GaInN-based Green Light Emitting Diode for Energy Efficient Solid State Lighting

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Abstract—In metal organic vapor phase epitaxy we developed GaInN/GaN quantum well material suitable for 500 – 580 nm light emitting diodes by defect suppression and improving alloy uniformity towards energy efficient green light engines. This endeavor stands up against a formidable challenge in the green spectral region. By the choice of crystallographic orientation, the dipole of piezoelectric polarization in the quantum wells can be optimized for highest diode efficiency. We explored the feasibility through homoepitaxy on polar c-plane, and non-polar a-plane and m-plane GaN. We report progress towards the goal of a reduction of the efficiency droop at longer wavelengths.

Index Terms—a-plane GaN, GaInN, Green light emitting diode, m-plane GaN

I. INTRODUCTION

In order to match up with the growing demand of energy worldwide, multiple approaches seek higher efficiency devices to consume available energy at a lower rate. Residential, public, and industrial users are now highly motivated to reduce environmental impact by lowering their carbon footprint. Among those tasks, developing a highly efficient light emitting diode (LED) is being pursued to serve as a next generation artificial light source for better energy savings. Currently, commercially available LED-based light bulbs employ a down conversion process using a combination of blue LED and yellow phosphors. These light bulbs do not only suffer significant Stokes losses in the conversion of the photon energy but they also provide poor color rendering and poor color stability due to the degradation of phosphor materials over time. To overcome such limitations, direct emission from a LED-based light bulb with multiple LED chips with their combined wavelengths covering the visible spectral regime is highly desirable.

The blue spectral region can most efficiently be generated in AlGaInN-based LEDs,[1]–[2] while the yellow and red spectral region currently is best addressed with AlGaInP LEDs.[3] Nevertheless, in between for green, the best candidates are GaInN/GaN heterostructures of the former type even when their efficiency for photon emission still is not higher than some 20%.[4]

In this work, we have successfully improved the efficiency in the green spectral region by eliminating common nano pits known as "V-defects" from the active layers of GaInN-based LEDs. Besides, we have extended our development along different crystallographic orientations, in particular non-polar planes of {11-20} and {10-10}, typically known as a-and m-planes, respectively.

II. DEFECT SUPPRESSION

Grown in heteroepitaxy on readily available c-plane sapphire, GaN-based structures always show high densities of threading dislocations (TD, $10^9 – 10^{10}$ cm$^{-2}$) as initiated in the interface of both materials.[2] Various efforts of complex growth, processing and re-growth concepts have been developed over time to reduce the number of those line defects; however, the TDs still penetrate the active quantum well (QW) region at a density of at least $10^7$ cm$^{-2}$ and most-likely at significantly higher density. Upon their interaction with the GaInN layers of the QWs, threading dislocations frequently induce pit formation caused by higher index facet growth at reduced growth rate. The cross section of such pits is typically observed as V-shapes in transmission electron microscopy (TEM).[5]

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Fig. 1 Surface morphology of the last barrier in V-defect free (a) and defective (b) GaInN/GaN MQW for green LEDs as observed in AFM. Their PL peak wavelengths are 540 (a) and 541 nm (b), respectively.[6]
For example, there is a large number of V-defects in a typical (GaInN/GaN)$_k$ MQW of a 541 nm green LED as depicted in atomic force microscopy (AFM) of the last barrier of the active QW region (Fig. 1 (b)). The total V-defect density of this sample is about 6x10$^8$ cm$^{-2}$. Analyzing the distribution of the defect diameter, we found that 3/4 of these defects were generated during epitaxial growth of the 3$^{\text{rd}}$ and 4$^{\text{th}}$ GaInN QW layers. This situation worsens with higher numbers of QWs. From TEM analysis of 10 period GaInN/GaN MQWs, we have not only observed that the total V-defect density increased to approximately 1 – 4 x 10$^{10}$ cm$^{-2}$ but the thickness of both GaInN QW and GaN barrier layers in the peripheral area of the defects was also gradually increased up to 50% and 35%, respectively. As a consequence, the light output power (LOP) was decreased by an order of magnitude while the emission wavelength was shifted to 570 nm with an additional peak arising at 450 nm.[5] However, there is not enough data to identify whether there is a change in In composition in the GaInN layers or not. In addition there were GaInN/GaN MQWs formed on the defect walls, i.e., {10-11} planes. Besides, when increasing the InN fraction in the QW in order to reach an emission color in the deep green region, we found that the density of V-defects increased to 2.8x10$^9$ cm$^{-2}$ for 560 nm MQWs and defects also grew in size strongly deteriorating the active region quality.[7]

Through the growth optimization of the GaInN/GaN active region, we have succeeded in avoiding the generation of such V-defects in green LEDs up to at least 570 nm.[6],[7] The morphology of the last barrier of the active QW region shows substantially reduced surface roughness when V-defect generation can be suppressed (Fig. 1 (a)). As seen in Fig. 2, the roughness of the reference MQW samples increases from 1 to 4 nm (root mean square, RMS) as the PL wavelength is increased from 510 nm to 565 nm. By avoidance of the V-defects, roughness is reduced to 0.2 nm and 0.9 nm RMS for the 540 nm and 565 nm MQWs, respectively. There is also a similar trend of increasing roughness in the V-defect-free MQWs as the InN fraction increases. However, these numbers for the V-defect-free MQWs are only a few times larger than those of the n-GaN platform layer itself which ranges from 0.1 nm to 0.3 nm RMS.

![Fig. 2 Roughness of green and deep green GaInN/GaN MQWs with and without V-defects as a function of PL peak wavelength. V-defect density in the defective samples is 2 – 50 x 10$^8$ cm$^{-2}$. The average roughness for the n-GaN template is 0.19 nm RMS. Dashed lines are guides to the eye.[7]](image)

![Fig. 3 TEM images (bright field) from cross-sections of green LEDs with (a) and without (b) V-defects. Each sample contains ten pairs of GaInN QWs and GaN barriers. V-defects initiated by TDs were observed in (a). No V-defect was generated in (b).[5]](image)

![Fig. 4 LOP of green and deep green GaInN-based LEDs with V-defects as a function of drive current. An average V-defect density in the defective samples is 2-5x10$^9$ cm$^{-2}$. Labels indicate the dominant wavelength at a current density of 12.7 A/cm$^2$.[6],[7]](image)
Fig. 3 shows the bright field TEM images of samples taken along the [11-20] zone axis. The white arrows indicate the growth direction [0001]. For a green LED with V-defects (Fig. 3(a)), many V-defects initiated by TDs were found in the active region. The pinholes that we observed in AFM correspond to those V-defects. Each V-defect was decorated by sets of thinner QWs on its sidewalls. The number of these narrower sets matches the number of QWs grown after the initiation of the V-defect. As more V-defects were generated, some merge into each other and convert into a larger one. The density of TDs in the active region was determined to be $6 - 8 \times 10^9$ cm$^{-2}$ by cross-sectional TEM. Most of the TDs were generated in the QWs, with a few that propagated from the n-GaN. After the formation of V-defects, TDs still propagate within the V-defect and some of them extend to the free surface.

Fig. 3(b) shows the cross-sectional TEM image of a green LED without V-defects. No generation of V-defects was observed in the active region although some TDs were initiated. The high resolution TEM suggests highly homogenous QWs (image not shown). The width of QWs and GaN barriers (QB) remains uniform throughout the ten periods of the QWs.

In the 516 nm, 540 nm, and 561 nm reference wafers with a V-defect density in the mid 108 cm$^{-2}$, the maximum LOP reaches only 8 mW, 3 mW and 1.5 mW, respectively. Emitting at 521 nm (dominant), LED epitaxial wafers without V-defects achieve LOPs of 18 mW at a current density of 90 A/cm$^2$ in continuous wave (CW) electroluminescence (EL) mode as measured through the substrate (Fig. 4). For even longer wavelengths of 528 nm, 542 nm, 549 nm, and 559 nm, the maximum LOP values observed at 90 A/cm2 are 14 mW, 14 mW, 13 mW, and 8 mW, respectively (Fig. 5). Compared to the reference LED wafers, the V-defect-free devices exhibit an increase of the LOP by a factor of four or more, in particular at the very high drive current densities of 90 A/cm$^2$ projected for the next generation 700 mA high power lamps. We, therefore, find with increasing emission wavelength throughout the green to the yellow, the avoidance of V-defects in the active region becomes more and more important.

Fig. 5 LOP of green and deep green GaInN based LEDs without V-defects as a function of drive current. Labels indicate the dominant wavelength at a current density of 12.7 A/cm$^2$ [6],[7]

Fig. 6 exhibits the LOP distribution as a function of dominant wavelength for both types of LEDs under injection current density of 12.7 A/cm$^2$. On average the V-defect-free LEDs emit two fold higher light intensities than the defective ones at a dominant wavelength of 550 nm. The difference in output power becomes even wider with increasing injection current. These results confirm the significant leap EL performance of the V-defect-free green LEDs and possibility of closing up the spectral gap on the short wavelength front (520 – 550 nm).

Fabricated LED dies of dimensions 350 m by 350 m were attached on gold plated headers by using silver epoxy, and wire bonded to apply electrical bias. No encapsulation material was applied. In an accelerated stress test, dies were driven by a continuous forward current of 30 mA while placed in an oven at an ambient temperature of 80 °C. After consecutive time intervals summing up to 168 hours of aging, the stress conditions were interrupted for EL testing at standard conditions.

After 168 hours (1 week) of aging green and blue LEDs with high densities of V-defects behave as shown in Fig. 7. For better comparison, the data is shown as a point-by-point ratio of LOP after aging to that before aging. Apparently, with such aging, the LOP of the reference 525 nm green LED has dropped by 36 % (at 20 mA) while the reference 467 nm blue LEDs has dropped only 10 - 20%. In all of the reference LEDs, LOP tends to drop more at lower forward currents. In case of the 525 nm reference LED, such deficit can be as large as 70% at a current of 1 mA. This is a highly unsatisfactory reliability behavior in those reference LEDs. In contrast, however, the V-defect-free green LEDs manifest only a slight degradation of a few percent over the course of these standard test conditions. These findings provide evidence of a strong correlation of LED reliability with the number and the dimension of V-defects formed inside the
active region. This mechanism is found to be even more relevant in the green spectral region where with increasing InN fraction the density of V-defects increases in the standard reference materials.

We find that avoiding the V-defect decoration of threading dislocations in the active region grows in importance as the emission wavelength is extended from the green into the deep green spectral region. When such defects are suppressed, the device performance in terms of LOP and reliability of such GaInN-based green and deep green LEDs, is significantly enhanced.

III. HOMOEPIXTIAL GROWTH ON NON-POLAR GaN SUBSTRATES

To reduce or avoid the electron-hole separation within the electric dipole of the piezoelectric QW, epitaxial growth of QW structures along crystallographic axes of GaN with either decreased or lacking piezoelectric polarization is highly preferable.[8],[9]

However, the absence of the piezoelectric dipole in the QWs also makes it more difficult to reach the longer wavelengths of green light emission in LEDs. The major challenge is therefore to incorporate a higher amount of indium into the GaInN/GaN QW in order to achieve a peak wavelength over 500 nm without introducing any crystallographic defects. After many series of growth optimization of GaInN/GaN active layers, we have achieved LEDs emitting in the green spectral region for both, non-polar $a$-axis and $m$-axis growth on native bulk GaN substrates. [10] – [13]

Fig. 7 Relative change in LOP after 168 hours in GaInN LEDs with and without V-defects as a function of forward current. A relative LOP value of 1 means a value equivalent to LOP before the stress test at each forward current for the same device.[7]

The actual alloy composition was determined from an analysis of the $0\text{-}20$ x-ray diffraction pattern around growth plane (11-20) and (10-10) for $a$- and $m$-plane LEDs, respectively. The actual QW thickness was determined by TEM and a model of strain anisotropy. Details of the method are described in Ref. 9. For instance, the d spacing of the zeroth peak of the GaInN/GaN active region for a 516 nm green m-plane LED as shown in Fig. 8, is 0.2776 nm while the value of the GaN substrate is 0.2761 nm. Since this zeroth peak represents an InN fraction averaged over wells and barriers the d spacing value can be written as

$$d = (d_w * Z_w + d_b * Z_b)/(Z_w + Z_b).$$

Here $d$ is the lattice spacing and $Z$ is the thickness of the layer, index $w$ stands for the QW and index $b$ stands for the GaN barrier. With thickness information from TEM, the actual value of $d_w$ is identified. This estimated $d_w$ is important to define the strain along the growth axis. Since there is no shear stress in this non-polar crystallographic system, the epitaxial layer can freely extend or contract along the growth direction. In the consequence, the stress in this direction vanishes. Therefore, the $m$-axis stress of GaInN QW with an InN fraction of $x$ can be assigned as follows:

$$C_{13}(x) * \varepsilon_{aa}(x) + C_{13}(x) * \varepsilon_{ag}(x) + C_{13}(x) * \varepsilon_{ma}(x) = 0 \quad (2)$$

Here, $\varepsilon_{aa}(x)$, $\varepsilon_{ag}(x)$, and $\varepsilon_{ma}(x)$ are interpolated strains along in-plane $c$-, in-plane $a$-, and growth direction $m$-axes as a function of $x$, respectively. $C_{13}(x)$ and $C_{33}(x)$ are the interpolated stiffness constants, also as a function of $x$. From the reciprocal space mapping, we have confirmed that the QW layers are
pseudomorphically grown on GaN. By solving the stress along the growth axis, it is possible to estimate the InN fraction of the QW layer in each $m$-axis grown device. Through the above calculation, we have derived an InN fraction of 18.6% for the 4.6 nm thick QWs in this $m$-plane green LED. For an $a$-plane LED, the stress along the growth axis is expressed as follows:

$$C_{12}(x)\varepsilon_{xx}(x) + C_{11}(x)\varepsilon_{yy}(x) + C_{13}(x)\varepsilon_{zz}(x) = 0 \ (3)$$

With the anisotropic stress model, we have concluded the correlation between PL peak wavelength and InN fraction in $a$- and $m$-plane GaInN/GaN MQWs in Fig. 9, respectively. In order to achieve an emission peak wavelength beyond 500 nm, a minimum InN-fraction of ~14% is needed for $a$-plane QWs and ~12% for $m$-plane QWs, while ~8% are enough for 3 nm thick $c$-plane QWs. However, the green light emission (wavelength > 500 nm) can be retrieved by increasing either the InN-fraction $x$ or the well width $Z_w$.

Fig. 10 summarizes device performance of $a$-plane LEDs in a direct comparison of a green $a$-axis LED grown on an $a$-plane GaN template on $r$-plane sapphire and one on an $a$-plane bulk GaN. The dominant wavelength reaches up to 535 nm in the bulk-based sample and interestingly increases slightly with current density, which is opposite to the performance of $c$-axis polar material (Fig. 10(a)). The light output power reaches 160 $\mu$W in the same sample, three times as high as that of the sapphire based one (Fig. 10(b)). The external quantum efficiencies in these bare dies, as measured through the substrate side, are still quite low and actually do drop with current density (Fig. 10(c)). A contribution in this drop is certainly die heating due to the low electrical conductivity of the substrate used here as an n-layer and possibly also due to early development stages of p-type doping in $a$-axis growth.

EL performance of a blue-green and a green $m$-axis LED is summarized in Fig. 11. These LEDs were driven up to 30 A/cm². The 489 nm, 494 nm, and 511 nm LEDs (sample A, B and C) reach maximum partial LOPs of 4.5 mW, 1.3 mW, and 0.2 mW, respectively (Fig. 11(a)). LOP of a 490 nm LED, as measured on bare fabricated but unencapsulated (350 $\mu$m) dies through the substrate manifests comparable achievement levels of several mW at 35 A/cm². However, there is a roll-off of LOP stretching over nearly two orders of magnitude as the emission wavelength extends from 480 nm to 510 nm. A similar trend has

Fig. 9 PL peak emission wavelength of GaInN/GaN MQW grown on $a$-plane GaN (a) and $m$-plane GaN (b). $Z_w$ indicates the thickness of the GaInN layer.[11]

Fig. 10 EL performance of $a$-axis grown LEDs on $a$-plane bulk GaN in comparison with one on $r$-plane sapphire. Device area is 1 mm in diameter.[10]

Fig. 11 EL performance of $m$-axis grown LEDs on $m$-plane bulk for dominant wavelength of 483 nm (A), 494 nm (B), and 511 nm (C).[13]
also been observed in the internal quantum efficiency of the active region. After characterizing the structural quality of the GaInN/GaN active layers by TEM, we tentatively attribute these efficiency losses to an increasing density of defects in the longer wavelength LEDs. Further improvements in epitaxial processes should allow to overcome such problems.

An important aspect of the non-polar m-plane LEDs is their stable emission wavelength (Fig. 11 (b)). Up to 30 Å/cm², the dominant wavelength of samples A, B and C shows a blue shift of not more than 3 nm. For comparison, in our 510 nm c-plane LEDs, the dominant wavelength typically shows a blue shift up to 12 nm when varying injection current within the same range.

**SUMMARY**

Defect reduction and strive for utmost alloy uniformity prove to be successful factors for the achievement of GaInN/GaN LEDs spanning the green spectral region. Reduction of V-defect decoration of existing threading dislocations is the significant steps towards this goal. Upon the availability of thick GaN bulk pieces, slices of arbitrary crystal orientation can be prepared and utilized as native substrates for homoepitaxy. By tilting the epitaxial growth direction away from the common c-axis growth direction, avoidance of piezoelectric polarization becomes possible. We demonstrate achievement of green LEDs homoepitaxially grown along non-polar a-axis and m-axis of GaN. In absence of this polarization dipole, emission wavelength proves widely unaffected by variation of LED drive current.

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**REFERENCES**