Spectral engineering with defect multiple-quantum-well structures

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It is shown that it is possible to significantly modify optical spectra of Bragg multiple-quantum-well structures by introducing wells with different exciton energies. The reflection spectrum of the resulting structures is characterized by high contrast and tuning possibilities. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1630852]

The concept of bandgap engineering facilitated creating materials with predetermined electrical properties. From the point of view of optical or optoelectronic applications, it is also important to be able to design materials with predetermined optical spectra. This requires the development of the spectral engineering through controllable alteration of the interaction between light and matter. The realization that such a possibility exists led to the development of the field of photonic crystals.[1,2] Additional opportunities in controlling the light–matter interaction arise in photonic structures made of materials with internal resonances lying in the spectral region of the photonic band structure.[3–5] Light propagates through such materials in the form of polaritons, in which electromagnetic waves are coupled with internal excitations of the materials. By changing properties of the material excitations, one can manipulate the properties of light as well. Combining polaritonic effects with photonic-crystal effects, one obtains a greater flexibility in designing optical properties and an opportunity to tune them after the growth. An interesting one-dimensional example of such systems is given by Bragg multiple quantum wells (BMQWs).[6] In these structures, the wavelength of the QW exciton radiation λ matches the period of the MQW structure d: $\lambda=2d$. As a result, the radiative coupling between QWs causes a very significant modification of exciton radiative properties, which are effectively controlled by geometrical parameters of the structure. Such structures, therefore, are good candidates for the spectral engineering.

In Ref. 7, it was found that by replacing a single base structural element of BMQW structure with an element with different properties (a defect), one can significantly alter optical spectra of these structures. It was shown that by introducing different types of the defect, a great variety of different spectral types could be created.[7,8] However, Ref. 7 dealt with ideal structures, and it was not clear if these effects can be reproduced in realistic structures suffering from homogeneous and inhomogeneous broadenings, and whose lengths are limited by technological capabilities.

The goal of this letter is to show that realistic BMQW structures with defects (DBMQW) can be designed to exhibit reflection spectra with sharp features characterized by a high contrast, even in the presence of relatively large values of the broadenings. We will also show that the spectra of these structures can be tuned after their growth with the help of the quantum confined Stark effect (QCSE).[9] This makes DBMQW structures a potential candidate for spectral engineering, with applications for tunable switching and modulating devices.

We consider a structure consisting of $N=2m+1$ QW barrier layers. The layers are identical except for one in the the middle, where the QW has a different exciton frequency. While our calculations are of rather general nature, we will have in mind a GaAs/AlGaAs system as an example. In this case, such a defect can be produced either by changing a concentration of Al[10,11] in the barriers surrounding the central well, or the width of the well itself[12] during the growth. While both these methods will also affect the optical width of the defect layers, this effect is negligibly small for the systems under consideration, and we will assume that the exciton frequency is the only parameter differentiating the defect well from the others.

The reflection spectra are calculated using the transfer matrix approach. The inhomogeneous broadening of the QW excitons is taken into account within the framework of the effective-medium approximation,[13] which was shown to describe the main contribution to the reflection coefficient.[14] Within this approach the exciton susceptibility, which determines the reflection and transmission coefficients for a single QW, is replaced with its value averaged over the distribution of the exciton frequencies along the plane of a QW:

$$\chi_{h,d}(\omega)=\int d\omega_0 f_{h,d}(\omega_0)\frac{\Gamma_0}{\omega_0-\omega-i\gamma}. \tag{1}$$

Here, Γ_0 is the effective radiative rate of a single QW, characterizing the strength of the coupling between excitons and electromagnetic field, γ is the parameter of the nonradiative homogeneous broadening, and $f_{h,d}$ are distribution functions of the exciton energies of the host and defect QWs, respectively. The variance of this function (Δ) is interpreted as the parameter of the inhomogeneous broadening. The functions f_h and f_d differ in their mean values, which are ω_h and ω_d for the host and defect QWs, respectively. The defect-induced effects are most pronounced if $|\omega_h-\omega_d|\gg\Delta$ when the inhomogeneous broadening of the host wells is negligible in the vicinity of ω_d. Since all the defect-induced modifications of the spectra lie at these frequencies, we can study them taking into account the inhomogeneous broadening of the defect well only.

If the length of the BMQW structure is not very large (for GaAs/AlGaAs it should be less than $\simeq 500$ periods[14]), the reflection coefficient can be presented in a form

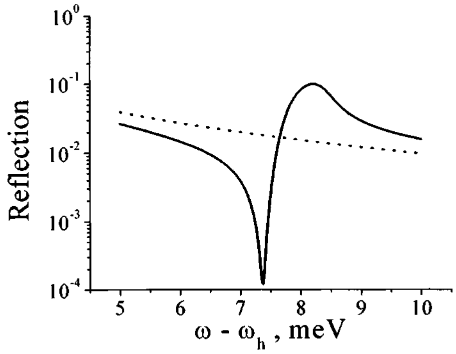

FIG. 1. A typical dependence of the reflection coefficient on frequency is shown in log scale for the MQW structure with Ω-defect with length $N = 15$ (solid line). For reference, the reflection coefficient of a pure system is provided (dotted line).

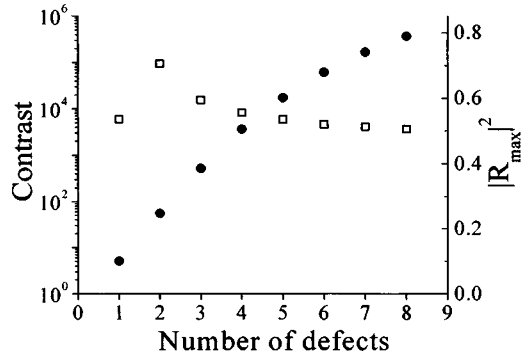

FIG. 2. Dependencies of the maximal reflection (filled circles, left scale) and the contrast (empty squares, right scale) upon the number of the defects in BMQW structures.

$$r = \frac{i\bar{\Gamma}}{\omega_h - \omega + i(\gamma + \bar{\Gamma})}\, \frac{\Omega_s - \Gamma_0 D_d}{i\Gamma_0 - \Gamma_0 D_d}, \tag{2}$$

where $D_d = 1/\chi_d$, $\bar{\Gamma}$ is the radiative width of the pure BMQW structure[6]

$$\bar{\Gamma} = \frac{\Gamma_0 N}{1 - i\pi q N}, \tag{3}$$

and $\Omega_s = (\omega_d - \omega_h)/N$.

The reflection spectrum is characterized by the presence of the minimum and the maximum (Fig. 1), both of which lie in the vicinity of ω_d, but are shifted with respect to it. The position of the minimum is determined mostly by parameter Ω_s: $\omega_{\min} = \omega_d - \Omega_s - \gamma^2/\Omega_s$. When $\Omega_s > \Delta$, the inhomogeneous broadening of the defect well does not affect the value of the reflection at $\omega_{\min}$. For this to happen the number of wells must satisfy the condition $N < N_c$, where $N_c \approx 27$ for GaAs/AlGaAs,[15] and $N_c \approx 36$ for $CdTe/Zn_{0.13}Cd_{0.87}Te$.[16] In this case, the value of the reflection at the minimum is determined by the rate of the nonradiative relaxation

$$R_{\min} = \frac{|\bar{\Gamma}|^2 \gamma^2 N^4}{(\omega_d - \omega_h)^4 (N-1)^2}, \tag{4}$$

which can be very small when the latter is small. Meanwhile, $\omega_{\max}$ lies in the spectral region, where the host system is almost transparent, and the value of the reflection at this frequency ($R_{\max}$) by the order of magnitude, can be estimated as that of a single-defect QW:

$$R_0 = \frac{4\Gamma_0^2}{(\pi\tilde{\gamma} + 2\Gamma_0)^2}. \tag{5}$$

The highest values of the contrast, defined as the ratio of the maximum and minimum reflections $\eta = R_{\max}/R_{\min}$

$$\eta \approx \left(\frac{\omega_d - \omega_h}{N\sqrt{\gamma\tilde{\gamma}}} \right)^4 \tag{6}$$

are obtained when the number of periods in the structure is small. For low-temperature values of γ, the contrast can be as large as 10^4. However, these large values of the contrast are accompanied by rather small values of $R_{\max}$. For switching or modulating applications, it would be useful to have a large contrast and a large maximum reflection. The latter can be improved by considering structures with multiple-defect wells. This leads, of course, to an increase in the total number of wells, but as we show, one can achieve a significant increase in $R_{\max}$ for a quite reasonable total length of the structure without compromising the contrast too much. Figure 2 shows the results of numerical computations of the dependence of the $R_{\max}$ and the contrast upon the number of defects. The structures were constructed of several blocks, each of which is a nine-period-long BMQW with a single-defect well in the middle.

One can see that, indeed, the spectrum of such multidefect structures exhibits large $R_{\max}$ (up to 0.8 for structures no longer than 80 periods), while preserving high values of the contrast (on the order of 10^4).

Applications of DBMQW structures for switching or modulating devices are based upon the possibility to change the value of the reflection coefficient at a working frequency ω_w by switching between $\omega_w = \omega_{\max}$ and $\omega_w = \omega_{\min}$ using, for instance, the QCSE in order to change the value of ω_d. The structures under consideration, however, also allow for tuning of the working frequency of the device by shifting the entire spectrum of the structure using QCSE in host wells. There are several different ways to implement this idea, but here we only want to demonstrate its principal feasibility. The main possible difficulty results from the fact that shifting ω_h will detune the whole system from the Bragg resonance, and may destroy the nice spectral features discussed earlier. In order to see how the detuning affects the spectrum, we assume for simplicity that ω_h and ω_d change uniformly, and study the reflection spectrum of an off-Bragg structure.

It was shown in Ref. 17 that the small detuning from Bragg resonance results in opening up a propagating band at the center of the forbidden gap, significantly complicating the spectrum. It turns out, however, that as long as $\omega_{\min}$ and $\omega_{\max}$ are well separated from ω_h, the detuning did not affect the part of the spectrum associated with the defect. Indeed, we show that the reflection spectrum of an off-Bragg structure is described by the same expression [Eq. (2)] as that of the Bragg structure. The only modification is the change of the definition of $\bar{\Gamma}$, which now becomes

$$\bar{\Gamma} = \frac{\Gamma_0 N}{1 - iN \sin \pi(\omega - \omega_B)/\omega_B}. \tag{7}$$

Thus, for such shifts of the exciton frequencies (ω_s) that satisfy the condition

$$N \sin\left(\pi \frac{\omega_s}{\omega_B}\right) \ll 1, \tag{8}$$

the destructive effect of the detuning of the structure away from the Bragg resonance is negligible in the vicinity of ω_d. It is important to note that the small size of the shift is required in comparison with the relatively large exciton frequency rather than, for example, with the width of the reflection band. Because of this circumstance, our structures can tolerate as large changes of the exciton frequencies as are possible with QCSE. The result of such a change is simply a uniform shift of the part of the spectrum shown in Fig. 1 by ω_s.

Additionally, Eq. (7) demonstrates a stability of the considered spectrum with respect to weak perturbations, such as the small mismatch of refraction indices of wells and barriers, different optical widths of the host and defect QWs, and others.

In this letter we considered reflection spectra of one special case of DBMQW structures; namely, those in which the defect well differs from that of the host in the value of the exciton energy. We showed that if the frequency of the defect lies at the edge of the host reflection band, the spectrum of such a structure becomes significantly modified: in a vicinity of the defect frequency it becomes nonmonotonic, with a well-defined minimum and a maximum. The value of the reflection at the minimum $R_{\min}$ is determined mostly by the rate of the nonradiative relaxation of excitons, and can be very small at low temperatures. The small value of the reflection leads to a giant contrast, defined as $R_{\max}/R_{\min}$, which can be as large as 10^4. The contrast is one of the figures of merit for structures considered for switching or modulating applications; however, the maximum reflection $R_{\max}$ in such structures is rather low. We showed that $R_{\max}$ can be significantly increased for structures with several defects without compromising the value of the contrast.

An additional advantage of the proposed structures is their tunability. We demonstrated that shifting the host and defect exciton energies by several widths of the hosts' reflection band leads to the uniform shift of the entire spectrum without any significant adverse effects on the spectral region in the vicinity of the defect frequency. This shift can be realized using, for instance, QCSE, so that the spectra of the considered structures can be electrically tuned.

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