# Modeled the Front End Process for fabrication of GaN based LASER Diode

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***Abstract***- *In this paper, we have presented the modeling and simulation of GaN based LASER diodes (LDs). Here the complete structure of MQW (InGaN) blue LD is grown on Epitaxial laterally overgrown GaN (ELOG) and sapphire substrate. ELOG is used to improve the lifetime of LDs. The choice of materials and thickness of each layer is taken from literature. In addition, a literature survey is included here to show various properties of GaN for the fabrication of blue LDs. The complete layered architecture of GaN LDs are also discussed. Simulation is done on SILVACO.*

***Keywords***- Gallium Nitride, Blue laser diode (LDs), Wide band gap, ELOG, LD characteristics, Dev-edit..

## I. INTRODUCTION

Laser diodes are the most versatile and convenient coherent light sources. Their emission wavelength over a broad spectral range can be almost freely customized that depends on the semiconductor crystal composition [1]. The UV LDs (Laser diode) have gained much attention for multiple applications including laser printers, medical engineering, read-write laser sources for information storage of high-density, sterilization and undersea optical communications [2]. The nitride semiconductors like GaN of III-V group are most promising for realization of these devices, due to their wide energy band-gap [3]. One of the most important characteristics of GaN is its optical properties like when compared to nitride, gallium is good absorber and it can absorb large amount of light. Hence less of nitride will results in reduction of the transmission rate of GaN [4].

The cross sectional view showing two sections of GaN laser diode is shown in figure1. It has two sections, an electron absorption modulator and an amplifier (gain) sections that are coupled optically, sharing the same MQW (InGaN) active layer. But by a dry-etched trench, they are electrically separated. To enable lasing operation enough gain is to be produced by a constant forward current that would biased the amplifier section, provided that another section is in state of low loss. Also the switching of the laser device can be between the state of ON and OFF by controlling the optical loss in modulator section and just by reverse biasing it. This approach is termed as Q-switching, that provides an advantage of smaller dissipated power which is required to switch laser devices between its ON and OFF states [5].

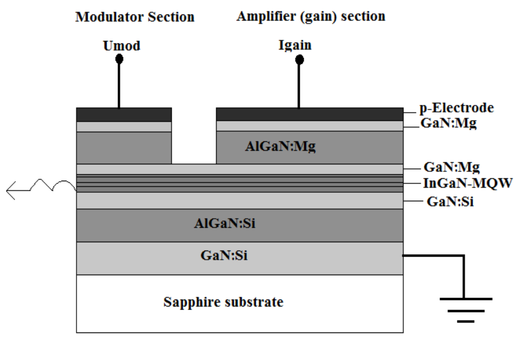


Fig1. Cross sectional view of LD [5]

Superior electrical properties are possessed by semiconductor materials with wide band gap and can operate at higher temperatures. Some of these properties are tabulated in table I for Si and most popular wide band gap materials.

TABLE I
ELECTRICAL PROPERTIES OF Si AND MOST POPULAR WIDE BAND SEMICONDUCTOR MATERIALS [6]

| Properties | Si | 6H-SiC | 4H-SiC | GaN |
|---|---|---|---|---|
| band gap, Eg (eV) | 1.12 | 3.03 | 3.26 | 3.45 |
| thermal conductivity (W/cm.K) | 1.5 | 4.9 | 4.9 | 1.3 |
| saturated electron drift velocity, $V_{sat}$ ($10^7$cm/s) | 1 | 2 | 2 | 2.2 |
| electron mobility, $u_n$ ($cm^2$/Vs) | 1500 | 500 80 | 1000 | 2000 |
| hole mobility, $u_p$ ($cm^2$/Vs) | 600 | 101 | 115 | 850 |
| dielectric constant | 11.9 | 9.66 | 10.1 | 9 |
| electric breakdown field, $E_c$ (KV/cm) | 300 | 2500 | 2200 | 2000 |

It is clear from the table that GaN is having highest band gap. It will result in light emission at shorter wavelength. Also both GaN and SiC have high critical field compared to Si that allows them to work with lower leakage current and at higher voltages. The electron saturation velocity as well as electron mobility of GaN is higher than both SiC and Si. This means that for high frequency it should be the best device [7].

Since nitride based devices have several applications over another semiconductor material. Table II illustrated advantages of nitride devices with their corresponding properties.

TABLE II
ADVANTAGES FOR NITRIDE ELECTRONIC DEVICES [8]

| Properties | Advantages |
|---|---|
| high mobility, high saturation velocity, high sheet carrier concentration, high breakdown field | high microwave power, power electronic devices |
| high microwave power, power electronic devices | high temperature operation |
| chemical inertness, good ohmic contacts, no micropipes. | holds promise for reliable device fabrication |
| SiO2/AlGaN and SiO2/GaN good quality interfaces | insulated gate transistors possible |

## II. WORKING PRINCIPLE OF LASER DIODE

Laser diodes constitutes three semiconductor layers, the layer with narrow band gap (InGaN) is sandwiched between two cladding layers of wide-band gap (AlGaN), generally upper layer is p-type and bottom layer is n-type. When the external electrical field is applied the charge carriers are injected into the undoped middle layer (InGaN) where charge carriers are trapped due to differences in band gap and thus large carrier densities can be achieved. If the thickness of sandwiched layer is reduced to few nanometer, quantum effects (quantum well) will occur. The stimulated emission exceeds the absorption in the QW and amplification of light occurs at sufficiently high carrier injection. The lasing can be achieved by placing two mirrors to create a Fabry-Perot cavity around the gain medium. To maximize the amplification of light both the charge carriers and the emitted light are confined in vertical direction. In between the QW and the cladding layers, two extra wave guiding layers are inserted which are having an intermediate band gap [1]. Figure3 shows the voltage versus current (V-I) and light output power versus current (L-I) characteristics of blue LDs with 460nm emission wavelength under 25oC.

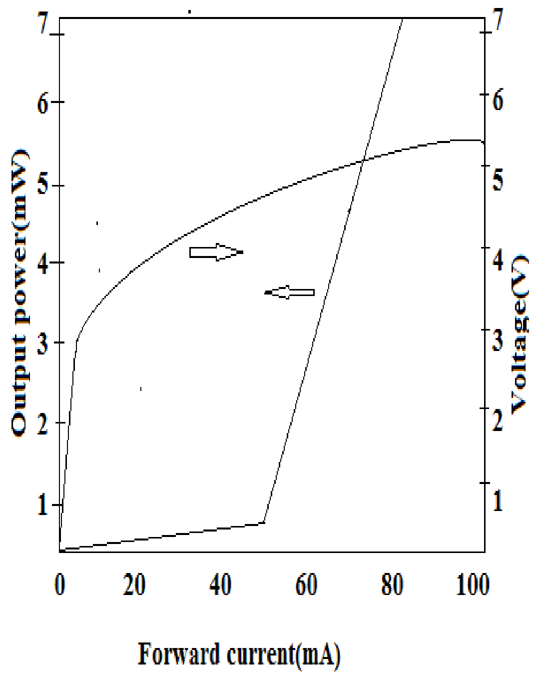


Fig.2 V-I and L-I characteristics of blue LDs at 25oC [9].

The graph shows that when input current was less than threshold value of 55mA no light was emitted having a threshold current density of 3.3kAcm-2 value. And in the pure blue region this is the lowest value ever reported for LDs based on III-V nitrides. By a uniform and high quality crystal quality of InGaN layer this low threshold current density can be achieved, as by using the GaN substrate with ELOG we could achieve the dislocation density reduction [9].

## III. DEVICE STRUCTURE, CHOICE OF MATERIALS AND FABRICATION PROCESS

A. Device structure

1) The structure of GaN based laser diode is shown in fig.2 that was grown on sapphire substrate. The ELO (Epitaxially lateral overgrown) GaN layer formation is used because for GaN based LDs the dislocation density is high in the material when sapphire substrate is used [4]. These dislocations densities can be reduced that originates because of the interface between sapphire substrate and GaN due to large lattice mismatch of 15% using ELOG [10].

2) The active region is consist of one to five InxGa1-xN QWs. To capture electrons in active region and thereby releasing a photon by allowing electrons to jump the bandgap quantum wells are designed. Each well is of thin layer surrounded by different materials of thicker layer. The active material used for well layer has refractive index lower than the layers that

surround them. Also for producing the light of a desired wavelength the dimension of the well must be of the same order. To achieve population inversion the current density is small due to small size of QWs and hence the threshold current density is low of QW structures. As the number of QW increase the value of threshold current also increase but it decreases with composition of x in InxGa1xN/GaN [11].

3) The MQW-based active region is followed by a larger bandgap material i.e. Al0.2Ga0.8N:Mg blocking layer for electron i.e. EBL in the p-side to increase the efficiency of carrier injection by controlling overflow of the carriers and thermionic emission from QWs. Recently, it was proposed to use AlGaN EBL to improve the threshold of GaN and also to obtain high temperature/ high power operations [11].

4) The p- and n- type GaN are serving as wave guiding layers. These are sandwiched between upper and bottom cladding layers namely p-type Al0.08Ga0.92N/GaN:Mg and n-type Al0.08Ga0.92N/GaN:Si super lattices, respectively. To confine carriers to the active region the surrounding cladding layers provide an energy barrier. The injection of charge carriers and light confinement are two functions that are served by cladding layers.

5) Finally a heavily doped layer with Mg i.e. GaN is utilized as a contact layer of p-type electrode.

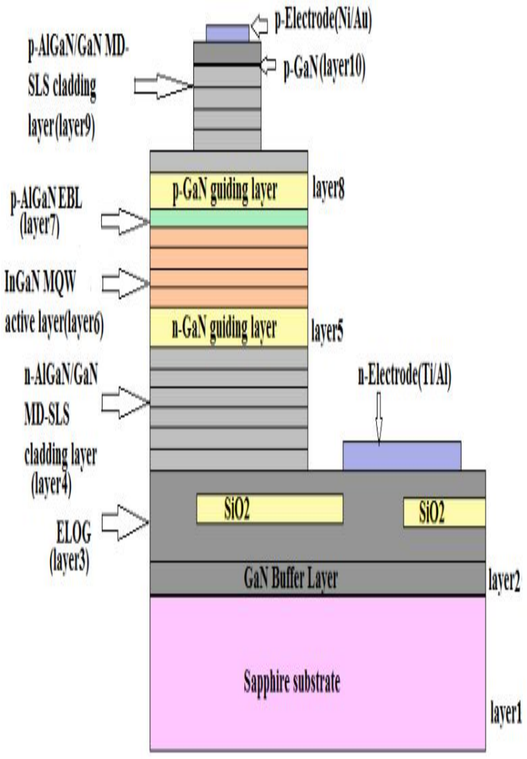


Fig.3 Structure of GaN based laser diode [10]

B. Steps of Fabrication Process [2]

1) Two flow and low pressure MOCVD is one of the major method for the fabrication of laser diodes based on nitrides of III-V groups.

2) At atmospheric pressure, the growth was conducted. Here the substrate used was (0001)C-face sapphire on which a GaN buffer layer of thickness 300A° was grown at 550oC. (Layer1-layer2)

3) ELOG layer (layer3) formed is to reduce the dislocation densities. This layer is formed in following ways- First deposit a n-type GaN layer of 3um thickness with Si doped. Then prior to the growth of second thick GaN layer deposit the stripes of SiO2. Over the mask areas some voids may occur but these usually merge after the growth of about 7um and flat GaN surface was produced. The wafer with 20um of overgrown GaN and flat surface is termed as ELOG substrate [12].

4) Then for the n-GaN deposit a metal contact (Titanium/ aluminum).

5) After an n-type i.e. silicon doped Al0.08Ga0.92N/GaN cladding layer of thickness 0.5um was deposited. (layer4)

6) An n-type GaN: Si acted as light guiding layer of thickness 0.1um is deposited over n-type cladding layer. (layer5)

7) To form the MQW which is made of three layers with a thickness of 35A° In0.15Ga0.85N and doped with Si thus resulting in a gain medium separated by barrier layers.( layer 6)

8) After that deposit a p-type Al0.2Ga0.8N of thickness 200A° with Mg doped. This layer is called electron blocking layer and is used to increase the efficiency of carrier injection. (layer7)

9) Again deposit a GaN doped with a p-type material (p-type material used is Mg) with a layer thickness of 0.1um. This layer also acted as light guiding layer. (layer8)

10) Now deposit another cladding layer of thickness 0.5um. The material used now is p-type Al0.08Ga0.92N/GaN:Mg. (layer9)

11) Finally a p-type GaN:Mg of thickness 0.3um is deposited (layer10) followed by the another metal contact (Nickel/ Gold) deposition for p-GaN.

TABLE III
CHOICE OF MATERIAL FOR GALLIUM NITRIDE BASED LASER DIODES WITH THEIR REFRACTIVE INDEX AND REGION NAME [11]

| Material | Refractive Index (n) | Regions |
|---|---|---|
| p-$Al_{0.12}Ga_{0.88}N$/GaN | 2.53 | modulation doped SLS cladding |
| p-GaN | 2.55 | p-Guiding layer |
| p-$Al_{0.35}Ga_{0.65}N$ | 2.42 | e-blocker |
| $In_{0.1}Ga_{0.9}N$/GaN(QWs) | 2.685/2.55 | active regions |
| n-GaN | 2.55 | n-Guiding layer |
| n-$Al_{0.12}Ga_{0.88}N$/GaN | 2.53 | modulation doped SLS cladding |
| Sapphire | 1.77 | substrate |

## IV. MODELING AND SIMULATION OF GaN BASED LASER DIODES

1) In Silvaco tool click on dev edit icon, Dev edit window appears as given follow.

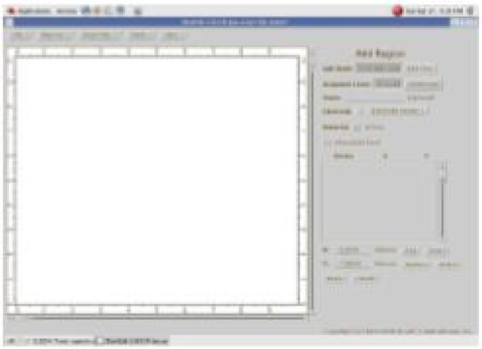

Fig.4 Dev Edit Window

2) Select the work region parameter from work region menu, as given below:

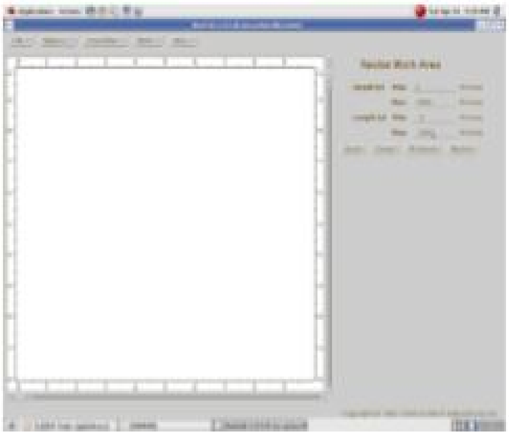

Fig.5 Work Area window

3) From right side window select Sapphire substrate from material tab on which device is fabricated, corresponding structure is represented below.

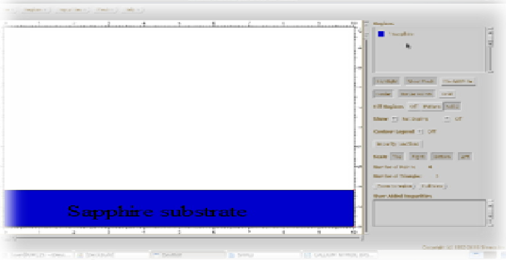


Fig.6 Growth of Sapphire substrate

4) For deposition of GaN buffer layer, from region menu select add region, followed by selecting GaN from material tab.

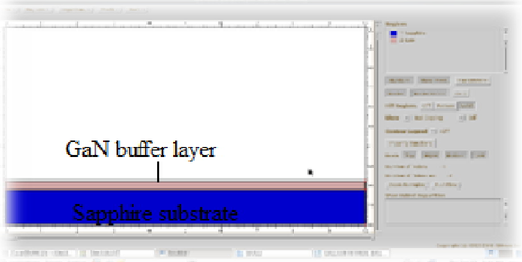


Fig.7 Deposition buffer layer of GaN

5) The ELOG layer is formed by growing a layer of GaN of 3um on sapphire substrate.

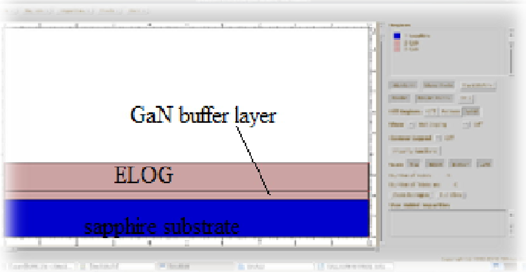


Fig.8 Formation of ELOG

6) Now before the growth of another thick GaN layer deposit the stripes of SiO2 of 2um thickness.

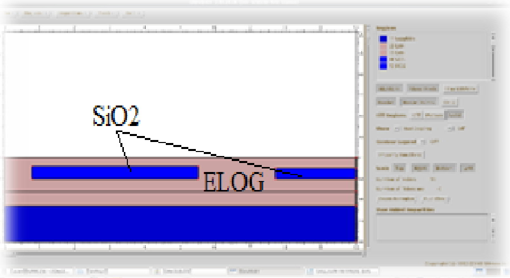


Fig.9 Deposition of stripes of SiO2

7) For n-type GaN layer a metal contact (Titanium/Aluminum) is deposited.

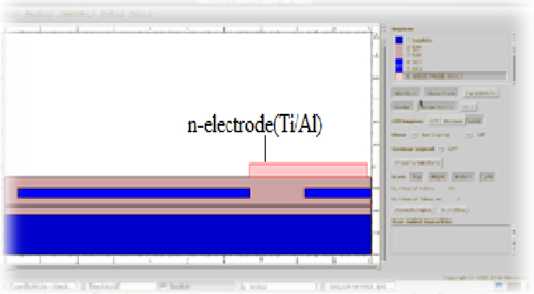


Fig.10 Formation of metal contacts

8) Deposition of n type AlGaN/Gan Modulation Doped-SLS cladding layer.

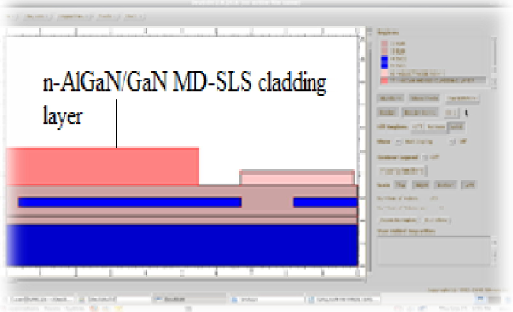


Fig.11 n- type Cladding layer formation

9) Deposition of n type GaN guiding layer

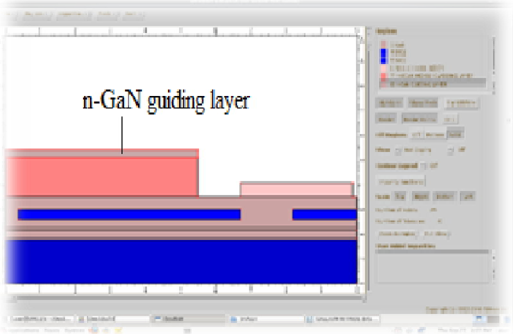


Fig.12 n-type guiding layer formation

10) Deposition of InGaN MQW active layer

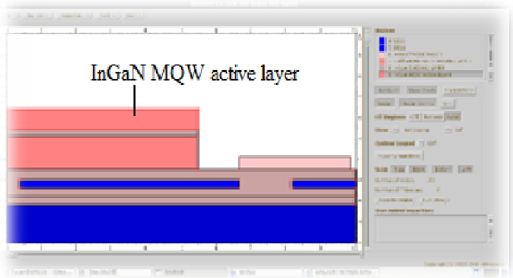


Fig.13 Formation of active layer of InGaN

11) Deposition of p type AlGaN Electron blocking layer (EBL).

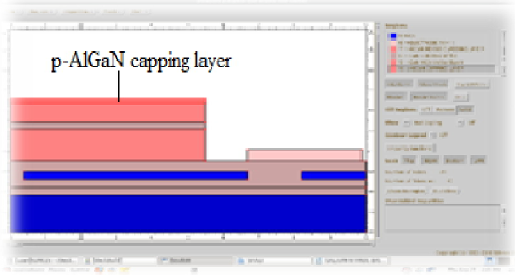


Fig.14 EBL Formation

12) Deposition of p type GaN guiding layer.

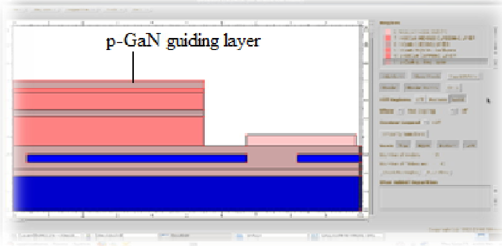


Fig.15 p-type Guiding layer formation

13) Deposition of p type AlGaN/Gan Modulation Doped-SLS cladding layer.

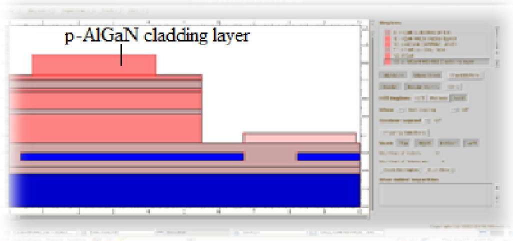


Fig.16 p-type Cladding layer formation

14) Finally a p-type GaN:Mg layer is deposited followed by the another metal contact (Nickel/ Gold) deposition for p-GaN.

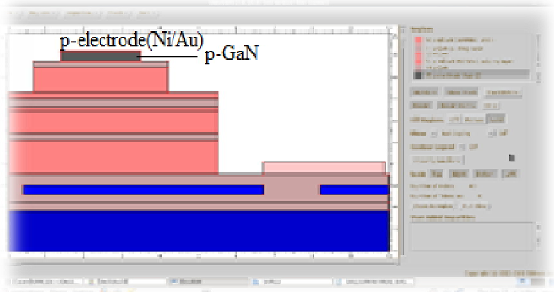


Fig.17 Formation of metal contacts for p-GaN layer.

## V. CONCLUSIONS

Several applications in commercial market has been opened for semiconductors after development in GaN technology. GaN based blue semiconductor laser diode which are grown on sapphire substrate has been demonstrated here, used in high speed devices like microwaves. It used dry etched facets and top side n-contacts on sapphire based substrate. The work on this paper illustrates a simple and easy modeling of GaN based laser diode for complex fabrication process. It can be used for implementing real time devices.

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