

# S-shaped Negative Differential Resistance in III-Nitride Blue Quantum-Well Laser Diodes Grown by Plasma-Assisted MBE

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**Introduction:** Group III-Nitride semiconductor quantum heterostructures have revolutionized efficient visible light emitters [1]. Even though efficient nitride light emitting diodes (LEDs) and laser diodes (LDs) are now commercially mature, there are several physical effects in them that are poorly understood. Furthermore, light emitters in the UV [2] and green and longer wavelengths [3, 4] remain challenging. The presence of built-in electric fields due to spontaneous and piezoelectric polarization in these quantum heterostructures leads to rather remarkable effects in the N-shaped negative differential resistance (NDR) in resonant tunnel diodes (RTDs) [5]. Much rarer are S-shaped NDR, which was reported recently in GaN tunnel switch diodes [6]. To our surprise, we have observed strong, persistent, S-shaped NDR in GaN quantum well laser diodes at room temperature. The S-NDR in the laser diode is strong enough to drive an external circuit into sustained oscillations, and is likely caused by the strong internal polarization fields.

**Growth and fabrication:** Laser diode structures were grown by MBE on high quality GaN substrates [7]. Fig. 1 shows the layer structure with 3X periods of InGaN quantum wells (QW), and to ensure good light confinement, thick AlGaIn claddings and InGaIn and GaN waveguides are used. The waveguide layers were intentionally undoped. The change in the unintentional doping level due to the difference in growth temperature (650°C for InGaIn vs 730°C for GaN), was observed. SIMS measurements on similar LD structures indicated an oxygen level of  $<5 \times 10^{16}$  atoms/cm<sup>3</sup> for GaN and  $5-10 \times 10^{17}$  atoms/cm<sup>3</sup> for InGaIn. An LED structure was grown as a control sample, with the only difference between the LED and LD (Fig. 1) structures being the absence of the 100 nm GaN:UID, 700 nm AlGaIn:Si and 400 nm AlGaIn:Mg layers. Ohmic metal contacts were deposited on both sides of the crystal. The size of the p-type contacts was 300 x 300 μm<sup>2</sup> while n-type contact covered the whole backside surface, no mesas were introduced.

**Results and discussion:** I-V characteristics measured with current scans for both the Laser Diode and the LED samples are presented in Fig. 2 a) and b), respectively. For comparison, the theoretically simulated I-V curves for both structures using SiLENSe package [8] are included, which neglects tunneling and is based on drift/diffusion. In Fig. 2 a) for the laser diode, a clear S-shaped NDR behavior near the turn on voltage can be seen, and is shown zoomed in in Fig. 2 c). The S-shape of I-V characteristics was measured for both upward, and downward sweeps of the current. Electroluminescence (EL) spectra collected at different currents across the NDR region are presented in Fig. 2. d). The ~380 nm emission that matches well with the InGaIn waveguide band gap dominates the spectrum in NDR bias region. Spectra collected for peak voltage at 1.03 mA exhibit jagged signal for wavelength associated with QW emission. For this sample SiLENSe predicts an abrupt turn on near the voltage at which NDR can be experimentally observed. On the contrary, for the LED structure, no such NDR behavior was experimentally observed; no abrupt change in I-V characteristic is expected from simulations (Fig. 2 b)). Analysis of the self-consistent Schrodinger-Poisson calculated energy band diagram shown in Fig. 3 suggests that the S-shaped NDR is likely associated with the tunneling through GaN:UID layer (marked by blue arrow) or 20 nm AlGaIn:Mg layer (marked by green arrow) in the presence of the GaN:UID layer. To further confirm the existence of the S-shaped NDR in the structure, voltage oscillations were measured. A constant current was applied to reach the middle of NDR region, with external inductance in the circuit. The voltage was monitored with time using an oscilloscope. Stable and sustained oscillations with frequency around 7 kHz were obtained as shown in Fig. 4.

**Conclusions:** The presence of an undoped polar barrier GaN layer was found to cause a S-shaped Negative Differential Resistance (NDR) in GaN Laser diodes. Such behavior can be attributed to tunneling through the barrier formed at the interface between GaN:UID and InGaIn waveguide or the electron blocking layer (20 nm AlGaIn:Mg layer) in p-n junction. The NDR behavior was found to coincide with abrupt turn on expected from SiLENSe simulations, and can potentially lead to self-oscillating light pulse sources in a similar vein as mode-locking, Q-switching, or harmonic generation without the need for external saturable absorbers, or Q-switch elements.

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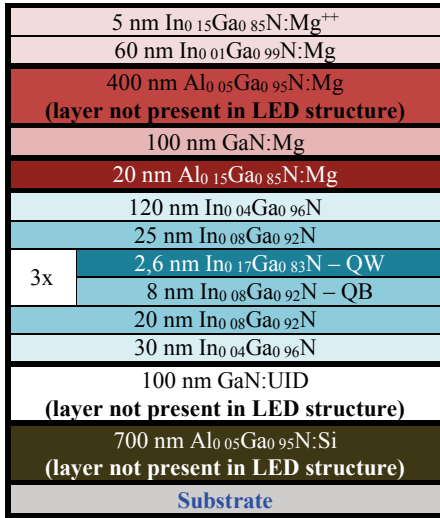


Fig. 1. Blue Laser diodes structure grown by MBE.

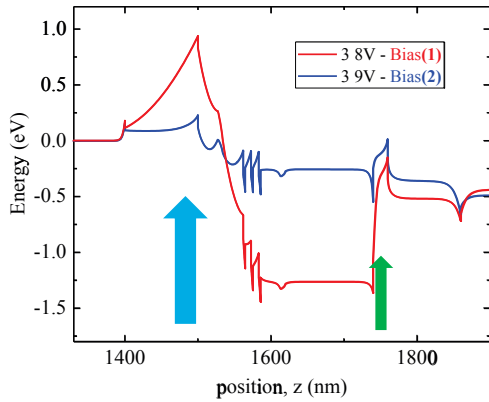


Fig. 3. Conduction Energy Band diagram near the active region calculated by self-consistent Schrodinger and Poisson simulations for LD structure by SiLENSE package for voltages near the turn on: 3.8V and 3.9V. This values correspond to Bias(1) and Bias(2) indicated in Fig. 2 a). Blue and green arrows denote the position of 100 nm  $\text{GaN}:\text{UID}$  and 20 nm  $\text{AlGaN}:\text{Mg}$  layers, respectively.

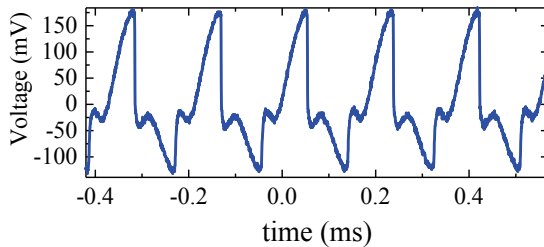


Fig. 4. Stable and sustained voltage oscillations for bias conditions inside the NDR region in the laser diode.

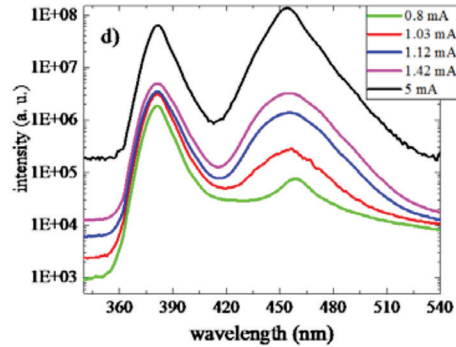
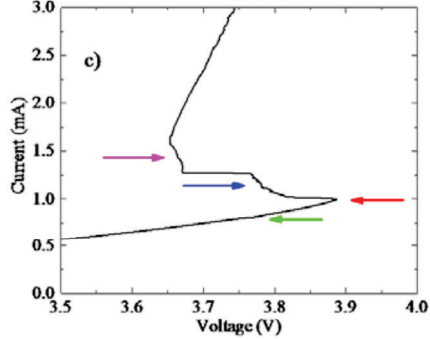
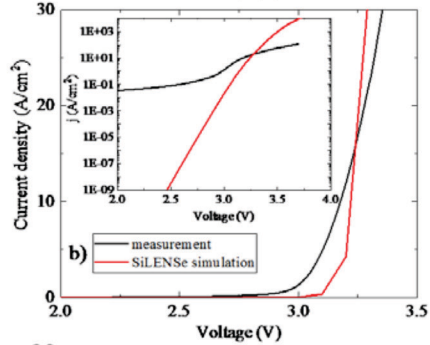
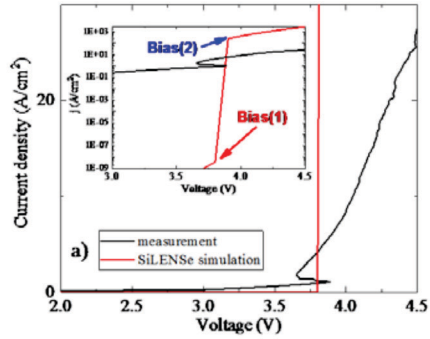


Fig. 2. Current density as a function of voltage for a) LD and b) LED structure. Insets present the same plots in logarithmic scale for current density ( $j$ ). In inset a) distinct bias conditions are indicated with arrows: Region (1) and (2). Zoomed in plot of the S-shaped NDR region measured for LD sample is presented in c). Arrows in c) indicate current at which EL spectra presented in d) were obtained.