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Monolithically p-down nitride laser diodes and LEDs obtained by MBE using buried tunnel junctions design

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ABSTRACT

New approach towards efficient light emission with bottom-tunnel junctions is developed. The bottom-tunnel junction design aligns the polarization fields in a desired direction in the vicinity of quantum well, while simultaneously eliminating the need for p-type contacts, and allowing efficient current spreading. By preventing electron overshoot past quantum wells, it disables carrier recombination in undesired regions of the heterostructures, increasing injection efficiency and opening new possibilities in heterostructure design. InGaN-based buried-tunnel junction is used to construct first monolithically grown p-type-down laser diode on n-type, Ga-polar bulk GaN substrate. Unique advantages of such construction that enables to separate design of carrier injection and optical mode confinement for such laser diode structures is discussed.

Keywords: Nitrides, GaN, tunnel junction, laser diodes, light emitting diodes, Gallium polarity, Nitrogen polarity, molecular beam epitaxy,

1. INTRODUCTION

Gallium Nitride and its related family of alloys have truly unique features that distinguish them from other compounds. A key example is their wide bandgap tunability enabling light emitting diodes (LEDs) and laser diodes (LDs) that emit light across the spectral range from deep ultraviolet to infrared. Nitride LEDs are so widely demanded that the invention of the blue Nitride LED by Isamu Akasaki, Hiroshi Amano and Shuji Nakamura earned the 2014 Nobel Prize in Physics.[1-3] Nitride LEDs are now mature and produced on a large scale, but dominant strategy currently used for both applications mentioned above involves growth along the Ga-polar, or [0001], direction, with few groups pursuing growths along other orientations. One main reason for this is the lack of large area non-polar and semi-polar substrates (though UC Santa Barbara has developed LEDs and LDs on such substrates). However, it is impossible to use the same explanation to understand why there are so few reports of light emitters grown along the N-polar, or [000-1],[4, 5] direction, which requires the same substrates as Ga-polar growth.

Lack of abundant N-polar structures is even harder to explain when taking into account a few expected improvements in device operation for N-polar structures over Ga-polar ones, like e.g. higher injection efficiency for LEDs grown at N-polar substrates. Qualitative differences between Ga-polar and N-polar structures can be observed with p-n junctions. Due to the extreme difference in conductivity of p-type and n-type layers induced by high acceptor (Mg) ionization energy in GaN and low hole mobility, n type substrates are generally used to ensure low resistivity of the bottom terminal. This constrains LEDs of all polarities to be grown with p-type on the top (Fig. 1). With this geometry, LEDs grown on N-polar substrates have the built-in polarization field aligned along the p-n junction field in the forward bias (Fig. 1(b)). This effect should increase injection efficiency for N-polar LEDs comparing to Ga-polar (commonly used) ones by moving barrier for electron (hole) transport from n- (p-) to p- (n-) side, respectively. For LD this will lead to decreased threshold current.

The main difficulties that block development of N-polar devices are: lower chemical stability (compared to Ga-polar) leading to more complicated substrate preparation[6] and post growth device processing[7] and specifics of growth on the N-polar surface that lead to higher oxygen contamination (10 to 100 times depending on growth technique)[8-10] and close to 30 times lower Mg incorporation compared to Ga-polar growth,[11] leading to poor p-type doping.

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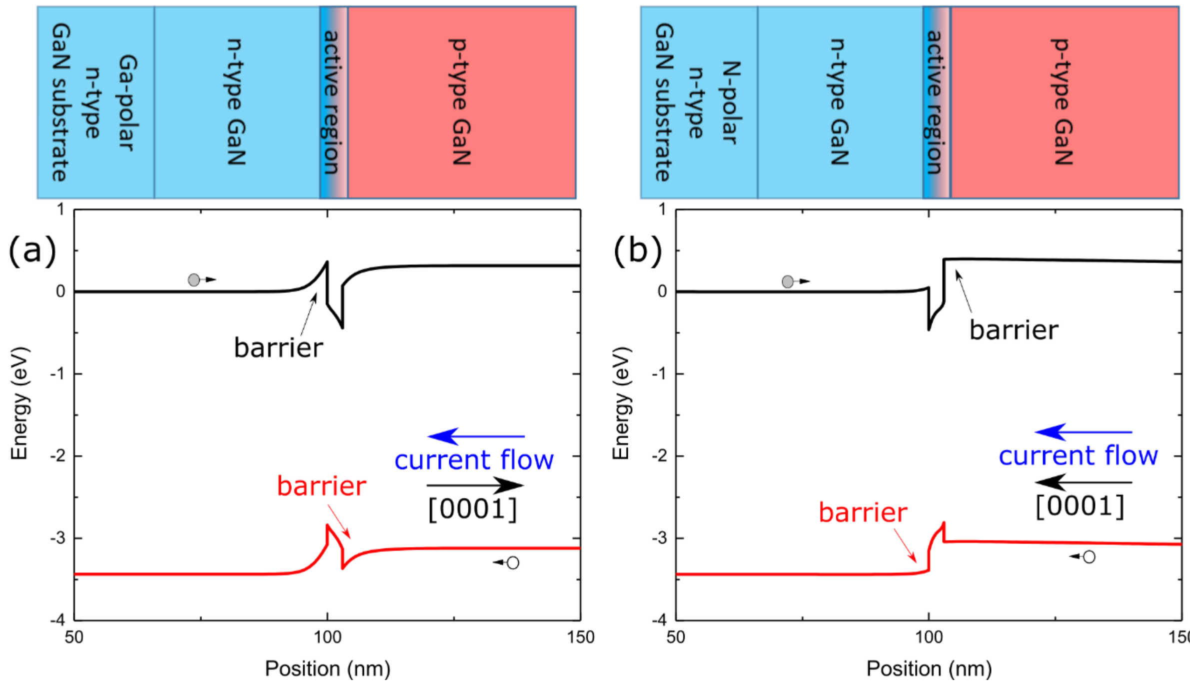

Figure 1. Schematic images of LED structures grown at (a) Ga-polar substrate and (b) N-polar substrate. Different colors are used to present n-type (blue) and p-type (red) material. Below the structures, band diagrams for 3V forward bias for a single quantum well LEDs are shown. Hole injection direction and [0001] crystallographic directions are indicated for reference. Barriers for electrons and holes indicated in (a) block carrier injection, reducing injection efficiency and in (b) block carrier overflow, increasing injection efficiency.

Solution to go around the material problems associated with growth along [000-1] and still profiting from the beneficial alignment between built-in field and current flow directions is to grow the structure along [0001] but inverse the n- and p- type ordering.[12-14] Then to obtain active buried p-type layers one can use hydrogen-free growth technique like e.g. plasma-assisted molecular beam epitaxy (PAMBE). To overcome poor p-type substrates conductivity, on the other hand, buried tunnel junction (TJ) grown on standard n-type substrate can be used to efficiently inject holes from the bottom of the devices. As it was shown before, TJ can be efficiently obtained using PAMBE[15-17] also as a contact layer for lasers[18, 19].

2. EXPERIMENTAL

The growth of nitride laser structures presented in this paper was performed using a customized Gen20A PAMBE reactor equipped with two Veeco RF plasma sources. We used low dislocation density bulk GaN substrates with threading dislocation density below $5 \cdot 10^4$ cm^{-2}, grown by ammono-thermal method[20]. The epi-ready bulk substrates were prepared by mechanical polishing and mechano-chemical polishing. Miscut angle was 0.5 degree towards [1-100] direction. For growths, 10x10 mm^2 or 1/4 of 1 inch bulk GaN substrates were attached to 2 inch GaN/Al_2O_3 template wafers using gallium.

Schematic image of the investigated structure together with its transmission electron microscopy image was presented in Fig 2. As indicated in Fig 2(a) structure can be divided into parts: tunnel junction – TJ and laser diode – LD. The progress in InGaN growth by PAMBE allows us to implement the InGaN waveguides for LDs as presented before.[21-23] For LD presented in this work waveguide consisted of 140 nm undoped $In_{0.08}Ga_{0.92}N$, divided into: 60 nm below and 80 nm above the active region, and was supported by 500 nm thick $Al_{0.07}Ga_{0.93}N$ cladding from the top. Active region consisted of a single 25 nm $In_{0.17}Ga_{0.83}N$ layer.[24, 25] To show high injection efficiency capabilities associated with inverted LD structure 300 nm thick undoped GaN spacer was grown just below the waveguide. This gives total distance between the active region and p-type layers equal to 360 nm. Even though no electron overflow is expected 20 nm thick $Al_{0.14}Ga_{0.86}N$:Mg electron blocking layer (EBL) doped with Mg at the level of $2x10^{19}$ cm^{-3} was used to ensure similar doping levels as for previously grown LD structures. Below the EBL, 200 nm GaN:Mg layer with Mg concentration at the level of $3x10^{18}$ cm^{-3} was grown. To ensure high crystal quality and smooth surface after the TJ growth, we used the same TJ layer structure as for previously obtained LD stacks.[26] Namely, 10 nm thick $In_{0.15}Ga_{0.85}N$ layer half doped with Mg ($8x10^{19}cm^{-3}$) and half with Si ($1x10^{20}$ cm^{-3}) was sandwiched between 60 nm $In_{0.02}Ga_{0.98}N$:Mg ($3x10^{19}cm^{-3}$) and 60 nm $In_{0.02}Ga_{0.98}N$:Si ($3x10^{19}cm^{-3}$) from the top and bottom, respectively. Below TJ standard 100 nm GaN:Si ($5x10^{18}$ cm^{-3}) buffer layer was used.

All GaN and AlGaN layers were grown at temperatures around 730-740°C under gallium-rich conditions using growth rate of 0.35 µm/h, while all InGaN layers were grown at 650-660°C under indium-rich conditions using growth rate of 0.9 µm/h with In content controlled by Ga flux.[27]

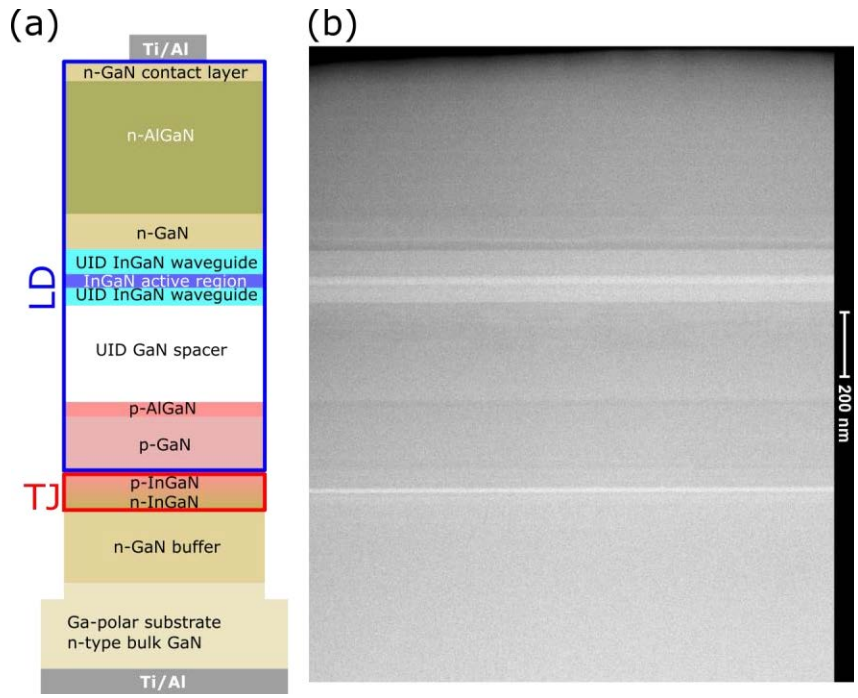

Figure 2. (a) Schematic image illustrating investigated laser diode layer structure with indicated tunnel junction (TJ) and flipped traditional laser diode layer stack (LD). (b) Transmission electron microscopy image of the grown structure corresponding to scheme presented in (a).

Grown structures were processed into LDs with stripe widths of 5 µm and resonator length of 1000 µm. Mesa etch depth was chosen so that it reaches 100 nm below the EBL. Only cleaved mirrors were used for all devices presented in this paper.

3. RESULTS

Processed laser chips were measured under pulse and continuous wave (CW) operation. Light-current (L-I) and light-current-voltage (L-I-V) plots are presented in Fig 3. Some threshold current density variation visible on Fig. 3(a) was probably caused by inhomogeneities related to mesa sidewalls roughness. We believe that significant improvement in threshold current density can be obtained by optimizing etching conditions for deep mesa etching that is not used in standard p-up LD processing. For CW operation we chose the best performing diode from the Fig 3(a) and mounted it in copper clamps for better heat dissipation. Under such conditions threshold current density improved from about 4.5 kA/cm^2 in pulse mode to 3.4 kA/cm^2 under CW operation.

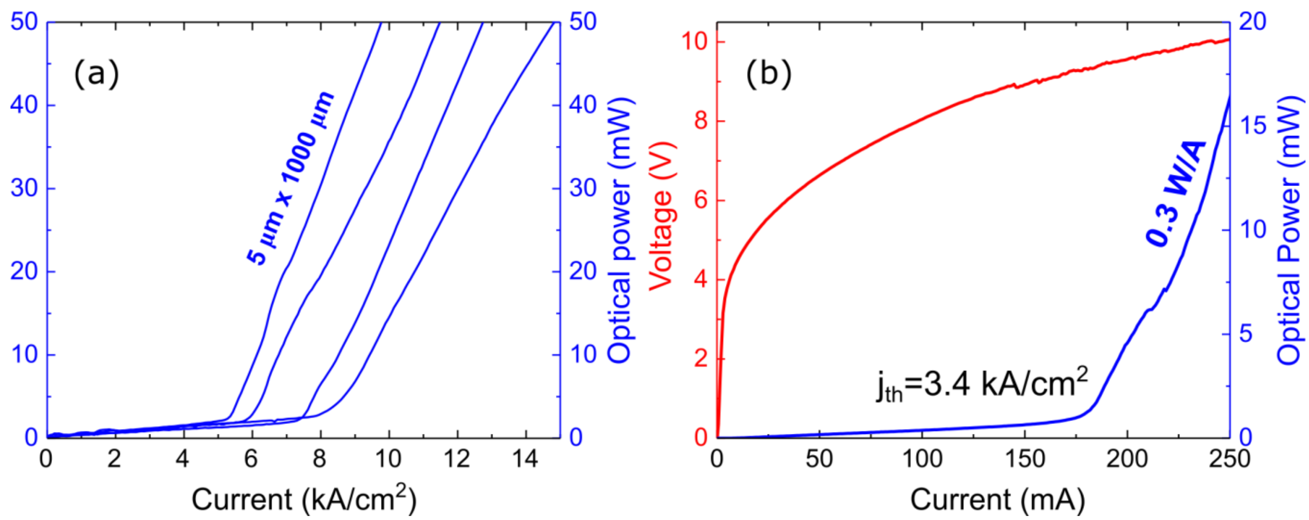

Figure 3. (a) Light-current characteristics of the inverted LDs under pulse operation. (b) Light-current-voltage characteristics of the best inverted LD from (a) under continuous wave operation.

As it is presented in Fig. 3(b) inverted LD under CW suffers from high voltage. This voltage is not related to thick undoped GaN spacer, as such structure without the undoped GaN spacer was also grown for comparison, but rather comes from still not optimal construction of the buried tunnel junction.

4. CONCLUSIONS

Here we presented how PAMBE, as a hydrogen-free growth technique where no annealing procedure is needed for p-type conductivity, can be used to obtain new class of nitride light emitters. InGaN-based buried-tunnel junction is used to construct first monolithically grown p-type-down LD on n-type, Ga-polar bulk GaN substrate. Unique advantage of such construction is that improved carrier injection associated with large built-in field allows for separation of highly absorptive p-type layers from the active region and the optical mode. As it was shown, 300 nm thick undoped GaN spacer between QW and p-type doped layers was used to profit from high injection efficiency of inverted built-in fields and to limit the optical losses. Continues wave operation of the inverted LD at room temperature was obtained. Further improvement in the operating parameters is expected by optimizing structure processing and tunnel junction design.

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