Resonant Bragg structures with GaN/AlGaN Quantum Wells

D S Arteev¹, A V Sakharov¹, W V Lundin¹², E E Zavarin¹, S O Usov³, V V Chaldyshev¹, A S Bolshakov¹, M A Yagovkina¹, A F Tsatsulnikov²³

¹Ioffe Institute, 26 Politekhnicheskaya, 194021 St. Petersburg, Russia
²National Research University of Information Technologies, Mechanics and Optics, Kronverskyi 49, 197101 St. Petersburg, Russia
³Submicron Heterostructures for Microelectronics, Research & Engineering Center, RAS, 26 Politekhnicheskaya, 194021 St. Petersburg, Russia

E-mail: dima0724@gmail.com

Abstract. Optical properties of the resonant Bragg heterostructures with 10 and 30 GaN/AlGaN quantum wells were studied. The increasing of reflectivity at the resonance wavelength under condition of the Bragg wavelength and optical transition wavelength matching was observed experimentally at room temperature. The computer simulation of the optical transition wavelength in quantum wells and the optical reflectivity spectra at different reverse bias was implemented to evaluate radiative and non-radiative broadening parameters of the exciton in GaN/AlGaN quantum wells.

1. Introduction

Bragg reflector is a periodic structure typically formed from two alternating layers with different refractive index. If one of the layers is thin enough to form a quantum well and the wavelength of the electron-hole transition is equal to the Bragg wavelength, the effect of exciton-polariton resonance is observed. When the multiple quantum well system of N quantum wells is used, a superradiant exciton-polariton mode is formed by electromagnetic coupling of excitons in all quantum wells. Such structures, called Resonant Bragg Structures (RBS), were first theoretically proposed by E L Ivchenko et al. [1].

Formation of the superradiant mode was observed in RBS based on different material systems such as GaAs/AlGaAs [2–4], InGaAs/GaAs [5–6], CdTe/CdZnTe [7] and CdTe/CdMgTe [8]. It is worth mentioning that exciton-polariton resonance effect in these material systems occurs only at cryogenic temperatures. However, using InAlGaN-based periodic structure enables obtaining the effect at room temperature due to large exciton binding energy in GaN (~20 meV in bulk GaN compared to 4 meV in GaAs [9]). Resonant exciton enhancement in RBS based on InGaN quantum wells separated by GaN barriers at room temperature was demonstrated recently [10]. Furthermore, applying the external voltage to the structure makes it possible to change the optical transition energy of the exciton due to strong quantum-confined Stark effect (QCSE) in III-nitride quantum well. This effect was demonstrated in InGaN/GaN and GaN/AlGaN electroabsorption modulators in lateral geometry [11], but vertical geometry seems to be preferable in terms of usability. The totality of these factors makes InAlGaN RBS attractive for using as electro-optic modulator operating at room temperature.
In this paper for the first time we present efficient reflectivity modulation in vertical geometry resonant Bragg structure based on GaN/AlGaN quantum well system at room temperature.

2. Samples and experimental details.
Two samples were grown by metalorganic chemical vapor deposition (MOCVD) on sapphire (0001) substrates. Trimethylgallium and trimethylaluminum were used as the group-III source materials; ammonia was used as the nitrogen source. A set of several GaN quantum wells (10 and 30 QWs in the first and the second sample, respectively), separated by Al$_{0.12}$Ga$_{0.88}$N barriers, was grown on double Al$_{0.16}$Ga$_{0.84}$N/Al$_{0.12}$Ga$_{0.88}$N buffer layer. In contrast to the InGaN/GaN-based heterostructures, conventionally grown on well-established GaN buffer layer, GaN/AlGaN-based optoelectronic structures require AlGaN buffer layer to avoid optical absorption. The buffer layer was Si-doped and the others were unintentionally doped. The samples were capped in-situ with dielectric Si$_3$N$_4$ layer. The hybrid top contact, consisting of transparent ITO, encircled by NiAu (figure 1), was formed by optical lithography, sputtering and etching in order to enable applying voltage to active region of RBS.

X-Ray diffraction measurements were performed using D8 Discover Bruker diffractometer. Room temperature photoluminescence studies were carried out using excitation by a He-Cd laser (325 nm) focused in a 0.3 mm$^2$ spot. AvaSpec-2048 Fiber Optic Spectrometer was used to obtain PL spectra. Normal-incidence optical reflectivity measurements were performed using a deuterium lamp as a white light source and CCD-spectrometer. Focusing of the incident and reflected light was carried out with UV transmitting lenses.

According to the XRD-analysis, thicknesses of GaN QWs and AlGaN barriers in 10 QW structure are 2.7 and 70 nm, respectively. It should be noted, that the sample with 30 QWs was intentionally grown having barrier thickness gradient along the diameter of the structure, while the sample with 10 QWs has constant barrier thickness throughout the structure.

3. Results.
The experimental and simulated normalized zero-voltage PL spectra at room temperature are plotted in figure 3. As one can see, they are in good agreement with each other. Unfortunately, micro-PL
measurements at different voltage were made impossible by low photoluminescence efficiency resulted from the absence of localization centers in GaN/AlGaN QW as well as from higher dislocation density compared to InGaN/GaN heterostructures. Therefore, computer simulation of the dependence of the reverse bias on the optical transition energy in QWs was implemented. Figure 4 shows that the optical transition wavelength has minimum at ~45 V, corresponding to the flat bands in QW. It should be noted that the transition wavelength on figure 4 was derived from $\lambda = E_{eh}/hc$, where $E_{eh}$ is difference between calculated electron and hole levels in quantum well, without any broadening taken into account, while the PL spectrum on figure 3 was simulated using Lorentzian broadening function, leading to the redshift, and therefore a small discrepancy between the PL peak wavelength and optical transition wavelength exists. Conduction and valence bands in wurtzite GaN-based polar QW are tilted due to the build-in internal electric field caused by spontaneous and piezoelectric polarization. Applying the reversed bias decreases the electric field in QW, resulting in the blueshift of the interband transition wavelength, until the internal field is fully compensated by the external one and the bands in QW become flat. With further reverse voltage increasing, after the external field has become greater than the internal one, bands tilt in the opposite direction, causing redshift (figure 5).

**Figure 3.** Experimental and simulated photoluminescence spectra of 10 QW structure.

**Figure 4.** Simulated electron-hole transition energy.

**Figure 5.** Conduction and valence bands (black lines), electron (blue) and hole (red) wave functions (color solid lines) and energy levels (color dashed lines) in quantum well at the voltage of 0V, -40V and -60V.
The obtained values of the transition wavelength were used to simulate optical reflectance spectra and compare them with the experimental ones. The relative change in optical reflection \( \Delta R/R(0) = (R(U) - R(0))/R(0) \) is plotted in figure 6. Good agreement is found between experimental and simulated curves; the maximum value of the relative optical reflection (OR) change is \( \sim 5.5\% \) at the Bragg resonance wavelength.

In order to enhance exciton-polariton resonance effect, the structure with 30 quantum wells has been grown. A special growth conditions with non-uniform precursor gases distribution were used to obtain gradient of growth rates along the diameter of the structure. As a result the structure has different thicknesses of the layers and therefore different values of the transition wavelength and the Bragg resonance wavelength. The PL measurements show that the peak of the QW emission is nearly constant, while OR peak varies significantly (figure 7). Therefore, the constant quantum wells thickness of 2.7 nm and varying \( \text{Al}_0.12\text{Ga}_0.88\text{N} \) barrier thickness can be considered. Thus, we can get a match between optical transition and Bragg resonance wavelengths at normal incidence via choosing the appropriate point on the surface of the structure. In case of that match (at 10 mm) a dramatic increase in reflectance (more than 50\%) is observed, indicating exciton-polariton resonance. Unfortunately, high reverse leakage current through the Schottky contact, causing heating of the structure and changing of the refractive index, arising from insufficient crystal quality, prevented OR measurements of the biased structure.

![Figure 6](image-url)

**Figure 6.** Relative change in optical reflection spectra with voltage.

Simulation of OR spectra in different points was performed as follows. The Bragg resonance wavelength position was fitted by changing \( \text{AlGaN} \) barrier thickness; slight adjustments of the buffer layer thickness were done to fit the Fabry-Pérot oscillations. Simulation at each point was performed with and without taking into account exciton in quantum well. When the Bragg wavelength and the exciton wavelength are detuned (at -10 mm point), the difference between calculated spectra with and without exciton contribution is almost negligible (figure 8, top). But if the double resonance condition is met, the values of the reflectance, obtained with and without exciton contribution, differ greatly in the area near the resonance wavelength (figure 8, bottom). As can be seen, exciton accounting gives the value of reflectance 52.7\% at the resonance wavelength (which is in a good agreement with the experimental value of \( \sim 53\% \)). Disregarding of exciton contribution gives underestimated value of the reflectance (\( \sim 43\% \)); even the shape of the spectrum curve is qualitatively different from the experimental one in the area near the resonance wavelength. The totality of the experimental and
simulated results provides strong evidence that the effect of exciton-polariton resonance takes place in the structure. The exciton parameters in GaN QW estimated from the simulation are as follows: non-radiative broadening parameter $\Gamma$ is 40 meV at RT; radiative broadening parameter $N\Gamma_0$ for systems of 10 QWs and 30 QWs is 4 meV and 11 meV, respectively, giving $\Gamma_0=0.37–0.4$ meV.

**Figure 7.** Photoluminescence (PL) and optical reflection (OR) peak wavelengths depending on the coordinate.

**Figure 8.** Experimental and simulated (with and without taking into account exciton in QWs) spectra at -10 mm and 10 mm.

### 4. Conclusions.

The possibility of fabrication of the electro-optic modulator based on periodical resonant Bragg structure with GaN/AlGaN quantum wells, operating at room temperature was demonstrated. The obtained maximum value of the relative modulation of the reflectivity is ~5.5% for the structure with 10 quantum wells. Computer simulation results provide strong evidence of exciton-polariton resonance existence in the structure. The calculated values of the exciton non-radiative $\Gamma$ and radiative $\Gamma_0$ parameters are 40 meV and 0.37–0.4 meV, respectively.

### Acknowledgements

The XRD characterizations were performed using equipment owned by the Joint Research Center “Material science and characterization in advanced technology” (Ioffe Institute, St.-Petersburg, Russia).

### References

[1] Ivchenko E L, Nesvizhskii A I, Jorda S 1994 *Phys. Sol. State* Bragg reflection of light from quantum-well structures 36 7 1156–61

[2] Chaldyshev V V, Shkol’nik A S, Evtikhiev V P and Holden T 2006 *Semiconductors* Optical reflection and contactless electroreflection from GaAlAs layers with periodically arranged GaAs quantum wells 40 1432–5

[3] Goldberg D, Deych L I, Lisiansky A A, Shi Z, Menon V M, Tokranov V, Yakimov M and Oktyabrsky S 2009 *Nat. Photonics* Exciton-lattice polaritons in multiple-quantum-well-based photonic crystals 3 662–6

[4] Chaldyshev V V, Chen Y, Poddubny A N, Vasil’ev A P and Liu Z 2011 *Appl. Phys. Lett.* Resonant optical reflection by a periodic system of the quantum well excitons at the second quantum state 98 073112
[5] Hübner M, Prineas J P, Ell C, Brick P, Lee E S, Khitrova G, Gibbs H M and Koch S W 1999 *Phys. Rev. Lett.* Optical Lattices Achieved by Excitons in Periodic Quantum Well Structures **83** 2841–4

[6] Hayes G 1999 *Physica B* Suppression of exciton–polariton light absorption in multiple quantum well Bragg structures **272** 488–90

[7] D’Aubigné Y M, Wasiela A, Mariette H and Dietl T 1996 *Phys. Rev. B* Polariton effects in multiple-quantum-well structures of CdTe/Cd$_{1-x}$Zn$_x$Te **54** 14003–11

[8] Ivchenko E L, Kochereshko V P, Platonov A V, Yakovlev D R, Waag A, Ossau W and Landwehr G 1997 *Phys. Sol. State* Resonance optical spectroscopy of long-period quantum-well structures **39** 1852–8

[9] Muth J F, Lee J H, Shmagin I K, Kolbas R M, Casey H C, Keller B P, Mishra U K and Denbaars S P 1997 *Appl. Phys. Lett.* Absorption coefficient, energy gap, exciton binding energy, and recombination lifetime of GaN obtained from transmission measurements **71** 2572–4

[10] Chaldyshev V V, Bolshakov A S, Zavarin E E, Sakharov A V, Lundin W V, Tsatsulnikov A F, Yagovkina M A, Kim T and Park Y 2011 *Appl. Phys. Lett.* Optical lattices of InGaN quantum well excitons **99** 251103

[11] Ozel T, Sari E, Nizamoglu S and Demir H V 2007 *J. Appl. Phys.* Violet to deep-ultraviolet InGaN/GaN and GaN/AlGaN quantum structures for UV electroabsorption modulators. **102**(11), 113101. doi:10.1063/1.2817954

[12] Bolshakov A S, Chaldyshev V V, Zavarin E E, Sakharov A V, Lundin W V, Tsatsulnikov A F and Yagovkina M A 2017 *J. Appl. Phys.* Room temperature exciton-polariton resonant reflection and suppressed absorption in periodic systems of InGaN quantum wells **121** 133101

[13] Tisch U, Meyler B, Katz O, Finkman E and Salzman J 2001 *J. Appl. Phys.* Dependence of the refractive index of Al$_x$Ga$_{1-x}$N on temperature and composition at elevated temperatures **89** 2676–85