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Mixing of States in Quantum Wells for Terahertz Polariton Emitters

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Abstract—Two possible InGaAs/GaAs quantum-well structures ensuring the presence of radiative transitions between the polariton states in a microresonator with a quantum well, which are accompanied by generation of terahertz photons, are discussed in this work. For the first structure, symmetry breakdown that is required for the emission of a terahertz photon is conducted in a quantum well with refractive index gradient profile, which results in mixing of the states of a polariton and a dark exciton. Parameters of the quantum well, in which the energy of the second exciton level corresponds to the upper polariton energy, are determined. A double quantum well with exciton states split due to quantum-mechanical tunneling through a barrier is used in the second structure. Symmetry breakdown, which allows one to mix an exciton with a "dark" exciton, is ensured by adjusting the energy of electron levels in a double quantum well by applying an electric field to the structure. A hole remains localized in one of the wells.

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The interaction between polariton systems and terahertz radiation has become an object of intense theoretical and experimental research [1–3], and various constructions of a terahertz polariton emitter have been proposed [4–7]. In terahertz polariton emitters, radiative transitions occur between the macroscopically populated bosonic states, resulting in a significant increase in transition probability. In terahertz polariton emitters based on quantum microresonators [4–6], a terahertz photon can be emitted due to mixing of the states of the upper polariton and a "dark" exciton. This Letter was aimed at designing a GaInAs/GaAs quantum-well structure that would ensure mixing of exciton and polariton states and the equal distance between the dimensional quantization levels of an exciton and Rabi splitting.

The mechanism of terahertz emission in a polariton microresonator that was proposed in [4] is based on stimulated radiative transitions from the upper polariton state to the lower one. This transition is not allowed in regular polariton microresonators, but may be possible in quantum wells (QWs) with the potential gradient obtained by varying the composition or by applying an external electric field as shown in Fig. 1a. The Hamiltonian of the system of excitons $|1X\rangle$ (e1hh1) and $|2X\rangle$ (e1hh2) interacting with the optical mode of the microresonator $|C\rangle$ can be written as

$$H = \begin{pmatrix} E_{1X} & \delta/2 & \Omega/2 \\ \delta/2 & E_{1X}+\Delta & 0 \\ \Omega/2 & 0 & E_C \end{pmatrix}, \qquad (1)$$

where E_{1X} is the energy of exciton e1hh1, Δ is the distance between the first and second dimensional quantization levels of heavy holes, E_C is the energy of the optical mode of the microresonator, Ω is Rabi splitting, and δ is the coupling factor between excitons $|1X\rangle$ and $|2X\rangle$. The eigenmodes (polariton modes) of the Hamiltonian can be expressed via exciton states and the optical mode of the resonator as

$$\begin{pmatrix} |L\rangle \\ |U1\rangle \\ |U2\rangle \end{pmatrix} = \begin{pmatrix} H_C^L & H_{1X}^L & H_{2X}^L \\ H_C^{U1} & H_{1X}^{U1} & H_{2X}^{U1} \\ H_C^{U2} & H_{1X}^{U2} & H_{2X}^{U2} \end{pmatrix} \begin{pmatrix} |C\rangle \\ |1X\rangle \\ |1X\rangle \end{pmatrix}, \qquad (2)$$

where H_α^β are the Hopfield coefficients. Without allowance for mixing of exciton states, when $E_C = E_{1X}$, the energy of the upper and lower polaritons would be equal to $E_C \pm \Omega/2$. If coupling factor between the exciton states δ is low as compared to Rabi splitting Ω, and the distance between the dimensional quantization levels of an exciton is Ω, state $|L\rangle$ will possess an energy close to the lower polariton energy, while the energy of states $|U1\rangle$ and $|U2\rangle$ will be close to the upper polariton energy. The probability of a radiative transition accompanied by emission of a terahertz photon will be linked with the Hopfield coefficients and dipole element M between the states $|1X\rangle$ and $|2X\rangle$ via the equation

$$W \sim (H^{U2}_{2X}H^{L}_{1X} + H^{U1}_{2X}H^{L}_{1X})^2|M|^2. \qquad (3)$$

It has been demonstrated [4] that the maximum efficiency of terahertz emission is achieved when the energy of the dark exciton $|2X\rangle$ corresponds to the minimum energy of the upper polariton. In an optimized structure, the value in front of the squared matrix element in expression (3) can be as high as 0.2; hence, the probability of a terahertz transition is close to the values used in [4–6].

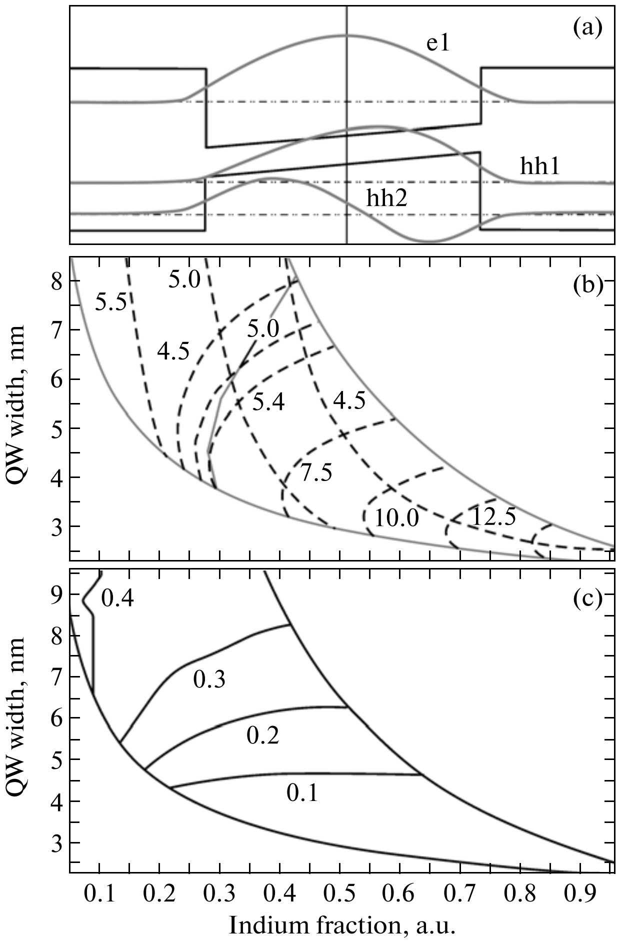

Fig. 1. (a) Wave functions of electrons and holes in a quantum well with the gradient potential. (b) Isolines of the distance between the dimensional quantization levels of an exciton in the QW (thin dashed lines) and Rabi splitting isolines. The solid curve corresponds to the resonance of the upper polariton state and the e1hh2 exciton. (c) Isolines of the Hopfield coefficient corresponding to the contribution of the e1hh2 exciton to the upper polariton state. Upper hyperbola (b) and (c) shows the critical thickness of QW as a function of In content; the lower hyperbola shows the minimal thickness of a QW required for the existence of two-dimensional quantization levels of heavy holes in the QW.

Let us consider a standard microresonator manufactured using AlAs/GaAs with $In_xGa_{1-x}As$ PW. Due to the mismatch between lattice parameters of InAs and GaAs, the QW is strained; the crystal structure of the QW does not disintegrate until maximum thickness of the quantum well $L_{\max}$ is reached. The $L_{\max}$ value is determined by Eq. [8]:

$$L_{\max} = \frac{4(1-\nu/4)}{\pi(1+\nu)\mu}\ln(L_{\max}/4+1), \qquad (4)$$

where ν is the Poisson's ratio and μ is the relative mismatch between the lattice parameters of the QW and the adjacent regions. On the other hand, in order to ensure mixing, the QW needs to be appreciably thick so that two-dimensional quantization levels of heavy holes can exist in it. Minimal thickness $L_{\min}$ is determined by the equation

$$L_{\min} = \pi\hbar/\sqrt{2mU}, \qquad (5)$$

where m is the heavy hole mass and barrier height U is determined by indium content in the heavy solution. Thus, the range of In content in the solid solution and the range of QW thicknesses, for which the QW is stable and contains two-dimensional quantization levels, is included between two hyperbolas shown in Figs. 1b and 1c. In order to ensure efficient generation of terahertz radiation, the Rabi splitting of the polariton levels needs to be equal to the distance between dimensional quantization levels of heavy holes $\Delta = \Omega$. The Rabi splitting value is determined by the expression

$$\Omega = \sqrt{N}\sqrt{\frac{2c\Gamma_0}{n_x(L_{DBR}+L_C)}}, \qquad (6)$$

where N is the number of quantum wells in a resonator, Γ_0 is the radiation damping of an exciton, L_{DBR} is the depth of light penetration into microresonator mirrors, and L_C is the width of the microresonator cavity base. The Γ_0 value depends on the parameters of a QW (thickness and composition) and is determined by the expression

$$\Gamma_0 = \frac{1}{2}k\omega_{LT}\pi a_b^3\Big[\int\Phi(z)\cos(kz)dz\Big]^2, \qquad (7)$$

where a_b is the Bohr exciton radius, ω_{LT} is transverse-longitudinal splitting, k is the wave vector of light, and $\Phi(z)$ is the exciton wave function. Figure 1b (dashed curves) shows the isolines of Rabi splitting and of the distance between dimensional quantization levels Δ. The solid curve corresponds to dependence $\Delta = \Omega$. An external electric field value equal to 20 kV/cm was used for calculations. One can see that, for a single InGaAs QW limited by GaAs from both sides, the con-

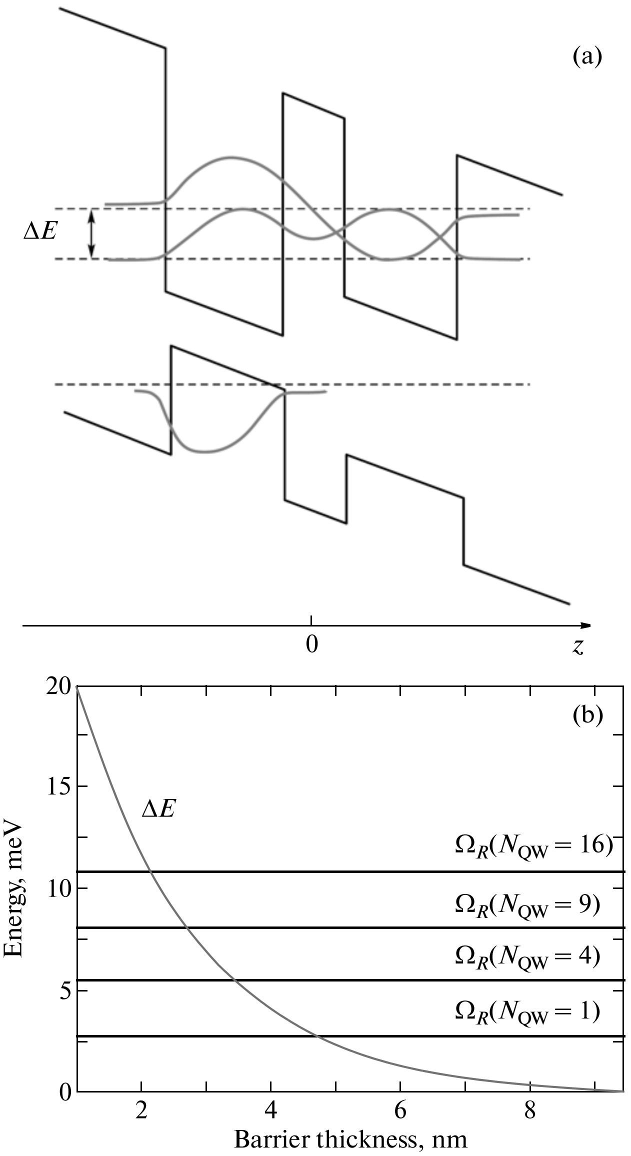

Fig. 2. (a) Wave functions of electrons and holes in the double quantum wells. (b) Distance between the energy of the excitons formed by the symmetric and antisymmetric electronic states and the hole localized in one of the wells as a function of barrier thickness.

dition $\Delta = \Omega$ can be fulfilled when the splitting is equal to 4.5–5.5 meV, which corresponds to 1.1–1.3 THz. For higher numbers of quantum wells, the generation frequency can be increased to 2–3 THz.

In order to enhance the efficiency of generation of terahertz radiation, one needs to ensure significantly high Hopfield coefficients, which correspond to mixing of exciton $|2X\rangle$ to the upper polariton. Figure 1c shows the isolines having the value $\left|H_{2X}^{U2}\right|^2$. It is clear that the relative fraction of $|2X\rangle$ in the upper polariton varies from 20 to 30% in the region corresponding to the fulfillment of the condition $\Delta = \Omega$.

A double quantum well placed in the external electric field is an alternative structure ensuring mixing of exciton states in the upper polariton (Fig. 2a). The possibility of exciton–polariton formation in these systems has been demonstrated experimentally [9, 10].

The parameters of the well have been selected in a special manner so that a hole can localize only in one of the wells, while the electrons are characterized by localized states in both wells; the energies of the localized states are equal in both wells. Due to the tunneling through a barrier, the electronic states in two wells can form symmetric and antisymmetric combinations $\phi_s(z)$ and $\phi_a(z)$, respectively. Along with the hole localized in one of the wells, these electron states can be formed by excitons, the wave functions of which are determined by the expressions

$$\Psi_{1X}(\rho, z) = \exp(-\rho/a_b)\phi_{hh1}(z)\phi_s(z), \tag{8}$$

$$\Psi_{2X}(\rho, z) = \exp(-\rho/a_b)\phi_{hh1}(z)\phi_a(z). \tag{9}$$

When interacting with the resonator eigenmode, these excitons may result in polariton formation. Both exciton-radiation damping and splitting between the exciton levels depend on the width of a barrier between QWs. By accurately choosing the parameters of a QW and a microresonator, one can reach a situation in which the Rabi splitting is equal to the splitting between the symmetric and antisymmetric electron state. It can be concluded from Fig. 2a and Eqs. (8) and (9) that the overlap integral between the wave functions of exciton states Ψ_{1X} and Ψ_{2X} is nonzero and the dipole element describing the probability of a radiative transition accompanied by terahertz photon emission is nonzero as well. Figure 2b shows splitting of the symmetric and antisymmetric electron states as a function of the thickness of the barrier between QWs and the Rabi splitting for a microresonator containing different numbers of double quantum wells. One can see that the situation when Rabi splitting becomes equal to splitting of the electron levels can be attained. In this situation, efficient generation of terahertz radiation caused by transitions between excitons Ψ_{1X} and Ψ_{2X} is possible. By varying the number of QWs in a microresonator and thus changing the width of a barrier between the QWs, one can vary the generation frequency within a broad range.

In summary, different variants of quantum-well structures to be used in terahertz polariton emitters were discussed in this Letter.

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