Blue lasing at room temperature in an optically pumped lattice-matched AlInN/GaN VCSEL structure

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Laser action with low threshold average pump power density ($\sim 50\ \mathrm{W\cdot cm^{-2}}$) at room temperature is reported for a crack-free planar vertical cavity surface emitting laser (VCSEL) structure based on a bottom lattice-matched AlInN/GaN distributed Bragg reflector (DBR) and a top dielectric DBR. The cavity region, formed by *n*- and *p*-type GaN layers surrounding only three InGaN/GaN quantum wells, corresponds to a typical active region suitable for an electrically driven VCSEL. In addition to low threshold, a spontaneous emission coupling factor $\beta \sim 2\times 10^{-3}$ is derived for this ready-to-be-processed laser structure.

In recent years III-nitride semiconductor optoelectronic devices have undergone tremendous development with the progressive commercialisation of blue-violet and white light emitting diodes and that of blue-violet edge-emitting laser diodes (LDs) [1]. However, demonstration of an electrically pumped compact laser source such as vertical cavity surface emitting lasers (VCSELs) has not been reported. Recent advances in the growth of high quality epitaxially-grown nitride-based distributed Bragg reflectors (DBRs) have allowed for significant improvement of the quality factor $Q(=\lambda/\Delta\lambda)$ of planar microcavity (MC) structures [2] with the recent demonstration of Q values up to 2800 in a crack-free empty lattice-matched (LM) AlInN/GaN-based MC [3]. Lasing in planar nitride VCSEL structures under optical pumping has been reported by several groups [2, 4–7] but usually the active region consists of more than ten quantum wells (QWs) to increase modal gain and overcome optical losses. Actually, in electrically pumped LDs there is usually a trade-off between modal gain and threshold current which leads to an optimum number of wells between three and five. So far there is, to the best of our knowledge, only one report of room-temperature lasing action in an optically pumped nitride VCSEL structure containing less than ten QWs, namely in a 4λ AlGaN cavity with three InGaN QWs sandwiched between two high reflectivity ($R \sim 99\%$) dielectric (SiO_2/ZrO_2) DBRs [8]. However, the realisation of the latter structure requires lengthy and advanced processing steps which are not compatible with an electrical injection scheme.

In this Letter we report on the blue-violet lasing action, at ~ 422 nm, under optical pumping with a low average threshold power density of $50\ \mathrm{W\cdot cm^{-2}}$ in a crack-free planar hybrid $5\lambda/2$ GaN MC containing three InGaN QWs with a bottom LM AlInN/GaN DBR and a top dielectric (SiO_2/Si_3N_4) DBR. The cavity region has both *n*- and *p*-type regions as well as an AlGaN electron blocking layer on the *p* side making such a planar design in all points identical to that of a real structure ready to be processed to fabricate mesas and deposit electrical contacts. A spontaneous emission coupling factor $\beta \sim 2\times 10^{-3}$ is derived from the input-output characteristics for this VCSEL structure.

The nitride vertical cavity structure was grown by metal organic vapour phase epitaxy (MOVPE) on a 2-inch *c*-plane sapphire substrate in an AIXTRON 200/4 RF-S reactor. Following the deposition of a standard 3 µm-thick GaN buffer layer, a 39.5 pair LM $Al_{0.82}In_{0.18}N/GaN$ DBR ($R > 99\%$) was grown. The cavity region consists of a 43.5 nm-thick non-intentionally doped (*nid*) GaN layer followed by a 165 nm *n*-GaN layer ($[\mathrm{Si}] \sim 3\times 10^{18}\ \mathrm{cm^{-3}}$), an $Al_{0.82}In_{0.18}N$ layer used for current confinement (25 nm thick, LM to GaN and *n*-doped ($[\mathrm{Si}] \sim 1\times 10^{19}\ \mathrm{cm^{-3}}$) to improve its electrical characteristics), a 12 nm *n*-GaN spacer, a 3 period $In_{0.14}Ga_{0.86}N$ (3 nm)/GaN:Si (12 nm) multiple QW active region, a 20 nm $Al_{0.2}Ga_{0.8}N$:Mg electron-blocking layer and a 126 nm *p*-GaN layer ($[\mathrm{Mg}] \sim 2\times 10^{19}\ \mathrm{cm^{-3}}$). The layer thicknesses were chosen to match that of an ideal $5\lambda/2$ cavity structure. Subsequent to the MOVPE growth, a 13 pair high reflectivity ($R > 99\%$) SiO_2/Si_3N_4 DBR was deposited on top of the cavity by plasma enhanced chemical vapour deposition. The reason for the presence of the AlInN layer in the *n*-type cavity region is that it can be subsequently oxidised to form current micro-apertures allowing access to high current densities ($> 20\ \mathrm{kA\cdot cm^{-2}}$) compatible with the injection requirements of nitride-based VCSELs [9]. Fig. 1 shows a schematic cross-section of the structure fabricated for this work. This structure was shown to be free of cracks as checked by phase contrast optical microscopy, whereas the dislocation density is $\sim 10^9\ \mathrm{cm^{-2}}$ on average owing to the hetero-epitaxial growth on sapphire substrate. The planar MC structure was optically pumped by means of 150 fs pump pulses at 297 nm produced by frequency doubling the visible output of a 250 kHz optical parametric amplifier. The pulses are focused down to a 60 µm diameter spot on the top dielectric DBR and incident at an angle of 30°. The light emitted along the normal to the sample is then collected by a UV multimode collection fibre coupled to a 0.5 m monochromator and liquid N_2-cooled CCD. All results were obtained at room temperature (RT) under a duty cycle of 50% in order to minimise heating effects likely to occur in the top DBR.

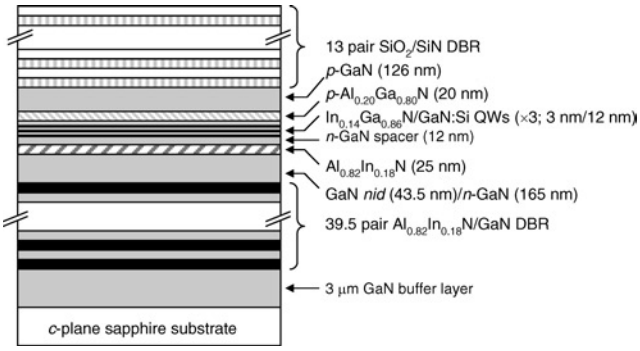

Fig. 1 *Schematic cross-section of VCSEL structure*

Fig. 2*a* shows the evolution of the RT emission spectra for increasing pump powers I_{pump} ranging from 50 µW to 2.0 mW. A clear threshold is observed at an average incident pump power of ~ 1.4 mW, i.e. an average power density P_{av} of $50\ \mathrm{W\cdot cm^{-2}}$ otherwise corresponding to a pump energy density of $200\ \mathrm{\mu J\cdot cm^{-2}}$. The spectral width of the emission below threshold is about 3.1 nm (Fig. 2*b*). The reason for such a broad linewidth, considering the nominal reflectivity of the bottom and top DBRs, is essentially due to cavity thickness fluctuations. Similar AlInN/GaN MCs indeed reveal in-plane cavity disorder leading to a decrease of the effective Q factor with increasing spot size, and with the measured cavity mode revealing the contributions of several narrow modes [3]. This aspect is further confirmed above threshold where several peaks contribute to the stimulated emission (Fig. 2*b*) with the narrowest mode being about 0.37 nm wide, close to the spectral resolution limit of the system. Furthermore, it is also known that *p*-type GaN layers usually exhibit an increased surface roughness compared to *nid* or *n*-type GaN layers, which could increase the disorder in the post-grown top dielectric DBR.

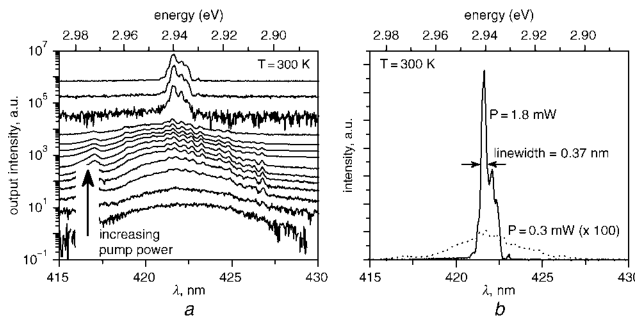

Fig. 2 *Semi-logarithmic plot displaying RT emission spectra at pump powers ranging from 50 µW to 2 mW at 0°, shifted for clarity, and linear plot showing two emission spectra (below and above threshold)*

a Variation of emission spectra for various pump powers at 0°
b Spontaneous emission spectrum and VCSEL spectrum

Fig. 3 shows the spectrally-integrated input-output characteristics of the VCSEL structure on a logarithmic scale. Besides a lasing threshold occurring at an average pump power $I_{thr} \sim 1.4$ mW, we can extract the spontaneous emission coupling factor β from this plot. The solution of the standard rate equation model gives the dependence of the output integrated intensity, $I_{out} \propto r - 1 + \sqrt{(r-1)^2 + 4\beta r}$ where $r = I_{pump}/I_{thr}$ is the normalised pump rate [10, 11]. We obtain the best fit with

$I_{thr} = 1.4$ mW for a β value equal to $\sim 2 \times 10^{-3}$ (See Note). Note that such a value is more than two orders of magnitude larger than that usually reported for edge emitting lasers ($\beta \simeq 10^{-5}$) as expected for a vertical cavity laser with fewer modes supporting spontaneous emission [4, 10]. In addition we point out that the realisation of the present structures is well adapted to standard planar processing technologies as no lift off and flip-chip techniques are required. This is in contrast to the case of the VCSEL structure described in [8] which requires somewhat advanced and costly processing steps such as SiC substrate removal and wafer-bonding techniques.

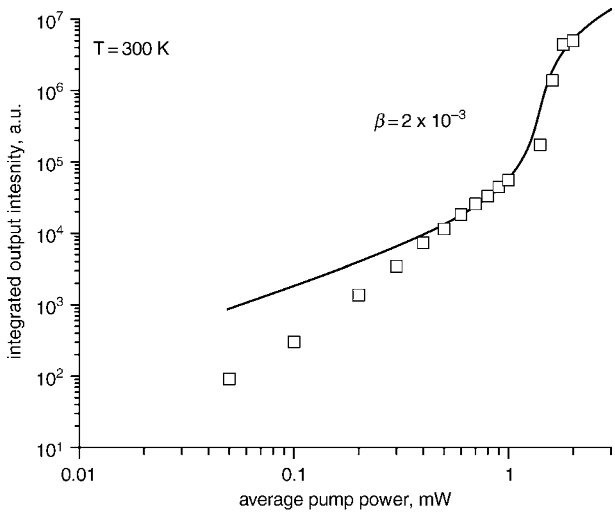

Fig. 3 *Integrated output intensity against average incident pump power (squares) and corresponding fit (line) as described in text*

Conclusion: We have reported low threshold lasing action ($P_{av} \sim 50$ $W \cdot cm^{-2}$) at RT in a planar VCSEL structure using only three InGaN/GaN QWs as an active region surrounded by *n*- and *p*-type GaN regions, in a crack-free laser structure that would be suitable for electrical injection following complete processing. Further improved optical characteristics will be achieved using free-standing GaN substrates since our recent measurements performed on AlInN/GaN DBRs reveal a higher uniformity over the surface compared to similar DBRs grown on *c*-plane sapphire substrates. Such substrates would also be more suitable for electrical injection purposes owing to improved thermal management.

Note: The discrepancy between experimental data and fit at low pump powers is commonly seen in such laser structures and could be ascribed to dislocation related nonradiative defects. Note however that our value of β is likely overestimated owing to the contribution of many modes in the spontaneous emission below threshold compared to the stimulated emission originating from a smaller number of modes, for which the gain is maximum, above threshold (cf. [12]), the latter aspect being often disregarded in the analysis of optically pumped nitride-based VCSELs.

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