comes to the SPP, estimating the exact amount of absorption enhancement is not straightforward for at least three reasons. First of all, in the emission process the energy of the excited atoms couples into the continuum of SPPs and gets enhanced by the Purcell factor associated with the density of the SPP modes. But in the absorption process the light couples into one particular SPP mode and the enhancement follows a rather complex dependence on various decay rates (hence *Q*-factors) of the SPP mode. On one hand, the efficient in-coupling of light favors large radiative decay rate of the SPP mode (or small radiative *Q*-factor). On the other hand, once the light is coupled in, in order to obtain enhanced absorption by maintaining a strong SPP field, it is desirable that the SPP mode has a small overall decay rate that includes radiative, nonradiative, and absorption contributions. Second, as SPPs emitted by excited atoms propagate in every direction only a fraction of them can be coupled into radiating modes by a grating, while in the SPP absorption this is not an issue as we are dealing with a single SPP mode. Third, the SPP mode itself, when excited by the atom is characterized by a real frequency of the atomic transition while the metal losses are manifested by the imaginary part of the wave-vector. But when the SPP is excited by a plane wave via the grating the wave-vector is real and the losses must be taken into account by assigning an imaginary part to the frequency. Hence a rigorous treatment of absorption enhancement by the SPPs is needed and is the subject of this work.

Specifically, we study the absorption enhancement of an InGaN quantum well (QW) that is positioned near the GaN/Ag interface, as shown in Fig. 1, where an incident plane wave propagating in a radiation mode gets coupled into a SPP mode creating a strong field intensity that is localized near the boundary and is responsible for the absorption enhancement. The choice of InGaN material allows varying of the QW absorption edge with In composition. The wave-vector matching required for coupling of incident

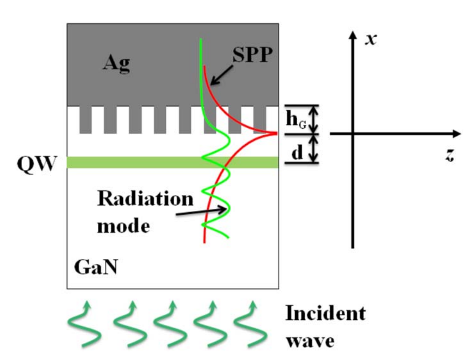

FIG. 1. (Color online) Schematic of the absorption enhancement in QW by SPP.

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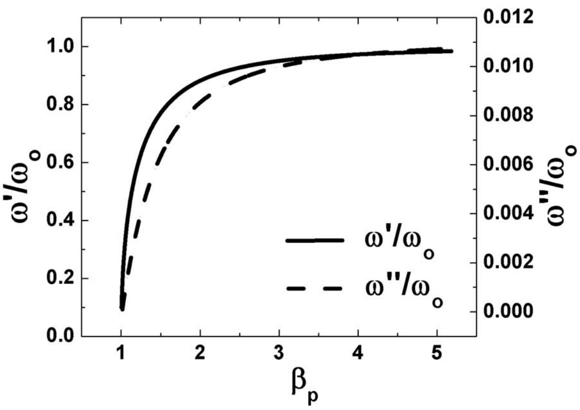

FIG. 2. Dispersion of the SPP showing its real and imaginary frequency normalized by the frequency of SPP resonance ($\hbar\omega_o$=3.161 eV).

plane wave into the SPP is provided by a grating formed at the interface. Using the notation in our earlier work on SPP,[5] the electric field of the SPP as a transverse magnetic wave at the interface between a metal layer with a Drude dielectric function $\varepsilon_M=1-\omega_p^2/(\omega^2+j\omega\gamma)$ ($\hbar\omega_p$=8.115 eV and $\hbar\gamma$=68.2 eV for Ag) and a dielectric medium with a dielectric constant ε_D=5.97 (GaN) can be written as $E_p=A_p(t)e_p(\beta_p,x)e^{j(\beta_p z-\omega t)}$ where the normalized SPP eigenmode amplitude can be obtained

$$\mathbf{e}_p(\beta_p,x)=\begin{cases}\dfrac{\sqrt{2}}{\varepsilon\sqrt{w_p(2\beta_p^2-1)}}(j\beta_p\hat{\mathbf{x}}+q_M\hat{\mathbf{z}})e^{-q_Mx}, & x>0,\\ \dfrac{\sqrt{2}}{\sqrt{w_p(2\beta_p^2-1)}}(j\beta_p\hat{\mathbf{x}}-q_D\hat{\mathbf{z}})e^{q_Dx}, & x<0,\end{cases} \tag{1}$$

with $\varepsilon=\varepsilon_M/\varepsilon_D$. All wave vectors are normalized to the radiation mode wave vector in the dielectric $k_D=\sqrt{\varepsilon_D}\omega/c$, while the coordinates are normalized to k_D^{-1}. The effective width of the SPP mode (also normalized to k_D^{-1}) is w_p,[5] and the energy density per unit area U_p is related to the SPP amplitude A_p as $|a|^2\equiv U_p=\varepsilon_o\varepsilon_D k_D^{-1}|A_p|^2$. As mentioned above, the plasmon wave vector β_p computed iteratively is shown in Fig. 2 while the frequency $\omega=\omega'-j\omega''$ is normalized to the SPP resonance frequency $\omega_o=\omega_p/\sqrt{1+\varepsilon}$. Below the resonance the SPP decay rate $2\omega''$ is small since the mode spreads into dielectric, but as it comes close to resonance the mode localization inside the metal causes the decay rate to approach $\gamma/2$ asymptotically.

Next we consider coupling between SPP and the continuum of waves that are propagating normal to the surface in the dielectric with real wave vector $k_r=1$ and are evanescent with $q_r=\sqrt{-\varepsilon}$ in the metal. These modes can be written as $E_r=A_r(t)\mathbf{e}_r(x)e^{-j\omega_r t}$ where the eigenmode

$$\mathbf{e}_r=\begin{cases}\dfrac{2k_r}{\sqrt{L_x(1-\varepsilon)}}e^{-q_rx}\hat{\mathbf{z}}, & x>0,\\ \dfrac{2k_r}{\sqrt{L_x(1-\varepsilon)}}\left(\cos k_rx-\dfrac{q_r}{k_r}\sin k_rx\right)\hat{\mathbf{z}}, & x<0,\end{cases} \tag{2}$$

is normalized on some arbitrary length L_x such that the incident power density at the surface is $|s_+|^2=(2\omega_r\varepsilon_o\varepsilon_D/k_DL_x)|A_r|^2$. The strength of coupling between SPP mode and the propagating mode is characterized by the overlap between the two modes and 50% duty cycle grating with period $\Lambda=2\pi/\beta_p$ and height h_G, $C_{rp}=[(1-\varepsilon)/2\pi]\int_0^{h_G}\mathbf{e}_p\mathbf{e}_r^*dx$. Then applying Fermi Golden Rule and noticing that the density of radiative states is $\rho(\omega_r)=L_x/2\pi\omega_r k_r$, one obtains the expression for the radiative decay rate of SPP (Ref. 5)

$$\gamma_{\text{rad}}=\frac{\omega'(1-\varepsilon)q_M^2}{2\pi^2\varepsilon^2w_p(2\beta_p^2-1)(q_M+q_r)^2}[1-e^{-(q_M+q_r)h_G}]^2, \tag{3}$$

where quantization lengths L_x in the expressions for the square of the overlap integral and density of states cancel each other. Now the in-coupling coefficient from the radiation mode to SPP can be obtained using the reciprocity between coupling and radiation discussed by Haus[11] as $\kappa_{\text{in}}=\sqrt{\gamma_{\text{rad}}}$ and we can establish the rate equation for the amplitude a of the SPP

$$\frac{da}{dt}=-\frac{1}{2}(\gamma_{\text{rad}}+2\omega'')a+\kappa_{\text{in}}s_+, \tag{4}$$

with the steady state solution for energy density

$$|a|^2=\frac{4\gamma_{\text{rad}}}{(\gamma_{\text{rad}}+2\omega'')^2}|s_+|^2. \tag{5}$$

In order to compare absorption improvement, it is necessary to obtain an energy absorption rate of SPP by the QW, $R_{\text{SSP}}=\gamma_{\text{abs}}|a|^2$, where γ_{abs} is the SPP decay rate due to the QW absorption. For absorption processes that include transitions from heavy-hole and light-hole to conduction subband, we can evaluate $\gamma_{\text{abs}}=4\pi\alpha\omega' e^{-2q_Dd}/3nw_p$ using the $\mathbf{k}\cdot\mathbf{p}$ theory,[12] where α is the fine structure constant and d is a separation between the grating and QW, and we have assumed that the reduced effective mass is close to the electron effective mass for which a standard relation $m_o/m_e\approx 2P^2/m_o\hbar\omega'$ can be used. In the absence of metal, the energy absorption rate of the normal incident wave by the same QW is related to the incident power by $R_0=\alpha_{\text{QW}}|s_+|^2$, where the dimensionless absorption coefficient of the QW that takes into account the same effective mass assumptions is $\alpha_{\text{QW}}=4\pi\alpha/3n$. This brings us to the enhancement factor

$$F=\frac{R_{\text{SPP}}}{R_0}=\frac{4Q_{\text{rad}}^{-1}}{w_p(Q_{\text{rad}}^{-1}+Q_{\text{nrad}}^{-1})^2}e^{-2q_Dd}, \tag{6}$$

where we have introduced the Q-factors, $Q_{\text{rad}}=\omega'/\gamma_{\text{rad}}$ and $Q_{\text{nrad}}=\omega'/2\omega''$ associated with both forms of decays. The result of this enhancement for a grating height of 20 nm is shown in Fig. 3 for several values of the separation d between the QW and metal-dielectric interface. While the steep reduction in F with increase in separation d is obvious, the fact that for fixed separation F has a peak at a frequency below the SPP resonance ω_o requires explanation that can be inferred from the trend in the SPP effective width w_p (also plotted in Fig. 3). At lower frequency, the SPP mode spreads out broadly into the dielectric with a large effective width, resulting in a weak in-coupling of the incident power into the SPP mode (larger Q_{rad}) As the SPP mode becomes increasingly localized with the increase in frequency, the grating height extends over a larger fraction of the SPP effective width producing an effective coupling between the incident wave and SPP (smaller Q_{rad}). With the further increase in frequency the SPP field becomes localized away from the

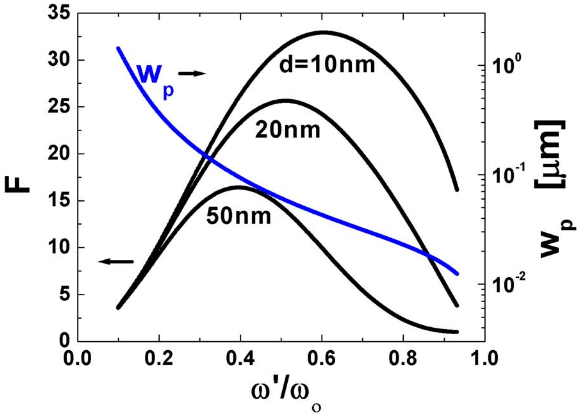

FIG. 3. (Color online) Absorption enhancement as a function of normalized frequency ($\hbar\omega_o$=3.161 eV) for several values of QW separation from the metal-dielectric interface with a fixed 1D coupling grating height h_G =20 nm. Also shown is the effective width of the SPP.

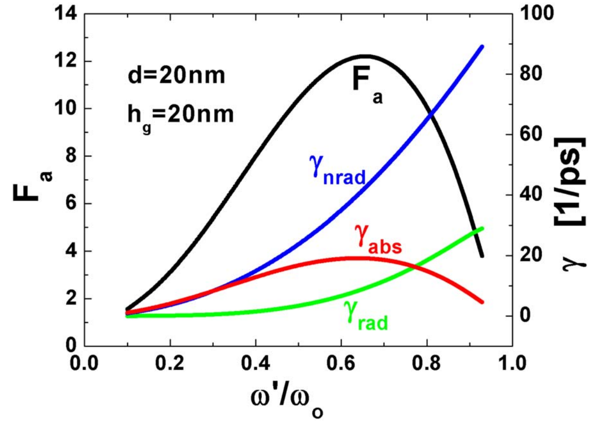

FIG. 4. (Color online) Absorption enhancement along with all decay rates of SPP as a function of normalized frequency ($\hbar\omega_o$=3.161 eV) for a single QW separated from the metal-dielectric interface d=20 nm with the grating height h_G=20 nm, taking into account the absorption decay of SPP.

QW itself and as exponential factor in Eq. (6) decays so does F.

The result in Eq. (6) predicts that the absorption enhancement is the same for all absorbers, but this is certainly not true, and, as we have shown in our previous work with metal nanoparticles,[13] the stronger the absorber the more difficult it is to enhance it. In QWs absorption is strong and thus must definitely be taken into account, which can be done by introducing additional decay rate $\gamma_{\text{abs}}a/2$ into Eq. (4). The enhancement factor in Eq. (6) can thus be modified by including another Q-factor $Q_{\text{abs}}=\omega'/\gamma_{\text{abs}}=3nw_P e^{2q_D d}/4\pi\alpha$ to obtain the enhancement factor that takes into account the QW absorption,

$$F_a = \frac{4Q_{\text{rad}}^{-1}}{w_p(Q_{\text{rad}}^{-1}+Q_{\text{nrad}}^{-1}+Q_{\text{abs}}^{-1})^2}e^{-2q_D d}. \quad (7)$$

The result is shown in Fig. 4 along with the various decay rates of the SPP. In comparison with the result obtained by ignoring the absorption (Fig. 3), the enhancement is reduced by a factor of 2, and the peak of the enhancement is shifted toward the SPP resonance. This can be explained by the fact that at lower frequencies absorption loss is comparable to the radiative loss, but at higher frequencies it becomes less important, eventually being eclipsed by the radiative loss. It is important to mention here that these results assume the presence of a single QW excited not far above the bandgap (lowest transition between confined states). Having more QWs or going further above the bandgap will lead to decrease in Q_{abs} and commensurate reduction in enhancement.

In conclusion, we have analyzed the enhancement in absorption by a semiconductor QW in the vicinity of a corrugated interface with a metal and have shown that due to interplay of various loss mechanisms there exists an optimum frequency at which maximum enhancement in about an order of magnitude can be achieved.

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