Title: High Performance Green LEDs by Homoepitaxial MOVPE – Final Report

Prime Recipient: Rensselaer Polytechnic Institute

Agreement Number: DE-FC26-06NT42860
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EXECUTIVE SUMMARY

This work's objective was the development of processes to double or triple the light output power from green and deep green (525 - 555 nm) AlGaInN light emitting diode (LED) dies within 3 years in reference to the Lumileds Luxeon II. The project paid particular effort to all aspects of the internal generation efficiency of light.

LEDs in this spectral region show the highest potential for significant performance boosts and enable the realization of phosphor-free white LEDs comprised by red-green-blue LED modules. Such modules will perform at and outperform the efficacy target projections for white-light LED systems in the Department of Energy's accelerated roadmap of the SSL initiative.

GOALS AND ACCOMPLISHMENTS

This work's objective was the development of processes to double or triple the light output power from green and deep green (525 - 555 nm) AlGaInN light emitting diode (LED) dies within 3 years in reference to the Lumileds Luxeon II. The project paid particular effort to all aspects of the internal generation efficiency of light. This implies that no particular effort was paid to enhance the light extraction efficiency but instead concentrate on bare LED epi processes.

The corresponding target was quantified in terms of achievement of 5 – 7.5 mW at 525 nm bare epi-up die at 20 mA.

The means for achievements were continued reduction of structural defects and optimization of the piezoelectric polarization by employing low-dislocation-density bulk GaN templates of various crystallographic orientations.

By the end of the project, a performance of 3.7 mW at 545 nm in bare epi-up die at 20 mA was achieved. According to the correlation of power with wavelength, such that performance can be interpolated to an expected 5.2 mW at 525 nm. This demonstrates accomplishment of the project targets. From the rate of progress, the achievement of further ambitious goals in the future are extremely likely.

The target performance was achieved in *c*-plane oriented epitaxial growth on nano-patterned substrate. While an enhancement of the light output power due to enhanced light extraction in these structures is likely, evidence strongly suggests that a major contribution in the enhancement by the nano-patterned substrate is an improvement to the internal quantum efficiency. That would squarely fall into the objectives of this project.

The approaches of polarization control by means of non-polar substrate orientation resulted in green and deep green LEDs with highly desirable properties, such as an emission wavelength that does not vary with drive current. Another promising aspect is evidence of reduced droop in *m*-plane growth with higher drive current density. An overall light output and efficiency advantage over polar material, however cannot be claimed within this project. This is most likely not a limitation inherent to the studied crystal orientations but rather an indication of insufficient development of growth technologies for those particular growth planes. Further improvement by growth of such structures therefore is extremely likely.

Highlights of significant achievements include the following:

- Nano-patterned sapphire substrates, triples the light output power at 537 nm to 6 mW at 12.7 A/cm^2 in scratch diode geometry (November 2008).
- Wavelength-stable cyan LEDs in non-polar *m*-plane growth (February 2009).

- Misfit dislocation-free MQW growth on *m*-plane GaN up to a wavelength of 480 nm (May 2009).
- Wavelength-stable green LEDs in non-polar *m*-plane growth (April 2009).
- Wavelength-stable 481 nm, 1-mW blue LEDs in semi-polar (11-22)-plane growth (March 2009).
- Epi growth on nano-patterned sapphire substrate boosts light output power up to 3x by primarily boosting the internal quantum efficiency (April 2009).
- 481 nm blue-green LED on semipolar GaN with mW class LOP (June 2009).
- 580 nm yellow LED on *c*-plane bulk GaN with half mW class LOP (July 2009).
- (11-22) semipolar GaN structures on *m*-plane sapphire (August 2009).
- LEDs on nano-patterned sapphire substrate boosts efficiency 150% at 545 nm (September 2009).
- LED die mounting on header brings reaches the 5 mW / 525 nm / 20 mA regime (December 2009).

In the international competition, this project was the first to publish green emitting quantum wells on any non-polar growth plane of GaN, i.e. *m*-plane and *a*- plane. The same record holds for the first *a*-plane green LED. The latter record has so far been unbroken. For green *m*-plane LED on bulk GaN a close tie was achieved with one other US-based group.

SUMMARY OF PROJECT ACTIVITIES

This project addressed the challenges in novel and unique ways. The team's prior experience in the development of high performance green LED die processes provided strong evidence that – unlike for the development of blue LEDs – structural defects act as an important detriment to the performance of green LEDs. Consequently this team has proposed

a) to develop bulk GaN substrates with low dislocation density and turn them into epi-ready substrates;
b) to maintain the substrate's dislocation density throughout the active epi region;
c) to control the piezoelectric polarization by crystallographic orientation of the bulk substrate;

To achieve these goals, six distinct but interdependent tasks had been identified:

- Performance yield spectroscopy,
- Precursor efficiency optimized MOVPE,
- Polarization controlled low dislocation density GaN substrates,
- Nano-textured nucleation layer growth, and
- Polarization-optimized green and deep green LED dies.

This team is proud of its achievements summarized in the sequence of the above tasks. Listed also are the primary investigators performing work under the respective topics including its reporting.

Task 1: Performance yield spectroscopy

Yufeng Li and Christian Wetzel

This task's goal is to separate the electronic and optical processes in green LEDs. The understanding of the well-known performance droop in GaInN/GaN heterostructure LEDs under increasing current density in general and the overall lower efficiency in green and deep green LEDs in particular must hold the critical clues for any performance improvements. The task seeks answers to these questions: Is the droop a property of the electronic carrier injection, such as related to carrier transport? Or is the droop an effect in the domain of the generated photons?

To answer those questions we have combined electrical excitation and photo excitation on the same location of LED devices, i.e. applied a photon bias to LEDs under electrical operation. We find that the LED light output performance as a function of current when scanned over several orders of magnitude up to high power operation current densities of LED lamps can substantially be enhanced by the photon bias, up to a factor of 1.75 (note, this is not intended to be a method to enhance device performance, it rather is a way of characterizing the material).

Figure 1 shows three microphotographs of an LED sample under 408 nm laser excitation (photoluminescence, PL) (Fig 1a), under electrical injection only (electroluminescence, EL) (Fig. 1b), and under both excitations simultaneously (Fig 1c). All photographs use the identical intensity scale. While on this scale, no PL can be seen (Fig 1a), substantial enhancement is seen to the EL by comparison of Fig. 1c with Fig. 1b. The biggest differences can be seen in the darker areas of Fig. 1b. Figure 2 shows the same effect presented in the emission spectra. Here, a quantitative assessment can be made: Under photon bias, EL is enhanced by 75 %.

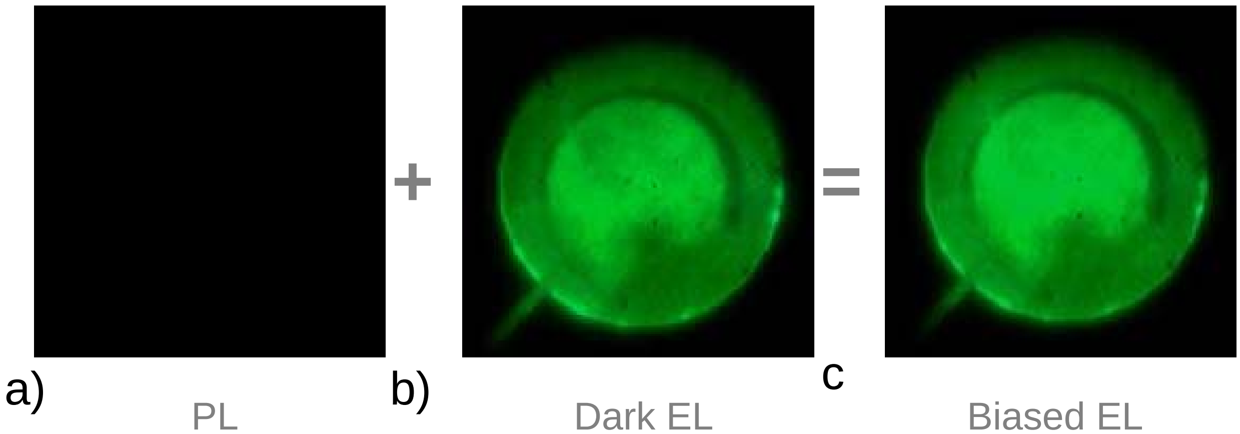


Figure 1*: Microphotographs under constant exposure conditions of PL (a), EL (b) and combined electrical and photon excitation of a 100 µm diameter green LED. By help of the photon bias that by itself would not result in significant PL, EL is substantially enhanced.*

The effect has been studied under various photon wavelengths such as 325, 408, and 488 nm and we find the following very general correlation: The higher the internal quantum efficiency of an LED, as determined from low-temperature PL, the higher the EL enhancement factors.

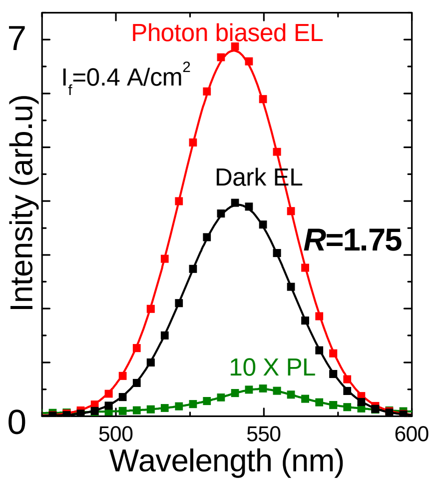


Figure 2*: Luminescence spectra under 408 nm photon excitation (PL, green), under electrical injection (EL, black), and under combination of photon and electrical injection (photon biased EL, red). The latter shows a 75% intensity enhancement over the EL alone.*

We furthermore find, that for all those photon wavelengths, that directly excite the QWs but not he barriers, the relative EL enhancement follows through a maximum as a function of drive current that strongly resembles the maximum of the LED efficiency and its characteristic droop. In fact, results of a proper scaling of both excitation densities to each other indicate, that in both cases we monitor the identical efficiency maximum. Such a correlation has a priori been assumed in a study by researchers at Philips Lumileds, whom we regularly keep informed about our project plans, progress, and developments. In Appl. Phys. Lett. **91**, 141101 (2007), Y.C. Shen *et al*. achieved such an efficiency droop under purely optical excitation. This would indicate that the problem of performance droop should not be a result of the electrical injection itself, but possibly lie in the level of dynamical carrier densities or later, after recombination, in the photonic side of the device. In this work the authors argue for an origin of the droop in non-radiative Auger recombination under high injection levels. An alternate interpretation published by members of this team is assumed in enhanced carrier overflow into the p-side due to a piezoelectric field limited recombination in the quantum wells (M.-H. Kim *et al*. Appl. Phys. Lett. **91**, 183507 (2007)).

In further analysis of our results across different samples and excitation conditions, we find, that the current density of maximum EL enhancement scales closely with the threshold current below which the LED reverts to a solar cell with a relevant reverse current (Fig. 3). This is equivalent with a statement that the better performing LED is also the better performing solar cell under their respective appropriate bias conditions. From this we conclude that the loss mechanisms acting in this range of the efficiency maximum of the LED can simply by described by a shunt current path. Figure 3 gives an interpretation of the respective current voltage characteristics in terms of a shunt resistance. Values of 100 – 200 k Ω are obtained in this way across different LEDs and different photon bias conditions.

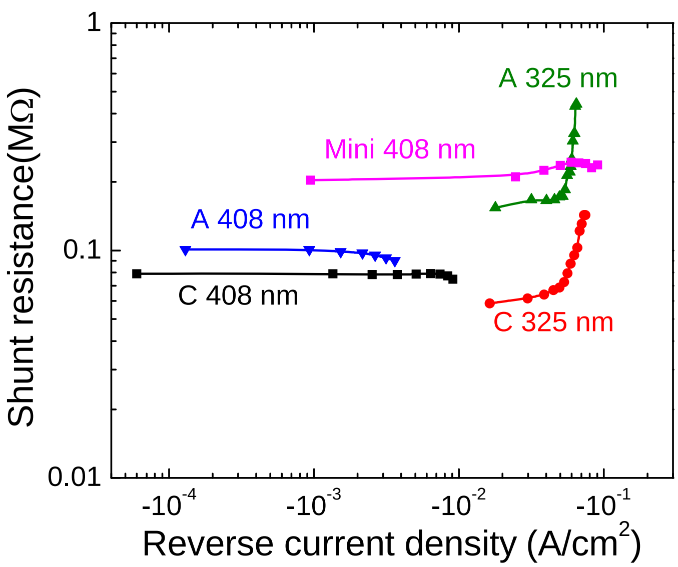


Figure 3*: Shunt resistance of 3 green LEDs: A (high efficacy), C (low efficacy) and Mini (100 µm diameter) as a function of reverse current as determined under a photon bias of various wavelengths. The shunt resistance is consistently higher in the better performing LED.*

The correlation of photo-enhanced EL and reversion to solar cell operation can be explained in a simple carrier balance model. Figure 4 (a) shows the sketch of the LED structure: n-GaN; active region; p-AlGaN; and p-GaN. (b) and (c) show the charges in both the active region and the p-GaN when the LED is under small and large forward bias, respectively. Arrows indicate the direction of the carrier movement. By photo generation, electron-hole dipoles are generated that locally screen the piezoelectric polarization and its associated local potential barriers. This is evidenced in the reduction of forward voltage and EL blue shift under photo bias. In the consequence wave functions the overlap in the quantum wells is increased and the radiative recombination is enhanced improved.

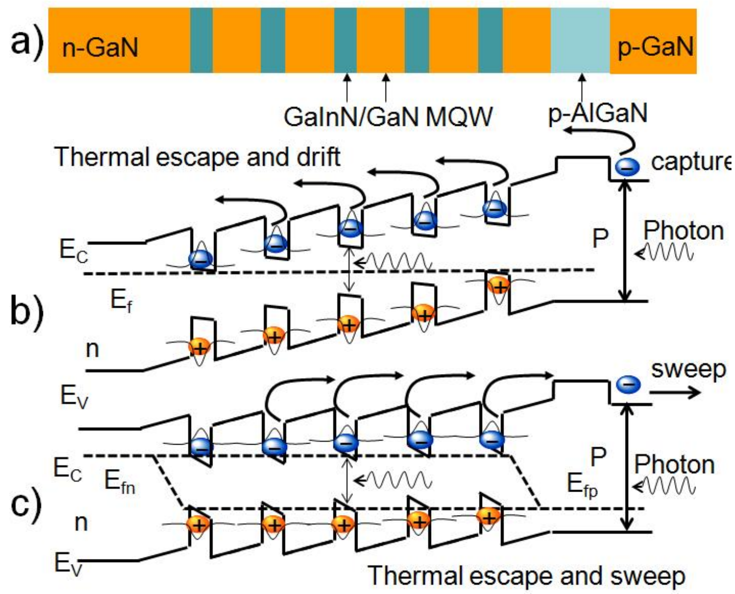


Figure 4: *Sketch of the structure of LED (a); Carrier dynamics under small forward bias (b), and large (c) forward bias.*

Comparing further details of the model with the experiments, we find a delicate balance of photocarriers being either drawn in reverse direction by the built-in junction field or in forward direction by the applied external bias. Within this balance there apparently is an ideal situation where electrons and holes are kept in the balance for an enhanced radiative recombination. This picture is consistent with models ascribing the efficiency droop to a carrier overflow into the p-region.

Milestone Discussion

Milestone A - Obtain LED performance enhancing modulation under external modulation.
Planned Date: February 2007
Description & Verification Method: By help of external modulation, create a condition that enhances device efficacy over 10 lm/W at 525 – 560 nm in bare epi-up die at 36 A/cm^2.

Achieved Performance: At 36 A/cm^2 (26 mA) the unencapsulated, epi-up, bare die sample C with a peak wavelength of 525 nm has an efficacy of 4.65 l/W (LpW). Under standard packaging and flip chip mounting, this scales to 10.7 l/W. At 0.5 A/cm^2, we find an 11-fold efficacy enhancement. At 14 A/cm^2, we observe an actual decrease to a factor of 0.996. Our current accuracy cannot yet identify a variation at a current density of 36 A/cm^2. The strong increase at low current and slight decrease at 14 A/cm^2 are valuable indications nevertheless.
Achievement Date: April 2007

Milestone C - Derive LED design rules from performance yield spectroscopy.
Planned Date: August 2007
Description & Verification Method: Demonstrate that an efficacy enhancement achieved by external modulation can be translated into an efficacy enhancement in an LED structure. An example is enhancement from 10 lm/W to 12 lm/W at 525 – 560 nm at 36 A/cm^2.

Achievement: Light output power enhancements was demonstrated in green and blue LEDs at current densities of up to ~6 A/cm^2. This number in principle can be enhanced by better optical suppression of light emission in unmodulated parts of the LED.
Achievement Date: September 2007

Task 2: Precursor optimized MOVPE

Theeradetch Detchprohm and Christian Wetzel

This task aims to implement our green LED process into improved MOVPE equipment. The process is characterized by polar *c*-axis grown LED structures on *c*-plane sapphire substrate. Progress of green and deep green LED epi has been good and steady. In our group, some wafers have been fabricated into dies of variable size including (350 µm)^2 and (700 µm)^2 with a mesa area of (300 µm)^2 and (600 µm)^2, respectively. Figure 5 shows the analysis of those deep green dies under pulsed current of 50 µs length at 1 % duty cycle. Dies have not been separated and all power measurements were performed at a wafer level through the substrate into the 1 cm orifice of an integration sphere connected to an intensity-calibrated spectrometer. This is indicated by the prefix “partial” in the axis labels. Typical; fractions of 30% — 50% of the full value are measured only in this way. Such measurements are commonly referred to as "wafer-level" measurement. The pulsed operation conditions are a reasonable approximation to a good thermal packaging to separated and thinned dies.

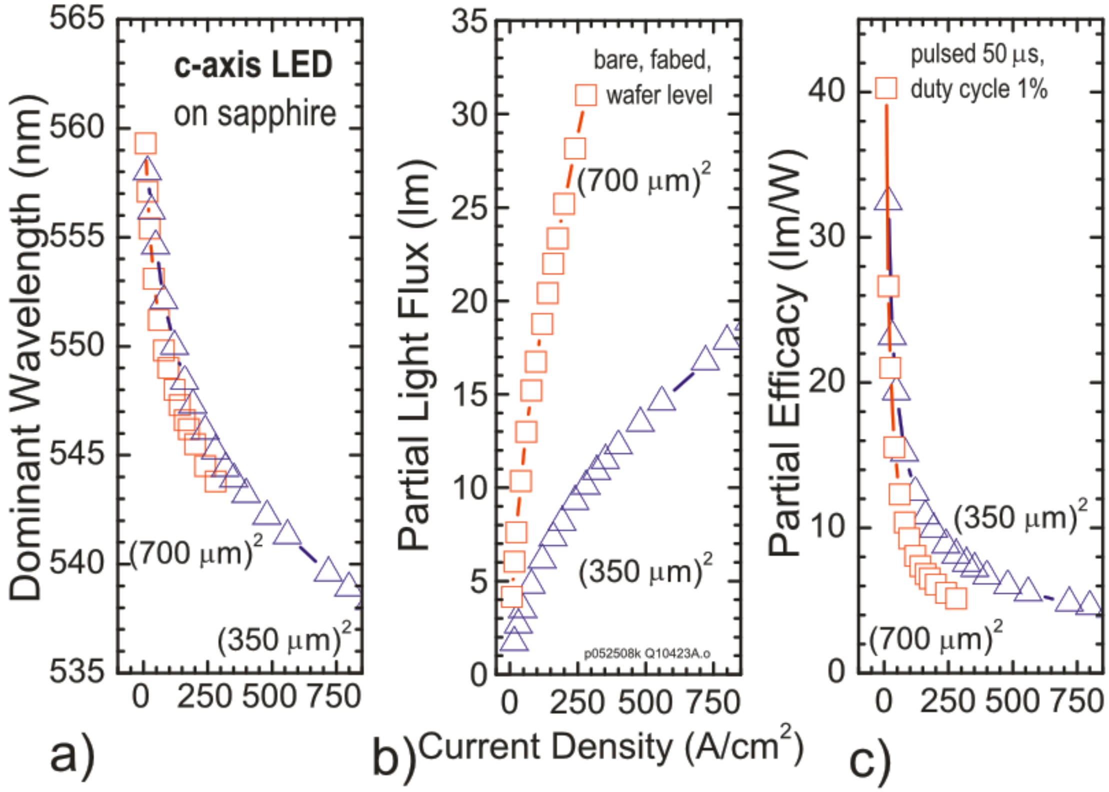


Figure 5*: Light output performance of bare, fabricated deep green LED dies on a wafer level under pulsed current. a) Dominant wavelength; b) partial light flux; c) partial efficacy. Partial refers to the fraction collected in a 1 cm orifice through the substrate side.*

Apparently, current densities up to 780 A/cm^2 could be sustained in a pulsed operation mode. The typical 1-W high power LED lamp is quoted at 350 mA in a (1 mm)^2 chip, corresponding to about 35 – 50 A/cm^2. In this measurement, we substantially exceed these values. Even at the highest current density of 780 A/cm^2, the dominant wavelength stays above 536 nm (Fig. 5a). The partial light flux in the bare die as measured through the substrate reaches 31 lm in the larger die and 22 lm in the smaller one (Fig. 5b). The partial efficacy still shows the well-known droop in these polar *c*-axis structures (Fig. 5c). A peak efficacy of 40 lm/W is measured at 6 A/cm^2 and a minimum of 5 lm/W in the small die and 4 lm/W in the large die, both at 700 mA. At the standard conditions of the 1-W device, that have also been used in the milestone definition of 36 A/cm^2, we measure a dominant wavelength of 551 nm, a light flux of 12 lm in the larger die, and 3.5 lm in the smaller die. The luminous efficacy of 13.6 lm/W is achieved in the small die and 18.8 lm/W in the large die. This establishes accomplishment of Milestone E.

A set of green and deep green epi wafers was provided to Philips Lumileds for evaluation with Lumileds' established methods. Figure 6 shows the results of a determination of the internal quantum efficiency (IQE) using temperature and laser power dependent photoluminescence (PL) spectroscopy. Figure 6a) shows the PL intensity of a 530 nm green and a 555 nm deep green wafer as a function of temperature. As an excitation source, a 405 nm laser with a maximum power of 800 mW was used for resonant excitation directly in the quantum wells. This avoids the problem of quantification of the fraction of carrier trapping into the wells. Per common approach, the maximum of the PL intensity was assigned with the reasonably achievable theoretical maximum of ~ 100% of internal quantum efficiency. Compared to this value, the 530 nm wafer shows at 40% efficiency at room temperature while the 555 nm wafer shows a 10% efficiency. These are very good results! Figure 6b) shows the variation of the PL intensity at room temperature under variation of the excitation laser power. Besides the conditions used in Figure 6a) (1% excitation power), there are conditions that would produce slightly higher efficiencies at higher excitation densities. These graphs show a maximum that can reasonably be assumed to parallel the maximum of EQE as a function of current density.

The electroluminescence data measured at the bare wafer level in scratch diode geometry as a function of current density shown in Figure 7a) therefore can be scaled to IQE data obtained from Figures 6 as shown on in Figure 7a) for a larger set of samples. Using this current density behavior, the IQE performance of the wafers can be estimated also at the typical operation point of high power LEDs, i.e., 50 A/cm^2. This is shown in Figure 7b) for various sample spots of the wafers as a function of peak emission wavelength. Apparently, under such high power operating conditions we achieve IQE values of 20% at 530 nm and 9% at 555 nm. Extrapolated to the lower current densities, quoted in DOE MYPP 2010, we find values of 27% at 530 nm and 11% at 555 nm. These values are really quiet impressive and received the compliments from the Philips Lumileds scientists.

This external quantification of our progress provides the relevant important performance metrics for our in-house wafer progress evaluation.

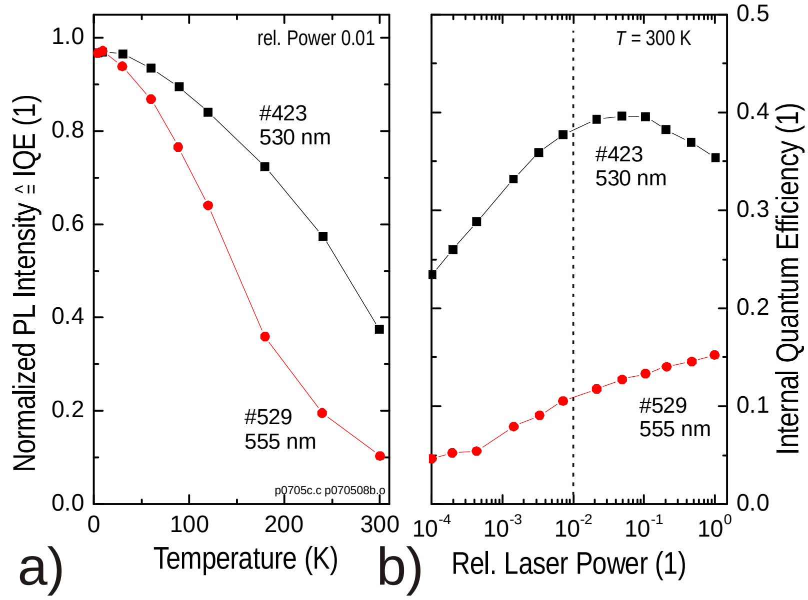


Figure 6*: Photoluminescence in two green and deep green LED epi wafer. a) QW PL intensity as a function of temperature normalized to the theoretical maximum at low temperature under 1% of full pump laser excitation. b) The same at room temperature under variation of laser power density. Together they allow a scaling of the internal quantum efficiency (right hand axis)*

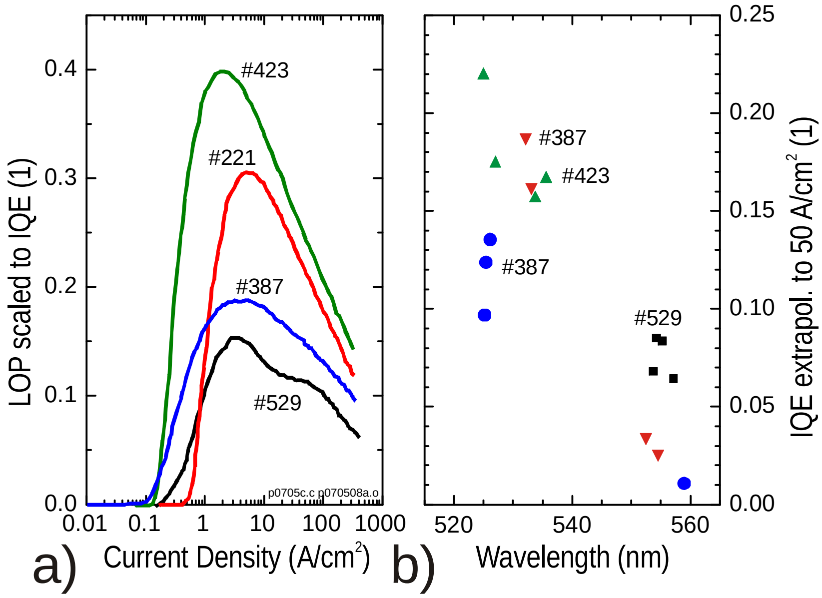


Figure 7*: Light output power of various green and deep green epi wafers scaled in terms of the internal quantum efficiency. a) As a function of current density in scratch diode geometry when scaling their LOP maximum to the IQE maximum as a function of laser power. b) IQE of locations on various wafers as shown in a) analyzed to typical high power LED operation conditions of 50 A/cm^2. Values of 20% are obtained at 530 nm and 9% at 555 nm.*

Milestone Discussion

Milestone E - Achievement of 13 lm/W at 525 – 560 nm in bare epi-up die at 36 A/cm^2 in newly optimized MOVPE.

Planned Date: February 2008

Description & Verification Method: Performance of epi material is demonstrated by achievement of 13 lm/W at 525 – 560 nm in bare epi-up (350 μm)^2 die at 36 A/cm^2 after standard processing..
Achievement: At 36 A/cm^2 in bare epi-up (350 μm)^2 die, a dominant emission of 551 nm was achieved at a luminous efficacy of 13.6 lm/W. Considering the very long wavelength in comparison to the width of the target from 525 – 560 nm, this achievement by far exceeds the minimum requirements.
Achievement Date: May 2008

Task 3: Polarization controlled bulk growth

Drew Hanser and Christian Wetzel

A primary tenet for this project is the availability of bulk GaN as an ideal substrate for high performance AlGaInN-based epitaxially grown devices, in particular green LEDs. Kyma Technologies Inc. can achieve thick GaN film growth on foreign substrate that, after substrate removal, can be treated as freestanding bulk GaN with uniformly very low treading dislocation densities around $5x10^6$ cm^{-2}. The availability of such thick *c*-axis grown material also allows for the slicing of wafer bars of virtually arbitrary crystal orientation including non-polar *m*-plane and *a*-plane material.

In the course of this project, development for the non-polar (*a*-plane and *m*-plane) substrates has proceeded in three different areas: crystal growth for improved substrates; orientation control of substrates sliced from bulk crystals; and surface preparation of non-polar substrates.

Crystal growth development has focused on increasing the thickness of the GaN crystal grown in the *c*-direction. The non-polar substrate size is primarily limited by the size of the crystal grown in this direction, and the number of defects (such as cracks and polycrystalline regions) encountered in the direction perpendicular to the *c*-direction. Overcoming these limitations involves improvements and optimization of the GaN crystal growth initiated on sapphire seeds. Control of the growth stress that builds up in the crystal over >5 mm thickness has been the primary challenge.

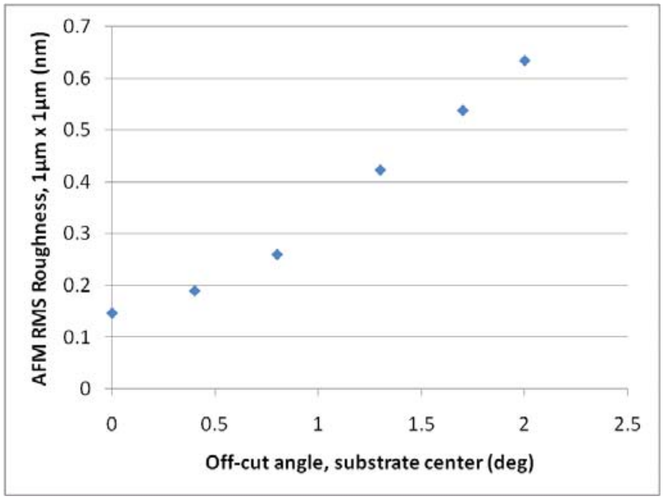


Figure 8*: Roughness of the CMP-prepared surface of c-plane bulk GaN as a function of off-cut angle as currently achieved by Kyma. Our working hypothesis is that a similar relation holds for the non-polar material and that therefore better angle control will help achieve smoother m-, and a-plane material*

A big impact on the roughness of the epilayer seems to stem from the off-cut of the substrate. Figure 8 shows the AFM roughness vs. off-cut angle as measured by X-ray diffraction for *c*-plane substrates. There appears to be a good correlation. There is good reason to assume, that the same holds for the non-polar surfaces of the *a*-plane and the *m*-plane materials. Consequently, we have focused substantial efforts to improve the off-cut angle control. A major leap was achieved by the acquisition of a multi-wire saw, the development of alignment hardware, and procedures that allow for precise X-ray measurement of the crystal alignment, and the repeatable translation of this alignment to the wire saw for high angular control during cutting. Process optimization of the cutting procedure on the wire saw, along with the implementation of the alignment hardware enabled the demonstration of alignment to < ±0.1º via X-ray diffraction, and off-axis control in the *c*-direction and *a*-direction of < ±0.25º for *m*-plane substrates after cutting on the multi-wire saw. Kyma is now implementing these new procedures in all its non-polar substrate cutting processes.

A big role also must be assigned to the role of the substrate surface preparation. Kyma and RPI therefore worked on repeated iteration loops to identify the proper surface preparation and cleaning procedures to allow best possible growth initiation. The crucial parameters include the residual roughness after chemical mechanical polishing (CMP), polishing scratches and contamination induced by CMP and contamination resulting from the polishing process. Furthermore, a high degree of off-cut angle variation (>±0.5º) in the non-polar substrates has ultimately been identified as a cause for complications in the epitaxial overgrowth as directly measured as a large surface roughness.

As a result, Kyma has been working on improvements such as the multi-wire saw and hardware that has shown to improve the crystal alignment and reduce the off-cut angle variation. Along with these improvements, additional characterization steps have been implemented to more completely evaluate the surface finish following the CMP processing. Now, additional optical microscopy and atomic force microscopy imaging are used to characterize the surfaces and identify known and potentially new issues. Additional characterization via cathodoluminescence imaging has been used to evaluate surface and sub-surface damage in the substrates.

Over the course of the project, Kyma has prepared and delivered polar *c*-plane, non-polar *m*-plane and *a*-plane, as well as various semipolar GaN wafers at the area equivalent of 8.3 full 2" wafers (Figure 9). Table 1 lists the details of total and usable area per wafer orientation.

Table 1*: A Tally of bulk GaN wafer of different orientations in fractions of 2"-wafers delivered by Kyma Technologies over the course of the project.t*

Orientation	Total delivered area as a fraction to 2" wafer	Total usable area as a fraction to 2" wafer (1mm edge exclusion)
C	2.07	1.68
A	1.25	0.97
M	2.69	2.00
(10-11)	0.80	0.63
(10-13)	0.64	0.54
(20-21)	0.64	0.52
(11-22)	0.24	0.17

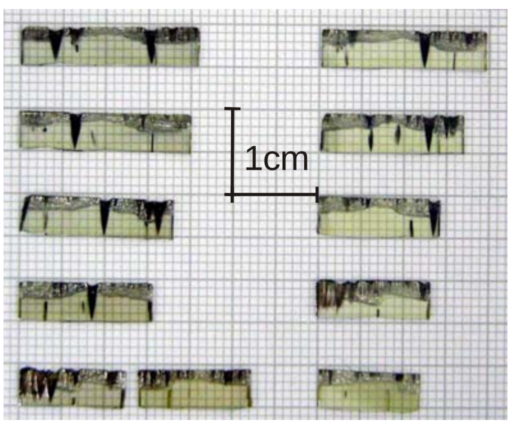


Figure 9*: m-plane wafer as delivered by Kyma. Bars are 4 mm in height.*

Fabrication typically follows this procedure: The crystalline directions in the boule were identified via X-ray diffraction prior to slicing on a fixed-abrasive multi-wire saw. After slicing, X-ray diffraction was used to measure the crystalline properties of the substrate. From the ω scan angle offset in rocking curve data, the on-axis accuracy is determined, typically found to lie within $< \pm 0.25^o$ in both, the polar and non-polar directions. The data also usually shows no substantially lattice tilting along the in-plane polar and non-polar axes, indicating a high degree of crystalline orientation and alignment within the substrate.

Following the slicing, substrates were prepared for an epi-ready growth surface. Where needed, a 30-µm diamond lap was used to planarize and flatten the substrates to a thickness of 475 µm with a variation of ± 5 µm across each piece. Then a 4-µm diamond mechanical polishing, and a chemical-mechanical polishing (CMP) followed. CMP removal rates were found to differ between crystallographic surfaces, and process times had to be adjusted. Atomic force microscopy of the prepared *a*- and *m*-plane surfaces reveal roughness values of ~0.2 nm (RMS), which are comparable to those obtained on Ga-face (0001) *c*-plane substrates.

Monochromatic cathodoluminescence maps were used to count dislocation densities (Figure 10 b) and c) of a prepared *m*-plane substrate as shown in the optical micrograph (Figure 10 a), different scale). Similar dislocations densities of $8x10^5$ cm^{-2} were determined in both images within the exited near-surface volume with non-radiative recombination characteristics. The optical micrograph also shows regions of discoloration along the upper edge (Figure1 a) that correspond to regions near large pitting defects. These defects are common to the growth process employed here and in part are desired as an effective mechanism of large scale lattice relaxation. CL in an area near such a defect is shown in Figure 10 b). The dislocation density is found unaffected by the presence of these defects. The decrease of emission intensity itself is likely caused by point defects associated with the pits boosting non-radiative recombination.

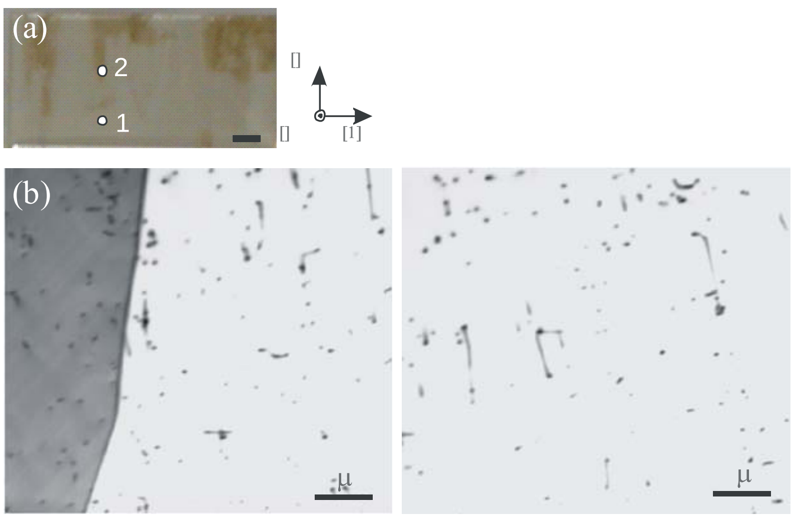


Figure 10*: (a) Optical micrograph of an m-plane substrate sliced from a GaN boule. (b) and (c) panchromatic CL images taken from spots 2 and 1, respectively, as indicated in (a).*

All measurements of dislocation densities via CL imaging on these and other epi-ready non-polar substrate surfaces met the development target of $<5x10^6$ cm^{-2}.

Previous work found that for *m*-plane material, a slight offcut of ±0.2° in the [0001] direction and ±0.25° in the [11$\underline{2}$0] direction can result in improved morphology of epitaxial layers. Besides, the miscut itself, its maintenance across the size of the substrate needs to be maintained. This proves a particular challenge in the small sample sizes of the non-polar substrates, where edge-effects from the polishing process can result in a cushion shaping of the substrate. Such data cannot be obtained from standard X-ray diffraction since it is a property of the surface. Therefore, white light interferometry (WLI) was employed to measure the parallel flatness of the substrate (Figure 11). Software was developed to combine the WLI surface shape map with the XRD off-cut data to calculate the total off-cut and to identify wafer regions within the specifications. Analysis of the shown substrate resulted in a crystal lattice off-cut in the [11$\underline{2}$0] direction of ±0.1° and as large as 0.7° (mean <0.3°) in the [0001] direction as measured across the substrate.

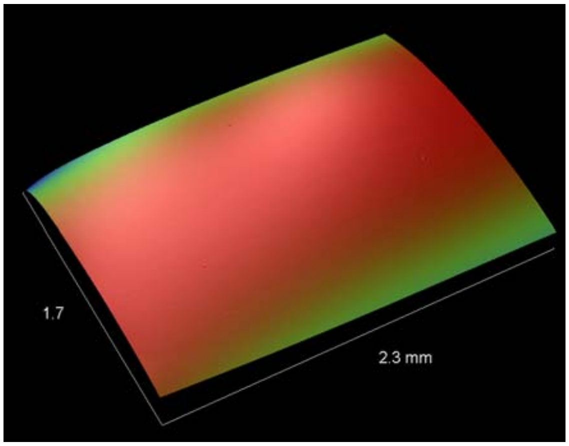


Figure 11*: White light interferometry map of a region of the surface of an m-plane GaN substrate. The color scale indicates a beveling of the wafer surface towards the edges. This is the result of the polishing process on the small sample pieces.*

Per our rapid progress with non-polar *a*-plane and *m*-plane GaN, Kyma also developed (10-13), (10-11), (20-21) (110-1) and (11-22) oriented semi-polar GaN substrates of sizes 5 mm x 50 mm. Growth on such planes will not result in non-polar growth, but polarization will be somewhere in between polar and non-polar. Unlike non-polar *a*- and *m*-plane orientations studied earlier, growth planes are at an angle between 20 and 40 degrees to the *c*-axis promising polarization strengths about half that of the *c*-plane. By reducing rather than eliminating the polarization, we hope is to push the sweet spot of LED from the blue to longer wavelengths.

As a first step, GaN layer growth was attempted on all of them with relevant first success for a subset thereof. Initial growth runs proved suitable for smooth surface morphology as judged from optical microscope and AFM for a subset of samples. Interestingly, QW growth however shows a saw tooth structure of regular nm-sized steps. The growth orientation seems to be particularly suited for green emitters, efficiency, however is not yet up to par.

Milestone discussion

Milestone B - Homoepitaxial LED with $<3x10^8$ cm^{-2} V-defect density in the active region.
Planned Date: February 2007
Description & Verification Method: Achievement is demonstrated by homoepitaxial LED with $<3x10^8$ cm^{-2} V-defect density in the active region assessed by plane-view TEM, CL imaging, and AFM etch pit density.

Achieved Performance: The crystalline quality of homoepitaxial LED dies has been assessed using plan view TEM micrographs and CL mapping. CL mapping finds values of $7x10^4$ to $3.6x10^5$ cm^{-2} when measured on the p-side. Not all defects show up in CL. From plan view TEM from the p-side a V-defect density of 1.4×10^8 cm^{-2} or below is being determined. Values of the active region should generally be lower than those values of the p-side.
Achievement Date: April 2007.

Milestone H1 - Reduce defect density on epi-ready surface of bulk nitride substrate to $< 5x10^6$ cm^{-2}.
Planned Date: August 2008

Description & Verification Method: Achievement is demonstrated by defect density on epi-ready surface of bulk nitride substrate of < $5x10^6$ cm^{-2}. Dislocation density will be assessed by plane-view TEM, CL imaging, and AFM etch pit density.

Achievement: Data provided by Kyma reveals that in panchromatic CL images dislocation densities of about $8x10^5$ cm^{-2} were achieved in non-polar *m*-plane bulk GaN. This establishes accomplishment of the milestone.
Achievement Date: August 2008.

Task 4: Nano-textured nucleation layer growth

Wonseok Lee, Jaehee Cho, Kaixuan Chen, Jong Kyu Kim, and E. Fred Schubert; edited by C. Wetzel

In reference to the proposed task in general support of green LEDs, this sub-team has developed and investigated the following subtasks:

- Ray-tracing simulations of LED structures for light-extraction efficiency
  - flat sapphire/GaN interface
  - micro-patterned sapphire/GaN interface
  - nano-patterned sapphire/GaN interface
  - area-scaling of the above.
- Patterning of sapphire substrates
  - lithographical patterning
  - nano-imprint patterning

Ray-tracing simulation of LEDs with patterned sapphire substrates

Performance of LEDs can be attributed to the product of the factors of internal quantum efficiency of the active region and light-extraction efficiency. While the former reflects the crystal quality of an epitaxially grown structure, the latter strongly depends on the particular geometric design of an LED. Modeling tools such as the ray-tracing technique can simulate the light-extraction efficiency and so foresee approaches to enhance light extraction.

Ray-tracing simulation has been performed with varying pattern sizes and etching depths in checkerboard shaped nano-patterns. The maximum predicted enhancement in light extraction efficiency due to patterning of the sapphire substrate was found to be 65%. Effects of pattern size, etching depth and sidewall angle are shown in Figure 12.

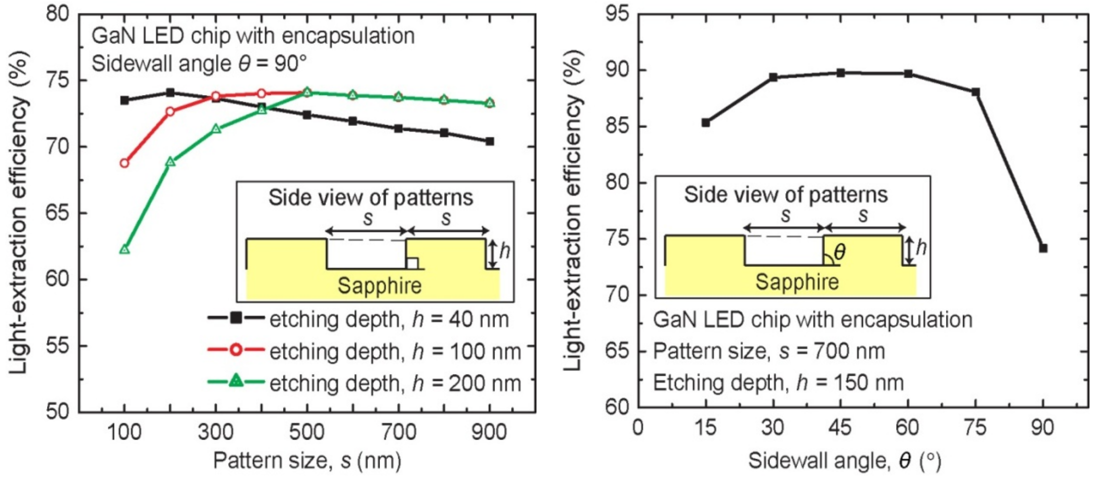


Figure 12*: Ray-tracing simulations of light extraction efficiency of GaN LEDs on patterned sapphire substrates epoxy encapsulated (left) with varying pattern sizes and etch depth and (right) with varying sidewall angles. Insets show schematic side views of the patterned substrate assumed.*

For circular-shaped pillars in a hexagonal pattern, we find a higher light extraction efficiency than from square-shaped pillars (Figure 13). The light extraction efficiency increases as the pattern size decreases and etch depth increases. Therefore, a high aspect ratio of etch depth to feature size is important.

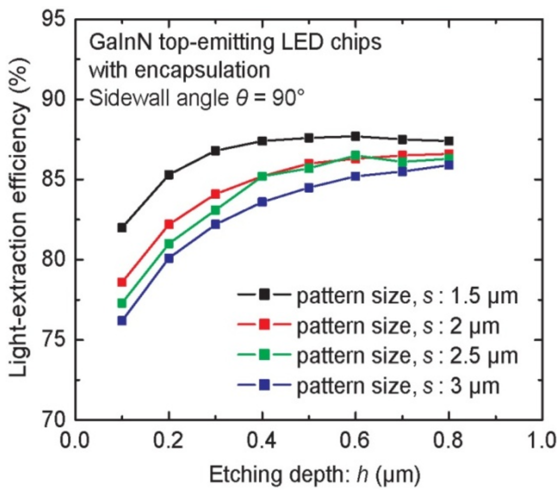


Figure 13*: Ray-tracing simulations of light extraction efficiency of patterned sapphire substrates encapsulated with epoxy for varying pattern sizes and etch depths.*

Based on pattern suggested by C. Wetzel we find in ray-tracing simulation that the nano-size patterning of the sapphire substrate can significantly increase the light-extraction efficiency in GaInN LEDs.

In an approach to implement the simulated patterns, conventional lithographical patterning was utilized to pattern sapphire substrate which has various pattern shapes and sizes. Figure 14 shows scanning electron microscopy (SEM) and optical microscope (OM) images of various patterned sapphire substrates.

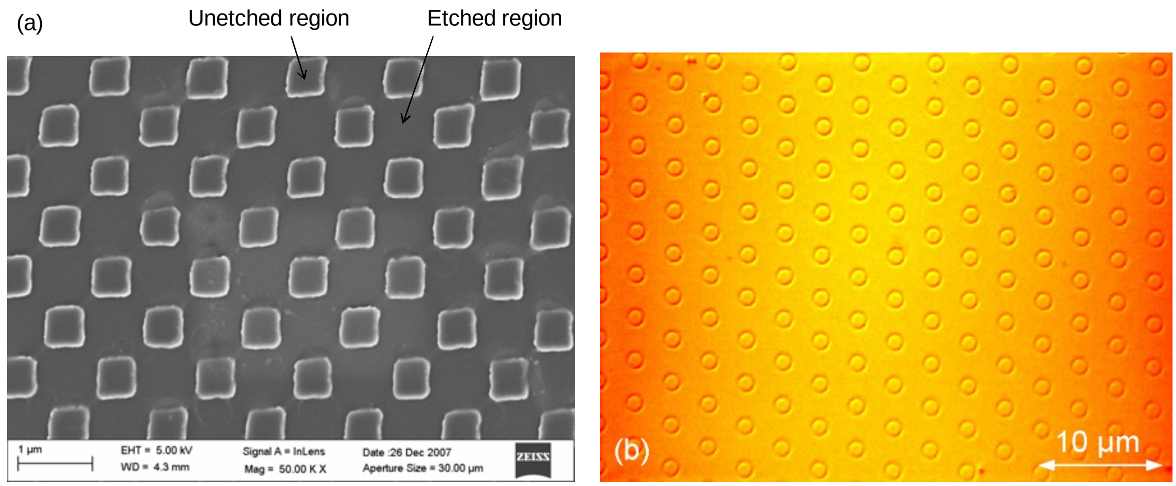


Figure 14: *(a) SEM image of sapphire etched by CAIBE. The pattern size is 700 nm by 700 nm. (b) An optical microscope image of a 3 µm by 3 µm sized patterned in sapphire substrate.*

Nano-imprinting usually transfers only a thin polymer onto the target. This layer is insufficient to withstand the chemically assisted ion-beam etching (CAIBE) conditions due to insufficient selectivity versus sapphire. Therefore, a reinforcement of the pattern is required. This team proposed an approach by oblique-angle deposition (Figure 15a). By controlling the deposition angle the deposition of the SiO_2 or metal nanorod mask can be limited to the nano-imprinted polymer pillars (Figure 15b). The nanorod masks proves to withstand the etching process (Figure 15c), leaving the pillar-shape nano-pattern in the sapphire (Figure 15d).

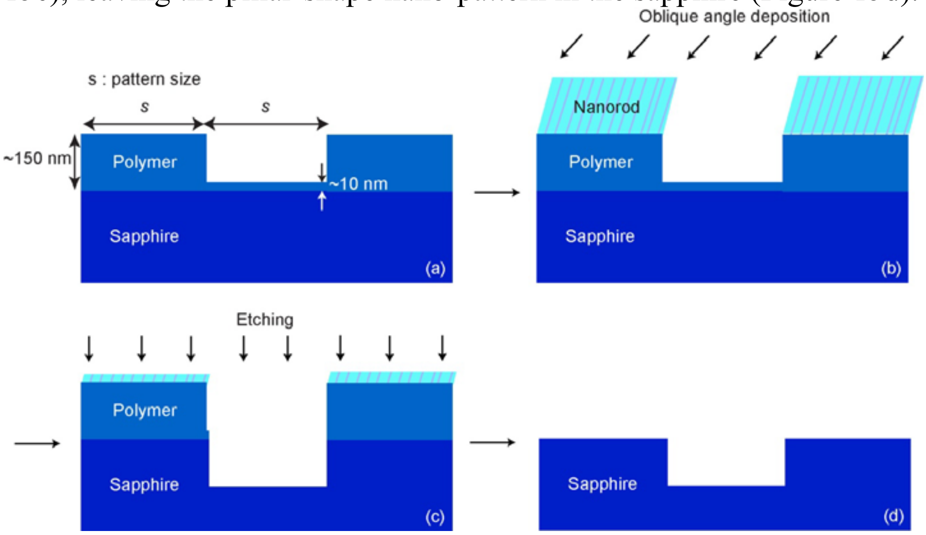


Figure 15*: Schematics of the nano-patterning procedure of sapphire using an oblique-angle-deposited nanorod mask to enhance the nano-imprinted polymer. (a) Nano-imprinted sapphire substrate (b) Deposition of mask material using oblique angle deposition (c) CAIBE etching (d) Final pillar-shape nano-patterns.*

We find that under optimized conditions well-defined nano-patterning can be achieved on sapphire in this approach: SEM (Figure 16) and AFM (Figure 17) reveal the circular shaped pillars in a uniform hexagonal pattern.

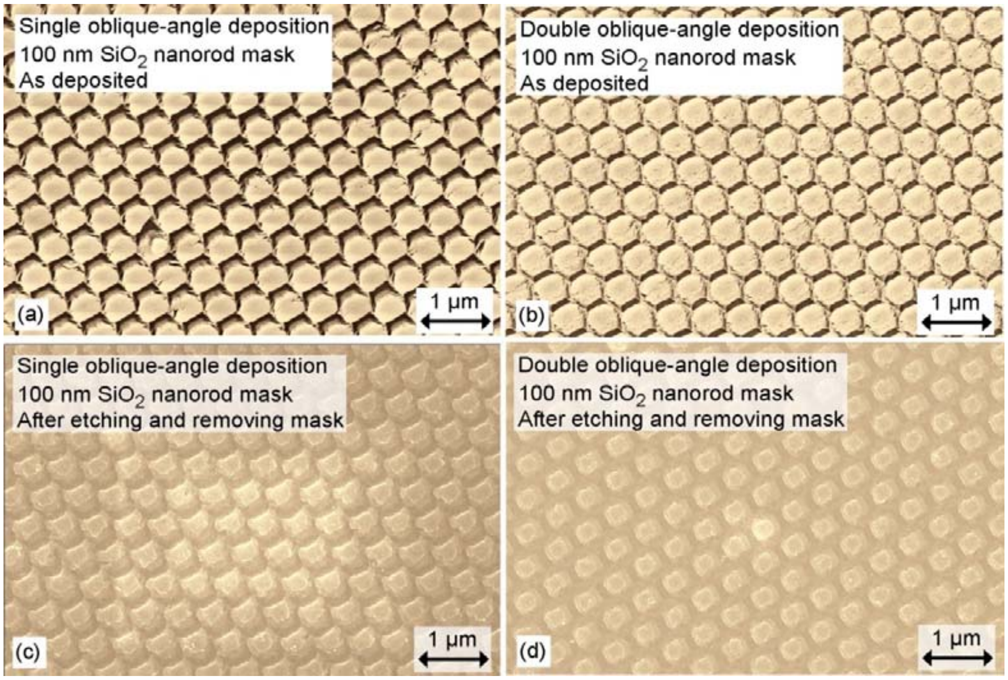


Figure 16*: SEM of a) as-deposited 100 nm thick SiO_2 nanorod film on the nano-imprinted sapphire substrate by using single step oblique-angle deposition, b) the nano-patterned sapphire after etching and removing the mask, c) as-deposited 100 nm thick SiO_2 nanorod film on the nano-imprinted sapphire substrate by using double oblique-angle deposition, and d) the nano-patterned sapphire after etching and removing the mask. The etching was done for 6 minutes in a CAIBE system.*

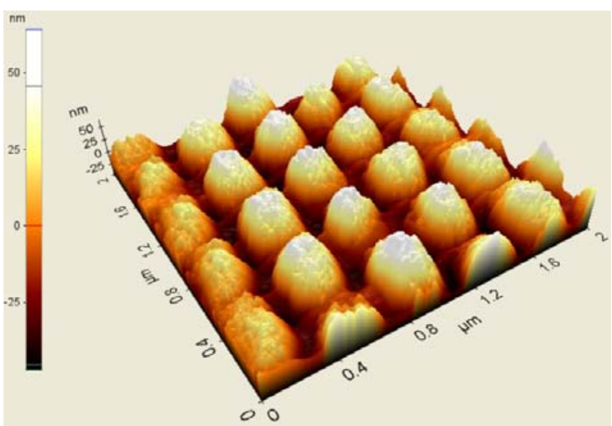


Figure 17*: AFM of the resulting nano-patterned sapphire substrate.*

LEDs implemented on nano-imprinted sapphire

In the in-house preparation of patterned substrates, such nano-patterned substrates have been obtained from a company in Japan. Prepared in a nano-imprint method they contain a hexagonal arrangement of pillars and holes at periodicities of 200 nm, 300 nm, 400 nm, and 500 nm at a pattern depth of 150 nm. The size of the features was 50% pillar, 50% hole, respectively. Figure 18 shows the surface morphology of the patterned sapphire in AFM. Four quadrants of the wafer reveal the different nano-patterns.

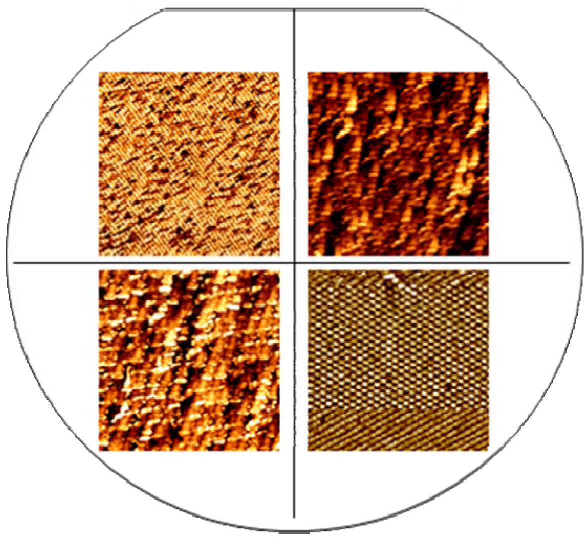


Figure 18*: The 4 quadrants of a patterned sapphire surface in AFM of 5 µm x 5 µm areas.*

Full green LED structures have been grown on both types of prepared sapphire substrates – the in-house series, as well as the externally prepared ones. The LED growth succeeded on two patterns of the externally prepared substrates with promising results. Light output power versus dominant wavelength at the scratch diode level (no mesa etching) in comparison with standard green LED epi is shown in Figure 19.

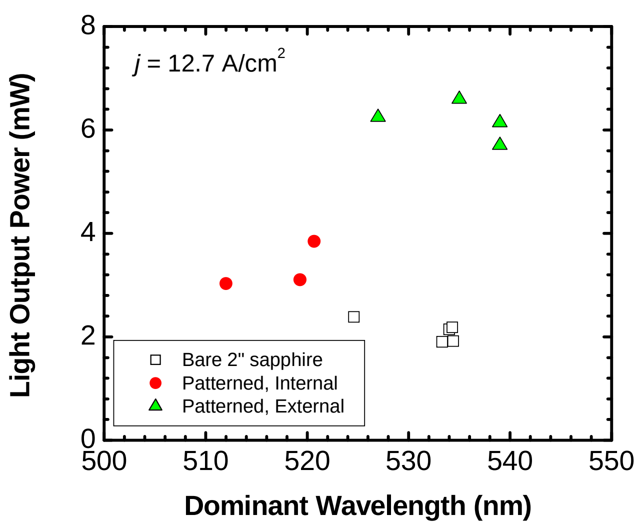


Figure 19*: Light output power versus dominant wavelength in green LED epi on in-house and externally prepared nano-patterned sapphire substrate in comparison with regular un-patterned sapphire substrate.*

Apparently, the performance of the in-house prepared substrates is in line with the wavelength dependence of standard green LED material. This is likely due to the insufficiently developed uniformity of the etch depths. Yet, the LEDs on the externally prepared substrates show a 3-fold performance gain over the same reference. This is a significant performance advantage at this level! Figure 20 shows the wavelength (left) and light output power performance (right) as a function of current density at the same scratch diode stage. Table 2 lists the data of several wafer locations. The wafer edge refers to an unpatterned reference part of the wafer.

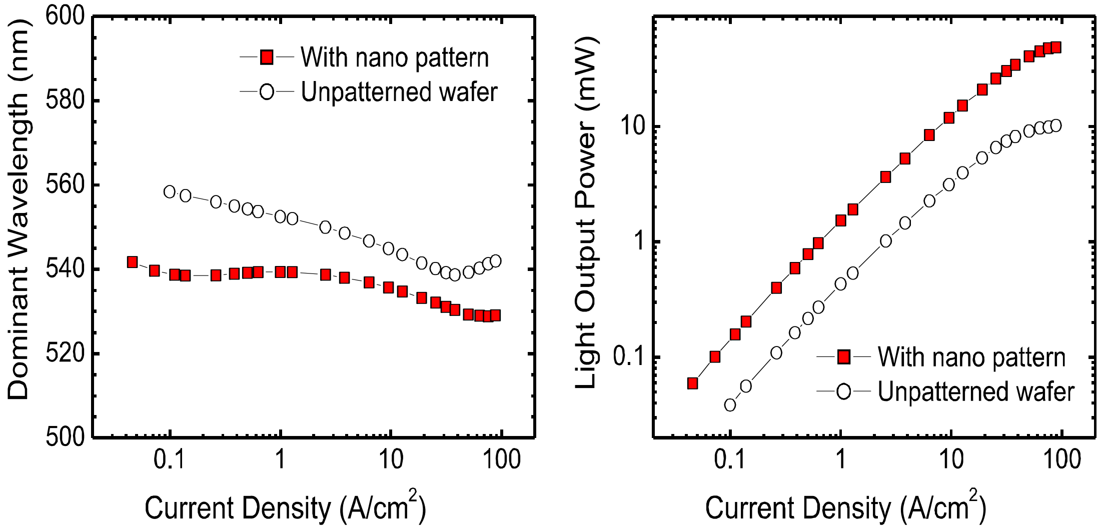


Figure 20*: (left) Dominant wavelength and (right) light output power as a function of current density in scratch diodes on nano-patterned and un-patterned sapphire substrate.*

Table 2*: Scratch diode performance on nano-patterned substrate*

Periodicity (nm)	Feature size (nm)	Current (mA)	Wavelength dom. (nm)	Power (uW)	Luminance (mL)
wafer edge	---	20	535	595	298
200	100	20	545	1574	912
200	100	20	539	1627	871
200	100	20	545	692	394
500	250	20	532	1265	626
wafer edge	---		533	2441	1229
200	100	100	539	6139	3347
200	100	100	535	6596	3436
200	100	100	539	5702	3100
500	250	100	527	6243	3003

This advantage of light output performance might be considered to be an extraction enhancement only and it could interfere with light extraction efforts at other stages of the LED preparation process. Yet, it is the epi-grower who has to adopt his processes to such a patterned interface between substrate and active LED layers. Unless using lift-off processes, this interface would not be accessible to light extraction post processing.

Figure 21 shows the external quantum efficiency in bare LED epi as a function of current density under 1-mm^2 contacts. A maximum is reached in both near 5 A/cm^2 of 2.5 % in the standard LED and 8.5 % in the nano-pattern LED, a 3.4-times gain.

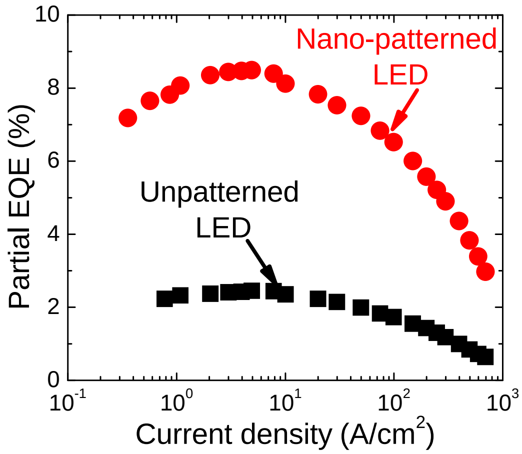


Figure 21*: Partial external quantum efficiency (EQE) as a function of current density for nano patterned(red dots) and unpatterned LED (black square).*

Counting dark lines in cathodoluminescence at 77 K reveals only marginal differences (~2x10^7 cm^{-2}). Photoluminescence (PL) shows a ~3-fold gain in the nano-patterned structure and significantly better spatial uniformity. From temperature dependent PL, an approximation of the internal quantum efficiency is obtained at room temperature (Figure 22).

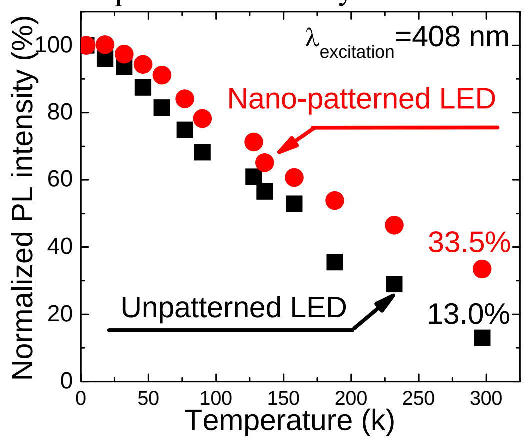


Figure 22: *Normalized PL intensity as a function of temperature of nano-patterned and unpatterned LED.*

While the un-patterned structure achieves a value of 13% at room temperature, the nano-patterned LED reaches 33.5%, an advantage of 2.6x. This factor should not be affected by the properties of light extraction. Various theory models of light extraction efficiency find a 1.54x advantage for the nano-patterned structure. The product of both, 3.9x, comes close to the observed ~3-fold gain. Comparing both contributions, the preeminent advantage seems to lie in an enhancement of the internal losses raising IQE rather than the intuitive aspects of extraction enhancement.

LED devices have been fabricated at mesa sizes of 0.3 mm x 0.3 mm and exactly four times the area of 0.6 mm x 0.6 mm. Light output power as a function of drive current was measured through the substrate into the 1-cm orifice of power and wavelength calibrated spectrometer. Figure 23 plots the ratio of the light output powers of the large die with the small die as a function of current density for various fabricated dies on the nano-patterned substrate. Dashed lines y = 3.5, 4, 4.6 mark the levels at which the LOP P scales with the mesa area A, i.e. according to $P = A^r$ with r = 0.9, 1.0, 1.1, respectively. For current densities above 3 A/cm^2, most approaches reach the direct proportionality, i.e. $r = 1$ and for higher current even reach a ratio of 5. This clearly demonstrates achievement of Milestone requiring $r > 0.9$.

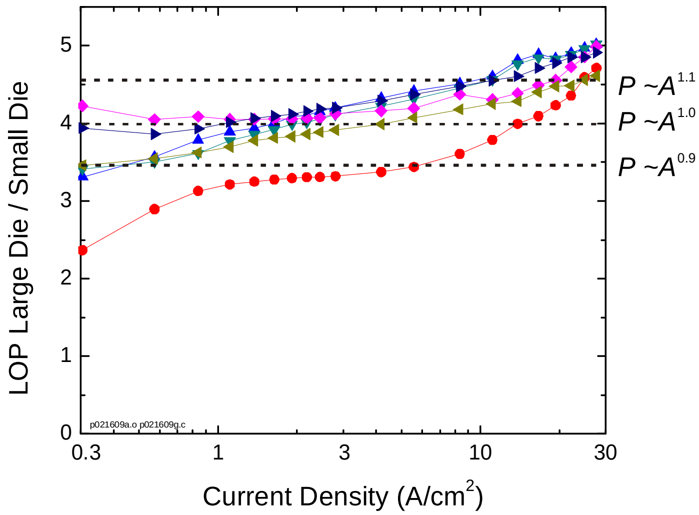


Figure 23*: Ratio of LOP from large die to LOP of small die in dies on various nano-patterned sapphire substrates as a function of current density. For a ratio of 4, LOP scales directly with the mesa area. This level is surpassed in most nano-patterning approaches for current densities higher than 3 A/cm^2*

Milestone Discussion

Milestone D - LED demonstration on nano-patterned substrate at standard performance.
Planned Date: August 2007
Description & Verification Method: Achievement is demonstrated by an LED efficacy of 10 lm/W at 525 – 560 nm in bare epi-up (350 µm)^2 die at 36 A/cm^2 after standard processing using a nano-patterned substrate or alternate device structure.
Achievement: LOP improvement by 200 % in patterned substrate devices has been achieved in scratch diode measurements.
Achievement Date: October 2008

Milestone I - Reach area scalability of emission power according to (area)^r with $0.9 < r < 1.0$.
Planned Date: August 2008
Description & Verification Method: An area-scalable LED output shall be achieved using a nano-patterned substrate. Area scalability is demonstrated by scaling of output power P in relation to die area A according to $P = A^r$ with $0.9 < r < 1.0$ when A goes from (350 µm)^2 to (1000 µm)^2. Alternatively, AlN templates on sapphire shall be achieved. Related to Task 4.
Achievement: Achievement of this task is being demonstrated by the above.
Achievement Date: January 2009

Task 5: Conformal buffer layer growth

Theeradetch Detchprohm and Christian Wetzel

This task primarily concerns the replication of the crystalline quality achieved in the bulk GaN material within the epitaxial layers. For the case of AlN epitaxial growth on bulk AlN this has proven to be very difficult. During the homoepitaxial overgrowth, a very rough surface morphology typically develops that seems to reveal subsurface damage in the AlN template which was not apparent after chemomechanical polishing. Similar issues might therefore play a role in the homoepitaxy of GaN and might most directly be assessed by an analysis of the surface morphology before and after overgrowth.

Nomarski micrographs under the optical microscope for homoepitaxy of undoped GaN on *m*-plane GaN is shown in Figure 24. This fast and first step characterization reveals significant achievements.

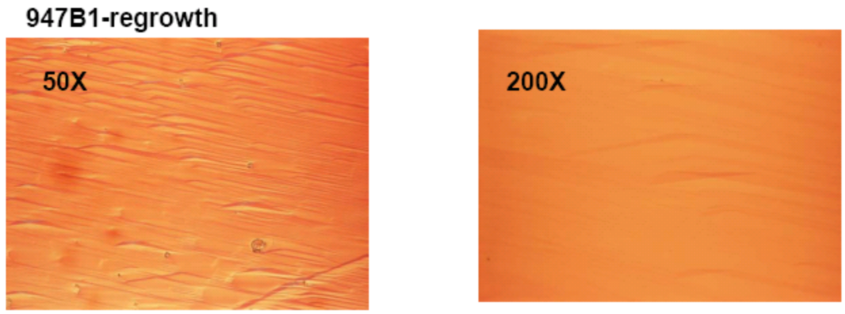


Figure 24*: Optical Nomarski microscope image of the heteroepitaxial undoped GaN on m-plane bulk substrate. (left) 50x objective, (right) 200x objective. Very smooth surfaces are revealed on both length scales.*

A more detailed analysis of the surface morphology is performed by atomic force microscopy (AFM). Figure 25 (upper row) gives a roughness analysis of the bare bulk substrate for *m*-plane, *a*-plane, and *c*-plane GaN over the standard area of 5 µm x 5 µm. Shown also is the morphology of the same samples after homoepitaxial growth of an MQW structure (*m*-plane and *a*-plane) or a full LED structure (*c*-plane). While as prepared, *a*-plane and *c*-plane GaN exhibit a roughness of 0.38 nm and 0.33 nm, respectively, the *m*-plane GaN shows a value of 2.9 nm (all RMS). After homoepitaxial growth, values are 1.78 nm (*m*-plane), 2.77 nm (*a*-plane), and 2.1 nm (*c*-plane, LED). Apparently, the epitaxial process in *a*-axis and *c*-axis growth is quiet successful in keeping the roughness low throughout the structures, including n-GaN, MQW region and in the case of *c*-plane material also the p-side. Surface roughness in the *m*-axis growth not only is the lowest after growth among the set, but it also demonstrates a decrease in roughness when compared to the bare bulk template.

We conclude that surface preparation of the *m*-plane material needs improvement.

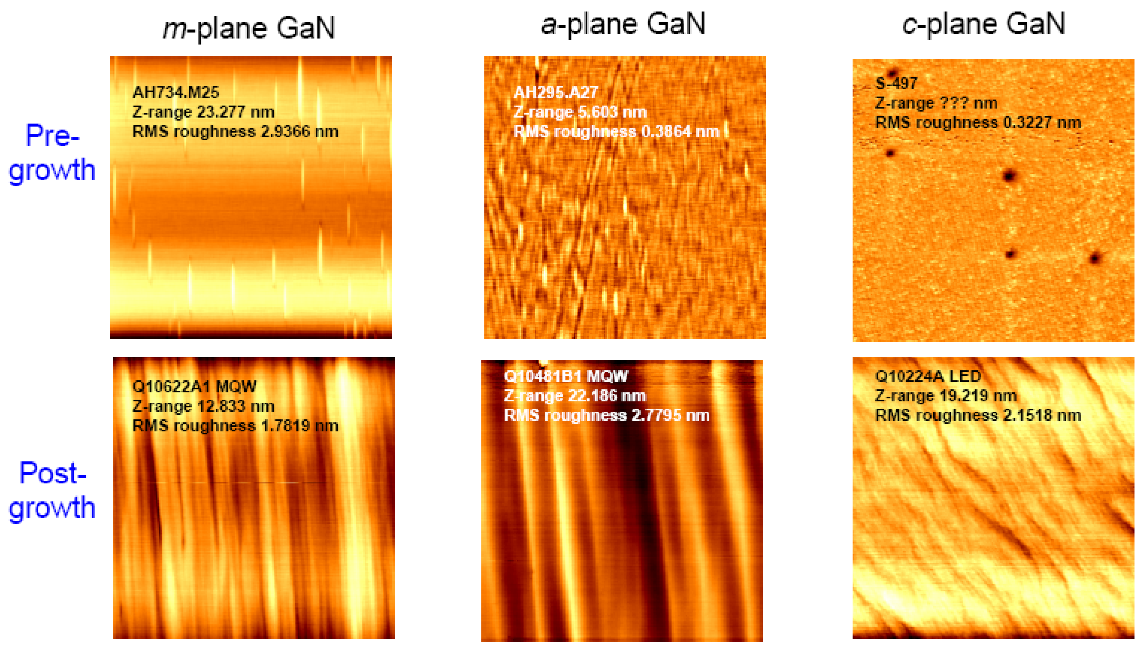


Figure 25*: AFM surface morphology of bulk GaN substrates of different orientation before (upper row) and after homoepitaxy of an MQW or LED structure. On the raw template, roughness is highest on the m-plane, while after homoepitaxy, roughness is not only smallest on the m-plane GaN, but it also is lower than prior to homoepitaxy.*

Milestone Discussion
Milestone G - Reduce threading dislocation densities in the active region to 10^7 cm^{-2}.
Planned Date: August 2008
Description & Verification Method: Success is demonstrated by maintaining the threading dislocation density of the underlying bulk substrate. An increase by not more than one order of magnitude is also acceptable. Treading dislocation density will be assessed by plane-view TEM, CL imaging, and AFM etch pit density.
Achievement: Achievement of this a threading dislocation density of 5x10^7 cm^{-2} in homoepitaxy on *c*-plane GaN and of *c*-axis and 1x10^7 cm^{-2} in homoepitaxy on *a*-plane GaN has been demonstrated in large scale cross sectional TEM micrographs.
Achievement Date: August 2008

Task 6: Polarization-optimized green and deep green LED die

Mingwei Zhu, Theeradetch Detchprohm, and Christian Wetzel

The successful replication of bulk GaN quality in homoepitaxy is best demonstrated when comparing to alternate approaches used in the literature to achieve e.g. non-polar *a*-plane GaN by direct growth on r-plane sapphire. Within a justified approach of growth optimization a direct comparison for green *a*-plane LEDs was performed by growth in separately optimized growth conditions on the *a*-plane of low-dislocation-density *c*-axis-grown bulk GaN and *a*-axis grown GaN on *r*-plane sapphire.

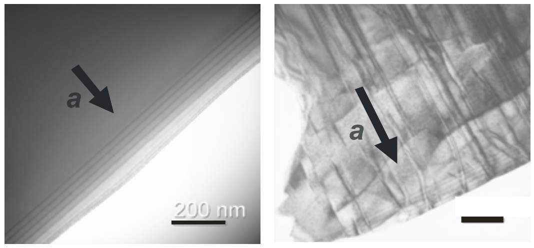
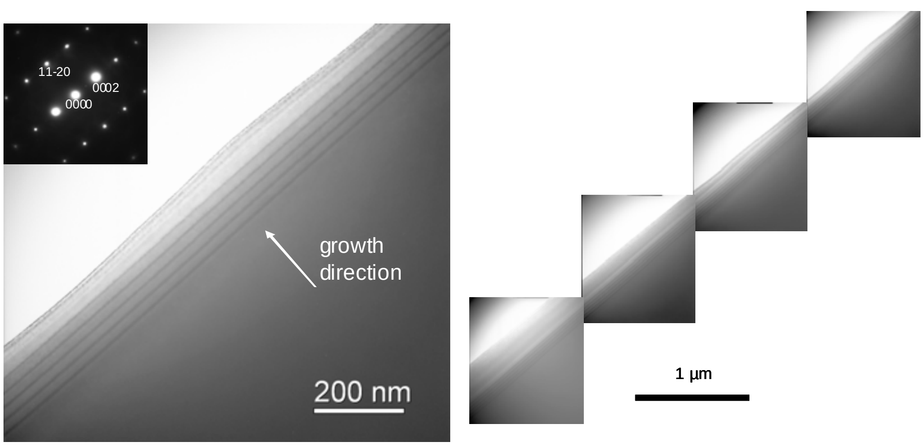


Figure 26*: Transmission electron microscope images of LED samples on a-plane bulk GaN (left) and r-plane sapphire (right). The threading dislocation density is <10^7 cm^{-2} in the first and as high as 2x10^{10} cm^{-2} in the latter on sapphire. Vectors* ***a*** *indicate the a–axis growth direction.*

Cross-sectional transmission electron micrographs (TEM) of both sample types are shown in Figure 26 (acceleration voltage 120 kV). It can be seen that the sapphire-based LED (Figure 18, right) suffers a high density (2x10^{10} cm^{-2}) of threading dislocations propagating along the *a*-axis growth direction throughout the device structure of n-GaN, QWs and p-layers. Despite the high defect density, there are no additional epitaxial defects, such as V-defects, induced during the growth of the QWs. The situation is very different in the bulk-based growth (Figure 27, left). Here, during the process of homoepitaxy layers inherit the high crystalline quality of the GaN bulk substrate without generation of any additional threading dislocations. Under high-resolution TEM analysis, the average thickness of the GaInN QW is estimated to be 2.75+/-0.25 nm.



a) b)

Figure 27*: A wide range view of a-plane green LED on bulk GaN in TEM. a) QWs undisturbed by any threading dislocations are observed along 1.4 μm. b) The same over an extension of 5 μm.*

A wide range TEM of the *a*-axis grown green LED on *a*-plane bulk GaN is shown in Figure 27. Figure 27 a) shows a 1.4 µm wide section and Figure 27 b) covers a large range of 5 µm. From the fact that no dislocation can be observed along this stretch we conclude a maximum linear defect density 0.2x10^4 cm^{-1}, and, under the assumption that a similar value holds in the not-observed direction of depth, a maximum area density of 1x10^7 cm^{-2}.

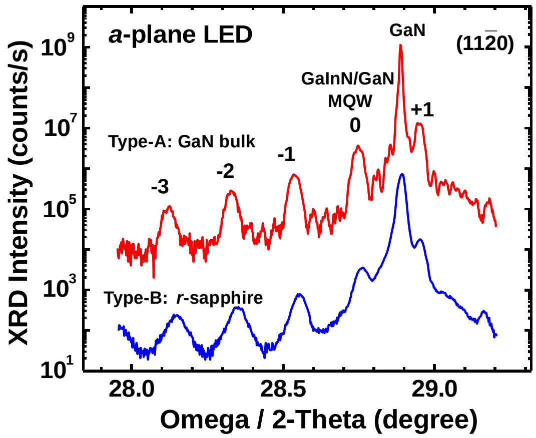


Figure 28*: Ω - 2θ XRD scan around the GaN 112¯0 diffraction in nonpolar LED structures of type-A grown on bulk GaN and type-B grown on r-sapphire substrates.*

X-ray diffraction (XRD) using the Cu Ka line in a ω/2θ scan around the (11$\bar{2}$0) diffraction of GaN provides fine details (Figure 28): In the bulk GaN-based samples, satellite peaks appear with well-resolved intermediate fringes. These result from the interference of the individual QWs with the p-side layers. Their appearance indicates abrupt interfaces in all layers and uniform composition. In contrast, the absence of such fringes in the sapphire-based LED structures suggests poor interface quality and/or composition inhomogeneity. These XRD results are in good agreement with the results from surface morphology and TEM analysis.

In order to determine the InN-fraction of the QWs, we adopt the model of Tsuda *et al*. (Jpn. J. Appl. Phys. **45**, 2509 (2006).) for determination of the AlN-fraction in AlGaN grown on *a*-plane GaN: Within the ternary layer, an anisotropic in-plane strain is assumed and shear forces are reasonably neglected. Therefore, the growth *a*-axis remains stress-free. Under these assumptions the alloy composition can be determined. Applying the model to the coherently grown GaInN/GaN MQW, we distinguish lattice periods parallel and perpendicular to the in-plane *c*-axis. They can be expressed in terms of the constants c_{GaN} (along *c*-axis) and a_{GaN} (along *a*-axis) of the underlying GaN layer as c_{GaN} and $\sqrt{3}\, a_{\mathrm{GaN}}/2$, respectively. The lattice constant of the (11$\bar{2}$0) plane separation $\mathrm{d}_{(11\bar{2}0)\mathrm{GaInN}}$ in the QW can then be expressed as 2 $\mathrm{d}_{(11\bar{2}0)\mathrm{GaInN}}$. Its value can be determined from the 0^{th}-order superlattice peak of the MQW structure. In this model, the elastic stiffness constants of the $\mathrm{Ga}_{1-x}\mathrm{In}_x\mathrm{N}$ alloys are linearly interpolated from those of GaN and InN. Using an average QW thickness as obtained from the high-resolution TEM analysis, the InN-fraction was determined to be 14% in the 3.7 nm thick QWs of type-A and type-B MQW samples that achieve light emission near 500 nm (Table 3). In comparison, our 3.0 nm compressively strained QWs grown along the *c*-axis of GaN require an InN-fraction of merely 7.7 % to reach the same wavelength range. Apparently, the InN-fraction needed for a green LED in non-polar growth geometry is roughly twice as high. This can, in part, be explained by the disappearance of the QCSE. According to our previous findings, the disappearing dipole across the QW should alleviate the large Stokes-like redshift in the emission spectrum.

Similar results were obtained in electroluminescence (EL) spectra. Dominant emission wavelengths of 525 nm or larger are achieved in polar LED structures grown along the *c*-axis for InN-fractions of ~9%. In non-polar type-A, and type-B LED structures, the same wavelengths can be achieved for x = 18.8% and 18.0%, respectively. The correlation of alloy fractions as derived from the XRD analysis and the emission wavelength in PL and EL is summarized in Table 3.

Table 3*: InN-fractions of the $Ga_{1-x}In_xN$ QW layers for type-A and type-B samples and their reference samples grown along the c-axis of GaN. Zw is the QW thickness.*

Sample	Wavelength (nm), peak type	*Z*w (nm)	InN-fractions (%)	
			Fully strained	Relaxed
Type-A MQW (PL)	503, peak	3.7	13.5	20.2
Type-B MQW (PL)	517, peak	3.7	14.3	23.6
c-axis MQW (PL)	501, peak	3.0	7.7	21.7
Type-A LED (EL)	527, dominant	2.8	18.8	31.1
Type-B LED (EL)	539, dominant	3.7	18.1	30.7
c-axis LED (EL)	524, dominant	3.0	9.0	23.9

It should be noted that in the literature there is wide disagreement as to what alloy compositions are required to achieve a certain emission wavelength. To the best of our understanding, this is mostly due to different interpretation of widely similar structures.

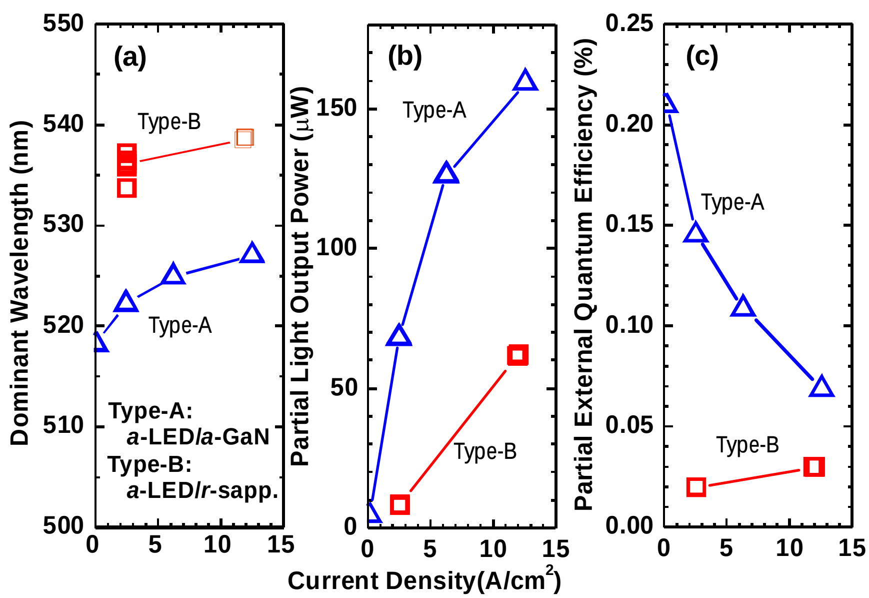


Figure 29*: EL characteristics of type-A LED structure grown on bulk GaN and of type-B LED structure grown on r-sapphire LEDs as a function of current density: (a) dominant wavelength, (b) partial light output power (EQE), and (c) partial external quantum efficiency. Partial refers to the fraction that can be measured through the substrate of the epi wafers. Solid lines are guides to the eye.*

Both, types of LEDs show a single narrow EL emission line in the green range: Dominant wavelength of 520 – 540 nm (Figure 31a) and linewidth of 38 – 48 nm. The partial optical output power measured through the substrate of the epi wafers reaches 60 μW at a current density of 12.7 A/cm^2 in the structures on *r*-sapphire, while a threefold higher value of 160 μW is reached in the structures on bulk GaN (Figure 31b). The (partial) EQE of the latter shows a monotonic decrease as a function of drive current (Figure 31c). Within this current range, the values are consistently several times higher than those of the first. As the drive current increases, there is a red shift (≤ 10 nm) in the dominant wavelength for both LED types (Figure 31c). This is unusual since in all polar *c*-plane material, particularly in the green spectral region a shift towards shorter wavelength is observed. We attribute the better device performance of the bulk GaN-based LEDs to the higher crystalline quality when compared to the sapphire-based type. However, the (partial) EQE of these particular non-polar devices is still an order of magnitude lower than that obtained from polar (0001) green GaInN/GaN LEDs. Most likely, this is due to the early development stage of these devices and could possibly be improved with better junction placement. At the current low efficiency level, we cannot precisely distinguish possible thermal effects from the system-inherent effects in the drop of EQE with increasing current density. The observed redshift of the emission wavelength suggests a dominance of the thermal effects.

In conclusion, the crystalline quality and the electro-optical performance of green LEDs grown along the non-polar *a*-axis of GaN has been improved significantly by employing low-dislocation-density *a*-plane $(11\bar{2}0)$ GaN bulk substrates. We observed a threefold increase in light output power when compared to those on high-dislocation-density *a*-plane GaN grown on *r*-plane sapphire, although the overall power still is lower than that obtained in conventional *c*-plane device structures. We found that the InN-fractions in the QW have to be twice as high as in polar (0001) *c*-axis growth to reach the 500 – 540 nm green emission region. We attribute this to the elimination of the piezoelectric dipole across the QWs.

Equivalent analysis of the achieved *m*-plane material shows the following: A micrograph of the sample under laser excitation (Figure 30, left) and the PL spectrum in reference to a standard sample (Figure 30, right) (black) reveals very strong photoluminescence intensity s at 488 nm and quiet uniformly peak wavelengths across the wafer piece.

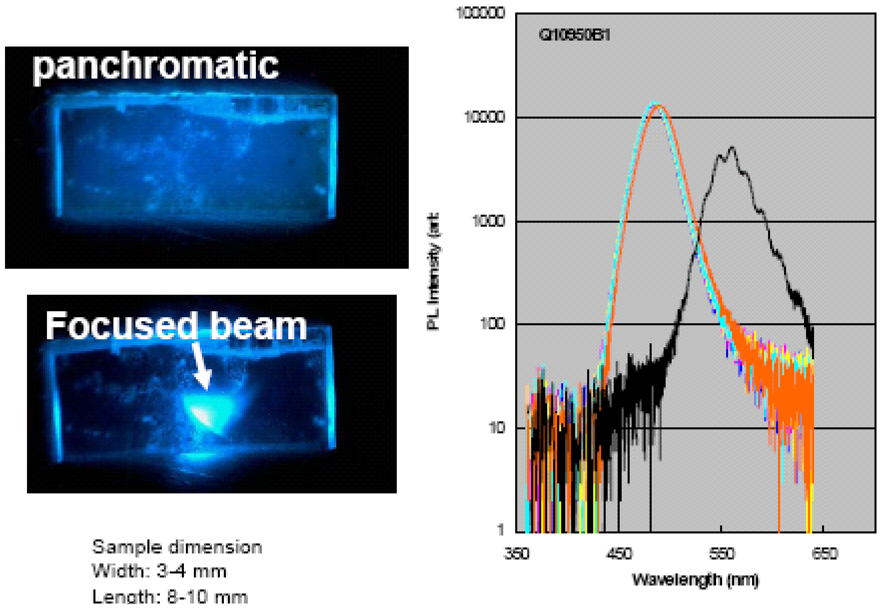


Figure 30*: Photoluminescence of m-axis GaInN/GaN MQW sample on m-plane bulk GaN: (left) Optical micrograph under diffuse (upper) and focused (lower) 325 nm laser excitation; (rigth) PL on a log intensity scale spectrum of the same peaking uniformly at 488 nm. The black spectrum is that of a c-plane reference sample.*

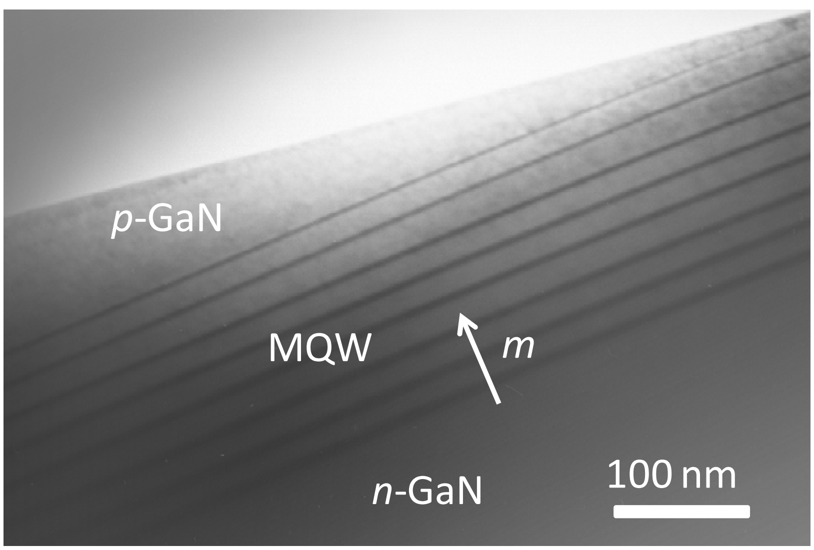


Figure 31: *Cross-sectional TEM micrograph of 480 nm m-plane MQW LED. Avoidance of generation of any misfit dislocations is seen corresponding to a density not higher than 10^8 cm^{-2}. Due to a wedge shaped sample preparation, the darker QWs appear as thinner lines in the regions of smaller sample thickness near the p-side.*

The cross-sectional TEM micrograph of the 480 nm *m*-plane MQW sample on bulk GaN is shown in Figure 31. Over a stretch of 0.6 µm no indication of any treading dislocations or other line or structural defects can be observed.

For the further discussion it is critical to distinguish the facts that, like in the *a*-plane growth on bulk GaN, no interface between the bulk material and the overgrown epitaxial material can be identified in TEM. In both cases, such an interface cannot be concluded from any increase in defect densities or the starting point of any additional defects. Furthermore it is important to distinguish that this *m*-plane material represents a 480 nm blue emitting structure and that structural defects as typically observable in TEM cannot be observed in neither, the n-GaN part, the active QW region, nor the p-layer side.

LED performance in the cyan spectral region below 500 nm is shown in Figure 32and Figure 33. We compare two *m*-plane grown non-polar LEDs to a *c*-plane grown LED all of which have been grown in homoepitaxy on bulk GaN substrates.

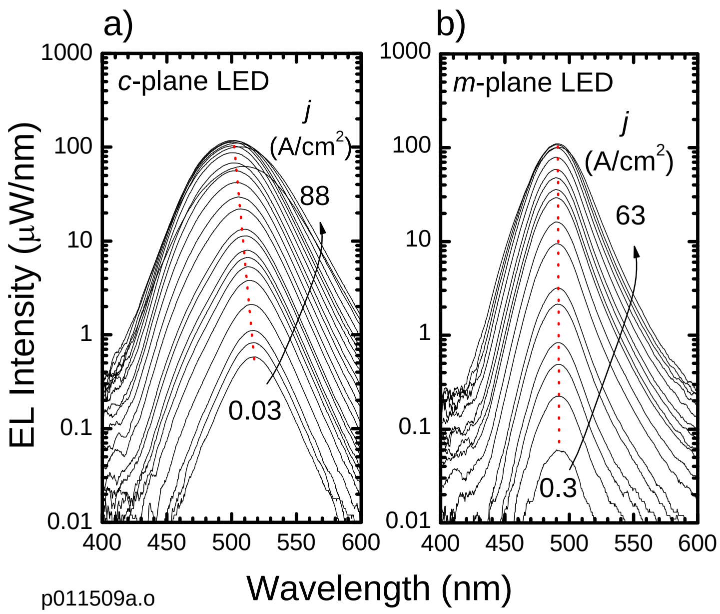


Figure 32*: Spectra of cyan LEDs under variable current injection. a) LED on sapphire grown along the polar c-axis shows a strong spectral shift with current density. b) LEDs on bulk GaN substrate grown along the non-polar m-axis shows little relative spectral variation with increasing current density.*

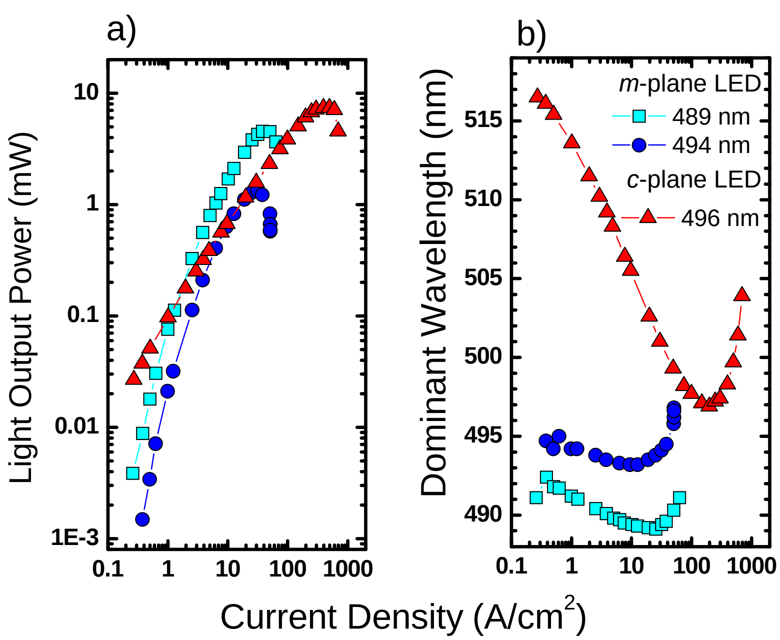


Figure 33*: Light output power (LOP) (a) and dominant wavelength (b) of cyan LEDs on as a function of current injection. a) LOP in the non-polar structures on bulk GaN starts out at lower levels but rapidly reaches or surpasses that of the polar structure on sapphire. b) Shift of the dominant wavelength in significantly smaller in the non-polar structures than the in the polar c-plane one. At high current density, a high serial resistance saturates LOP, which can also been in the reversal of wavelength shift.*

In the *m*-plane LED on bulk GaN at high power 1-W lamp standard of 35 A/cm^2 we obtain a light output power of 4.5 mW (scratch diode geometry, on-wafer testing) (luminous flux 0.96 L, external quantum efficiency 0.6%, wall plug efficiency 0.1 %).

After reporting on cyan LEDs we achieved LED performance in the green spectral region above 500 nm as shown in Figure 34 and Figure 35. We compare an *m*-plane grown non-polar LEDs to a *c*-plane grown LED, all of which have been grown in homoepitaxy on bulk GaN substrates.

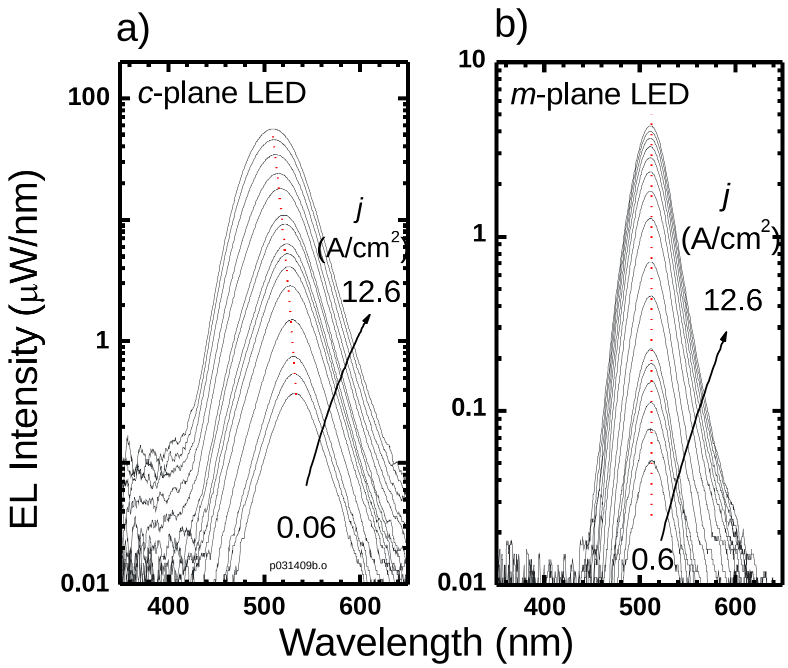


Figure 34*: Spectra of green LEDs under variable current injection. a) LED on sapphire grown along the polar c-axis shows a strong spectral shift with current density. b) LEDs on bulk GaN substrate grown along the non-polar m-axis shows little relative spectral variation with increasing current density.*

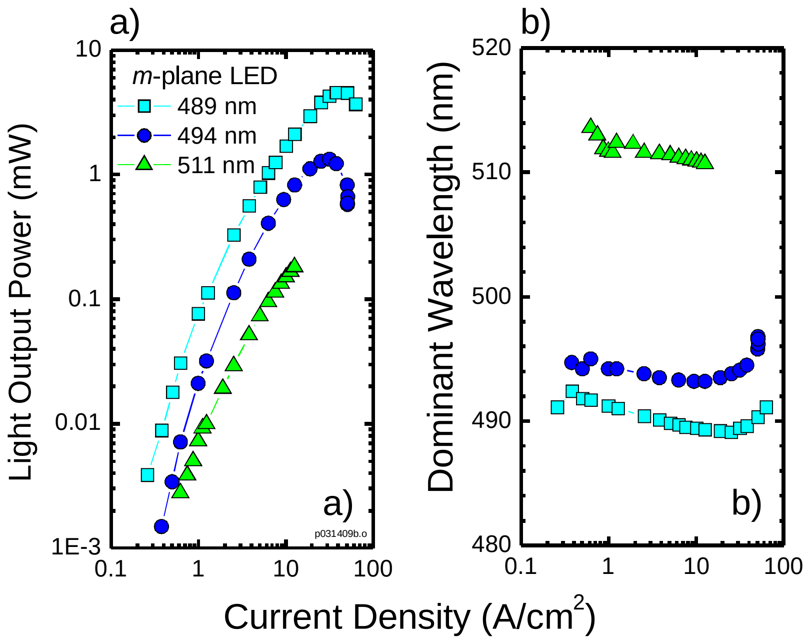


Figure 35: *Light output power (LOP) (a) and dominant wavelength (b) of cyan and green LEDs on m-plane GaN as a function of current injection. The shift of the dominant wavelength in the green and cyan non-polar structures is similarly small and much smaller than in polar c-plane structures.*

In the *m*-plane LED on bulk GaN at 13 A/cm^2, we obtain a light output power of 0.18 mW (scratch diode geometry, on wafer testing) (luminous flux 0.069 L, external quantum efficiency 0.08%, wall plug efficiency 0.02 %).

The current status of LOP versus dominant wavelength is shown in Figure 36b). Apparently there is a significant drop in performance once the wavelength is pushed beyond 500 nm.

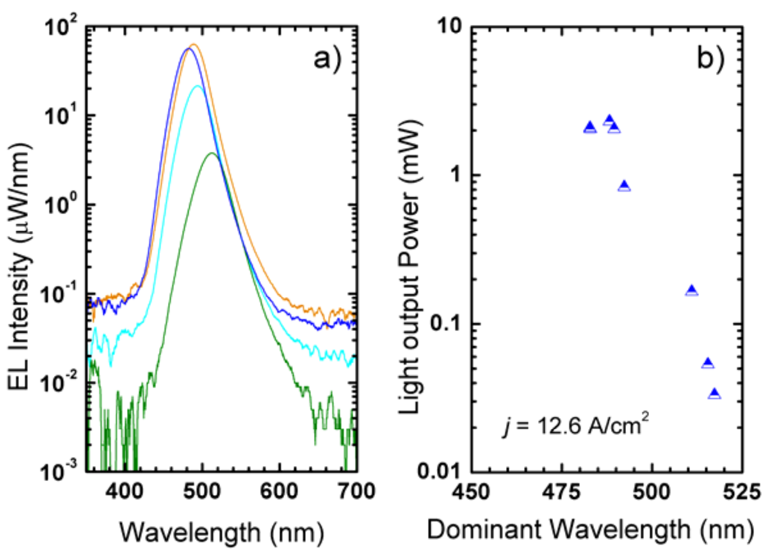


Figure 36: *Electroluminescence (EL) properties of m-plane cyan and green GaInN/GaN LEDs at 12.6 A/cm^2: a) emission spectra and b) light output power.*

One of the major hurdles so far in our non-polar *a*- and *m*-plane LEDs has been a high forward voltage reaching some 10-15 V at 100 mA. We found this to be a combination of insufficient conductivity of n- and p-layers. In a series of growth optimization runs in *a*-plane non-polar growth we have now succeeded in n-type conductivity at resistance values comparable to those of regular *c*-plane material. This is a very important step in raising the overall device efficiencies in non-polar LEDs. As a next step we concentrate on growth optimization of the p-layers. Consequently, the achievement of the efficiency mark for green emitting non-polar LEDs on *m*-plane material seems within reach.

Deep green LEDs in polar c-axis growth

T. Detchprohm, C. Wetzel

A likely reason for the precipitous performance drop for longer wavelengths is the high density of misfit dislocations generated within the QWs. By successive process optimization, avoidance of misfit dislocation generation has now become possible at wavelengths as long as 480 nm.

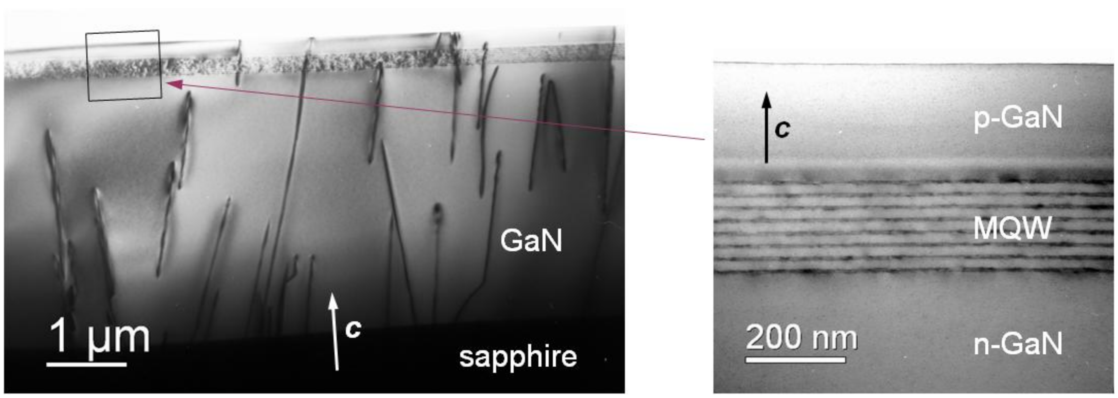


Figure 37*: Cross-sectional TEM of 553 nm deep green LED structure on c-plane sapphire revealing the absence of V-defects and misfit dislocations generated in the active region.*

In newly refined epitaxy approaches, the generation of V-defects and misfit dislocations can now be suppressed in sapphire based green LEDs with a wavelength as long as 553 nm. Figure 37 shows the cross-sectional image of the structure in lower resolution (left) and higher resolution (right). The density of treading dislocations, all originating from the n-GaN layers is ~ $5x10^8$ cm^{-2}. Scratch diode data promises new records in electroluminescence performance. Such epi wafers are now being processed to full LED structures.

After many development cycles, our green and deep green epi material has reached a level of performance that is likely to reach and exceed our program goals. Figure 38 presents L-I data on dies from the same 550 nm (peak) deep green LED wafer on sapphire in different stages of die mounting.

At the wafer level, LED performance can only be measured through the substrate side into the 1 cm orifice of a integration sphere coupled to a detector. Corresponding data is labeled "wafer level". Further traces correspond to the same epi material separated into dies and mounted "epi-up" on a copper header. For measurement, those headers now were held inside the integrating sphere (red and green data traces). In this arrangement, the previous light extraction through the substrate side is now obscured by the header. We therefore implemented a sputter deposited silver mirror onto the substrate before mounting on the header. In this case, as measured inside the integration sphere, the blue data traces labeled "Ag mirror, bonded, inside sphere" were obtained. This sequence results in a roughly twofold power enhancement over the bare epi wafer as measured in this arrangement.

Furthermore, under pulsed drive operation, the light output as measured in dies without Ag mirror show another 50% increase in LOP. The details of this enhancement are subject to ongoing investigation. It is not obvious that this must be due to the better thermal management under low duty cycle. Overall, a power as high as 4.6 mW at 27 mA can be measured in the (350 µm)^2 LED dies-on-header at 545 nm.

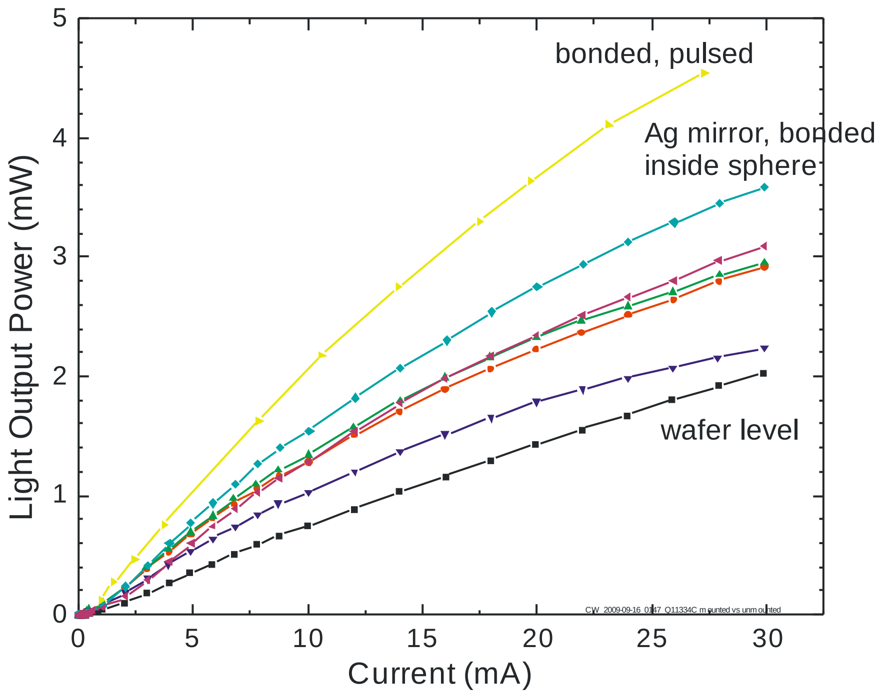


Figure 38*: EL LOP measurements of deep green fabricated (350 µm)^2 LED on nano-patterned substrate. Compared are wafer level measurement through the substrate, mounted dies measured inside the integration sphere and dies under pulsed measurement. Measured LOP varies by 230% and reaches as high as 4.6 mW at 27 mA.*

Figure 39 shows the dominant wavelength of some of the same dies as a function of current. The strongest blue shift is seen in the bare wafer level die while for the mounted die the wavelength shift is substantially less. This suggests that thermal issues are likely a limiting factor in the power performance as well.

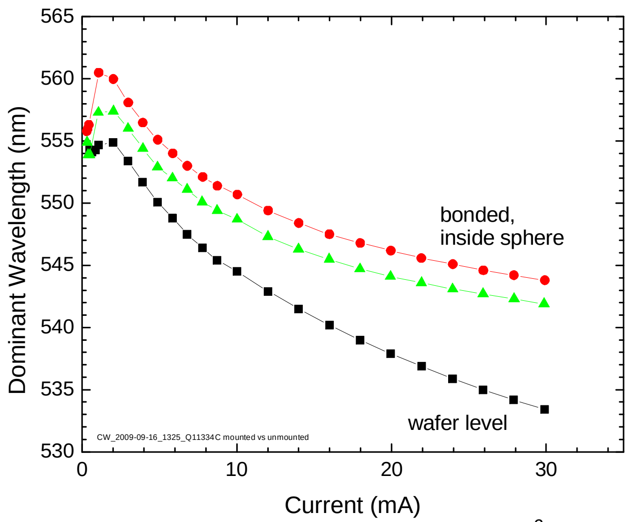


Figure 39*: Dominant wavelength of (350 µm)^2 fabricated LEDs on nano-patterned substrate as a function of DC drive current. Compared are performance at the wafer level and header mounted die. The stronger variation of wavelength in the bare epi wafer indicates a heating issue compared to the header mounted dies.*

The above data is for dies performing at 545 nm. The milestones call for 525 nm where it is very reasonable to obtain higher light output performance. It therefore is likely that we should have surpassed the criteria for the milestone of 5 – 7.5 mW at 525 nm at 20 mA.

According to the slope of power loss with wavelength in our best material, that performance can be scaled to 5.2 mW when reducing the wavelength from 545 nm to the required 525 nm. This therefore establishes achievement of the project goals.

To evaluate the possible casue of persisting performance loss iwht increasing wavelngth also in homoepitaxial growth on low-dislocation density bulk GaN, TEM analysis (Figure 40) was performed on polar *c*-plane deep green LED epi wafers on bulk GaN (left) in comparison to such on sapphire (right). The layers of *n*-GaN, multiple QWs (MQWs), *p*-AlGaN and *p*-GaN are identified in both cases.

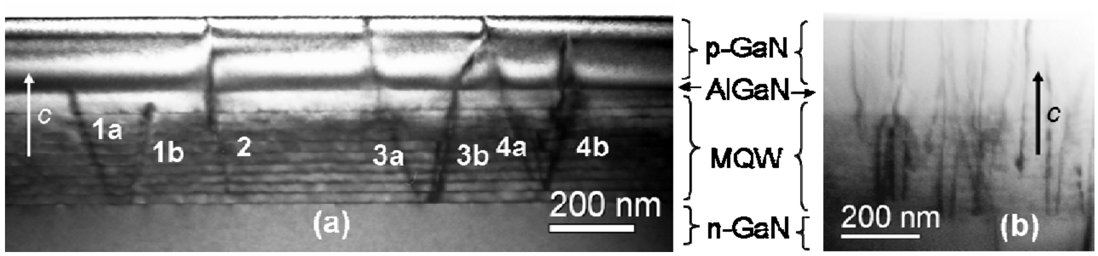


Figure 40*: TEM image of green LED on bulk GaN (a) and sapphire substrates (b). Inclined dislocations and IDPs were observed in (a). Most of the dislocations in (b) are not inclined.*

In the sample on bulk GaN we did not find any TDs generated in the epitaxial interface nor propagating from the bulk substrate throughout the observable sample width of 10 µm. This is consistent with the low TD density of the bulk substrate identified at 10^6 cm^{-2}. However, misfit dislocations (MDs) appear to be generated in the active region of the sample. They start within the first few QWs and propagate at some significant angle off the *c*-axis growth direction. Most come in pairs to form inclined dislocation pairs (IDPs) and propagate to different sides of the [0001] directions. Despite a density of 6×10^9 cm^{-2}, these defects do not lead to the formation of V-defects.

The wavelength equivalent structure on sapphire does not show any inclined dislocations (Figure 40 b). Most dislocations are generated in the quantum wells, while others propagated from the n-GaN template underneath. The same picture holds for a larger set of samples.

The propagation direction of the inclined dislocations was determined from TEM analysis while tilting the sample at different angles (Figure 41). The results are summarized in a top view illustration (Figure 41d). Each inclined dislocation is represented by a basal plane projection of its unit length vector: the vector's length corresponds to the sin of the inclination angle (for clarity, vectors are slightly offset).

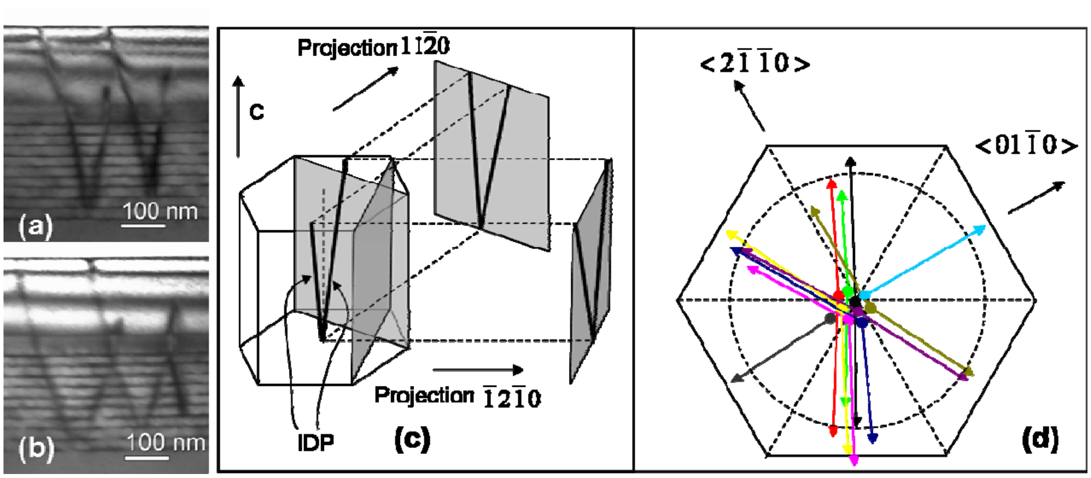


Figure 41*: TEM images of IDPs recorded along (a)* $[11\bar{2}0]$ *zone axis; (b)* $[\bar{1}2\bar{1}0]$ *zone axis. (c) Reconstructing the propagating direction of IDPs in the three dimensional crystal by projections of IDPs in different orientations. (d) Illustration of inclined dislocations and IDPs in top view. They are predominantly inclined from [0001] by 18 to 23º to the* $<1\bar{1}00>$ *direction.*

Dislocations in the same pair share the same color and starting point. The dashed circle is the projection of a cone with opening angle of 40º. Arrows ending on the dashed circle have an inclination of 20º versus [0001]. Most of the inclined dislocations are inclined towards either of the $<1\bar{1}00>$ directions at angles between 18 and 23º. Dislocations of the same IDP branch off in

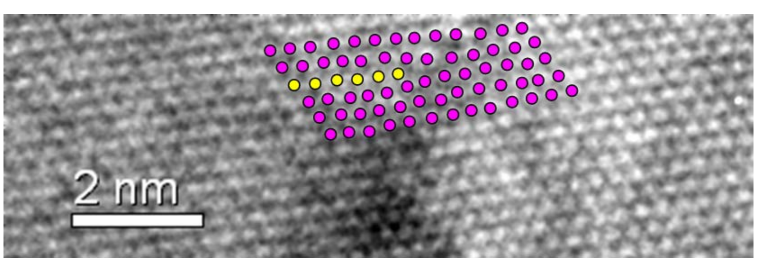


Figure 42*: High resolution plan-view TEM image of the green LED on bulk GaN. The pink and yellow dot array is the Ga atoms around a dislocation. An additional plane of 1/3* $\{11\bar{2}0\}$ *is inserted (yellow dot array).*

opposing directions, some at 180º separation, while most show a 120º separation. Consequently, all inclined dislocations and IDPs are orientated with a high degree of symmetry.

Figure 42 is the plan-view high-resolution TEM image around one inclined dislocation. Counting the lattice sites, an additional 1/3 $\{11\bar{2}0\}$ (*a*-plane) of Ga atoms becomes apparent between two neighboring *a*-planes to the left of the dislocation. This indicates that the Burgers vector of inclined dislocation has a component of **a**=1/3$<11\bar{2}0>$.

Milestone Discussion

Milestone F - LED on non-polar substrate at standard performance.
Planned Date: February 2008
Description & Verification Method: Success is demonstrated by the achievement of an LED efficacy of 13 lm/W at 525 – 560 nm in bare epi-up (350 μm)^2 die at 36 A/cm^2 after standard processing on non-polar substrate..
Achievement: An achievement of the milestone cannot be reported.

Milestone H2 - Identify best growth, polarization axis for green LED.
Planned Date: August 2008
Description & Verification Method: Success is demonstrated by the selection of the crystal orientation that allows device efficacy better or equal to the better of *c*-axis, and non-polar orientations. Efficacy shall be accessed at 525 – 560 nm in bare epi-up (350 μm)^2 die at 36 A/cm^2 after standard processing.
Achievement: An achievement of the milestone cannot be reported.

Milestone K: Achievement of 5 – 7.5 mW at 525 nm bare epi-up die at 20 mA.
Planned Date: August 2009
Description & Verification Method: Contingent upon achievement of the above deliverables, success in this phase will be established by a minimum emission power in unencapsulated (400 μm)^2 die at 525 nm of mW at 20 mA.
Achievement: A performance of 3.7 mW at 545 nm in bare epi-up die at 20 mA was achieved fabricated LEDs on nanopatterned sapphire. According to the slope of power loss with wavelength in our best material, that performance can be scaled to 5.2 mW when reducing the wavelength from 545 nm to the required 525 nm. This demonstrates accomplishment of the milestone and project target.
Date of Achievement: November 2009

Discussion of project-wide results:

Significant findings, conclusions, and developments,

Weighing the overall project, very important progress has been in made in the growth of polar as well as non-polar growth of green and deep green LEDs. In fact, for the proper assessment of the non-polar LED performance, a strong line of growth along the polar growth directions is essential. Some of the most important achievements are: in polar *c*-axis growth, generation of V-defects has virtually been eliminated; in homoepitaxy on *c*-plane, *m*-plane, — and so some lesser extend – on *a*-plane, the low dislocation density of the substrate can be maintained throughout the epitaxial GaN without generation of any new dislocations; For the case of *a*- and *m*-axis growth, the unique approach to use the non-polar side walls of *c*-axis grown HVPE bulk GaN proves the most effective way to avoid any and all stacking faults that result from approaches of direct non-polar growth. For polar homoepitaxy on low-dislocation density *c*-plane GaN, a new type of defect is observed to form in the In-rich layers of deep green LEDs. Those inclined dislocation pairs seem to appear only in the absence of high densities of threading dislocations. In growth along the non-polar *a*-axis direction, we now achieve 530 nm green LEDs without any dislocations in the QWs. Not even the new type of inclined dislocation pairs has been observed in our non-polar structures. This important level of achievement finally allows to move the focus of materials development from line defects to point defects. Here dopants – intentional and unintentional contaminations now become a relevant topic.

An equivalent of the performance droop with current density and with emission wavelength has now been obtained in purely optical and mixed, electrical and optical experiments. In a first step, scaling of electrical and optical excitation to each other has so become possible. In the next step, this will allow an association of the droop to either the optical or the electrical domain.

Technology transfer activities

Invited talks related to this project

The following is a listing of invited talks explicitly acknowledging this project's sponsorship.

1. "How do we lose excitation in green LEDs?", Workshop on Frontiers in Electronics, Rincon, Puerto Rico, December 13-16, 2009.
2. “Wavelength-Stable Green Light Emitting Diodes in Non-Polar GaInN/GaN Quantum Well Growth”, European-Materials Research Society, 2009 Fall Meeting of the European Materials Research Society, Warsaw, Poland, September 14-18, 2009. *invitation to C. Wetzel, given by T. Detchprohm*
3. "Highly Efficient Green GaInN Based Light Emitting Diodes For Solid State Lighting Applications", The 17th American Conference on Crystal Growth and Epitaxy, Lake Geneva, WI, August 13, 2009. *Invited and given by T. Detchprohm*
4. "Green LED development in polar and non-polar growth orientation", Ninth International Conference on Solid State Lighting, SPIE Symposium on SPIE Optical Engineering + Applications, San Diego, California, USA, August 2-6, 2009.
5. "Saving Energy with Semiconductors - Solid-State Lighting with LEDs," Research Experience for Undergraduate Students at Rensselaer, June 16, 2009.
6. "Green Light Emitters in Polarization Controlled Epitaxy", 2009 Spring Meeting of the European Materials Research Society, Strasbourg, France, June 8 - 12, 2009.
7. "Fundamental Issues for High Brightness Green Sources", Army Research Laboratory Workshop on Nitride Semiconductor Optoelectronics for Logistics in Energy, Health, and Safety, Arlington, VA, May 19 – 20, 2009.
8. "Polarization Control for Deep Green Light Emitters", 45th Annual Workshop on Compound Semiconductor Materials and Devices, Fort Myers, FL, February 15-18, 2009.
9. "Closing the "Green Gap" in LED Materials", U.S. Department of Energy Solid State Lighting R&D Workshop, San Francisco, CA, February 3-5, 2009.
10. "Bridging the Green Gap in GaInN/GaN Light Emitting Diodes", Christian Wetzel and Theeradetch Detchprohm, Indo-US Workshop on Visible and Ultraviolet Sources for Solid State Lighting and Water Purification, January 5-7, 2009, Chennai, India.
11. “Grünes Licht aus Piezoelektrischen Halbleitern: Leucht- und Laserdioden aus GaInN/GaN”, Institut für Halbleiterphysik, Technical University Dresden, Dresden, Germany, Oct 2, 2008.
12. “Grünes Licht aus Piezoelektrischen Halbleitern: Leucht- und Laserdioden aus GaInN/GaN”, Physik Kolloquium, University Regensburg, Regensburg, Germany, October 13, 2008.
13. “Grüne Emitter in polaren und nicht-polaren GaInN/GaN Schichten,“ Walter Schottky Institute, Technical University Munich, Germany, September 30, 2008.
14. “Solid-State Lighting with Polar and Nonpolar Nitride Structures,” Forschergruppe der Deutschen Forschungsgemeinschaft, Riezlern, Austria September 25, 2008.
15. “Solid-State Lighting with Wide Bandgap Semiconductors,” Department of Physics & Astronomy, Union College, Schenectady, NY, May 8, 2008.
16. “Development of Green LEDs in GaInN and Perspectives for Solar Cells,” Applied Materials, Santa Clara, March 4, 2008.
17. “Deep Green Light Emission LEDs in Polar and Non-Polar Growth,” The Workshop on Compound Semiconductor Materials and Devices, Palm Springs, CA, February 18, 2008.

18. “Solving the "Green Gap" in LED Technology,” Transformations in Lighting, 2008 DOE, Solid-State Lighting R&D Workshop,” Atlanta, GA, January 30, 2008.
19. “... seminar on preparing proposals for NSF and other govt. agencies,” C. Wetzel, RPI Grant Writing Seminar, Troy, NY, December 10, 2007.
20. "Green Laser Diode Structures in Non-Polar Homoepitaxial MOVPE," DARPA/MTO Visible InGaN Injection Lasers Kickoff Meeting, Arlington, VA, November 5-6, 2007.
21. "Green and Deep Green LEDs in Polarization Controlled GaN," 10th International Conference on Advanced Materials, Bangalore, India, October 8 - 13, 2007.
22. "LED Development on Polar and Non-Polar GaN Substrates," 5th International Workshop on Bulk Nitride Semiconductors, Salvador, Bahia, Brazil, September 24-28, 2007.
23. "Green and Deep Green LEDs in Polarization Controlled GaN," 2007 China International Forum on Solid-State Lighting, Shanghai, China, August 22-24, 2007.
24. "Polarization Screening as a Concept for a Memory Cell," European Multifunctional Materials Workshop, Averøy, Norway, June 17-21, 2007.
25. "High Performance Green LEDs by Homoepitaxial MOVPE", Solid State Lighting Peer Review, Washington, DC June 5, 2007.
26. “Development of high efficiency green and deep green light emitters in piezoelectric group-III nitrides,” The Conference on Photonic Applications, Systems and Technologies, PhAST 2007, Baltimore, Maryland, USA, May 7-10, 2007.
27. “Piezoelectric Quantum Structure for Full Spectrum Light Emitters,” The International Conference on Metallurgical Coatings and thin Films, ICMCTF 2007, San Diego, California, USA, April 23-27, 2007.
28. “Optimization of Green GaInN/GaN Light Emitting Diodes in Piezoelectric Group-III Nitrides,” Hong Kong University of Science and Technology, Hong Kong, October 20, 2006.

Contributed talks related to this project

The following is a listing of contributed talks explicitly acknowledging this project's sponsorship. Student co-author's names under the guidance of the PI are underlined.

1. “Inclined Dislocation Pair Formation as a Mechanism of Partial Strain Relaxation in GaInN/GaN Quantum Wells on Low-Dislocation Density Bulk GaN," Mingwei Zhu, Shi You, Theeradetch Detchprohm, Tanya Paskova, Edward E. Preble, Drew Hanser, Christian Wetzel, European-Materials Research Society, 2009 Fall Meeting, Warsaw, Poland, September 14, 2009.
2. “Depth profile of donor-acceptor pair transition revealing its effect on the efficiency of LEDs", Y. Xia, Y. Li, W. Hou, L. Zhao, T. Detchprohm, and Christian Wetzel, 25th International Conference on Defects in Semiconductors, St.-Petersburg, Russia, July 20 - 24, 2009. Given by Christian Wetzel.
3. "Recycling defect trapped carriers to boost green LED efficiency", Christian Wetzel, Yong Xia, Wei Zhao, Wenting Hou, Mingwei Zhu, and Theeradetch Detchprohm, 8th International Conference on Nitride Semiconductors, Jeju Island, Korea, October 18 – 23, 2009.
4. "Various misfit dislocations in green and yellow GaInN/GaN light emitting diodes", Mingwei Zhu, Shi You, Theeradetch Detchprohm, Tanya Paskova, Edward A. Preble, and Christian Wetzel, 8th International Conference on Nitride Semiconductors Jeju Island, Korea, October 18-23, 2009.

5. "Cyan and Green Light Emitting Diode on Non-Polar m-Plane GaN Bulk Substrate", T. Detchprohm, M. Zhu, S. You, Y. Li, L. Zhao, E. A. Preble, T. Paskova, D. Hanser and C. Wetzel, The 8th International Conference on Nitride Semiconductors, Jeju, Korea, October 21, 2009.
6. "Direct Emitting Full Spectrum LEDs – Green", Christian Wetzel and Theeradetch Detchprohm, DOE Roundtable Discussions for Multi-year Program Plan (MYPP) for Solid State Lighting, Washington DC, November 3 and 4, 2009.
7. "Inclined Dislocation Pair Formation as a Mechanism of Partial Strain Relaxation in GaInN/GaN Quantum Wells on Low-Dislocation Density Bulk GaN," Mingwei Zhu, Shi You, Theeradetch Detchprohm, Tanya Paskova, Edward E. Preble, Drew Hanser, Christian Wetzel, European-Materials Research Society, 2009 Fall Meeting, Warsaw, Poland, Sep 14, 2009.
8. "Blue-Green GaInN/GaN Light Emitting Diode on Non-Polar m-Plane Bulk GaN", M. Zhu, T. Detchprohm, S. You, W. Zhao, W. Hou, Y. Li, Y. Xia, L. Zhao, S. Tomasulo, T. Paskova, E. A. Preble, D. Hanser, and C. Wetzel. 2009 Electronic Materials Conference, Penn State University, University Park, PA, June 2009.
9. "Device Performance of Fabricated Yellow Emitting GaInN/GaN LED on C-plane Bulk GaN Substrate", Wenting Hou, Wei Zhao, Mingwei Zhu, Theeradetch Detchprohm, and Christian Wetzel, 2009 Electronic Materials Conference, Penn State University, University Park, PA, June 2009.
10. "Polarization Study of Yellow Defect Luminescence from Polar and Non-polar Bulk GaN", S. You, Y. Xia, Y. Li, T. Detchprohm, C. Wetzel, 2009 Electronic Materials Conference, Penn State University, University Park, PA, June 2009.
11. "Enhanced Device Performance of GaInN-Based Deep Green Light Emitting Diodes with V-Defect-Free Active Region", T. Detchprohm, M. Zhu, W. Zhao, Y. Wang, Y. Li, Y. Xia and C. Wetzel. International Workshop on Nitride Semiconductors, Montreux, Switzerland, October 5 – 10, 2008.
12. "Growth and Characterization of Green GaInN-Based Light Emitting Diodes on Free-Standing Non-Polar GaN Templates," T. Detchprohm, M. Zhu, Y. Li, Y. Xia, L. Liu, D. Hanser, and C. Wetzel; Second International Symposium on the Growth of III-Nitrides, Izu Japan, July 6 – 9 (2008).
13. "Optical Properties of Polar and Non-polar GaInN/GaN Quantum Well Structures under Pulsed Laser Excitation," J. Senawiratne, Z. Zhang, S. Tomasulo, S. You, Y. Li, M. Zhu, W. Zhao, Y. Xia, T. Detchprohm, P.D. Persans, and C. Wetzel; Electronic Materials Conference, Santa Barbara, CA, June 25 – 27 (2008).
14. "Inclined Dislocation Pairs in Homoepitaxial Green GaInN/GaN Light Emitting Diodes," Mingwei Zhu, T. Detchprohm, S. You, Y. Xia, W. Zhao, Y. Li, J. Senawiratne, C. Wetzel, L. Liu, E. A. Preble, D. Hanser; Electronic Materials Conference, Santa Barbara, CA, June 25 – 27 (2008).
15. "High Density Photon Injection Induced Large Optical Absorption Variation in Green GaInN/GaN Structures," Wei Zhao, Yufeng Li, Mingwei Zhu, Yong Xia, Jayantha Senawiratne, Theeradetch Detchprohm, and Christian Wetzel; Electronic Materials Conference, Santa Barbara, CA, June 25 – 27 (2008).
16. "Suppression of Non-Radiative Recombination by V-defects in Single GaInN/GaN Quantum Well Structure with a GaInN Underlayer," Y. Xia, T. Detchprohm, M. Zhu, Y. Li, W. Zhao, J. Senawiratne, C. Wetzel, D.D. Koleske, M.H. Crawford, S.R. Lee, and K.H.A. Bogart;

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17. "Wavelength dependent photon modulated electroluminescence of green LEDs," Yufeng Li, W. Zhao, M. Zhu, J. Senawiratne, Y. Xia, T. Detchprohm, and C. Wetzel; Electronic Materials Conference, Santa Barbara, CA, June 25 – 27 (2008).
18. "Enhanced Performance of GaInN Based Green Light Emitting Diodes on Non-Polar GaN," T. Detchprohm, M. Zhu, Y. Li, Y. Xia, W. Zhao, J. Senawiratne, L. Liu, D. Hanser and C. Wetzel; 7th International Symposium on Semiconductor Light Emitting Devices, Phoenix, AZ, Apr 27 – May 2, 2008.
19. "Electroluminescence of Green and Blue GaInN/GaN Multiple Quantum Well Light Emitting Diodes under Photon Bias," Y. Li, J. Senawiratne, Y. Xia, W. Zhao, M. Zhu, T. Detchprohm, and C. Wetzel, 7th International Symposium on Semiconductor Light Emitting Devices, Phoenix, AZ, Apr 27 – May 2, 2008.
20. "Junction Temperature Analysis and Temperature Dependent Quantum Efficiency in GaInN based Green Light Emitting Diodes", J. Senawiratne, T. Detchprohm, W. Zhao, M. Zhu, Y. Li, Y. Xia, and C. Wetzel; 7th International Symposium on Semiconductor Light Emitting Devices, Phoenix, AZ, Apr 27 – May 2, 2008.
21. "Inclined Dislocation Pairs in Green GaInN/GaN Light Emitting Diodes Grown on Bulk GaN Substrate", M. Zhu, T. Detchprohm, S. You, Y. Xia, W. Zhao, Y. Li, J. Senawiratne, L. Liu, D. Tsvetkov, D. Hanser, and C. Wetzel; March Meeting of the American Physical Society, New Orleans, LA, Mar 10-14, 2008.
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23. "Green Light Emitting Diodes under Photon Modulation" Y. Li, J. Senawiratne, Y. Xia, M. Zhu, W. Zhao, T. Detchprohm, and C. Wetzel; Fall Meeting of the Materials Research Society, Boston, MA, Nov 26 – Dec 2 (2007).
24. "Structural Analysis in Low-V-defect Blue and Green GaInN/GaN Light Emitting Diodes," M. Zhu, T. Detchprohm, Y. Xia, W. Zhao, Y. Li, J. Senawiratne, S. You, L. Liu, E.A. Preble, D. Hanser, and C. Wetzel; Fall Meeting of the Materials Research Society, Boston, MA, Nov 26 – Dec 2 (2007).
25. "Photon Modulated Electroluminescence of GaInN/GaN Multiple Quantum Well Light Emitting Diodes," Y. Li, J. Senawiratne, Y. Xia, W. Zhao, M. Zhu, T. Detchprohm, and C. Wetzel; International Conference on Nitride Semiconductors, Las Vegas, NV, Sept 16 – 21 (2007).
26. "Improved Performance of GaInN Based Deep Green Light Emitting Diodes through V-Defect Reduction," C. Wetzel, M. Zhu, Y. Xia, Y. Li, W. Zhao, J. Senawiratne, and T. Detchprohm; International Conference on Nitride Semiconductors, Las Vegas, NV, Sept 16 – 21 (2007).
27. "V-defect Analysis in Green and Deep Green Light Emitting Diode Structures," M. Zhu, T. Detchprohm, S. You, Y. Wang, Y. Xia, W. Zhao, Y. Li, J. Senawiratne, Z. Zhang, and C. Wetzel; International Conference on Nitride Semiconductors, Las Vegas, NV, Sept 16 – 21 (2007).
28. "Junction Temperature Measurements and Thermal Modeling of GaInN/GaN Quantum Well Light-Emitting Diodes," J. Senawiratne, Y. Li, M. Zhu, Y. Xia, W. Zhao, T. Detchprohm, A. Chatterjee, J.L. Plawsky, and C. Wetzel; Electronic Materials Conference, South Bend, IN,

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30. "Spectroscopic Cathodoluminescence of V-Defects in GaInN/GaN Quantum Wells," Y. Xia, T. Detchprohm, J. Senawiratne, Y. Li, W. Zhao, M. Zhu, C. Wetzel, D. D. Koleske, M. H. Crawford, S. R. Lee, and K. H. A. Bogart; Electronic Materials Conference, South Bend, IN, June 20-22 (2007).
31. "Current and Optical Low-Frequency Noise of GaInN/GaN Green Light Emitting Diodes," S.L. Rumyantsev, C. Wetzel, and M.S. Shur; Fourth SPIE International Symposium on Fluctuations and Noise, 20-24 May 2007, Florence, Italy, Proc. of SPIE Vol. 6600 66000I-1.
32. "Loss of Quantum Efficiency in Green Light Emitting Diode Dies at Low Temperature," Y. Li, W. Zhao, Y. Xia, M. Zhu, J. Senawiratne, T. Detchprohm, E.F. Schubert, and C. Wetzel; Fall Meeting of the Materials Research Society, Boston MA, Nov 27 - Dec 1 (2006).
33. "Low-Temperature Cathodoluminescence Mapping of Green, Blue, and UV GaInN/GaN LED Dies," Y. Xia, T. Detchprohm, J. Senawiratne, Y. Li, W. Zhao, M. Zhu and C. Wetzel; Fall Meeting of the Materials Research Society, Boston, MA, Nov 27 - Dec 1 (2006).
34. "Light intensity noise in GaInN/GaN green light emitting diodes," S. L. Rumyantsev, C. Wetzel, and M. S. Shur, 2006 Fall Meeting of the Materials Research Society, Boston, Nov 27 – Dec 1, 2006.
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37. "Extremely High Quality AlN Grown on (0001) Sapphire by Using Metal-Organic Vapor-Phase Epitaxy," Y.A. Xi, K.X. Chen, F. Mont, J.K. Kim, C. Wetzel, E.F. Schubert, W. Liu, X. Li, J. A. Smart. 2006 Fall Meeting of the Materials Research Society, Boston, MA, Nov 27 – Dec 1, 2006.
38. "An Alternate Model of Radiative Recombination in Piezoelectric Quantum Wells," C. Wetzel. International Workshop on Nitride Semiconductor 2006, Kyoto, Japan, October 22-27, 2006.
39. "Temperature Dependence of the Quantum Efficiency in Green and Deep Green GaInN/GaN Light Emitting Diodes," Y. Li, W. Zhao, Y. Xia, M. Zhu, T. Detchprohm, E.F. Schubert, and C. Wetzel. International Workshop on Nitride Semiconductor 2006, Kyoto, Japan, October 22-27, 2006.

Reviewed journal publications related to this project

The following is a listing of reviewed archival journal publications explicitly acknowledging this project's sponsorship.

1. "Inclined Dislocation Pair Relaxation Mechanism in Homoepitaxial Green GaInN/GaN Light Emitting Diodes," Mingwei Zhu (朱明伟), Shi You (尤适), Theeradetch

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3. "Junction Temperature, Spectral Shift, and Efficiency in GaInN-based Blue and Green Light Emitting Diodes," J. Senawiratne, A. Chatterjee, T. Detchprohm, W. Zhao, Y. Li, M. Zhu, Y. Xia, X. Li, J. Plawsky, and C. Wetzel, Thin Solid Films **518**, 1732-1736 (2010). doi:10.1016/j.tsf.2009.11.073
4. "Enhanced Device Performance of GaInN-Based Deep Green Light Emitting Diodes with V-Defect-Free Active Region", T. Detchprohm, M. Zhu, W. Zhao, Y. Wang, Y. Li, Y. Xia and C. Wetzel. Phys. Status Solidi C **6**, No. S2, S840–S843 (2009). doi:10.1002/pssc.200880800
5. "Growth and Characterization of Green GaInN-Based Light Emitting Diodes on Free-Standing Non-Polar GaN Templates," T. Detchprohm, M. Zhu, Y. Li, Y. Xia, L. Liu, D. Hanser, and C. Wetzel, J. Cryst. Growth **311**, 2937–2941 (2009) doi:10.1016/j.jcrysgro.2009.01.060
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9. "Green Light Emitting Diodes on a-Plane GaN Bulk Substrates," Theeradetch Detchprohm, Mingwei Zhu, Yufeng Li, Yong Xia, Christian Wetzel, Edward A. Preble, Lianghong Liu, Tanya Paskova, and Drew Hanser, Appl. Phys. Lett. **92**, 24119 (2008) doi:10.1063/1.2945664
10. "Junction Temperature Analysis of Green Light Emitting Diodes on GaN and Sapphire Substrates," J. Senawiratne, W. Zhao, T. Detchprohm, A. Chatterjee, Y. Li, M. Zhu, J. L. Plawsky and C. Wetzel; Phys. Stat. Sol. C 5 (6), 2247 – 2249, (2008). doi:10.1002/pssc.200778648
11. "Photon Modulated Electroluminescence of GaInN/GaN Multiple Quantum Well Light Emitting Diodes," Y. Li, J. Senawiratne, Y. Xia, W. Zhao, M. Zhu, T. Detchprohm, and C. Wetzel; Phys. Stat. Sol. **5**(6), 2293 – 2295 (2008). doi:10.1002/pssc.200778713
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16. "Radiation effects on InGaN quantum wells and GaN simultaneously probed by ion beam-induced luminescence," J. W. Tringe, A. M. Conway, T. E. Felter, W. J. Moberly Chan, J. Castelaz, V. Lordi, Y. Xia, C. G. Stevens and C. Wetzel; IEEE Trans. Nucl. Sci. (No. TNS-00138-2008.R1), **55**(6), 3633-3637 (2008). doi:10.1109/TNS.2008.2006169
17. "Structural Characterization of Homoepitaxial Blue GaInN/GaN Light-Emitting Diodes by Transmission Electron Microscopy," M. Zhu, Y. Xia, W. Zhao, Y. Li, J. Senawiratne, T. Detchprohm, and C. Wetzel; J. Electron. Mater. **37**(5), 641-645 (2008). doi:10.1007/s11664-008-0392-9
18. "Junction Temperature Measurements and Thermal Modeling of GaInN/GaN Quantum Well Light-Emitting Diodes," J. Senawiratne, Y. Li, M. Zhu, Y. Xia, W. Zhao, T. Detchprohm, A. Chatterjee, J.L. Plawsky, and C. Wetzel; J. Electron. Mater.**37**(5), 607-610 (2008). doi:10.1007/s11664-007-0370-7
19. "Green Light Emitting Diodes under Photon Modulation" Yufeng Li, Jayantha Senawiratne, Yong Xia, Mingwei Zhu, Wei Zhao, Theeradetch Detchprohm, Christian M Wetzel; in Nitrides and Related Bulk Materials, edited by R. Kniep, F.J. DiSalvo, R. Riedel, Z. Fisk, and Y. Sugahara (Mater. Res. Soc. Symp. Proc. Volume 1040E, Warrendale, PA, 2008), 1040-Q03-08. http://www.mrs.org/s_mrs/sec_subscribe.asp?CID=11340&DID=209952&action=detail
20. "Structural Analysis in Low-V-defect Blue and Green GaInN/GaN Light Emitting Diodes" Mingwei Zhu, Theeradetch Detchprohm, Yong Xia, Wei Zhao, Yufeng Li, Jayantha Senawiratne, Shi You, Lianghong Liu, Edward A. Preble, Drew Hanser, Christian Wetzel; in Nitrides and Related Bulk Materials, edited by R. Kniep, F.J. DiSalvo, R. Riedel, Z. Fisk, and Y. Sugahara (Mater. Res. Soc. Symp. Proc. Volume 1040E, Warrendale, PA, 2008), 1040-Q03-02. http://www.mrs.org/s_mrs/sec_subscribe.asp?CID=11340&DID=214486&action=detail
21. "Superluminescence in Green Emission GaInN/GaN Quantum Well Structures under Pulsed Laser Excitation" Jayantha Senawiratne, Stephanie Tomasulo, Theeradetch Detchprohm, Mingwei Zhu, Yufeng Li, Wei Zhao, Yong Xia, Zihui Zhang, Peter Persans, Christian Wetzel; in Nitrides and Related Bulk Materials, edited by R. Kniep, F.J. DiSalvo, R. Riedel, Z. Fisk, and Y. Sugahara (Mater. Res. Soc. Symp. Proc. Volume 1040E, Warrendale, PA, 2008), 1040-Q05-05. http://www.mrs.org/s_mrs/sec_subscribe.asp?CID=11340&DID=212409&action=detail
22. "Current and Optical Low-Frequency Noise of GaInN/GaN Green Light Emitting Diodes" S.L. Rumyantsev, C. Wetzel, and M.S. Shur; Fourth SPIE International Symposium on Fluctuations and Noise, 20-24 May 2007, Florence, Italy, Proc. of SPIE Vol. 6600 66000I-1. http://spie.org/x648.html?product_id=724282

23. "Low-Temperature Cathodoluminescence Mapping of Green, Blue, and UV GaInN/GaN LED Dies," Y. Xia, T. Detchprohm, J. Senawiratne, Y. Li, W. Zhao, M. Zhu and C. Wetzel; Mat. Res. Soc. Symp. Proc. Vol. 955 0955-I15-45 (2007). http://www.mrs.org/s_mrs/sec_subscribe.asp?CID=7889&DID=194154&action=detail.

Press releases related to this project

The following is a listing of facsimiles of press releases related to the project.

http://news.rpi.edu/update.do?artcenterkey=1688

Rensselaer Researchers Aim To Close “Green Gap” in LED Technology

Troy, N.Y. — A team of researchers from Rensselaer Polytechnic Institute has received $1.8 million in federal funding to improve the energy efficiency of green light-emitting diodes (LEDs). As part of the U.S. Department of Energy’s (DOE) Solid-State Lighting Program, the team aims to close the “green gap” in LED technology by doubling or tripling the power output of green LEDs in three years, an advance that ultimately could lead to the replacement of incandescent and fluorescent lamps in general illumination applications.

“Making lighting more efficient is one of the biggest challenges we face,” says Christian Wetzel, the Wellfleet Career Development Constellation Professor, Future Chips, and associate professor of physics at Rensselaer. “Substantial reductions in the nation’s dependence on primary energy imports will be possible once highly efficient solid-state light sources replace wasteful incandescent and fluorescent lighting.”

Wetzel will be leading a team of scientists and engineers attempting to help meet the aggressive performance targets laid out in DOE’s solid-state lighting accelerated roadmap, which calls for the development by 2025 of advanced solid-state lighting technologies that are much more energy efficient, longer lasting, and cost competitive than conventional lighting technologies.

The prime contender to meet this goal, according to Wetzel, is a white-light unit made from a combination of high-performance red, blue, and green LEDs. Researchers have made major strides in advancing the design of red and blue LEDs, but the technology behind green LEDs has lagged behind substantially, he says.

Wetzel notes that green light is an essential piece of the puzzle because it addresses the peak of the human eye’s sensitivity, providing balance to the colors of red and blue light. Researchers originally discovered that green LEDs could be made by simply adding indium (In) to the gallium nitride (GaN) materials that composed blue LEDs, but the materials produced to date have been inefficient, resulting in green LEDs that are too dim to be used for lighting homes and offices.

“The indium segregates under certain conditions, clustering in areas where there are already defects in the material,” Wetzel says. A correlation between the indium clustering and the limited device performance has been proposed, but Wetzel suggests that this may just be a coincidence.

He plans to focus instead on aspects of the “piezoelectric effect” — a property of some materials that causes them to produce an electrical field when pressure is applied. By controlling this effect, he and his colleagues hope to develop a process to make higher-intensity green LEDs that convert electricity into light more efficiently.

Wetzel will be collaborating with co-principal investigator E. Fred Schubert, the Wellfleet Senior Constellation Professor of the Future Chips Constellation at Rensselaer, as well as Theeradetch Detchprohm, a research associate in Wetzel’s lab, and four Rensselaer graduate students: Yong Xia, Wei Zhao, Yufeng Li, and Mingwei Zhu.

The team will be partnering with Kyma Technologies Inc., a developer of gallium nitride (GaN) substrates and related products and services to the nitride semiconductor device market; and Crystal IS Inc., maker of single-crystal aluminum nitride (AlN) substrates for the production of optoelectronic devices such as blue and ultraviolet lasers.

The research was one of 16 projects selected for funding through DOE’s Solid-State Lighting Core Technologies Funding Opportunity Announcement, which seeks to support multiple enabling or fundamental solid-state lighting technology areas for general illumination applications. The selections are expected to fill key technology gaps, provide enabling knowledge or data, and represent a significant advancement in the solid-state lighting technology base, according to DOE.

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http://www.ledsmagazine.com/articles/news/3/8/17/1
LEDs Magazine

US research team aims to close the "green gap" in LEDs

23 Aug 2006
A team of US researchers has received $1.8 million in federal funding to improve the energy efficiency of green LEDs.

A project entitled "High Performance Green LEDs by Homoepitaxial MOVPE", which aims to improve the performance of green LEDs, has been awarded $1.8 million as part of the U.S. Department of Energy's (DOE) Solid-State Lighting program.

The team, led by Christian Wetzel and Fred Schubert of Rensselaer Polytechnic Institute (RPI), aims to close the "green gap" in LED technology by doubling or tripling the power output of green LEDs in three years.

Researchers have made major strides in advancing the design of red and blue LEDs, but the technology behind green LEDs has lagged behind substantially, says Wetzel. This has important consequences for applications such as illumination or backlighting of displays that may require the use of high-performance red, blue, and green LEDs to make white light.

The DOE's solid-state lighting roadmap calls for the development by 2025 of advanced solid-state lighting technologies that are much more energy efficient, longer lasting, and cost competitive than conventional lighting technologies. The prime contender to meet this goal, according to Wetzel, is a white-light unit made from a combination of red, blue, and green LEDs – hence the need to plug the so-called "green gap."

Wetzel notes that green light is an essential piece of the puzzle because it addresses the peak of the human eye's sensitivity, providing balance to the colors of red and blue light. He plans to focus on aspects of the "piezoelectric effect" -- a property of some materials that causes them to produce an electrical field when pressure is applied. By controlling this effect, he and his colleagues hope to develop a process to make higher-intensity green LEDs that convert electricity into light more efficiently.

"Making lighting more efficient is one of the biggest challenges we face," says Wetzel, who is the Wellfleet Career Development Constellation Professor, Future Chips, and associate professor of physics at Rensselaer. "Substantial reductions in the nation's dependence on primary energy imports will be possible once highly efficient solid-state light sources replace wasteful incandescent and fluorescent lighting."

GaN growth on native non-polar substrates

Another member of the research team is Kyma Technologies, a North Carolina company that supplies high quality bulk GaN-based substrates and epiwafers. Key improvements in the development of green LEDs based on III-nitride materials are expected to arise from use of Kyma's low-defect-density native GaN substrates.

Under the program, Kyma will continue to develop its patented manufacturing technology for native crystalline GaN materials and will also provide both polar and non-polar native GaN substrates to the Rensselaer researchers for epitaxial growth, device fabrication and device performance testing. The addition of native non-polar GaN substrates to Kyma's product line was announced earlier this year.

Experts recognize the potential of non-polar GaN to enable commercially important LED performance improvements. However, the efficiency of initial devices made from non-polar GaN-based materials has been limited by the presence of defects which result from fabrication on non-native substrates such as sapphire or silicon carbide (these are the commonly-used starting materials in commercial LED production). Use of Kyma's native GaN substrates should enable reduction of such defects by a factor of over 10,000 compared to such non-native approaches.

Drew Hanser, Kyma's co-founder and chief technology officer, Hanser commented, "While much progress has been made in developing blue and green LEDs on sapphire and silicon carbide substrates, much more progress is required, especially in the green, before nitride LEDs can begin to realize their full commercialization potential. We believe that Kyma's native GaN substrates have the potential to enable the development of green LEDs with the kind of price point and operating characteristics that fulfill the promise of solid state lighting for general illumination."

http://lfw.pennnet.com/Articles/Article_Display.cfm?ARTICLE_ID=267220&p=12
Laser Focus World Online Article

Rensselaer researchers aim to close LED "green gap"

August 29, 2006, Troy, NY--A team of researchers from Rensselaer Polytechnic Institute has received $1.8 million in federal funding to improve the energy efficiency of green light-emitting diodes (LEDs). As part of the U.S. Department of Energy's (DOE's) solid-state-lighting program, the team aims to close the "green gap" in LED technology by doubling or tripling the power output of green LEDs in three years, an advance that ultimately could lead to the replacement of incandescent and fluorescent lamps in general-illumination applications.

"Making lighting more efficient is one of the biggest challenges we face," says Christian Wetzel, the Wellfleet Career Development Constellation Professor, Future Chips, and associate professor of physics at Rensselaer. "Substantial reductions in the nation's dependence on primary energy imports will be possible once highly efficient solid-state light sources replace wasteful incandescent and fluorescent lighting."

Wetzel will be leading a team of scientists and engineers attempting to help meet the aggressive performance targets laid out in DOE's solid-state lighting accelerated roadmap, which calls for the development by 2025 of advanced solid-state-lighting technologies that are much more energy-efficient, longer-lasting, and cost-competitive than conventional lighting technologies.

The prime contender to meet this goal, according to Wetzel, is a white light unit made from a combination of high-performance red, blue, and green LEDs. Researchers have made major strides in advancing the design of red and blue LEDs, but the technology behind green LEDs has lagged behind substantially, he says.

Green light is an essential piece of the puzzle because it addresses the peak of the human eye's sensitivity, as well as providing balance to the colors of red and blue light. Although green LEDs can be created by simply adding indium to the gallium nitride materials that compose blue LEDs, green LEDs produced to date have been inefficient, and are less than optimum for lighting homes and offices.

"The indium segregates under certain conditions, clustering in areas where there are already defects in the material," Wetzel says. A correlation between the indium clustering and the limited device performance has been proposed, but Wetzel suggests that this may just be a coincidence.

He plans to focus instead on aspects of the piezoelectric effect--a property of some materials that causes them to produce an electrical field when pressure is applied. By controlling this effect, he and his colleagues hope to develop a process to make higher-intensity green LEDs that convert electricity into light more efficiently.

Wetzel will be collaborating with co-principal investigator E. Fred Schubert, the Wellfleet Senior Constellation Professor of the Future Chips Constellation at Rensselaer, as well as Theeradetch Detchprohm, a research associate in Wetzel's lab, and four Rensselaer graduate students: Yong Xia, Wei Zhao, Yufeng Li, and Mingwei Zhu.

The team will be partnering with Kyma Technologies (Raleigh, NC), a developer of gallium nitride substrates and related products and services to the nitride semiconductor device market; and Crystal IS (Green Island, NY), a maker of single-crystal aluminum nitride substrates for the production of optoelectronic devices such as blue UV lasers.

The research was one of 16 projects selected for funding through DOE's Solid-State Lighting Core Technologies Funding Opportunity Announcement, which seeks to support multiple enabling or fundamental solid-state lighting technology areas for general illumination applications. The selections are expected to fill key technology gaps, provide enabling knowledge or data, and represent a significant advancement in the solid-state lighting technology base, according to DOE.

Press release by Kyma Technologies Inc related to this project as mirrored by Compound Semiconductor.NET

http://compoundsemiconductor.net/articles/news/10/8/29/1

Compound Semiconductor.NET

Kyma aims to plug 'green gap' in DoE project

23 August 2006

Nitride substrate developer Kyma Technologies is working with LED specialists at Rensselaer Polytechnic Institute on materials that will form the basis for much more efficient green emitters.

Scientists at Rensselaer Polytechnic Institute (RPI) will develop high-brightness LEDs based on native GaN substrates from materials company Kyma Technologies in a bid to plug the so called 'green gap'.

While highly-efficient blue and red emitters based on GaN or AlInGaP are routinely made using sapphire, SiC or GaAs substrates, the development of green emitters has not been quite so successful.

Now, under the US Department of Energy's solid-state lighting core technologies program, RPI and Kyma will work together to produce improved materials and develop better processes that should lead to higher-performance green emitters.

The improvement should result from use of Kyma's low-defect density native GaN substrates. Both polar and cutting-edge non-polar materials will feature in the development program.

Because they do not suffer from electric fields in the crystal lattice that can degrade device performance, non-polar LEDs should have much better performance characteristics than the conventional polar GaN devices that are the mainstay of today's high-brightness LED industry.

However, initial results with devices grown on r-plane sapphire substrates have suffered from relatively low power output that is thought to result from high defect densities in the crystal lattice.

"Use of Kyma's native GaN substrates should enable reduction of such defects by a factor of over ten thousand compared with such non-native approaches," claims the Raleigh, NC, company.

Kyma CTO and co-founder Drew Hanser will work closely with Christian Wetzel and Fred Schubert from RPI's Future Chips Constellation on the new program. They will focus on developing improved, commercially-viable green emitters that should help to fulfill the promise of solid-state lighting for general lighting applications.

Kyma is also working with the Air Force Research Laboratory (AFRL) under a cooperative research and development agreement (CRADA), aiming to improve the reliability of GaN-based transistors through the use of native nitride substrates.

John Blevins at AFRL and Kyma's Drew Hanser are leading the three-year effort, which will focus on characterization techniques such as X-ray and Hall analysis, among others.

Field-effect transistors grown on GaN substrates will be characterized all the way through to high-frequency reliability testing as part of the effort.

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Office lighting that's bearable?

Jessica Bloustein (2006-08-31)
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ALBANY, NY (WAMC) - The United States Department of Energy has given researchers at Rensselaer Polytechnic Institute a $1.8 million grant to improve light-emitting-diode technology. LED's, if used commercially to replace flourescent and incandescent lighting, could double energy savings. WAMC's Capital District Bureau Chief Jessica Bloustein talked with the head researcher at RPI:

http://electronicdesign.com/article/components/project-green-light14119.aspx

Project Green Light

John Edwards | ED Online ID #14119 | November 12, 2006

While the telegraph is but a memory and steam locomotives have mostly chugged into history, the incandescent light bulb—and other similarly ancient lighting technologies—still burn on. But perhaps not for much longer.

Artificial lighting's future lies in solidstate devices, particularly light-emitting diodes (LEDs) that promise to burn just as brightly, but last longer and consume far less energy than conventional lights (see the Figure). "Substantial reductions in the nation's dependence on primary energy imports will be possible once highly efficient solid-state light sources replace wasteful incandescent and fluorescent lighting," says Christian Wetzel an associate professor of physics at Rensselaer Polytechnic Institute in Troy, NY.

Wetzel is leading a research team that's working to solve one of the last roadblocks to developing an LED lighting source that's not only cheap, long lasting and energy efficient, but pleasing to the human eye. The technology that's the most promising candidate, says Wetzel, is a white-light system constructed from modules containing red, blue and green LEDs. "These types of luminaries would parallel, very much, what the transistor has done to the radio tube," he claims.

While it's not difficult to produce high-quality, efficient red and blue LEDs, a practical green technology has so far eluded researchers. Green light is an essential piece of the LED lighting puzzle, however, since it provides a necessary counterbalance to the other colors. Removing green from the lighting equation leaves a garish hue that's more suited for a disco or strip club than a home or office.

Green LEDs can be made quite easily by adding indium to the gallium nitride materials that are used to create blue LEDs. Unfortunately, the LEDs made this way are far too dim for use in everyday lighting applications. "It has been easily possible to make a good blue LED, but for a green it is just exponentially more complicated," Wetzel says.

The problem with adding indium to gallium nitride is that the indium tends to segregate and cluster in areas of the material that contain defects. Wetzel believes he can improve green LED technology by taking advantage of the piezoelectric effect, which allows some materials to produce an electrical field when pressure is applied. By controlling this effect, Wetzel and his colleagues hope to develop a process that allows green LEDs to convert electricity into light more efficiently. "It may be difficult to make [the material] homogeneous, but the driving force is actually the piezoelectric field itself," Wetzel says.

Wetzel believes that his green LED research could lead to a commercially available LED lighting module within three to five years. "Eventually, it will be available in Home Depot," he predicts.

The U.S. Department of Energy's Solid-State Lighting program is underwriting Wetzel's research with a $1.8 million grant. The team is also working with Kyma Technologies, a gallium nitride substrates developer located in Raleigh, NC, and Crystal IS, a Green Island, NY-based producer of single-crystal substrates for the production of optoelectronic devices.

Replacing existing lighting technologies with solid-state devices promises immediate and substantial economic benefits. "The Department of Energy estimates customer savings of $115 billion by the year 2025 and a 10 percent reduction in greenhouse gases," Wetzel says. "Making lighting more efficient is one of the biggest challenges we face."

Press release 9/2/2009
http://green.rpi.edu/archives/greenleds/index.html

Greenlighting A Greener World

Just a few years ago, most conversations Christian Wetzel had about his research began with a quick explanation of LEDs.

More recently, however, he's noticed that the mention of LEDs — light-emitting diodes — no longer prompts puzzled looks. He rarely has to delve into the elevator pitch about LEDs needing only a fraction of the energy required by conventional light bulbs, or mention that LEDs contain none of the toxic heavy metals used in the newer compact fluorescent light bulbs. He no longer has to sell the idea that LEDs are incredibly durable and long-lived.

The virtues of sustainability and efficiency are now so engrained in the public consciousness, Wetzel said, that he can usually skip over the nuts and bolts of solid-state lighting and instead launch right into his work on developing a high-performance, low-cost green LED.

"Going green means different things to different people. For most, it means being more conscious about the environmental and global impacts of one's actions. For companies, going green also means making a profit by selling equipment and services that allow one's customers to be more efficient and reduce costs," said Wetzel, professor of physics and the Wellfleet Professor of Future Chips at Rensselaer. "I'm doing both of those, but I'm also trying to make an LED that literally shines green light."

First discovered in the 1920s, LEDs are semiconductors that convert electricity into light. When switched on, swarms of electrons pass through the semiconductor material and fall from an area with surplus electrons into an area with a shortage of electrons. As they fall, the electrons jump to a lower orbital and release small amounts of energy. This energy is realized as photons — the most basic unit of light. Unlike conventional light bulbs, LEDs produce almost no heat.

The color of light produced by LEDs depends on the type of semiconductor material it contains. The advancement of LED technology, Wetzel said, has followed a specific progression. The very first LEDs were red, and not long thereafter researchers tweaked their formula and developed some that produced orange light. Next in line, after considerable research efforts and some key breakthroughs, were blue LEDs, which can easily be found today as blue light sources in mobile phones, CD players, laptop computers, and other electronic devices.

The holy grail of solid-state lighting, however, is a true white LED. Wetzel said the white LEDs commonly used in novelty lighting applications, such as key chains, auto headlights, and grocery freezers, are actually blue LEDs coated with yellow phosphorus — which adds a step to the manufacturing process and also results in a faux-white illumination with a noticeable bluish tint. The key to true white LEDs, Wetzel said, is all about green.

"We have high-performance red LEDs, we have high-performance blue LEDs, and if we paired them with a high-performance green LED we would be able to produce every color visible to the human eye — including true white," he said. "Every computer monitor and television produces its picture by using red, blue, and green. That means developing a high-performance green LED would likely lead to a new generation of high-performance, energy-efficient display devices. The problem, however, is that green LEDs are much more difficult to create than I, or anyone else, imagined."

Simple preliminary attempts to create green LEDs, by merely adding more indium (In) to the gallium nitride (GaN) materials that composed blue LEDs, were unsuccessful. The resulting green LEDs just weren't strong or bright enough to stand toe-to-toe with red or blue. Wetzel and his research group have been working to tweak precisely how to add more indium, and how to grow the structure more carefully into a device, with the goal of boosting the strength and light output of green LEDs. They're endeavoring, he said, to "close the green gap."
Once they overcome the challenge of developing efficient green LEDs, he envisions LED technology will quickly evolve from its current applications in signs and small displays and grow into a universally adopted, globally used replacement for traditional light bulbs and compact fluorescence tubes. Wetzel said lights for general lighting applications, as well as the lighting of televisions, computer screens, and other electronics devices, will be cheaper, more energy efficient, and more reliable if we used LEDs.

"This is a new and exciting technology that holds immense promise, but the technological landscape is constantly in flux and we still have a ways to go before we are able to fully realize the energy and cost savings of LEDs," Wetzel said. "But I know that people are interested in lighting their homes and powering their devices with LEDs because they're always asking me, 'so when can I buy one?'"

Wetzel has been working on this problem for several years, and in recent months received an additional $1.8 million in funding from the U.S. Department of Energy. He has also partnered with several companies, large and small, to join efforts and finally close the "green gap" once and for all.

For general information on Wetzel's research, visit his bio.

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