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Material and device development of AlGaN based deep UV emitters

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Sandia National Laboratories

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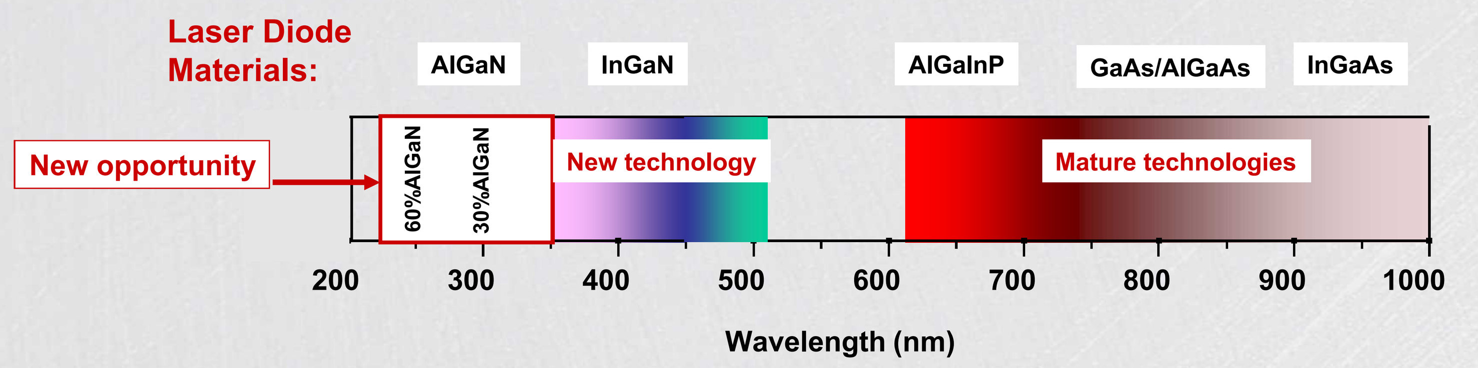
Challenge

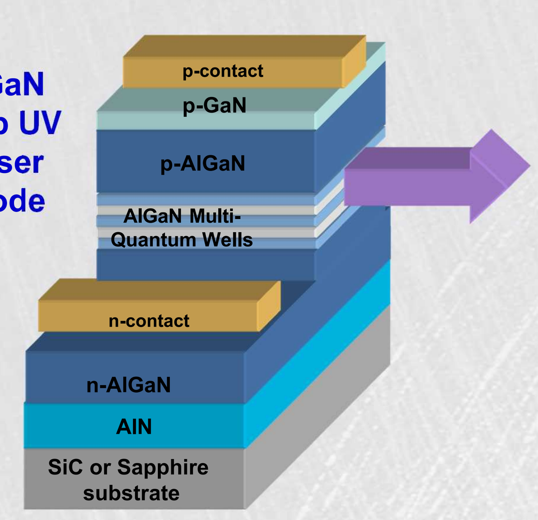
Opportunity:

- Chemical sensing and material processing applications would greatly benefit from a compact, high performance laser diode at deep UV wavelengths (≤ 280 & 340 nm).
- AlGaN semiconductor alloys are emerging as a promising candidate for extending semiconductor laser diode technology into deep UV wavelengths.



Challenge:

- AlGaN semiconductors present several **major materials roadblocks** to laser demonstration:



(1) Ineffective p-type doping of AlGaN epilayers
→ large (> 200 meV) acceptor ionization energies

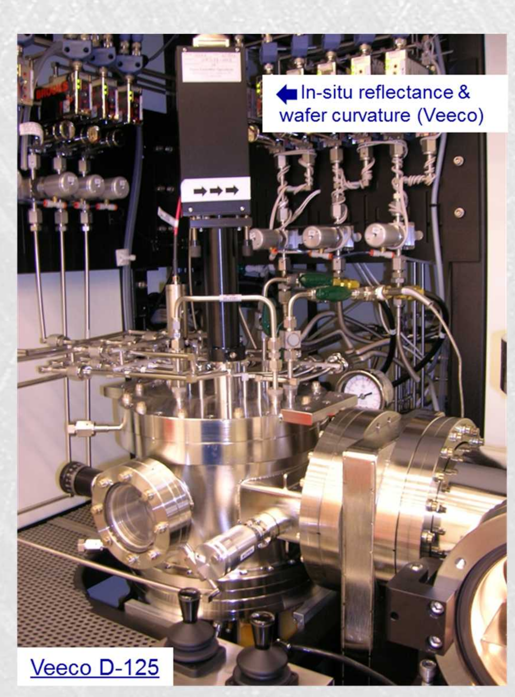
(2) Non-radiative point defects (vacancies, impurities)
→ reduces efficiency, impacted by growth conditions

(3) Lack of a lattice-matched substrate (extended defects)
→ high threading dislocation density > 1x10^9 cm^{-2}; reduces efficiency, precludes reliable LD operation.
→ AlN substrates lead to high sheet resistance and optical loss.

Results

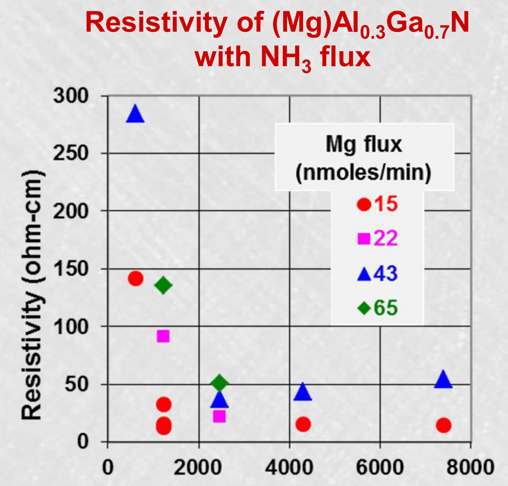
(1) P-type $Al_xGa_{1-x}N$ growth by MOCVD in a Veeco D-125 System

- **Temp:** 990-1010° C
- **Pressure:** 75 torr
- **Sources:** TMAl, TMGa, NH_3, H_2, N_2
- **Growth Rate:** 0.3-0.4 μm/hr (AlGaN), 0.07-0.12 μm/hr (AlN)
- **V/III Ratio:** 4000, 5000 (AlGaN, AlN)
- **Dopants:** Cp2Mg (flow is not modulated in SL)
- **Sapphire:** 0.2° off toward m-plane

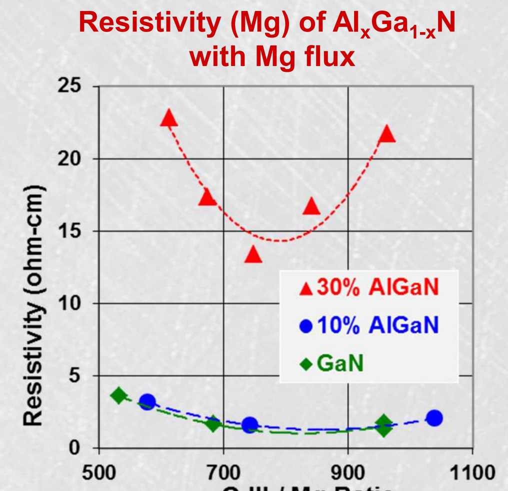


Veeco D-125

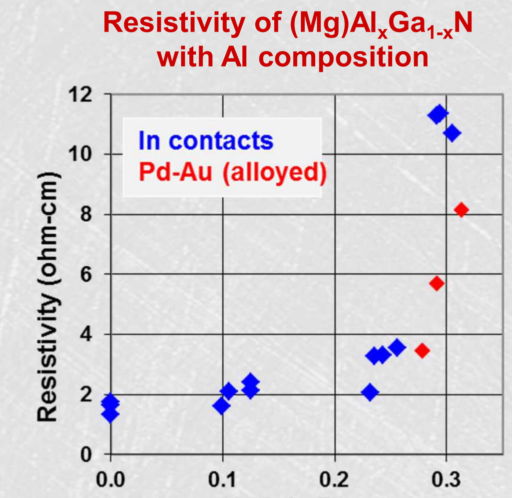
(1a.) P-type doping of $Al_xGa_{1-x}N$ epilayers (X < 0.3)



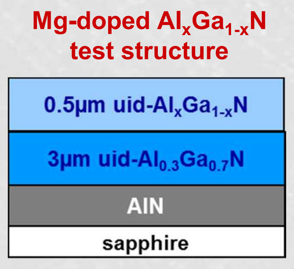
Resistivity is largely independent of V/III ratios exceeding 1200.



Resistivity is more sensitive to Mg flux for AlGaN films with higher Al composition.

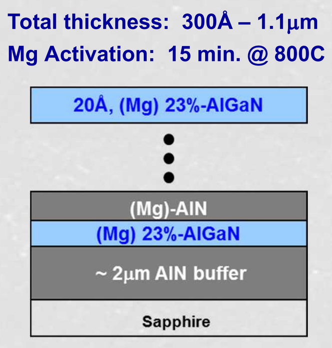


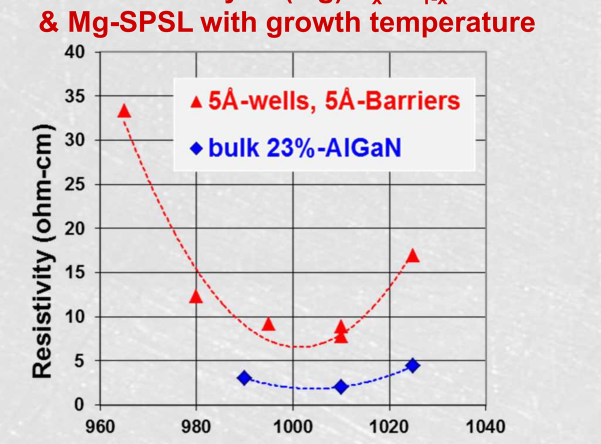
The increase in resistivity reflects the increase in Mg acceptor activation energy with higher Al composition.



Mg-doped Short-Period Superlattice (Mg-SPSL)

- Barriers: AlN (5-15Å)
- Wells: $Al_{0.23}Ga_{0.77}N$ (5-15Å)
- Total thickness: 300Å – 1.1μm
- Mg Activation: 15 min. @ 800C in N2



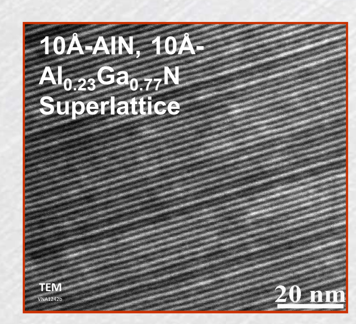


Resistivity of AlGaN epilayers and Mg-SPSL are weakly dependent on temperature

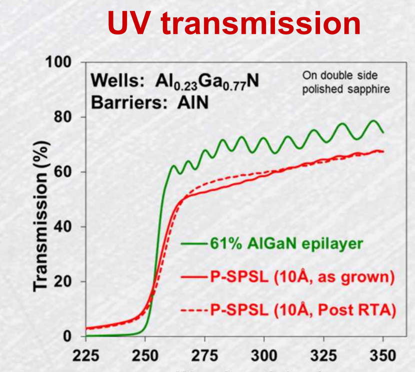
Results (con't)

(1) AlGaN/AlN Mg-doped polarization superlattices for p-type doping of "$Al_xGa_{1-x}N$" (x > 0.5)

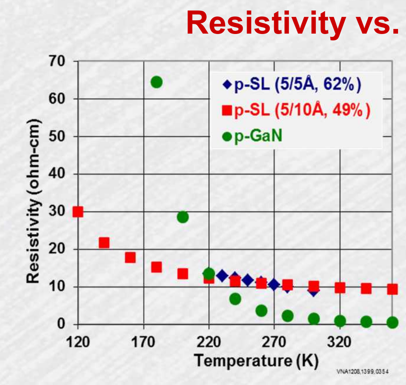
TEM of AlGaN/AlN SL



UV transmission



Resistivity vs. temperature

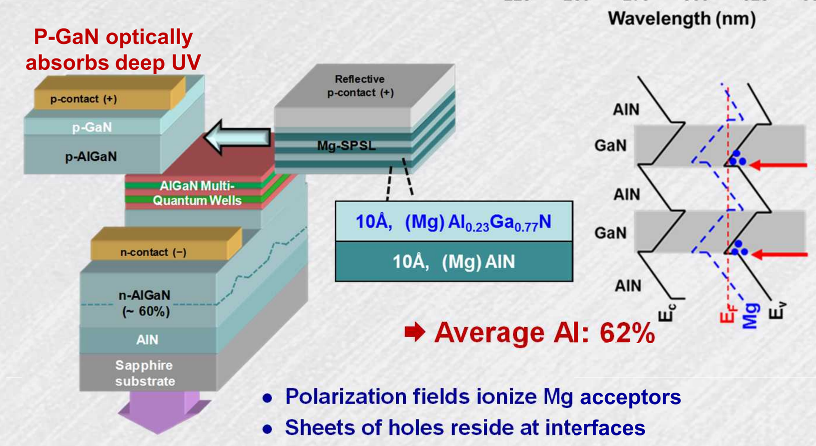


$\rho \propto \exp(E_a/kT)$

- p-GaN: E_a = 150meV
- 5Å / 5Å (62%): E_a = 29meV
- 5Å /10Å (49%): E_a = 18meV

Hole activation energy ~ kT

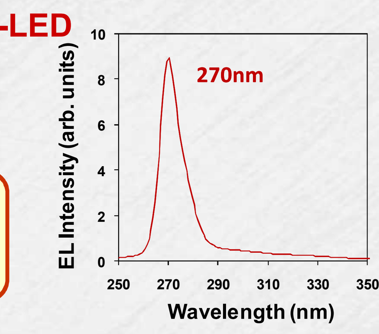
Allerman et. al., JCG 2010



- Polarization fields ionize Mg acceptors
- Sheets of holes reside at interfaces

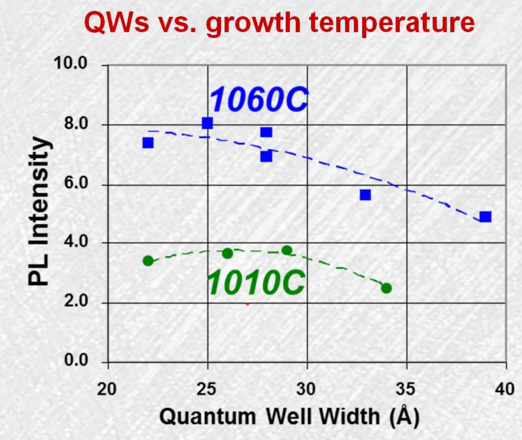
Thermal ionization not required
Optically transparent to UV
Low in-plane hole resistivity

Electroluminescence of Mg-SPSL UV-LED



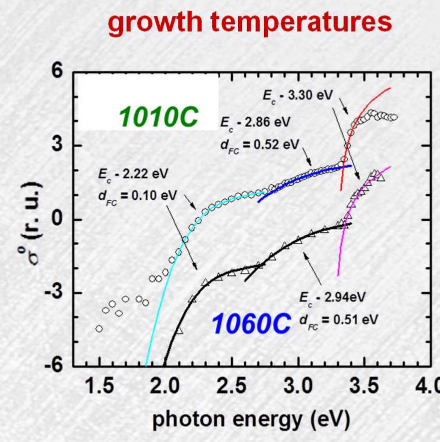
(2) Deep Level Optical Spectroscopy (DLOS) to quantify point defects

Photoluminescence of 340 nm AlGaN QWs vs. growth temperature



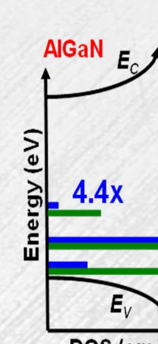
PL increased with higher growth temperature

DLOS data for two growth temperatures



Three deep level traps detected in $Al_{0.08}Ga_{0.92}N$ used in wells

Defect energies and relative densities

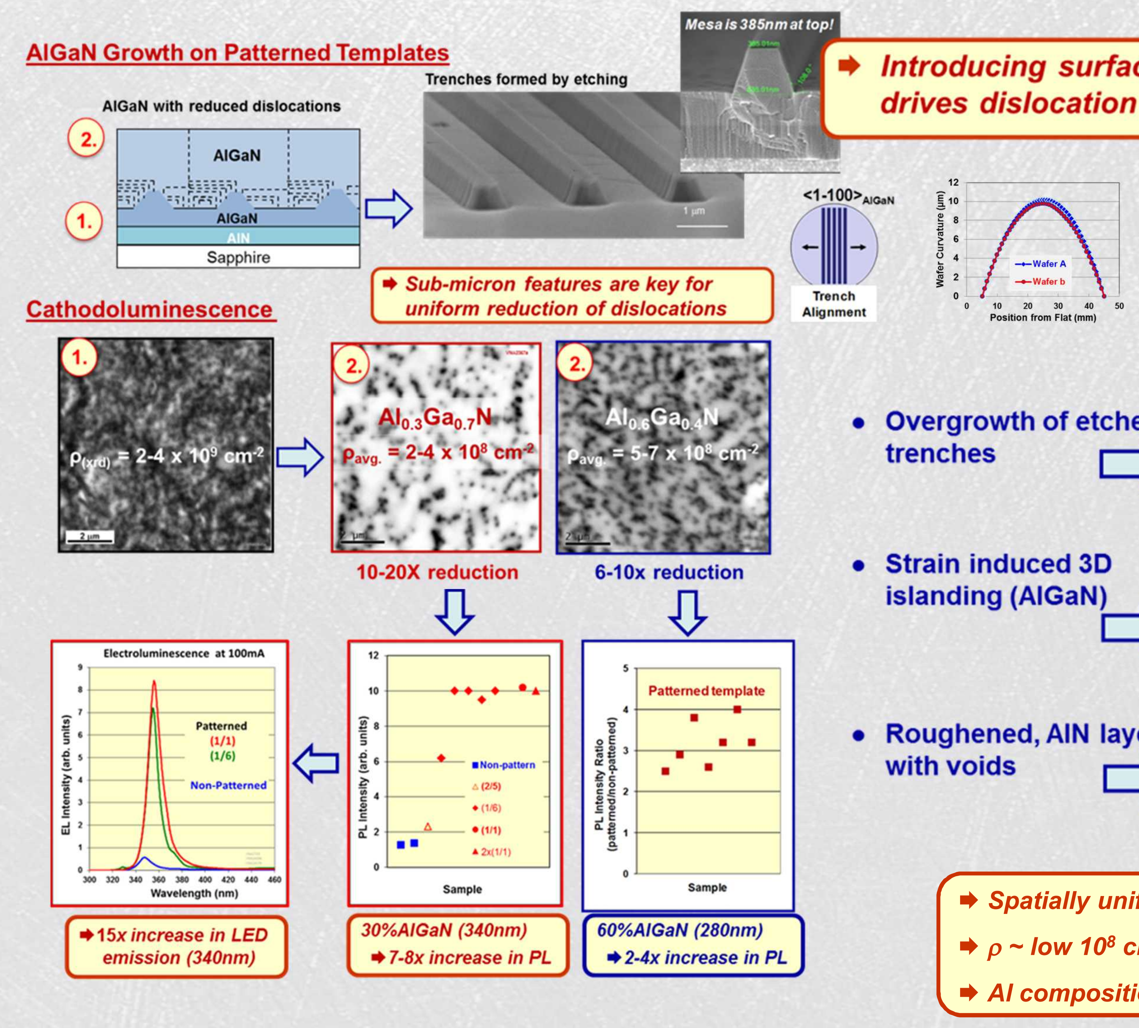


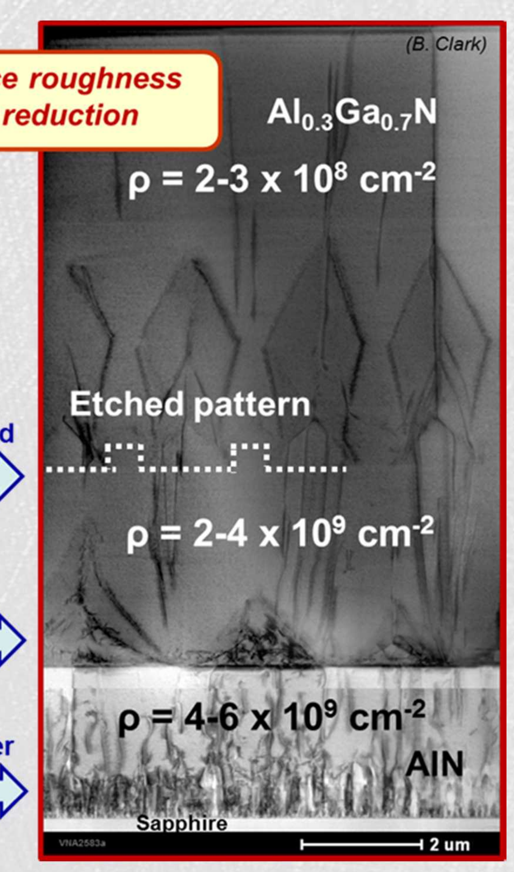
Level (eV)	T_g = 1010° C	T_g = 1060° C	Δ
2.22	6.5e15	1.3e15	5X
2.9	2.8e16	10e16	3.6X
3.30	8.3e15	3.6e16	4.3X

Armstrong et al., APL 2011

Large reduction in trap density with growth at higher temperature

(3) AlGaN regrowth over etched trenches to reduce extended defects



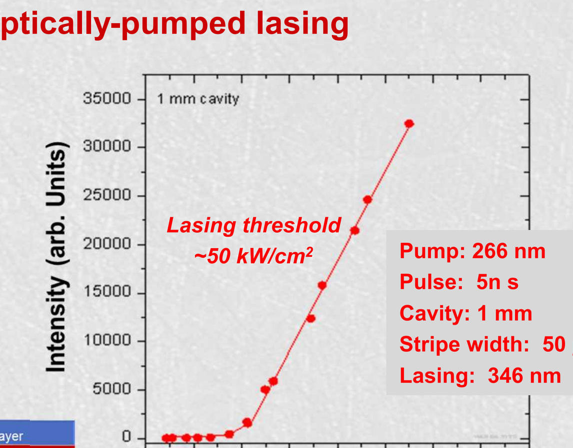


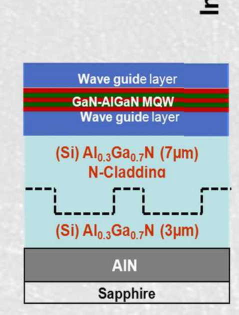
- Overgrowth of etched trenches
- Strain induced 3D islanding (AlGaN)
- Roughened, AlN layer with voids

Spatially uniform reduction in dislocation density
ρ ~ low 10^8 cm^{-2} (x = 0.3), mid 10^8 cm^{-2} (x = 0.65)
Al compositions; 0 < Xal < 1

(4) Laser diode processing and testing

Optically-pumped lasing

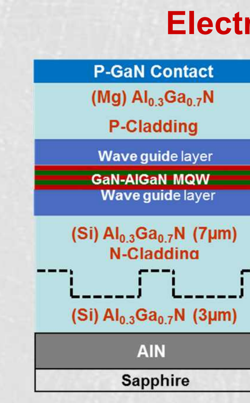


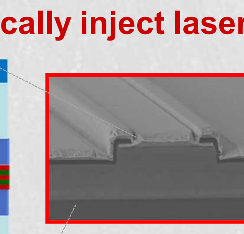


OP laser structure

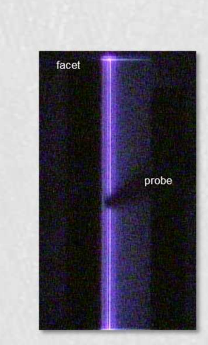
Low lasing threshold ~50 - 150 kW/cm²

Electrically inject laser design

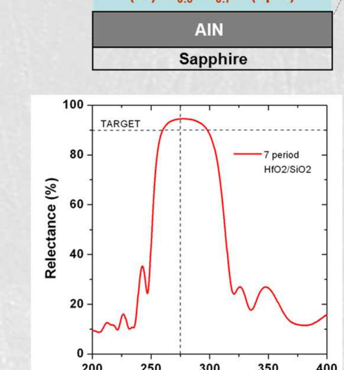


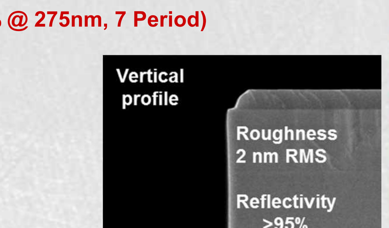


Ridge waveguide LD cross-section



Reflectance of HfO_2/SiO_2 mirror stack (> 90% @ 275nm, 7 Period)





Etched laser facet (AlGaN-on-sapphire)