Buried tunnel junction for p-down nitride laser diodes

Henryk Turski[1], Marcin Siekacz[1], Grzegorz Muziol[1], Mikolaj Zak[1], Shyam Bharadwaj[1,2],
Mikolaj Chlipala[1], Krzesimir Nowakowski-Szkudlarek[1], Mateusz Hajdel[1],
Huili Grace Xing[2], Debdeep Jena[2] and Czeslaw Skierbiszewski[1]
[1]*Institute of High Pressure Physics, Polish Academy of Sciences, Sokolowska 29/37, 01-142 Warsaw, Poland*
[2]*Cornell University, Ithaca, NY 14853, USA*
Email: henryk@unipress.waw.pl / Phone: +48 22 876-0444

Introduction

Most commercially available nitride devices are obtained along [0001] direction. That is why the internal polarization-induced electric fields in violet to green nitride light emitting diode (LED) and laser diode (LD) structures point in a direction opposite to what is desired for efficient flow of electrons and holes. This arrangement persist because of the need to have p-type layers on top of the structure to activate it and the lack of efficient structures grown along [000-1] direction. To go around these problems one can use plasma-assisted molecular beam epitaxy (PAMBE) to grow buried tunnel junction (TJ) and invert current flow direction with respect to the built-in polarization [1,2]. Recent progress in PAMBE resulted in obtaining LDs in wide spectral range (Fig 1) and enabled combining these structures with TJs [3] and even stacking two LDs together [4].

Growth and fabrication

In the present work we report on the optoelectronic devices with p-down arrangement of layers grown on (0001) bulk GaN substrates by PAMBE. Cross-section transmission electron microscopy image of a LD structure is presented in Fig 2. To obtain low series resistance of buried TJ, which is necessary for LD current regime, InGaN interlayer half doped with Si and half with Mg both at the level 1×10^{20} cm^{-3} was used. 500 nm thick GaN:Mg cladding layer with Mg concentration around 3×10^{18} cm^{-3} was used to separate optical mode from highly absorbing TJ region. P-type region ends with electron blocking layer made of AlGaN:Mg. Light confinement was assured by the use of InGaN waveguide of total thickness 180 nm. Active region consisted of 20 nm thick $In_{0.17}Ga_{0.83}N$ layer. For top cladding layer 500 nm $Al_{0.05}Ga_{0.95}N$:Si was used. Crystal was processed into 5 x 1000 μm^2 stripes with mesa depth reaching the middle of GaN:Mg layer. Mesa sidewalls were isolated with SiO_2.

Simulations

To show the potential standing behind optoelectronic devices using bottom TJ design SiLENSe package was used. LDs having exactly the same layer structure obtained on (0001) and (000-1) substrates were simulated. Due to the difference in built-in polarization field direction electrons and holes are well separated significantly reducing parasitic recombination in vicinity of active region for N-polar grown device (Fig 3(a)). This implies increase in injection efficiency further translating to higher current density recombining radiatively (Fig 3(b)). The same increase in injection efficiency should be possible by growing TJ below the active region on Ga-polar substrate to invert current flow direction.

Results and discussion

Light-current-voltage characteristics obtained for the first bottom-TJ LD is presented in Fig 4. It lased at 453 nm at room temperature in continuous wave mode. Threshold current density and slope efficiency at the level of 5 kA/cm^2 and 0.12 W/A, respectively, were obtained. At present state of development parameters of the bottom TJ LD fall behind parameters obtained for standard LDs grown by PAMBE.

Conclusion

We showed that p-type down LD structure can be realized by the use of TJ. The main challenge in the growth of such structures is to keep high surface quality during the growth of p-type layers not to disturb the growth of the active region. Higher injection efficiency in the case of bottom TJ LD can be used to design structure with lower Mg doping or thicker spacer between active region and p-type layers to decrease optical absorption losses.

Acknowledgements: This work was supported partially by the Homing POIR.04.04.00-00-5D5B/18-00 and TEAM-TECH/2016-2/12 projects of the Foundation for Polish Science co-financed by the European Union under the European Regional Development Fund and the Polish National Centre for Research and Development Grants LIDER/29/0185/L-7/15/NCBR/2016.

References

[1] M. J. Grundmann et al., *Phys Status Solidi C* **4**, 2830 (2007).
[2] H. Turski, et al., *J. Appl. Phys.*in press (2019).
[3] C. Skierbiszewski, et al., *Appl. Phys. Express* **11**, 034103 (2018).
[4] M. Siekacz et al., Opt Express 27, 5784 (2019).

978-1-7281-2111-6/19/$31.00 ©2019 IEEE

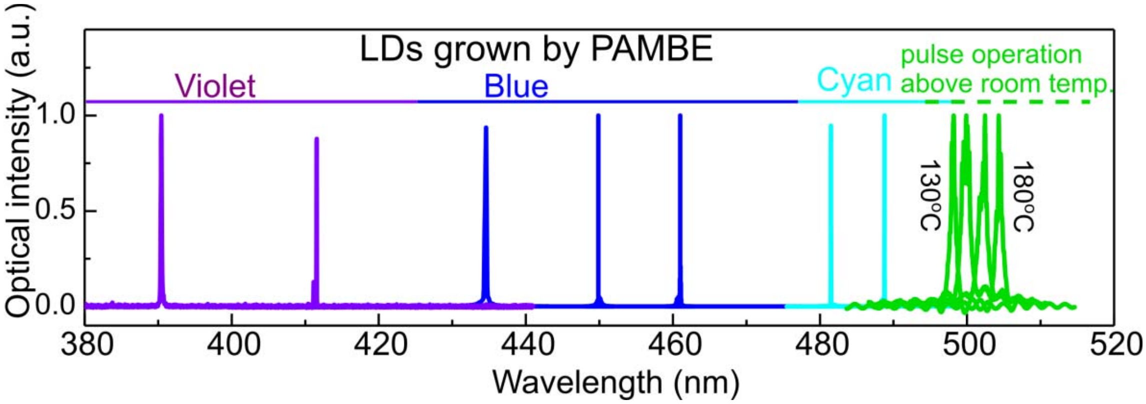

Fig. 1. Normalized lasing spectra as a function of wavelength for continuous wave operation at room temperature for violet to cyan emission and for pulse operation at temperatures 130-180°C for green emission. All structures were obtained by plasma-assisted molecular beam epitaxy to date with the p-up diode configuration.

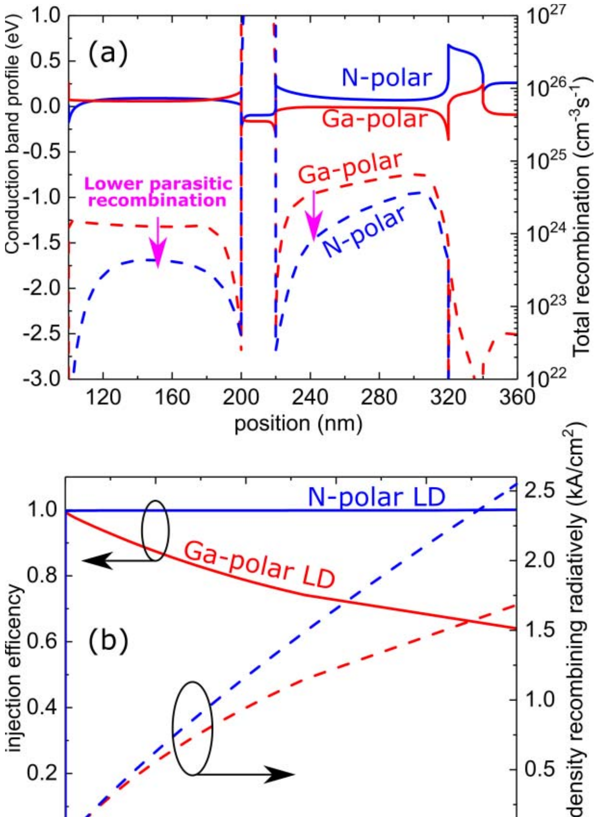

Fig. 3. Comparison of (a) conduction band profile and total recombination in the vicinity of quantum well and (b) injection efficiency and radiative current vs current density, simulated by SiLENSe package for the same LD structure for Ga-polar [0001] and N-polar [000-1] growth direction. N-polar case corresponds to bottom tunnel junction structure. (a) is for 1 kA/cm^2 current density. Magenta arrows in (a) indicate improvement in parasitic recombination when moving to N-polar (bottom-TJ) LED structure.

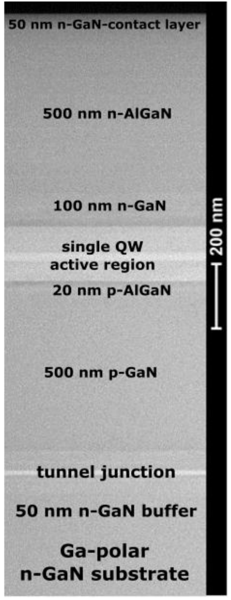

Fig. 2. Transmission electron microscopy image of the laser diode structure with tunnel junction. Growth direction proceeds upwards.

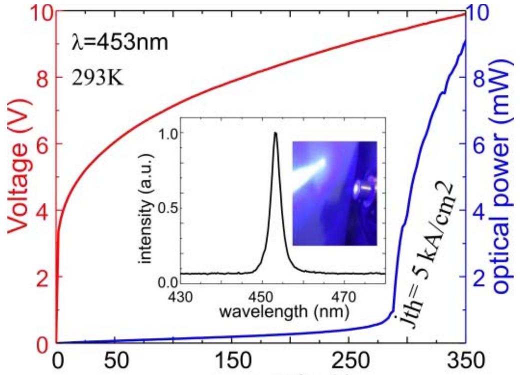

Fig. 4. Light-current-voltage characteristics of the laser diode with tunnel junction place below the active region. Inset shows low resolution spectra above threshold and a picture of the operating device.