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A Near Ultraviolet Optically Pumped Vertical Cavity Laser

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Abstract

Optically pumped near ultraviolet vertical cavity laser operation (VCSEL) has been obtained under quasi-continuous wave conditions at room temperature near 383 nm from shallow InGaN/GaN multiple quantum wells (MQW). Low loss optical resonators were fabricated by using in-situ grown (Al,Ga)N distributed Bragg reflectors that featured strain engineering design for excellent optical morphology, in combination with low loss dielectric multilayer mirrors.

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One current challenge for III-nitride based lasers is the extension to the near ultraviolet (NUV) regime below 400 nm. Application areas, including chemical/biochemical sensing, would benefit from compact NUV coherent light sources. In parallel, there are early precursors for nitride lasers in vertical cavity, surface emitting geometry in the blue. Stimulated surface emission [1,2], including VCSEL operation with well defined far field patterns [3], has been observed in optically pumped structures that feature specific fabrication paths to low-loss vertical microresonators.

In this paper, we utilize this experience to demonstrate quasi-continuous wave (cw) operation, at room temperature, of an optically pumped $In_xGa_{1-x}N$ (x~0.03) MQW VCSEL at near λ=383 nm. We employ a vertical cavity scheme which combines a high reflectivity in-situ grown multilayer $GaN/Al_{0.25}Ga_{0.75}N$ and post-growth dielectric SiO_2/HfO_2 distributed Bragg reflector (DBR). The in-situ grown nitride DBR is designed by inclusion of AlN strain compensating interlayers within the multilayer stack, which serve to eliminate tension-induced cracking [4] usually encountered during growth of AlGaN/GaN heterostructures on GaN. The presence of cracks, which propagate along well-defined crystallographic planes is a major impediment in a nitride VCSEL since they form 'accidental' resonators which greatly enhance the onset of lateral stimulated emission along the heterostructure layer plane, disabling true VCSEL operation [3]. The low index of refraction contrast between GaN and AlGaN (or AlN) demands a large number of layer pairs for high reflectivity. In this work, R≈0.99 has been reached, an adequate value compensated by the top dielectric DBRs (R=0.995) in our 'hybrid' microresonators. Hybrid structures were used by Someya et al [1]. Many reports have appeared on the growth of (Al,GaN)-based DBRs including recent advances by Ng et al [5] using MBE growth techniques for GaN/AlN broad bandwidth mirrors. We believe that the combination of high reflectivity and crack-free morphology in the as-grown DBRs achieved in this work has not been reached todate.

The III-nitride heterostructure was grown by organometallic vapor phase epitaxy (OMVPE) on (0001) sapphire substrate. Following the growth of 1 μm GaN using a standard 2-step nucleation [6], a 200 Å thick AlN layer was grown for strain compensation of the subsequent 60 layer pairs of the quarter-wave $GaN/Al_{0.25}Ga_{0.75}N$ stack. Subsequent insertion of additional AlN strain relief layers every 20 or so layer pairs greatly reduces the number of cracks in such a thick mirror structure (~5 μm) so that crack-free wafer surfaces were obtained over several cm^2 [4]. A peak reflectivity of R=0.99 was measured using a calibrated standard, and the spectral width of the maximum reflectance band was approximately 15 nm. The active region was grown directly atop the GaN/(Al,GaN) DBR, composed of 20 $In_{0.03}Ga_{0.97}N$ quantum wells (L_w=40 Å) with GaN barriers (L_B=60 Å). The as-grown DBR and the QW indium concentration were designed for spectral overlap between the high reflectivity region of the former with the photoluminescence emission of the latter. The structure was capped by a 1000 Å thick $Al_{0.1}Ga_{0.9}N$ carrier confinement layer. Finally, a multilayer λ/4 stack of SiO_2/HfO_2 was deposited by reactive ion beam sputtering. HfO_2 is a high index, low absorption material in the NUV (to below 300nm), with high quality crystal microstructure [3]. The broad reflection bandwidth (~80nm) of the dielectric DBR was tailored to overlap the near bandedge (In,Ga)N emission. The growth of the nitride heterostructure was optimized for high optical flatness as good morphology is crucial to the realization of true VCSEL operation. AFM studies of the surface of the as-grown wafer and the complete microcavity indicated a mean roughness of approximately 2 nm over areas on the order of several hundred μm^2.

The vertical cavity structures were optically pumped by a frequency tripled, continuous-wave (cw) modelocked Nd:YAG laser at 355 nm, operating at a repetition rate of 76 MHz. The individual pulse duration was approximately 0.1 nsec and the radiation was focused at near normal incidence to a ≈20 μm diameter spot. The high repetition rate pumping is referred to as quasi-cw, as used in the literature. The wavelength of excitation laid outside the reflectance band of the top dielectric DBRs and slightly below the bandgap of the top AlGaN confinement layer, ensuring a creation of electron-hole pairs directly into the InGaN QWs. Given the thickness of the InGaN MQW (800 Å), only a fraction of the pump photons (estimated less than 25%) were usefully absorbed. **Figure 1(a)** shows the room temperature spontaneous emission spectrum at an average incident power of approximately 14 mW. Two well defined cavity modes are seen, while a third lies at the rapidly falling edge of reflectivity band of the GaN/(Al,Ga)N bottom DBR, and is thus strongly broadened. Within the high-Q region the modal linewidth is approximately 0.8 nm, limited by a combination of the reflectivity of the nitride DBR and scattering from residual morphological roughness presently under investigation. **Figure 1(b)** shows the emission spectrum from a device under photopumping at an incident average pump power of approximately 40 mW, exceeding the lasing threshold. The spectral width of the emission at 383.2 nm (<0.1 nm) was unresolved by our equipment. Above threshold, an intense low divergence beam of circular cross section was observed visually in the laboratory with fluorescent screens. A portion of the beam is shown in the photo as inset of Fig. 2, where a screen was placed along the beam of circular cross section, to scatter light into a blue enhanced digital camera. We measured an angular (full)width of 7.4 degrees, in very good agreement with the expected divergence dictated by the device aperture, as defined by the pump spot size.

Figure 2 shows input/output power characteristics of a particular device where the above referred spectral coincidences are nearly optimal. The lasing threshold occurs at a rather low average pump power of 30 mW, while average output powers up to 3 mW were measured. However, finite thickness variation across the wafer led to spectral shifts of the cavity modes (relative to InGaN MQW gain spectrum) so that significant increases in threshold were encountered for devices fabricated from near the edge of the wafer (up to 100 mW beyond). It was possible to 'lose' the lasing altogether. When accounting for the optical excitation volume, the fractional absorption of the pump, and using an electron-hole recombination time of approximately 0.5 nsec, we estimate that the threshold in Fig. 2 corresponds roughly to a carrier density of approximately 10^{19} cm^{-3}. Such a density is within the range of typical injection conditions employed in the best edge emitting blue and violet (In,Ga)N MQW diode lasers. It is encouraging, given the relatively shallow QWs (ΔE_G~160 meV) employed in our structures (low indium concentration). Still, absolute efficiency of the VCSELs was difficult to establish at this point, given the uncertainty in the relevant parameters (fractional pump absorption and possible carrier overflow in the QWs), factors which also make the estimate of the threshold carrier density only a rough guide.

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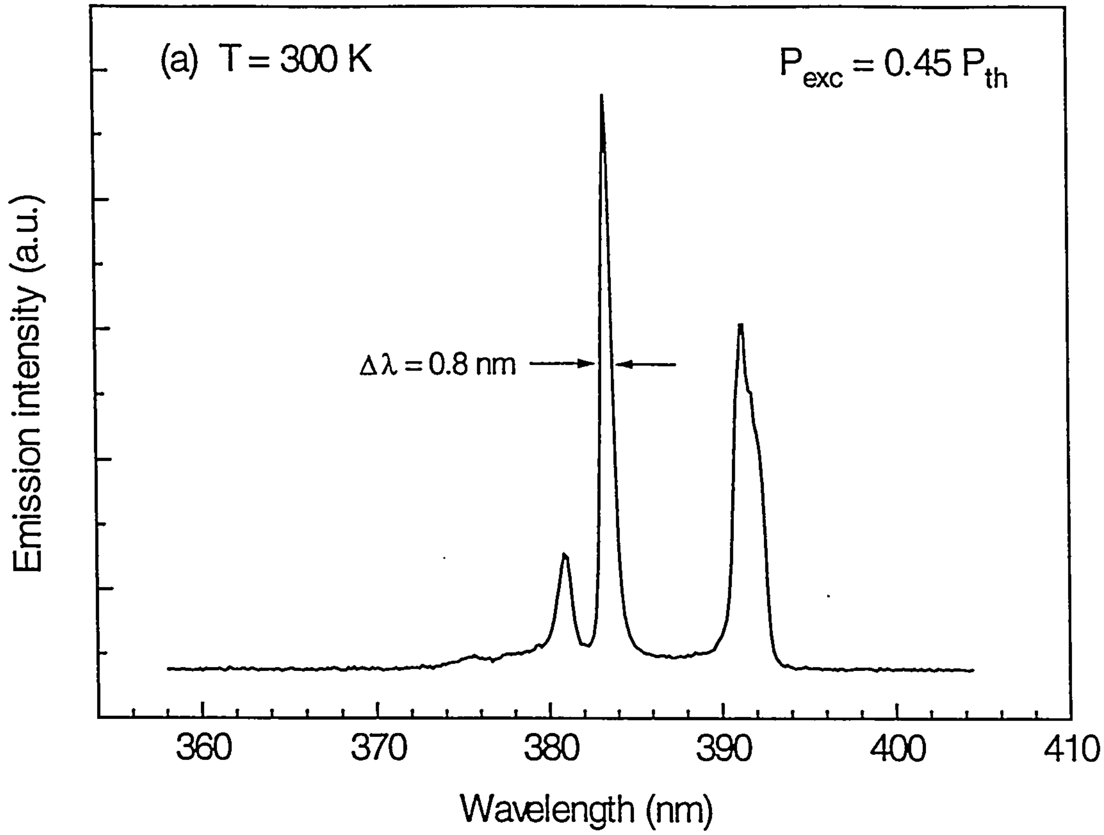
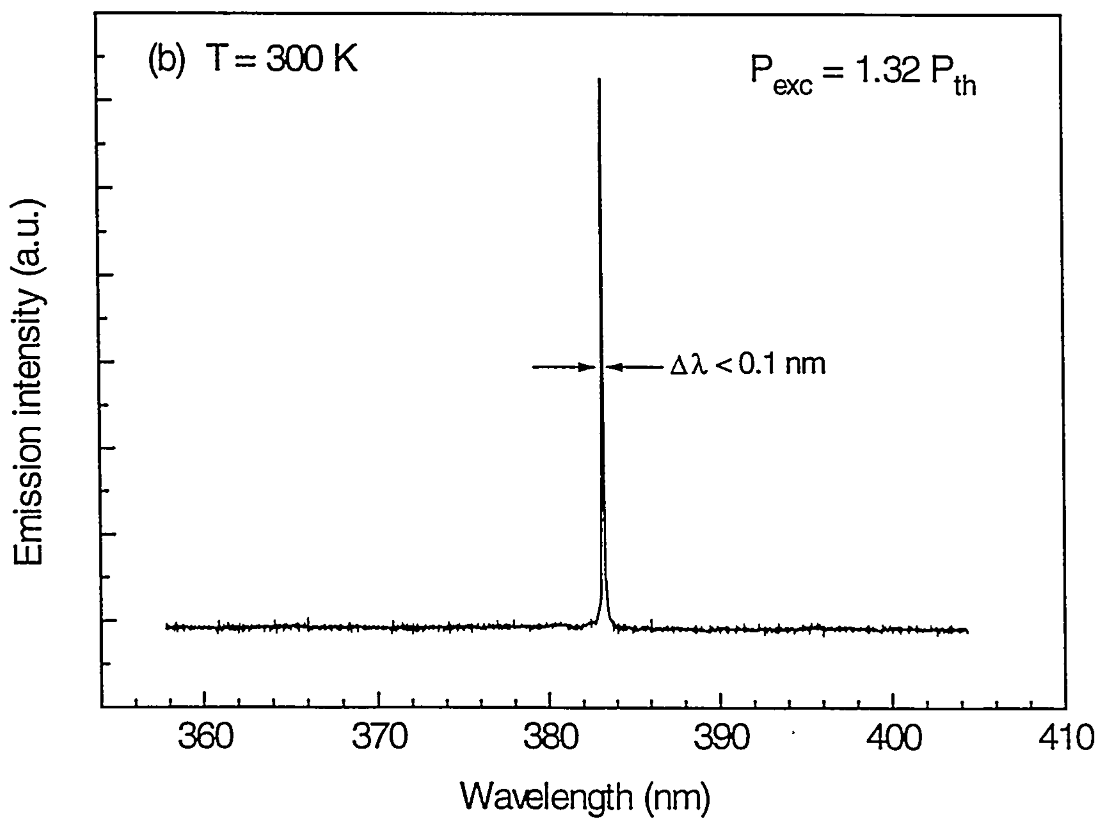
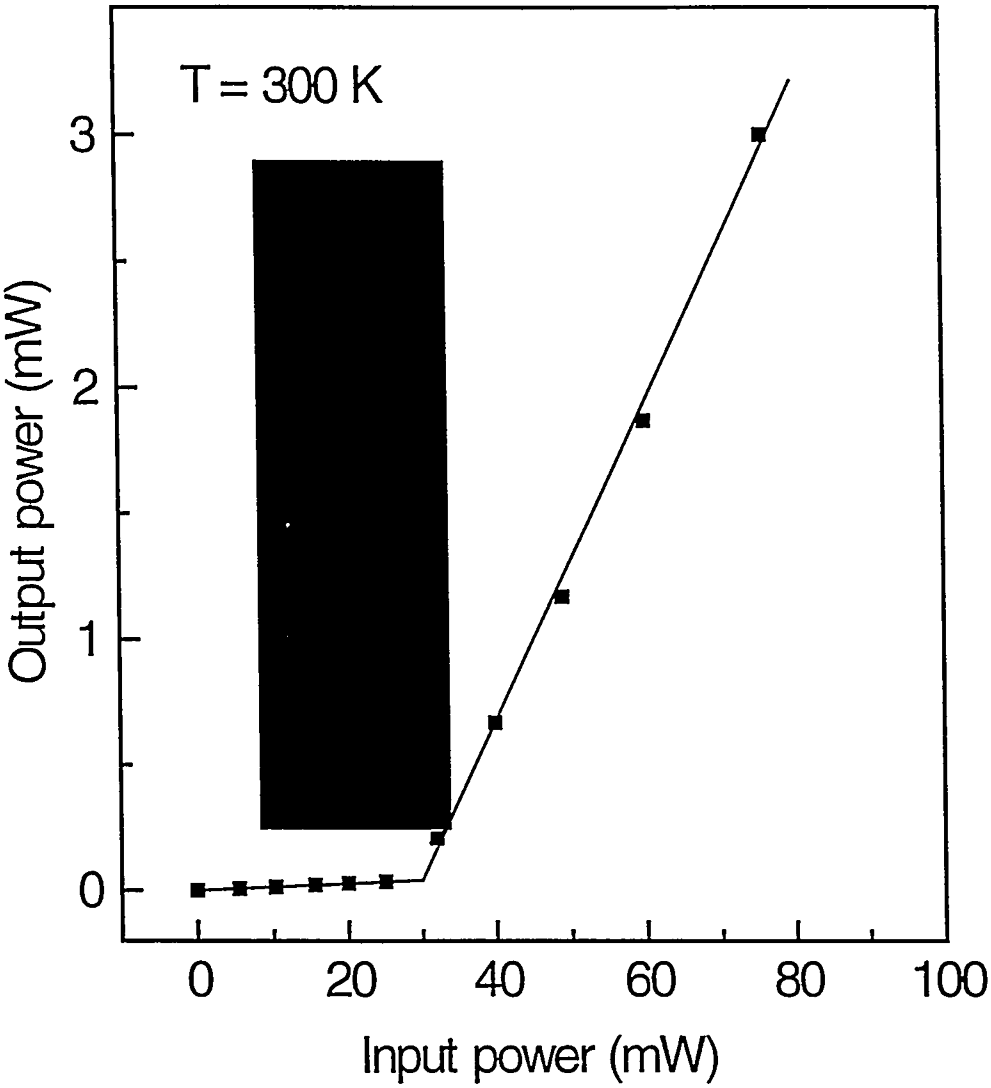
Figure Captions:

Figure 1: (a) Spontaneous emission spectra at excitation level of 45% relative to threshold; (b) spectrum of VCSEL emission at 132% relative to threshold.

Figure 2: Average input vs. output power of a VCSEL device. The inset shows the beam far field (side) profile captured on a screen.


(a) T = 300 K
P exc = 0.45 P th
Δλ = 0.8 nm
Emission intensity (a.u.)
360
370
380
390
400
410
Wavelength (nm)


(b) T = 300 K
P exc = 1.32 P th
Δλ < 0.1 nm
Emission intensity (a.u.)
360
370
380
390
400
410
Wavelength (nm)


T = 300 K
Output power (mW)
3
2
1
0
0
20
40
60
80
100
Input power (mW)