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Photopumped InGaN/GaN/AlGaN Vertical Cavity Surface Emitting Laser Operating at Room Temperature

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Room temperature operation in the wavelength range of 401 to 415 nm has been successfully realized in InGaN/GaN/AlGaN vertical cavity surface emitting lasers (VCSELs) under photoexcitation. The VCSELs are grown by metal-organic vapor phase deposition and composed of a 2λ vertical cavity including twelvefold stacked multiple InGaN insertions in a GaN matrix grown on top of a quarter-wave strain-compensated $Al_{0.15}Ga_{0.85}N$/GaN distributed Bragg reflector.

Currently there exists a strong interest in GaN and related alloys as promising materials for optical emitters operating in the amber-to-ultraviolet spectral range, see e.g. [1, 2]. GaN-based vertical cavity surface emitting lasers (VCSELs) are potentially particularly important for applications in optical storage or in laser displays, as they provide good beam quality, include monolithically-integrated mirrors and allow planar technology. A possibility to achieve stimulated emission in surface geometry has been addressed in a number of publications [3, 4, 5]. In spite of the fact, that surface lasing at low temperatures has been demonstrated in structures with [5] or even without highly-reflecting AlN–GaN distributed Bragg reflectors (DBRs) [6], no vertical lasing at room temperature has been reported so far. On one side this can be explained by difficulties in fabrication of AlGaN/GaN DBRs with high reflectivity due to small difference in refractive indices and noticeable lattice mismatch between GaN and AlGaN alloys. On the other hand a pioneering approach to realize ultrahigh modal gain permitting lasing in the vertical direction in VCSELs having small mirror reflectivity appeared only recently [6, 7]. In this work we fabricated two VCSEL structures with 2λ cavity formed by a 37-period quarter-wave $Al_{0.15}Ga_{0.85}N$/GaN DBR on the one side of the active layer and an GaN–air interface on the other. A multilayer structure composed of twelvefold stacked thin InGaN insertions in a GaN matrix served as an active layer providing ultrahigh material gain and making possible vertical lasing without the use of an upper Bragg reflector [8]. This possibility originates from ultrahigh material gain values due to spontaneous formation of dense array of nanoscale InGaN QDs having an exceptionally high area density (above 10^{12} cm^{-2}) [9]. In this paper, we report photopumped sur-

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face lasing at room temperature in structures with strain-compensated DBRs. The emission wavelengths are 401 and 415 nm for two VCSEL structures. The threshold pulsed excitation densities are 400 and 550 kW/cm^2, respectively.

The VCSEL structures consisted of a 1.1 μm thick $Al_{0.08}Ga_{0.92}N$ buffer layer grown on top of a low-temperature-deposited AlGaN nucleation layer. Afterwards, a 37-period $Al_{0.15}Ga_{0.85}N$/GaN quarter-wave DBR and a 2λ vertical cavity were grown. A twelvefold-stacked InGaN/GaN multilayer structure composed of thin InGaN insertions was used as an active medium and was placed in the center of the 2λ cavity. The average Al content in the DBR was chosen to be the same as for the underlying AlGaN buffer layer and the thickness of the quarter-wave layers were well below the critical thickness reported for the AlGaN/GaN system [10]. Fabrication of strain-compensated DBRs allowed us to solve the problem of noticeable lattice mismatch between the DBR and the thick buffer layer (if the GaN buffer layer is used, its thickness should be lower than 400 nm to prevent formation of cracks [11]).

The structures were grown on (0001) sapphire substrates using metal-organic vapor phase epitaxy. Trimethylgallium (TMG), trimethylaluminum (TMA), trimethylindium (TMI) and ammonia were used as precursors. AlGaN buffer layers and DBR were grown utilizing H_2 as a carrier gas at a cell pressure of 200 mbar and a substrate temperature of 1050 °C and were doped with Si. TMG and TMA gas flows were 36 and 2.4 μmol/min during the AlGaN buffer layer growth. During the DBR growth the flow of TMG was 36 μmol/min for the GaN quarter-wave layers, while for growth of the AlGaN quarter-wave layers the flows of TMG and TMA were 18 and 2.4 μmol/min, respectively. The details of AlGaN growth on sapphire substrates are given elsewhere [12]. The InGaN/GaN active region was grown in Ar ambient at a cell pressure of 600 mbar. Initially, a 25 nm thick InGaN layer with low In content was grown at 850 °C (structure A) or 825 °C (structure B) using TMG and TMI flows of 4 μmol/min each. The active region represented twelvefold stacked InGaN insertions in a GaN matrix, and was formed by temperature cycling between 780 °C and 910 °C (structure A) or 755 and 885 °C (structure B) keeping all the gas flows constant. Different growth temperatures allowed us to obtain structures with different indium content in the InGaN insertions as the indium incorporation coefficient strongly depends on the substrate temperature. The period of the structure derived from X-ray characterization was 12 nm being in good agreement with the growth rate calibrations. The estimated average thickness of the InGaN regions was about 5 nm. The cavity region of the VCSEL structures was completed by GaN cap layer grown at 1050 °C in a H_2 ambient at 200 mbar.

Photoluminescence (PL) measurements were performed using a nitrogen gas laser as excitation source. The excitation density was changed using neutral density filters. Optical reflectance (OR) spectra were taken at normal incidence using the broad spectrum emission of a tungsten lamp. Emitted or reflected light was dispersed through a double-pass monochromator and detected by a cooled photomultiplier.

Realization of effective DBRs (maximum reflectivity >90%) [13] allows us to successfully achieve laser generation in the vertical direction even if 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. 1 we show excitation density dependence of the PL spectra of the structures as recorded at room temperature. As it follows from Fig. 1, a remarkable narrowing of the luminescence emission with excitation density is observed at 3.1 and

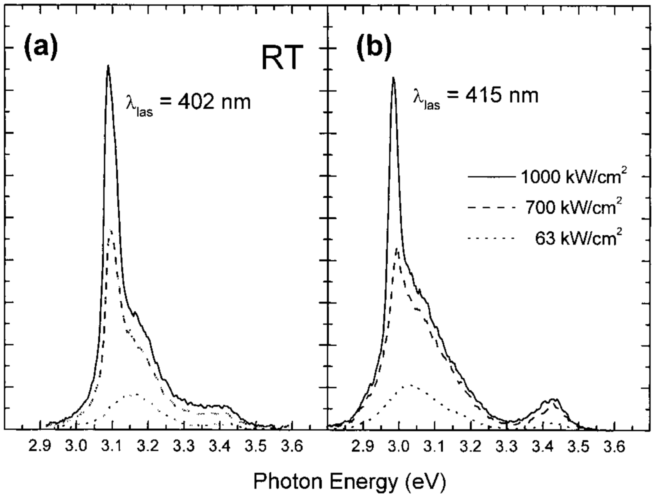

Fig. 1. Room-temperature photoluminescence (PL) spectra of the VCSEL structure a) A and b) B at different excitation densities (solid line 1000 kW/cm^2, dashed line 700 kW/cm^2, short dashed line 480 kW/cm^2, and dotted line 63 kW/cm^2)

3.0 eV for structures A and B, respectively. This narrowing is accompanied by a clear superlinear growth of the corresponding peak PL intensities as it is shown in Fig. 2 (solid circles). This behavior clearly points to stimulated emission in the vertical direction. The threshold excitation densities are 400 kW/cm^2 for structure A, and 550 kW/cm^2 for structure B, respectively, as it follows from Fig. 2.

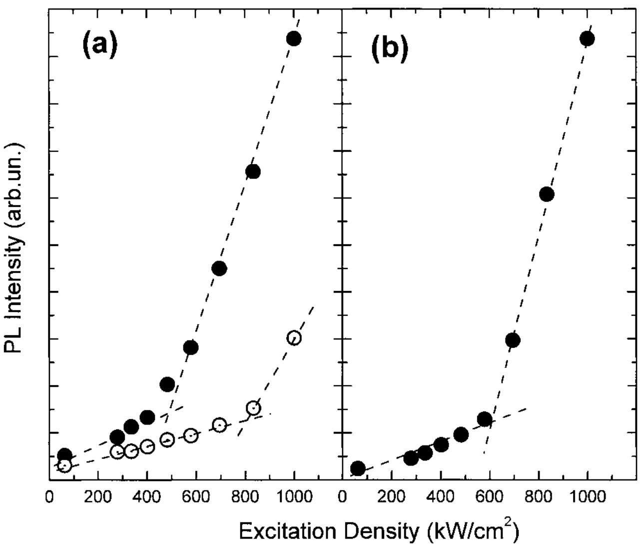

Fig. 2. Peak PL intensity dependence on excitation density at room temperature for VCSEL structure a) A and b) B. Solid circles (●) correspond to the case when distributed Bragg reflector is tuned to active region while open circles (○) correspond to detuned case

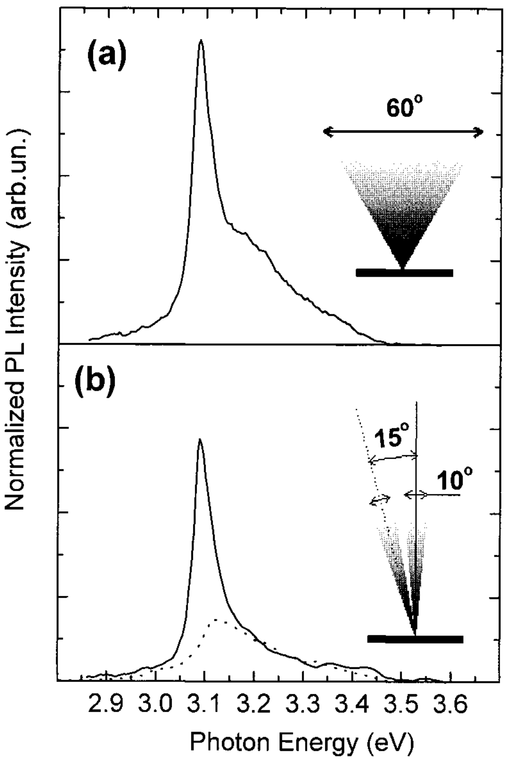

Fig. 3. Room-temperature PL spectra taken at different collected angle of registration system: a) 60° and b) 10°. The spectra presented by solid lines correspond to normal registration (the sample normal is parallel to the registration system axis) while for the spectrum presented by the dotted line the sample normal is tilted by 15° from the registration system axis

No special measures were taken to prevent thickness nonuniformity of the structures. It results in a spatial gradient of DBR maximum reflectivity wavelength [13], while the emission wavelength of the InGaN/GaN active region remained essentially the same across the wafer. It gave us a possibility to study the effect of the mirror reflectivity on the threshold excitation density. Figure 2a shows two dependences of the PL intensities on excitation density for two different excitation spots on the wafer surface. In the first case (solid circles) the DBR maximum reflectivity wavelength is corresponding to the PL wavelength of the active region emission, while in the second case (open circles) the DBR maximum reflectivity wavelength and the wavelength of the PL emission are different. The 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 twice. 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 have a similar nature, but the importance of the feedback in the system is different in both cases. Laser emission must have a narrow far-field intensity distribution, while stimulated emission has, generally, the same angle behavior as spontaneous emission, as it has a single-pass nature. In our case the spectra presented in Fig. 1 and the spectrum shown in Fig. 3a were recorded using a short focus length lens for light collection having a collection angle of 60°. In this case all the luminescence is collected. In Fig. 3a one can see both the narrow luminescence line and the broad spontaneous emission. Decrease in the collection angle of the lens down to 10° results in a significant change in the PL spectra. The intensity of the spontaneous emission is strongly decreased, while the intensity of the sharp line remained weakly affected (Fig. 3b, solid line). On the contrary, the narrow PL line completely disappears already at small tilt angles (15°) of the sample surface away from the optical axis of the registration system (Fig. 3b, dotted 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 broad spectrum spontaneous emission.

According to our best knowledge this is the first clear demonstration of laser action at room temperature in InGaN/GaN/AlGaN VCSELs. Someya et al. [5] reported on lasing in a DBR structure, however, they were able to achieve photopumped lasing only at liquid nitrogen temperature at excitation densities similar to those reported in this work for room temperature.

To conclude, we demonstrated photopumped operation at room temperature of InGaN/GaN/AlGaN VCSELs. The lasing is confirmed by a narrowing of the PL emission, superlinear threshold-like growth of the PL intensity, and by a narrow far-field pattern of the lasing emission.

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