C5.2 Optically pumped lasing and current injection lasing in GaN-based laser structures

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A INTRODUCTION

Group III-nitrides AlN, GaN and InN and their alloys have direct energy gaps spanning the wavelength range of ~200 nm to ~650 nm at room temperature and are considered to be the most promising UV-blue laser diode (LD) materials. The optical pumping technique is the method capable of providing very high excitation densities necessary for the occurrence of stimulated emission (SE) and lasing. The advantage of the optical pumping technique is that the study of SE and lasing phenomena can be conducted without electrical contacts on samples so that somewhat complicated device processing procedures can be avoided. Usually a pulsed laser has to be used for optical pumping in order to generate sufficient numbers of carriers in the conduction band. Details of the experimental optical pumping scheme are given in [1].

The achievement of coherent light emission from nitride based current injection diodes was reported more than twenty years after the first observation of optically pumped lasing in GaN [2,3]. This partially reflects the difficulties associated with materials growth, p-type doping and device fabrication of wide bandgap nitrides [4]. In spite of these difficulties, several groups have reported LD operation in the last two years or so. Most of the LDs reported, however, were in the pulsed injection mode, indicating that the main technical challenges must still be overcome in order to readily achieve continuous wave (CW) GaN-based LD operation. Detailed discussion on the various recent issues concerning current injection InGaN LDs is given in Datareview C5.1; thus the emphasis here will be on optical pumping.

B OPTICALLY PUMPED STIMULATED EMISSION AND LASER ACTION

The first observation of optically pumped lasing in GaN was made by Dingle et al using needle-like GaN single crystals at the sample temperature of 2 K [3]. Since then, there have been a number of investigations on optically pumped SE and laser action in GaN and related InGaN/GaN and GaN/AlGaN heterostructures in recent years [4-26]. The reported values of the pumping threshold for SE and lasing in these materials vary by a few orders of magnitude depending on growth techniques, substrate materials and nitride structures. The measured threshold values from double-heterostructure (DH) or separate-confinement-heterostructure (SCH) samples are generally lower than the values for bulk-like GaN epifilms by approximately one order of magnitude. This reduction in threshold is due mainly to the effects of carrier confinement and waveguiding associated with the DH and SCH structures [14].

Optically pumped SE and lasing were also observed in GaN and InGaN/GaN MQWs significantly above room temperature [11,12,22-25]. The SE or lasing threshold was found not to be very sensitive to the temperature change [22,23]. The first above room temperature optically pumped UV lasing was observed by Yang et al in GaN grown on sapphire up to 375 K [12]. The samples were cut into bar-like specimens of various thicknesses ranging from 150 to 1000 μm, to form the lasing cavity. FIGURE 1 shows an example of the lasing spectra of GaN at 375 K taken at different pumping densities.

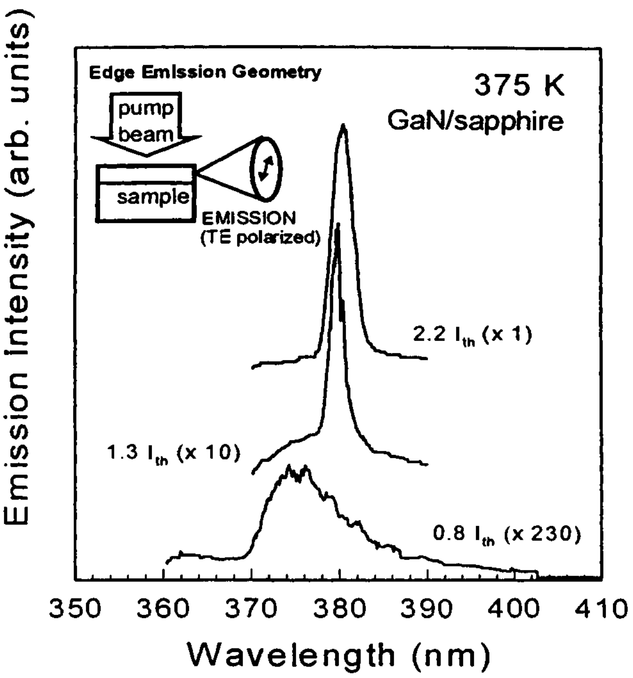

FIGURE 1 Emission spectra from a GaN sample with a cavity length of 330 μm under different pump power densities. The curves are vertically displaced for clarity. The threshold pump power density I_{th} was determined to be 1.2 MW/cm^2 at 375 K. The insert shows the excitation and emission configuration.

Recently, Bidnyk et al observed SE in GaN films grown on 6H-SiC and (0001) sapphire substrates in the temperature range of 20 to 700 K [24]. The temperature dependence of the SE threshold roughly followed an exponential dependence. The SE threshold for one of the samples grown on the SiC substrate was measured to be 0.57 MW/cm^2 at 300 K, 1.7 MW/cm^2 at 500 K and 5.6 MW/cm^2 at 700 K as shown in FIGURE 2. The solid line in FIGURE 2 represents the results of the best least-squares fit of the experimental data to the empirical form $I_{th}(T) = I_o \exp(T/T_o)$ for the temperature dependence, with T_o ~170 K [27]. The energy positions of the SE and spontaneous emission peaks were shown to shift linearly to longer wavelengths with temperature. The energy separation between the spontaneous and SE peaks gradually increases from 90 meV at 300 K to 200 meV at 700 K [24]. Both this large energy difference and the relatively high values of SE thresholds in this temperature range effectively eliminate exciton-related effects from consideration of the SE mechanism and suggest free carrier recombination or an electron-hole plasma as the likely SE mechanism in GaN thin films for temperatures above 300 K.

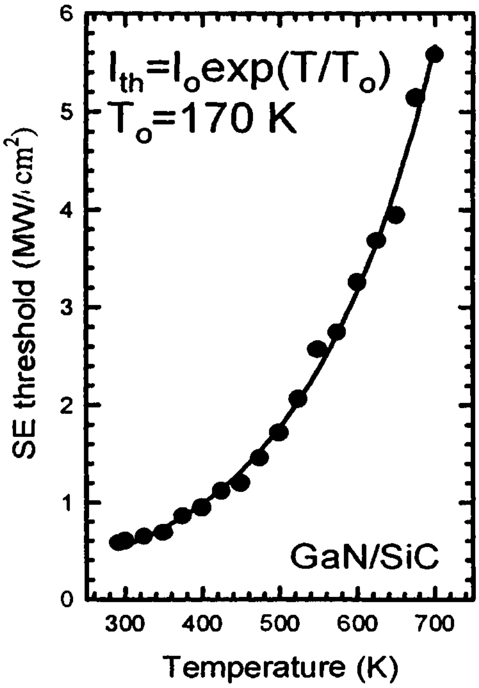

FIGURE 2 SE threshold as a function of temperature for a GaN thin film grown on SiC. The solid line represents the best least-squares fit to the empirical form $I_{th}(T) = I_o \exp(T/T_o)$, which yielded T_o ~ 170 K.

High-temperature SE was also observed in MOCVD-grown InGaN/GaN MQWs up to 575 K [23]. The number of periods of the MQWs was 12, the nominal well and barrier layer thicknesses were 30 and 45 Å, respectively, and the sample width was ~1 mm. The SE threshold was found to be low and exhibit weak temperature dependence; for example, ~25 kW/cm^2 at 175 K, ~55 kW/cm^2 at 300 K and ~300 kW/cm^2 at 575 K for one of the MQWs. The T_0 of this MQW was deduced to be ~160 K in the temperature range 175 - 575 K. FIGURE 3 shows the SE spectra of an InGaN/GaN MQW sample taken at 200 K and 450 K, along with the corresponding spontaneous emission spectra. The SE emission spectra are comprised of many narrow peaks of less than 1 Å FWHM, which is on the order of the instrumental resolution of this work [23]. The SE peak emerges on the high energy side of the broad spontaneous emission spectra with increase of the pumping power, as shown in FIGURE 3. In these MQW samples, optically pumped SE was also observed for excitation energies well below that of the MQW absorption edge. Further, even at a fixed temperature, the SE peak position was found to red shift as the pumping photon energies are tuned, as shown in FIGURE 4. This red shift of the emission for pump beam photon energies below a certain value was also observed in the spontaneous emission spectra [28]. This observation indicates that large potential fluctuations are present in the InGaN active regions, resulting in strong carrier localisation. The large potential fluctuations very likely reflect the spatial inhomogeneity of the InGaN active layers arising from large fluctuation of the indium mole fraction, possible indium phase segregation, interface irregularities and/or quantum-dot-like features in the active region [25,29]. The large spatial variations in crystalline potential, and consequently in the conduction and valence band energies, produce inhomogeneously broadened low-energy tail states in the k-space.

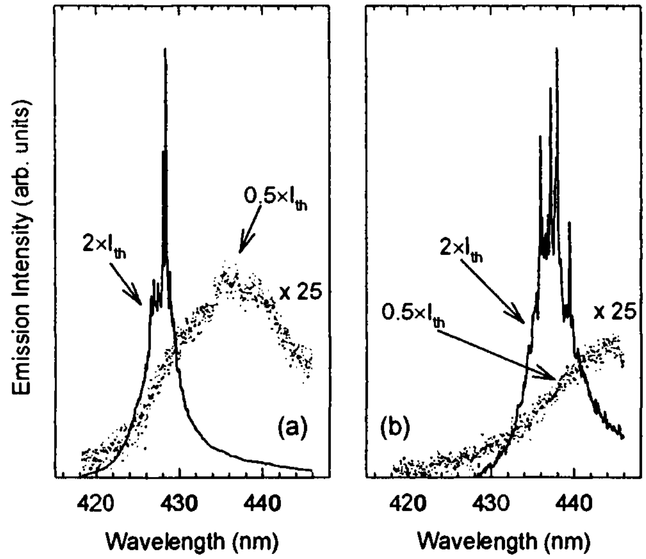

FIGURE 3 Emission spectra from an InGaN/GaN MQW sample for two different temperatures: (a) 200 K and (b) 450 K. Dotted lines represent the broad spontaneous emission spectra (taken at 0.5 × I_{th}). SE spectra taken at 2 × I_{th} are shown with continuous lines.

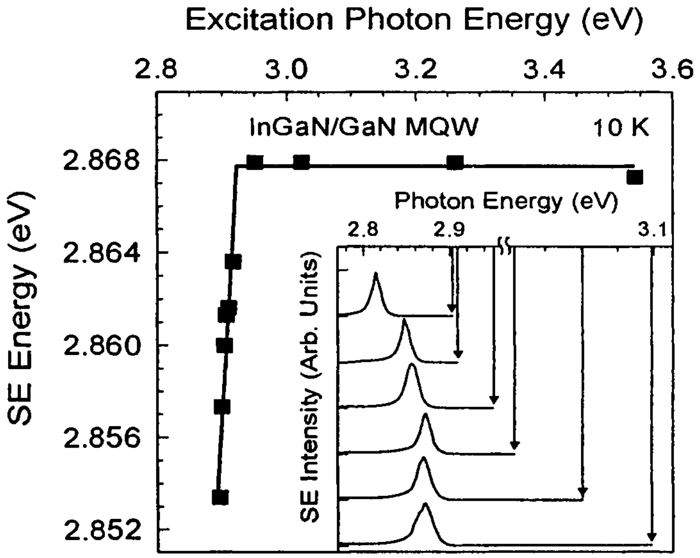

FIGURE 4 SE peak position as a function of excitation photon energy, E_{exc}, for an InGaN/GaN MQW. The solid lines are given only as a guide for the eye. The inset shows the red shift of the SE peak with decreasing E_{exc}. The E_{exc} values for the given SE spectra are represented by the arrows in the inset.

The localised carriers in those tail states may play a significant role in InGaN MQW lasing. However, further studies are required to better understand the lasing phenomena in these MQWs.

Reports on optically pumped SE and lasing in quantum well structures with GaN active layers are very limited [14,26]. In the GaN/AlGaN SCH structure, MBE-grown on sapphire, Schmidt et al observed a room temperature SE peak at 361.5 nm at a threshold around 90 kW/cm^2. The active layer was a single GaN well of thickness ~70 Å. The SE wavelength observed was ~3.5 nm shorter than the GaN SE wavelength of 365 nm [14]. A similar short wavelength SE peak at 363 nm was observed at a pumping threshold of ~65 kW/cm^2 from MOCVD-grown GaN/AlGaN SCH structures [26]. Recently, Tanaka et al reported the observation of SE at 364.5 nm from GaN quantum dots with an average size of ~100 Å width and ~10 - 20 Å height embedded in AlGaN at a threshold of ~750 kW/cm^2 [30]. It was suggested that the relatively high threshold is due to insufficient absorption of the pump beam in AlGaN layers surrounding quantum dots and the inadequate carrier/optical confinement structure. The RT SE from $Al_xGa_{1-x}N$ (x ~ 0.05) was observed at ~364 nm by Wiesmann et al [20]. To further blue shift the SE and lasing wavelength, aluminium concentration in the active layer should be substantially increased, while maintaining the high optical quality of the AlGaN. Growing high quality $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ heterostructures such as SCHs and MQWs is still a challenge to the MOCVD growth laboratories, and therefore the generation of a short UV (<350 nm) SE or laser beam will greatly depend on the progress of MOCVD AlGaN growth technology.

Electron beam pumping can also be used to induce SE and lasing in semiconductors. Using an MOCVD-grown in-plane laser heterostructure with an InGaN/GaN MQW active region, 80 K lasing at 402 nm and RT lasing at 409 nm was demonstrated by Kozlovsky et al [31]. The threshold e-beam current densities have been estimated as 60 A/cm^2 for 35 keV electron energy at 80 K using a scanning e-beam and 200 - 300 A/cm^2 at RT using pulsed e-beam pumping.

C CURRENT INJECTION LASER DIODES

Tremendous efforts have been directed toward achieving practical current injection laser diodes using GaN-based materials. Akasaki et al first reported the observation of room temperature coherent emission in an InGaN/GaN quantum well (QW) structure using pulsed current injection [2]. The device used actually has an SCH structure consisting of an InGaN active layer ~7.5 nm thick, GaN waveguide layers with a total thickness of ~0.4 μm and AlGaN cladding layers ~0.5 μm thick for both p- and n-type sides. Strong and narrow coherent emission with an FWHM of 3 nm was clearly observed, in addition to the broad near-band-edge spontaneous emission at a current density of 1 kA/cm^2. In December 1995, the fabrication of LDs using wide-bandgap nitride materials was announced for the first time by Nichia Chemical, Inc. [32]. The active lasing medium was InGaN MQWs, and the threshold current density was 4 kA/cm^2 under pulsed operation at room temperature. Below the threshold, spontaneous emission was observed at 410 nm with an FWHM of 20 nm. Above the threshold current, strong coherent emission at 417 nm with an FWHM of 1.6 nm became dominant. An elliptical far-field pattern could also be observed once the coherent emission occurred. Since then, the performance of Nichia InGaN LDs has been gradually improved [33-46], and the lifetime of LDs under CW conditions at RT has been recently estimated to exceed 10,000 hours [45]. Several industrial research laboratories and university research groups have also succeeded in the fabrication of InGaN/GaN/AlGaN-based blue LDs operating at RT [47-58]. TABLE 1 summarises GaN-based LDs reported in chronological order.

TABLE 1 Current injection InGaN-based laser diodes reported in the literature. The lasing medium in each case is InGaN quantum well(QW)-based. The number of QWs in the active region, the operation mode (pulsed, CW), the lasing threshold current, J_{th}, and the output wavelength are given, along with the corresponding references.

Number of QWs	Operation regime	Temperature	J_{th} (kA/cm^2)	Wavelength (nm)	Ref
26	pulsed	RT	4.0	417	[32]
20	pulsed	RT	9.6	416	[33]
20	pulsed	RT	8.0	410	[34]
10	pulsed	RT	13.0	419	[35]
7	pulsed	RT	4.6	406	[37]
1	pulsed	RT	2.9	376	[47]
3	CW	233 K	8.7	411	[38]
25	pulsed	RT	50	417.5	[48]
3	CW	RT	9.0	409	[39]
3	CW	RT	7.0	400	[40]
4	CW	20 - 70°C	3.6	406	[41]
4	CW	RT	7.3	399 - 401	[42]
4	CW	RT	3.6	405 - 407	[43]
8	pulsed	RT	48	402.8	[49]
	CW	RT	11	404 - 435	[50]
10	pulsed	RT	12.7	420	[51]
5	pulsed	RT	12	405 - 425	[52]
5	pulsed	RT	9.5	417.5	[53]
10	pulsed	RT	25	419 - 432	[54]
	CW	20 - 60°C	1.5	390 - 440	[45]
	pulsed	RT	10.6	412 - 417	[55]
	pulsed	RT	15	410 - 420	[56]
10	pulsed	79 K	1.4	405	[57]
4	CW	RT	4	396 - 397	[46]
5	pulsed	RT	8.5 - 14	395 - 408	[58]

One of the unique features of InGaN/GaN laser diodes is that despite the existence of a large number of dislocations (~10^8 - 10^{10} cm^{-2}), the devices can sustain a very high injection current, which leads to lasing. However, a drastic reduction of the dislocation density is imperative to improve LD performance in terms of the threshold current, output power and lifetime, etc. A very recent development in defect reduction efforts is to use the epitaxial lateral overgrowth (ELO) approach, first introduced by Nichia [44]. The details of ELO and related processing are described in [45] and [46]. The latest development is that Nichia has grown high quality InGaN MQW LD structures on an ~80 μm thick pure GaN substrate, which was obtained by polishing the sapphire substrate after the ELO procedures. The LDs grown on GaN obtained in this manner showed a small thermal resistance of 30°C/W and a lifetime longer than 780 hours, despite a large threshold current density of 7 kA/cm^2, in comparison to the LDs grown on sapphire substrates with a high thermal resistance of 60°C/W and a lifetime of 200 hours under RT CW operation. Considering Nichia's success in current injection LD growth over ELO substrates, similar approaches in substrate preparation are likely to be adopted by many laboratories, accelerating current injection III-nitride laser technology development.

D CONCLUSION

Stimulated emission and lasing in GaN-based structures can be achieved by both optical pumping and current injection. We have presented some of the most recent results of optically pumped SE and laser action studies in GaN and related heterostructures. Current injection LD operation reported in the literature has been presented in a table in chronological order.

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