IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

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Volume 5, Number 6, December 2013

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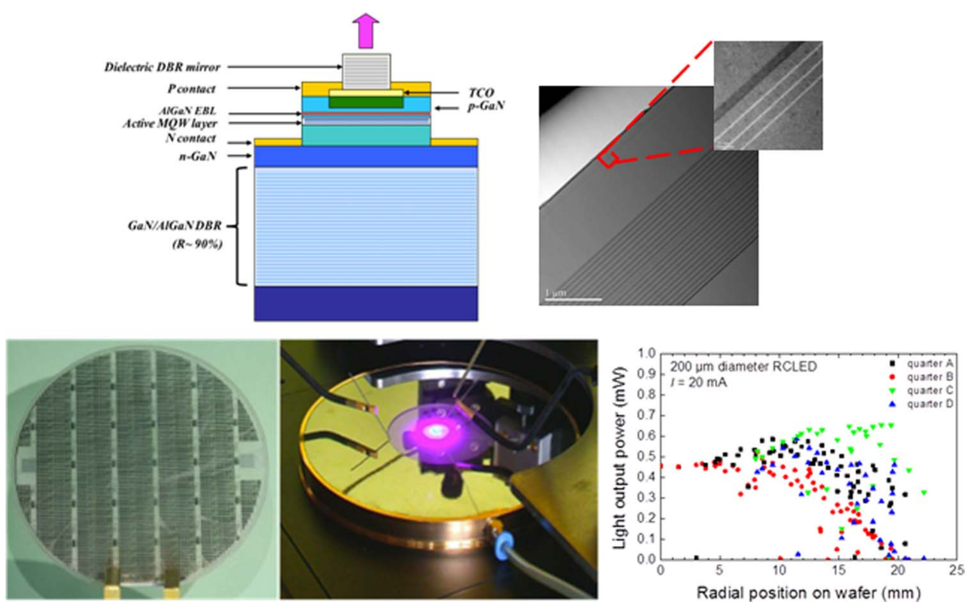

DOI: 10.1109/JPHOT.2013.2287558
1943-0655

Design, Fabrication, and Characterization of Near-Milliwatt-Power RCLEDs Emitting at 390 nm

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DOI: 10.1109/JPHOT.2013.2287558
1943-0655 © 2013 IEEE

Manuscript received July 31, 2013; revised October 11, 2013; accepted October 11, 2013. Date of current version November 6, 2013. This work was supported in part by the French Agence Nationale de la Recherche (ANR) and in part by the Fraunhofer Society within the framework of PICF VERTIGAN project (convention n°2009 CARN 01101). Corresponding author: T. Moudakir (e-mail: tarik.moudakir@georgiatech-metz.fr).

Abstract: We report on the realization and first demonstration of CW near-milliwatt-power emission at $\lambda = 390$ nm from resonant-cavity light-emitting diode (RCLED) on GaN templates. The vertical cavity consists of a bottom AlGaN/GaN distributed Bragg reflector and a top dielectric SiO_2/ZrO_2 mirror enclosing a GaInN/GaN multiple-quantum-well active layer. RCLEDs with total optical output of about 600 μW at an injection current of 20 mA were achieved before packaging, taking account of current growth and processing considerations. Dislocations generated during the growth of the RCLED structure seem to be affecting the mean light output. This can be further improved by the use of high-quality low-dislocation-density GaN templates or freestanding GaN substrates.

Index Terms: Distributed Bragg reflector (DBR), GaN, AlGaN, resonant-cavity light-emitting diode (RCLED), UV, fiber coupling.

1. Introduction

Resonant-cavity light-emitting diodes (RCLEDs) can be regarded as a hybrid between vertical-cavity surface-emitting lasers (VCSELs) and conventional light-emitting diodes (LEDs). When compared to the output from non-resonant cavity LEDs, the light output from RCLEDs is brighter, highly directional, spatially coherent, and spectrally pure [1]. Even though III-nitride-based blue and green LEDs have reached maturity, high-efficiency RCLEDs emitting below 400 nm and in the deep ultra-violet (DUV) range are still missing. GaInN quantum well based RCLEDs emitting around 380–400 nm are very attractive for applications in industry, instrumentation or medicine such as photocatalysis, photolithography with and without mask, fibered light sources for spectroscopic sensing, photodynamic therapy for skin cancer and actinic keratosis treatment, fluorescence endoscopy, fluorescence microarrays and microscopy [2]–[4].

In the past decades, extensive work has been dedicated to the development of vertical cavity devices emitting in the UV and near-UV wavelength range. In particular, there have been some encouraging developments in the fabrication of these vertical structures based on GaN systems, such as the demonstration of optically pumped vertical lasers [5], [6] and RCLEDs [7]. GaInN based

RCLEDs emitting around 510 nm and 460 nm for plastic optical fiber communications have been successfully demonstrated [8], [9]. Diagne *et al.* also demonstrated RCLEDs (413 nm) featuring an optical resonator composed of an *in situ* grown, stress engineered GaN/AlGaN distributed Bragg reflector (DBR) and a high reflectivity dielectric mirror [10]. However, design and fabrication of RCLEDs emitting at the wavelength below 400 nm remains challenging and undemonstrated so far because of the requirement of high quality optical resonators.

Different growth architectures were reported in the literature to realize these resonators. Metallic, epitaxially grown (GaInAl)N/GaN DBR, and oxide-based DBR (e.g., SiO_2/TiO_2) mirrors are generally used. Both metallic and oxide DBR bottom mirrors require difficult, expensive and complex lift-off processes [7], [11], rendering an (Ga, In, Al)N/GaN growth the preferable choice. Several GaN/AlGaN and AlInN/GaN based DBR structures have been reported, grown by molecular beam epitaxy and metal-organic chemical vapor deposition (MOCVD) [12], [13], [15]. To have high reflectivity $(R > 90\%)$ (GaInAl)N/GaN DBRs, require a large number of pairs due to the relatively low refractive index contrast between AlInN, AlGaN and GaN. The crystal quality of these high reflective $(R > 90\%)$ DBRs degrades severely due to an increase in strain after a certain number of pairs are grown. Consequently, the quality of bottom DBRs will affect the active region of the cavity. Recently, a VCSEL on free-standing GaN featuring an AlInN/GaN DBR emitting at 420 nm was demonstrated [16]. But AlGaN/GaN DBRs have specific growth advantages over AlInN/GaN DBRs which suffer from a strong temperature dependence of In incorporation which can lead to a strong radial dependence of the spectral position of DBR stopband and a significant difference in growth temperatures of AlInN and GaN that involves a number of ramping steps and growth stops in realizing the DBR [17]. Hence, the development of AlGaN/GaN DBRs for RCLEDs emitting below 400 nm is particularly interesting for many applications were manufacturing costs are critical.

Apart from the realization of crack-free GaN-based DBRs with high reflectivity around 90% with a minimum number of pairs, there are many critical problems associated with the fabrication of high performance, UV-emitting RCLEDs on AlGaN/GaN DBR. First and foremost is the control of defects in the active region propagating from the bottom mirror, as well as the position of the active region, optimization of metallic or dielectric top mirror and device processing issues. There are only limited reports responding to these critical issues towards realization of high quality RCLED structures emitting below 400 nm. In this article, we report the successful demonstration of design and fabrication of GaInN-based RCLEDs emitting near milliwatt power light around $\lambda = 390$ nm on high reflective, crack free, coherently strained 20 pair AlGaN/GaN DBR and with SiO_2/ZrO_2 top mirror stacks.

2. Device Design and Growth of RCLEDs

For these RCLEDs, a hybrid structure containing a top dielectric and a bottom semiconductor Bragg mirror was fabricated. For the semiconductor bottom mirror, for a first approach, a simple solution consisting of a "traditional" stack of 20 quarter wavelength pairs of $Al_{0.27}Ga_{0.73}N/GaN$ layers grown by MOCVD was used. This solution made it possible to achieve structures with the aimed reflectivity $(R > 90\%)$ at 390 nm. However, due to the too high lattice mismatch occurring between the AlGaN and GaN layers, the surface of such mirrors revealed a significant crack density prohibitive for the realization of efficient quantum well active regions on top. So, to inhibit crack formation, thin AlN layers were inserted in the mirror structure in order to control the strain relaxation. The exact positions of the AlN insertion layers were determined via interferential *in situ* light reflection monitoring during growth. A typical mirror with modified design limiting the crack formation were fabricated as follows: First, a thin AlN buffer layer was grown on a GaN template, then a classical quarter wavelength AlGaN/GaN DBR was grown normally except for one AlGaN layer in the middle of the structure which was replaced by an AlN/GaN/AlN multilayer. The optical thickness of this multilayer was calculated so as not to break the periodicity of the mirror for constructive interferences. Further details of the DBR structure growth conditions and their characterizations can be found in Ref. [18], [19]. Owing to this modified design, "crack-free" AlGaN/GaN mirrors with $R > 90\%$ at 390 nm on 2" GaN template wafers could be provided. The cavity containing a

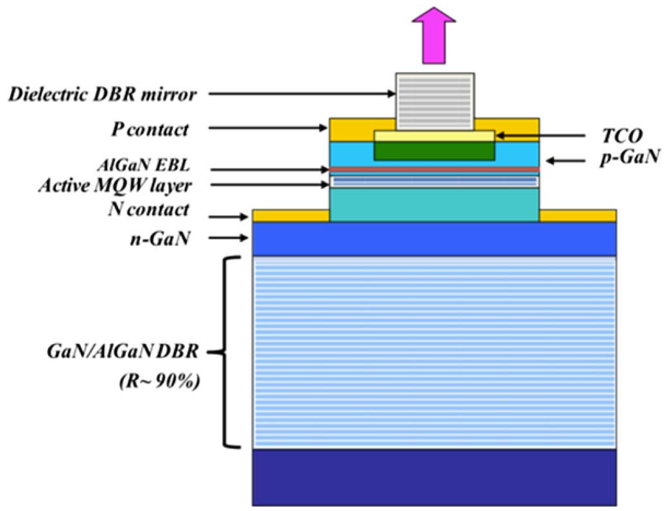

Fig. 1. Cross section of a RCLEDs device designed for light emission at 390 nm.

GaInN/GaN multi-quantum well (MQW) region was then designed and regrown by low pressure MOCVD on the 2" "crack-free" DBR wafers. This cavity was formed, starting from the AlGaN/GaN mirror, as follows: a 30 nm thick GaN layer, a 870 nm thick Si-doped n-GaN layer necessary for lateral current injection, three 2.7 nm thick GaInN quantum wells embedded in 9 nm thick nominally undoped GaN barriers for an emission near 390 nm, a 18 nm thick GaN spacer layer, a 10 nm thick Mg-doped $Al_{0.1}Ga_{0.9}N$ electron blocking layer, and finally a 119 nm thick Mg-doped GaN injection layer. This cavity was designed in order to position the quantum wells at the anti-nodes of the electromagnetic field in the structure. The regrown wafers were then processed into operating RCLEDs. The different lithographic steps included circular mesa definition with diameters ranging from 5 to 200 μm, the deposition of a 55 nm thick intracavity transparent In_2O_3Sn (ITO) contact layer for lateral current injection, the deposition of metal contacts and the fabrication of a final 2.5 pairs SiO_2/ZrO_2 dielectric top mirror by plasma-assisted electron beam evaporation, exhibiting a 75% reflectivity at 390 nm, to complete the RCLEDs. A cross section of the final device is as shown in the Fig. 1.

3. Results and Discussions

3.1. High Resolution X-Ray Diffraction

Fig. 2 shows the measured high-resolution X-ray diffraction $2\theta - \omega$ scan for 002 reflection of the RCLEDs without top mirror, AlGaN/GaN DBR and the GaInN/GaN MQW grown on GaN templates. The satellite diffraction peaks of the DBRs up to the 11th order were observed, revealing a high degree of periodicity and abrupt interfaces. The scan of the RCLED has similar peaks and does not feature the characteristic satellite peaks of the InGaN/GaN MQW.

The high intensity diffraction signal from the AlGaN/GaN DBR is masking characteristic satellite peaks of the active region of the RCLED structure. But, the $2\theta - \omega$ scan of the control sample grown on GaN templates clearly shows the satellite peaks from the active region confirming the high quality of the device active region.

Fig. 3(a)–(c) show the reciprocal space map (RSM) of the asymmetric 114 reflection for the GaInN/GaN QW control sample on GaN template, the AlGaN/GaN DBR, and the RCLED without the top mirror samples, respectively. Similar to the $2\theta - \omega$ scan we see intense, higher order peaks for the AlGaN/GaN DBR and the RCLED structures. It is also interesting to note that the DBR structure is coherently strained on the GaN template. The RSM of the control sample show that the GaInN/GaN MQWs are fully strained over GaN and also shows the less intense characteristic

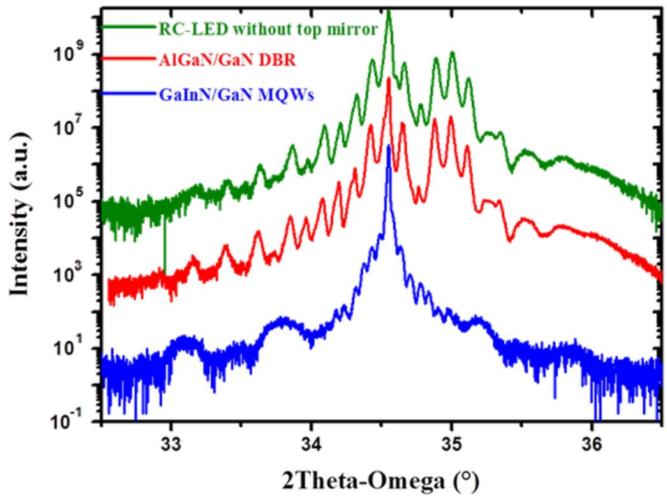

Fig. 2. $2\theta - \omega$ scan around 002 reflection of RCLED without top mirror, AlGaN/GaN DBR and GaInN/GaN QW active region grown on GaN templates.

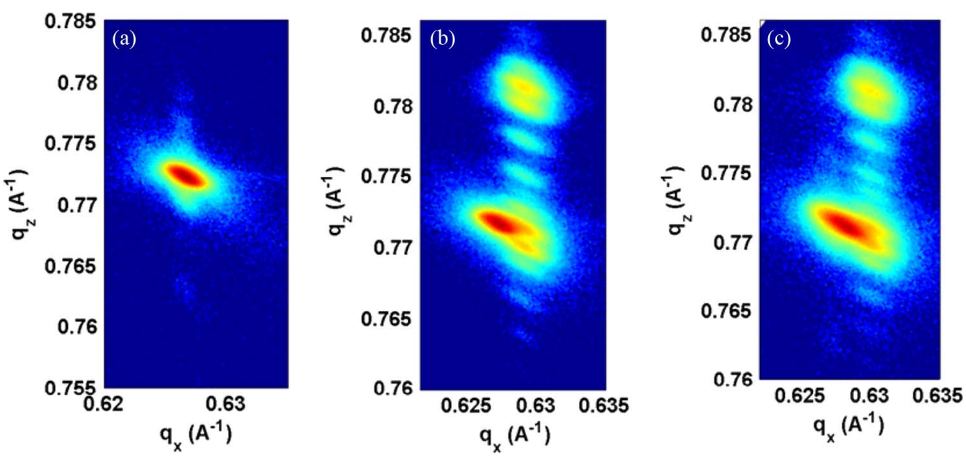

Fig. 3. RSM of the asymmetric 114 reflection of (a) InGaN/GaN MQWs grown on GaN template, (b) AlGaN/GaN DBR structure grown on GaN template and (c) RCLED without top mirror.

satellite peaks of the MQWs. Comparing the intensities in the Fig. 3(a) and (b), it is vivid that the high intensity peaks from the AlGaN/GaN DBR in the RCLED are masking the feeble satellite peaks from the GaInN/GaN MQW active region as shown in Fig. 3(c), which confirm the observations in the $2\theta - \omega$ scans of the sample.

3.2. Transmission Electron Microscopy Studies

Fig. 4 shows a Z-contrast scanning transmission electron microscopy (STEM) image of the RCLED structure on the GaN templates without the top SiO_2/ZrO_2 dielectric mirror. AlN buffer layer (bottom most dark layer) and AlN/GaN/AlN multilayer (very thin layers in the middle of the DBR structure) are clearly observed in the RCLED structure. Higher magnification image of the RCLED active region is shown in the inset of the figure. Very sharp abruptness at the interfaces was clearly seen between the bright (GaN) and dark (AlGaN) multilayers. It is in good agreement with the topography from AFM images, which show a smooth and flat surface with atomic terraces and low

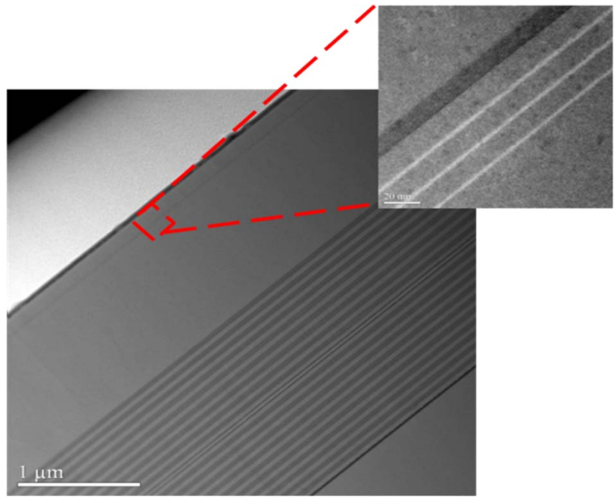

Fig. 4. HAADF-STEM image of RCLED structure without top mirror. The zoom corresponds to the InGaN/GaN MQW region. The scale line represents 20 nm.

RMS surface roughness of 0.9 nm over an area of 5 μm $\times$ 5 μm comparable with the roughness of MQW grown on GaN template.

As high angle angular dark field (HAADF) STEM imaging is sensitive to the local atomic number of the atoms (Fig. 4), the homogeneous contrast in the GaInN and AlGaN layers, when compared to that of GaN, physically means that the compositional homogeneity is preserved in the entire structure. No cracks were observed on the RCLEDs fabricated on the AlGaN/GaN DBRs, but the density of dislocations in the DBR increases (from 5×10^8 cm^{-2} in the GaN template) to 5×10^9 cm^{-2}. Energy dispersive X-ray measurements on the localized areas in the quantum wells and the DBR layers confirmed that the expected composition was retained after the growth of entire RCLED structure. This confirms that the increase in dislocation density in the DBR structure has only minimal effects on the structural quality and In composition in the MQW.

3.3. Reflectance Uniformity Over 2'' Wafer

For the DBR, the peak reflectance at 392 nm is around 90%, and the stop bandwidth is 18 nm. To realize a high-yield RCLED process, the homogeneity of the DBR structure is very important. Fig. 5 presents the reflectance measurements carried out across the 2" AlGaN/GaN DBR wafer. As shown in this figure, the standard deviation of the measured peak wavelength in this case is less than 3 nm (excluding the measurement on the 5 mm thick exclusion zone of the templates) which highlights the good uniformity over the entire area of the sample and makes the implementation of the technological RCLED process over a maximum area possible.

3.4. Device Characteristics

Fig. 6 presents low-temperature (15–50 K) photoluminescence (PL) spectra taken at different temperatures for the RCLED structure without dielectric top DBR and a classical LED structure. The PL spectrum of the RCLED structure consists of two peaks which change their intensity with temperature. In contrast, the PL spectrum of the classical LED structure consists of only one peak which changes only slightly with temperature.

The two peaks in the PL spectrum of the RCLED structure are attributed to different cavity modes where the cavity is formed by the bottom DBR and the GaN/air interface due to the high refractive index difference between GaN and air. The spectral positions of the two peaks correspond to the modes of the cavity with the best overlap with the quantum well emission. The intensity change with temperature can be explained with different temperature dependence of the quantum well band gap energy and of the AlGaN/GaN DBR stop band wavelength. The latter is directly linked to the

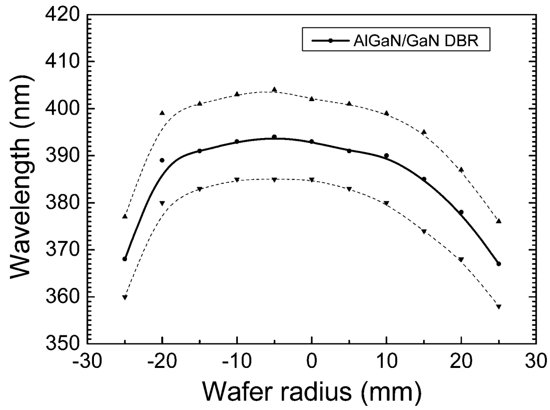

Fig. 5. Peak and half intensity wavelength of AlGaN/GaN DBR reflectance.

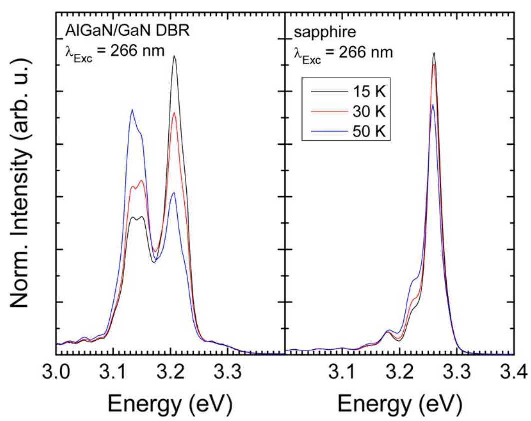

Fig. 6. Photoluminescence spectra of RCLED structure without dielectric top DBR (left) taken at different temperatures compared with spectra of classical LED structure (right).

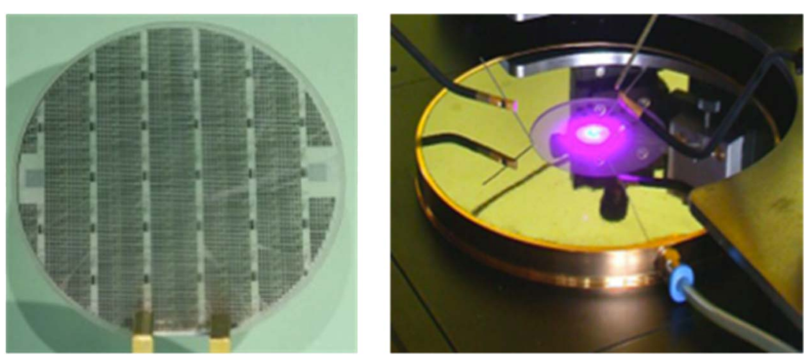

Fig. 7. RCLED wafer after full lithographic processing (left) and wafer level probing of RCLEDs showing light emission at 390 nm (right).

refractive index of GaN and AlGaN which shows a much smaller temperature dependence than the band gap energy.

Fig. 7 shows the final processed RCLED wafer and the light emission from the RCLED structure, visible to the naked eye, respectively.

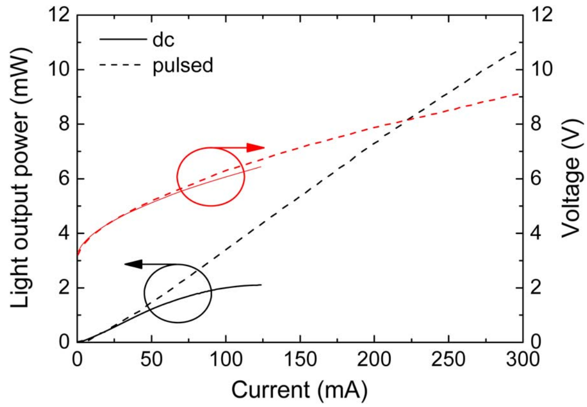

Fig. 8. Light output power current and voltage current characteristics from a 200 μm diameter RCLED in dc and pulsed mode (pulse width 1 μs, 0.1% duty cycle) at room temperature.

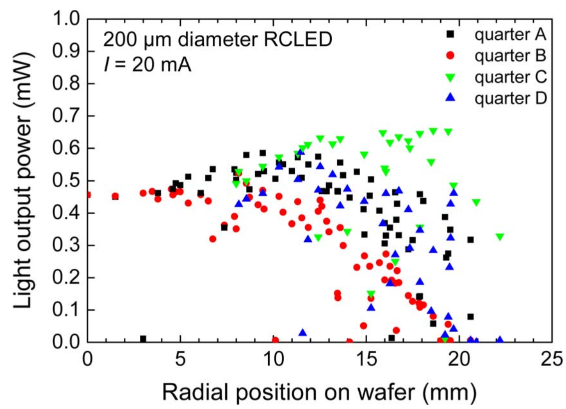

Fig. 9. Light output power from 200 μm diameter RCLEDs across the radius of 2'' wafer at 20 mA injection current at room temperature.

Fig. 8 presents the light output power-current and voltage-current characteristics of a 200 μm diameter RCLED measured at room temperature. The light output power of this specific RCLED is 430 μW at an injection current of 20 mA and reaches its maximum of 2.1 mW at 125 mA in dc mode. The light output power is limited by severe heating of the device at this high current density. In pulsed mode (pulse width 1 μs, 0.1% duty cycle), the light output power linearly increases to 10.8 mW at 300 mA which corresponds to an external quantum efficiency of 1.2%. A low voltage of 4.3 V at 20 mA can be extracted from the voltage-current characteristics. The voltage is higher at higher injection currents in pulsed mode compared to dc mode due to the temperature dependence of the pn junction.

Fig. 9 shows the light output in dc mode at room temperature from 200 μm diameter RCLEDs measured with 20 mA injection current versus the radial position on the 2" AlGaN/GaN "crack-free" DBR wafer.

The maximum light output power measured was about 650 μW in dc mode at room temperature and an injection current of 20 mA, which is satisfactory for many applications mentioned above. One can also remark once again the high homogeneity of the emission properties of the different similar devices processed over the entire surface of the wafer besides a small deviation from the rotational symmetry. From a general point of view, the output power of such RCLEDs developed by GaInN MQW region regrowth on AlGaN/GaN "crack-free" DBR remains however moderate. The still low quantum efficiency of the active region is thought to be due to the increase of the dislocation density in the AlGaN/GaN DBR structure. The dislocation density in the MQW active region is estimated to be around (5×10^9 cm^{-2}). Using high-quality, low dislocation density substrates (one order of magnitude less) could compensate this increase of dislocation density and result in a further improved better light output power.

4. Conclusion

We have demonstrated group III-nitride based RCLEDs featuring a strain engineered, 20 pairs AlGaN/GaN DBR bottom mirror emitting at 390 nm. Very encouraging results on the structural, optical and device performance of RCLEDs emitting at 390 nm were obtained. The increase in dislocation density by an order of magnitude during the growth of AlGaN/GaN DBR was found to affect the light output. We expect that as we reduce the losses in the RCLED structures by the use of ultra-low dislocation density GaN templates, these devices can be pushed to a much significantly higher light output at low injection current.

Acknowledgment

The authors would like to thank S. Bühler, C. C. Leancu, S. Liu, K. Schäuble, R. Schmidt, and J. Wiegert for valuable contributions.

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