PHYSICAL REVIEW B VOLUME 62, NUMBER 11 15 SEPTEMBER 2000-I

Excitons in GaAs nanocavities under the influence of perpendicular magnetic fields

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(Received 2 February 2000; revised manuscript received 24 May 2000)

Studies are presented on the optical response of magnetoexcitons in GaAs microcavities with an external magnetic $\mathbf{B}_p$ field applied in the perpendicular configuration. Incident light of definite polarization is considered in order to calculate reflectivities with the same polarization and the conversion from one to the other polarization. Results show that the reflectivity minimum of light with s polarization for light incident with the same polarization splits into two minima as produced by the strong interaction of the exciton-polariton states with the nanocavity modes and assisted by the $\mathbf{B}_p$ field. In contrast, this splitting is inhibited by the applied field when light is incident with p-polarization. Comparisons with experimental data show good qualitative agreement.

I. INTRODUCTION

Exciton confinement in heterostructures has been extensively used to enhance exciton binding energies and optical properties.[1] Moreover, effects of applied magnetic fields on the exciton optical response have attracted attention as the field provides additional confinement and modifies the optical properties.[2] Different orientations of the magnetic $\mathbf{B}$ field have been explored, the perpendicular ($\mathbf{B}_p$) configuration[3] being one of them. Recent experimental studies[2] on the optical properties of microcavities have been reported with consideration of the spectral regime of excitonic transitions and accounting for an applied $\mathbf{B}_p$ field. The reflectivity spectra display minima splitting as produced by the strong interaction of the exciton-polariton states with nanocavity modes, assisted by the applied magnetic field, an effect termed *Rabi splitting*. On the other hand, theoretical investigations have been conducted on the optical properties of superlattices with applied $\mathbf{B}_p$ fields.[4] The dispersion relations of the collective normal modes that propagate in the structures exhibit minibands and minigaps of bulk magnetoplasmons, and the discussions are presented either in terms of the Bloch wave vector[3] or in terms of the parallel component of the wave vector.[4]

Depending upon the magnetic field direction, a variety of physical aspects take place,[3–6] such as the appearance of surface, bulk, hybrid surface-bulk, and complex magnetoplasmon modes. For the investigations, transfer matrix approaches have been developed to explore the minibands of magnetoplasmons in semiconductor superlattices with applied magnetic fields. In addition, studies on the optical response of magnetoplasmons have been also reported.[3] Results exhibit the coupling of light with the normal modes that may propagate in the layered system, forming a very rich structure with a dependence on the structural parameters and on the strength of the applied magnetic field.

In this paper we investigate semiconductor nanocavities that were constructed[2] by sandwiching GaAs layers between Bragg reflectors made up of bilayers of AlAs and GaAs. Within the cavities, three spatially separated quantum wells of InAs that support the excitonic transitions are included. An external magnetic field is included in the perpendicular geometry; as a result, the excitonic active layers are described by a dielectric tensor and behave as birefringent materials, and the nonactive layers are considered as isotropic media. The birefringent materials support four propagating modes; consequently the transfer matrix of these materials are of dimension 4×4. Using those matrices, the optical response is calculated. Both p- and s-polarized light are considered to obtain the reflectivities R_{pp} for p polarization, R_{ps} for the conversion from p to s polarization, R_{ss} for s polarization, and R_{sp} for the conversion from s to p polarization. Comparisons with experimental data are also performed for spectra in the regime of excitonic transitions. In the simplified model calculation presented in this paper, the dielectric tensor is independent of the momentum associated with the center of mass of the excitons. This approach of infinity exciton mass avoids the necessity of additional boundary conditions, as no additonal waves are generated. The work is organized as follows: Section II is devoted to the outline of the reflectivity calculations for light incident with p polarization. In Sec. III, we present the results and conclusions.

II. FORMALISM

Let us consider a semiconductor multilayered array, similar to that studied by Martinez *et al.*,[3] with the difference being that in the present case the system is finite. An applied external magnetic $\mathbf{B}_p$ field is applied along the superlattice growth direction, namely, the z direction. Light propagation takes place on the yz plane, which in turn defines the wave vector as $\mathbf{q}=(0,Q,q_z)$, with $Q=q_0\sin\theta$ and $q_0=\omega/c$. The elements of the field-dependent local dielectric tensor $\tilde{\epsilon}(\omega)$ for a layer can be written as

$$\epsilon_{xx}=\epsilon_L+\frac{\omega_p^2(\omega_T^2-\omega^2-i\Gamma\omega)}{(\omega_T^2-\omega^2-i\Gamma\omega)^2-(\omega\omega_c)^2}, \tag{1}$$

$$\epsilon_{xy}=-\epsilon_{yx}=i\epsilon_L\frac{\omega\omega_c\omega_p^2}{(\omega_T^2-\omega^2-i\Gamma\omega)^2-(\omega\omega_c)^2}, \tag{2}$$

$$\epsilon_{zz}=\epsilon_L+\frac{\omega_p^2}{\omega_T^2-\omega^2-i\Gamma\omega}, \tag{3}$$

where ϵ_L, ω_p, ω_T, ω_c, and Γ are the background dielectric constant, a measure of the oscillator strength of the excitonic transitions, the frequency of the excitonic transition, the cyclotron frequency, and the damping factor, respectively.

The wave vector $-q_z^2=\alpha_{1,2}^2$ of the modes that propagate in a single layer have the form

$$\alpha_{1,2}^2=\frac{1}{2\epsilon_{zz}}\{(\epsilon_{xx}+\epsilon_{zz})Q^2-2q_0^2\epsilon_{xx}\epsilon_{zz} \pm[(\epsilon_{xx}-\epsilon_{zz})^2Q^4+\Lambda^2]^{1/2}\}, \tag{4}$$

where $\Lambda^2=4(Q^2-q_0^2\epsilon_{zz})q_0^2\epsilon_{xy}^2\epsilon_{zz}$. Then the electric field takes the form

$$\mathbf{E}(\mathbf{r},t)=\sum_{n=1}^{2}[\mathbf{E}_n^+e^{iq_nz}+\mathbf{E}_n^-e^{-iq_nz}]e^{i(Qy-\omega t)}, \tag{5}$$

and the magnetic field is obtained from Faraday's equation. Following a familiar procedure[3] one may construct the 4×4 transfer matrix $\mathbf{M}_1$ for a semiconductor layer, with the elements are as given by Martínez *et al.*[3] Once the transfer matrix of a single layer is obtained, the boundary conditions are applied to obtain the transfer matrix of a multilayered array in terms of a product of matrices that takes the form $\mathbf{M}=\mathbf{M}_n\mathbf{M}_{n-1}\cdots\mathbf{M}_1$, where the subindices label the layers. The relationship between the fields at the right z^r and left z^l boundaries takes the form

$$\begin{bmatrix}\mathbf{E}\\ \mathbf{H}\end{bmatrix}_{z^r}=\mathbf{M}\begin{bmatrix}\mathbf{E}\\ \mathbf{H}\end{bmatrix}_{z^l}, \tag{6}$$

where $\mathbf{E}^T=(E_x,E_y)$ and $\mathbf{H}^T=(H_x,H_y)$.

As pointed out above, the system we are dealing with is finite, in contrast to the semi-infinite array sutudied earlier[3] and with some similarities to those studied by other authors;[7,8] therefore, we outline the calculations of the reflectivities. When light with definite polarization is incident on the system, the wave encountering the surface may excite two outgoing modes into the anisotropic medium in addition to the reflected one with the same p or s polarization and a component with s or p polarization. To calculate the reflectivity for light incident with p polarization, we write the tangential components of the electric field in vacuum as

$$E_y(z)=E_p^+e^{iq_zz}+E_p^-e^{-iq_zz},\quad E_x(z)=E_s^-e^{-iq_zz}, \tag{7}$$

where E_p^+ and E_p^- are the amplitudes of the incident and reflected waves with p polarization, and E_s^- is the reflected amplitude for the s-polarization component. By applying the surface impedance $Z_p(0)=E_y(0)/H_x(0)$ method, we write the reflectivity $R_{pp}=|r_p|^2=|E_p^-/E_p^+|^2$, which is given by

$$R_{pp}=\left|\frac{Z_p(0)-Z_v}{Z_p(0)+Z_v}\right|^2,\quad Z_p(0)=\frac{b_1a_{22}-b_2a_{12}}{b_2a_{11}-b_1a_{21}}, \tag{8}$$

where $Z_v=-\cos\theta$, with θ the angle of incidence, $a_{11}=M_{42}z_p'-M_{22}$, $a_{12}=M_{44}z_p'-M_{24}$, $z_p'=q_{zs}/q_0\epsilon_s$, $a_{21}=M_{32}z_s'-M_{12}$, $a_{22}=M_{34}z_s'-M_{14}$, $z_s'=q_0/q_{zs}$, $b_1=-M_{41}z_p'+M_{21}+[M_{43}z_p'-M_{23}]/z_s$, $b_2=-M_{31}z_s'+M_{11}+[M_{33}z_s'-M_{13}]/z_s$, $z_s=q_0/q_z$ and $z_p=q_z/q_0$. q_{zs} and ϵ_s are for the substrate. For the s-polarized amplitude we have

$$R_{ps}=|r_{ps}|^2=\left|\frac{(-M_{12}+M_{32}z_s')(E_p^++E_p^-)+(M_{14}-M_{34}z_s')(-E_p^++E_p^-)/z_p}{M_{11}-M_{31}z_s'-(M_{13}-M_{33}z_s')/z_p}\right|^2. \tag{9}$$

In a similar fashion, the reflectivity components R_{ss} and R_{sp} can be calculated when light with s polarization is incident.

III. RESULTS AND DISCUSSION

The system considered for the studies is made up of a nanocavity of GaAs with three thin layers of InAs that play the role of quantum wells. The wells are sandwiched between two Bragg reflectors constructed with bilayers of GaAs and AlAs, as the one in Ref. 2. The excitonic active media are the quantum wells; therefore we apply the dielectric tensor model as given in Sec. II. The parameters[2] for the actual calculations are $\omega_p^2=(f_{osc}e^2\hbar^2)/(m_0\epsilon_0L_z)$, where f_{osc} is the oscillator strength per unit area, e (m_0) is the charge (mass) of the electron, and L_z is the quantum well thickness. $\epsilon_{GaAs}=12.566\,34$, $\Gamma=3$ meV, $f_{osc}=5\times10^{12}$ cm^{-2}, and $\epsilon_{\mathrm{InGaAs}}=12.890\,04$ at temperature $T=4.2$ K and concentration of Ga of $x=0.87$. The energy of the excitonic transition is $E_T=\hbar\omega_T=1.355$ eV and the cavity mode has $E_{cav}=1.355$ eV. In the excitonic active media, four waves propagate; as a result we describe them by employing 4×4 transfer matrices. The GaAs/AlAs bilayer dielectric functions are independent of magnetic field and they are treated as isotropic systems.

Numerical studies are performed for the reflectivities R_{pp} of p-polarized light, R_{ps} for the conversion from p to s polarization when light is incident with p polarization, and R_{ss} of s polarization and R_{sp} for the conversion from s to p polarization for light incident with s polarization. At the end of this section, results of the comparison between the experimental data and theoretical calculations are discussed. We focus our attention in the frequency domain of the excitonic transitions neglecting nonlocal effects as we consider the excitonic mass to be infinity; therefore, no additional modes are excited in the excitonic active media and consequently no additional boundary conditions are needed. Studies of exci-

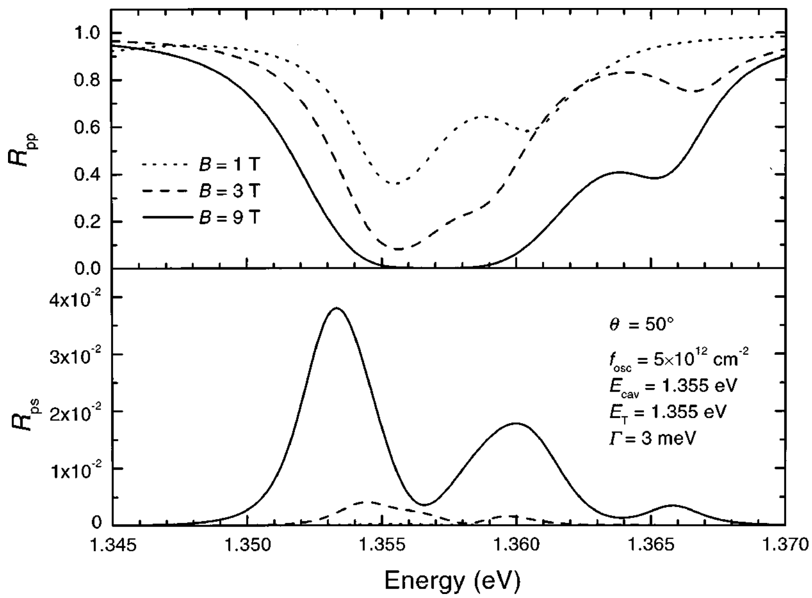

FIG. 1. Reflectivity for light incident with p polarization at an angle $\theta=50°$ and for different values of the applied B field: Upper panel is for light reflected with p polarization R_{pp} and lower panel is for light reflected with s polarization R_{ps} ; other parameters are shown in the inset.

tons in nonlocal theory in nanocavities without an applied external magnetic field have been presented elsewhere.[9]

We present first the results of the reflectivities assuming incident light with p polarization; therefore we exhibit first R_{pp} and R_{ps}. Figure 1 displays R_{pp} in the upper panel and R_{ps} in the lower panel for a microcavity structure and applied external magnetic field with different strengths. Light is incident on the structure at an angle of 50° and couples to the modes with wave vector of parallel component $Q=\omega/c \sin 50°$. In a layer that shows no field-induced anisotropy, two noninteracting modes propagate to the right and left, one with p and one with s polarization. On the other hand, in an active excitonic medium two exciton-polariton modes, with no definite polarization, travel to the right and left with propagating wave vectors given by Eq. (4). These modes are independent in a layer but they couple at the interfaces since they should obey boundary conditions. These conditions also allow the coupling with those transverse modes of the adjacent isotropic layers. We can conclude that most of the reflectivity structure is due to the magentoexcitons that propagate in the quantum wells. It is noted that as effects of the applied magnetic field, R_{pp} evolves in such a way that the two minima degenerate into a minimum, that is, the applied external field inhibits the minimum splitting. At the same time, R_{ps} develops two broad peaks as the $\mathbf{B}_p$ field increases. The structure is exhibited in the lower panel of Fig. 1.

Light incident with s polarization may excite the same number of modes as the p-polarized light. However, one would expect nonsimilar reflectivity spectra since the incident waves have electric fields with different directions; therefore they should produce different effects on the reflectivities. In fact, when the incident light is s polarized, the reflectivity R_{ss} of s polarization displays a structure with a broad minimum at low fields and a splitting when the strength of the applied field increases, as shown in the upper panel of Fig. 2. It is apparent not only that minimum splitting occurs, but also the symmetrization of the minima produced by the magnetic field. In addition, R_{sp} exhibits two peaks for high magnetic field, depicted in the lower panel of Fig. 2.

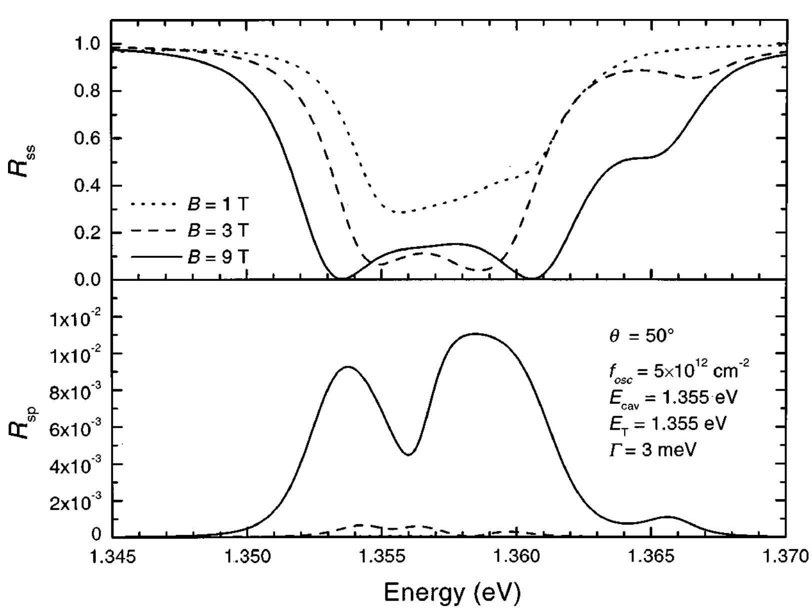

FIG. 2. The same as in Fig. 1 for light incident with s polarization.

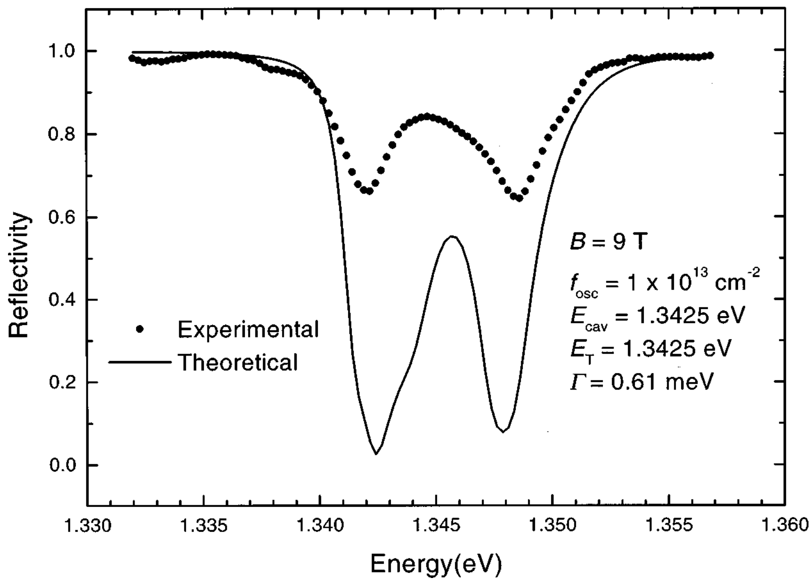

FIG. 3. This figure shows the comparison between theory and experiment of light reflectivity for a nanocavity with an applied external magnetic field of $B=9$ T. Light is normally incident and other parameters are shown in the inset.

The parameters are the same as in Fig. 1.

For the comparisons with the experimental data, we chose one spectrum of Ref. 2. In Fig. 3, we reproduce the experimental reflectivity and compare it with the calculations for the external magnetic field of 9 T and the structural parameters as indicated in the inset. Experimental data are presented as a dotted curve and theory is presented with a solid curve. It is evident that the spectra display a splitting (Rabi splitting) as described above. The energy of both experimental minima are reproduced in the calculations, but the depths are different, with the difference being attributed to the absence of spatial dispersion.[10] The approach adopted in this work is to take advantage of the absence of additional waves in the excitonic media. In other words, we consider a large excitonic mass in order to neglect nonlocal effects and present a simplified approach to study effects of applied external magnetic fields on exciton polaritons in nanocavities.

In conclusion, we have presented a study of magnetoexcitons in semiconductor nanocavities with an external magnetic $\mathbf{B}_p$ field applied in the perpendicular configuration using a local theory. Incident light with p and s polarization has been used for solving the wave equation, constructing the 4×4 transfer matrix to calculate the reflectances R_{pp} and R_{ss} for light with p and s polarization, respectively, when the incident light is with the same polarization, and the amplitude R_{ps} for the corversion from p to s polarization and R_{sp} for the corresponding conversion from s to p polarization. R_{ss} displays a splitting of the minimum as produced by the strong interactions of the exciton-polariton states with the nanocavity modes, assisted by the magnetic field and termed the Rabi splitting. In contrast, R_{pp} exhibits an inhibition of the splitting as the field strength increases. Comparisons with experimental data show the minimum splitting and qualitative good agreement.

ACKNOWLEDGMENTS

This work was partially supported by CONACyT-México Grant No. 26363-E.

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