Selecting the Right Growth-Plane within GaN Crystal for InGaN-based Yellow-Green or Yellow Lasers by Simulations

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For InGaN-GaN based lasers, the growth-plane within GaN crystal is having an important impact in producing 'direct' yellow-green or yellow lasers. The rigorous **k·p**-method with Hamiltonian (8 by 8), while taking full average over $360^o(\phi)$ is used to calculate dipole moments, effective mass and subbands. The optical gain is compared along with piezoelectric effects and effective mass due to strain in quantum well in order to predict the possibility of yellow-green lasers with right choice of growth-plane.

Keywords: Multiphysics of semiconductor lasers, yellow-green or yellow lasers, growth-plane within wurtzites crystals, polar, semipolar and nonpolar grown devices and piezoelectric effects.

Over the last decade there has been a challenge in producing yellow-green and yellow laser straight away without doubling the frequency. Hereby, GaN-based laser is playing an important role compared to other types of light emitting diode (LED) or lasers. However, there have been observations of undesired effects while growing the laser structure perpendicular to the c-plane (polar) of GaN crystal. That is due to the spontaneous polarization and internal stresses which could create electrostatic charges as high as 100 volts per micron. This leads to quantum confined stark effect (QCSE) [5] which mainly increases the energy separation between the first two energy levels and causes the *blue shift*. The quantum efficiency could drop after 550 nm due to a well-known problem, so-called 'green-yellow gap'. By growing the laser structure on an appropriate crystal planes, e.g.($20\bar{2}1$) of GaN, as shown in Fig.1, these undesired effects can be avoided to a large extent [3] [4]. The laser sources with emission wavelength in the range from 550 nm to 600 nm have attracted a lot of attention for a numerous applications in medicine [1], biology, Bose-Einstein condensation and display technology [2]. Much research has been devoted in order to achieve full coverage of the visible light region by using GaN-InGaN based LED or lasers. It remains a challenge and a possibility towards producing a stable direct yellow-green and yellow LED or lasers.

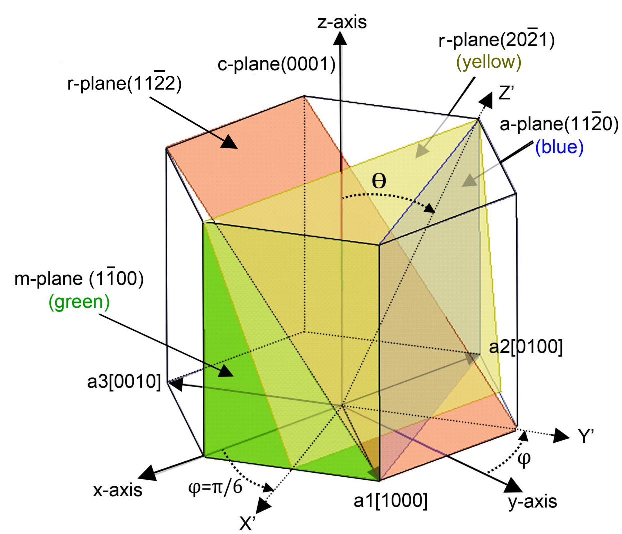

FIG. 1: Proposed r-plane ($20\bar{2}1$) and relevant planes.

A well-known Crosslight Software Inc.[8] has been exploited in order to make right choice for the growth-plane (e.g. defined by Miller indices) within GaN crystal. Hereby, the electronic and optical properties of InGaN-GaN laser grown on different planes have been investigated. This software offers a vast range of choices for the parameters which are playing an important role. The structure of the lasers comprises wurtzite $In_{0.15}Ga_{0.85}N$-GaN with compressively strained single or three quantum wells of *n*-doped InGaN (30 Å) with a barrier of GaN (120 Å). There is a blocking layer of p-AlGaN on the top of the active region. A cladding layer is on both sides and it is grown on a thick GaN substrate layer. The percentage (x) of In in $In_xGa_{1-x}N$-GaN and the thickness of the quantum well controls the bandgap in order to reach the longer wavelength for yellow-green or yellow emission. The higher number of quantum wells are contributing to the higher polarization charge at the interfaces, i.e. their advantage against a single quantum well can not be fully utilized. The strain at the interface has been taken into account by minimizing the elastic energy [7]. Main part of the theory is based on quantum mechanical calculation of band structure using the Hamiltonian based on **k·p**-method for a-, c-, m-, r-plane grown crystal orientations (Fig.1).

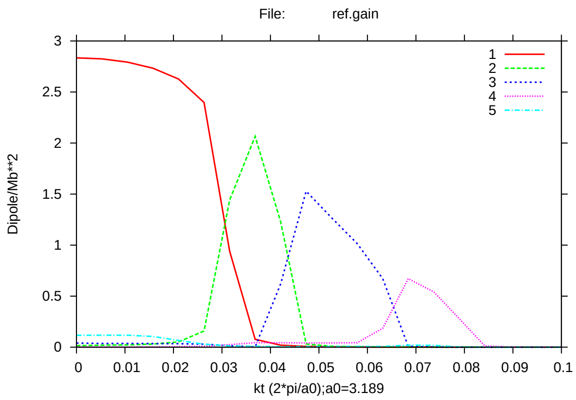

FIG. 2: Dipole transitions from valence subbands to the conduction band for growth-plane (20$\bar{2}$1).

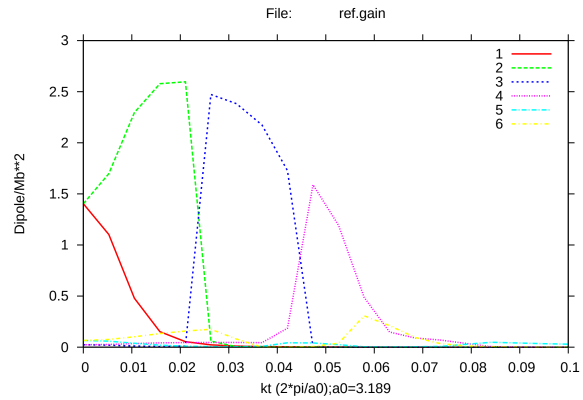

FIG. 3: Dipole transition fron valence subbands to the conduction band for growth-plane (0001).

This remains a new approach for a band structure engineering in order to calculate better optical properties. The interband optical momentum matrix elements are also calculated for TE or TM polarization in m-plane (1$\bar{1}$00), c-plane (0001) and r-plane (20$\bar{2}$1) grown orientations. For example, optical matrix elements for m-plane grown devices are polarization dependent.

The optical gain is related to optical matrix element, *i.e.* optical gain increases in a particular polarization direction if the optical matrix element decreases in that particular direction.

When comparing the results of Fig.2 and Fig.3, it can be clearly observed that transitions from top three valence subbands to the lowest conduction band are stronger in growth-plane (20$\bar{2}$1) (Fig.2) than in growth-plane (0001) (Fig.3). These transitions have more significant effect near $\mathbf{k_t} = \mathbf{0}$ causing direct transitions . There is a possibility to calculate the Hamiltonian for an arbitrary plane by choosing different Miller indices or choosing angles ϕ and θ, see Fig.1. This research is mainly based on publications by Park and Chuang [7].
These numerical simulation and mathematical modeling will offer a choice for the optimization of the laser performance and a better understanding of yellow-green and yellow lasers which are expected in the near future by choosing the right growth-plane and the amount of **In** in the $In_xGa_{1-x}N$-GaN. The growth-plane (20$\bar{2}$1) seems to be a promising candidate so far [3]. More research is required in order to continue towards even higher wavelength, e.g. up to 600 nm. In case, these challenges are met, GaN will become the most important semiconductor next to silicon.

GaN will play a significant role in novel applications, *e.g.* pico-projectors [4] and laser TV [5]. Such simulations remain an alternative tool towards cost-efficiency for the experimental work.

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