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Optical investigations of bulk and multi-quantum well nitride-based microcavities

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Abstract

The light-matter coupling has been investigated in $\lambda/2$ and in λ-GaN microcavities. It is shown that the optical properties of the cavity are affected by the strong absorption in the GaN active layer when its thickness increases. Results obtained on a microcavity including GaN/AlGaN multi-quantum well (MQW) are also reported and the oscillator strengths of excitons are deduced from the fit of reflectivity spectra. Nevertheless improvement of the design and material quality of the MQW microcavity will be necessary to observe the strong coupling.

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1. Introduction

Many studies have demonstrated the strong light-matter interaction in III–V and II–VI semiconductor microcavities since its first observation in 1992 [1–3]. The so-called strong coupling regime appears when photons and excitons have the same energy and strongly interact in the material leading to the creation of new quasiparticles, intermediate between photons and excitons, called cavity polaritons. Planar microcavities containing either a bulk material [4,5] or quantum wells (QWs) [6,7] are suitable to study the strong coupling. Among all the III-V semiconductor compounds, GaN, which is characterized by large excitonic binding energies and huge exciton oscillator strengths, is a promising candidate for the realization of novel optoelectronic devices such as polariton light emitters [8]. In this paper, we present the optical characterization of two bulk $\lambda/2$ and λ-GaN microcavities grown by molecular beam epitaxy on AlN/$Al_{0.2}Ga_{0.8}N$ distributed Bragg reflectors (DBRs) elaborated directly on silicon(1 1 1) and the preliminary experimental results obtained on an $Al_{0.2}Ga_{0.8}N$ microcavity including GaN multi-quantum wells.

2. Sample description and experimental setup

Three microcavities grown by molecular beam epitaxy on silicon substrate have been studied. In each sample, the bottom mirror is a DBR constituted by $\lambda/2$ pairs of $Al_{0.2}Ga_{0.8}N$/AlN layers (10 pairs and 10.5 pairs for sample 1 and 2, respectively) grown directly on Si. λ corresponds to the resonance wavelength of the cavity and is related to vacuum wavelength λ_0 by λ_0/n where n is the refractive index, and $\lambda_0 = 350$ nm. The thickness of the GaN active layer is $\lambda/2$ and λ for samples 1 and 2, respectively. Both samples are covered by a 100 Å thick aluminium layer which acts as the top mirror. Sample 3 contains a DBR

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constituted by 9.5 pairs of $Al_{0.2}Ga_{0.8}N$/AlN layers deposited on Si, a $3\lambda/2$ $Al_{0.2}Ga_{0.8}N$ cavity in which 9 GaN quantum wells (2 nm thick) are embedded and a top mirror constituted by seven $\lambda/2$ pairs of SiN/SiO_2 layers. In order to tune the optical mode, a thickness gradient was introduced during the growth along the sample. Microcavities are studied through angle-resolved reflectivity measurements at room and low temperature ($T = 5$ K). The sample is mounted inside a rotating cryostat with quartz cylindrical windows. The light source is a halogen lamp whose beam is sent through a polarizer on the sample by a mirror positioned at 45°. The halogen lamp, the polarizer and the mirror are fixed on a mobile rail which allows measurement from 2° to 85°. The reflectivity signal is focused on the slit of the monochromator and detected by a photomultiplier using a lock-in amplification. For the photoluminescence (PL) experiments, a 325 nm continuous He–Cd laser is used for the excitation and the detection system is the same as before. Reflectivity measurements are compared to calculated spectra using a standard transfer matrix formalism in which the contribution of excitons to the dielectric function is modeled through harmonic oscillators [9]. The convolution of the homogeneous Lorentzian lines with a Gaussian distribution accounts for the inhomogeneous broadening of the excitonic transitions [10]. The absorption due to the band-to-band transitions including the exciton effects is taken into account with the Elliott's formula [11]. The enhancement of the real part of the refractive index closed to the band-gap energy is determined from the Kramers–Kronig transformation of the imaginary part of the dielectric function.

3. Results and discussion

Angle-resolved reflectivity measurements are performed for transverse electric (TE) and transverse magnetic (TM) polarizations. The TE (TM) polarization is characterized by an electric field perpendicular (parallel) to the plane of incidence.

3.1. Bulk microcavities

The evolution of experimental reflectivity spectra of samples 1 and 2 at low and at room temperature (RT) is reported as a function of the incidence angle θ on Fig. 1.

For both samples, the optical mode is large and negatively detuned with a low quality factor ($Q = \lambda/\Delta\lambda = 60$). For sample 1, at low temperature and $\theta = 5°$, the optical mode is observed at 3459 meV while A and B excitons are located at 3519 meV and 3538 meV respectively. When the incident angle increases, the cavity mode shifts to the high energy side and an anticrossing is clearly observed between the photonic and excitonic modes for $\theta = 40°$. The evolution of the low energy mode corresponds to the lower polariton branch and the high energy mode is the upper polariton branch. The anticrossing is the signature of the strong light-matter coupling and a Rabi splitting value (minimum energy difference between the two modes) equal to 56 ± 2 meV is measured. At RT the strong coupling persists and the resonance position occurs for θ lying between 27.5° and 30°, with a Rabi splitting equal to 39 ± 4 meV. In the aim to observe a larger Rabi splitting, sample 2 whose active layer is larger (λ thick) is investigated [12]. At low temperature, the optical mode lies at 3450 meV and A and B exciton resonances are clearly detected at 3505 meV and 3519 meV in Fig. 2a. The lower polariton branch is identified but an unusual behavior is observed: A and B exciton positions do not move whatever the incident angle. In order to understand this behavior, simulations have been performed with or without including the GaN band-to-band absorption (Fig. 2b and c, respectively).

It is worth nothing that the numerical simulation accounts well for the evolution of the experimental spectra when both exciton and band-to-band absorption contributions are included (Fig. 2b). When the incident angle is increased above 5°, the lower polariton mode moves towards the excitonic features. But even when the photon energy corresponds to the excitonic resonance the excitons remain uncoupled. This phenomenon is interpreted as the vanishing of the strong coupling regime due to the high excitonic absorption in the GaN. Therefore the active layer appears as a semi-infinite medium for the photon. Then, it is difficult to detect clearly the upper polariton branch in this sample because of the GaN band-to-band absorption which strongly reduces the photonic confinement. On the opposite the expected dispersion of the upper polariton mode is clearly in evidence through simulation when the band-to-band absorption is removed (Fig. 2c). These results demonstrate the difficulty to evidence a strong coupling in a λ-GaN cavity because of the high excitonic and band-to-band absorptions in GaN.

3.2. Quantum well microcavities

The experimental results obtained on a QW microcavity are then analysed. Measurements are first performed on sample 3 before the deposition of the top mirror. The angle-resolved reflectivity measurements recorded at RT for TE and TM polarizations are displayed on Fig. 3. The optical mode observed at 3330 meV for $\theta = 5°$ moves toward the high energy side with the increase of the incident angle. Regarding the overall evolution of the spectra, a significant difference can be noted between the two polarizations, especially around 65° where the reflectivity intensity for TM polarization is decreased. This phenomenon arises for an incidence angle closed to the zero reflexion Brewster angle in $Al_{0.2}Ga_{0.8}N$. In our case, this angle is approximatively equal to 68° for an energy around 3400 meV (the Brewster angle depends on energy through the refractive index). This evolution of the spectra is well reproduced by our simulation. Concerning the excitons, the excitonic mode is detected at a constant energy