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Lasing and Gain Mechanisms in AlGaN-GaN-Double Heterostructures: Correlation with Structural Properties

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Abstract

Photoluminescence, stimulated emission, and gain studies were performed to investigate an AlGaN/GaN/AlGaN heterostructure. A stimulated emission peak at 3.46 eV exhibits a strong superlinear growth with excitation intensity with a slope of 2. Gain values up to 250 cm^{-1} are obtained. The specific surface morphology of the heterostructure is suspected to be responsible for an optical feedback in the sample. From AFM measurements an almost perfect periodic corrugation of the surface is observed. The periodicity of the corrugation of λ=110-120 nm perfectly matches the stimulated emission wavelength and reflects the strong correlation of structural features and optical properties in this structure.

Introduction

A remarkable progress has been achieved in developing III-V-nitride based light emitting devices. For the first time lasing under current injection has been obtained in a InGaN-AlGaN heterostructure [1]. A further shift towards the ultraviolet spectral range can be realized by GaN/ AlGaN heterostructures [2]. The influence of the structural features of this material system on their optical properties, however, are little investigated and hardly understood.

It is known from investigations on bulk GaN that even for high temperatures LO-assisted excitonic processes and many particle effects are responsible for gain values up to 130 cm^{-1} [3]. The focus of this paper is to compare the optical properties of an AlGaN/GaN/AlGaN double heterostructure to the properties of bulk GaN and to investigate the impact of its structural properties on lasing and gain mechanisms.

Experimental Setup

The results presented here were obtained from an AlGaN/GaN double heterostructure grown by MOCVD at a pressure of 200 mbar. The substrate material is (0001) optical grade polished sapphire. The sample consists of a 0.5 μm thick GaN buffer layer, followed by a 2.5 μm thick AlGaN barrier layer, a 0.4 μm thick GaN active layer, and terminated by a 0.08 μm thick AlGaN upper barrier layer.

The structural characterization was performed by transmission electron microscopy (TEM) and atomic force microscopy (AFM). TEM images have shown a gradual decrease in the dislocation density in the lower AlGaN barrier layer in the direction from the buffer layer to the active layer. The estimated dislocation density at the substrate interface is in the range of $(1\text{-}4.2)*10^{10}$ cm^{-2}. Near the sample surface the defect density decreases noticeably.

Gain measurements were performed using the variable stripe length method [4]. The photoluminescence spectra was recorded from the top of the structure with a cw Helium Cadmium laser. To obtain high excitation densities a dye laser pumped by an excimer laser was used, providing pulses with a duration of 15 ns and a maximal pulse energy of 20 µJ at 340 nm. The sample were mounted in a bath cryostat at 1.8 K.

Results

In Figure 1 and 1a the AFM images of the surface morphology of the sample are displayed. The most striking feature is a quasi-periodic corrugation with a periodicy of λ = 110-120 nm. The overall flatness of the surface is extremly good, which is quantified by an RMS value of $\sigma_{z\ RMS}$ = 3.5 Å and a maximum amplitude of Δz_{max} = 3 nm.

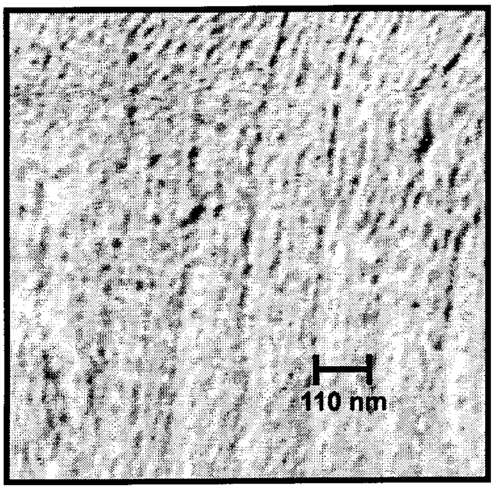

Fig. 1a:AFM image of the surface morphology. The quasi-periodic corrugation of l = 110 nm is clearly visible.

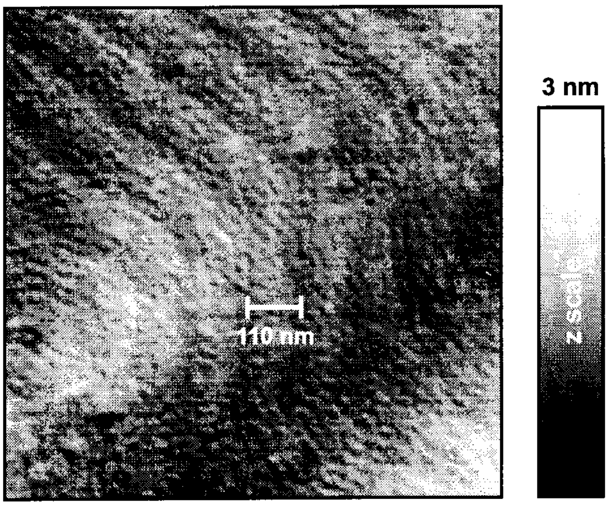

Fig. 1b:AFM image of a larger surface area of the sample. An angle of 120° between the pseudo-gratings can be recognized, reflecting the hexagonal symmetry of the crystal.

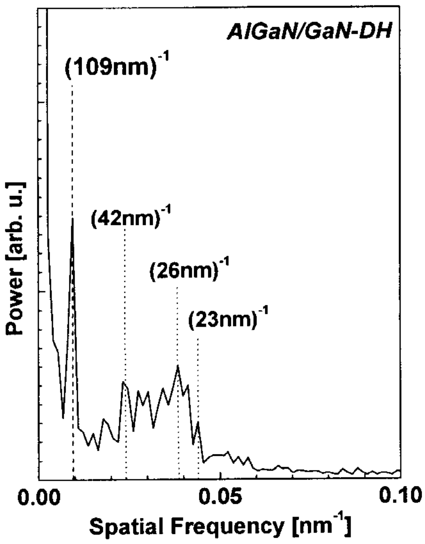

Fig. 2:Linear power spectrum from various AFM images. A distinct peak at a spatial frequency of (110 nm)$^{-1}$ is observed, resembling the quasi-periodic corrugation

The periodicity of the grating like corrugation is confirmed by power spectra calculated from various AFM images (5 µm x 5 µm areas) showing a strong contribution of spatial frequencies around (110 nm)$^{-1}$, as shown in Fig. 2.

To obtain detailed information on the optical properties of the sample, the spontaneous and stimulated emission has been studied under cw and pulsed excitation. The photoluminescence from the edge under high excitation densities and from the top under low excitation densities is shown in Fig. 3. In the inset a PL spectrum at low cw excitation is depicted. This spectrum is dominated by the donor bound excitonic emissions from the active GaN layer with a maximum at 3.498 eV and the AlGaN barrier layers with a maximum at 3.685 eV. Further the donor-acceptor-pair- (DAP) and deeper bound states like the „yellow" luminescence are observed. For higher excitation densities the stimulated emission spectra is dominated by a broad emission peak at 3.502 eV. With increasing excitation

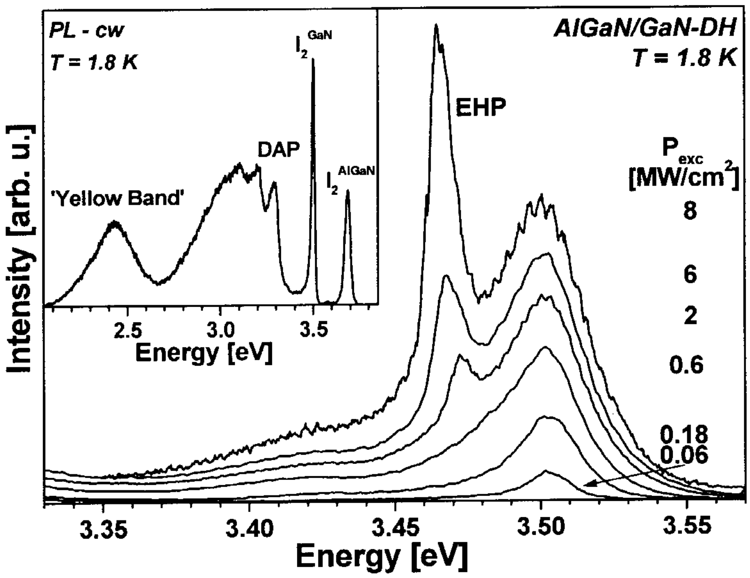

Fig. 3: Edge luminescence for increasing excitation densities. The Inset shows the cw-PL from the top of the structure at 1 W/cm^{-2}.

density the luminescence shows a strong broadening and no shift of the peak position can be observed. Therefore, excitonic processes are likely to contribute to this recombination band.

Above excitation densities of 2 MW/cm^2 a narrow stimulated emission peak (FWHM $\approx$ 10 meV) at 3.46 eV is observed in the PL spectra. The remarkable feature of this emission is a superlinear growth of the integrated luminescence intensity with excitation density with a slope of 2 even though no resonators were used. Up to highest excitation densities the peak position shifts 8 meV to lower energies. Because of this typical behavior we can identify the electron-hole-plasma (EHP) as the dominating stimulated emission process in the investigated structure [5].

In Figure 4 the gain spectra are displayed for excitation densities up to 6 MW/cm^2. The gain spectra are dominated by a high-energy structure (labeled B) at 3.5 eV for an excitation density of 60 kW/cm^2. A strong blue shift (50 meV) of the peak position of B up to highest excitation densities is observed. Gain values amount up to 375 cm^{-1}. The gain above the GaN band edge originates from band-to-band-transitions and can be explained by band filling processes, where the blue shift of the crossover gain-absorption is caused by a shift of the respective quasi-Fermi levels of holes and electrons into the valence and conduction bands [6]. This process is known to be responsible for optical gain in InGaN-QW structures [7] and epitaxial layers [3] as well.

For higher excitation densities the gain spectra are broadened. An additional gain peak (labeled EHP) appears at 3.46 eV and shows a slight shift to lower energies reaching gain values of 250 cm^{-1}. Because to this behavior and the agreement with the energy position of the stimulated emission peak an electron-hole plasma is proposed to be responsible for this gain peak.

For higher excitation densities the A-LO transition contribute to optical amplification as well. The energy position do not shift with increasing excitation density which indicates the exitonic nature of the recombination.

In comparison to thin GaN-epilayers [3] the same gain mechanisms can be observed, but at lower excitation densities and significantly higher gain values. This can be explained by the structural properties of the sample. The reduced thickness of the active layer of 400 nm is responsible for higher gain values due to a better confinement of the highly excited carriers.

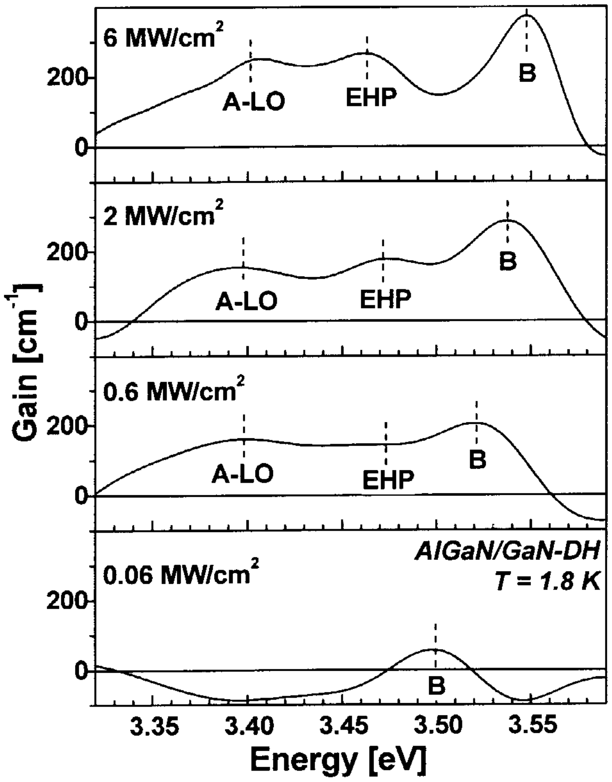

Fig. 4: Intensity dependent gain spectra of the AlGaN/GaN double heterostructure

The lateral corrugation of the surface and interface morphology causes quasi-periodic modulation of the refractive index. Taking into account a refractive index n = 3.11 measured by photoreflectometry [8], the periodicity of the corrugation perfectly matches the stimulated emission wavelength and the detected gain peak EHP. The arising locally DFB effect [9] results in a higher efficiency of stimulated emission and makes the light output versus excitation density dependence similar to that of lasing. Therefore we attribute the effect of strong increase in slope efficiency for the stimulated emission to the lateral corrugation of the surface and interfaces, related to the columnar nature of the nitride growth.

Conclusion

In conclusion, we investigated the correlation between the surface morphology, stimulated emission and gain processes in an AlGaN/GaN double heterostructure under optical excitation. Band-band transition, electron-hole plasma and phonon-assisted processes contribute to optical gain for an excitation density up to 6 MW/cm^2. Gain values between 100 cm^{-1} and 375 cm^{-1} were obtained at an energy range from 3.35 eV to 3.56 eV. The specific morphology of the heterostructure is proposed to be responsible for the optical feedback in the sample. The quasi-periodic corrugation with a periodicity of λ = 110 - 120 nm perfectly matches the stimulated emission wavelength and the spectral maximum of the gain profiles. This indicates the correlation of structural and optical properties.

References

[1] S. Nakamura, M. Senoh, N. Iwasa, T. Yamada, T. Matsushita, H. Kiyoku, Y. Sugimoto, Jpn. J. Appl. Phys. **35** (1996), L74

[2] H: Amano, N. Watanabe, N. Koide, I. Akasaki, Jpn. J. Appl. Phys. **32**, (1993), L1000

[3] J. Holst, L. Eckey, A. Hoffmann, I. Broser, H. Amano, I. Akasaki, MRS- NSR Internet J. 1997, to be published

[4] C. Benoit a la Guillaume, J.M. Denber and F. Salvan, Phys. Rev. 177 (1969), p. 567

[5] M.Maximov, A. Sakharov, V. Lundin, A. Usikov, B. Pushnyi, I. Krestnikov, N. Ledentsov, P. Kop'ev, Zh. Alferov, V. Rozum, Techn. Phys. Lett. **23**, 53-59 (1997)

[6] G. Lasher, F. Stern, Phys. Rev. B 133 (1964), p. A553

[7] G. Frankowsky, F. Steuber, V. Harle, F. Scholz, A. Hangleiter Appl. Phys. Lett. **68** (26), 3746 (1996).

[8] A. Hoffmann, Adv. in Sol. State Phys., ed. by R. Helbig (Vieweg, Braunschweig/Wiesbaden) Vol. 36 (1996), p. 33

[9] J. Christen, T. Hempel, F. Bertram, N. N. Ledentsov, D. Bimberg, A. V. Sakharov, M. V. Maximov, A. S. Usikov, W. V. Lundin, B. V. Pushnyi, Zh. I. Alferov, Proc. MSS-8, Physica B (1997), to be published

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