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The influence of the Al-content on the optical gain in AlGaN heterostructures

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Abstract

In the present contribution we report on the investigation of the optical gain properties of AlGaN epilayers with aluminum contents varied between 0 and 0.23. The samples were grown by MBE on (0 0 0 1)sapphire with a thickness of about 1 μm. We performed photoluminescence and gain measurements at various excitation densities up to 5 MW/cm^2 using nanosecond excimer-laser pulses. Band filling processes and electron–hole plasma are the dominating gain mechanisms accompanied by phonon-assisted recombinations. With increasing Al content we observe that for a given excitation density the role of band filling processes increases in comparison with the electron–hole plasma. Also the threshold intensity for gain due to electron–hole plasma increases. These observations will be discussed with respect to the defect content of the samples. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

The physical processes causing stimulated emission in III-nitride-based laser structures are still subject to discussion. Localized biexcitons [1], the electron–hole plasma [2] and band filling processes [3] have been claimed responsible for the laser mechanism in group-III-nitride heterostructures. Meanwhile, the properties of GaN and especially AlGaN at high excitation levels are not understood in detail. In our previous work [4] we studied the gain spectra of thin quasi-bulk GaN between 2 K and room temperature and found that excitonic processes add to the gain at high temperatures. The purpose of the present paper is to analyze optical gain spectra obtained from thin AlGaN epilayers at very high excitation levels and to study the influence of increasing Al content on the gain in these epilayers. For the identification of the mechanisms providing optical amplification in AlGaN, useful

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information is obtained from high-density effects on the spontaneous and stimulated photoluminescence (PL).

2. Experimental procedure

The results presented here were obtained from a series of $Al_xGa_{1-x}N$ samples grown by MBE on (0 0 0 1)sapphire with a thickness of about 1 μm [5]. The low-excitation measurements were performed using a frequency-doubled Ar-Ion laser with an excitation wavelength of 244 nm. To obtain the high excitation density necessary for our investigations we used an excimer laser, providing pulses with a duration of 15 ns at a rate of 30 Hz and a total energy of up to 20 μJ at 308 nm. The samples were mounted in a bath cryostat at 1.8 K. Gain measurements were performed using the stripe length method, e.g. [6].

3. Results

The low-excitation photoluminescence measurements of AlGaN samples with an Al content between 0 to 0.23% are displayed in Fig. 1. The energy position of the donor-bound exciton transition in the GaN sample was 3.467 eV indicating a tensile strain due to the reduced layer thickness. The spectral positions of the I_2 were observed to be 3.625 eV (0.08% Al), 3.815 (0.17% Al), and 3.903 eV (0.23% Al) which is in good agreement with the reported values [7]. For higher Al-content the FHWM of the donor-bound emission line significantly broadens due to a decrease in the crystal quality of the layers.

Figs. 2 and 3 display a comparison of high-excitation photoluminescence and gain spectra taken at 1.8 K from $Al_xGa_{1-x}N$ samples with x equal to 0.08 on the left-hand side and 0.17 on the right-hand side of Fig. 2 and with x equal to 0.23 in Fig. 3. The excitation density was varied between 50 kW/cm^2 and 5 MW/cm^2. From low-density PL measurements the excitonic band edge of these samples is found at 3.63 eV ($x = 0.08$), 3.82 eV ($x = 0.17$) and 3.91 ($x = 0.23$) at 1.8 K. Both the luminescence and gain spectra of the samples extend to energies well above these values, shifting further to higher energies with increasing excitation density. This behavior gives strong evidence for band filling processes. The quasi fermi-levels of the electrons and holes are shifted in the conduction and valence band, respectively. This results in the observed blue shift of the spectral position with increasing excitation density.

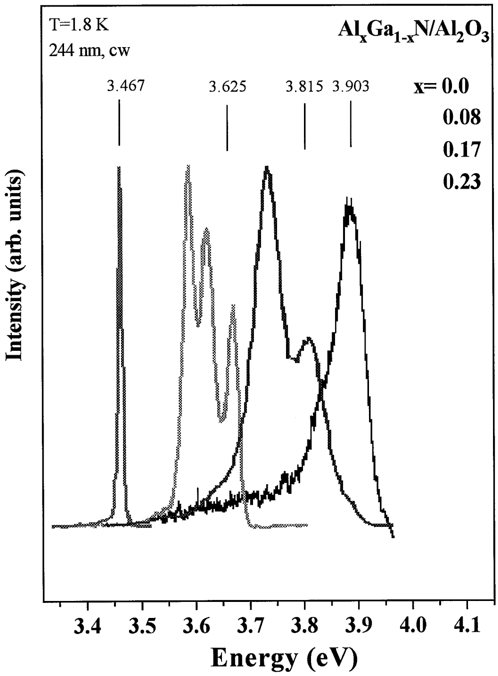

Fig. 1. Low excitation photoluminescence spectra at 1.8 K.

In Fig. 3 this behavior is clearly observed for the sample with the highest Al-content of 23%.

The gain spectra of the samples exhibit more contrast and structural detail allowing the separate identification of the involved gain processes. The gain spectrum of $Al_{0.08}Ga_{0.92}N$ in Fig. 2 exhibits a pronounced peak around 3.57 eV strongly shifting to lower energies with increasing excitation density. This allows an attribution of this band to the electron–hole plasma, labelled EHP, reaching a gain value of 110 cm^{-1}. No indication of a stimulated peak is observed in the luminescence spectra up to 5 MW/cm^2. The weak low-energy gain structure around 3.5 eV is found one LO phonon energy below the free exciton and strongly increases with

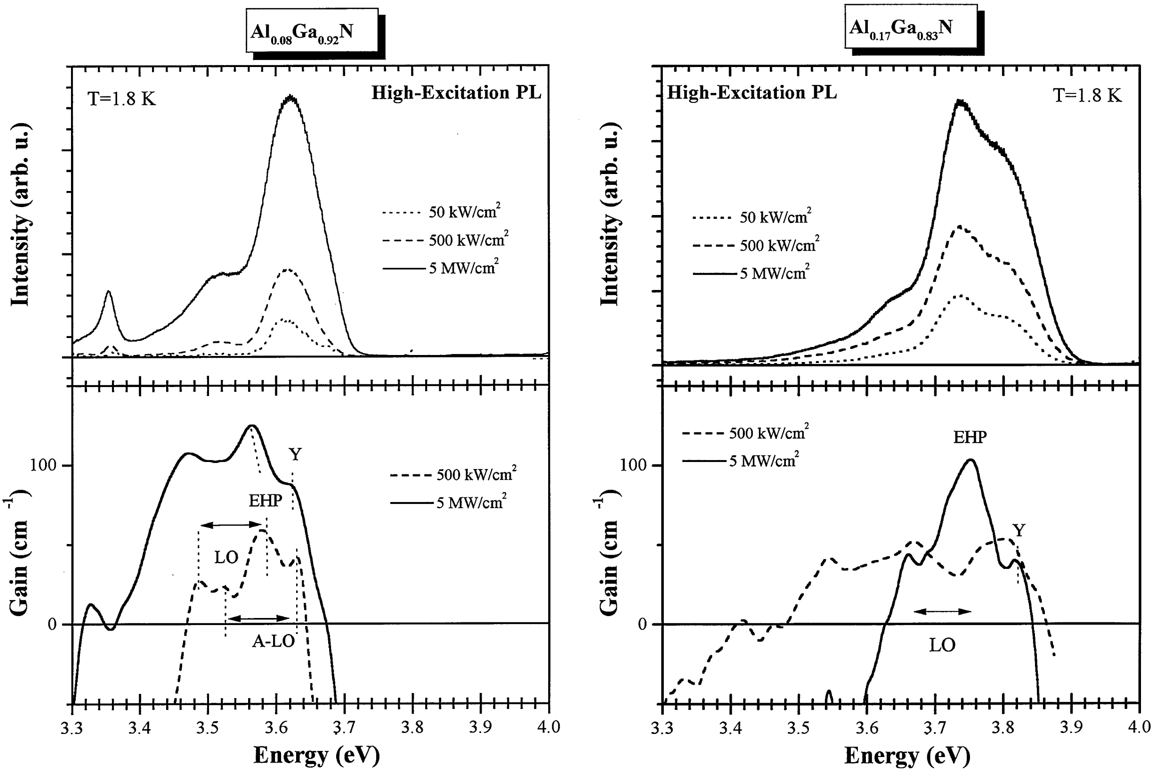

Fig. 2. Comparison of low-temperature high-excitation luminescence and optical gain spectra from two $Al_xGa_{1-x}N$ samples.

increasing pump power. Therefore, from the energy position we assign the A-LO transition to be the responsible gain mechanism.

The role of phonon-assisted processes is stronger here because the excitation energy (4 eV) is above the higher band gap producing a plasma with higher effective temperature whose relaxation towards thermal equilibrium creates a larger number of phonons available for a stimulated emission process. We ascribe this to the higher density of excited carriers due to the small thickness of 1 μm. Similar considerations apply to the gain spectra of the $Al_{0.17}Ga_{0.83}N$ sample in Fig. 2. The maximal gain value is $100\,cm^{-1}$.

For the $Al_{0.23}Ga_{0.77}N$ sample, optical gain is observed only for an excitation density of $5\,MW/cm^2$, displayed in Fig. 3. In this sample the band filling processes are dominant in the gain spectrum, reaching a gain value of $50\,cm^{-1}$. The electron–hole plasma and the A-LO transition give rise to optical gain as well.

Our observation of gain caused by plasma, free carriers, and excitonic processes at highest excitation levels does not imply that they all occur simultaneously. In our time-integrated measurements we detect all processes which produce optical gain after the excitation pulse. Therefore, a spatial and temporal separation of excitonic and many-particle processes has to be considered. Thus, our observations are in perfect agreement with the typical behavior observed in other direct wide-gap semiconductors [8].

With increasing Al content the gain values for the observed mechanisms decrease. This can be explained by the reduced structural quality of the sample with increased Al incorporation. The raised dislocation density is detrimental to the efficiency of the optical amplification in the samples.

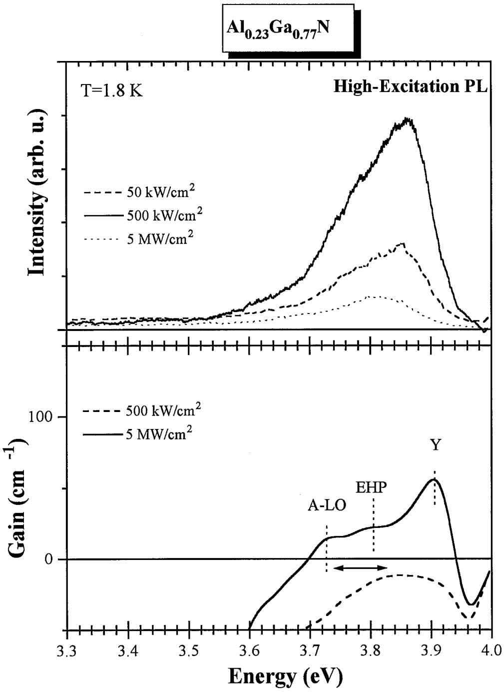

Fig. 3. High-excitation luminescence and gain spectrum of the $Al_{0.23}Ga_{0.77}N$ sample.

From the results obtained to this point we conclude that the AlGaN samples investigated show gain mechanisms very similar to those of thin GaN epilayers [4]. Band filling processes and many particle effects provide optical gain up to the highest excitation densities. Unlike the results for GaN even at low temperatures excitonic processes do not seem to contribute much to the optical gain at the given excitation densities in these samples.

4. Conclusions

In conclusion, we compared the luminescence and optical gain properties of AlGaN epilayers at high excitation densities. With increasing pump intensity band filling processes and the electron–hole plasma exhibits the highest gain reaching values of 150 cm^{-1}. While these values are somewhat lower than in GaN, our results show the possibility to fabricate laser structures with active AlGaN layers operating in the ultraviolet spectral range. With increasing Al content the efficiency of optical amplification is reduced. This was explained by the increased defect density during the incorporation of Al.

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