Nitride emitters go nonpolar

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Received 16 April 2007
Published online 25 April 2007

PACS 42.55.Px, 77.65.–j, 81.05.Ea, 85.60.Jb

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Science is at its most exciting when a new field of research emerges and fundamental breakthroughs are being announced that were previously unthinkable. This is the case for GaN optoelectronics where activities in the area of nonpolar and semipolar nitrides are rapidly expanding, with more and more groups worldwide joining this new facet of nitride semiconductor research. The research community already witnessed a paradigm shift a little bit over a decade ago, when first GaN-based blue and green light emitting diodes (LEDs) were demonstrated and shortly thereafter the first violet laser diodes were realized. Today, white LED modules with a total output power of more than 1000 lm, brighter than a 50 W halogen lamp, and an efficiency of 75 lm/W are being commercialized [1].

Mass-production of 405 nm laser diodes for applications in optical storage devices, e.g. Blu-Ray and HD-DVDs, is ramping up as well [2, 3]. So why the bustling activity on polarity control for nitride semiconductor materials? It is expected that nitride based LEDs will largely replace conventional light sources – incandescent, fluorescent, and halogen lamps – in general as well as automotive lighting within the next years [4]. For this ambitious goal every percentage point increase in efficiency and total light-output is worth major efforts, because of the tremendous impact on the global market and energy saving. Displays are another application that spurs major research efforts due to the commercial potential that semiconductor laser projection displays would have. In order to realize such systems, the development of high power semiconductor laser sources emitting in the blue and green spectral regions are a prerequisite.

One of the most pressing physical problems hindering further advances in nitride emitters is the presence of large piezoelectric fields in these materials. Because of the hexagonal lattice symmetry without a center of inversion the piezoelectric coefficients for wurtzite nitrides are non-zero. The active regions of nitride LEDs or laser diodes are typically comprised of InGaN quantum wells (QWs) which are under biaxial compressive stress due to the larger lattice constant of InGaN compared to GaN. Consequently, InGaN quantum wells grown along the crystallographic c-axis exhibit an internal piezoelectric field in the MV/cm range, and electrons and holes are pulled to opposite interfaces of the QW. This spatial separation of wave functions causes a decrease of the transition matrix element and suppresses radiative recombination with respect to non-radiative recombination, diminishing the efficiency drastically. The problem becomes worse both for thicker QWs and at higher indium content, necessary in devices designed for longer wavelength operation. The strong piezoelectric field significantly contributes to the notoriously low efficiency of green InGaN LEDs [5]. It also limits the operation of InGaN laser diodes to wavelengths shorter than 482 nm [6]. The piezoelectric field also causes an undesired current-dependent red-shift in the emission due to the so called Quantum Confined Stark Effect (QCSE) [7].
**Figure 1** Piezoelectric polarization of an $\text{In}_{x}\text{Ga}_{1-x}\text{N}$ quantum well grown pseudomorphically between relaxed GaN barriers. The lattice planes of particular polar, semipolar, and nonpolar orientations are shown as insets. $P'_z$ is the polarization perpendicular to the growth plane.

In order to overcome these problems nitride heterostructures and QWs need to be grown along crystallographic directions where the piezoelectric field is small or zero. This is, for example, the case for $a$-plane or $m$-plane GaN. Waltereit and colleagues at the Paul Drude Institute in Berlin first demonstrated the absence of the piezoelectric field in $m$-plane GaN/AlGaN QWs grown on LiAlO$_2$ substrates [8]. However, this approach is plagued with poor crystal quality. Nonpolar GaN is notorious for its high density of threading dislocations and stacking faults. Epitaxial lateral overgrowth (ELOG), which is well established as a defect reducing technique in $c$-plane GaN, poses tremendous problems for nonpolar GaN because of the large differences for the optimum growth conditions of N-face and Ga-face GaN. Therefore the growth of high quality nonpolar GaN on foreign substrates seemed futile.

Another approach is semipolar GaN. As was pointed out by Park and Chuang [9], the piezoelectric field can be cancelled out for certain oblique crystal directions (see Fig. 1). While it is still being debated if and for which orientation the field vanishes exactly, a reduction in piezoelectric field strength has been experimentally verified for nitride heterostructures grown along $\{1\bar{1}0\bar{1}\}$, $\{1\bar{0}T\}$, and $\{1\bar{1}2\bar{2}\}$ directions [10, 11]. Furthermore, epitaxial growth along these semipolar directions appears to be much easier to control. One particularly intriguing approach is to use facet-controlled ELOG to create three-dimensional structures with angled facets that exhibit the desired crystal orientations [10, 12].

Within the last year the availability of low defect density bulk GaN substrates opened an entirely new approach towards different non- and semipolar crystal orientations. These novel substrates are sliced from cm-thick boules of hydrogen vapor phase epitaxy (HVPE) grown $c$-plane GaN and a number of companies, e.g. Mitsubishi Chemical, Furukawa, and Kyma Technologies, have started to produce first non- and semipolar GaN wafers. Although their area is still limited to the order of a square centimeter and their costs are forbidding high for any commercial application, these first samples provide a low dislocation density template that allows exploration of a number of different crystal orientations for proof of concept experiments. Blue, green, and amber LEDs have been achieved on semipolar bulk GaN [13], as well as blue LEDs on nonpolar GaN [14]. In this issue Kwang-Choong Kim and collaborators from UCSB demonstrate a nonpolar violet LED with a very high external quantum efficiency (EQE) of $41\%$ at 200 mA (see Fig. 2 and [15]). Its negligible wavelength shift with increasing injection current is a direct evidence for the nonpolar character. Most important, only a small drop of the EQE over the current density range from 1 A/cm$^2$ to 350 A/cm$^2$ is observed. Taking into account that the chip was encapsulated in a package only optimized for light extraction without efficient thermal management, the achieved EQE is clearly a remarkable result, demonstrating the potential of polarization reduced InGaN LEDs for highly efficient light generation.

These results are very encouraging, but there are still a number of obstacles that have to be overcome in order to make non- and semipolar nitrides successful in real world applications.
applications. One of the greatest challenges certainly will be the development of large area and inexpensive non-polar and semipolar GaN substrates. This may be made possible either by growing large boules of GaN crystals at low cost or by finding effective techniques for defect reduction for nonpolar GaN films grown on foreign substrates. Both of these goals are not yet within reach. Another alternative approach is facet-controlled growth on c-plane GaN, with the disadvantage, however, that one has to deal with three-dimensional structures that may pose difficulties for device fabrication. Indium incorporation efficiency for different crystal planes represents a further concern [16]. Most devices demonstrated on nonpolar surfaces so far are operating in the violet spectral range where only small amounts of indium in the QWs are required. There are some indications that the indium incorporation efficiency for nonpolar surfaces is significantly lower than for c-plane grown heterostructures [15], which might make it more difficult to reach the interesting blue and green spectral range. Another critical point is the doping efficiency that also depends on the crystal orientation and growth surface. Whether it will be possible to obtain a uniform doping profile when non- or semipolar crystal facets are involved is still an open question. Another important aspect that has not been investigated yet are device lifetimes. Although one could argue that this issue should be solved by using low dislocation density GaN substrates, the defect formation along the non- and semipolar crystal surfaces is different to the established c-plane GaN and therefore it will be certainly necessary to address this problem.

The final question is whether polarization-controlled nitrides provide a pathway towards true green laser diodes. Almost simultaneously two research groups have recently demonstrated first laser diodes grown on nonpolar GaN [17–19]. Yet both of the lasers emit in the violet spectral region, similar to the first c-plane InGaN laser diodes. Will it be possible to grow high quality InGaN QWs of high indium concentration in nonpolar or semipolar direction to achieve lasing in the green spectral region? The race is definitely open. And while semipolar and nonpolar substrates might remain too expensive for commercial use in LEDs, the high price for laser diodes certainly warrants the effort, with myriads of applications from miniature projection displays in cell phones to HDTV home theaters.

References