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Laser threshold and optical gain of blue optically pumped InGaN/GaN multiple quantum wells (MQW) grown on Si

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Optical and laser properties of a series of MQW heterostructures with varying geometry grown on silicon with Al predeposition were investigated. Photoluminescence (PL) band positions covered a spectral range of 430 – 460 nm under I_{exc}=1 MW/cm^2 and 445-505 nm under I_{exc}=0.15 W/cm^2. Laser action was achieved under transversal optical pumping at room temperature using only cleaved lateral facets of the samples as laser mirrors. The laser threshold rose from 137 kW/cm^2 to 300 kW/cm^2 with laser wavelength increase from 440 nm to 465 nm. Numerical simulation of the laser conditions shows that the minimal threshold is realized on the fifth order mode. However, the calculated value of material optical gain of InGaN at the laser threshold increases only from 750 cm^{-1} to 1020 cm^{-1}, mainly due to absorption rise in the substrate with increasing wavelength. Correlation was observed between PL characteristics and laser threshold.

1 Introduction Silicon substrates are promising for mass production of GaN-based devices because of their high thermal conductivity, large-area availability, lower cost and better crystal quality than the commonly used sapphire and silicon carbide (SiC). In addition, Si substrates allow in principle the integration of GaN-based light emitting and RF devices with Si-based electronics which would be very attractive. Since the high lattice mismatch still remains the main issue for the creation of high-quality devices with properties comparable or better than those fabricated on sapphire or SiC, further improvement of the MOVPE growth technology on Si is needed. Several methods have been proposed for improvement of GaN growth on Si, including the use of patterned substrates [1], selective area growth [2] as well as the use of various buffer layers of AlGaN/GaN [3], SiC [4], or AlAs [5]. For the first time laser action in optically pumped GaN pyramids overgrown on Si was achieved [6]. A consequent improvement of the MOVPE growth technology using AlGaN/AlN strain reducing layers on silicon has led to the creation of GaN layers and InGaN/GaN/Si MQWs with laser quality [7, 8]. But laser properties of InGaN/GaN MQWs grown on Si and their correlation with PL characteristics have not been investigated sufficiently up to now.

2 Experimental The samples were grown in AIXTRON MOVPE reactors on 2-inch silicon substrates. The layer sequence from top to substrate is as follows: GaN(40 nm)/GaN(10 nm)/5*{InGaN(x)/GaN:Si(9.6 nm)} QWs/GaN(~1 µm)/AlN(LT)/GaN(600 nm)/$Al_{0.31}GaN_{0.69}N$ (180 nm)/$Al_{0.55}Ga_{0.45}N$(180 nm)/AlN(LT)/AlN(HT) 80 nm)/ Al (2 sec predeposition) /Si. The QWs with x=2.1 nm and x=1.8 nm were grown at temperature T_g=740 °C. A cw He-Cd laser (λ = 325 nm, I_{exc} = 0.1 - 30 W/cm^2) and a pulsed N_2 laser (λ = 337.1 nm, I_{exc} = 1 - 2000 kW/cm^2, τ_p=8 ns) were used for the excitation of the samples for PL measurements and lasing experiments at room temperature (RT). Laser cavities were fabricated by cleaving the samples. The length of the cleaved cavities was 1000-1300 µm which leads to weak dependence of the laser threshold on the cavity length. Spectral-angular distribution of the laser emission in the far-field was registered using an optical fibre (the angle was counted out of the heterostructure plane). For the estimation of the lasing condition, calculations of the electromagnetic field distribution of the laser radiation in the heterostructures as in [9] and of the reflection coefficient as in [10] were carried out in the approximation of plane electromagnetic waves.

3 Results and discussion Laser action was achieved at RT under transversal optical pumping using cleaved lateral facets of the samples without any coatings as laser mirrors. Lasing regime was detected by the drastic increase of emission intensity from cavity edge above threshold accompanied by a spectral narrowing (Fig. 1). The stimulated emission has TE polarization.

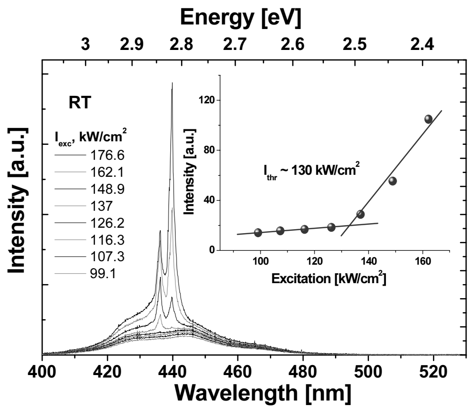

Figure 1 Emission spectra of the sample with 2.1 nm QWs in dependence on excitation intensity. Inset: emission intensity versus excitation intensity.

The far-field pattern of radiation has a complex structure symmetrical relative to the heterostructure plane with two main bright spots formed by radiation propagating at angles about 50 degrees relative to the heterostructure plane, as well as with two spots with lower intensities placed under smaller angles. Figure 2 shows the density plot of the spectral-angular distribution of the laser emission in the far-field.

As seen from Fig. 2 containing also the calculated angular function of the 5th transversal mode intensity in the far-field, the experimental maxima coincide well with the theoretical result. Thus, lasing takes place on the transversal mode of 5th order.

The numerical calculation showed that the maximum value of the optical confinement factor Γ (1.08% for 2.1 nm QW and 0.92% for narrower wells) is reached again for the 5th order mode. Taking into account the calculated optical mirror losses (with reflection coefficient R and cavity length L_c) and absorption losses in Si substrate

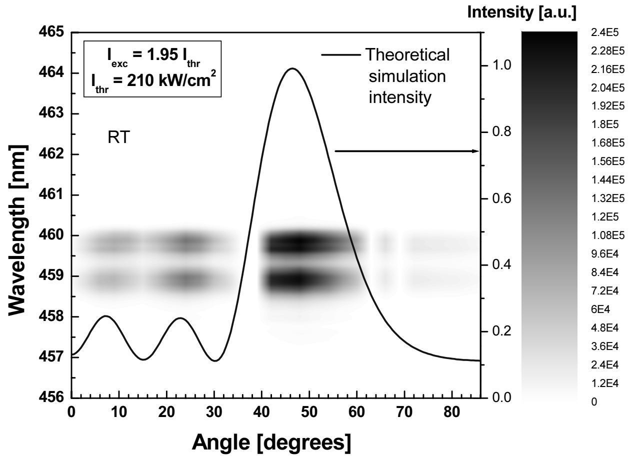

Figure 2 Density plot of spectral-angular distribution of the laser emission in the far-field and calculated intensity distribution for the 5th order transversal mode.

(α_{si}) using formula

$$\alpha_{InGaN}^{thr} = \frac{\frac{1}{L_c}\ln\left(\frac{1}{R}\right) + \alpha_{Si}}{\Gamma} \qquad (1)$$

it was demonstrated that the minimum threshold gain of InGaN α_{InGaN}^{thr} is realized namely for the 5th order modes. This is an additional evidence of the appearance of lasing on the 5th order transverse modes.

As shown in Fig. 3, laser action was achieved in the spectral range of 440–465 nm for samples from different epitaxial runs. At that, the laser threshold rose from 137 kW/cm^2 to 300 kW/cm^2 with laser wavelength increase from 440 nm to 465 nm. As it is seen in the inset of Fig. 3, a nearly linear increase of the laser threshold with laser wavelength is observed in contrast to the exponential increase for InGaN/GaN MQW on Al_2O_3 in the blue spectral region [11]. The dependence slope is larger for 2.1 nm QWs and it is about 6.5 kW/nm, the slope for 1.8 nm QWs is 3.0 kW/nm.

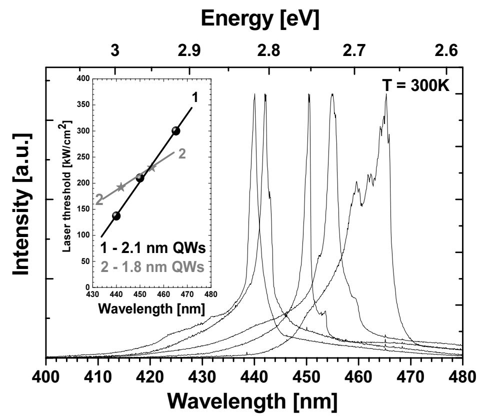

Figure 3 Emission spectra of different samples above threshold. Inset: laser threshold in dependence on the radiation wavelength for 2.1 nm QWs (1) and 1.8 nm QWs (2).

Material optical gain of InGaN at the laser threshold was calculated for all samples. It increases substantially from 1035 cm^{-1} (λ = 442 nm) to 1289 cm^{-1} (λ = 455 nm) for 1.8 nm QWs and from 750 cm^{-1} (λ = 440 nm) to 1020 cm^{-1} (λ = 465.2 nm) for 2.1 nm QWs. Figure 4 demonstrates dependences of InGaN material optical gain on wavelength in comparison with the laser threshold dependences.

As the calculations showed, the optical confinement factor reduces quite insignificantly with wavelength increase mainly for the account of an increase of the emission penetration into the $Al_{0.31}Ga_{0.69}N$ (180 nm)/ $Al_{0.55}Ga_{0.45}N$ (180 nm)/LT AlN/ HT AlN (80 nm) cladding layers. Because the optical confinement factor changes weakly, the observed significant alteration of the optical gain with wavelength is due to the optical losses, mainly due to absorption rise in the substrate with wavelength.

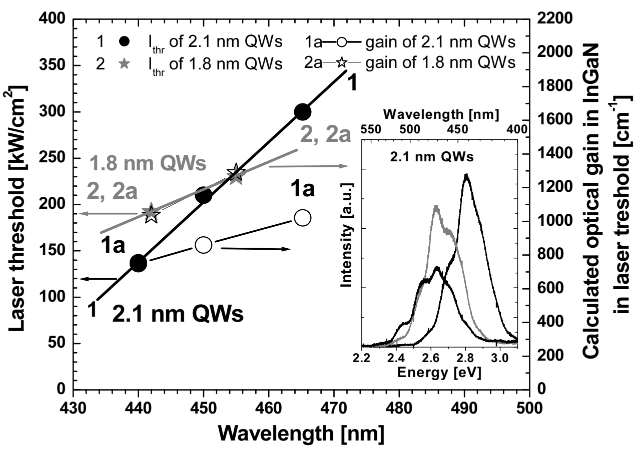

Figure 4 Laser threshold (1, 2) and calculated optical gain of InGaN (1a, 2a) dependences on wavelength for 2.1 nm (1, 1a) and 1.8 nm (2, 2a) QWs. Inset: PL spectra of 2.1 nm QWs at high excitation level.

Comparison of the experimental threshold with optical gain at the threshold showed proximity of the dependences for gain and threshold for thin QWs. Such dependence can be realised if full width at half maximum (FWHM) and efficiency of the spontaneous emission depend weakly on wavelength, besides gain depends nearly linearly on pumping. Indeed, PL intensities and FWHMs differ insignificantly for these samples.

In contrast to the dependence for 1.8 nm QWs, a stronger dependence of the laser threshold in comparison with gain dependence on wavelength for thicker 2.1 nm QWs is observed. Laser threshold depends on spontaneous emission parameters as:

$$I_{thr} \sim \frac{(h\nu)^2 \cdot \Delta h\nu}{\eta_{sp}} \quad (2)$$

where hν is the photon energy for the spectrum maximum, $\Delta h\nu$ the FWHM of the PL spectrum and $\eta_{sp}(h\nu)$ the spontaneous emission efficiency at laser threshold. Therefore, these parameters can contribute to threshold increase with wavelength. The observed difference in gain and threshold behavior is possible if quantum efficiency of spontaneous emission decreases with wavelength rise for 2.1 nm QWs. Indeed, a substantial drop of the PL intensity is observed for 2.1 nm QWs with emission wavelength rise as it is clearly seen in the inset of Fig. 4. Namely this causes a sharp increase of the threshold in comparison with the optical gain.

4 Conclusion Lasing in InGaN/GaN MQW heterostructures grown on Si was obtained under optical pumping in the region of 440-465 nm. The minimum laser thresholds were 137 kW/cm^2 and 300 kW/cm^2 for 440 nm and 465 nm, correspondingly. It was shown that laser action occurs on the transversal mode of 5th order for both QW thicknesses. Material optical gain of InGaN at the laser threshold was estimated. It increases substantially from 1035 cm^{-1} (I_{thr} = 190 kW/cm^2, λ = 442 nm) to 1289 cm^{-1} (I_{thr}=230 kW/cm^2, λ=455 nm) for 1.8 nm QWs and from 750 cm^{-1} (I_{thr} = 137 kW/cm^2, λ = 440 nm) to 1020 cm^{-1} (I_{thr} = 300 kW/cm^2, λ = 465.2 nm) for 2.1 nm QWs with wavelength. It was shown that laser threshold and optical gain depend equally on wavelength for 1.8 nm QWs and threshold depends sharper than gain for 2.1 nm QWs; that is caused by a drop of the emission quantum efficiency.

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