True-blue laser diodes with tunnel junctions grown monolithically by plasma-assisted molecular beam epitaxy

Czesław Skierbiszewski¹,²*, Grzegorz Muziol¹, Krzesimir Nowakowski-Szukdarek¹, Henryk Turski¹, Marcin Siekacz¹, Anna Feduniwicz-Zmuda⁴, Anna Nowakowska-Szukdarek⁴, Marta Sawicka¹,², and Piotr Perlin¹,²

¹Institute of High Pressure Physics, Polish Academy of Sciences, Sokolska 29/37, PL-01-142 Warsaw, Poland
²TopGaN Ltd., Sokolska 29/37, PL-01-142 Warsaw, Poland
*E-mail: czeslaw@unipress.waw.pl

We demonstrate true-blue 450 nm tunnel junction (TJ) laser diodes (LDs) grown by plasma-assisted molecular beam epitaxy (PAMBE). The absence of hydrogen during PAMBE growth allows us to achieve TJs with low resistance. We compare TJ LDs with LDs of standard construction with p-type metal contact. For both types of LD, the threshold current density is around 3 kA/cm² and the slope efficiency is 0.5 W/A. We do not observe any significant changes in optical losses and differential gain in TJ LDs compared with standard LDs. The differential resistivity of the TJs for current densities higher than 2 kA/cm² is below 10⁻⁴ Ω cm². © 2018 The Japan Society of Applied Physics

One of the most challenging issues for nitride-based devices such as light-emitting diodes (LEDs) and laser diodes (LDs) is the poor conductivity of the p-type region.¹ The resistance of the p-type contact affects the performance and determines the design of InGaN LEDs and LDs. The p-type conductivities of GaN and (In,Al,Ga)N alloys are limited owing to the high effective mass and low concentration of holes. The latter is a consequence of the high activation energy of the Mg acceptor. In addition, the lack of metals with sufficiently high work function makes the realization of ohmic contacts to p-type layers very challenging.

Recently, increasing attention has been given to the use of the interband tunnel junction (TJ) for carrier conversion between n- and p-type regions in nitride LEDs, LDs, and solar cells.²–¹⁰ Efficient TJs may find very important applications in injecting holes into the p-type region of LEDs and LDs, and thus TJs can open new possibilities in the design and architecture of III–nitride devices. The implementation of TJs to interconnect LD structures grown on top of another paves the way to high-power nitride devices. As a result, stacks of LDs could operate in the range of hundreds of watts in the pulse mode (in the violet-green region), as demonstrated for infrared GaAs LDs. In addition, the application of TJs will be extremely important for (a) UV LDs and LEDs, in which the challenges for p-type conductivity are more serious than those for visible optoelectronics owing to the larger Mg activation energy and (b) monolithic vertical-cavity surface-emitting lasers (VCSELs) or edge-emitting LDs where new designs of device architectures are needed.³,⁵,⁹,¹⁰ The edge-emitting LDs with TJs have more freedom in the design of the upper cladding and top metal contact. For example, owing to the high conductivity of n-type layers on top of the TJ, the metal contact can be deposited outside the laser mesa. In such design, air (with refractive index equal to 1) acts as a cladding and helps to confine the optical mode inside the waveguide, and the top AlGaN cladding thickness can be substantially reduced.¹⁰

Despite the high application potential and extensive efforts in incorporating TJs into the nitride device structure, there are no such devices available in the market. This is due to fundamental challenges with the activation of p-type conductivity in buried Mg-doped layers in devices grown by the commonly used metalorganic vapor phase epitaxy (MOVPE). The Mg dopant in a material grown by MOVPE is by default compensated by hydrogen and has to be activated by the postgrowth thermal removal of hydrogen. The intrinsic difficulty in the MOVPE growth of TJs arises from the fact that hydrogen cannot diffuse through n-type layers.¹¹ Experimental results can be explained by theoretical works¹² where significant differences in barriers for hydrogen diffusion in p- and n-type GaN are found. These barriers are equal to 0.7 eV in p-type and 3.4 eV in n-type GaN. The Fermi level dependence of hydrogen diffusion is a more general behavior in semiconductors. It is also observed, for example, in Si and InP, in which H diffusion through the n-type region is suppressed.¹³,¹⁴ Therefore, when a Mg-doped nitride layer is covered by n-type GaN, the activation of p-type conductivity, which relies on the hydrogen removal, is blocked. An attempt to overcome this problem by H removal from the sides of the device via etched trenches did not give fully satisfactory results.¹⁵

On the other hand, there is no such limitation for structures grown by plasma-assisted molecular beam epitaxy (PAMBE). The advantage of PAMBE is the absence of hydrogen introduced during growth. Therefore, p-type conductivity is achieved without the postgrowth activation process.¹⁶–¹⁹ This makes the PAMBE technique an ideal tool for the growth of devices incorporating TJs. Promising results for new types of edge-emitting LD or VCSEL have been reported recently for hybrid MOVPE/MBE growth in which the active part of the device was grown by MOVPE and the p–n TJ was made by MBE.⁵–¹⁰

The p–n tunnel junction was demonstrated for narrow-bandgap materials in 1958.²¹ The theory of the p–n TJ indicates that the transmission probability of carriers through such a junction depends on the depletion width. The intriguing part of the story of the TJ applied in the wide-bandgap III–nitride system is that the large depletion width of the p–n junction leads to a very low transmission probability and a high resistance of such a junction. Therefore, initially, the concept of the use of the TJ for carrier injection was regarded as unrealistic. However, recent reports have shown that by
exploiting the strong internal piezoelectric fields present in nitride heterostructures, it is possible to reduce the depletion width of the p–n junction and achieve the strong tunneling of carriers through such a structure.\textsuperscript{22,23) For example, by inserting an InGaN well into the p–n junction region, it is possible to reduce the specific resistance of the junction to $10^{-4}$ $\Omega$ cm.\textsuperscript{24) It was also demonstrated that by introducing GdN nanoislands, the tunneling through the midgap states inside the TJ was enhanced.\textsuperscript{24) For future development of the vertical integration of several devices interconnected by TJs, it is important to show monolithic devices grown by one technology without the need to interchange between different epitaxy systems during growth. We already showed that it is possible to grow efficient nitride LDs by PAMBE operating in the wavelength ($\lambda$) range of 390–490 nm.\textsuperscript{25) In this work, we will demonstrate true-blue LDs with TJs used for hole injection grown entirely by PAMBE in a single process. To demonstrate the impact of TJs on the parameters of LDs, we compared the standard LD and the TJ LD. Schematic diagrams of these structures are shown in Fig. 1.

The standard LD structure [see Fig. 1] consists of a 700 nm Al$_{0.065}$Ga$_{0.935}$N:Si cladding, followed by 100 nm GaN:Si (Si doping level is $2 \times 10^{18}$ cm$^{-3}$), and an 80 nm undoped In$_{0.02}$Ga$_{0.98}$N bottom waveguide. An active region is composed of In$_{0.17}$Ga$_{0.83}$N QWs followed by a 60 nm In$_{0.08}$Ga$_{0.92}$N upper waveguide. The EBL of 20 nm thickness consists of Al$_{0.15}$Ga$_{0.85}$N with a Mg doping level of $5 \times 10^{19}$ cm$^{-3}$. This is followed by a 500 nm GaN:Mg cladding. The LD structure is capped with 60 nm In$_{0.02}$Ga$_{0.98}$N:Mg acting as a contact layer.

In the case of the TJ LD [see Fig. 1], above the 500 nm GaN:Mg upper cladding, the TJ is grown. It consists of a 60 nm In$_{0.02}$Ga$_{0.98}$N:Mg layer (with a Mg doping level of $5 \times 10^{19}$ cm$^{-3}$) followed by a 10 nm In$_{0.17}$Ga$_{0.83}$N single quantum well (SQW). The first 5 nm of this well is doped with Mg at a level of $1 \times 10^{20}$ cm$^{-3}$ and the next 5 nm with Si at a level of $5 \times 10^{20}$ cm$^{-3}$. Then, 20 nm of n-type In$_{0.01}$Ga$_{0.99}$N:Si and 50 nm of GaN:Si are grown. Both layers have a Si concentration of $3 \times 10^{19}$ cm$^{-3}$. The SQW is placed inside the TJ to reduce the depletion width. There are two factors that enhance the tunneling probability: (a) InGaN has a lower bandgap than GaN and (b) there are built-in spontaneous and piezoelectric fields present in InGaN grown on Ga-polar GaN.\textsuperscript{4) The LDs were grown either on bulk Ammono-GaN substrates with threading dislocation densities (TDDs) on the order of $10^{5}$–$10^{6}$ cm$^{-2}$ or Saint Gobain HVPE GaN substrates with TDDs in the range of $(1–5) \times 10^{7}$ cm$^{-2}$. The epi-ready substrates were prepared by chemical and mechnochemical polishing processes. The crystals had miscut 0.8° towards the [1100] direction. The GaN and AlGaN cladding layers were grown at 720°C under gallium-rich condition, whereas InGaN layers were grown at 650°C under indium-rich condition. The growth of AlGaN in the EBL was performed at 650°C with indium as a surfactant. The growth rates for the GaN and AlGaN layers were equal under indium-rich condition, whereas InGaN layers were grown at 650°C under gallium-rich condition. The growth of AlGaN in the EBL was performed at 650°C with indium as a surfactant. The growth rates for the GaN and AlGaN layers were equal under indium-rich condition. The growth of AlGaN in the EBL was performed at 650°C with indium as a surfactant. The growth rates for the GaN and AlGaN layers were equal under indium-rich condition. The growth of AlGaN in the EBL was performed at 650°C with indium as a surfactant. The growth rates for the GaN and AlGaN layers were equal under indium-rich condition. The growth of AlGaN in the EBL was performed at 650°C with indium as a surfactant. The growth rates for the GaN and AlGaN layers were equal under indium-rich condition. The growth of AlGaN in the EBL was performed at 650°C with indium as a surfactant. The growth rates for the GaN and AlGaN layers were equal under indium-rich condition. The growth of AlGaN in the EBL was performed at 650°C with indium as a surfactant.
versus current density.

structure for the determination of series resistance. (b) Diode with Mg at a level of 10^20 cm^-2. The lower than 10 kA/cm^2 mesa. The diode that n++ structure was heavily doped: because the n++ region was heavily doped: 5 nm In0.02Ga0.98N:Mg doped at a level of 5 × 10^19 cm^-3, and a 10 nm In0.17Ga0.83N SQW. Above the SQW, 20 nm In0.02-Ga0.98N:Si and 100 nm GaN:Si doped at a level of 3 × 10^19 cm^-3 are grown. We obtained the best results when the SQW region was heavily doped: first, 5 nm of the SQW was doped with Mg at a level of 10^20 cm^-3 and the next 5 nm of the SQW was doped with Si at a level of 5 × 10^20 cm^-3. The current–voltage (I–V) characteristics are shown in Fig. 3(a) for a processed sample with a mesa size of 30 × 30 µm^2. The n/p+/n++ structure reaches a current density of 10 kA/cm^2 at 4.55 V. Up to −10 V, no leakage has been observed because the n/p++ junction is in the reverse bias. Figure 3(b) shows the differential resistivity dU/dj vs the current density j. Our TJ design allowed us to achieve a differential resistivity lower than 10^−4 Ω·cm^2 for current densities higher than 2 kA/cm^2, which is very promising for LD applications and is one of the best results among those reported in the literature.4,8,23,29

An interesting remark can be given from the comparison of the differential resistivities of the standard LD, TJ LD, and test TJ n/p++/n++ structure. Figure 4 shows the differential resistivities of the standard PAMBE and TJ LDs (the I–V characteristics of which are depicted in Fig. 2). For the TJ LD, the resistivity is slightly higher, but there is no substantial increase in this value when compared with that of the standard LDs. For high current densities of 3–5 kA/cm^2, the differential resistivity is at a level of 10^−3 Ω·cm^2, which is one order of magnitude higher than that of the test TJ n/p++/n++ structure. Moreover, the difference in differential resistivity between the TJ and standard LDs (marked with a red dashed line in Fig. 4) follows the differential resistivity of the test tunnel junction n/p++/n++ structure.

The main factor that decreases the wall-plug efficiency of TJ LDs is the increase in the operating voltage by 0.6 V. In Fig. 5, we present a band diagram of the TJ LD where this voltage drop is depicted. For the TJ LDs grown on (0001) GaN, the TJ operates in the reverse bias mode (Zener diode). The increase in LD operating voltage is related to the required polarization of the TJ for a high tunneling current density; a high applied voltage decreases the depletion region width. However, in the future, the increase in TJ LD operating voltage can be compensated partially by the reduction in the width and thus the resistance of the upper p-type part of the LDs. Additionally, a new design of the LDs with a metal contact deposited outside of the mesa will allow us to use air as a cladding and reduce the thickness of the p-type upper cladding, which in turn can substantially reduce the voltage on LDs. As demonstrated by Malinverni et al.,10 a 200 nm AlGaN:Mg cladding (instead of 500 nm) was sufficient to achieve good parameters of LDs.
In conclusion, we have demonstrated monolithic tunnel junction laser diodes grown by PAMBE operating in the CW mode at the wavelength $\lambda$ of 450 nm. The application of TJs allows us to make n-type ohmic contacts for both device sides eliminating the problematic p-type contact. The absence of hydrogen during PAMBE growth allows us to achieve TJs with low resistance. The serial resistivity of the n/p++/n++ test structures was below $10^{-4}\,\Omega\cdot\text{cm}^2$ for current densities higher than 2 kA/cm$^2$, while for TJ LDs, it was one order of magnitude higher. The lasing threshold current density and slope efficiency of TJ LDs were the same as those of the standard PAMBE LDs. The differential resistivities of TJ and standard LDs are in the same range, while the turn-on voltage increased for TJ LDs by 0.6 V. This result opens new perspectives for the growth of devices operating at high current densities such as VCSELs or cascades of laser diodes.

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