Optical gain and stimulated emission of cleaved cubic gallium nitrite

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In this letter, we report on the observation of optically excited stimulated emission of *c*-GaN layers grown by molecular-beam epitaxy (MBE). Stimulated emission was observed at 1.8 K and room temperature. The threshold intensity for excitation of stimulated emission from our MBE-grown *c*-GaN layers is significantly lower than that reported for *c*-GaN grown by metalorganic chemical vapor deposition (MOCVD). The experimental data of optical gain and stimulated emission presented in this letter demonstrate that this material has a good potential for the future realization of cleaved cavity blue light-emitting laser diodes. © *1999 American Institute of Physics.* [S0003-6951(99)02713-8]

The epitaxy of metastable, cubic GaN on GaAs (001) substrates has attracted some interest recently. Although the epitaxy of *c*-GaN has been performed for many years[1–7] only few experiments concerning the optical properties of cubic GaN under high excitation densities are reported.[8–11] This may be due to the fact that only recently the molecular beam epitaxy (MBE)[12,13] and metalorganic chemical vapor deposition (MOCVD)[14] of layers free micron-sized crystals and hexagonal inclusions was successfully achieved.

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. Because of this application, high optical excitation experiments have been used to measure the gain in *c*-GaN/GaAs(001) grown by MBE[8,9] revealing some insight into involved recombination mechanisms.[9] The stimulated emission from *c*-GaN has been reported for MOCVD[11] and metalorganic vapor phase epitaxy (MOVPE)[10] grown epilayers. In our previous work[9] we studied the gain spectra of MBE-grown *c*-GaN epilayers 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 letter is to analyze the influence of cleaved cavities and the sample geometry on the efficiency of the stimulated emission and the processes of optical gain in thin *c*-GaN epilayers at high excitation levels. The results will be compared with the results of MOCVD-grown *c*-GaN.

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 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.[12] Details of the growth procedure were reported in Ref. 12. The optical properties of the *c*-GaN layers investigated under low and high excitation intensities were reported in Refs. 9 and 13. 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.

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 $l \times 50\ \mu m^2$ 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.

The typical cw photoluminescence (PL) spectrum of the *c*-GaN sample investigated is dominated by the superposition of the free-exciton and the donor-bound-exciton recombination at 3.26 eV with a full width half maximum (FWHM) of 19 meV, a donor–acceptor pair transition at 3.14 eV, and another donor–acceptor pair band at 2.98 eV with its longitudinal optical (LO) replica.[9] 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 liner 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 transverse electric (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. 1(a) (inset of Fig. 1) the results of intensity dependent edge emission measurements for the 250, 450, and 550 μm long cleaved *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. The threshold for the onset of

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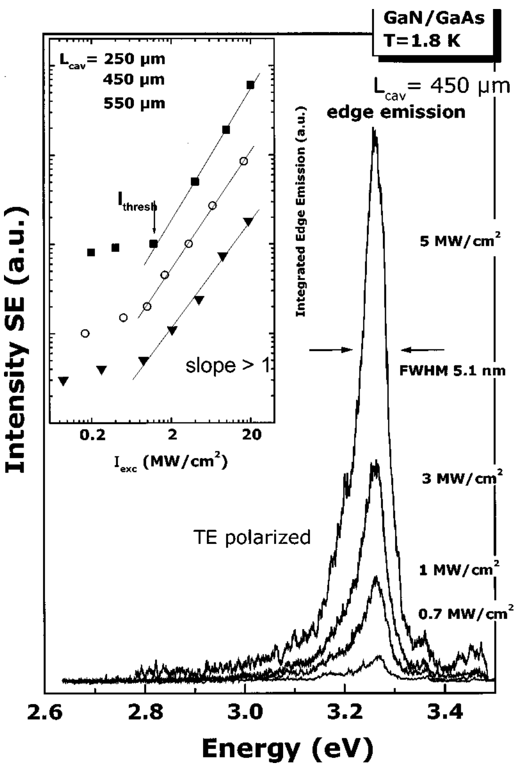

FIG. 1. Polarized edge emission from a cleaved *c*-GaN/GaAs sample with a 450 μm cavity at different excitation densities at 1.8 K. (a) (inset of Fig. 1) Summarized data of intensity dependent edge emission spectra from cleaved cavity samples (integrated edge emission versus excitation density).

stimulated emission increases with reduced cavity length L which is in accordance with the well known formula $I_{\mathrm{thres}} \sim 1/L$.[16]

The room temperature spectrum of the edge emission of the cleaved sample is displayed in Fig. 2 and exhibits similar

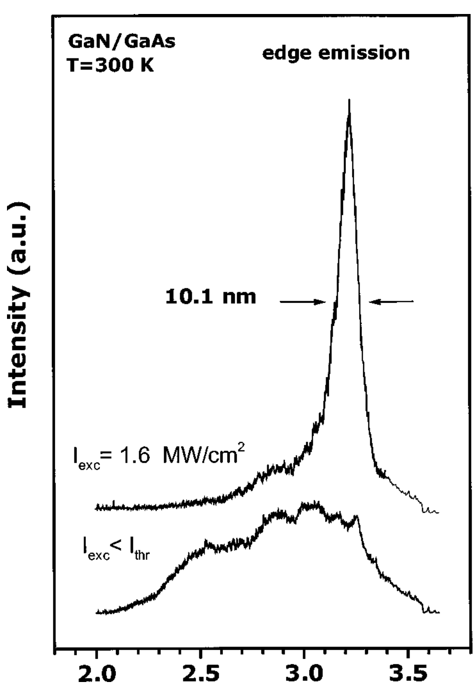

FIG. 2. Edge emission at room temperature from a *c*-GaN sample with a cavity length of 450 μm, the upper spectrum shows the stimulated emission above 1.6 MW/cm^6, the lower spectrum is the broad, unstructured emission below threshold.

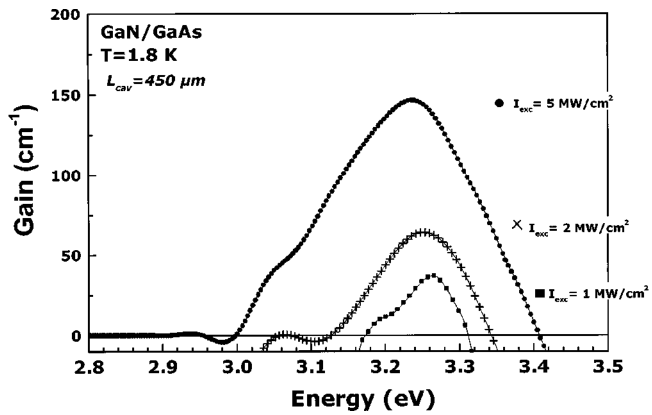

FIG. 3. Gain spectra of *c*-GaN (450 μm cavity) for various excitation densities up to 5 MW/cm^2 at 1.8 K.

optical features as strong TE polarization and superlinear increase of edge emission. From these features the peak can be attributed to the stimulated emission of *c*-GaN. However, no Fabry–Pérot modes are observed which are expected to be separated by about 0.4 meV due to our resolution. 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 microphotoluminescence measurements where it was found that most part of the light is emitted from the cleaved facets of the samples.

The threshold value of 1.6 MW/cm^2 at room temperature indicates that *c*-GaN also exhibits a similar temperature dependence of the onset of stimulated emission as *h*-GaN.[18] The threshold of stimulated emission of GaN is less sensitive to changes in temperature compared to other wide-gap semiconductors. We believe that this is due to the high stability of the III–V–nitrides, especially GaN toward temperature. 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. Above an excitation intensity of 1 MW/cm^2 optical gain in the 450 μm sample is observed and the spectrum exhibits two structures at 3.26 and 3.18 eV. The shoulder of the gain structure at 3.18 eV can be attributed to an *X*–LO recombination excitonic processes from the energy position. Therefore, the uncommon shape of the gain structure at 1 MW/cm^2 can be explained by a spectral superposition of many-particle processes and excitonic contributions. These processes are spatially and temporally separated in the sample due to a gradient in excitation density. This feature is known from other wide-gap semiconductors.[19,20] At higher excitation densities 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 a gain process. The quasi-Fermi levels of the electrons and holes are shifted in the conduction and valence band, respectively. This results in the observed blueshift 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 band gap renormalization under high excitation densities.

In conclusion we reported on stimulated emission data and gain measurements of cleaved *c*-GaN samples. Excitonic processes contribute to the gain mechanism for moderate excitation densities, while with increasing pump intensity band filling processes become more dominant and the electron–hole plasma dominates the optical gain. At low temperatures 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 length room temperature stimulated emission is observed at 1.6 MW/cm^2. These are significantly lower threshold values for cleaved cubic GaN than reported in Ref. 11. Due to the simple procedure of cleaving laser facets in this material the high potential for light-emitting device applications is evident.

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