Surface-mode lasing from stacked InGaN insertions in a GaN matrix

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We report surface-mode lasing in a structure with 12-fold stacked InGaN insertions in a GaN matrix without using of Bragg mirrors. At high excitation densities, one of the modes of the Fabry–Perot cavity formed by the GaN sapphire and the GaN air interfaces, shows a strong superlinear increase in intensity with excitation density rise. The possibility to reach surface lasing in a very low finesse microcavity is due to the ultrahigh material gain of the InGaN insertions. The strong modulation of the absorption-gain spectrum with increase in the excitation density results in a pronounced energy shift of the cavity modes. We found that the threshold excitation density is weakly affected by temperature up to 110 K, while increases at higher temperatures. This behavior is attributed to thermal evaporation of carriers from InN-rich nanodomains and is typical for quantum dot lasers.
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Devices using compound semiconductors based on group-III nitrides have been rapidly and successfully developed in recent years as efficient emitters of visible light. Long-lived blue laser diodes[1] along with high brightness blue, green, and, most recently, amber light emitting diodes have been demonstrated.

GaN-based surface emitting lasers have attracted particularly strong interest because of naturally integrated mirrors, low beam divergence and possibilities to fabricate dense two-dimensional arrays of short-wavelength diode lasers important for high-density optical storage applications. At the same time, fabrication of such devices was thought to be rather complicated, because of the necessity to grow epitaxially highly conductive distributed Bragg reflectors based on the lattice-mismatched GaN–AlGaN system.

However, it was recently demonstrated for II–VI compounds, that ultrahigh modal gain can be realized in structures with stacked dense arrays of quantum dots (QDs) allowing to achieve surface lasing even without using of Bragg reflectors.[2] As the formation of QD-like structures was demonstrated both by deposition of ultrathin InGaN layers resulting in spontaneous formation of dense arrays of nanoislands,[3] and by spontaneous spinodal decomposition of the InGaN alloys,[4,5] one can expect similar effects for structures with stacked InGaN insertions. Indeed, high modal gain in 0.1-μm-thick InGaN layers at high excitation densities allowed some authors[6,7] to observe stimulated emission in vertical direction, however, no evidence of the importance of the feedback in the system resulting in appearance of the lasing modes was reported. Recently, Someya and co-workers[8] reported optically pumped (VCSEL) based on 0.18-μm-thick InGaN layer operating at 77 K and having Bragg reflectors on both sides of the cavity.

In this letter, we report on growth and structural and optical properties of the structure composed of closely stacked ultrathin InGaN insertions. We demonstrate possibility to achieve surface lasing under optical pumping without using of high-reflectivity Bragg mirrors.

The sample used in this study was grown by low-pressure metalorganic chemical vapor deposition (MOCVD) employing an AlGaN nucleation layer[9] deposited at 530 °C on (0001)-oriented sapphire substrates. Ammonia, trimethylindium (TMI), trimethylgallium (TMG), and thrimethylaluminum (TMA) were applied as component precursors. Purified hydrogen and argon were used as carrier gases. Argon and hydrogen are used as bubbling gases for TMI, TMG, and TMA, respectively. The sample comprised of a 2.5-μm-thick GaN layer deposited at 1050 °C at the total pressure of 200 mbar, using H_2 as a carrier gas. An active region is formed at 600 mbar pressure using Ar as carrier gas. The active region consisted of a 25-nm-thick relaxed InGaN layer with a low indium content (10% In) deposited at 800 °C. This layer was followed by a strain-compensated multilayer structure composed of 12 periods and having the same average In content. The multilayer structure was formed by temperature cycling between 730 and 860 °C, resulting in a modulated In compositional profile, as the In incorporation is strongly affected by substrate temperature. A 0.1-μm-thick GaN cap layer was deposited at 1050 °C. During the growth of the active region the flows of TMI and TMG were constant.

The structure was characterized using a single-crystal x-ray diffractometry (XRD) using Cu $K\alpha_1$ and Cu $K\alpha_2$ radiation. The spectra obtained clearly show higher-order satellite peaks indicating a good layer periodicity. The period of the structure derived from the XRD data was 10.5 nm being in a good agreement with the growth rate calibrations.

Cross-sectional transmission electron microscopy (TEM) image of the structure is shown in Fig. 1. The darker regions correspond to a higher In content. The interface between the GaN layer and the low-In-composition InGaN layer is also resolved in Fig. 1. The image shows predominantly a stripe-

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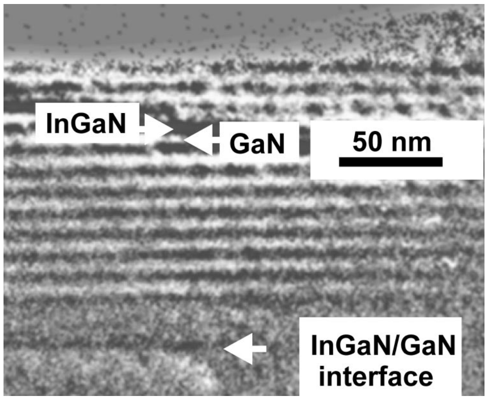

FIG. 1. Cross-section TEM image of the structure. The GaN/InGaN interface and one of the InGaN insertions are marked by arrows.

like contrast due to the InGaN insertions with locally resolved In-rich domains, having a size of about 4–8 nm. More precise information on geometry and composition of these nanodomains or QDs will be obtained after applying image-processing high-resolution TEM techniques.[10]

Photoluminescence (PL) measurements were performed in the temperature range 16–300 K by using a closed-cycle He cryostat. The samples were excited by a He–Cd laser ($\lambda = 325$ nm) or by a pulsed N_2 laser ($\lambda = 337.1$ nm). The excitation density was changed by using neutral glass filters. The emission was analyzed by a double-pass monochromator and detected by a cooled photomultiplyer.

Low-temperature photoluminescence, lasing and optical transmission spectra, all in the direction perpendicular to the sample surface, are shown in Fig. 2. The PL spectrum shows a single relatively broad peak with extended tails on both high and low energy sides. This, together with a significant energy shift between the PL maximum and the onset of the pronounced InGaN absorption in the transmission spectra, agree with formation of In-rich nanodomains with significant size dispersion.

At large excitation densities, PL intensity maximum shifts to higher photon energies, narrows and its intensity superlinearly increase with excitation density (see Fig. 2, insert). These effects taken together point to observation of stimulated emission in surface geometry. As it will be shown in the following, the analysis of the mode structure clearly indicates surface lasing. We note that the PL maximum, also in the latter case, remains in the very vicinity of the onset of the absorption induced by the InGaN insertions.

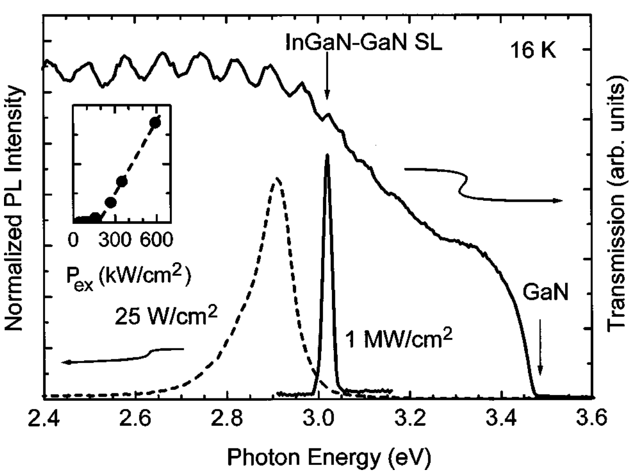

FIG. 2. Low-temperature PL spectra at low and high excitation densities and optical transmission spectrum of the structure. PL intensity vs excitation density is shown in the insert.

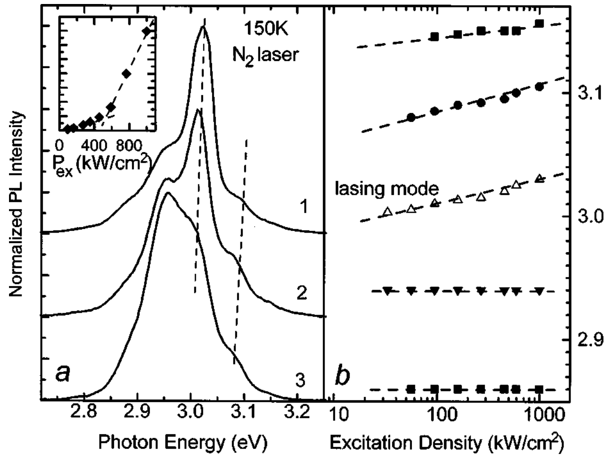

FIG. 3. PL spectra at different excitation densities (a) 1—1 MW/cm^2, 2—0.59 MW/cm^2, 3—0.16 MW/cm^2 (PL intensity vs excitation density is shown in the insert), and cavity mode energies vs excitation density (b).

The dependence of the PL intensity on excitation density at 150 K is shown in Fig. 3(a). PL spectra for different excitation densities are shown in Fig. 3(b). The reduced differential efficiency of the lasing mode at higher temperatures makes the spectral changes related to the increase in excitation density more evident. It can be seen from the figure that all the PL spectra are modulated by the modes of the Fabry–Perot microcavity formed by the GaN/Al_2O_3 interface and the GaN surface. It is clearly seen that at high excitation densities (>600 kW/cm^2) one of the cavity modes starts to dominate in the PL spectra and its peak intensity grows superlinearly. Single-mode emission together with a strong increase in the slope efficiency indicates the presence of the feedback in the system despite of the remarkably low finesse of the cavity. To the best of our knowledge, this is a first demonstration of lasing in vertical direction for structures with stacked InGaN insertions, and a first demonstration of the possibility to reach surface lasing in group-III nitrides without using of high-reflectivity Bragg mirrors.

The structure demonstrates stimulated emission also in edge direction. We found that it starts at excitation densities of about one order of magnitude lower than those required for vertical lasing. As the stimulated emission in edge geometry reduces the radiative lifetime, and prevents increase in gain with further pumping, it serves as a major obstacle for lasing in the direction perpendicular to the surface. A strong improvement in surface lasing performance can be expected, if the stimulated emission in edge geometry is suppressed.

The threshold gain ($g_{\rm th}$) necessary to overcome external losses ($\alpha_{\rm ext}$) and achieve surface lasing can be written as

$$g_{\rm th} = \alpha_{\rm ext} = \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right), \tag{1}$$

where R_1 and R_2 are the reflectivity coefficients for the both interfaces forming the cavity, and L is the cavity length. Here we neglected any internal losses. We estimate the reflectivity coefficients to be 2.4% for GaN/Al_2O_3 and 17% for GaN/air interfaces assuming, that refractive indices are: unity for the

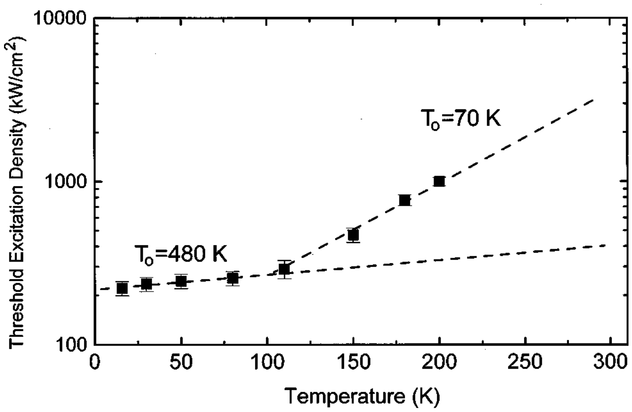

FIG. 4. Temperature dependence of the threshold excitation density for lasing in the direction perpendicular to the surface.

air, and 2.4 and 1.75 for GaN and sapphire, respectively. Then, taking into account that the active region, resulting in gain, has a thickness of 0.15 μm, we obtain a value of $2\times10^5\,\mathrm{cm}^{-1}$ for the threshold gain necessary to overcome external losses.

As it follows from Fig. 3(b), a short-wavelength shift of the cavity modes is observed with increase in the excitation density. The larger shift (up to 3.2 nm) is manifested for the high-energy modes, while the low-energy modes show practically no shift. This effect can be described via Kramers–Kroning equations, which relate real and imaginary part of dielectric susceptibility, and result in a strong modulation of the refractive index in the vicinity of the lasing energy. To explain the observed shift one needs to assume a value of the change of refractive index in the active region of 0.4. This giant value agrees, however, with the estimated maximum gain of $10^5\,\mathrm{cm}^{-1}$ to achieve surface lasing in accordance with Eq. (1) given in Ref. 11. Recently, Jain and Huang have calculated[12] for small 4 nm-InGaN QDs (similar to reported in our letter) values of the maximum gain and the refractive index change of $\sim1.6\times10^5\,\mathrm{cm}^{-1}$ and ~0.2–0.5, respectively. Thus, the theoretical estimates of both Ref. 11 and Ref. 12 are in a good agreement with our experimental results. The effect of interaction of gain spectrum and cavity modes has been reported for vertical cavity lasers based on dense arrays of both InGaAs/GaAs QDs[11] and II–VI QDs.[2]

Temperature dependence of the threshold excitation density for lasing perpendicular to the surface is shown in Fig. 4. In a temperature range between 16 and 110 K, the threshold excitation density remains weakly affected, while it increases at higher temperatures.

The temperature dependence can be extrapolated in two regions via empirical equation:

$$P_{\mathrm{th}}=P_0\exp(T/T_0) \tag{2}$$

with $T_0=480\,\mathrm{K}$ in the low-temperature range and $T_0=70\,\mathrm{K}$ in the high-temperature range. Similar temperature dependencies were reported for InGaAs/GaAs quantum dot lasers. Increasing of the threshold excitation density at higher temperatures is due to thermal evaporation of carriers from QDs.[13]

To conclude, we have demonstrated vertical lasing without Bragg reflectors in a structure with multiple InGaN–GaN insertions. Laser action is confirmed by superlinear dependence of the output intensity versus excitation density and by appearance of a single lasing mode defined by a vertical Fabry–Perot cavity formed by GaN/air and GaN/sapphire interfaces. Effect of interaction between the gain spectrum and the cavity modes is demonstrated.

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