JOURNAL OF APPLIED PHYSICS **101**, 033113 (2007)

Fabry-Perot effects in InGaN/GaN heterostructures on Si-substrate

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(Received 14 November 2006; accepted 4 December 2006; published online 8 February 2007)

A strong intensity modulation is found in spatially and angular resolved photoluminescence spectra of InGaN/GaN heterostructures and quantum wells epitaxially grown on Si(111) substrates. This Fabry-Perot effect results from the high refractive index contrasts at the GaN/Si and the Air/InGaN interfaces. It can be used for a wavelength stabilization of the sample upon temperature change and, e.g., in the case of light emitting diodes, to additionally reduce the blueshift at increasing injection currents. A simple geometric approach has been chosen to calculate the influence of layer thickness, absorption and refractive indices, as well as detection angle. The cavity can be described quantitatively by a simple three layer Fabry-Perot model. An analytical expression is derived for the external luminescence line shape. Microphotoluminescence measurements at samples with the silicon substrate locally removed corroborate the model. © *2007 American Institute of Physics*.
[DOI: 10.1063/1.2434010]

INTRODUCTION

The fabrication of high quality microcavities (MCs) has attracted much attention both for fundamental studies[1,2] and technological applications.[3–5] Introducing MCs in resonant cavity light emitting diodes (RCLEDs) can result in higher external efficiency due to an improved light extraction, higher spectral purity, and spatially narrower and more directed emission.[3,5] Furthermore in high finesse cavities a strong enhancement of the spontaneous emission for the resonance wavelength can be achieved (Purcell effect).[6] This concept has been proven successful in the gallium arsenide material system so far. In the group-III-nitride system mostly nitride MCs with high reflectivity Bragg reflectors on sapphire[7–11] and silicon[12] substrates have been studied. Optically pumped lasing in nitride vertical-cavity surface-emitting laser (VCSEL) has been demonstrated at room temperature.[13]

EXPERIMENT

In this paper we describe a different approach. Simple InGaN/GaN heterostructures were grown by metal organic chemical vapor phase epitaxy on Si(111) substrate using a ~15 nm thin AlN nucleation layer. The optical resonator structure comprises a thick GaN cavity layer plus an InGaN active region. No bottom or top Bragg reflectors were included. Solely due to the high contrast in refraction index at the GaN/Si interface and the nitride/air interface, an intrinsic cavity is formed with the GaN acting as a waveguide. Two different types of samples were studied. Sample A consists of a ~100 nm thick InGaN epilayer grown at 800 °C on a ~1.24 μm thick GaN layer. The indium content was determined by x-ray diffraction (XRD) to 20.8%. Sample B is an optimized LED structure consisting of InGaN/GaN multiquantum wells grown at ~855 °C on a ~1.3 μm thick GaN layer with SiN interlayers to improve the epilayer quality.[14] The total cavity thickness in this sample adds up to 1872 nm. For further investigations the Si substrate of sample B was locally removed by etching with a HF/HNO_3 solution to change the reflectivity at the bottom interface.

RESULTS AND DISCUSSION

Figure 1(a) shows a photoluminescence (PL) spectrum of sample A at a temperature of $T=260$ K on a logarithmic and linear scale (inset) detected perpendicular to the sample surface. The elevated temperature was chosen in order to further extend the emission profile of the InGaN luminescence towards lower energies by adding the yellow luminescence. Multiple interference peaks are clearly resolved (marked by dotted lines) visualizing the presence of a Fabry-Perot (FP) effect in the Si/(GaN/InGaN)/Air cavity. Figure 1(b) is a compilation of these results by plotting $2n(\lambda_{\text{peak}})/\lambda_{\text{peak}}$ over the peak numbers i, with n being the refractive index of GaN and λ_{peak} the peak wavelength. The slope of the peak positions directly yields the reciprocal of the cavity thickness d,

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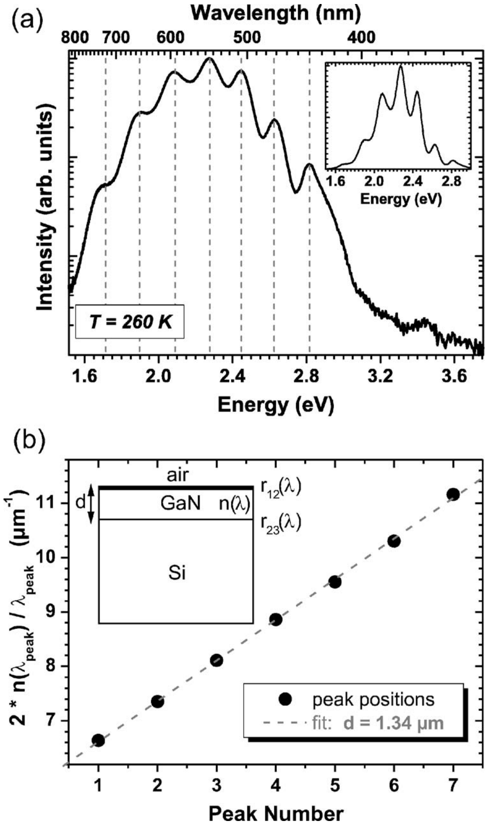

FIG. 1. (a) PL spectrum of sample A at 260 K in logarithmic and in linear scale (inset). The pronounced maxima of the Fabry-Perot oscillations are visible and marked by dotted lines. (b) Fit of the Fabry-Perot peak positions according to Eq. (1). The schematic sample structure used for the calculations is depicted in the inset.

$$i\frac{1}{d} = \frac{2n(\lambda_{\text{peak}})}{\lambda_{\text{peak}}}. \qquad (1)$$

In agreement with scanning electron microscopy (SEM) measurements the thickness of the sample structure is 1.34 μm. A Sellmeir function as described by Billeb *et al.*[15] has been adopted for the refractive index of GaN at RT.

In order to measure the angular dependence of the FP emission we measured the PL spectra as a function of detection direction. Figure 2 shows a subset of four PL spectra of sample A measured for different detection angles Θ, as indicated in the inset, integrated over both polarizations. With decreasing Θ all five Fabry-Perot peaks systematically shift towards higher energies. The angle $\Theta = 0°$ coincides with the *c* axes of the crystal. This is summarized in Fig. 3. The additional peak labeled (a) originates from near band edge recombination in GaN. This GaN luminescence as well as the InGaN peak of highest energy (b) are absorbed throughout the whole cavity and show no or only minor angular dependence. In contrast, a strong monotonous blueshift with decreasing Θ is observed for the other peaks [(c)–(f)] where reabsorption of the InGaN layer plays a minor role. This shift can be described analytically by the expression

$$E_{\text{peak}}(\Theta) = \frac{E(\Theta = 0)}{\sqrt{1 - \cos^2(\Theta)/{n_{\text{GaN}}}^2(E)}}, \qquad (2)$$

based on a three layer Fabry-Perot resonator model consisting of a Si/(GaN+InGaN)/air stack. In this simple model the InGaN layer has not explicitly been taken into account and reabsorption is not considered. However, this model perfectly fits for an ultrathin quantum well (QW) on top of the GaN layer.

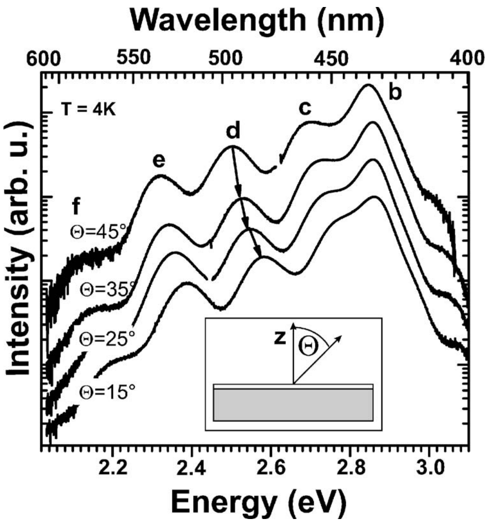

FIG. 2. Set of four PL spectra recorded at different angles Θ as indicated and defined in the inset.

We will now calculate the line shape of the luminescence for different detection angles using a basic geometric optical approach. Due to the multiple reflections at the Fabry-Perot boundaries an interference pattern of the light leaves the resonator. The modulation of light intensity is then given by[16]

$$M = \frac{1 + R_{23}^2 \exp[-4(\alpha d)] + 2R_{23}\exp[-2(\alpha d)]\cos\delta}{1 + R_{21}^2 R_{23}^2 \exp[-4(\alpha d)] - 2R_{21}R_{23}\exp[-2(\alpha d)]\cos\delta}, \qquad (3)$$

with the phase shift,

$$\delta = \frac{4\pi(d)}{\lambda}\sqrt{n_2^2 - n_1^2 \sin^2\Theta}, \qquad (4)$$

where d is the thickness of the GaN layer (including the InGaN), α is the absorption coefficient of GaN, and R_{21} and R_{23} are the reflectivities at the GaN/air and GaN/substrate interfaces, respectively. n_1 and n_2 are the refractive indices of air and GaN, respectively. The refraction index n_3 of Si is

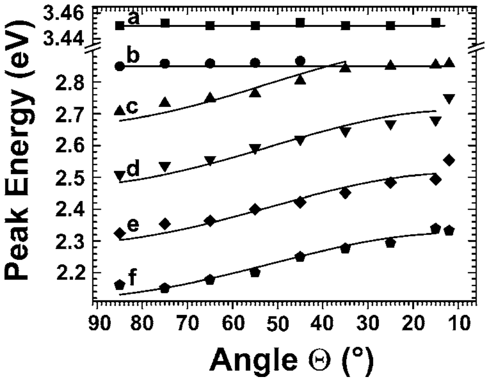

FIG. 3. Energetic shift of the Fabry-Perot maxima taken from Fig. 2 vs angle of detection (data points) fitted according to Eq. (2) (full lines).

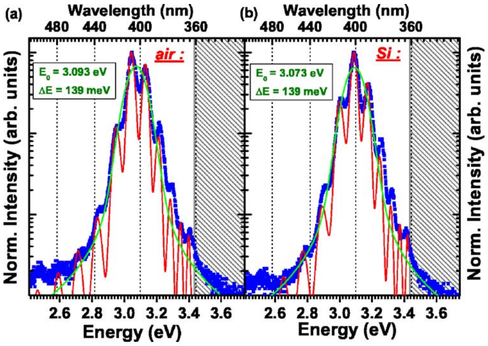

FIG. 4. (Color online) Comparison of the $T=5$ K PL spectra of sample B without (a) and with (b) silicon substrate. The measured luminescence spectra are plotted (blue) together with the calculated luminescence line shapes $I(\lambda)$ (red) using Voigt profile for the spontaneous emission $B(\lambda)$ (green) according to Eqs. (5) and (6). The hatched area indicates the region of strong absorption.

taken from Ref. 17. The observed luminescence $I(\lambda,\Theta)$ can be written as the product of the modulation M and the unperturbed luminescence $B(\lambda)$,

$$I(\lambda,\Theta) = M(\lambda,\Theta)B(\lambda). \qquad (5)$$

For negligible absorption in the cavity, i.e., assuming transparency of the GaN waveguide for the low energetic InGaN luminescence ($\alpha=0$) and perpendicular observation ($\Theta=0$), i.e., $R_{21}=(n_2-n_1/n_2+n_1)^2$ and $R_{23}=(n_3-n_2/n_3+n_2)^2$, Eq. (2) simplifies to

$$M(\lambda) = \frac{1 + R_{23}^2 + 2R_{23}\cos(4\pi d/\lambda^*)}{1 + R_{21}^2 R_{23}^2 - 2R_{21}R_{23}\cos(4\pi d/\lambda^*)}, \quad \text{with}$$

$$\lambda^* = \frac{\lambda_{\mathrm{Vac}}}{n_2(\lambda)}. \qquad (6)$$

Figure 4(a) shows the excellent quantitative agreement between a perpendicular RT PL measurement of sample B (blue) and the calculated luminescence $I(\lambda)=M(\lambda)B(\lambda)$ (Eqs. (5) and (6)) (red) over three orders of magnitude. A Voigt profile is assumed for the unperturbed spontaneous emission profile $B(\lambda)$ (green). Since sample B consists of an InGaN multiquantum well (MQW) reabsorption in the active region does not affect the modulation. However, the absorption of the GaN still eliminates the modulation at elevated energies (hashed area).

In a further experiment sample B was modified by locally removing the Si substrate with a HF/HNO_3 etching solution. Figure 5(a) shows a plan view microscopic picture across the etching border. In Fig. 5(b) a micro-PL wavelength image, i.e., a mapping of the local peak wavelength, is shown for the identical sample area (spatial resolution <1 μm). At the etched border an abrupt change towards lower wavelengths on the nonetched Si area is visible. The exchange of the optical more dense medium Si by the optical less dense medium air results in a phase shift of π in the modulation function $M(\lambda)$. The two PL spectra recorded from the opposite sides of the etched border are compared in Figs. 4(a) and 4(b). In both cases the luminescence is strongly modulated with interference fringes, with maxima having a distance of ~90 meV evidencing identical cavity thicknesses. However, the peak energies are shifted by ~65 meV. The removal of the Si substrate results in two effects. Firstly, the phase shift π mentioned above resulting in a shift of ~45 meV. Secondly, the relaxation of the tensely stressed InGaN/GaN layer on the Si substrate causes a shift of the spontaneous emission profile $B(\lambda)$ by 20 meV to higher energies from 3.073 to 3.093 eV as indicated in Figs. 4(a) and 4(b) (green). Note that with the exception of this peak energy shift in $B(\lambda)$ and phase shift π in $M(\lambda)$, identical fitting parameters were used for $M(\lambda)$, i.e., cavity thickness d and reflectivities R_{21} and R_{23}, as well as for $B(\lambda)$, i.e., $\Delta E=139$ meV! The theoretical amplitude modulation is not fully reached due to interface imperfections. In addition, statistical fluctuations in peak emission wavelength caused by inhomogeneous In content of the alloy are visible across the whole sample.

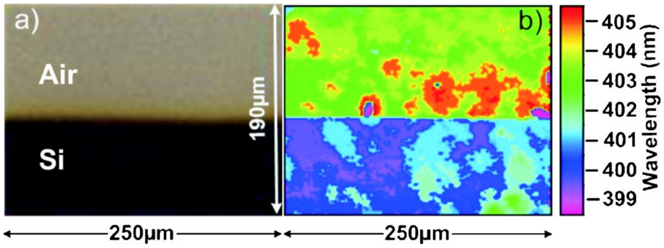

FIG. 5. (Color online) Optical microscope image (a) and micro-PL image (at $T=5$ K) mapping the local peak wavelength (b) across the boarder between etched and nonetched areas of sample B.

SUMMARY

In summary a strong cavity effect for simple InGaN/GaN heterostructures on Si(111) substrate has been demonstrated. Due to the high refractive index change at the interface an intrinsic cavity is formed which can be described in a Fabry-Perot resonator model giving expressions for the energetic positions of the inference maxima as a function of cavity thickness and detection angle. The calculations have been verified by angular dependent photoluminescence measurements. A simple analytical expression is derived for the FP modulated luminescence line shape achieving excellent quantitative agreement with experiment. A comparison of a thick InGaN layer and an InGaN MQW reveals the influence of reabsorption in InGaN and GaN. Removal of the Si substrate causes an abrupt phase change of π. This effect can be used, e.g., for wavelength stabilization upon temperature change or of a blueshift due to band filling effects of optoelectonic devices as LEDs.

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