Optical Tamm state polaritons in a quantum well microcavity with gold layers*

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A new type of cavity polariton, the optical Tamm state (OTS) polariton, is proposed to be realized by sandwiching a quantum well (QW) between a gold layer and a distributed Bragg reflector (DBR). It is shown that OTS polaritons can be generated from the strong couplings between the QW excitons and the free OTSs. In addition, if a second gold layer is introduced into the bottom of the DBR, two independent free OTSs can interact strongly with the QW excitons to produce extra OTS polaritons.

Keywords: semiconductor microcavity, polariton, optical Tamm state, surface plasmons

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1. Introduction

Cavity polaritons, which exhibit neither exciton nor photon characteristics, are half-matter half-light quasiparticles arising from the strong coupling between excitons and photons.[1,2] As the coherent emission can be obtained from cavity polaritons without the requirement for population inversion, it is possible to realize novel optoelectronic devices, such as thresholdless polariton lasers and high-speed optical switches, with cavity polaritons.[1−3] Usually, cavity polaritons are generated in microcavities constructed by sandwiching quantum wells (QWs) between two distributed Bragg reflectors (DBRs), as the strong coupling between the confined photons (i.e. cavity mode) and the QW excitons can be obtained in this way.[3,4]

Surface plasmons (SPs) are collective oscillations of free electrons and can be excited by transverse-magnetic (TM) polarized light at the dielectric/metal interface. Surface plasmon waves are associated with short effective wavelengths and strong field enhancement effects, making them very attractive for a variety of applications.[5,6] The dispersion of the surface plasmon lies outside the light cone given by $k = \omega/c$, where k is the in-plane wave vector, ω is the angular frequency, and c is the vacuum light speed. So the direct optical excitation of surface plasmons in a planar structure composed of an isotropic dielectric medium is impossible. As a result, SPs are usually excited using prisms or diffraction gratings. Recently, a special type of interface mode, called the optical Tamm state (OTS), in analogy with the Tamm state for electrons at crystal boundaries, was proposed to realize polariton lasers.[7,8] It was shown that OTSs can be realized at the interface between metal and DBR. The OTSs are lossless interface waves within the light cone and can be generated by direct optical excitations of both TE (transverse-electric) and TM polarizations,[8,9] which is significantly superior when compared with SPs. Moreover, if the metal layer and the sequence of the high- and the low-index layers of the DBR are properly arranged, the eigenstates of the OTSs can be varied with the plasma frequency of the bulk metal. Obviously, the combination of cavity polariton and OTS is of great importance for fast and compact optical processing.

Hence in this paper, we propose to realize a new type of cavity polariton, the OTS polariton, through the strong interaction between OTSs and cavity excitons. This is done by sandwiching a quantum well (QW) between gold layers and a DBR. In contrast to previous studies, both the top and bottom gold layers are considered in our structure. In particular, the second gold layer added to the bottom of the DBR can support the generation of additional OTS, which provides addition freedom to form cavity polaritons.

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In Section 2, the theoretical method to investigate the proposed cavity polaritons is studied. In Section 3, the strong couplings between the OTSs and QW excitons for both single-metal-layer and double-metal-layer cavities are analysed.

2. Theory

Figure 1 shows a schematic diagram of the microcavity to be considered in our analysis. The microcavity consists of a top gold layer, a bottom GaAs/AlAs stack DBR, and a single GaAs QW sandwiched between two AlGaAs cladding layers. It is similar to that of the conventional microcavities except that the top DBR is replaced by a metal layer. The OTS polaritons can be excited in the proposed microcavity with or without a gold layer on the bottom of the DBR, and their optical characteristics will be discussed in the following study.

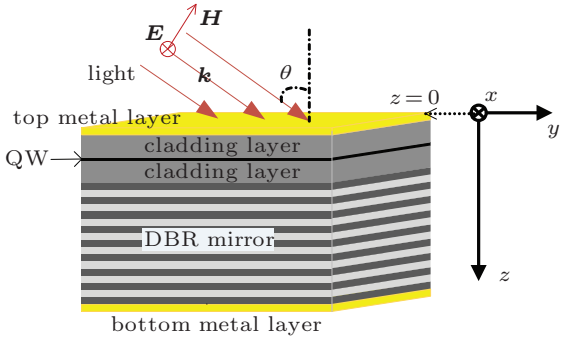


Fig. 1. (colour online) Schematic diagram of the microcavity. Incident light is assumed to be TE polarized. Surface of the top metal layer is defined as the plane of $z = 0$.

The DBR is designed to have 16.5 pairs of GaAs/AlAs layers with a Bragg frequency of ω_0. Its first and last layers each possess a higher refractive index, so as to form OTSs with frequencies below the bulk plasma frequency of the metal. The permittivity of the gold layer is taken to have the Drude form,[10–12] $\varepsilon_{\rm g}(\omega) = 1 - \omega_{\rm p}^2/(\omega^2 - {\rm i}\omega\gamma)$, where $\hbar\gamma$ (=0.027 eV) is the electronic collision energy, and $\hbar\omega_{\rm p}$ (=8.9 eV) is the bulk plasma energy. The relative permittivity of the QW satisfies the Lorentzian oscillator form[4]

$$\varepsilon_{\rm QW}(\omega) = \varepsilon_0 + \frac{4\pi f\omega_{\rm ex}^2}{\omega_{\rm ex}^2 - \omega^2 - {\rm i}\omega\Gamma}, \tag{1}$$

where the first term is the background permittivity, $\varepsilon_0 = 12.5$, the second term denotes the exciton contribution to the permittivity, $\hbar\omega_{\rm ex}$ (=1.515 eV) is the exciton energy, Γ ($\hbar\Gamma = 0.5$ meV) is the broadening factor, and f (=3.16×10^{-4}) is the oscillator strength. The other parameters used in the calculation are given in Table 1.

Table 1. The parameters of the proposed microcavity ($\lambda_{\rm B}$ is the Bragg wavelength).

Parameter	DBR layers		Cladding layers	Gold layer	QW layer
	GaAs	AlAs			
Refractive index	3.7	3.0	3.3	$\sqrt{\varepsilon_{\rm g}(\omega)}$	$\sqrt{\varepsilon_{\rm QW}(\omega)}$
Thickness	$\lambda_{\rm B}/4$	$\lambda_{\rm B}/4$	$\lambda_{\rm B}/4$	50 nm	10 nm

With the above definitions, the OTS polaritons of the microcavities can be numerically analysed using the transfer-matrix method. In addition, the dispersion relations of the OTS polaritons can be deduced from their generation conditions. The excitation of the OTS polaritons requires that there exist non-trivial values of electromagnetic waves under the condition of no outside incident light on the cavity. At the upper (i.e. the interface between the cladding layer and the top metal layer) and the lower (i.e. the interface between the cladding layer and the first DBR layer) boundaries of the cavity, we assume that the amplitudes of the electrical fields incident on the boundaries from the cavity are 1 and η (a nonzero constant), respectively. Hence, the following relation can be established:

$$\begin{bmatrix} r_{\rm U} + 1 \\ (r_{\rm U} - 1)p_{\rm c} \end{bmatrix} = \boldsymbol{M}_{\rm C}\boldsymbol{M}_{\rm QW}\boldsymbol{M}_{\rm C}\eta \begin{bmatrix} 1 + r_{\rm L} \\ (1 - r_{\rm L})p_{\rm c} \end{bmatrix}, \tag{2}$$

where $p_{\rm c} = n_{\rm c}\cos\theta_{\rm c}$, with $n_{\rm c}$ being the refractive index and $\theta_{\rm c}$ the incident angle of the cladding layer; $r_{\rm U}$ and $r_{\rm L}$ are the reflection coefficients of the top-cover (i.e. the top metal layer) and the bottom-cover (i.e. all the DBR layers with or without the bottom metal layer) layers of the cavity, respectively; $\boldsymbol{M}_{\rm c}$ and $\boldsymbol{M}_{\rm QW}$ are the transfer matrices of the cladding and the QW layers, respectively. Then, we can obtain the eigenequation for the OTS polaritons from Eq. (2) as

$$\begin{aligned} &p_{\rm c}\,(r_{\rm U} - 1)\,[l_{11}\,(1 + r_{\rm L}) + l_{12}\,(1 - r_{\rm L})\,p_{\rm c}] \\ &\quad - (r_{\rm U} + 1)\,[l_{21}\,(1 + r_{\rm L}) + l_{22}\,(1 - r_{\rm L})\,p_{\rm c}] = 0, \end{aligned} \tag{3}$$

where l_{11}, l_{12}, l_{21}, and l_{22} are the four elements of matrix $\boldsymbol{M}_{\rm c}\boldsymbol{M}_{\rm QW}\boldsymbol{M}_{\rm c}$. Because equation (3) depends on the incidence angle that controls the in-plane wave vector, it is also named as the dispersion equation of the polaritons. Note that when the cavity layers are removed (i.e. there is no cladding layer or QW in the structure, $l_{11} = l_{22} = 1$ and $l_{12} = l_{21} = 0$), equation (3) reduces to $r_{\rm U}r_{\rm L} = 1$, which is the exact case reported in Refs. [7] and [8].

3. Results and discussion

First we discuss the case in which there is no bottom metal layer added to the microcavity (see Fig. 1). Figure 2 shows the corresponding reflection coefficient versus $\hbar\omega_0$ (i.e. the center of the DBR bandgap) and the photon energy. The dotted line gives the energy of the free OTS (i.e. the free cavity mode uncoupled from the exciton). The dashed-dotted line gives the energy of the exciton. The detuning Δ is defined as the energy of the free OTS minus the exciton energy. For moderate values of Δ, the excitons and the OTS can couple strongly, generating polaritons along two energy branches. Photons that are resonant with the polaritons can penetrate through the cavity due to the tunneling effect. Correspondingly, reflection dips appear in the spectrum at the polariton energies. In the mapping, the two branches, which mark relatively low reflection coefficients, indicate the realization of the OTS polaritons. It is observed that the two branches always show an anticrossing, the so called vacuum–field Rabi splitting. At the anticrossing point ($\Delta = 0$), the two OTS polariton modes are split by ~ 6 meV. The splitting increases as the detuning deviates away from 0 eV. At positive detunings, the upper polariton branch tends to the dotted line (photon-like), while the lower polariton branch tends to the dashed-dotted line (exciton-like). At negative detunings, the situation is reversed.

Figure 3 presents the reflection spectra of the structures for $\hbar\omega_0 = 1.619$ eV and $\theta = 0$. The case without a QW in the cavity is indicated by the thinner curve, wherein only one dip is observed at 1.514 eV. This dip corresponds to the free OTS supported by the structure. The detuning between this OTS and the QW excitons is -1 meV. Hence, when the QW is included in the cavity, the OTS and the excitons can strongly interact with each other. As a result, OTS polaritons can be realized. The Rabi splitting shown in the reflectivity spectrum (i.e. two dips in the reflection spectrum) reveals the presence of the OTS polaritons. The inset of Fig. 3 gives the spectral and spatial distributions of the electric field intensity. We can see that the intensities are relatively strong for energies that correspond to the two dips of the black (thick) curve. In the z direction, the highest intensity of the field is within the QW, indicating a well confinement of light by the metal and the DBR layers. The inset also verifies that the dip positions in the reflection spectra coincide with the eigenenergies of the OTS polaritons.

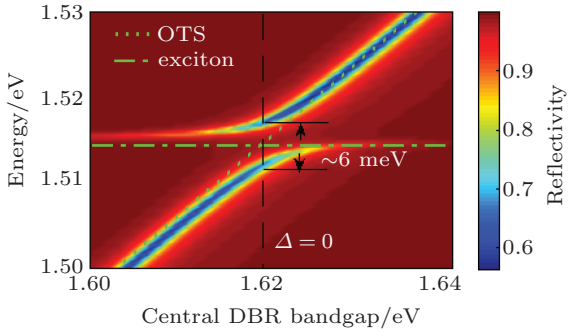


Fig. 2. (colour online) Reflection coefficient versus $\hbar\omega_0$ and photon energy for the microcavity without the bottom metal layer and $\theta = 0$.

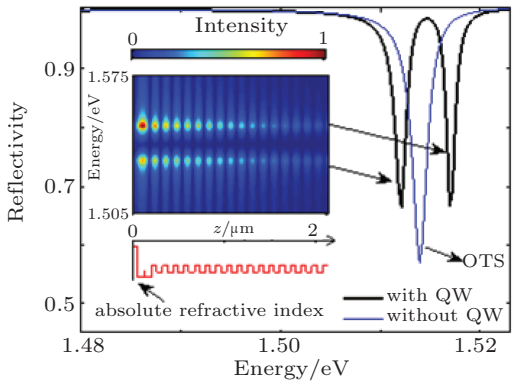


Fig. 3. (colour online) Reflection spectra for $\hbar\omega_0 = 1.619$ eV and $\theta = 0$; the inset gives the corresponding spectrum and z-direction distribution of the electrical field.

Hence, we have discussed the strong coupling between the OTS and the QW excitons as a means to achieve cavity polaritons based on a thin metal layer and a DBR mirror-formed QW microcavity. This is different from Refs. [7] and [8] where no confined exciton is included in their consideration.

It is known that an electronic Tamm state appears when the barrier at one end of the superlattice is higher than the rest of the potential barriers. If the barriers at both ends are raised, two electronic Tamm states appear. This suggests to us how to form two OTSs based on our structure. Figure 4 shows the reflection coefficient for the case when both the top and

the bottom metal layers are considered. The two dotted lines show the free OTSs supported by the structure in the absence of the QW. It can be seen that the presence of the bottom metal layer gives birth to two free OTSs that are separated by ~ 28 meV. We also check whether these two OTSs are within the first photonic band gap of the DBR mirror. In the mapping, two pairs of polariton branches appear, corresponding to the two free OTSs. Note that the QW excitons can interact with any one of the free OTSs, depending on the relevant detunings.

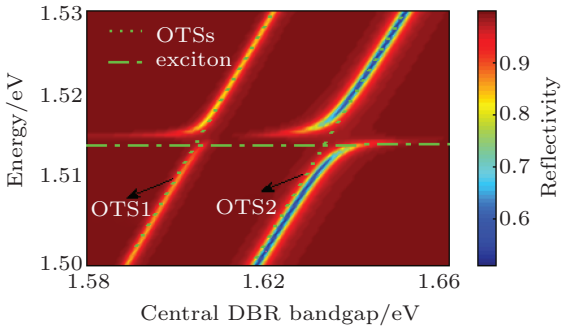


Fig. 4. (colour online) Reflection coefficient versus $\hbar\omega_0$ and photon energy for the microcavity with the bottom metal layer and $\theta = 0$.

It is worth mentioning that the 6 meV splitting in Fig. 2 corresponds to a strong coupling between the OTS and the excitons, namely, the strong coupling between the OTS and the excitons generates the OTS polaritons, which manifest themselves by Rabi splitting (the anticrossing of the polariton modes). For the case shown in Fig. 4, two OTSs, i.e. OTS1 and OTS2, appear corresponding to the two metal layers. Hence, the 28 meV separation denotes the energy difference between the two OTS modes.

To better understand the interaction between the QW excitons and the two OTSs, we give the reflection spectra of the structure for $\hbar\omega_0 = 1.6025$ eV and 1.63 eV in Figs. 5(a) and 5(b), respectively. In Fig. 5(a), the two free OTSs supported by the structure are at 1.487 eV (OTS1) and 1.513 eV (OTS2), as shown by the dips of the thinner curve. Obviously, the frequency of OTS2 is close to the exciton resonance, so the polaritons appear with respect to OTS2, which is revealed by the appearance of Rabi splitting in the spectrum (see the two upper dips in the black/thick curve). On the other hand, the interaction between OTS1 and the excitons is not so dominant, so the third polariton mode with respect to OTS1 remains free cavity mode-like, i.e. the lowest dip in the black (thick) curve is almost overlapping with that in the thinner curve. In Fig. 5(b), the case is reversed with respect to that of Fig. 5(a), i.e. OTS1 is closer to the exciton energy and Rabi splitting appears with respect to OTS1 rather than OTS2.

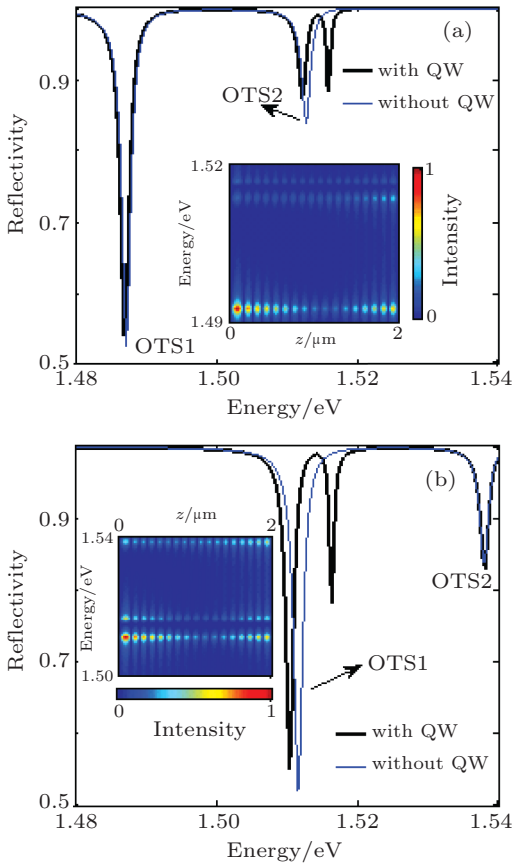


Fig. 5. (colour online) Reflection spectra for $\theta = 0$ and $\hbar\omega_0 = 1.6025$ eV (a) and 1.63 eV (b). The insets show the corresponding spectra and the z-direction distributions of the electrical field.

The insets in Figs. 5(a) and 5(b) indicate that the light with energies equal to those of the three polariton modes can be confined by the structure. In the z direction, the light mainly distributes inside the QW, which corresponds to the formation of the OTS polaritons. Moreover, the intensity of light at the interface between the DBR and the bottom metal is sill relatively strong, which corresponds to the formation of the Tamm plasmon polaritons.[7,8] Hence, the second metal layer not only introduces an additional OTS that provides the freedom for the generation of cavity polaritons, but also provides a link between the excitations of cavity polaritons and plasmon polaritons.

4. Conclusion

We demonstrate the realization of OTS polaritons using a gold layer and a DBR embedded with a single

QW. It is shown that the OTS polaritons can be realized if the light mode and the QW excitons are in the strong coupling regime. The OTS polaritons, which are spectrally separated (i.e. by Rabi splitting), can be revealed by the two dips in the reflection spectrum. On the other hand, if another gold layer is introduced into the bottom of the DBR, two OTSs can form. In this case, any of these OTSs can be strongly coupled to the QW excitons depending on their relevant detunings. Three OTS polariton modes can also be generated in the microcavity. Two of the OTS polariton modes are due to Rabi splitting with respect to one of the OTSs. However, the third OTS polariton mode remains free cavity mode-like. Compared with the conventional microcavities, our structure is simpler, because only one DBR is used. In addition, the proposed structure provides an inherent link between the cavity polaritons and the surface plasmon polaritons at the metal interfaces, which is believed to be a typical sample for the study of light–matter interaction, as well as the realization of polariton lasers.

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