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Advances in nitride-based blue and violet light emitters - most notably high-efficiency LEDs and edge-emitting diode lasers - now suggest possibilities for more advanced types of geometry such as those based on vertical-cavity surface-emitting structures.

Progress towards nitride blue and near-UV VCSELs

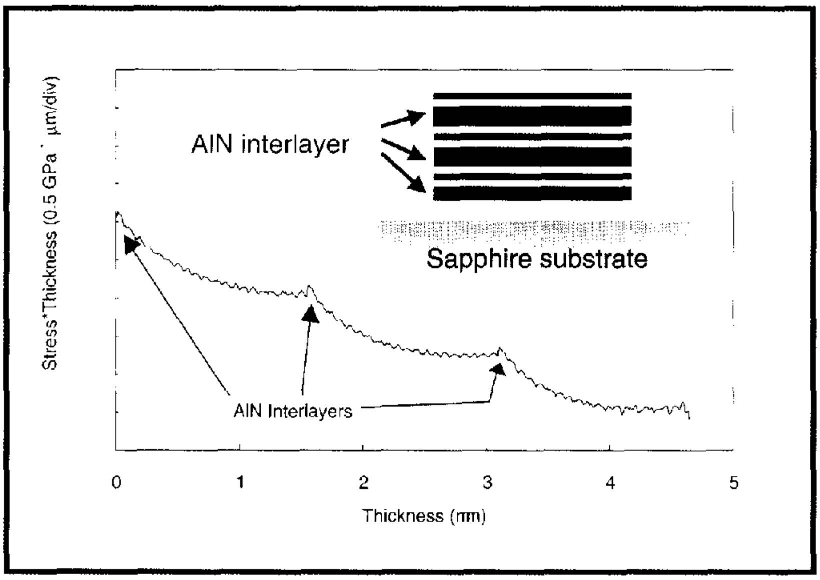

Figure 1. In-situ stress measurement during the growth of an AlGaN/GaN Bragg reflector with multiple interlayers.

The technological and economical advantages in migrating from conventional edge-emitting to surface-emitting configuration in the longer-wavelength regime (600-1500 nm) are readily established, witnessed by a growing presence of VCSEL components in both tele- and data-communication technologies. However, even in the absence of coherent light emission, the beam-like collimation from resonant-cavity light emitting diodes (RC-LEDs) can also be very useful through enhanced spontaneous emission.

Both devices are characterised by the need for an optical resonator - formed with planar mirrors parallel to the growth surface of the semiconductor heterostructures - which has high quality or Q-factor. The extension of these device concepts to the blue and near-ultraviolet (relatively unexplored so far) presents significant challenges and opportunities to III-nitrides technology.

The idiosyncrasies of GaN-based vertical-cavity devices range from issues of the gain spectrum of the InGaN quantum well medium to the fabrication of the optical resonator structure. For example, the low contrast in the index of refraction between GaN (n~2.35) and AlN (n~2.10) mandates a large number of layer pairs and high aluminium fraction in a multi-layer AlGaN distributed Bragg reflector (DBR) stack, in order to achieve sufficiently high reflectivity (R~0.99).

Furthermore, the (wavelength) bandwidth of the high-reflectance region is small (10-20 nm). A large mismatch in the lattice constant (2.4%) implies difficulties in strain management and potential occurrence of structural defects due to strain relief which can seriously compromise the optical integrity of a high-Q microcavity.

To circumvent the problems with as-grown AlGaN DBRs, lift-off methods have been used to separate the InGaN multi quantum well (MQW) heterostructure from its sapphire substrate in order to encase it within a high-Q cavity with two dielectric DBRs. In this way, quasi-continuous-wave optically pumped vertical-cavity lasing [1] and resonant-cavity LED operation [2] have been achieved in the 405-415 nm range, at excitation levels comparable to the equivalent current injection in a good edge-emitting diode laser.

Here, however, we focus on recent progress in the development of AlGaN DBRs and their incorporation in vertical-cavity emitters, including both optically pumped VCSEL demonstrations as well as initial proof-of-concept vertical-cavity LEDs.

AlGaN/GaN epitaxial DBR mirrors

In trying to further the boundary of III-nitride optoelectronic devices, there are early precursors for nitride lasers in a vertical-cavity, surface-emitting geometry in both the blue and violet.

Vertical-cavity III-N structures that feature as-grown AlGaN DBRs have also met with some initial success. For example, Someya *et al* (University of Tokyo, Japan) reported the crack-free growth of a 35-pair $Al_{0.34}Ga_{0.66}N$/GaN DBR with reflectivity up to 96% at 390 nm [3], while Krestnikov *et al* (Ioffe Institute, Russia and Technical University of Berlin, Germany) employed a 1.1 μm $Al_{0.08}Ga_{0.92}N$ template on sapphire for stress compensation and showed a reflectivity of 96% at 401 nm with 37 pairs of $Al_{0.15}Ga_{0.85}N$/GaN DBR mirrors [4]. Both groups have reported stimulated emission from such optically pumped structures under high excitation levels at low duty cycles, with the Tokyo group and collaborators using lateral patterning techniques [5].

Through the growth efforts at Sandia we have also addressed the very difficult problem of the morphological quality of the in-situ-grown AlGaN DBRs. Due to the large thickness of epitaxial DBRs necessitated by the small contrast of refractive indices, these DBRs are generally plagued by defects such as cracks which form "lateral cavities" and can readily lead to stimulated emission (or lasing) along the layer plane well before the threshold for true vertical-cavity lasing is reached.

In particular, by using a novel in-situ stress sensor and special strain management using AlGaN and AlN interlayers [6] we were able to monitor and engineer the growth stress during the DBR growth.

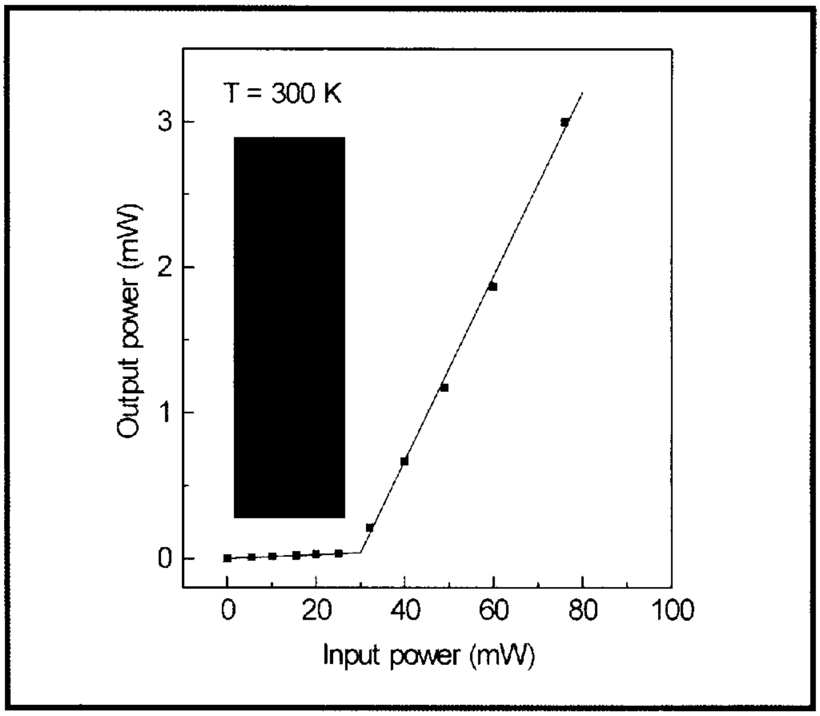

Figure 2: Input/output characteristics of a CW near-UV optically pumped VCSEL at 383 nm (inset shows side view of beam).

Figure 1 shows the evolution of the stress during the growth of 60-pair $Al_{0.20}Ga_{0.80}N$/GaN DBR mirrors on a 1 μm GaN template: multiple insertions of AlN interlayers enable an essentially compressive growth over the entire DBR (around 4.8 μm thick).

The peak reflectivity was determined to be around 99% near 380 nm wavelength. At the same time the surface can be essentially crack-free over most of a 2" wafer.

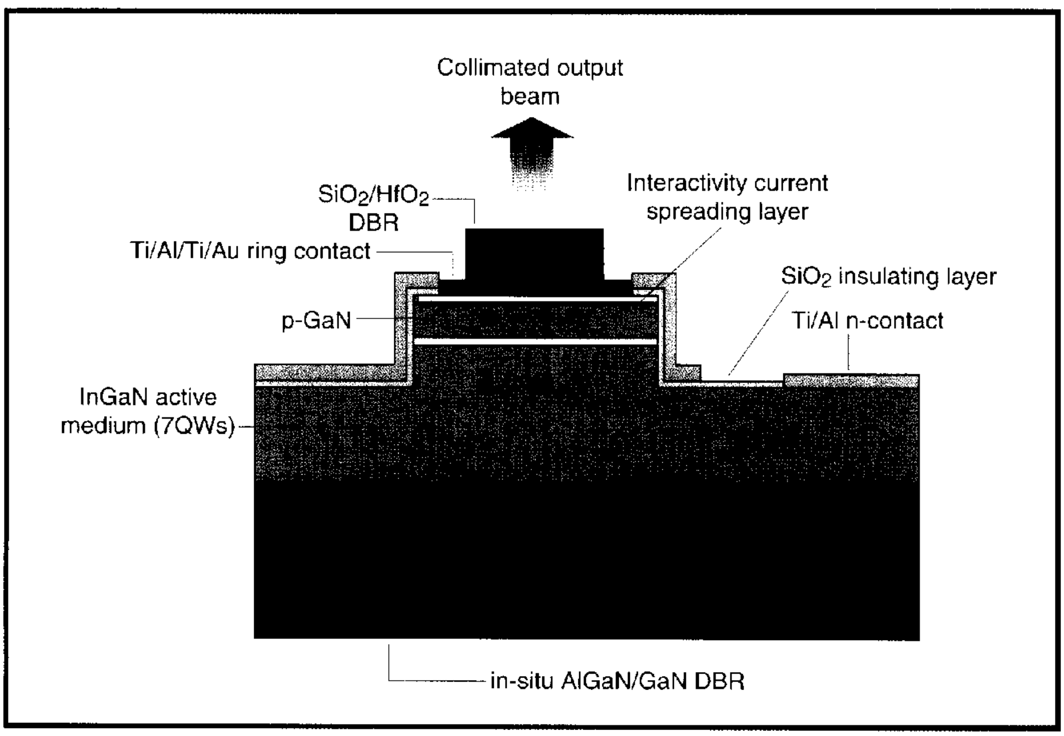

Figure 3: Schematic diagram of a resonant-cavity LED.

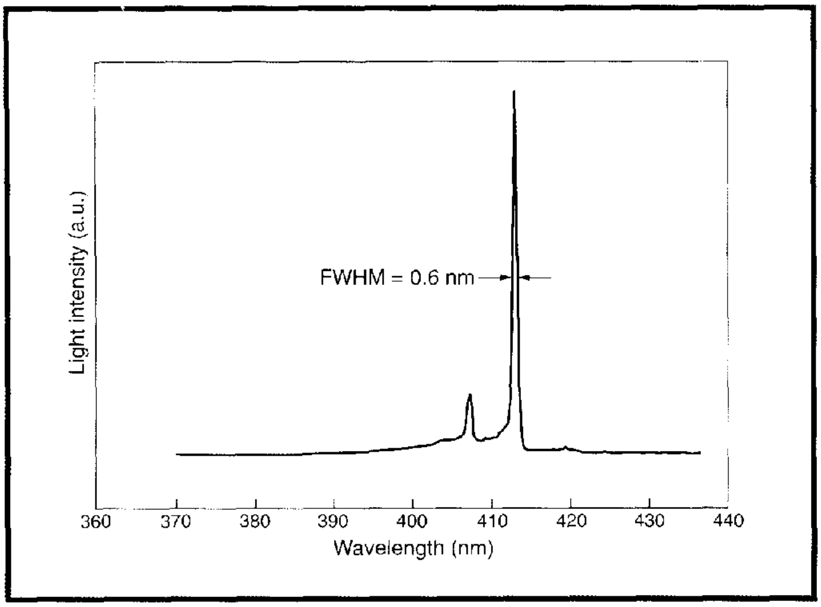

Figure 4: The emission spectrum of a device at J = 0.2 kA/cm². The presence of only two modes is due to the narrow spectral bandwidth of the AlGaN DBR reflector.

Finally, the surface morphology of the DBRs was optimised through a systematic study of the growth conditions, with detailed feedback acquired via topographical surface probes (AFM, optical interferometric surface profiling). This is an important technical point since, cracking apart, other morphological defects on the scale of the light wavelength readily lead to unacceptably high scattering losses for a prospective VCSEL device.

An optically pumped near-UV VCSEL

The as-grown AlGaN DBR mirrors have been incorporated within undoped InGaN QW heterostructures for optical pumping studies, whose primary purpose was to evaluate the optical quality of the microcavity resonators.

The active region was grown directly atop the GaN/(Al,GaN) DBR, composed typically of 10-20 $In_{0.03}Ga_{0.97}N$ QWs, each of width L_W=40Å with GaN barriers of L_B=60Å. 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 1000Å-thick $Al_{0.1}Ga_{0.9}N$ carrier confinement layer. Finally, a multi-layer 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 near-UV (to below 300 nm) with a high-quality microstructure.

The broad reflection bandwidth (~80 nm) of the dielectric DBR was tailored to overlap the near-bandedge (In,Ga)N emission. The growth of the nitride heterostructure was optimised for high optical flatness, as good morphology is crucial to the realisation 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 microns squared.

Figure 2 shows the input/output characteristics of a 383 nm optically pumped VCSEL under CW operation [7]. Above threshold, an intense low-divergence beam of circular cross section was observed visually in the laboratory using fluorescent screens. A portion of the beam is shown in the inset photo, 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°, in very good agreement with the expected divergence dictated by the device aperture (as defined by the pump spot size).

Electrically injected devices

While such progress is encouraging, major challenges exist for realising efficient resonant-cavity LEDs and blue/near-UV vertical-cavity diode lasers.

Apart from the requirements of a low-loss, high-Q-factor microcavity, the current injection into the optically active volume is difficult due to the insulating or high-resistivity nature of the DBRs. We note here new advances where the particularly acute problem of low lateral conductivity in p-GaN layers is ameliorated by the use of low-loss indium-tin oxide (ITO) as an intracavity current-spreading layer. We emphasise that, while ITO is a useful contemporary choice (including its ability to withstand very high current densities), it by no means represents the only solution to the problem. Indeed, it is likely that new "bandstructure engineering" solutions as well as current-aperture schemes (analogous to what has been used in oxide-based AlAs/GaAs long-wavelength VCSELs) will compliment the (limited) lateral hole conductivity directly within GaN-based heterostructures and likely provide a long-term solution.

For use as an intracavity hole-current-spreading layer, the typical resistivity of the ~1000Å-thick sputtered ITO films was about $3x10^{-4}$ Ω-cm, and their single-pass transmission loss was on the order of 1% in the range 390-450 nm. By using specific processing techniques, we have been able to fabricate two types of resonant-cavity LEDs.

First, the optical cavity was formed by two high-reflectivity (R~0.995) SiO_2/HfO_2 dielectric mirrors sandwiching the InGaN/GaN/AlGaN MQW heterostructure. Light emission efficiency from the devices was excellent, with directional properties, and they have been operated up to current densities of 1 kA/cm^2 under CW conditions and 10 kA/cm^2 under pulsed excitation [2]. Devices which include both an as-grown AlGaN and a dielectric DBR have yielded comparable results as near-UV and violet RC-LED structures (shown schematically in Figure 3 [8]).

Figure 4 shows an emission spectrum from such a device, displaying the well-defined cavity modes. The measured modal half-width is approximately 0.6 nm, corresponding to a cavity Q-factor of nearly 700. The results suggest that the intracavity optical losses are quite low, including contribution by the ITO layer. Surface morphology was studied by AFM and by optical interferometer profiler tools. In the best cases, mean-square roughness over macroscopic areas (several tens of square microns) was less than 2 nm, a value considered excellent for an RC-LED and adequate for a prospective VCSEL.

Figure 5 shows an example of the I-V characteristics of an RC-LED device, where the impact of the "contact" resistance of ITO is examined by comparing the I-V data of a conventional LED device with standard p-contact metallisation. The presence of ITO does lead to a finite extra voltage drop of 1.5-2.0 V; however, we believe that the ITO/p-GaN contact can be further improved. (The microscopics of this contact are unknown and quite fascinating, as ITO is presumed to be an n-type semi-metal).

These results are encouraging and suggest that further progress is likely for realising useful RC-LED devices. The optical and electrical characteristics reported also indicate that a short-wavelength VCSEL may be possible through the particular technical approach identified here.

Such a breakthrough may also facilitate the study of the interesting basic microcavity physics in the nitride compounds. This follows from recognition that electron-hole Coulomb correlation effects should be particularly pronounced in nitride quantum wells, allowing "polariton-like" coupling effects to be found and exploited in the design of efficient surface-emitting blue and near-UV devices.

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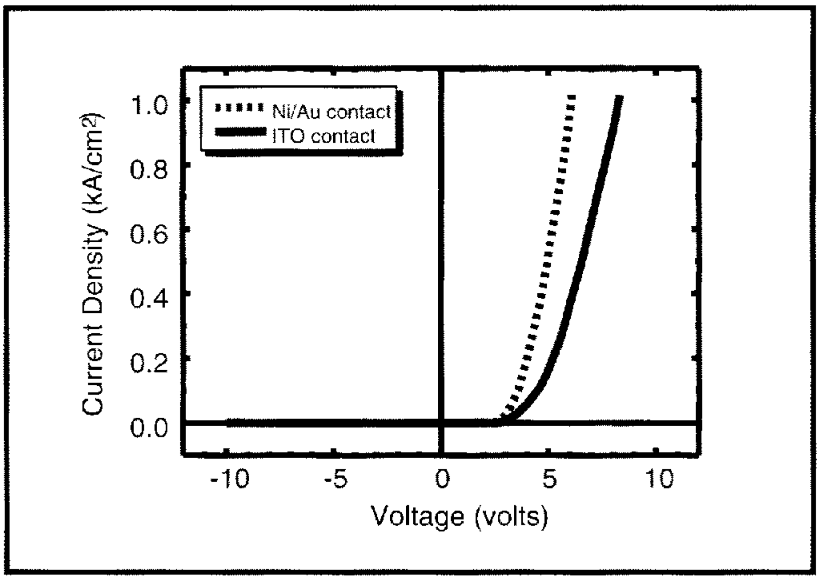

Figure 5: I-V LED characteristics with and without intracavity current spreading ITO layer.

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