Optical reflection spectra of resonant photonic structures based on a system of 100 InGaN quantum wells

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Abstract. The optical reflectance and transmittance spectra of a periodic InGaN semiconductor heterostructure with 100 quantum wells are studied at room temperature. Numerical modeling with a single set of parameters gave a quantitatively accurate fit of the experimental reflection and transmission spectra in a wide wavelength range. The radiative decay parameter is determined to be 0.25 meV and the nonradiative decay parameter is 40 meV.

1. Introduction
Photonic devices operating via exciton-polaritons may offer a fast and energy-efficient alternative to the modern electronics. Resonant Bragg structures (RBS) with quantum wells (QWs) are periodic semiconductor heterostructures with the period at which the wavelength of Bragg resonance upon reflection corresponds to the exciton excitation energy. Such systems are remarkable due to the fact that, in them, a decrease in the radiative lifetime of excitons in QWs is bound to be observed in proportion to the number of periods and be manifested in an increase in the exciton contribution to reflectance. Unfortunately, most of semiconductor materials and nanostructures exhibit substantial exciton resonance only at cryogenic temperatures due to a small exciton binding energy. When room-temperature operations are required, wide-band-gap III-N compounds seem to be materials of choice. In fact, the binding energy of excitons in GaN is \(\sim 26\) meV, which is comparable with thermal fluctuation energy at room temperature. That made possible to observe double exciton-Bragg resonance at room temperature in an RBS composed of 60 InGaN/GaN QWs \cite{1,2}.

In this paper we studied optical properties of an RBS composed on 100 periods of InGaN/GaN QWs.

2. Model simulations
An optical medium with periodic perturbations on the dielectric susceptibility shows an enhanced light-matter interaction when the Bragg resonance occurs at the frequency of the QW excitons, which results in formation of one superradiant exciton-polariton mode with all other modes being subradiant. Such a medium can be realized via a sequence of quantum wells with poles in the dielectric susceptibility provided by excitation of the quasi-two-dimensional excitons. The collective behavior of the excitonic system in response to the electromagnetic field gives rise to a superradiant optical mode that transforms into the photonic band gap when number of periods becomes large. Such resonant Bragg structures are quite attractive for all-optical and electro-optical applications since the excitonic states are sensitive to external and internal electric fields.
In order to estimate the optical properties of the RBS we performed computer-based simulation of the spectra using the method of transfer matrices. The matrices of transfer through the QW layers were formed on the basis of formulas for exciton-related reflectance and transmittance derived by Ivchenko [3,4]. Reflection and transmission coefficients for N quantum wells:

\[
r(kd = \pi) = \frac{-iN\Gamma_0}{\omega_0 - \omega - i(\Gamma + N\Gamma_0)}
\]

\[
t(kd = \pi) = (-1)^N \frac{\omega_0 - \omega - i\Gamma}{\omega_0 - \omega - i(\Gamma + N\Gamma_0)}
\]

where \(\omega_0\) is the QW exciton resonant frequency, \(\Gamma_0\) and \(\Gamma\) are the radiative and non-radiative broadening parameters of the exciton in a single QW. A detailed description of the model can be found in Ref. 5.

Figure 1 shows the calculated spectrum of reflection from the structure of InGaN 100 QWs under the double resonance conditions. If we take the nonradiative decay parameter equal to 1 meV then a photonic band gap is formed for the InGaN 100 QWs. It is evident that the exciton contribution plays a very important role in the observed resonant optical reflection.

**Figure 1.** Calculated spectra of the optical reflection from the RBS structure composed of InGaN 100 QWs with and without exciton contribution. The calculation has been performed under the double resonance conditions using the following parameters: the exciton energy is 3.162 eV, radiative decay parameter is 0.25 meV and the nonradiative decay parameter is 1 meV. The angle of the light incidence is 20°, S polarization.

**Figure 2.** Evolution of the reflection spectrum from the InGaN structure with an increase in the number of quantum wells under the double resonance conditions. Exciton parameters: excitation energy is 3.162 eV, radiative decay parameter is 0.25 meV and the nonradiative decay parameter is 40 meV. The angle of the light incidence is 20°, S polarization.

Plotted in Figure 2 are the calculated reflection spectra from the samples with different numbers of the InGaN QWs. Bragg reflection peak is broad and just visible for 10 QWs in the system, but it becomes well pronounced for 60 and 100 QWs. It is, of course, absent for the structure with a single QW.

3. Sample and experiment

Structure was grown by the metal-organic vapor-phase epitaxy (MOVPE). The sample was a combination of 100 equidistant InGaN/GaN QWs and was grown on a sapphire substrate. In order to prevent the penetration of dislocations into the active region of the sample, a GaN buffer layer with a
thickness of ~ 2.5 μm was grown between the above region and the substrate. The thickness of the InGaN QW was ~ 2 nm and the period of the structure amounted to ~ 75 nm. A rotation of the wafers was not employed during the growth process, so the structure intentionally had some gradient of the layer thicknesses and In concentration, hence optical properties of different sample regions vary from each other.

Optical reflectance and transmittance spectra were studied at different angles of incidence for different polarization of the incident light. All measurements were performed at room temperature.

The reflection and transmission spectra were measured by a standard procedure using a Namamatsu L2D2 (type L6565) deuterium lamp as a source of light, an OceanOptics HR4000CG-UV-NIR spectrometer combined with OceanOptics (“solarization resistant” type) optical fiber, and focusing lenses made of quartz glass. A Glan–Taylor prism was used as polarizers.

The experimental optical spectra were analyzed and fitted by model simulations described above. The radiative and nonradiative decay parameters was evaluated from the best fit between the calculated and experimental curves. The experimental and calculated optical reflection spectra are plotted in Figures 3 and 4 for the sample 100 InGaN QWs.

4. Results and discussion

Figure 3 shows the reflectivity spectrum in a vicinity of the main peak corresponding to the Bragg condition fulfilled near resonant frequency of QW excitons. The spectra were recorded for s-polarized light incident at 20°. Since the incident beam comes from ambient air and no antireflecting coating was used, the background reflection of about 0.2 is observed in accord to the Fresnel formula. The Bragg peak has a specific fine structure and appears on the background of the Fabry–Perot oscillations. The Fabry–Perot oscillations are pronounced at the long-wavelength side but diminish at the opposite side when approaching the GaN fundamental absorption edge at 365 nm.

**Figure 3.** Optical reflectivity spectra of the structure under study. Curve 1 is the experimental spectrum, curve 2 is the calculated spectrum with a contribution of the QW excitons and curve 3 is a result of calculations without exciton contribution. The angle of the light incidence is 20°, S polarization, room temperature.

**Figure 4.** Optical transmission spectra of the structure under study. Curve 1 is the experimental spectrum, curve 2 is the calculated spectrum with a contribution of the QW excitons and curve 3 is a result of calculations without exciton contribution. The angle of the light incidence is 20°, S polarization, room temperature.

Figure 4 shows experimental optical transmission spectra. The Fabry–Perot oscillations, which attenuate in the short-wavelength region, can also be seen in the above spectra. The fine structure is also
observed at the wavelength of Bragg resonance. A discrepancy between the calculation and experiment increases and becomes substantial below 385 nm. The most important reason for it is a tail of optical absorption in the GaN barriers and buffer layer. Some contribution to absorption at high energy can be due to excitons of other types. The calculations used excitons of A-, B-, and C-type with energy of 3.15, 3.2, and 3.23 eV, respectively.

The results of the calculations are shown in Figures 3 and 4 along with the corresponding experimental curves. The best-fit parameters of the calculations are as follows: resonant energy of the QW excitons is 3.15 eV, their radiative decay parameter is 0.25 meV and the nonradiative decay parameter is 40 meV. X-ray analysis showed that the structure has deviations of thickness from strict periodicity. The thickness of the structure was determined by 10 consecutive QWs as the average value in this sequence. Our calculations successfully describe the fine structure of the Bragg peak originated from the deviation of the exact periodicity of the structure.

5. Conclusion
By tuning the optical Bragg resonance of the QW system to the frequency of the QW excitons, we show a substantial enhancement of the resonant optical reflection, which indicates the formation of a super-radiant mode due to the electromagnetic coupling of the QW excitons. A good agreement is found between the experimental spectra and quantitative theoretical calculations, which proves the dominant role of the QW excitons in the resonant optical reflection. It is apparent that the excitons in the InGaN RBS are well suitable for room temperature operations.

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