MECHANISMS OF OPTICAL GAIN IN CUBIC GAN AND INGAN

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ABSTRACT

The epitaxial growth of zinc-blende (cubic) GaN and InGaN on GaAs with a common cleavage plane and readily high-quality, low-cost wafers may be considered as an alternative approach for the future realization of cleaved laser cavities. To obtain detailed information about the potential of cubic GaN and InGaN for device applications we performed optical gain spectroscopy accompanied by time-integrated and time-dependent photoluminescence measurements at 2 K and 300 K. From intensity-dependent gain measurements, the identification of the gain processes was possible. For moderate excitation levels, the biexciton decay is likely to be responsible for a gain structure at 3.265 eV in cubic GaN [10]. For the highest pump intensities, the electron- hole-plasma is the dominant gain process, providing gain values up to 200 cm $^{-1}$. Furthermore cubic GaN samples with different cavity lengths from 250 to 600 µm were cleaved to investigate the influence of the sample geometry on the gain mechanisms. In these samples increased gain values up to 150 cm $^{-1}$ as well as lower threshold excitation densities were observed, indicating the potential of cubic GaN for device applications. The results of GaN will be compared with intensity-dependent gain measurements on InGaN samples, grown on GaAs with varying In-content. The observed gain mechanisms in cubic InGaN will be discussed in detail.

INTRODUCTION

The epitaxy of metastable, cubic GaN on GaAs (001) substrates has attracted some interest recently since c-GaN layers and the GaAs substrate have a common cleavage plane, they are considered to be well suited for the fabrication of laser cavities with cleaved facets [1-8]. Because of this application, high optical excitation experiments have been used to measure the gain in c-GaN/GaAs (001) grown by MBE [9] revealing some insight into involved recombination mechanisms [10]. The stimulated emission from c-GaN has been reported for MOCVD [11] and MOVPE [12] grown epilayers. In our previous work [10] we studied the gain spectra of c-GaN at 2 K and found that excitonic processes add to the gain at moderate excitation densities and many particle processes are effective for increased excitation intensities. The purpose of the present paper is to analyze the mechanisms of optical amplification and the efficiency of the stimulated emission in cubic GaN and InGaN layers.

EXPERIMENTAL

Cubic GaN films with a phase purity better than 99.9% were grown on semi-insulating GaAs (001) substrates by RF-plasma assisted molecular beam epitaxy (MBE) at a substrate temperature of 720°C. Undoped epitaxial layers were grown under carefully controlled stoichiometric growth conditions[13]. Details of the growth procedure were reported in Ref.13. The optical properties of the c-GaN layers investigated under low and high excitation intensities are reported in Ref. 10. By cleaving we obtained c-GaN samples with cavity lengths of 550, 450 and 250 µm along the common (001) direction and performed high-excitation and gain measurements. The InGaN/GaN/GaAs (001) heterostructures were grown by plasma assisted MBE. The GaN buffer layers with a typical thickness in the range from 100-200nm were grown at T=720° C under carefully controlled stoichiometric conditions, exploiting Reflection High Energy Diffraction (RHEED) measurements of the surface reconstruction as an in-situ control of the composition of the layer surface during growth [14]. The InGaN layers had a thickness between 200-300 nm and were deposited at lower temperatures (T=610-680° C). During the InGaN epitaxy we used a Ga flux which was reduced by about 20% compared to that of the GaN layer deposition. The In flux was adjusted to establish a metal rich surface taking into account the extremely small and strongly temperature dependent sticking coefficient of In.

To obtain the high excitation density necessary for our investigations we used a dye laser pumped by 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 340 nm. The sample was mounted in a bath cryostat at 1.8 K. Gain measurements were performed using the variable-stripe-length method [15] . The excitation spot was focused onto a l x 50 µm^2 stripe, where l denotes the excitation length. The photoluminescence spectra were recorded from the top of the sample with a continuous-wave (cw) helium-cadmium laser.

RESULTS

Optical Amplification in cleaved c-GaN samples

Figure 1 shows the spectra of the edge emission from a cleaved sample with a cavity length of 450 µm at different excitation densities on a linear scale at 2 K. Above the threshold excitation of 1 MW/cm^2 a peak at 3.26 eV appears exhibiting a strong increase of the edge emission with excitation intensity and a strong polarization dependence. The emitted light is strongly TE polarized, as expected for an edge emitting cleaved facet. For higher densities up to 5 MW/cm^2 a slight shift to lower energies of the peak position is observed, indicating the increased carrier density in the sample. In Fig. 1a (inset of Fig. 1) the results of intensity dependent edge emission measurements for the 250, 450 and 550 µm c-GaN samples are summarized. For all the samples the same optical features were observed- a strongly polarization dependent stimulated emission peak occurs above a certain threshold, exhibiting a superlinear increase with increased excitation density.

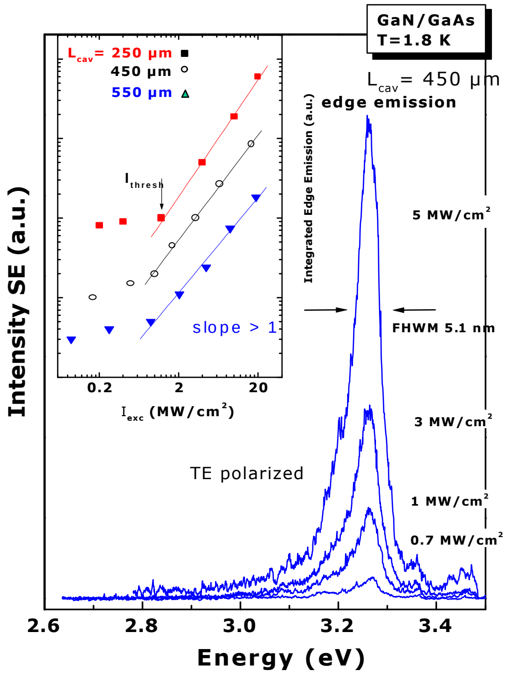

Fig. 1:Edge emission of a cleaved c-GaN sample (Inset: slope of excitation density versus integrated emission intensity for c-GaN samples with different cavity lengths)

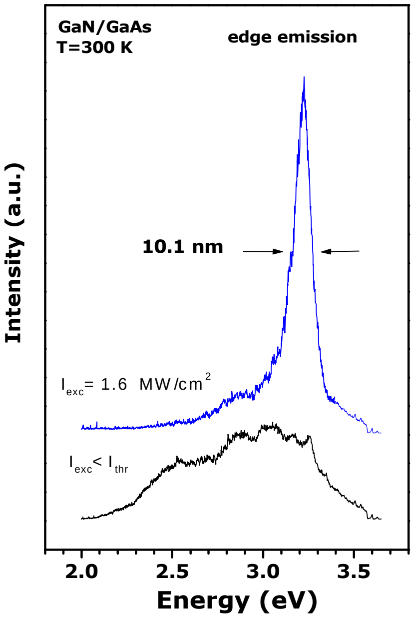

Fig. 2: Room temperature edge emission of a cleaved c-GaN sample with 450 µm cavity length

The threshold for the onset of stimulated emission increases with reduced cavity length L which is in accordance with the well known formula $I_{thres} \propto {}^{1}\!/_{L}$ [16].

The room temperature spectrum of the edge emission of the cleaved sample is displayed in Fig. 2 and exhibits similar optical features as strong TE polarization and superlinear increase of edge emission. From these features the peak can attributed to the stimulated emission of c-GaN.

However, no Fabry-Perot modes are observed which are expected to be separated by about 0.4 meV. Imperfections of the cavity facets, excitation pulse variations and mode hopping are reasons to explain the unstructured stimulated emission spectra. We believe that the lateral confinement is caused by the interface sample-air on one side and the illuminated and nonilluminated parts of the sample on the other. The magnitude of the pump power locally changes the refractive index and therefore, a lateral confinement necessary for the feedback is provided [17]. This is confirmed by micro-photoluminescence measurements where it was found that the most part of the light is emitted from the cleaved facets of the samples.

To reveal more insight into the involved processes providing optical amplification gain measurements on the cleaved samples were performed and are shown in Fig. 3. At excitation densities of 1 MW/cm^2 the gain structure broadens and its peak position shifts to lower energies. This can be explained by the increased number of excited carriers in the sample, where the Coulomb interaction is screened and many particle effects are effective as gain process. The quasi Fermi-levels of the electrons and holes are shifted in the conduction and valence band, respectively.

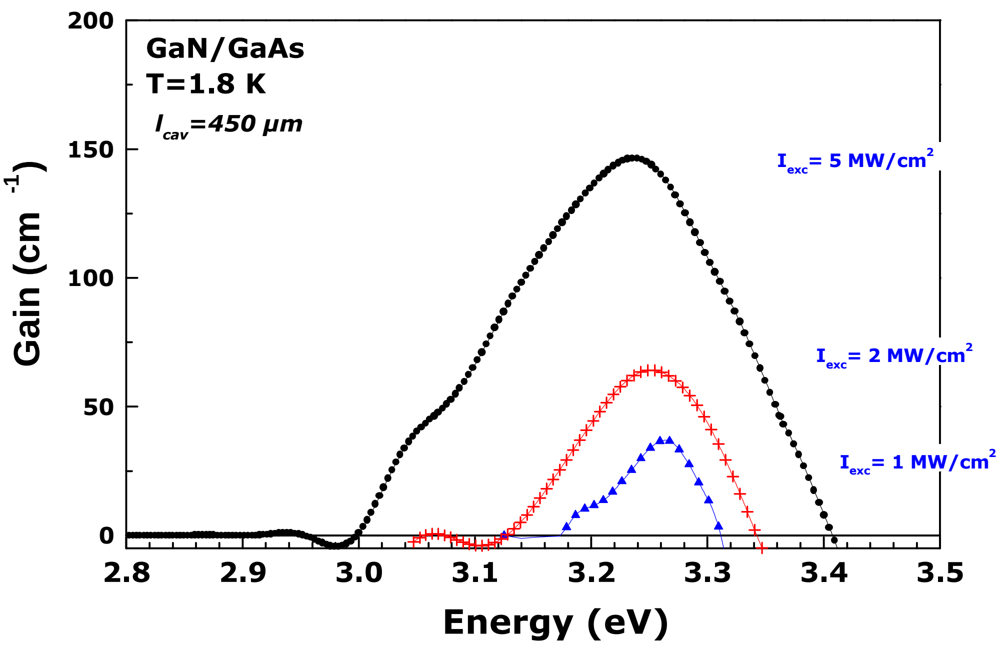

Figure 3: Gain spectra of a cleaved c-GaN sample with a cavity length of 450 µm at 2K

This results in the observed blue shift of the crossover gain-absorption on the high energy side with increasing excitation density. On the other hand the low energy side of the crossover gain-absorption is shifted to the red which is due to bandgap renormalization under high excitation densities. These are typical features of an electron-hole-plasma.

Optical Gain in c-InGaN

In Figure 4 low-temperature gain measurements of InGaN samples with varying In-content are shown. With increasing In-incorporation the gain structure shifts to lower energies and the gain values are increased. This is depicted in Fig. 4a where the obtained gain values for the samples

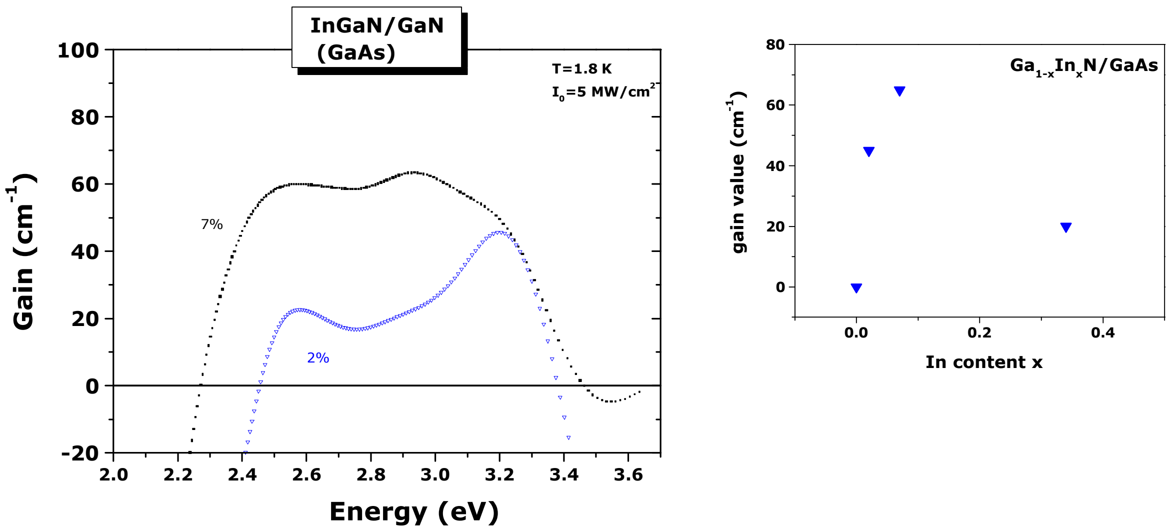

Fig. 4 : (left hand side) Gain spectra for In_x Ga_{1-x} N with an varying In-content at a fixed excitation density (right hand side) Gain values for In-contents up to 50 %

with different In-content are shown. Samples with In-contents higher than 30 % exhibit lower gain values due to the reduced sample quality and the effects of In-clustering inhomogeneously distributed over the sample. The In-clustering is detrimental to the optical properties of InGaN as known from the hexagonal phase [18]. The optical gain of these "highly In-doped" InGaN samples occurs in the same energy range as for the InGaN samples with much lower In-contents as 7% in our case. This indicates the strong influence of the inhomogeneous distribution of In in these samples. The transition energy is very sensitive to the degree of compositional In-fluctuations in the samples.

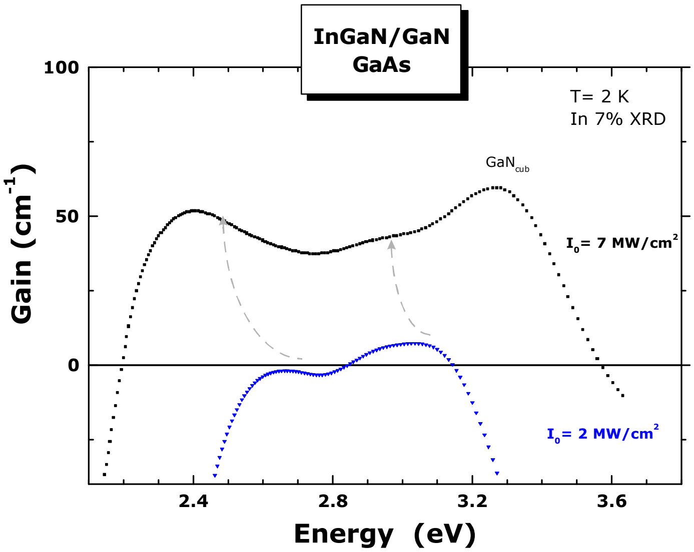

Fig. 5: Gain spectra of an InGaN sample with 7 % In for different excitation densities

Increasing the excitation density in the sample with 7% In-content the gain structures are shifted to the low energy side, see Figure 5. This is a typical feature of an electron-hole plasma, where the peak shifts into the lower energy spectral range and the gain structure broadens due to the increased number of excited carriers. It is interesting to note that at 2.4 eV optical gain is observed, indicating the strong shift of the emission into the green spectral range at significantly lower In-contents than in the hexagonal phase. This is due to the fact that a quantum-confined Stark effect due to piezoelectric fields is *not* expected the cubic phase. The absorption on the low energy side of the gain structures can be explained by the inhomogeneous distribution in the InGaN layers, which causes an increased number of defects. Additionally, another gain peak occurs at 3.23 eV which can be attributed from its energy position to be generated in the c-GaN layer.

CONCLUSION

In conclusion we reported on stimulated emission data and gain measurements of cleaved c-GaN samples. Excitonic processes as well as band filling processes dominate the optical gain at 2K. Above a threshold power density of 0.9 MW/cm^2 a stimulated emission peak was observed, exhibiting the typical optical features as polarization dependence and superlinear increase with pump intensity. For decreased cavity lengths the optical amplification and the threshold values increase. This indicates the influence of the cavity on the optical properties of highly excited c-GaN on GaAs. With a cleaved sample of 450 µm cavity room temperature stimulated emission is observed at 1.6 MW/cm^2. To our knowledge these are the lowest values reported for cleaved cubic GaN [12]. For the cubic InGaN samples a strong impact of the In-fluctuations on the optical gain is found. The energy position of the emission is very sensitive to the degree of In-distribution. Due to the stronger bowing parameter and the lack of strong piezoelectric fields in cubic InGaN the emission is strongly shifted into the green spectral range at lower In-contents compared with the hexagonal phase. These results are promising and indicate the high potential for light-emitting device applications of this material system.

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