Guided Bloch surface wave polaritons

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The authors report on a theoretical investigation of guided polariton states arising from the strong coupling between quantum-well excitons and a Bloch surface wave confined at the interface between a uniform dielectric medium and a Bragg mirror. It is shown that the exciton–photon coupling is almost doubled as compared to a similar structure made in a conventional planar microcavity. It is also shown that, by simple engineering of the sample surface with silicon oxide deposition, one can efficiently produce one-dimensional polaritons propagating within the structure with extremely low losses. The latter result evidences the usefulness of Bloch surface waves as a key component for the realization of "polaritonic integrated circuits." © *2011 American Institute of Physics*. [doi:10.1063/1.3571285]

The interaction of quantum-well (QW) excitons with the modes of high-finesse semiconductor microcavities (MC) allows to achieve the regime of strong light-matter coupling. Under such conditions, the elementary excitations of the system should be described as mixed radiation-matter states, called *MC polaritons*.[1,2] In the past ten years, it has been shown that MC polaritons can be useful in a number of optoelectronic device applications as well as fundamental studies.[3–7] The in-plane propagation of polaritons has also recently attracted a considerable research effort: superfluid behavior of MC polaritons has been demonstrated in their coherent state[8] while bistable switching of polariton waves has been proposed as a way to achieve optical logical gates.[9] Various strategies to guide the propagation of polaritons have been theoretically proposed or experimentally demonstrated, including wire MCs,[10] or the use of metallic deposition and the creation of hybrid Tamm-like exciton–polariton states.[11,12] Tamm states may be formed also in purely dielectric systems, e.g., at the interface between two Bragg mirrors.[13]

The rigid design of semiconductor MCs offers, however, little space for engineering the propagation of polaritons; more degrees of freedom can be obtained when coupling QW excitons to the modes of photonic crystals (PhCs).[14] In this letter, we propose a strategy to generate very low-loss propagating polaritons through the use of Bloch surface waves (BSWs), which are propagating photonic modes that exist at the interface between a PhC and a homogeneous medium.[15] We also show that the realization of a dielectric ridge on the multilayer allows to easily guide the propagation of polaritons without the use of post-growth etching techniques. The resulting structure allows for very shallow polariton states which could be exploited for the study of the propagation of polariton superfluids, switching waves in polariton bistability,[16] and the realization of polariton based devices such as polariton networks, gates, and switches.[9] Our proposed structure represents an optimal compromise between the use of Tamm states proposed in Ref. 11, which relies on metal deposition that can inevitably increase the losses, and the use of a fully dielectric structure like, e.g., in Ref. 13, which is closer to a conventional MC and less controllable by means of surface perturbations.

First, we demonstrate strong coupling between a single QW and a BSW supported by a GaAs/AlGaAs planar structure. We show that polaritons generated via BSW display a higher Rabi splitting as compared to a planar MC. Finally, we will discuss the possibility of confining polaritons in one dimension by means of a silica ridge deposited right above the same multilayer. The theoretical modeling is performed by means of the scattering matrix method.[17,18]

The structure under consideration is an $Al_{0.9}Ga_{0.1}As/GaAs$ periodic multilayer grown on a GaAs substrate [see Figs. 1(a) and 1(b)]. The first layer is a 30 nm

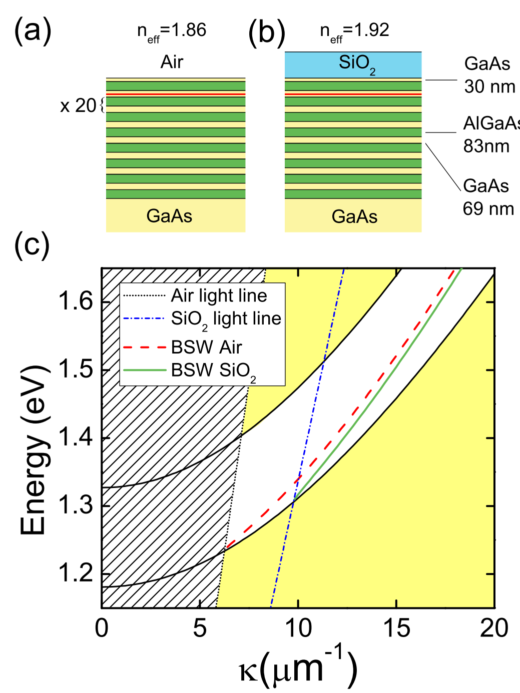

FIG. 1. (Color online) Scheme of the structures under investigation: (a) multilayer stack supporting in-plane propagating Bloch surface modes with the air cladding (b) same mutlayer with a 500 nm silica layer in the cladding. (c) Calculated mode dispersion of BSWs for the structure in (a) (dashed line) and (b) (solid line), as a function of the planar momentum, κ; The air and silica light lines and the Bragg gap of the multilayer are indicated.

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thick GaAs, followed by 20 periods of a repeated unit cell made of 83 nm thick $Al_{0.9}Ga_{0.1}As$ (refractive index $n_1 = 2.98$, suited for a target energy around 1.48 eV) and 69 nm thick GaAs ($n_2=3.58$). The calculated BSW dispersion as a function of the in-plane momentum, κ, is shown in Fig. 1(c) for the structures of Fig. 1(a) (dashed line) and Fig. 1(b) (solid line), respectively. In both cases, the BSWs are calculated for TE polarization (electric field orthogonal to the growth direction) and lay within the corresponding photonic band gap, which does not depend on the cladding materials, and below the air and silica light-lines, respectively. By comparing the two dispersion curves, we see that the effect of the silica layer is to change the BSW cut-off and to increase the mode effective index, going from 1.86 to 1.92 for the air and silica claddings, respectively, at the target energy of 1.48 eV. At this energy, the difference in effective indices corresponds to a redshift in the silica cladding mode by about 15 meV, at a given value of κ. We will show that this high energy difference can be exploited to confine the BSW (and the corresponding polariton) in a silica ridge obtained by a simple etching of the glass layer.

We consider a single $In_{0.05}Ga_{0.95}As$ QW of thickness $L_{QW}=8$ nm located in the second GaAs layer from the surface [see Fig. 1(a)]. In our calculations, the QW is modeled as a Lorentz oscillator, $\varepsilon(\omega)=\varepsilon_\infty[1+\tilde{\omega}_{LT}/(\omega_{ex}-\omega-i\gamma)]$, with a resonant energy $\omega_{ex}=1.48$ eV, damping rate $\gamma=0.1$ meV, and effective longitudinal/transverse (LT) splitting $\tilde{\omega}_{LT} = \hbar^2 e^2 f_{xy}/(2\varepsilon_0\varepsilon_\infty m_0 \omega_{ex} L_{QW}) = 0.22$ meV (given in SI units).[19] In the latter quantity, $\varepsilon_\infty = 12.8$ is the QW background dielectric constant, m_0 is the free electron mass, and $f_{xy}=4.8\times10^{16}$ m^{-2} is the oscillator strength per unit area for a 8-nm-thick InGaAs QW. Results are shown only for the case of air cladding, as qualitatively similar conclusions are expected and found also in the case of a silica cladding. To observe the interaction between the QW exciton resonance and the BSW, we calculate the attenuated total reflectance (ATR) spectrum through a ZnSe prism (index $n_3=2.51$) positioned 500 nm above the multilayer. As usual in the presence of absorption, the guided mode is marked by a dip in reflectance. This straightforward approach has the advantage of studying the system by considering a quantity that is experimentally accessible.[20] The ATR spectrum as a function of the incoming photon energy and the angle of incidence in the prism is shown in Fig. 2(a). Here, the thick solid line indicates the BSW dispersion without the QW, the dotted line marks the energy of the bare QW exciton, and the angle for which the Rabi splitting occurs is evidenced by a dashed line. Figure 2(a) shows the typical anticrossing indicating the strong coupling between the QW exciton and BSW. The predicted resonance splitting is about 6 meV, as shown in Fig. 2(b). This value is almost 50% larger as compared to the splitting that one would obtain, for the same QW parameters, in a conventional planar MC, as we have checked by simulating this latter structure (calculations not shown).[21] We can attribute the larger splitting mainly to the smaller confinement length of a BSW with respect to a MC mode, due to total evanescent decay in the upper cladding. This is evident by looking at Fig. 2(c), which shows the BSW field intensity profile. Besides the large splitting that is achievable in this structure, the advantage of using the BSW as the photonic mode interacting with the QW is threefold are as follows: (1) the design of multilayers supporting BSW has been demonstrated with several materials, even when the refractive index contrast is small;[22] (2) the BSW dispersion relation can be straightforwardly tuned by changing the cladding refractive index; (3) the propagation losses of this polaritons states depends essentially only on the QW absorption and on the polariton excitonic fraction. These three aspects make this system appealing as a platform for the highly controlled study of exciton–polariton effects.

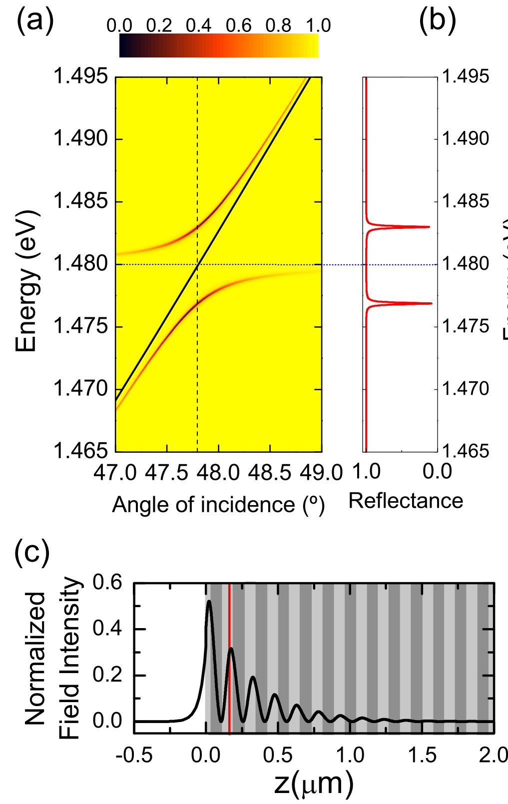

FIG. 2. (Color online) Calculated ATR spectra at variable angles, showing excitation of guided BSW polariton modes through a ZnSe prism in optical contact with the sample surface, for a structure as in Fig. 1(a): (a) color scale plot and (b) ATR spectrum for the angle of incidence corresponding to the maximum Rabi splitting, i.e., dashed line in (a). Dotted and solid lines indicate the bare exciton and BSW dispersions, respectively. (c) Field intensity profile along the growth direction for the guided BSW. The Bragg stack is superimposed, and the QW position is marked by a red line in the GaAs layer.

One of the main features of a BSW is the sensitivity of its dispersion relation to a change in the cladding refractive index. This property can be exploited, e.g., to guide the BSW in ridge geometries.[23] Following a similar approach, here we demonstrate 1D guided BSW polaritons confined by a silica ridge on the multilayer. In Fig. 3 we plot the calculated dispersion relation of a BSW polariton guided by placing a 1 μm wide and 500 nm thick silica ridge onto the AlGaAs/GaAs multilayer described before [see inset of Fig. 3(a)], identified by the dips in ATR spectra. The modes are excited by TE-polarized light with respect to the vertical plane of incidence along the ridge direction. The guided BSW polariton dispersion along the ridge is shown in black as a guide to the eye. Here we choose to work with a rather wide ridge to minimize the effect of the losses due to lateral silica/air interface, which are negligible with respect to those due to a QW absorption. The use of a wide ridge reduces the effect of the lateral confinement on the dispersion. The 1D BSW is redshifted by about 10–15 meV, that is our confinement po-

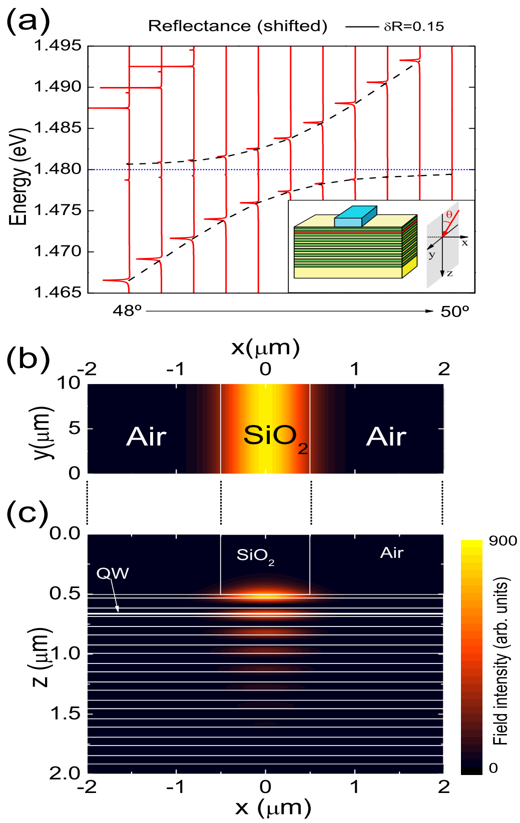

FIG. 3. (Color online) (a) Calculated ATR spectra at different incidence angles θ, in the yz-plane, for a ridge structure (see inset) through a ZnSe prism in contact with the SiO_2 ridge. Dashed lines are a guide to the eye to highlight the polaritonic nature of the excited modes inside the structure. [(b) and (c)] Color scale plot of the field intensity profile.

tential. In fact, the confinement in the transverse direction is due to the effective refractive index mismatch between the two BSWs supported by the multilayer with uniform air and silica claddings, respectively [see Fig. 1(c)]. By using the same theoretical tool, it is possible to calculate the mode field distribution, which is shown in Figs. 3(b) and 3(c). The electromagnetic field is orthogonally polarized with respect to the vertical plane of incidence, and it is laterally well confined below the silica ridge. Along the growth direction, the field decays exponentially in the silica ridge while it penetrates in the multilayer with the damped oscillations typical of the confinement due to a photonic gap. This characteristics can also be exploited to set more than just one QW in multiple layers of the DBR and yet having them strongly coupled to the BSW field. From the above calculations, it is clear that efficient 1D propagation of polaritons can be obtained just by patterning an oxide ridge waveguide on the surface of the sample with unequivocal technological benefits as compared to previous proposals.

In summary, we have given theoretical evidence of strong coupling between QW excitons and a BSW. We have shown that such a coupling can be exploited to obtain 1D polariton waveguides defined by a dielectric ridge on the multilayer surface. Notice that BSW polaritons have no energy minimum; nonetheless polaritons have been shown to condensate above the energy minimum,[10] and such increased propagation lengths should be particularly useful to study superfluid propagation of condensates. The use of BSW polaritons could also facilitate the electrical injection and control of polaritons; in fact, the electromagnetic field confined near the surface could allow the use of well established lateral doping technology[24] instead of highly resistive doped Bragg mirrors.

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