Comparison of Nonpolar III-nitride Vertical-Cavity Surface-Emitting Lasers with Tunnel Junction and ITO Intracavity Contacts

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ABSTRACT

We report on the lasing of III-nitride nonpolar, violet, vertical-cavity surface-emitting lasers (VCSELs) with III-nitride tunnel-junction (TJ) intracavity contacts and ion implanted apertures (IIAs). The TJ VCSELs are compared to similar VCSELs with tin-doped indium oxide (ITO) intracavity contacts. Prior to analyzing device results, we consider the relative advantages of III-nitride TJs for blue and green emitting VCSELs. The TJs are shown to be most advantageous for violet and UV VCSELs, operating near or above the absorption edge for ITO, as they significantly reduce the total internal loss in the cavity. However, for longer wavelength III-nitride VCSELs, TJs primarily offer the advantage of improved cavity design flexibility, allowing one to make the p-side thicker using a thick n-type III-nitride TJ intracavity contact. This offers improved lateral current spreading and lower loss, compare to using ITO and p-GaN, respectively. These aspects are particularly important for achieving high-power CW VCSELs, making TJs the ideal intracavity contact for any III-nitride VCSEL. A brief overview of III-nitride TJ growth methods is also given, highlighting the molecular-beam epitaxy (MBE) technique used here. Following this overview, we compare 12 μm aperture diameter, violet emitting, TJ and ITO VCSEL experimental results, which demonstrate the significant improvement in differential efficiency and peak power resulting from the reduced loss in the TJ design. Specifically, the TJ VCSEL shows a peak power of $\sim 550 \mu\text{W}$ with a threshold current density of $\sim 3.5 \text{ kA/cm}^2$, while the ITO VCSELs show peak powers of $\sim 80 \mu\text{W}$ and threshold current densities of $\sim 7 \text{ kA/cm}^2$.

Keywords: Tunnel-junction, vertical-cavity surface-emitting laser, flip-chip, intracavity contact, VCSEL, III-nitrides, violet, Lasers

1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) continue to find new and interesting applications at red and infrared emission wavelengths, leveraging the relatively mature AlGaInP/GaAs-based, AlGaAs/GaAs-based, and AlGaInAs/InP-based VCSEL technology.¹ In comparison, III-nitride VCSELs are still in their infancy,² however their potential to extend the available VCSEL emission wavelengths into the green, blue, violet, and ultraviolet (UV) make them of great interest for a number of sectors. VCSELs are particularly unique light-emitters because they can essentially act as three different devices: an illuminator, a transceiver, and a sensor.

III-nitride emitters, such as light-emitting diodes (LEDs), are most well known for their use in illumination, thus this is one of the most obvious applications for VCSELs. A single VCSEL alone typically has a low output power, but a high power density. This implies that VCSELs can be combined into high density 2D arrays to yield kilowatts of power.³

This makes III-nitride VCSELs appropriate for general laser-based lighting,^{4,5} or other applications requiring highly directional lighting, such as indoor vertical plant growth, or automobile headlights.⁶

If the illumination functionality of a III-nitride VCSEL is coupled with the transceiver functionality, one could transmit data at high speeds (Giga-bits/second) while simultaneously illuminating surfaces. This is essentially what has been demonstrated in the field of visible-light communication (VLC) and LiFi, where LEDs are currently being used.⁷ A number of VLC demonstrations using edge-emitting III-nitride lasers have been carried out,^{8,9} however III-nitride VCSELs have the potential to yield even higher modulation bandwidths than edge-emitters due to their smaller active regions.¹⁰ Naturally, VLC can be useful for indoor wireless communication, where the available bandwidth for data transmission is rapidly becoming crowded,¹¹ but it could also be useful in vehicle-to-vehicle communication.¹²

Another application for III-nitride VCSELs is in sensor technology, where VCSELs can be used as Doppler interferometers.^{13–15} The high modulation speeds and narrow spectral width of III-nitride VCSELs can also be advantageous to many techniques involving optical probing and detection of biomaterials.^{16–19} Furthermore, their small form factor and low power consumption makes them advantageous to emerging lab-on-chip technologies.²⁰ The ability to use a VCSEL as a Doppler interferometer to track motion, fluid flow rates, velocity, position, etc. could also be useful for many other applications, such as those in the internet of things (IoT) and robotics sector.¹³

III-nitride VCSELs may also be used for many display technologies.²¹ For conventional backlit LCD displays, one could replace LED backlighting with VCSEL based backlighting to achieve a higher dynamic range of luminance over a smaller range of drive currents. The modulation and sensing capabilities, along with their intrinsic low divergence angle and high beam quality with a circular emission profile, make III-nitride VCSELs appropriate for projection based display technologies as well. In this field, VLC data transmission through a (LED-based) projector has been demonstrated and could be achieved using III-nitride VCSELs.^{21,22} Additionally, the small form factor of III-nitride VCSELs make them advantageous to applications such as pico-projectors and more recent near-eye displays using holographic and diffractive optical elements, including Google Glass and Microsoft HoloLens.²¹ In the distant future, III-nitride VCSELs could be great candidates for light sources in collimated micro-projectors embedded in contact lenses.²¹ Currently, III-nitride VCSELs are still very inefficient and considerable development is necessary to allow their use in any of these applications, yet it is important to recognize the potential for any technology, regardless of its present state of development.

Here, we discuss the use of III-nitride tunnel-junction (TJ) intracavity contacts in violet emitting VCSELs, which show significant improvement in device performance over conventional tin-doped indium oxide (ITO) intracavity contacts. Prior to detailing the experimental results, we layout the general motivation for using III-nitride TJ intracavity contacts (Section 2), before giving a brief overview of the relative advantages of different growth techniques available to fabricating III-nitride TJs (Section 3). Section 4 describes the specific cavity design implications of using a TJ intracavity contact for III-nitride VCSELs, while Section 5 details the experimental results for violet emitting VCSELs with TJ and ITO intracavity contacts.

2. MOTIVATION FOR III-NITRIDE TUNNEL JUNCTION INTRACAVITY CONTACTS

III-nitride vertical-cavity surface-emitting lasers can be divided into two classes: dual dielectric distributed Bragg reflector (DBR) VCSELs,^{23–33} and hybrid DBR VCSELs.^{34–40} The latter consists of growing the n-side DBR (n-DBR) epitaxially, while dielectric layers are deposited for the p-side DBR (p-DBR). Dual dielectric DBR VCSELs, on the other hand, have dielectric n-DBRs and p-DBRs. This is typically achieved using a flip-chip design,^{23–32} however it has also been demonstrated recently using lateral epitaxial overgrowth (LAE).³³ The hybrid DBR is advantageous because of the high thermal conductivity of the epitaxial n-DBR layers, which improves heat dissipation from the active region of the device. However, epitaxial III-nitride DBRs are non-trivial to grow, due to the large lattice mismatch leading to cracking, in the case of AlGaIn/GaN-based DBRs,^{37,41,42} and the general complications involved in growth of high quality InAlN layers, for the case of AlInN/GaN-based DBRs.^{34,43} Furthermore, on c-plane, epitaxial DBRs can have V-defects present, creating interface roughness that can reduce the reflectivity and lead to local perturbations in the modal confinement.³⁷ Dual dielectric DBRs are advantageous as they allow one to more easily achieve a high reflectivity with highly uniform DBRs, however they suffer from very poor thermal conductivities, essentially requiring lateral heat dissipation around the dielectric DBR. Another advantage of dielectric DBRs is that they have a wider mirror stop-band (~70 nm) than epitaxial DBRs (~35 nm),³⁷ resulting from the large index contrast between the dielectric layers. This can

Figure 1 (color online) Refractive index and absorption coefficient dispersion for multi-layer ITO films used in some of UCSB's III-nitride VCSELs with ITO intracavity contacts.^{26,27,44} The measurements were made using a Tauc-Lorentz oscillator model to fit ellipsometer measurements of the ITO film deposited on a Si wafer. The model shows a low mean-square-error (MSE) of 7.39. It should be noted that the Tauc-Lorentz oscillator does not account for free-carrier absorption, which would dominate far from the band-edge.

the measured ellipsometer data (Tauc-Lorentz oscillator model) does not account for free-carrier absorption, which dominates far from the absorption edge.^{44,45} Regardless, from Figure 1 it is easily recognized that devices emitting in the violet regime (390 - 420 nm) will suffer from much higher ITO absorption losses than devices emitting in the blue (450 nm) or green (525 nm) regime. Furthermore, the longer emission wavelength and lower refractive index implies that the physical thickness of the $\frac{1}{4}$ -wave ITO layer is greater than that of ITO in violet VCSELs, making the spreading resistance of the intracavity contact lower for blue and green VCSELs. Thus for UV and violet emitting III-nitride VCSELs, an alternative intracavity contact is critical for achieving efficient device performance. III-nitride tunnel junctions are an ideal candidate for such an intracavity contact, and, as will be seen later, may offer a number of other advantages over ITO for blue and green emitting VCSELs. Besides these benefits for traditional VCSEL designs, III-nitride TJs also allow the fabrication of bipolar cascade (BC) III-nitride VCSELs, which could lead to significant improvements in III-nitride VCSEL output powers.⁴⁶

3. OVERVIEW OF III-NITRIDE TUNNEL JUNCTIONS

Tunnel junction (TJ) intracavity contacts have been popularly employed in InP-based VCSELs due to the poor p-type conductivity of InAlAs.¹ These TJs are typically also used to achieve lateral carrier and optical confinement using a buried TJ (BTJ) design, consisting of a high index n^+ InGaAs contact to p-InAlAs, surrounded by a thicker low index n-InP current spreading cap.^{1,47} Recently, a III-nitride micro-LED with a BTJ has been demonstrated,⁴⁸ proving that a similar technology could be used in III-nitride VCSELs as well. A number of material properties have prevented the wide-spread adoption of III-nitride TJs in LEDs and VCSELs generally. First of all, growing n-GaN on p-GaN via metal-organic chemical-vapor deposition (MOCVD), results in highly resistive TJ contacts.⁴⁹⁻⁵³ This is due to p-GaN hydrogen repassivation during the n-GaN TJ growth, and the intrinsic doping limits of MOCVD grown n-GaN.⁵⁴ Additionally, growing such an n-GaN layer prevents hydrogen from escaping from the p-GaN during the post-growth thermal activation of Mg dopants.⁵⁵ There are two primary methods for overcoming these issues: (1) activate the p-GaN using a side-wall activation method,⁵⁵ or (2) growth of the n-type TJ layers using molecular-beam epitaxy (MBE).^{27,48,56-60} Side-wall activation has been demonstrated, however it shows limitations in activating large-area devices (300 $\mu\text{m} \times 300 \mu\text{m}$ mesa size).⁵⁵ Because VCSELs are very small devices ($\leq 100 \mu\text{m} \times \leq 100 \mu\text{m}$ mesa size), it seems quite plausible that side-wall activation could be used to make high quality III-nitride TJ intracavity contacts for VCSELs using MOCVD, which would greatly simplify the processing and growth procedure, compared to the MOCVD-MBE TJ VCSEL method. The MOCVD-MBE approach has also faced some challenges in achieving high quality TJs. To overcome this, researchers have inserted AlN,⁵⁶ InGaN,^{57,58} or GdN nanoisland⁵⁹ layers between the p-GaN and n-GaN TJ layers, which have improved tunneling. The AlN and InGaN interlayers, in particular, leverage the polarization fields present in the c-

be beneficial because it increases the tolerance for error in aligning the cavity resonance wavelength with the DBR resonance wavelength (i.e. the peak reflectivity of the DBR). In both cases, the poor p-GaN conductivity necessitates the use of an intracavity contact to improve the uniformity of current injection into the aperture. ITO, being the most common transparent conductive oxide (TCO) used for III-nitrides, has been the conventional intracavity contact of choice for III-nitride VCSELs. Using ITO in a VCSEL is complicated by the necessity to achieve highly smooth and highly transparent ITO films, to minimize the scattering loss and internal loss, respectively.⁴⁴ Furthermore, for III-nitride VCSELs, the ITO must be $\sim \frac{1}{4}$ -wave thick ($\sim 50 \text{ nm}$) to minimize the overlap between the cavity mode and the ITO layer, thereby minimizing the absorption loss introduced by the ITO. Beyond these critical considerations in using ITO in III-nitride VCSELs, it is also important to consider the absorption coefficient dispersion for ITO. Figure 1 shows the refractive index and absorption coefficient dispersion for a representative multi-layer ITO film used on many of UCSB's III-nitride VCSELs.^{26,27,44} The model used to fit

plane III-nitride crystal orientation. On nonpolar (m-plane) III-nitride devices, such as those demonstrated here, this polarization lies in the growth plane, and would thus not affect tunneling. In the TJ intracavity contacts reported here, we achieve a high quality TJ contact to MOCVD grown p-GaN by simply growing a very highly doped n^{++} GaN contact layer via ammonia MBE. Immediately prior to growth, a solvent clean was carried out, before loading the sample into the MBE, and baking at 400 °C for one hour. Recent analysis on similar samples suggests that avoiding cleaning methods for removing native oxidation on the surface is beneficial, as a high oxygen spike at the TJ/p-GaN interface may be favorable for charge transport. Using the Hall method, the carrier concentration and resistivity of the n^{++} GaN layer was measured to be $1.1 \times 10^{20} \text{ cm}^{-3}$ and $4 \times 10^{-4} \Omega\text{-cm}$. Achieving such high doping levels via MOCVD is difficult without causing catastrophic crystal quality degradation.⁵⁴ Furthermore, the MOCVD grown n^{++} GaN layer was optimized in a method similar to that reported by B. P. Yonkee, et al.⁶¹ The final optimized 14 nm n^{++} GaN layer had a Mg doping concentration of $\sim 2 \times 10^{20} \text{ cm}^{-3}$, as measured by SIMS. Additional details on the MBE TJ growth and MOCVD epitaxy for the rest of the cavity can be found in Refs. 26 and 27, along with SILENSE simulations of the TJ, and details on the processing procedure used to fabricate these flip-chip dual dielectric DBR nonpolar III-nitride VCSELs.

4. ITO AND TJ VCSEL CAVITY DESIGN

Figure 2 shows the 1D mode profiles and refractive index profiles for the dual dielectric DBR nonpolar III-nitride VCSELs with ion implanted apertures (IIA) discussed here. The mode profile was calculated using the transmission matrix method.⁶² Figure 2(a) shows the VCSEL with an ITO intracavity contact, while Figure 2(b) shows the TJ intracavity contact. Both structures have 16 period (16P) p-DBRs and 12P n-DBRs (top-side DBRs) composed of $\frac{1}{4}$ -wave layers of SiO_2 and Ta_2O_5 . The effective cavity length is $\sim 6.95\lambda$ for the ITO VCSEL and $\sim 7.5\lambda$ for the TJ VCSEL, with the structures being designed for 405 nm emission. All the III-nitride layers, besides the TJ, were grown via MOCVD on free-standing m-plane GaN substrates with an intentional 1° miscut in the $[000\bar{1}]$ direction.^{63–65} Additional details on the layer thicknesses, doping, etc. can be found in Refs. 26 and 27. In general, III-nitride lasers with m-plane orientations are of interest due to the high peak material gain predicted for m-plane, compared to c-plane.^{66–68} For VCSELs in particular, m-plane is significant because it can yield stimulated emission with a polarization ratio of 100%.²⁵ This is a result of the intrinsic anisotropy in the transition matrix elements on m-plane, which is caused by the anisotropic strain present on m-plane.^{66–70} C-plane VCSELs have been shown to have emission with a polarization ratio of $\sim 80\%$,³⁷ however because of the isotropic nature of the transition matrix elements on c-plane, one would expect an array of c-plane VCSELs to have an average of 0% polarization.²⁴ Figure 3 shows data from a $4 \times$ nonpolar VCSEL array, experimentally demonstrating 100% polarized emission from m-plane VCSEL arrays (Figure 3(b)). This particular device was similar to that reported in Ref. 26, except it used 12P n-DBRs instead of 10P, and was bonded to a Ti/Au

Figure 2 (color online) 1D mode profile and refractive index profile vs. distance in the central part of the dual dielectric DBR nonpolar III-nitride VCSELs with ion implanted apertures (IIA). (a) shows the VCSEL with an ITO intracavity contact. (b) shows the similar device with a III-nitride tunnel junction (TJ) intracavity contact. In (a), the $\frac{1}{4}$ -wave (46.7 nm) ITO layer is aligned to a null of the mode using the $\frac{1}{8}$ th-wave Ta_2O_5 spacer to the left of the ITO. Aligning the ITO to the null of the mode minimizes the loss. In (b), the TJ layer is composed of alternating layers of highly doped n^{++} GaN and lower doped n-GaN, with the highly doped layers aligned to the nulls in the mode. The total TJ thickness is ~ 141 nm. Additional details on the 1D models can be found in Ref 27.

Figure 3 (color online) (a) voltage (V) and light output power (L) vs. current density (J) (LJV) curves for a $4 \times$ nonpolar VCSEL array. The devices have Al ion implanted apertures (IIA) and ITO intracavity contacts. The structure is the same as the reported in Ref. 26 except these devices have 12P n-DBRs, instead of 10P, and they were bonded to a Ti/Au coated Cu submount. (b) Emission spectra as a function of linear polarizer angle relative to the $c_{||}$ direction. The device was measured at 100 kA/cm^2 . The inset shows an optical microscope image of the array, with each individual VCSEL showing varying degrees of filamentation. The $a_{||}$ and $c_{||}$ directions are labeled. The entire array is measured to have a polarization ratio of 100 %, due to the intrinsic nature of the anisotropic gain on m-plane leading to 100 % polarized emission for each individual m-plane VCSEL.²⁵

coated Cu block, instead of a Ti/Au coated sapphire submount. This highly polarized emission can be advantageous in many of the applications discussed in the introduction.

Viewing Figure 2(a), we can see the ITO is aligned to a null of the cavity mode. This is achieved using the $1/8^{\text{th}}$ wave Ta_2O_5 spacer seen to the left of the ITO layer. This serves to minimize the internal loss contributed by the ITO, and is now the standard in III-nitride VCSELs with ITO intracavity contacts. Minimizing the loss in this way forces one to limit the intracavity contact thickness to $1/4$ -wave optical thickness. For 405 nm VCSELs, this implies an ITO thickness of $\sim 47 \text{ nm}$. If we calculate the contribution of the ITO absorption loss to the total internal loss in the cavity, as is done in Ref. 27, we find that the ITO contributes to $\sim 74\%$ ($\sim 30 \text{ cm}^{-1}$) of the total internal loss for these 405 nm VCSELs. This brings the threshold modal gain to $\sim 42 \text{ cm}^{-1}$. This high loss implies that one must use a high number of QWs to reach the threshold modal gain at a low threshold current density.^{27,62} Using a high number of QWs can be problematic from the perspective of strain, as it can lead to relaxation, but in VCSELs it can further complicate things because one must also attempt to maximize the overlap of one of the mode's peak intensities with the QWs (Figure 2), in order to maximize the enhancement factor, leading to a maximized confinement factor.

In contrast, the TJ VCSEL, shown in Figure 2(b), gives much more leverage over device design while simultaneously reducing the internal loss. In Figure 2(b) we can see the TJ intracavity contact is much thicker than the ITO intracavity contact. This is desirable because of the lower resistivity of n-GaN compared to ITO. In this initial demonstration of a TJ VCSEL, we chose to minimize the TJ loss by using alternating layers of high and low doped n-GaN, with the highly doped layers aligned to the nulls of the mode.²⁷ The sheet resistance of the TJ intracavity contact in this particular design is likely somewhat larger than that of the ITO intracavity contact, however it is important to note that we are not restricted in our TJ thickness like we are in our ITO thickness when designing the VCSEL. In our next generation of devices we plan to more than double the TJ thickness in an effort to improve the current spreading. More notable than the spreading resistance effects however, are the extremely low loss levels achieved by using the TJ. As discussed in Ref. 27, by using the TJ we are able to reduce the simulated threshold modal gain to $\sim 14 \text{ cm}^{-1}$, with the intracavity contact now contributing $< 5 \text{ cm}^{-1}$ of loss. As mentioned previously, this highlights the critical importance of TJs for violet and UV VCSELs, however for longer wavelengths (i.e. blue and green), where the ITO absorption coefficient is significantly lower (Figure 1), the advantages of III-nitride TJs are less obvious. Yet even these longer wavelength devices are limited to an ITO thickness of $1/4$ -wave, implying that the minimum spreading resistance is $\sim 100 \Omega$ in the intracavity contact. For a small aperture device, this is not an issue, however if one wishes to design a high-power VCSEL with a large aperture, then minimizing the spreading resistance is critical. In contrast to ITO, our restrictions on the TJ thickness are less severe due to the lower loss introduced by the n-GaN TJ, allowing the design of devices with thick TJs (100s of nm) to achieve equally low spreading resistance on the n-side and p-side of the device. Beyond these electrical benefits of using a TJ, we may also achieve significant thermal improvements, particularly in the

Figure 4 (color online) Schematic diagram of a representative dual dielectric DBR TJ VCSEL. The lateral heat dissipation path around the insulating dielectric p-DBR layer is highlighted.

Table 1 Typical room-temperature thermal conductivities for some of the materials on the p-side of the dual dielectric DBR VCSEL in Figure 4.^{75–78}

Material	Thermal Conductivity (W/cm-K)	Reference
GaN	1.3	75
ITO	0.05	76
Ta ₂ O ₅	0.0045	77
SiO ₂	0.007	78

case of dual dielectric DBR VCSELs. Considering the thermal conductivities of the various layers on the p-side of the device, listed in Table 1, it is easily recognized that there will essentially be no heat dissipation through the thick insulating 16P p-DBR. This implies that heat dissipation will primarily occur laterally around the p-DBR, as is shown schematically in Figure 4. Thus, maximizing the total thickness of the p-GaN and intracavity contact will minimize the lateral thermal resistance. In the case of an ITO VCSEL, one should increase the p-GaN thickness to improve heat dissipation; however this has the trade-off of significantly increasing the loss due to p-GaN's notoriously high absorption coefficient, compared to n-GaN.^{71–73} In the case of the TJ, one can maintain a thin p-GaN layer, while increasing the TJ n-GaN thickness to improve thermal dissipation. Naturally, the effectiveness of the lateral heat dissipation also depends on the p-DBR diameter to aperture diameter ratio, thus one should seek to minimize the alignment tolerance in order to place the metal contacts to the intracavity layer as close to the injection (aperture) area as possible (Figure 4). The alignment tolerance in the devices reported here is 5 μm . In summary, maximizing the TJ thickness and minimizing the p-DBR to aperture alignment tolerance are critical to achieving efficient thermal dissipation in flip-chip III-nitride VCSELs.

5. ITO AND TJ VCSEL DEVICE PERFORMANCE

Figure 5 shows several LJV curves for the ITO VCSELs (a), and the TJ VCSELs (b) with different aperture diameters. All measurements were taken under pulsed operation with a duty cycle of 0.3% (100 ns pulse width). It is of note that TJ VCSELs continued to lase under higher pulse widths (10's of μs), while the ITO VCSELs only showed spontaneous emission, due the misalignment of the peak gain and peak cavity mode wavelength (i.e. gain offset parameter) caused by internal heating. This is in agreement with the improvement in lateral heat dissipation expected from using a TJ (Figure 4). Also of note is that both these devices were used to test a new design geometry, which did not work as well as we had hoped, significantly limiting the yield on the chips and preventing a larger comparison of device results. A general comparison of the LJV curves for the ITO VCSEL (Figure 5(a)) and the TJ VCSEL (Figure

Figure 5 (color online) LJV for the ion implanted aperture (IIA) VCSELs. (a) shows the IIA VCSELs with an ITO intracavity contact. (b) shows the IIA VCSELs with tunnel junction (TJ) intracavity contacts. All measurements were made under pulsed operation with a duty cycle of 0.3% (100 ns pulse width).

5(b)), attests to the strong improvements in lasing performance offered by using a TJ intracavity contact. In Figure 5(a), we see that the ITO VCSELs with aperture diameters (ϕ) of 12 μm consistently give $\sim 7 \text{ kA/cm}^2$ (7.9 mA) threshold current densities, with variable peak output powers around 70–80 μW at $\sim 50\text{--}55 \text{ kA/cm}^2$. The threshold voltage is $\sim 5.5 \text{ V}$ and increases to $\sim 8.5 \text{ V}$ at 50 kA/cm^2 (56.5 mA). Device 5 corresponds to the ITO VCSEL reported in Ref. 27. The most direct comparison between the ITO VCSELs and the TJ VCSELs is realized by comparing the LJV curve for the 12 μm aperture diameter TJ VCSEL (device 1) shown in Figure 5(b). This was also the TJ VCSEL analyzed in Ref. 27. Unfortunately, this was the only 12 μm aperture diameter device to make it through the process, preventing a more statistically relevant comparison. Regardless, viewing the LJV curves for this device, we see the TJ VCSEL shows a marginal improvement in threshold current density, lasing at $\sim 3.5 \text{ kA/cm}^2$. This threshold is also confirmed in the spectral analysis shown in Figure 8, which will be discussed later. The threshold voltage is seen to increase to $\sim 6.5 \text{ V}$, highlighting the non-optimized nature of the TJ contact resistance. As this was our first test of the TJ VCSEL, we had no prior knowledge of what processing conditions would reduce the TJ contact resistance; however more recent results suggest that this contact resistance can be reduced to yield voltages equivalent to that of ITO contacts. On device 1 of the TJ VCSELs, we observe a significant improvement in differential efficiency and peak output power compared to the ITO VCSELs. Specifically, the 12 μm aperture diameter TJ VCSEL shows a peak power of $\sim 550 \mu\text{W}$ at $\sim 85 \text{ kA/cm}^2$. At 50 kA/cm^2 the power is $\sim 475 \mu\text{W}$ and the voltage is $\sim 10 \text{ V}$. The improvement in the differential efficiency is a result of the increased ratio of the mirror loss to the modal gain (mirror loss plus internal loss), which is directly proportional to the differential efficiency.²⁷ Considering the other TJ VCSEL devices with 8 and 10 μm aperture diameters, we see the threshold current density significantly increases with decreasing aperture diameter. This is in agreement with our previous studies on the aperture diameter dependence of the threshold current density on IIA+ITO VCSELs, shown in Figure 6. The results from Figure 6 are from a previous generation of ITO VCSELs, where the most notable difference was the use of 10 QWs in the previous generation, instead of 7 QWs used in the IIA+ITO VCSELs in Figure 5. In Figure 6 we also see the increase in threshold current density with decreasing aperture diameter. Simulating the lateral confinement factor variation vs. aperture diameter for the IIA design, we see, in Figure 7, that the confinement factor begins to rapidly drop off below 10 μm aperture diameters, which is likely the cause of the increase in threshold current density observed in the ITO VCSELs from Figure 6 and TJ VCSELs from Figure 5(b). Additional details on this simulation can be found in Ref. 26. We also note the increase in threshold current density for devices with aperture diameters greater than 12 μm (Figure 6), which is likely a result of the reduced current spreading efficiency with larger aperture diameters, yielding highly non-uniform current injection into the aperture. Moving back to Figure 5(b), we note that despite this increase in threshold current density with decreasing aperture diameter, even the poorest performing TJ VCSEL, with an 8 μm aperture diameter, still achieves a higher peak output power than any of the ITO VCSELs (Figure

Figure 6 (color online) Threshold current density (J_{th}) vs. aperture diameter for a previous generation of 405 nm IIA+ITO VCSELs. The cavity design was generally similar to that of the ITO VCSELs shown in Figure 2(a) and Figure 5(a), however the VCSELs here had 10QW active regions, instead of 7. Results from co-processed chips with 8, 10, and 12P n-DBRs are shown, with the 12P n-DBR sample giving the highest number of lasing devices.

Figure 7 (color online) Simulations of the total confinement factor, Γ_{total} , fill factor, Γ_{fill} , enhancement factor, Γ_{enh} , and lateral confinement factor, Γ_{xy} , as a function of aperture diameter for the 12P n-DBR devices shown in Figure 6. The enhancement factor was calculated using the 1D transmission matrix method models discussed in Ref. 27, while the confinement factor was calculated using the Fimmwave model discussed in Ref. 26.

Figure 8 (color online) Emission spectrum at various current densities for (a) the ITO VCSEL (device 5) and (b) the TJ VCSEL (device 1). The insets show the log plot of intensity vs. wavelength. In the log plots, the minor bump in the emission at ~430 nm shows the Fabry-Perot resonance mode spacing to be ~21 nm

5(a)).

Figure 8 shows the emission spectra vs. current density for the ITO VCSEL (device 5) (a) and the TJ VCSEL (device 1) (b). Here we see the lasing wavelength was significantly longer than the design wavelength of 405 nm, which is due to the unintentional incorporation of an extra Ta₂O₅ layer at the start of the n-DBR. For both cases the spectrometer limited FWHM is ~2 nm. Viewing the spectra on log intensity scales, we can see the slight bump in the emission at ~430 nm, giving a Fabry-Perot resonance mode spacing of ~21 nm. The mode spacing, $d\lambda$, can be calculated according to the formula, $d\lambda = \lambda^2 / (2n_g L_{eff})$, where λ is the lasing wavelength and L_{eff} is the effective cavity length with the ITO VCSEL having a 1199.3 nm thick cavity and the TJ VCSEL having a 1270.8 nm thick cavity.⁶² Assuming a group index, n_g , of ~3.3,⁷⁴ the mode spacing is calculated to be ~21.3 nm for the ITO VCSEL cavity and ~20.7 nm for the TJ VCSEL cavity, both of which are in good agreement with the measured value. Thus, both the TJ VCSEL and ITO VCSEL have single longitudinal mode emission.

6. CONCLUSION

In summary, we have discussed some of the intrinsic issues with using ITO as an intracavity contact in III-nitride VCSELs. Motivated by these issues, we analyzed the potential benefits of using III-nitride TJs, prior to discussing some of the various techniques for achieving III-nitride TJs and the challenges faced in making such intracavity contacts. Following these considerations, we analyzed two similar dual dielectric DBR III-nitride VCSEL cavity designs, one with an ITO intracavity contact and one with a TJ intracavity contact. The specific benefits of using the TJ intracavity contact for violet III-nitride VCSELs were analyzed, and the general advantages for TJs on longer emission wavelength VCSELs were highlighted. Finally, we considered the LJV characteristics from a number of ITO VCSELs and TJ VCSELs processed in parallel. Overall, the TJ VCSELs show significant increases in output power, compared to the ITO VCSELs. The threshold current density was observed to increase as the TJ VCSEL aperture diameter was decreased below 12 μm . This increase in threshold current density correlated well with similar aperture dependence trends observed on previous generations of ITO VCSELs. The aperture dependent trends revealed some of the challenges with achieving high lateral confinement in small aperture diameter III-nitride VCSELs with ion implanted apertures (IIA). Finally, single longitudinal mode emission is observed from the emission spectra of both the TJ VCSELs and ITO VCSELs with $\sim 7\lambda$ cavities.

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