Monolithic MOCVD-Grown III-Nitride Tunnel Junctions with Ultra-Low Resistance

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In this work, we report on the effect of activation annealing and doping on GaN-based interband tunnel junctions (TJs) grown by metal organic chemical vapor deposition (MOCVD). We demonstrate state-of-art low-resistance and voltage loss TJs, and lateral activation of buried p-layers for layer area diodes to enable future high power density multiple active region III-nitride light emitting diodes.

III-nitride light emitting diodes are very successful for a broad range of lighting applications, but the long-standing challenge of efficiency droop at high current densities remains unsolved. A proposed solution to this is to use multiple active region structures with interband TJs in between [1]. Such a topology allows achieving higher power density at lower currents. While excellent TJ resistance values have been reported before by MBE or hybrid MBE/MOCVD approaches [2], all-MOCVD based TJs still show an excess voltage and resistance compared to the current state-of-the-art results. In this work, we report our experimental results on reduction of the voltage losses through optimizing Mg activation for buried p-GaN layer and engineering of the p-doping.

The *p-n* diode samples used in this study were grown on GaN/sapphire templates by MOCVD. The TJs, consisting of *p*- and *n*-doped GaN layers with a high concentration of Mg and Si respectively, were grown above the *p-n* junction. In the first experiment reported here, we investigated the effect of high temperature annealing for Mg activation in the p-GaN layer through its sidewalls. The sidewall activation process have historically showed a dependence of turn-on voltage and resistance on device area due to challenges related to lateral activation. Devices with a larger dimension (>50 µm sides) have suffered from higher voltage penalty, resulting in non-uniform illumination from LEDs due to the insufficient activation. In this work, we processed square mesas with 54, 74 and 105 µm sides and the activation anneal was performed using a rapid thermal annealing system in N_2 atmosphere. Remarkably, the devices with Mg activation at an annealing temperature of ≥ 900°C (significantly higher than typical activation temperatures) exhibit flat voltage-drop characteristics with no dependence on the device areas indicative of complete Mg-activation in the active area. The devices show reasonably low leakage current with 9 orders of rectification between -4 to 4 V. The diodes also show an ideality factor of $\eta = 2$ in the ON-state with a series resistance of 2.7 mΩ-cm^2 indicative of electron-hole recombination.

Using the optimized activation conditions, we investigated the effect of the p-doping turn-on profile on the TJ resistance. Due to the time required to turn-on and turn-off the doping while growing the p-doped layers of the TJs, the doping profiles spread out at a few-nanometers scale. Therefore, the thickness of the p^+ layer was varied (6/9/12/18 nm) to understand the compensation effect of the *p*-dopants. The expected depletion width for the nominal doping concentration of 2e20 cm^{-3} is expected to be 12 nm. Remarkably, it is observed that the TJ-associated voltage drop decreases monotonically as the p-doping thickness is increased, suggesting that the Mg doping concentration has not reached its maximum value in the samples with the thinner p-doped layers. In this work, with respect to the reference *p-n* diode with metal ohmic contacts, the voltage penalties as low as 0.14 V (1 A/cm^2) and 0.47 V (100 A/cm^2) are achieved, which is also among some of the lowest ever reported for the monolithic MOCVD-grown for GaN homojunction TJs.

In conclusion, we have shown the feasibility of an all-MOCVD approach to realize large area lateral activation as well as excellent voltage losses in GaN PN tunnel junctions. The reported work shows the promise of tunneling based multiple active region LEDs.

[1] Akyol et al., *Appl. Phys. Lett.* **103**, 081107, 2013
[2] Alhassandull et al., *Appl Phys Express* 11.4, 042101, 2018

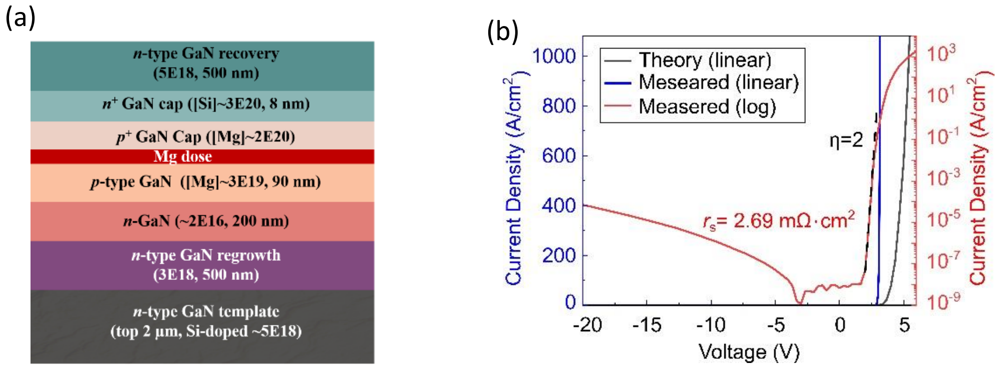

Fig.1. (a) Schematic of the GaN based tunnel junction integrated diode grown on n-type GaN template by MOCVD. The thickness of the p+ gaN cap layer was varied for the doping expeiment (b) Exemplar I-V characteristics of a processed device in linear and semi-log scales along with the theoretical curve in the linear scale.

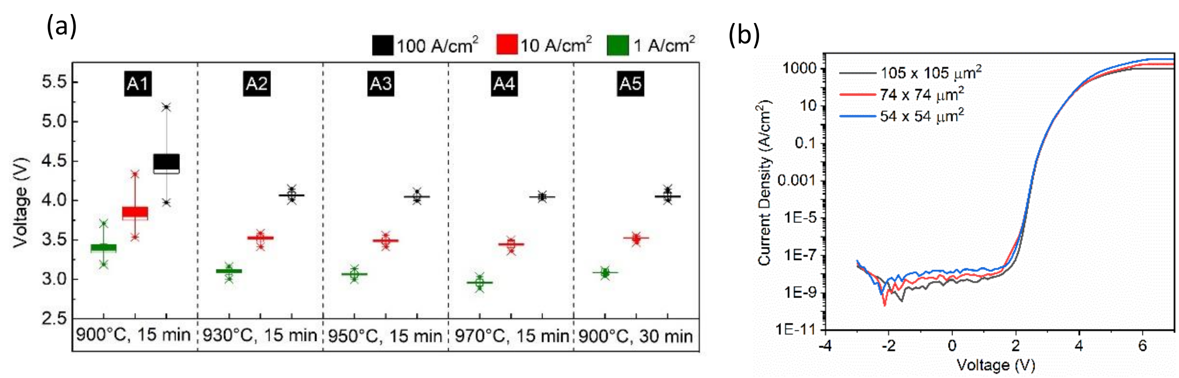

Fig.2. (a) Comparison of voltage drops of devices with respect to current density (1/10/100 A/cm^2) activated in different annealing conditions. At 900^{0}C/15 mins, due to insufficient activation of *p*-GaN, there is a variation in voltage drop with respect to device dimension. The variation becomes negligible after annealing above 930^{0}C/15 mins or 900^{0}C/30 mins. (b) I-V characteristics of different size devices activated at 900^{0}C for 30 mins.

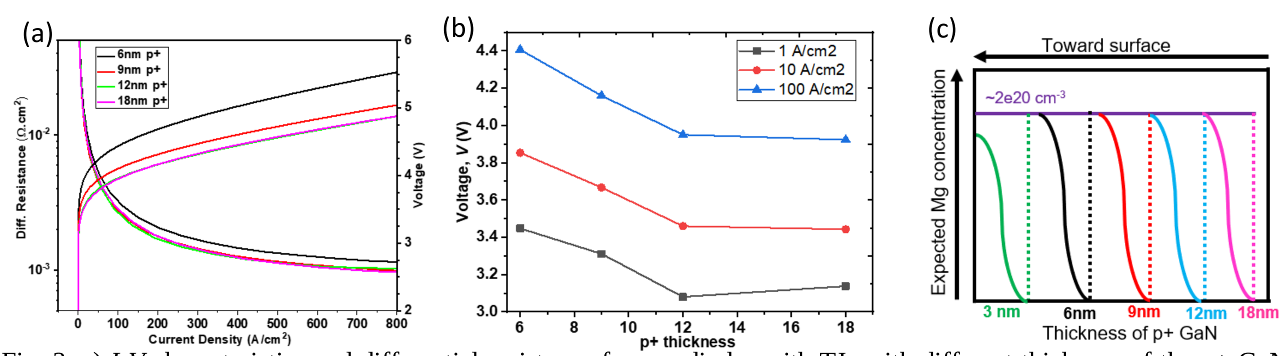

Fig. 3. a) *I-V* characteristics and differential resistance for *p-n* diodes with TJs with different thickness of the p+ GaN thickness. (b) The voltage drops of the devices at different current densities (1/10/100 A/cm^2). (c) Schematic diagram for Mg flux for p+ layer. The thickness is controlled by controlling the growth time. The dotted line indicates when the Mg flow was started, the solid line indicates the real scenario.