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Material and device development of AlGaN based deep UV emitters

Sandia National Laboratories

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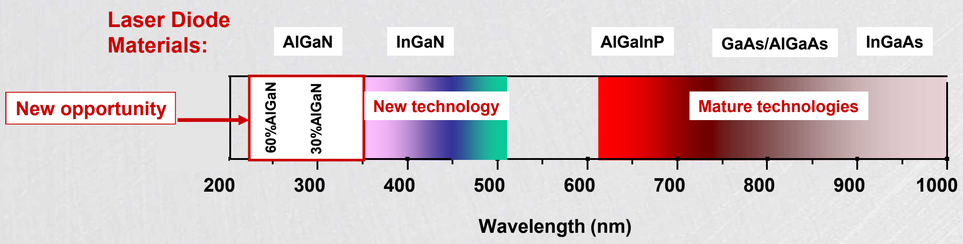
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Challenge

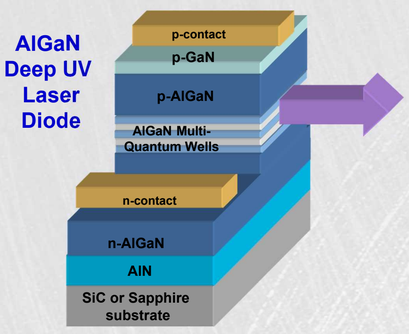
Opportunity:

- 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)

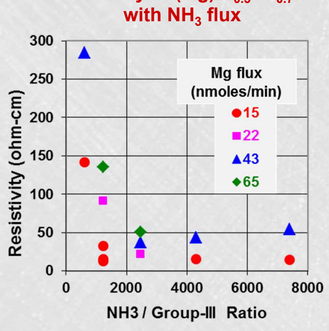
Dopants: Cp2Mg
(flow is not modulated in SL)

Sapphire: 0.2° off toward m-plane

Veeco D-125

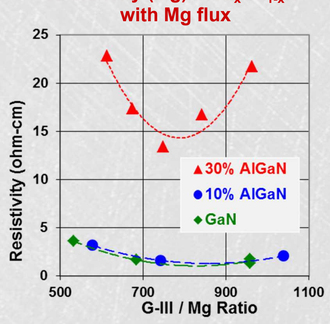
(1a.) P-type doping of $Al_xGa_{1-x}N$ epilayers (X < 0.3)

Resistivity of (Mg)$Al_{0.3}Ga_{0.7}N$ with NH_3 flux



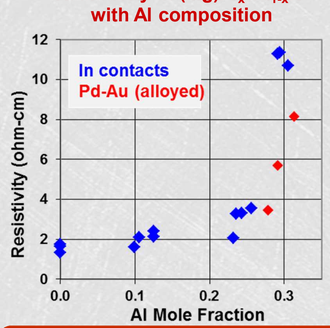
→ *Resistivity is largely independent of V/III ratios exceeding 1200.*

Resistivity (Mg) of $Al_xGa_{1-x}N$ with Mg flux



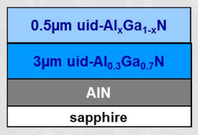
→ *Resistivity is more sensitive to Mg flux for AlGaN films with higher Al composition.*

Resistivity of (Mg)$Al_xGa_{1-x}N$ with Al composition



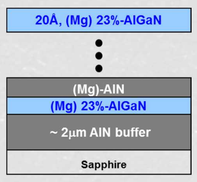
→ *The increase in resistivity reflects the increase in Mg acceptor activation energy with higher Al composition.*

Mg-doped $Al_xGa_{1-x}N$ test structure

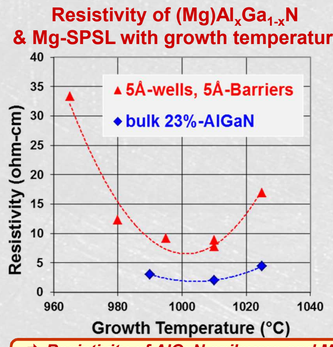


Mg-doped Short-Period Superlattice (Mg-SPSL)

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 (Mg)$Al_xGa_{1-x}N$ & Mg-SPSL with growth temperature

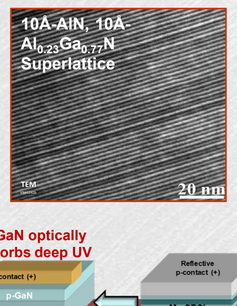


→ *Resistivity of AlGaN epilayers and Mg-SPSL are weakly dependent on temperature*

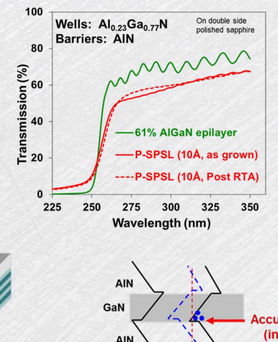
Results (con't)

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

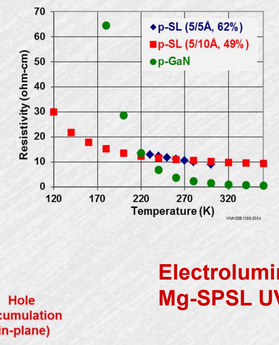
TEM of AlGaN/AlN SL



UV transmission



Resistivity vs. temperature



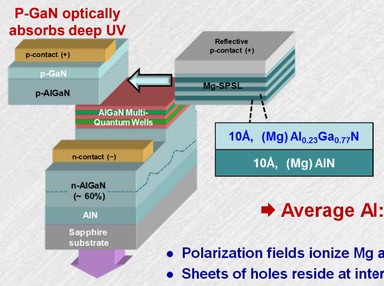
$\rho \propto \exp(E_a/kT)$

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

→ *Hole activation energy ~ kT*

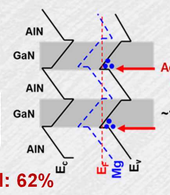
Allerman et. al., JCG 2010

P-GaN optically absorbs deep UV



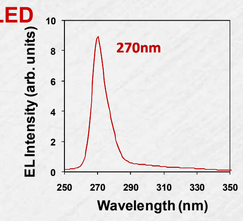
→ Average Al: 62%

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



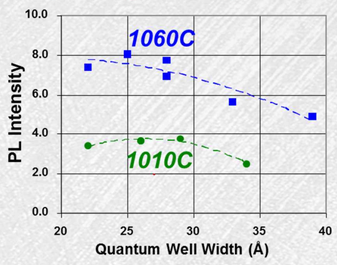
→ *Thermal ionization not required*
→ *Optically transparent to UV*
→ *Low in-plane hole resistivity*

Electroluminescence of Mg-SPSL UV-LED



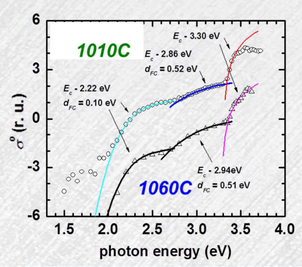
(2) Deep Level Optical Spectroscopy (DLOS) to quantify point defects

Photoluminescence of 340 nm AlGaN QWs vs. growth temperature



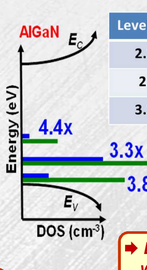
→ *PL increased with higher growth temperature*

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



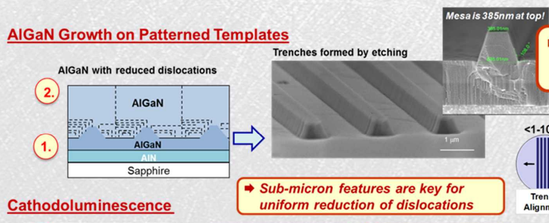
Level (eV)	T_g = 1010° C	T_g = 1060° C	Δ
2.22	6.5e15	1.3e15	5X
2.9	2.8e16	10e16	3.6X
3.30	8.3e15	3.6e16	4.3X

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

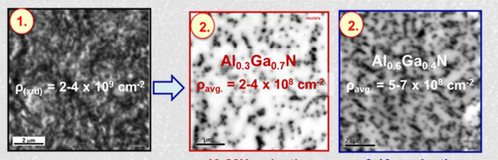
AlGaN Growth on Patterned Templates

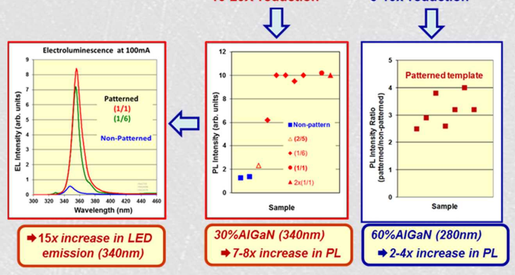


→ *Sub-micron features are key for uniform reduction of dislocations*

→ *Introducing surface roughness drives dislocation reduction*

Cathodoluminescence



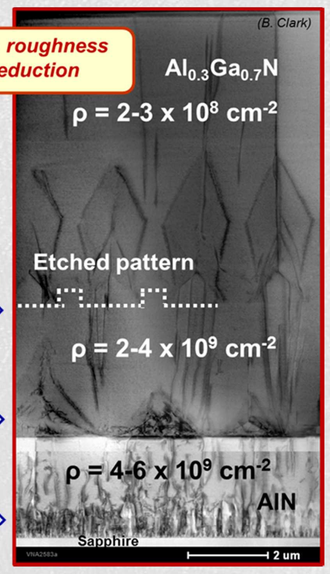


→ 15x increase in LED emission (340nm)

30%AlGaN (340nm)
→ 7-8x increase in PL

60%AlGaN (280nm)
→ 2-4x increase in PL

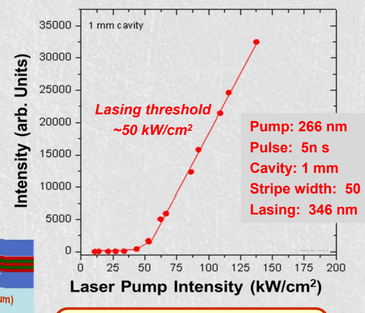
- Overgrowth of etched trenches
- Strain induced 3D islanding (AlGaN)
- Roughened, AlN layer with voids



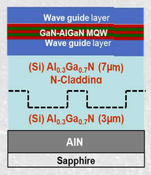
→ *Spatially uniform reduction in dislocation density*
→ *ρ ~ low 10^8 cm^-2 (x = 0.3), mid 10^8 cm^-2 (x = 0.65)*
→ *Al compositions; 0 < Xal < 1*

(4) Laser diode processing and testing

Optically-pumped lasing



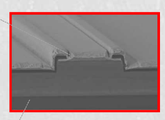
Pump: 266 nm
Pulse: 5n s
Cavity: 1 mm
Stripe width: 50 μm
Lasing: 346 nm



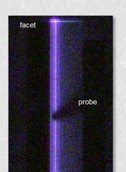
OP laser structure

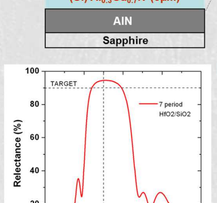
→ *Low lasing threshold ~50 - 150 kW/cm²*

Electrically inject laser design

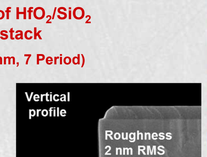


Ridge waveguide LD cross-section





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



Etched laser facet
(AlGaN-on-sapphire)

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