Characterization of tunneling and free-carrier screening in coupled asymmetric GaN/AlGaN quantum discs

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1. Introduction

- NOW: **Blue LED/LD for commercial applications (e.g. solid-state lighting, HD-DVD)**
- FUTURE: **Novel devices**

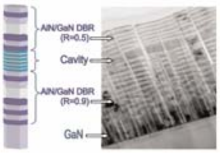


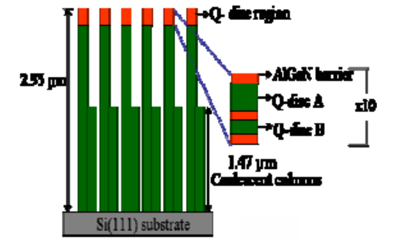
Figure from [2]

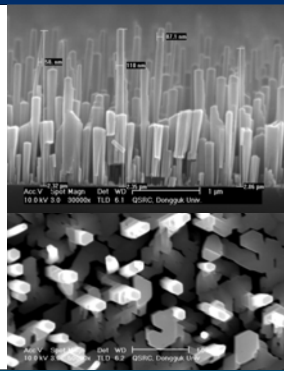
- SCOPE: **Systematic study of carrier tunneling and free-carrier screening in coupled asymmetric GaN Q-discs separated by AlGaN barriers**
- METHOD: **Combination of experimental and computational methods**
  - **Photoluminescence (PL) spectroscopy**
    - **Time-resolved (TR-) and time-integrated (TI-)**
  - **Multi-band k.p computational modeling**
    - **nextnano^3**
- MOTIVATION:
  - **Commercial importance of III-N materials**
  - **Free-carrier screening not observed for nano-column devices**
  - **Tunneling and screening in such structures has been suggested previously [1] and could play an important role in future devices.**

Self-organized GaN nanocolumns have gained interest in application for blue/ultra-violet wavelength optoelectronic devices. They possess desirable properties such as low defect density, good reproducibility, quantum confinement effects and can be produced using conventional growth techniques. These properties make nanocolumns an attractive basis for novel quantum optoelectronic devices (e.g. embedded quantum dots in nanopillar cavities for quantum information processing [2]).

Quantum discs (Q-discs) **are quantum well like structures grown at the tip of GaN nanocolumns are known as and demonstrate lateral confinement.**

2. Sample Details



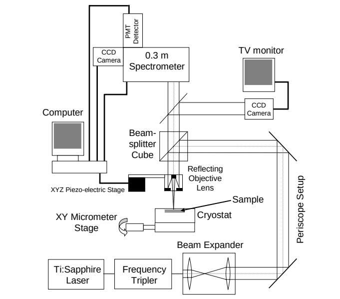


- **Ten periods of two alternating GaN Q-disc thicknesses**
  - **DA – 4 nm**
  - **DB – 3 nm**
- **Separated by $Al_{0.5}Ga_{0.5}N$ barrier (2, 4 and 8nm)**

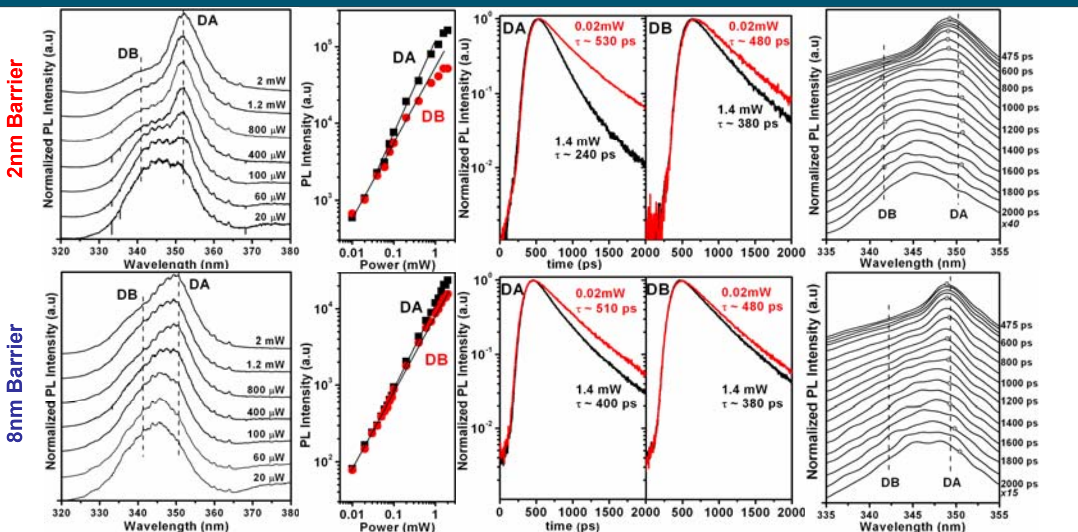
The GaN nanocolumn sample and the GaN Q-disc sample were grown by plasma assisted molecular beam epitaxy on a Si(111) substrate without any buffer layer. The growth of GaN nanocolumns was performed under N-rich conditions. The Ga flux was controlled to a beam equivalent pressure of 2×10^{-7} Torr, which is approximately ten times smaller than that used for GaN epilayers (4×10^{-6} Torr). The power and flow rate of the N plasma source were 350 W and 2.0 sccm, respectively. A growth temperature of 750 °C was used.

The hexagonal GaN nanocolumns exhibit various diameters ranging from 50 to 120 nm, with an average diameter of 100 nm and a density of 1×10^{9} cm^{-2}.

3. PL Measurements



- **EXCITATION: Frequency-tripled Ti:sapphire laser pulses at 266 nm (120 fs, 76 MHz)**
- **SAMPLE: Maintained at 4K (Janis ST-500)**
- **TI-PL: Spectral resolution of ~0.7 meV**
- **TR-PL: Commercial time-correlated single photon counting system with 100 ps rise-time**



TI-PL Results

- *Optical non-linearity:* **With increasing excitation, DA peak grows faster than DB peak. This is more evident in the 2 nm barrier sample**
- **Observed in asymmetric quantum well systems and associated with** *carrier tunneling* **[3]**
- **First indication of electron/holes tunneling: DB→DA**

TR-PL Results

- *2 nm barrier sample:* **DA lifetime decreased from 530 to 240 ps (for 0.02 to 1.4 mW at focus)**
- *8 nm barrier sample:* **DA lifetime decreased from 510 to 400 ps (for 0.02 to 1.4 mW at focus)**
- *DB lifetime:* **Varied from ~480 to 380 ps (0.02 to 1.4 mW) in both the 2 and 8nm samples**

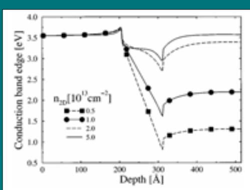


Figure from [4]

Free-carrier screening

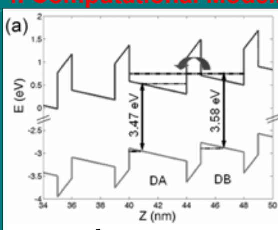
- *Source:* **Excited (e.g. by photo-excitation) electrons/holes**
- *Effect:* **Screens the built-in piezo-electric field → Increased electron-hole overlap → Decreased lifetime**

Enhancement of free-carrier screening

- *Source:* **Electrons/Holes tunneling from DB→DA**
- *Effect:* **Free-carrier screening effect is enhanced (decreases with barrier thickness)**

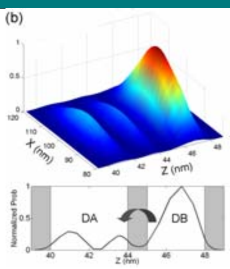
A series of TR-PL measurements (taken at 2nm intervals) indicate that the majority of interactions occur in the first 500 ps [9]. Here the DA peak blue-shifted (gain of free-carriers).

4. Computational Modeling



*next**nano³** device simulator: The program is available at www.wsi.tum.de/nextnano3*

- **Modeling consistent with the experimental observations**
  - **Electron/Hole tunneling DB → DA**
  - **Tunneling decreases with barrier thickness**



The Q-discs were modeled using nextnano³, ***a nanostructure simulator capable of solving the self-consistent 3D nonlinear Poisson-Schrödinger equation*** **for wurtzite materials including strain, deformation potentials and piezo- and pyroelectric charges. For the calculations, we employed the material parameters taken from [5]. The fully strained Q-discs were simulated by minimization of the elastic energy within a continuum model approach that takes into account the symmetry of the hexagonal crystal structure. For the airsemiconductor interface we assumed that the atoms at the GaN boundary of the Q-disc were not allowed to relax into the surrounding air material. In order to calculate the wavefunctions a single-band model for the electrons and a six-band k.p Hamiltonian for the holes were considered. This could be justified as GaN and AlN have large band gaps and therefore the coupling between the conduction and valence bands can be neglected for our purpose [6].**

5. Conclusion

- Free-carrier screening in asymmetric GaN/AlGaN Q-discs have been characterized. It consists of:
  - **Photo-excited electrons/holes**
  - **Electron/Hole tunneling (DB → DA)**
- Tunneling leads to an *enhancement* of the screening in DA, as it provides additional free-carriers
  - **Enhancement depends on the barrier thickness (i.e. tunneling)**
  - **Predicted by computer modeling (next**nano³**)**
  - **Previously only observed in quantum wells (i.e. not in nano-scale devices such as nanocolumns or Q-discs)**

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More details: K. H. Lee et al., *Appl. Phys. Lett*, 89, 023103 (2006)