Polarization-doped, nitride-based laser diodes and their operation at cryogenic temperatures

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Owing to their wide direct bandgap, nitride semiconductors are essential in optoelectronic applications, particularly blue LEDs for white-light sources and laser diodes in the UV–visible spectrum. An important breakthrough in nitride semiconductors is successful and efficient p-type doping with Mg. However, there are several drawbacks to using Mg as an acceptor. Firstly, the ionization energy of Mg in nitride semiconductors is several times higher than the thermal energy (kT) at room temperature, ranging from 160-200 meV for GaN to 630 meV for AlN. The second drawback is the low free hole concentration, which is also a consequence of the wide bandgap of the nitride semiconductors. Additionally, the hole concentration decreases dramatically with decreasing temperature, making cryogenic temperature applications problematic.

The wurtzite structure of nitride semiconductors helps overcome the doping problem owing to its high spontaneous and piezoelectric polarization. By incorporating a composition gradient in the layers in the growth direction, a fixed volume polarization charge can appear, leading to the occurrence of free carrier gas, enabling n-type or p-type conductivity within the layer. This phenomenon is known as polarization doping (PD). The number of free carriers can be adjusted by changing the gradient profile and the thickness of the layer. One crucial difference between Mg doping and polarization doping is that the carrier density is not affected by temperature, allowing for the design of structures suitable for cryogenic temperature applications.

In this paper, we present a laser diode with a polarization-doped cladding layer. The laser structure consists of symmetrical gradient layers to maintain high optical confinement and incorporates a conventional Mg-doped electron blocking layer (EBL) to ensure efficient carrier injection. The subcontact layer was also doped with Mg to prevent a possible metal-semiconductor Schottky barrier for the top metal contact. At room temperature, the samples have a threshold current of 40-45mA, and the slope efficiency is around 0.8-1W/A in continuous wave (CW) mode. The internal loss was estimated to be very low, < 10 cm^{-1}, measured by the Hakki–Paoli method. This low loss level is associated with the partial elimination of Mg acceptors from the volume of the optical mode. As expected, the PD laser diodes were able to operate at temperatures as low as 77 K. The threshold current showed a complex (non-monotonic) dependence on temperature, being low in a range of temperatures from 295 K to around 180 K. The slope efficiency initially decreases and then steeply increases below temperatures typically associated with Mg-related hole freeze-out (around 180K). The simultaneous increase of the slope efficiency and threshold current is a phenomenon difficult to be explained by the standard model of laser diode operation and remains to be explained.