Effects of Semipolar and Nonpolar Planes on Optical and Electronic Properties of InGaN-GaN Lasers

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Non(semi)polar plane grown GaN-based quantum well lasers are having big impact on the development of green and yellow-green lasers. In order to compare these effects, Hamiltonian, up to 8 by 8 **k**·**p**-method, is used. Thereby, dipole moments, effective mass and subbands are calculated. Obviously, the optical gain is enhanced and piezoelectric effects and effective mass are decreased due to internal strain and crystal orientation . These effects have been compared by simulations.

Keywords: semiconductor lasers, green lasers, yellow-green lasers, polar, semipolar and nonpolar grown devices, piezoelectric effects, multiphysics of semiconductor lasers.

Recently, there has been a race in producing green laser straight away without doubling the frequency which is a complicated and inefficient process [1, 2]. Due to internal stresses and electrostatic charges, a strong field is created perpendicular to the crystal's c-plane (0001) in between the active thin layers. It can be as big as 100 volts per micron [2]. This interaction of the polarization with the material on a quantum mechanical level is known as a quantum confined stark effect (QCSE) [1] which causes bandgap narrowing. As the current flows, it ends up in widening the bandgap and causes the *blue shift* [1]. These problems are less dominant if the crystalline GaN is sliced along non(semi)polar plane (Fig.1) at the start of growth, *i.e.* polarization charge [3] and internal stresses are much less and can give more stable green emission in InGaN-GaN based lasers [4]. A versatile software (Crosslight Inc.[5]) has been used extensively in order to compare the electronic and optical properties of InGaN-GaN lasers grown on different crystal planes defined by Miller indices and make predictive estimation for the real devices. It has a vast range of choices with respect to emerging new technologies, structures and algorithms.

The structure consists of a wurtzite $In_{0.15}Ga_{0.85}N$-GaN with compressively strained three quantum wells of *n*-doped InGaN (30 Å) with a barrier of GaN (120 Å), and there is a cladding layer on both sides and it is grown on a thick GaN substrate layer. Simulations are also done for higher percentage (x) of In in $In_xGa_{1-x}N$-GaN and with single quantum well. The number of quantum wells are related to the amount of polarization charge at the interfaces and the percentage of **In** is related to the bandgap.

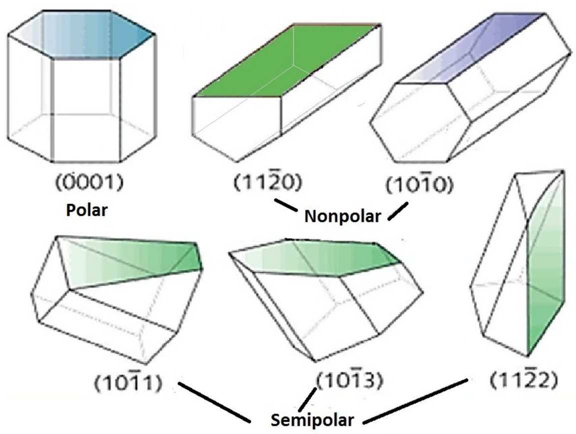

FIG. 1: Nonpolar, semipolar and polar planes with their Miller's indices in wurtzite crystal structure of GaN.

The strain is engineered by minimizing the elastic energy.

The key part of the theory is based on quantum mechanical calculation of band structure using the Hamiltonian based on **k**·**p**-method for a-plane, c-plane (0001), m-plane (10$\bar{1}$0) and a-plane (11$\bar{2}$2) grown crystal orientations. This method remains a new approach for band structure engineering in order to achieve better optical properties. The interband optical momentum matrix elements are also calculated for TE or TM polarization in m-plane and c-plane 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 (orientation) if

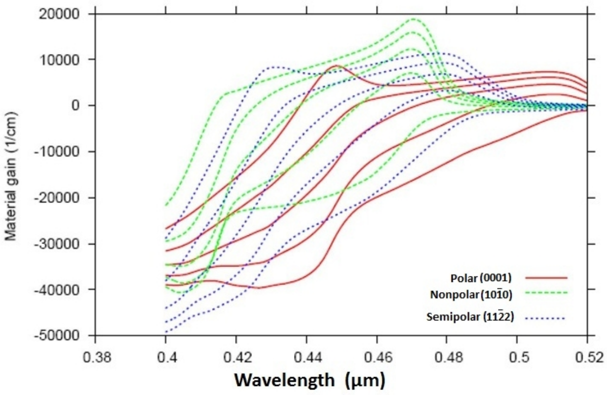

FIG. 2: Gain for different planes of growth with internal field at the interfaces of layers.

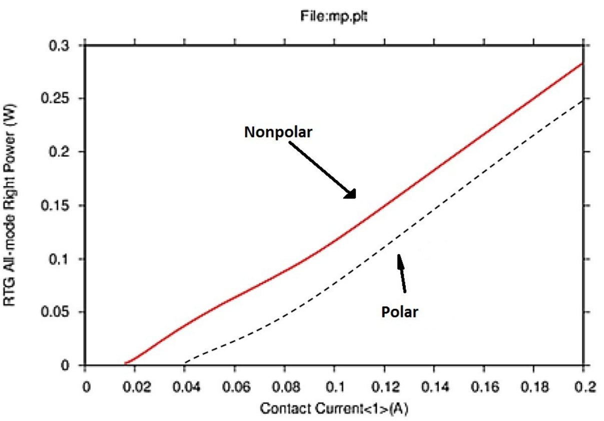

FIG. 3: Threshold current and power simulated for polar and nonpolar grown lasers.

the optical matrix element decreases in that particular direction. There is possibility to calculate the Hamiltonian for an arbitrary crystal orientation by choosing diffent planes of growth defined by Miller indices. This work is mainly based on publications by Venkatachalam, Park and Chuang [6, 9, 10].

When comparing the results in Fig. 2, it can be clearly observed how the gain behaves for different planes of growth (polar and non(semi)polar) of the crystal GaN. The gain for nonpolar and the semipolar grown crystlal are better and suitable for green emission. Moreover, the threshold current is less and the power is more for nonpolar grown lasers (Fig. 3).

These simulations offer a strategy for the *optimization* of the laser performance and better understanding of green lasers which are expected in near future by choosing the right amount of **In** in the $In_xGa_{1-x}N$-GaN and the right plane of the growth. Moreover, this research could continue towards yellow-green emission as described in [7], using the growth on semipolar plane (20$\bar{2}$1). It will play a significant role in novel applications, *e.g.* pico-projectors [4]. Such calculations are an alternative method towards investigating cost-efficiency as a designing tool. The availability of material parameters is an important and ongoing development for better modelling by numerical simulations.

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[1] A. Extance, 'Going for Green', *Physics World*, May 2010, p.43.

[2] R. Stevenson, 'Lasers Get the Green Light', *IEEE Spectrum*, March 2010, p.34.

[3] Vincent Fiorentini and Fabio Bernardini, 'Evidence of Nonlinear Macroscopic Polairization in III-V Nitride Alloy Heterostrucures', *Applied Physics Letters*, Vol. 80, No.7, 18 February 2002, p.1204.

[4] Shuji Nakamura and Michael Riordan, 'The Dawn of Miniature of Green Lasers', *Scientific American*, April 2009, p.70.

[5] Crosslight Inc,. *Photonic Integrated Circuit Simulator in 3D (PICS3D)*, Software 2012.

[6] A. Venkatachalam *et al.*, 'Design Strategies for InGaN-Based Green Lasers', *'IEEE Journal of Quantum Electronics'*, February 2010.

[7] S. Yamamoto *et al.*, 'High-Efficiency Single-Quantum-Well Green and Yellow-Green Light-Emitting Diodes on Semipolar (20$\bar{2}$1) GaN Substrates', *Applied Physics Express 3* (2010).

[8] T. Takeuchi *et al.*, 'Determination of piezoelectric fields in strained GaInN quantum wells using the quantum-confined Stark effect', Appl. Phys. Lett., vol. 73, pp. 1691-1693, 1998.

[9] Seoung-Hwan Park and Shun-Lien Chuang, 'Crystal-Orientation Effect on the Piezoelectric Field and Electronic Properties of Strained Wurtzite Semiconductors', *Physical Review B*, Vol. 59, No. 7, 15 February 1999, p. 4725.

[10] Seoung-Hwan Park, Doyeol Ahn and Shun-Lien Chuang, 'Electronic and Optical Properties of a- and m-Plane Wurtzite InGaN-GaN Quantum Wells', *IEEE Journal of Quantum Electronics,* Vol. 43, No. 12, December 2007.