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Lasing in Vertical Direction in Structures with InGaN Quantum Dots

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Lasing operation of InGaN/GaN/AlGaN vertical cavity surface emitting lasers (VCSELs) was successfully realized up to room temperature under optical pumping. VCSELs were grown by metal-organic vapor phase epitaxy and consisted of 2λ vertical cavity with twelvefold stacked ultrathin InGaN quantum dot-like insertions in a GaN matrix and strain-compensated $Al_{0.15}Ga_{0.85}N$/GaN distributed Bragg reflectors.

Introduction There exists a strong interest in GaN-based light-emitting devices operating in the visible to ultraviolet optical spectral range [1, 2]. Vertical cavity surface emitting lasers (VCSELs) are particularly advantageous as candidates for high-density optical storage applications in view of a low divergence of the beam, naturally-integrated mirrors and the possibility to fabricate dense arrays. However, there exists only a limited number of works related to GaN-based VCSELs [3 to 5]. Recently we reported the successful realization of room temperature (RT) optically pumped VCSEL [6]. Photopumped VCSEL operation was also presented by Someya et al. [7], using a different mirror technology. Here we report some more details of VCSEL structure design, properties, and growth procedure.

Experimental Procedure The structures were grown in a horizontal flow MOVPE growth machine (Epiquip VP-50 RP redesigned for III–N growth) with quartz reactor and inductively heated AlN-coated graphite susceptor. Thrimethylgallium (TMG), trimethylaluminum (TMA), thrimethylindium (TMI) and ammonia (NH_3) were used as component precursors, monosilane (SiH_4) was used for doping. Low-temperature AlGaN deposition was employed to form nucleation layer for further epitaxial growth. GaN and AlGaN layers were grown at 1050 °C at the total pressure of 200 mbar, using H_2 as a carrier gas, while InGaN-based active region was grown at reduced temperatures, at a total pressure of 600 mbar, using argon as a carrier gas. Photoluminescence

(PL) measurements were performed using nitrogen or He–Cd gas lasers as excitation sources. Optical reflectance (OR) spectra were taken at normal incidence using a tungsten lamp. Emitted or reflected light was dispersed through a double-pass monochromator and detected by a cooled photomultiplier. The electrical characteristics were measured in the temperature range 77 to 300 K employing the van-der-Pauw technique and a standard *I–V* curve tracer.

Results

InGaN active region The growth of InGaN/GaN heterostructures is complicated due to the high lattice mismatch and the difference in required growth conditions for GaN and InN. As a result, the growth of thick InGaN layers leads to a poor material quality. Only stimulated emission at low temperatures has been observed for such structures. The reduction of the InGaN layer thickness results in a significant improvement of material quality. However, a single thin InGaN layer can provide high gain values required for vertical lasing. Thus, we used an active region composed of multiple thin InGaN insertions in a GaN matrix.

The structures studied in this work were based on an active region consisting of a 25 nm thick relaxed InGaN layer with a low indium content (≈10% In), followed by a strain-compensated 12 period multilayer InGaN/GaN structure having the same average In content. The multilayer structure was formed by temperature cycling, keeping all gas flows constant. It resulted in a modulated In compositional profile, as the In incorporation is strongly affected by the substrate temperature. The active region was sandwiched between a 2 μm thick GaN buffer layer and 0.1 μm thick GaN cap layer deposited at 1050 °C.

Low-temperature photoluminescence, lasing and optical transmission spectra, all in the direction perpendicular to the sample surface, are shown in Fig. 1. 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, points to the formation of In-rich nanodomains with significant size and/or content dispersion. The presence of In-rich nanoislands with a lateral size of 3 to 10 nm was revealed by DALI

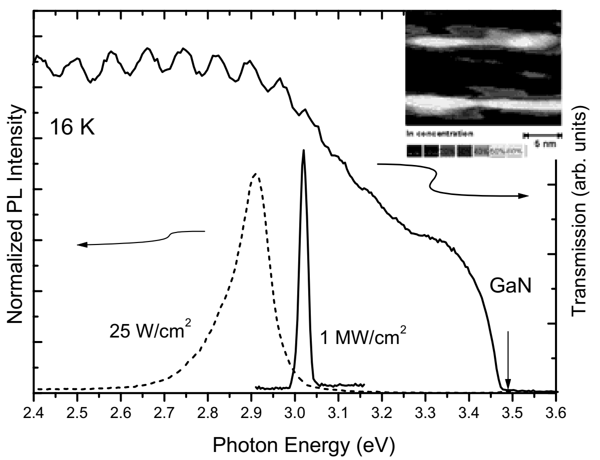

Fig. 1. Low-temperature PL spectra at low and high excitation densities and optical transmission spectrum of the structure. DALI processed HR TEM image is shown in the insert

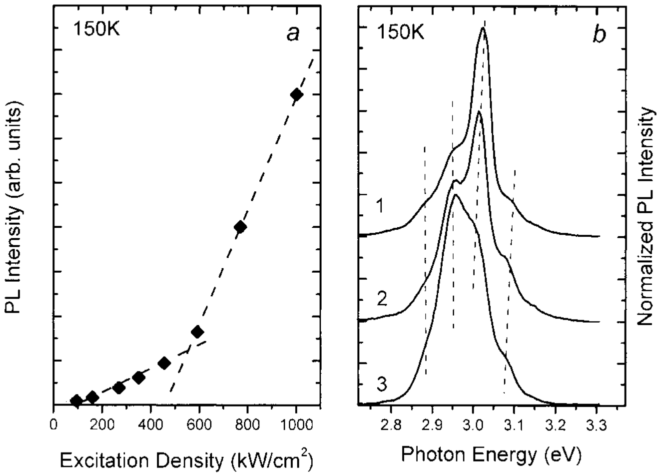

Fig. 2. a) PL intensity vs. excitation density and b) PL spectra at different excitation densities: (1) 1, (2) 0.59, (3) 0.16 MW/cm^2

processing of high resolution transmission electron microscopy (HRTEM) image (see inset in Fig. 1). For the structure described above we achieve surface lasing up to 200 K [8].

The dependence of the PL intensity on excitation density at 150 K is shown in Fig. 2a. The PL spectra for different excitation densities are shown in Fig. 2b. 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 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.

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

$$g_{th} = \frac{1}{2L_{act}} \ln\left(\frac{1}{R_1 R_2}\right), \qquad (1)$$

where R_1 and R_2 are the reflectivity coefficients for the both interfaces forming the cavity, and L_{act} is the thickness of the active region. Here we neglect 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 air, and 2.4 and 1.75 for GaN and sapphire, respectively. So, we obtain a value of 2×10^5 cm^{-1} for the threshold gain necessary to overcome external losses. This type of structures due to huge gain values can be useful for the active region of VCSELs.

Distributed Bragg reflector The most part of the external losses in the structure described above is due to the very low reflectivity of the GaN/Al_2O_3 interface. The losses can be significantly reduced by using AlGaN/GaN distributed Bragg reflector (DBR) instead of a GaN buffer layer. The fabrication of highly reflective AlGaN/GaN DBR is complicated due to significant lattice mismatch between GaN and AlN. The small difference in refractive indices makes it necessary to grow DBR composed of a large number of pairs. The growth of DBR on thick GaN buffers or directly on sapphire substrates results in crack formation. Someya et al. [5] used very thin GaN buffers to prevent cracking. In contrast, we used the concept of strain compensated structures. The DBR consists of 37 pairs of quarter wavelength GaN and $Al_{0.15}Ga_{0.85}N$ layers grown on top of a 1.1 μm thick $Al_{0.08}Ga_{0.92}N$ epilayer grown directly on sapphire [9]. The thickness of the layers was well below the critical one for the AlGaN/GaN growth and the average AlN mole fraction in the DBR was the same as in the underlying $Al_{0.08}Ga_{0.92}N$ layer. TMG mole flow was 36 μmol/min for the growth of GaN and $Al_{0.08}Ga_{0.92}N$ layers while for growth of $Al_{0.15}Ga_{0.85}N$ layers mole flows were 18 μmol/min for TMG and 2.4 μmol/min for TMA, respectively. Two TMG sources and one TMA source were used to obtain this growth procedure. The DBR and $Al_{0.08}Ga_{0.92}N$ buffer layers were doped with Si. The maximum reflectivity was above 90% in the range of 3.3 to 3.35 eV.

VCSEL structure The combination of highly reflective AlGaN/GaN DBR with a multilayer InGaN/GaN active region allowed us to achieve surface lasing up to room temperature. It should be pointed out that no highly reflecting top mirror was used. In our case the role of this mirror was played just by the GaN/air interface. In Fig. 3 we show the excitation density dependence of the PL spectra recorded at room temperature. As follows from Fig. 3, a remarkable narrowing of the luminescence emission with excitation density is observed. This narrowing is accompanied by a clear superlinear growth of the corresponding PL peak intensity as is shown in Fig. 3 (inset) by solid circles. This behavior clearly points to stimulated emission in the vertical direction. In spite of the remarkable narrowing of the PL line, the linewidth observed is still too broad as com-

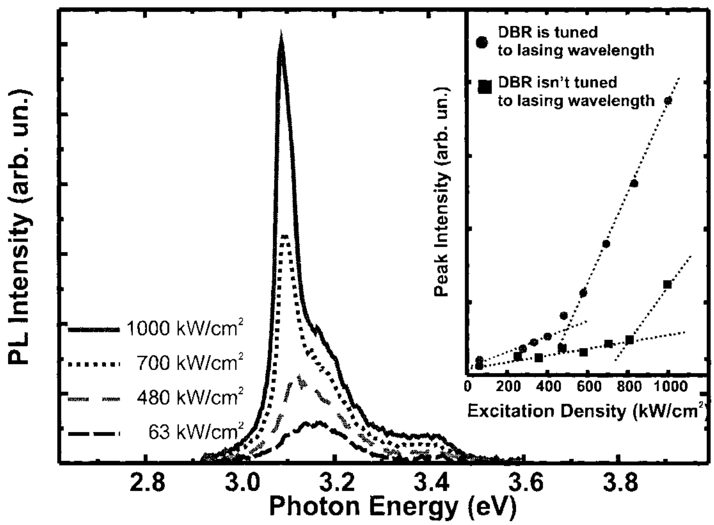

Fig. 3. Room temperature photoluminescence (PL) spectra of the VCSEL structure at different excitation densities. The inset shows the dependence of the peak PL intensity on excitation density

pared to the linewidth observed in VCSELs. We note, however, that in our case, this fact may be explained by two major reasons. First, due to the absence of the highly reflecting top mirror, the finesse of the cavity is very low, resulting in a cavity dip width comparable to the PL linewidth. Upon lasing, the emission spectrum narrows, but the final linewidth cannot be too narrow, as the effective lifetime of the photon in the cavity is too small to result in a strong narrowing of the emission spectrum. Additionally, no special measures were taken during the growth to prevent a layer thickness nonuniformity resulting in a spatial gradient of the DBR maximum-reflectivity wavelength. As the excitation spot had a significant size (≈100 μm) the stimulated emission is additionally broaden by at least 1 nm.

The spatial gradient of the DBR maximum-reflectivity wavelength gave us the possibility to study the effect of mirror reflectivity on the threshold excitation density as the emission wavelength of the InGaN/GaN active region remained essentially the same across the wafer. In the inset of Fig. 3 two dependences of the PL intensities on excitation density for two different excitation spots on the wafer surface are shown. In the first case (solid circles) the DBR maximum-reflectivity wavelength corresponds to the PL wavelength of the active region emission, while in the second case (solid squares) the DBR maximum-reflectivity and the PL emission wavelength are different. Detuning results in a significant enhancement of the threshold excitation density (from 400 to 700 kW/cm^2) and in a decrease in the slope efficiency by a factor of two. These facts directly point to the important role of high reflectivity DBR for the reduction of the threshold excitation density and improvement in differential efficiency.

Stimulated emission and laser generation generally are similar in nature, but the importance of the feedback in the system is different. Laser emission in a cavity must have a narrow far-field intensity distribution, while single-pass stimulated emission must have similar angle behavior to the spontaneous emission. In our case, the spectra presented in Fig. 3 were recorded using a short focus length lens for light collection having a collection angle of 60° placed close to the sample. In this case most of the luminescence is collected. In Fig. 4a one can see both the narrow luminescence line and the broad spontaneous emission. Using the set-up with the collection angle of 10° results in a significant change of the PL spectra. The intensity of the spontaneous emission is strongly decreased, while the intensity of the narrow line remained weakly affected (Fig. 4b, solid line). Moreover, the

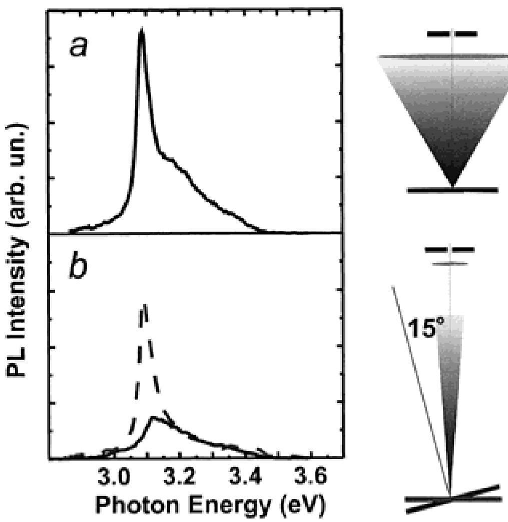

Fig. 4. Room temperature PL spectra taken at different collected angles of the registration system: a) 60° and b) 10°. The spectrum presented by the dashed line was measured in normal geometry while for the spectrum presented by the solid line the sample normal is 15° tilted from the registration system axis

narrow PL line completely disappeared already at small tilt angles (15°) of the sample surface away from the optical axis of the registration system (Fig. 4b, dashed line). The intensity of the spontaneous emission feature remains weakly affected in this case. From these studies one can unambiguously conclude that the narrow PL emission demonstrating superlinear growth of intensity with excitation density can be attributed to surface lasing, as it shows a much narrower far-field pattern as compared to the broad feature due to spontaneous emission.

On the way to VCSEL diode To fabricate current-driven VCSEL one must solve the problem of current passing through the structure with DBRs. As it was mentioned above, the described DBR was doped with Si. Electrical measurements were perfomed to check the possibility of using such n-type DBR structures as emitters and contact layers. The Hall mobility is 580 $cm^2\ V^{-1}s^{-1}$ at room temperature with concentration (2 to 3) $\times 10^{18}\ cm^{-3}$. This results indicate the excellent conductivity of Si-doped DBR giving the possibility of utilizing it as a conductive mirror of InGaN/GaN/AlGaN VCSEL without special intra-cavity contact layer.

The well-known problem of low conductivity of p-type GaN strongly limits the use of top dielectric mirrors or p-type GaN/AlGaN DBRs. On the other hand, we succeeded in the fabrication of Ohmic contacts to p-type GaN with reflectivity exceeding 50%. Only 20% reflectivity by the GaN/air interface is enough for lasing in the structure described above. Thus, these Ohmic contacts can serve as top mirrors for VCSELs.

Conclusions Ultrahigh gain in multilayered InGaN/GaN structure is proved by the lasing in vertical direction under optical pumping at low temperatures in structures without DBRs. Highly reflective AlGaN/GaN DBRs are fabricated using the concept of strain-compensated multilayer structure growth. The combination of an InGaN-based active region with high-reflective DBR allows to achieve surface lasing at room temperature.

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