Two-dimensional excitonic polaritons in a microcavity with quantum wires

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Maxwell's equations are solved with allowance for the nonlocal excitonic contribution to the dielectric polarization for a periodic system of quantum wires which is inserted into an optical microcavity. The calculation of the reflection and diffraction of light incident on the array of quantum wires made it possible to obtain the dispersion spectrum for two-dimensional excitonic polaritons in the system.

The interaction of low-dimensionality electronic excitations with only volume photons has been studied for a long time in the optical spectroscopy of nanostructures. Experimental[1,2] and theoretical[3,4] studies of the interaction of a quasi-two-dimensional light mode trapped in an optical microcavity, with a two-dimensional exciton introduced into the cavity space, have been carried out only recently. Several striking effects of a polariton nature were discovered, in particular, a giant Rabi splitting and a large decrease of the exciton lifetime under resonance conditions (see Refs. 1 and 2 and the references cited there). These effects open a new field in quantum electrodynamics and they show at the same time that a new object — microcavity with quantum wells — has promising applications in surface-emitting semiconductor lasers. A natural continuation in this direction is the analysis of two-dimensional polaritons, or photoexcitons, in a microcavity with an array of quantum wires or quantum dots.

Several different methods have now been developed for growing semiconductor heterostructures with a regular system of quantum wires or one-dimensional clusters. Theoretical analysis of optical reflection from such a structure has shown that the reflection coefficient depends strongly on the orientation of the polarization plane of the light and diffraction effects can play a large role if the spacing between the wires is greater than one-half the wavelength of the light at the frequency of the excitonic resonance.[5–7] In the present paper we report the results of an analysis of the particular features of the interaction of one-dimensional excitons with a two-dimensional light mode for an array of quantum wires placed at the center of a semiconductor optical microcavity.

Let us consider a linearly polarized electromagnetic wave which is incident from vacuum at an angle φ_0 on a structure which includes a Bragg reflector, consisting of M_1 double layers, on the left-hand side, a cavity (or active region) with quantum wires, and a Bragg mirror, consisting of M_2 pairs of layers grown on a thick, uniform substrate, on the right-hand side. Let the plane of incidence (x,z) be perpendicular to the wires. The distribution of the electric field in the cavity is found from Maxwell's equations and the equations of the material coupling that takes into account the nonlocality of the linear response:

$$D_\alpha(\vec{\rho})=\epsilon_B E_\alpha(\vec{\rho})+\frac{Q_\alpha}{\omega_0-\omega-i\Gamma}\sum_n \Phi(\vec{\rho}'-nd\mathbf{s})\int \Phi(\vec{\rho}-nd\mathbf{s})E_\alpha(\vec{\rho}')d\vec{\rho}'. \qquad (1)$$

Here $\alpha=x,y,z$; d is the period of the array; $\vec{\rho}$ is the component of the radius vector in the plane of incidence; s is a unit vector along the x axis; ϵ_B is the background permittivity (we ignore the difference between ϵ_B in the composite materials of the cavity and the wire); ω_0 and Γ are the resonance frequency and nonradiative damping of a one-dimensional exciton; $Q_\alpha=(4\pi/\hbar)(eP_{cv}^\alpha/m\omega_0)^2$; m is the mass of a free electron; P_{cv}^α is the interband matrix element of the momentum operator in E_α polarization; and the function $\Phi(\rho)$ is related to the envelope of the exciton wave function $\Psi(\rho_e,\rho_h)$, which is normalized to the length L of the wire, by the relation $\Phi(\rho)=\sqrt{L}\Psi(\rho,\ \rho)$. The overlapping of the states in neighboring wires is disregarded.

A method for solving Maxwell's equations for systems of quantum wires with the help of the Green's functions is described in Ref. 6 . The reflection spectra were calculated for normal incidence along the z axis (Ref. 6) and for oblique incidence in a simplified model of cylindrical wires (Ref. 7). Here we present expressions for the amplitude reflection coefficients r_j and transmission coefficient t_j for s-polarized light, i.e., $\mathbf{E}\|y$, near the resonance frequency of an exciton with a function $\Phi(\rho)$ which is symmetric under the transformation $x\to -x$ or $z\to -z$:

$$r_j=\frac{i\Delta_j}{\tilde{\omega}_0-\omega-i\left(\Gamma+\sum_{j'}\gamma_{j'}\right)}, \quad t_j=\delta_{j,0}+r_j, \qquad (2)$$

where

$$\gamma_j=\frac{k^2Q_y}{2dk_{jz}}I_j^2, \quad \Delta_j=\frac{I_0}{I_j}\gamma_j, \quad I_j=\int \Phi(\rho)\cos k_{jx}x\cos k_{jz}zd^2\rho,$$

$k=\sqrt{\epsilon_B}\omega/c$, $k_{jx}=k\sin\varphi+2\pi j/d$, $k_{jz}=\sqrt{k^2-k_{jx}^2}$, φ is the angle of incidence in the medium ($\sin\varphi=\sqrt{\epsilon_B}\sin\varphi_0$), and $\delta_{\alpha,b}$ is the Kronecker delta function. The summation in Eq. (2) extends over the values of j', for which $k_{j'z}$ is real; the summation over j' with imaginary $k_{j'z}$ is included in the renormalized resonance frequency $\tilde{\omega}_0$; the time $\tau_j=(2\gamma_j)^{-1}$ is the radiative lifetime of an exciton with respect to the emission of light with the wave vector $(k_{jx},0,\pm k_{jz})$. For oblique incidence of p-polarized light and with $Q_x,Q_z\neq 0$ the coefficients r_j and t_j-1 contain a sum and a difference of two pole contributions of the type (2), and t_j is different from $1+r_j$.

SHORT-PERIOD ARRAY OF QUANTUM WIRES

For $kd<\pi$ there is no diffraction, and when the excitonic mode is in resonance with the light mode, the dispersion of the two-dimensional polaritons can be found by solving the equivalent problem of two coupled oscillators. In this case the reflection and transmission of light for the entire structure as a whole can be found easily with the help of 2×2 transfer matrices.[4] For example, we obtain the following expression for the transmission from vacuum into a substrate at normal incidence:

$$T=\left|\frac{\sqrt{2\gamma_L\gamma_R}(\omega-\tilde{\omega}_0+i\Gamma)}{[\omega-\tilde{\omega}+i(\gamma_L+\gamma_R)](\omega-\tilde{\omega}_0+i\Gamma)-V^2}\right|^2. \tag{3}$$

Here $\tilde{\omega}$ is the resonance frequency of the light mode disregarding the interaction with the exciton, and $\tau_{L,R}=(2\gamma_{L,R})^{-1}$ is the lifetime of a two-dimensional photon with respect to the escape into vacuum or the substrate, respectively. The interaction parameter V can be expressed in terms of the damping γ_0 in Eq. (2) in the form

$$V^2=\bar{\Gamma}\gamma_0,\quad \bar{\Gamma}=\frac{2c}{n_c(\bar{L}+L_c)}, \tag{4}$$

where L_c is the width of the cavity space in the microcavity, n_c is the index of refraction in the cavity, and $\bar{L}$ is related to the phase $\psi_c(\omega)$ of the reflection of a Bragg mirror near the frequency ω_c at which the Bragg interference condition is satisfied by the relation $\psi_c(\omega)=n_c(\bar{L}/c)(\omega-\omega_c)$. The analytical formula (3), which is applicable for a microcavity with a quantum well, was derived under the assumption that the transmission of the Bragg reflectors is weak $\gamma_{L,R}\ll\bar{\Gamma}$ and that $\gamma_0\ll\bar{\Gamma}$, so that the approximate expansion $\exp(i\psi_c)\approx1+i\psi_c$ can be used.

LONG-PERIOD ARRAY OF QUANTUM WIRES

For $kd>\pi$ but far from the points $k_x=k\sin\varphi$ which are multiples of π/d, excitonic polaritons at resonance $\bar{\omega}\approx\tilde{\omega}_0$ can be calculated on the basis of a two-level approximation. If, on the other hand, k_x is close to one of the values $\pi m/d$ with integer m, then the mixing of four excitations must be taken into account: two two-dimensional photon modes with the wave vectors $k_1=k_x$ and $k_2=k_x-2\pi m/d$ and two excitonic excitations $|\mathrm{exc},k_l\rangle=N_x^{-1/2}\Sigma_n\exp(ik_ldn)|n\rangle$, where $l=1,2$, $|n\rangle$ is the wave function of the exciton in an isolated wire, and N_x is the number of wires. The characteristic frequencies of the excitonic polaritons are found by setting equal to zero the determinant of the matrix

$$\begin{pmatrix} \Omega_{\mathrm{exc}} & 0 & V & V \\ 0 & \Omega_{\mathrm{exc}} & V & V \\ V & V & \Omega_{\mathrm{ph}}^{(1)} & 0 \\ V & V & 0 & \Omega_{\mathrm{ph}}^{(2)} \end{pmatrix}, \tag{5}$$

where $\Omega_{\mathrm{exc}}=\tilde{\omega}_0-\omega-i\Gamma$, $\Omega_{\mathrm{ph}}^{(1)}=\bar{\omega}_l-\omega-i(\gamma_L+\gamma_R)$, the interaction parameter V differs from the parameter in Eq. (4) by a coefficient of order unity which depends on the angle φ,

$$\bar{\omega}_l=(N\pi c/n_c+\bar{L}\omega_c)/\sqrt{1-\frac{k_l^2}{k^2}}\,L_c+\bar{L}),$$

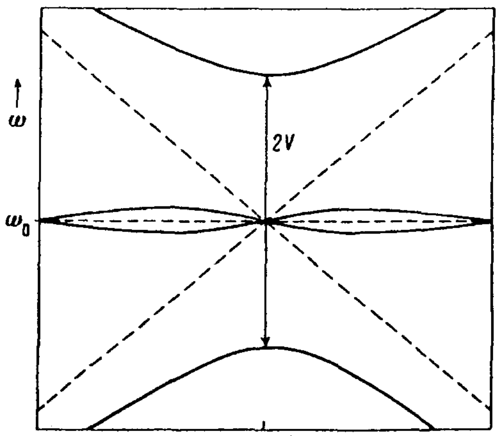

FIG. 1. Characteristic frequencies of polariton modes in a microcavity as a function of the angle of incidence φ. The dashed lines represent the frequencies of the excitonic and light modes in the absence of a polariton effect.

N is the number of half wavelengths that fit into L_c, and expression (4) holds for even N. In the matrix (5) allowance was made for the fact that for $k_1 \approx -k_2$ the difference between the integrals I_0 and I_{-2m} can be ignored.

Figure 1 shows schematically the characteristic frequencies of the polariton modes in a microcavity as a function of the angle φ. The parameters of the system were chosen in such a way that for $k \sin \varphi = \pi/d$ the condition $\bar{\omega}_1 = \bar{\omega}_2 = \bar{\omega}_0$ is satisfied. We see that the interaction of the two light modes with an exciton leads to the appearance of four polariton modes. The two central modes become degenerate at the point of anticrossing of the light and exciton modes and the splitting between the two extreme polariton modes at this point is equal to $2V$; i.e., it is twice the Rabi splitting upon the intersection of the excitonic mode and an isolated optical mode.[3] The excitonic polaritons under study can be observed experimentally in optical transmission upon excitation from the end face or in diffraction scattering by 90° under normal excitation.

In conclusion, we note that the introduction of an array of quantum wires into a microcavity substantially enriches the polariton spectrum as a result of the diffraction of light, if the period of the system of wires is greater than one-half the wavelength of the light at the frequency of the excitonic resonance. At the same time, the contribution of the array of wires to the spectrum decreases as the period of the array increases [see Eq. (2)]. From the standpoint of observing the diffraction effects, an optinum system is a system of wide (1000–1500 Å) quantum strips which are separated by barriers whose thickness is of the same order of magnitude.

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