

# Gallium Nitride – The perspective winner of the blue-laser competition?

GRZEGORZ KARCZEWSKI\*

Institute of Physics, Polish Academy of Sciences, and Institute of Vacuum Technology

A commercially available short wavelength (blue/green-ultraviolet) diode laser will find high volume markets in areas like optical recording, printing and full-color displays. Of all application envisioned for blue lasers, optical data storage would, however, be the most important one.

Since many years, two wide bandgap materials – zinc selenide (ZnSe) and gallium nitride (GaN) – belonging to two different semiconductor families – II-VI and III-V, respectively – were regarded as most promising candidates for diode lasers and other optoelectronic devices operating in the blue/green spectral region. Both these semiconductors have attracted attention of numerous research groups across the world because of their direct band gaps, excellent electrical and structural properties and extraordinary photoluminescence efficiencies at near bandgap energies. Basic parameters of ZnSe and GaN are compared in Table I.

Table I. Basic parameters of ZnSe and GaN.

Parameter	II – VI ZnSe	III – V GaN
Crystal structure	zincblende	wurtzite
n doping max. (cm <sup>-3</sup> )	Cl: $2 \times 10^{20}$	Si: $2 \times 10^{20}$
p doping max. (cm <sup>-3</sup> )	N: $2 \times 10^{18}$	Mg: $2 \times 10^{19}$
d/a %	+0.25/GaAs	+16/Al <sub>2</sub> O <sub>3</sub> +3.5SiC
QW/barrier	ZnCdSe/ZnSse	In <sub>0.2</sub> Ga <sub>0.8</sub> N/In <sub>0.05</sub> Ga <sub>0.95</sub> N
Device defect density	$1 \times 10^5$ cm <sup>-3</sup>	$1 \times 10^7$ – $1 \times 10^{10}$
λ (nm)	460	406
P <sub>th</sub>	350mAcm <sup>-2</sup>	3.6 kAcm <sup>-2</sup>
Lifetime	100hrs CW (RT)	30hrs CW(RT)

The steady flow of reports on GaN based light-emitting diodes published over last years has recently been crowned by producing GaN lasers that operate at room temperature in a continues wave mode for more than 30 hours. Due to this spectacular success achieved by Shuji Nakamura from Nichia Chemical Industries, Japan, the competition between ZnSe and GaN became extremely exciting. The new announcement closes the gap between GaN technology and the best ZnSe lifetime results obtained a year ago – in the end of 1995 researchers at Sony Corporation, Japan, have produced a ZnSe based blue/green semiconductor laser that operates at room temperature for more than 100 hours. The previous CW lifetime record for ZnSe lasers – which was also held by Sony – was an order of magnitude shorter.

The race towards construction of semiconductor blue/green lasers started in 1990, when Robert Park of the University of Florida and Kazuhiro Ohkawa at the Matsushita Central Research Laboratory developed a technique of using nitrogen radicals to produce high level p-type doping in ZnSe (on the order of  $10^{18}$  cm<sup>-3</sup>). That breakthrough directly led to ZnSe-based laser a year later at both, 3M Company and Brown/Purdue Universities [1,2]. At nearly the same time, in 1989, Isamyu Akasaki at Meijo University discovered that Mg doped GaN films would become p-type if the films were exposed to low energy electron irradiation. With a p-type doping capability Akasaki demonstrated first blue emitting LEDs, followed by Shuji Nakamura from Nichia Chemical developing Zn p-type doping for InGaN allowing candela-class blue emission in GaN/InGaN LEDs. Few years and many improvements later GaN LED's became so bright that one could hardly look at them. They were capable of putting out 2 cd. Since 1995 Nichia company is producing and supplying on the market one – two millions of such devices a month. The parameters of today's GaN LEDs are very impressive: blue LEDs (450 nm) with 2 cd output and very narrow emission spectra (20 nm linewidth); green LEDs (520 nm) with output 12 cd and 30 nm linewidth. The CREE Research also

\* Address for correspondence: Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, PL-02-668 Warszawa, Poland, phone: (+48)(22)43-13-31, fax (+48)(22)43-09-26, e-mail: karcz@ifpan.edu.pl

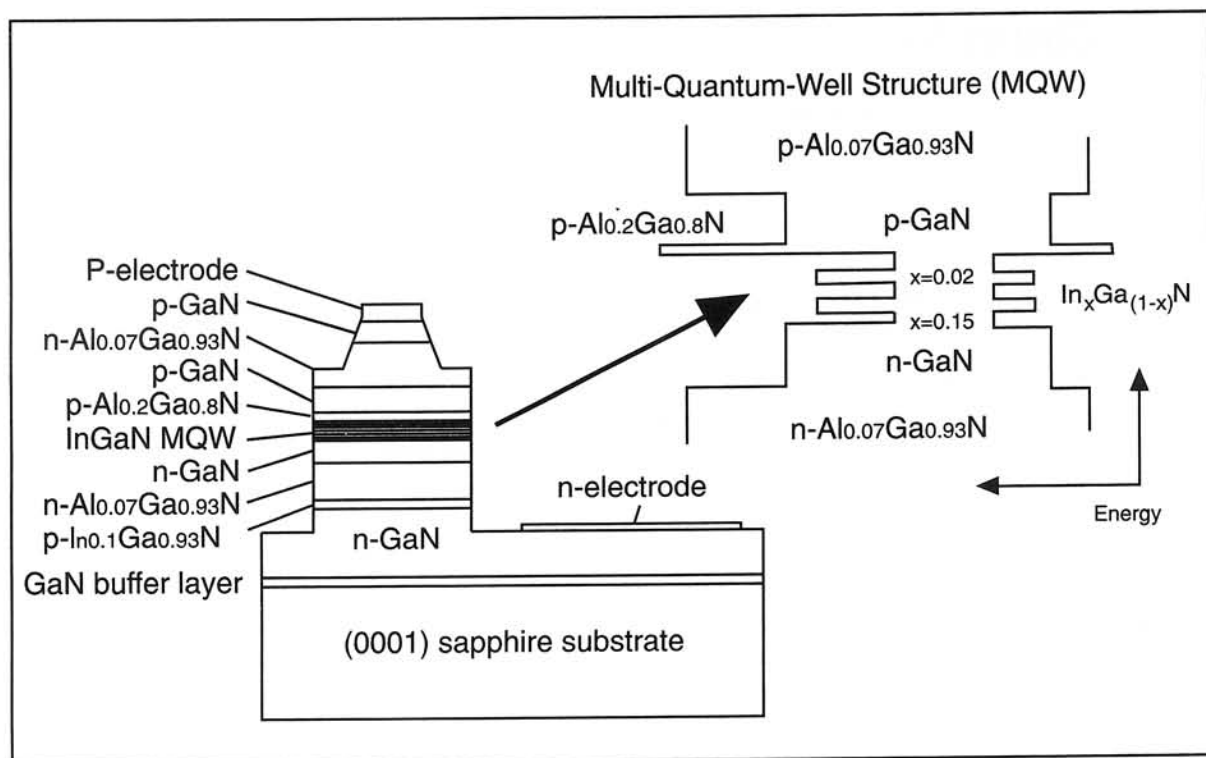


Fig. 1. Structure of the GaN-based, long lifetime (30 hours) diode laser.

reported the successful mass production of high brightness blue LEDs.

After accomplishing research on LEDs Shuji Nakamura started to work on his next target, a blue GaN diode laser. The first success on this field came very soon. On December 12, 1995 – Nichia Chemical Industries announced that Nakamura and coworkers had successfully demonstrated an InGaN-based multi-quantum well (MQW) laser diode operating at 417 nm under pulsed conditions at room temperature. This was the first report of lasing from the nitride materials system as well as the shortest wavelength ever generated by a semiconductor laser [3]. The threshold current density of the first lasers was 4 kA/cm<sup>2</sup> and the turn-on voltage 34 V.

Lately, in mid-November 1996, just eleven months after the announcement of the first observation of laser action in GaN-based structure, Nakamura announced the first successful room temperature continuous wave operation of GaN-based diode laser. His report was given at the LEOS'96 meeting (the ninth annual meeting of IEEE Laser and Electro-Optics Society) in Boston. The device was a separate confinement heterostructure (SCH) InGaN multi-quantum well (MQW) diode, shown in Figure 1. The active layer was an In<sup>0.15</sup>Ga<sup>0.85</sup>N/In<sup>0.02</sup>Ga<sup>0.98</sup>N MQW structure consisting of four 35 Å thick InGaN well layers forming a gain

medium separated by 70 Å thick In<sup>0.15</sup>Ga<sup>0.85</sup>N barrier layers. The structure of the ridge-geometry diode was almost the same as that described in earlier reports of pulsed operation. The device lased for more than 30 hours in the violet at 406 nm with threshold voltage of 5.5 volts and threshold current density of 3.6 kA/cm<sup>2</sup>. The success came just few weeks after his first report of low temperature CW operation and it capped a truly amazing year in the field of nitride research. Nakamura was able to attain more than 35 hours of room temperature operation in less than a year. One can believe that GaN will soon eclipse the best mark reported to date for II-VI diode laser (100 hours CW lifetime). This happened despite the fact that the II-VI's had a four-year head start [1, 2].

Most observers say that a blue semiconductor laser need to demonstrate at least 3 MW output power with lifetimes of 10<sup>4</sup> hours before it can be considered marketable. Both the II-VI and nitride efforts have a long way to go. The II-VI lasers need further reduction of defects, probably resulting from modification or manipulation of the substrate/epi interface. The new nitride lasers will require significant effort to reduce threshold voltage and currents, which also could be achieved by reducing dislocation densities. In GaN based structures grown on sapphire substrates (as in the case of Nakamura's lasers) one has to cope with a 16%

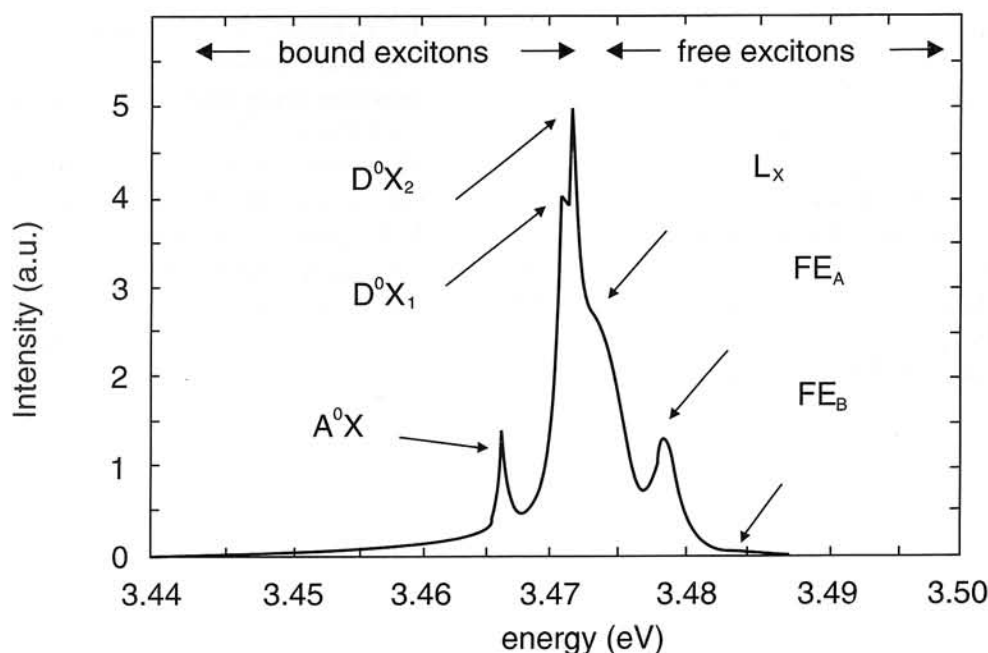


Fig.2. Low-temperature photoluminescence (4.2 K) of molecular beam grown homoepitaxial GaN layer.

lattice mismatch, yielding dislocation densities as high as  $10^9$ - $10^{10}$   $\text{cm}^{-2}$ . In spite of Nakamura's outstanding results there is a consensus that a better substrate material could improve the performance of the devices. The most important requirement for the ideal substrate is to have the same – or at least possibly close – lattice constants and thermal expansion coefficient as the epitaxially grown layer. Obviously, all of this can be achieved only in the case of homoepitaxy, when the GaN based structures are grown on GaN substrates.

The GaN substrates are the great hope of the nitride community. There is considerable work already in progress on this front. With the outstanding work performed at the Unipress, Poland, Sylwester Porowski and coworkers has recently produced GaN bulk substrates in useful sizes – up to  $9 \times 9$  mm. The crystals are grown in high pressures (15 kbar) and at extremely high temperatures (1600 C). The crystals reveal dislocation densities of  $10^2$   $\text{cm}^{-2}$  and a background carrier concentration of  $10^{19}$   $\text{cm}^{-3}$ . If GaN crystal size and availability can be further improved, it will have a major impact on many aspects of the development on GaN technology.

Employing GaN substrates could be the turning point not only in the evolution of GaN-based diode lasers, but also – for the first time - made high quality homoepitaxial GaN layers available for investigation of their basic physical properties. The latter issue remains of primary importance because the knowledge

of the basic properties of GaN is still fragmentary and – if not addressed systematically – may stand in the way of further technological progress. In particular, there is rather little known about band structure parameters of strain-free GaN, since strain is an omnipresent, hardly controllable parameter of all heteroepitaxial GaN films.

The GaN layers exhibiting excellent optical and crystal properties have been obtained with homoepitaxy. The low-temperature photoluminescence of this layers revealed rich excitonic spectrum with extremely narrow PL lines attributed to neutral acceptor bound excitons ( $A^0, X$ ) and two distinct lines related to excitons bound to neutral donors ( $D^0, X$ )<sup>1</sup> and ( $D^0, X$ )<sup>2</sup> (see Figure 2.). At low excitation densities and low temperatures the ( $D^0, X$ ) transitions are dominating. By increasing the excitation density or temperature the donor bound luminescence decreases in favor of increasing free exciton lines ( $FE_{A,B,C}$ ). The linewidth of these transitions is 0.5 meV, which is the lowest linewidth of excitonic transitions ever reported in GaN. Due to the narrowness of the free exciton transitions it becomes possible to determine the splitting of the valence band caused by the axial crystal field and spin-orbit interaction [4].

As was mentioned above, the quest for blue light emitters is often characterized as a race between ZnSe and GaN. In the last year GaN significantly decreased the distance to ZnSe and is about to take the lead in this race.

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