Hybrid states of Tamm plasmons and exciton polaritons

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Channeling of exciton polaritons in the plane of semiconductor microcavities can be achieved by the deposition of metallic mesas on the top of the semiconductor structure. We show theoretically that the regime of strong coupling between cavity polaritons and Tamm surface plasmons is possible in such structures. The effect is favorable for the spatial confinement of polaritons and the formation of hybrid one-dimensional plasmon-polariton modes. © *2009 American Institute of Physics*.
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Exciton polaritons in semiconductor microcavities[1] are extremely promising for various optoelectronic applications including polariton lasers,[2] light emitting diodes,[3] and optical parametric oscillators.[4] Being mixed light-matter quasiparticles, exciton polaritons can retain coherence when ballistically propagating over several hundreds of microns in planar microcavities,[5] which in principle makes possible their use in logic elements, such as "polariton neurons,"[6] based on the transport of spin or optical polarization over macroscopic distances. However, the realization of exciton-polariton integrated circuits based on a network of polariton neurons linked by logic gates with different geometries requires the creation in the plane of a microcavity of channels that are suitable for guiding the polaritons in the required directions. Such channels can be produced by etching the cavity heterostructures,[6] but a less demanding process would be preferred. A more straightforward approach is the deposition of metallic mesas on the surface of the semiconductor structure,[7,8] and this has been used to create lateral superlattices for exciton polaritons[7] resulting in potential barriers with a height of about 200 μeV. However, for the development of the next generation of polaritonic devices, including polaritonic logic devices, it is necessary to have practical techniques for the creation of potential barriers of the order of a few meV. The aim of this paper is to demonstrate theoretically that it is possible to use the resonant coupling of exciton polaritons and another type of excitation called a Tamm surface plasmon (TSP) (Ref. 9 and 10) to produce structures that provide a sufficiently large lateral modulation of the energy profile of exciton polaritons. Note that recently strong coupling of Tamm plasmon and quantum well (QW) excitons has been demonstrated experimentally.[11]

As with conventional surface plasmons,[12] TSPs can be strongly coupled to the optical cavity modes as we show here. The resonant coupling of the TSPs to cavity exciton polaritons results in the appearance of hybrid plasmon-exciton-polariton modes forming a characteristic triplet.

In this paper we consider the eigenstates of a laterally homogeneous structure of the type shown in Fig. 1. The same semiconductor is used for the layer adjacent to the metal, one type of DBR layer and the cavity (apart from the QW), and is taken to have a refractive index n_A which is greater than the value n_B for the other semiconductor used in the DBR. The choice $n_A > n_B$ is a necessary condition for the structure to support TSPs,[9] and a consequence is that there is zero phase change on reflection at the edges of the microcavity, and hence a cavity length of one wavelength is appropriate if there is to be an antinode in the electric field at the QW.

A convenient and effective approach is the coupled oscillator model, the hybrid system considered here can be conveniently represented as three coupled oscillators. In particular, the eigenenergies of the system can be found by solving the equation

$$\begin{vmatrix} \omega - \omega_C & \Omega_{C-X} & \Omega_{C-TP} \\ \Omega_{C-X} & \omega - \omega_X & 0 \\ \Omega_{C-TP} & 0 & \omega - \omega_{TP} \end{vmatrix} = 0, \quad (1)$$

where ω_{TP}, ω_C, and ω_X are the eigenfrequencies of the TSP, the bare cavity mode, and the exciton, respectively, while Ω_{C-X} and Ω_{C-TP} characterize the coupling strengths of the cavity mode with the exciton and the TSP, respectively.

The value of Ω_{C-X} is well known from the literature (e.g., Refs. 1, 13, and 14) as

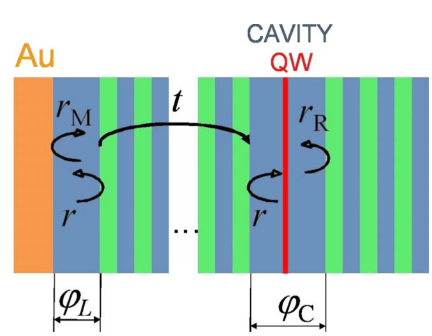

FIG. 1. (Color online) A schematic diagram of the type of structure that is suitable for the observation of hybrid Tamm plasmon-exciton-polariton states. The substrate is on the right-side of the structure but is not shown.

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$$\Omega_{C-X}^2 \approx \frac{2\Gamma_0 c}{n_A[L_{\mathrm{DBR}}+L_C]} = \frac{2\Gamma_0 \omega_C (n_A-n_B)}{\pi[2n_A-n_B]}, \qquad (2)$$

where Γ_0 is the exciton radiative decay rate, c is the velocity of light, L_C is the cavity length, and $L_{\mathrm{DBR}}=(\pi c/n_A^2\omega_0)\times[n_A n_B/(n_A-n_B)]$. In order to evaluate the cavity-TSP interaction strength Ω_{C-TP} we use the transfer matrix technique as described below.

The cavity-TSP interaction matrix element Ω_{C-TP} can be evaluated by using the transfer matrix technique. In the basis of positive and negative propagating waves, the relevant transfer matrix equation is

$$A\begin{pmatrix}1\\ r_R\end{pmatrix} = \begin{pmatrix}e^{i\varphi_C} & 0\\ 0 & e^{-i\varphi_C}\end{pmatrix}\begin{pmatrix}(t^2-r^2) & r\\ -r & 1\end{pmatrix}\begin{pmatrix}e^{i\varphi_L} & 0\\ 0 & e^{-i\varphi_L}\end{pmatrix}\begin{pmatrix}r_M\\ 1\end{pmatrix}, \qquad (3)$$

where A is a constant, φ_L is the phase gained by propagation from left to right through the semiconductor layer next to the metal, φ_C is the phase gained by propagation through the cavity, t and r are the amplitude transmission and reflection coefficient of the left DBR, r_R is the reflection coefficient of the right DBR, and r_M is the reflection coefficient of the metal layer for light incident from the adjacent semiconductor layer (see Fig. 1). Eliminating A from the two algebraic equations represented by Eq. (3) gives

$$\left(1-\frac{1}{r r_M e^{2i\varphi_L}}\right)\left(1-\frac{1}{r r_R e^{2i\varphi_C}}\right)=\frac{t^2}{r^2}. \qquad (4)$$

If the frequency of light is much lower than the plasma frequency ω_p of the metal, r_M can be approximated by[9]

$$r_M \approx \exp\left[i\left(\pi+\frac{2n_A\omega}{\sqrt{\varepsilon_b}\omega_p}\right)\right], \qquad (5)$$

where ε_b is the real part of the background relative permittivity of the metal. For frequencies close to the center of the stop bands of both DBRs, r_R and r can be approximated by[13]

$$r_R \approx r \approx \exp\left(i\beta\frac{\omega-\omega_0}{\omega_0}\right), \qquad (6)$$

where $\beta=\pi n_B/(n_A-n_B)$ and ω_0 is the Bragg frequency. The right hand side of Eq. (6) can be approximated by[1,15]

$$t^2/r^2 \approx -|t|^2 \approx -4(n_B/n_A)^{2N}, \qquad (7)$$

where it has been noted that the DBR between the metal and the cavity has an odd number $(2N+1)$ of layers and so $\arg t=\pi/2$ at the Bragg frequency.

For frequencies close to the center of the stop bands of the DBRs, and well below the plasma frequency, both terms in parentheses on the left hand side of Eq. (4) can be approximated by linear functions of frequency and the equation can be approximated and recast in the form $(\omega-\omega_{TP})(\omega-\omega_C)=\Omega_{C-TP}^2$, characteristic of two coupled oscillators, to obtain an expression for Ω_{C-TP} in terms of the known parameters of the system. The width of the semiconductor layer adjacent to the metal can be adjusted to tune the TSP frequency. For example, $\omega_{TP}=\omega_0$ when the equation $r r_M e^{2i\varphi L}=1$ is satisfied for the frequency ω_0, which occurs for a layer thickness

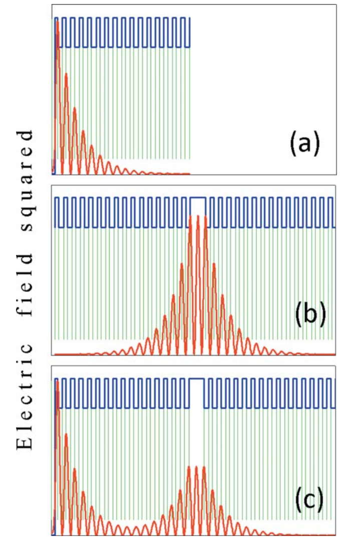

FIG. 2. (Color online) The profiles of the electric field squared and the refractive index for (a) the TSP localized at the interface between a 50 nm gold film and a Bragg reflector with complex energy 1.550 485 −0.001 099 731i eV, (b) the microcavity photon mode localized between two Bragg reflectors with energy 1.550 182−0.000 173 341 9i eV, and (c) the lowest energy coupled state of the Tamm plasmon and the microcavity photon mode with energy 1.546 08−0.000 468 495 7i eV. The refractive indexes are $n_A=3.7$, $n_B=3.0$. The Bragg frequency and the resonant frequency of the one-wavelength microcavity correspond to 1.55 eV. The thickness of the layer adjacent to the gold is chosen to tune the TSP to 1.55 eV and the plasma frequency of gold is taken as $\hbar\omega_p=8.9$ eV.

$$d_L=\frac{\pi c}{2n_A\omega_0}-\frac{c}{\sqrt{\varepsilon_b}\omega_p}. \qquad (8)$$

In that particular case, Ω_{C-TP} is given by

$$\Omega_{C-TP} \approx \frac{\sqrt{2}(n_B/n_A)^N(n_A-n_B)}{\pi\sqrt{n_A(2n_A-n_B)}}\omega_0, \qquad (9)$$

and interestingly does not depend on the parameters of the metallic mirror.

In the case of exact resonance between the cavity mode, the QW exciton, and the Tamm plasmon $(\omega_C=\omega_{TP}=\omega_X=\tilde{\omega})$, Eq. (1) gives the eigenfrequencies of the system as the solutions of

$$(\omega-\tilde{\omega})(\omega-\tilde{\omega}-\sqrt{\Omega_{C-TP}^2+\Omega_{C-X}^2})(\omega-\tilde{\omega}+\sqrt{\Omega_{C-TP}^2+\Omega_{C-X}^2})=0, \qquad (10)$$

and the offset of the hybrid state with respect to the cavity polariton is given by

$$\Delta=\sqrt{\Omega_{C-TP}^2+\Omega_{C-X}^2}-\Omega_{C-X}. \qquad (11)$$

Figure 2 shows the electric field squared profiles of (a) the TSP in the absence of a microcavity (b) the cavity mode in the absence of a metal layer, and (c) the hybrid cavity-Tamm mode, all calculated numerically using the transfer matrix method. The parameters used in the calculations correspond to a GaAs/AlGaAs structure with a resonant frequency of 1.55 eV covered by a layer of gold. The envelope of the hybrid mode exhibits two maxima, which are located at the metal-DBR interface and at the center of the cavity.

If the cavity contains a QW, the coupling of the cavity photon mode, Tamm plasmon, and QW exciton leads to the formation of a hybrid Tamm plasmon-exciton-polariton state. Figure 3 shows the complex eigenenergies of the hybrid

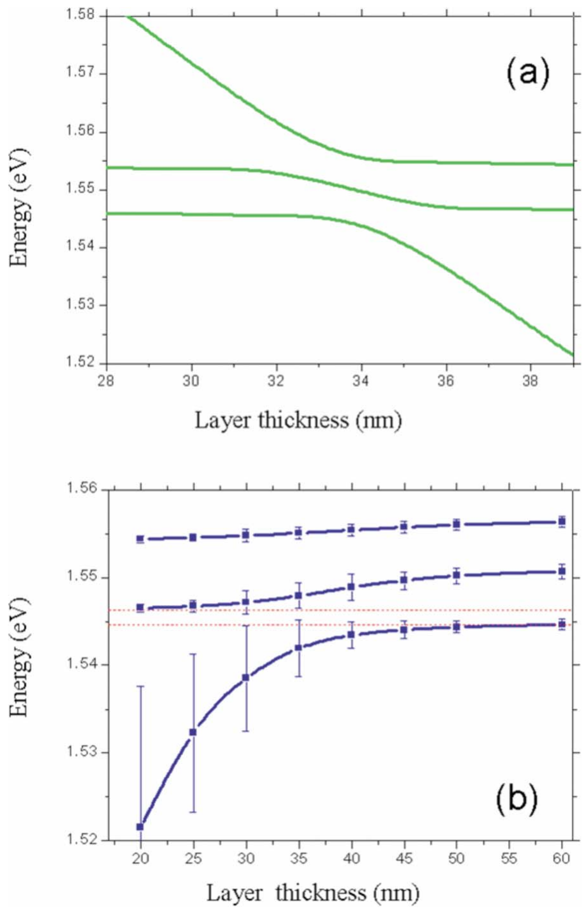

FIG. 3. (Color online) The real parts of the eigenenergies of the hybrid Tamm plasmon-exciton-polariton modes (a) as a function of the width of the semiconductor layer adjacent to the gold, and (b) as a function of the thickness of the gold. The vertical bars give the imaginary parts of the eigenenergies. The offset Δ of the hybrid state with respect to the cavity polariton state is indicated by the horizontal dashed lines. The parameters of the structure are the same as for Fig. 2(c) but there are four QWs in the cavity in this case. The QW exciton oscillator strength is taken as 0.026 meV.

modes calculated numerically as functions of the thickness (a) of the semiconductor layer adjacent to the metal and (b) of the gold layer. In both figures the curves exhibit double anticrossings characteristic of the strong coupling regime in a system of three oscillators. Therefore, to achieve a reasonably long lifetime for the hybrid state, the thickness of the gold layer should be not less than 50 nm. The offset Δ of the hybrid state with respect to the cavity polariton state for the chosen set of parameters, is indicated by the horizontal dashed lines in Fig. 3(b) and has a value of 1.7 meV, which

TABLE I. The in-plane effective masses relative to the electron mass m_e for the TE- and TM-polarized cavity modes, TSP, and exciton modes.

Excitation	m_j^{TE}/m_e	m_j^{TM}/m_e	$(m_j^{TE}-m_j^{TM})/m_e$
Cavity photon	3.68×10^{-4}	3.62×10^{-4}	6×10^{-6}
Tamm surface plasmon	3.1×10^{-3}	3.7×10^{-3}	-6×10^{-4}
Exciton	0.5	0.5	0

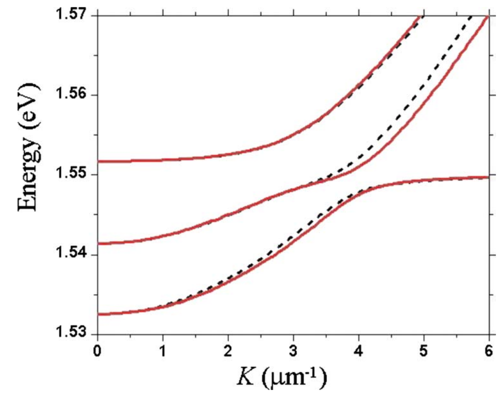

FIG. 4. (Color online) The in-plane dispersion curves of the hybrid Tamm-plasmon-exciton-polariton modes. The solid (dashed) lines correspond to the TE (TM) polarization.

is sufficient to realize in-plane localization. The corresponding value of Δ predicted by the algebraic theory [Eq. (11)] is 1.85 meV, in good agreement with the numerical result.

The in-plane modulation of the energy of the lowest state achieved with the resonant coupling of the Tamm plasmons and cavity polaritons, as considered here, is one order of magnitude larger than with nonresonant modulation of the energy of the cavity polariton using a metal film.[7,8] In other words, the deposition of a metal film on the top of a QW microcavity facilitates the lateral localization of exciton polaritons in a microcavity and opens the way for a practical demonstration of polaritonic logic gates.[16,17] Figure 4 shows the dispersion of hybrid modes which shows double anticrossing behavior. The masses of bare exciton, cavity mode and Tamm Plasmon are shown in Table I.

In conclusion, the resonant coupling of Tamm plasmons with cavity exciton polaritons results in the formation of hybrid excitations and provides a potential mechanism for the lateral confinement of the lowest energy eigenmode of the system. Specifically, directed in-plane propagation of exciton polaritons in planar microcavities can be achieved by the deposition of metallic mesa structures on the top of the semiconductor structure.

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