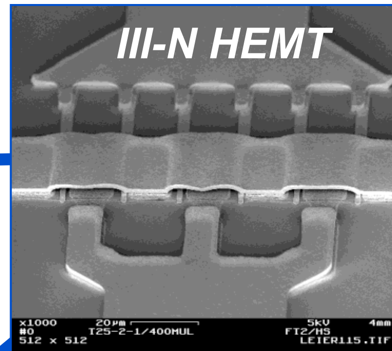
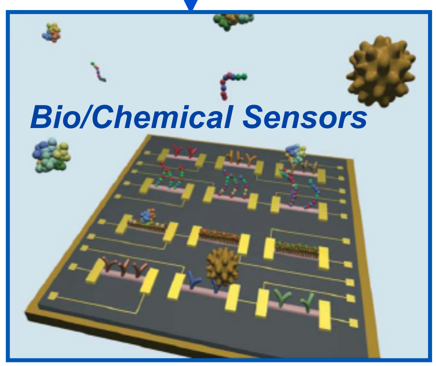
SVT MBE

Nitride

Engines for Thin Film Innovation

III-Nitride HEMTs

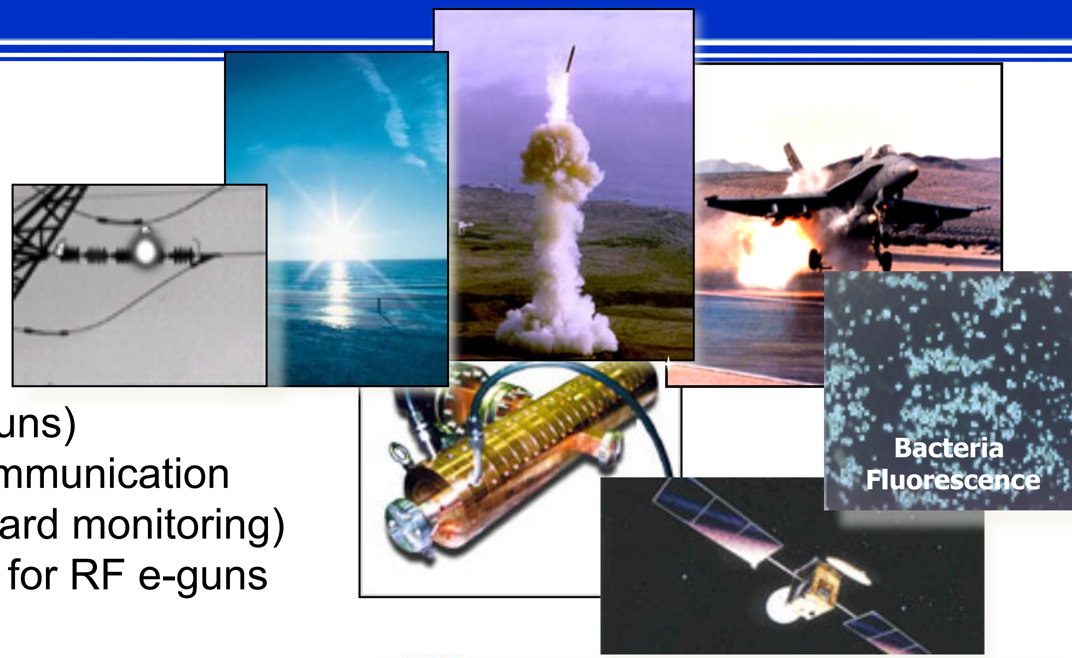


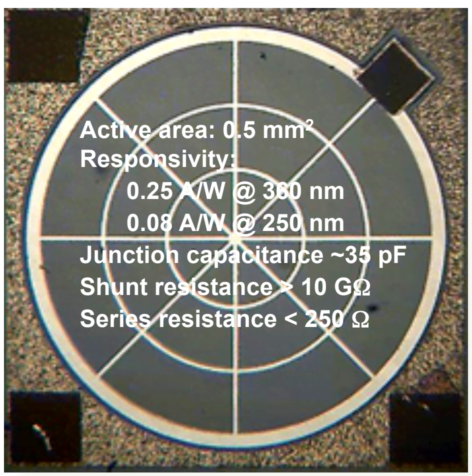


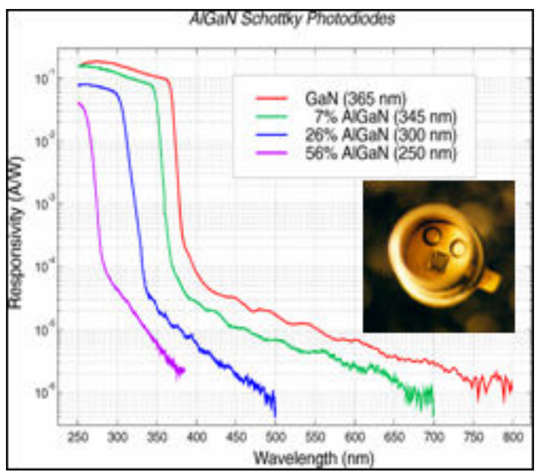
Some applications of high-frequency, high-power and high-temperature GaN-based HEMTs

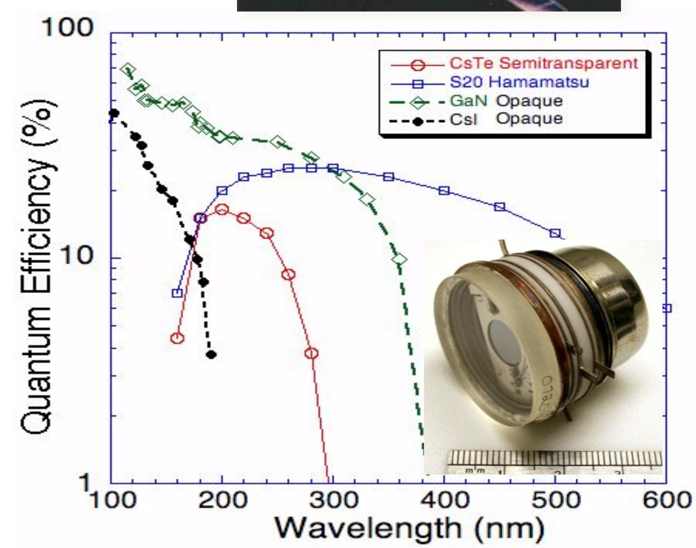
GaN-based UV Photodetectors and Photocathodes

- UV imaging
- UV curing and aging
- Air & water Purification
- Fire & electric arc detection
- Missile tracking & guidance
- Maskless UV photolithography
- High current emitters (in RF e-guns)
- Secure space or underwater communication
- Spectroscopy (bio/chemical hazard monitoring)
- High brightness electron source for RF e-guns





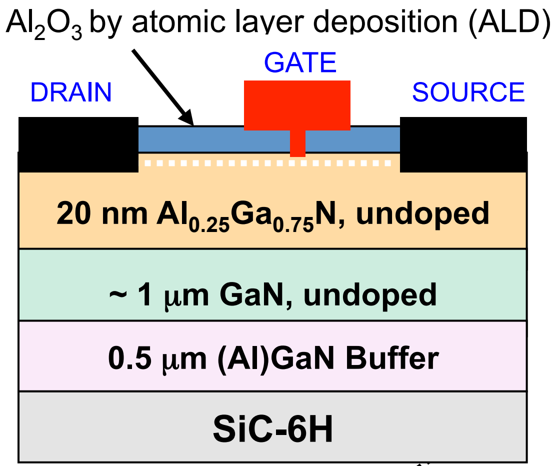


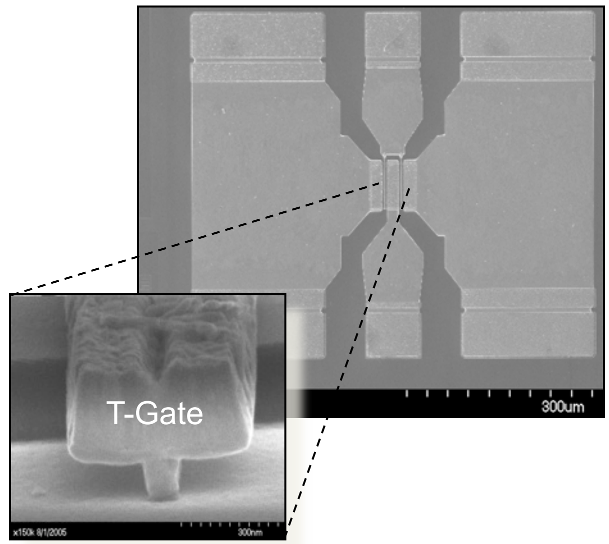


High Performance III-Nitride Devices – Grown By Molecular Beam Epitaxy

- ***High Electron Mobility Transistors:*** HEMT devices based on AlGaN/GaN heterostructures have demonstrated great potential for applications in very high power, high frequency and high temperature amplifiers. Further improvements in device performance is predicted for HEMTs with higher Al composition including AlN/GaN HEMTs, currently being developed at SVTA. Partially Funded by DoD Grants #W911QX-06-C-0083 and #W911NF-06-C-0190.
- ***UV Photodiodes and Photocathodes:*** High sensitivity, visible-blind ultraviolet (UV) photodetectors are needed for many military and civilian applications. GaN-based UV detectors and photocathodes have shown the reliability and sensitivity that are required for many of these applications. Reliable and efficient photocathodes are also sought for high-intensity and broad electron sources. Partially Funded by DoE Grant # DE-FG0206ER84506.
- ***High Efficiency UV LEDs:*** Compact, high efficiency solid-state UV light emitters are needed for applications in sterilization/decontamination, bio/chemical detection, UV curing, analytical instrumentation and non-line-of-sight covert communications. In a collaboration with Army Research Lab, SVTA is developing AlGaN-based UV LEDs, containing nano-compositional inhomogeneity, that show remarkable improvements in quantum efficiency.

High-performance AlGaN/GaN HEMTs grown by RF plasma assisted MBE



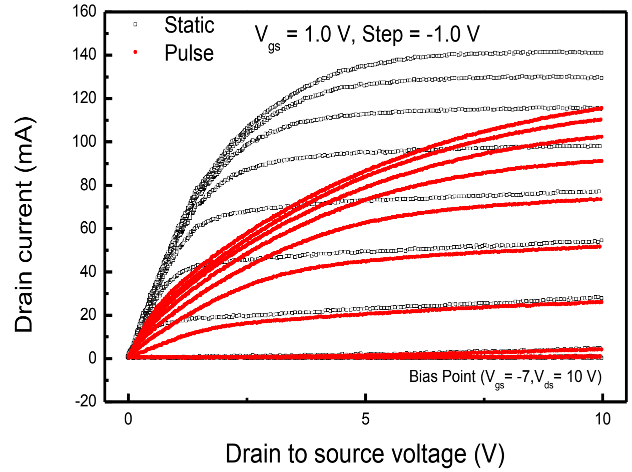


L_G = 0.25 μm or 0.12 μm

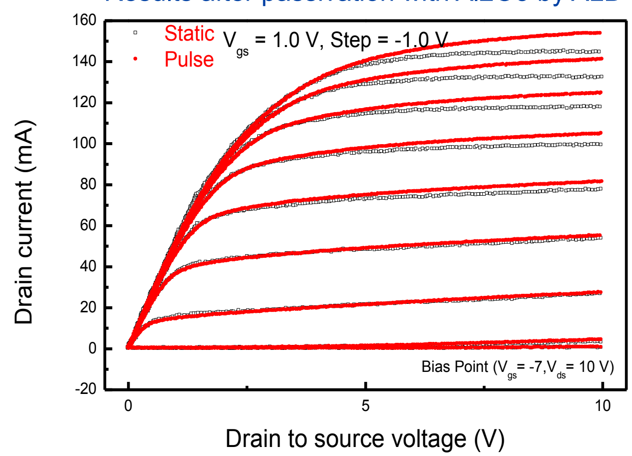
W_G = 100 μm

L_{fp} = 1.1 μm

Current collapse in unpassivated device



Results after passivation with Al2O3 by ALD

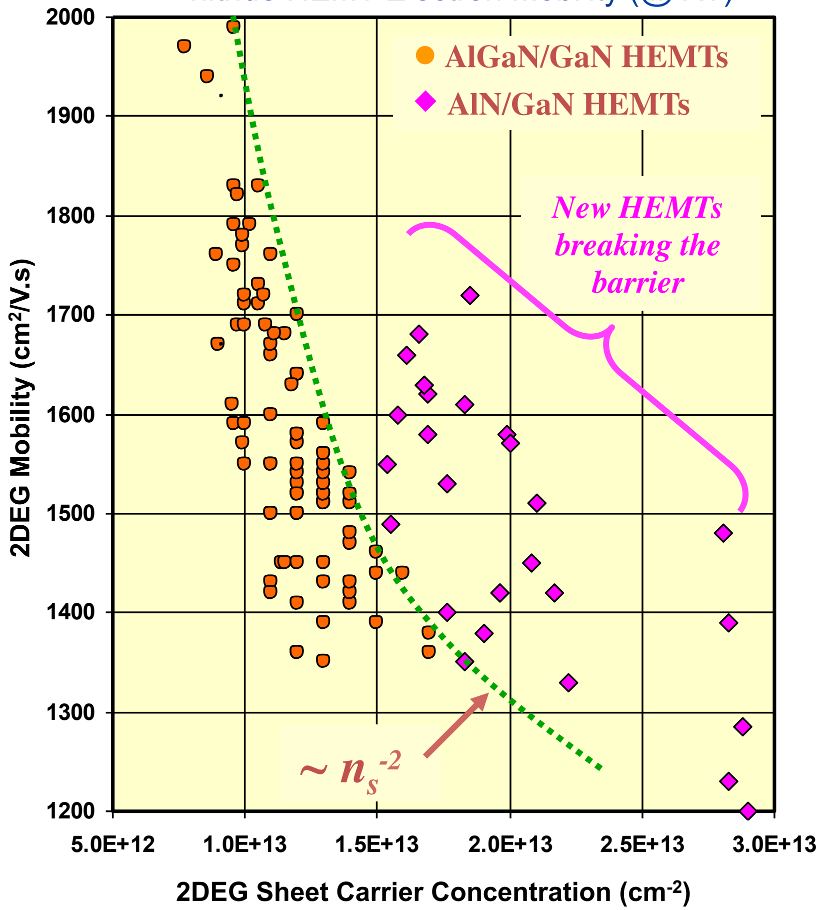


L_r (μm)		g_{mext} (mS/mm)	I_{Dmax} (A/mm)	Vth (V)	f_T (GHz)	f_{max} (GHz)
0.25	Reference	268	1.36	-5.8	65	137
	Passivated	272	1.45	-5.95	58	120
0.12	Reference	291	1.64	-7.05	120	140
	Passivated	294	1.75	-7.1	92	115

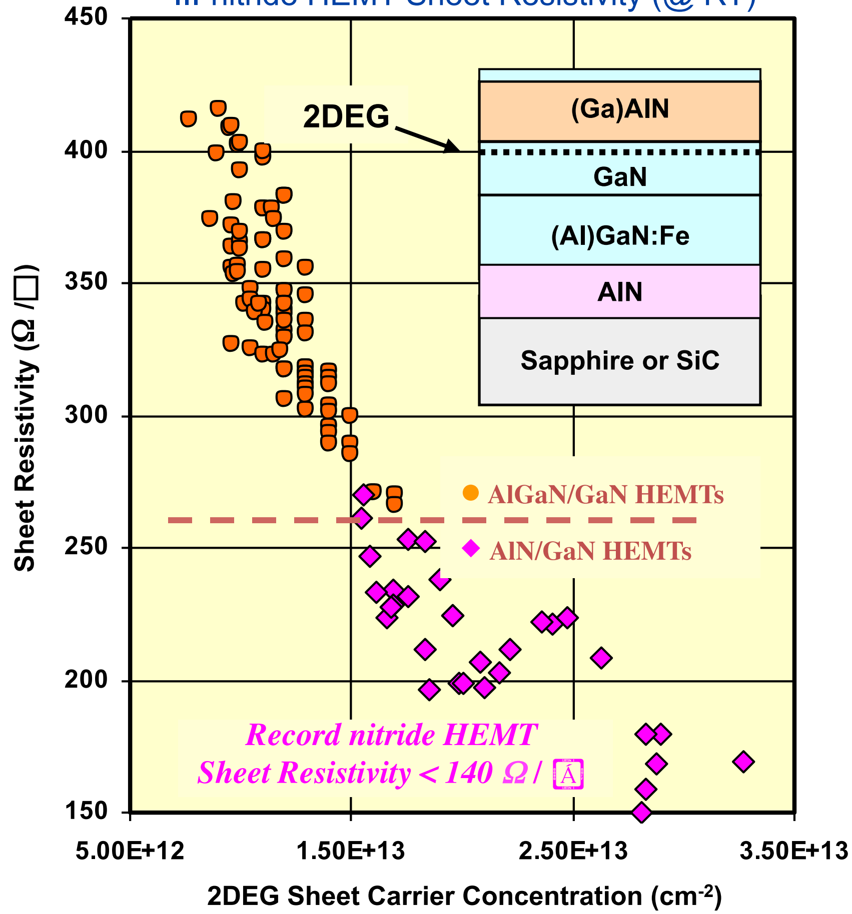
High-frequency & high power capabilities

MBE Grown AlN/GaN HEMTs with Record Performance

III-nitride HEMT Electron Mobility (@ RT)

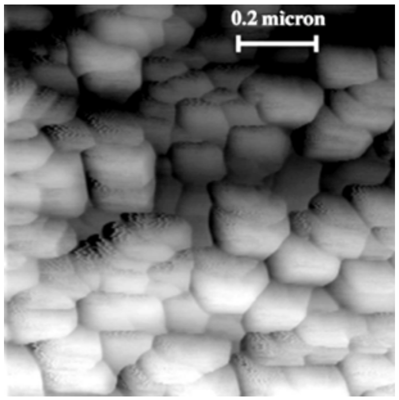


III-nitride HEMT Sheet Resistivity (@ RT)

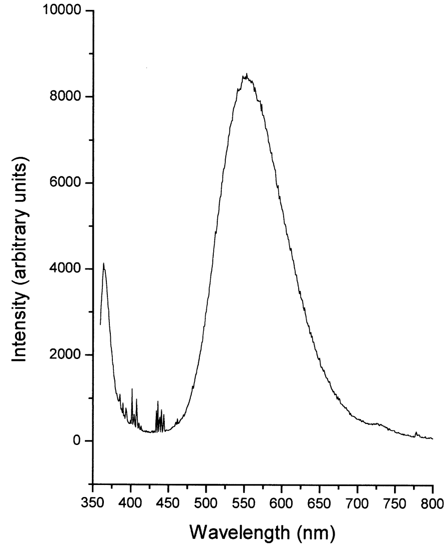


The channel conductivity of high-quality AlGaN/GaN HEMTs is limited to above ~250 Ω/□ by both surface roughness and alloy scattering. We have been able to overcome this barrier by growing high quality AlN/GaN HEMTs on sapphire and SiC with record properties as shown in above figures.

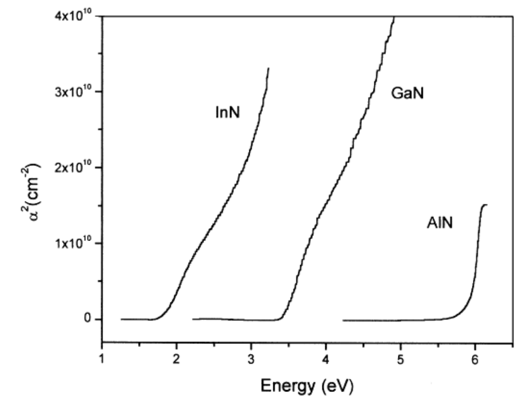
Nitride thin films grown by pulsed laser deposition assisted by atomic nitrogen beam



AFM image of an AlN/sapphire sample grown at 700 ºC. The imaged square has a 1mm side

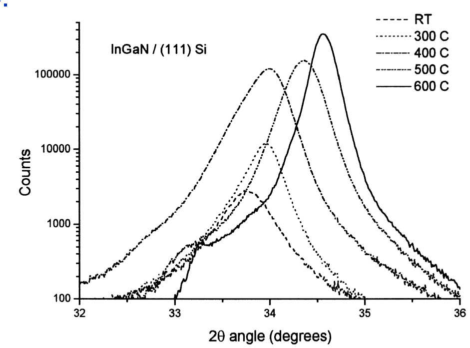


PL spectrum at room temperature for GaN/sapphire sample grown at 600 ºC.



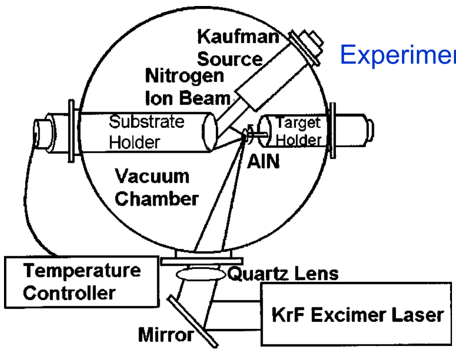
Square of the absorption coefficient as a function of photon energy, calculated for InN, GaN, and AlN thin films. Linearity indicates a direct transition bandgap. Onset of linearity is at bandgap energy value.

InN, GaN, AlN, and $In_xGa_{1-x}N$ thin films were grown by PLD assisted by atomic nitrogen beam. InN and GaN were grown from elemental metal targets. It is proven the growth of good quality films at reduced temperatures is possible.



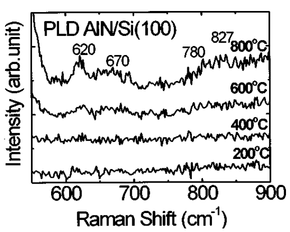
XRD θ-2θ scan for $In_xGa_{1-x}N$ films grown on (111) Si at different temperatures

Ion-assisted pulsed laser deposition of aluminum nitride thin films

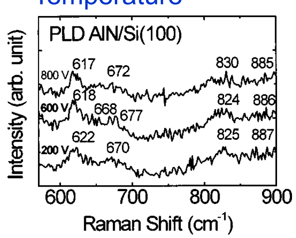


Experimental setup

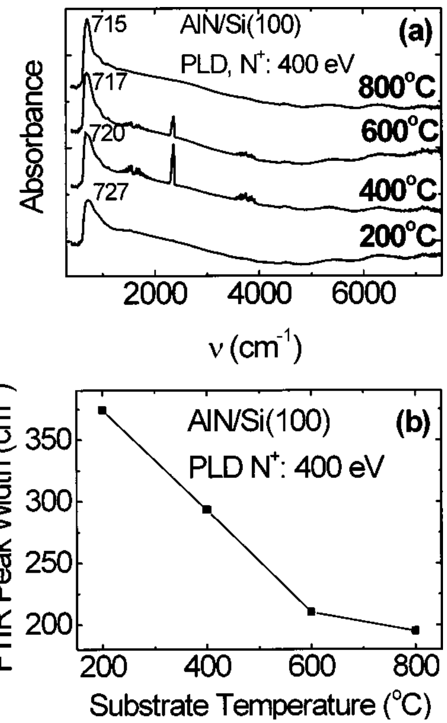
Nitrogen Ion Beam at 400 eV



Substrate at Room Temperature

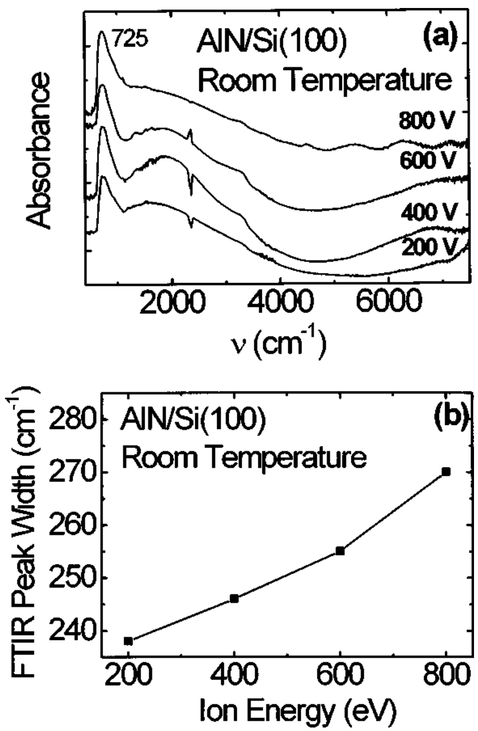


Nitrogen Ion Beam at 400 eV



FTIR spectra of AIN thin films deposited under different substrate temperatures: 200, 400, 600, and 800 °C.

Substrate at Room Temperature



FTIR spectra of AIN thin films deposited under different nitrogen ion beam bombardment: 200, 400, 600, and 800 eV. The substrate was at room temperature

High-performance Substrates for III-N Growth

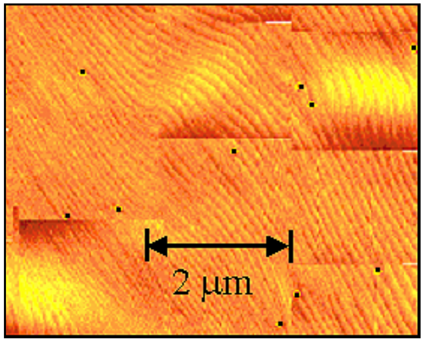
- Bulk AlN and GaN:
  - + Ultra Low Defect (ULD) Densities
  - + Thermal Expansion & Lattice Matched
  - + High Thermal Conductivity

Applications

- High Brightness UV and White LEDs
- Lasers
- Vertical Transport Devices (HBTs and BJTs)

Bulk AlN

ULD GaN

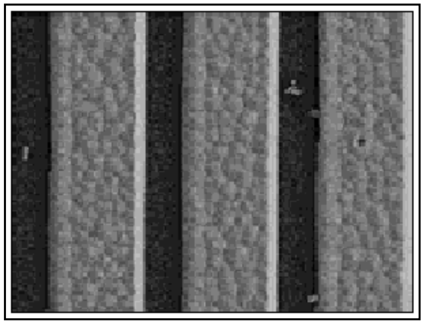


- High Resistivity GaN on Sapphire & SiC:
  - + Grown by MBE
  - + Excellent Device Isolation
  - + Improved DC and RF performance

Applications

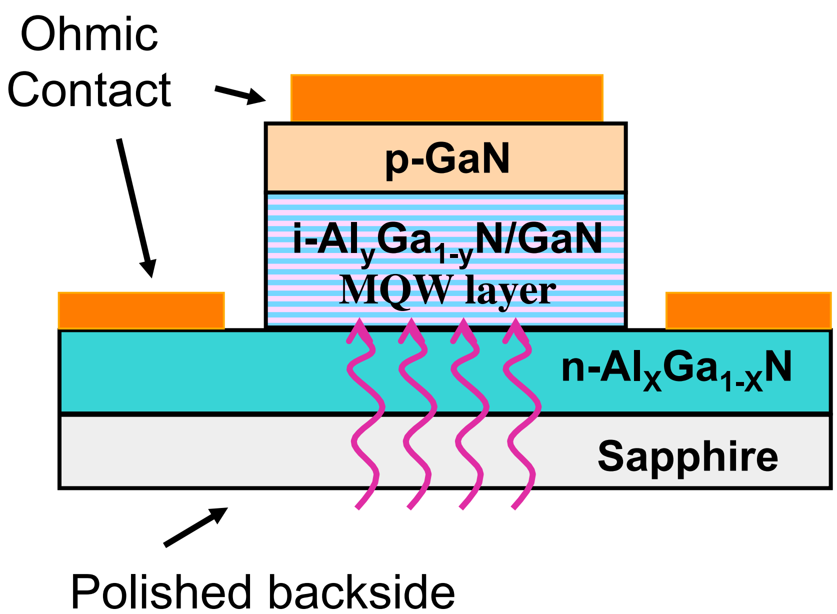
- High Electron Mobility Transistors (HEMTs)

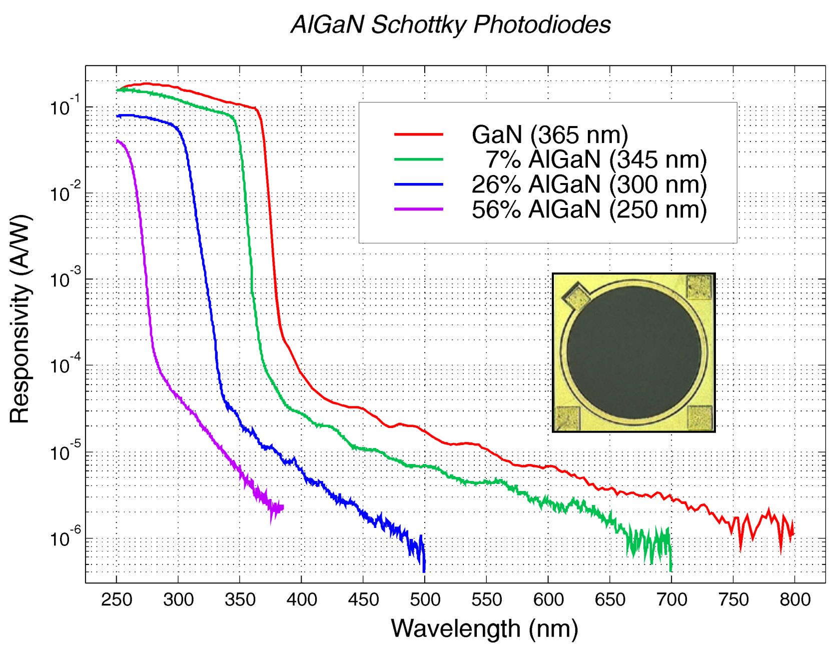
High Resistivity GaN buffer



Engines for Thin Film Innovation

Multi-Quantum Well UV Photodetector

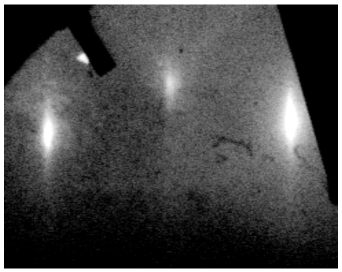




- Solar-blind UV detection
- High efficiency & sensitivity
- Adjustable band-pass design

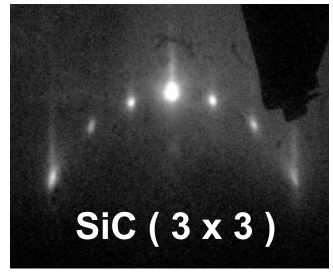
III-Nitride Substrate Preparation

SiC (6H or 4H) Thermal cleaning and annealing

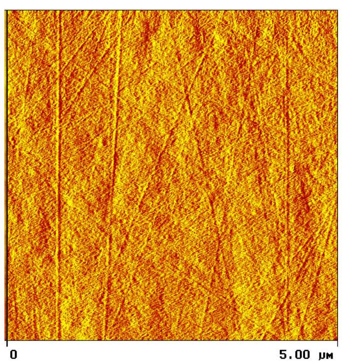


High temps plus annealing fluxes *

RHEED

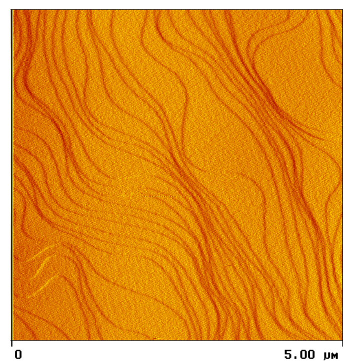


Sapphire (0001) Thermal cleaning and nitridation



Chemical and/or high temperatures

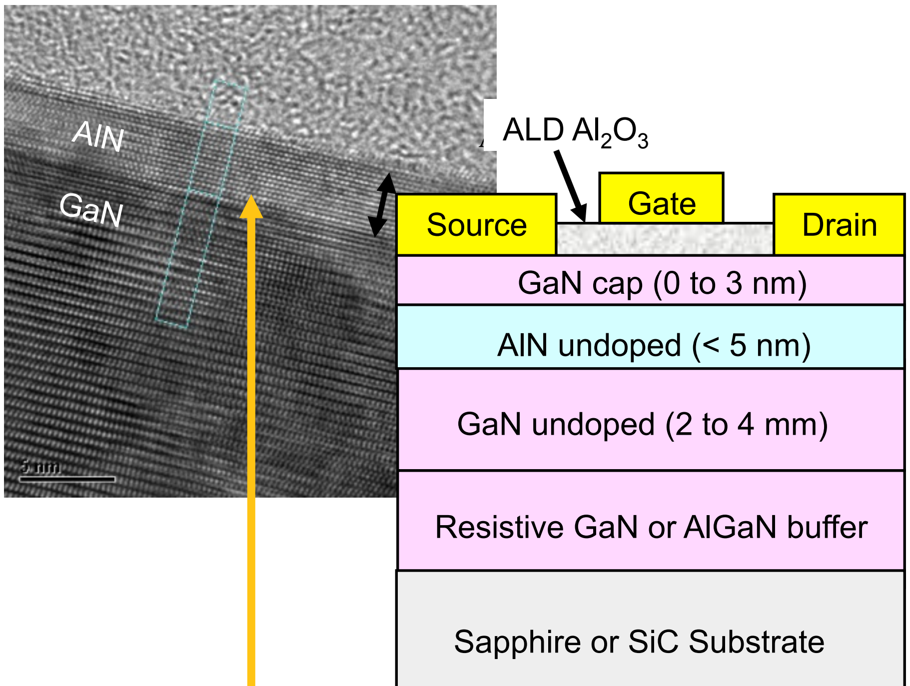
AFM



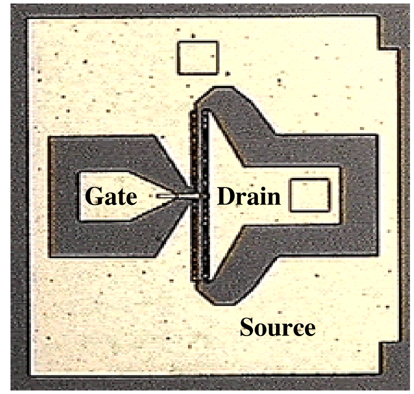
Then expose to NH_3 or N-plasma

*Temperature and flux control by RoboMBE & In-Situ 4000

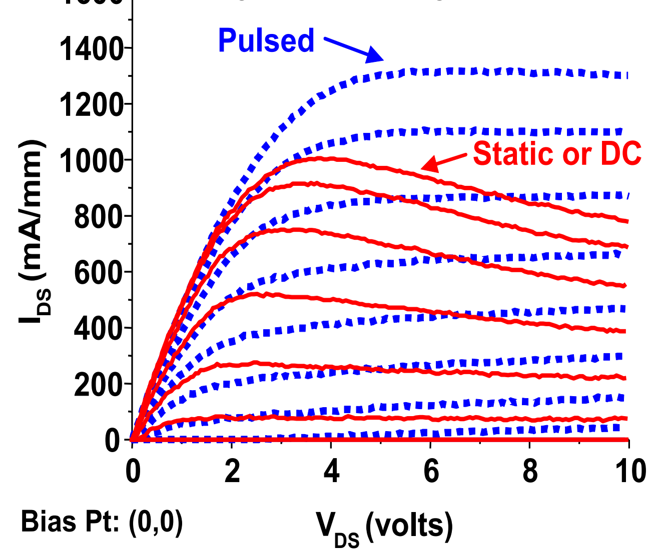
AlN/GaN MOS-HEMT with Al_2O_3 Gate Oxide formed by ALD



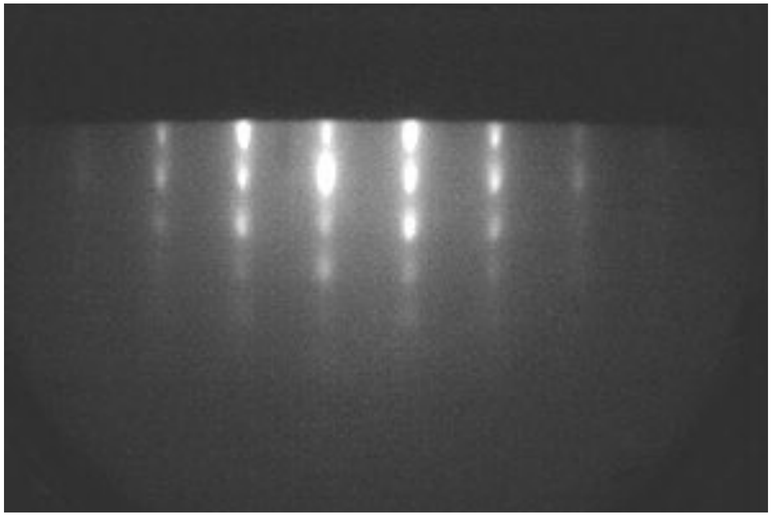
Nanometer scale AlN barrier layer requires low-damage gate-oxide deposition by ALD



DC and Pulsed I-V curves:
L_G = 1.2μm & L_{SD} = 4.5μm.



Structural Properties of Group III Nitrides Grown on SrTiO3 (111) Substrates by Pulsed Laser Deposition

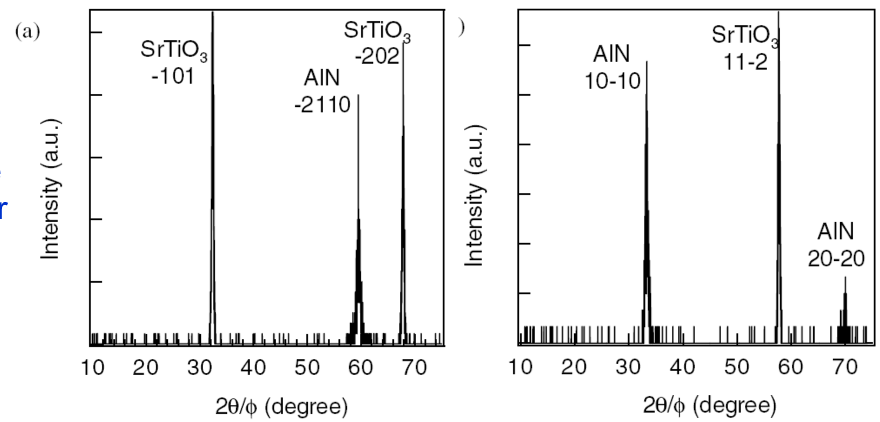


RHEED pattern from the 130 nm thick AlN film with the electron beam incidence along AlN[11–20] direction

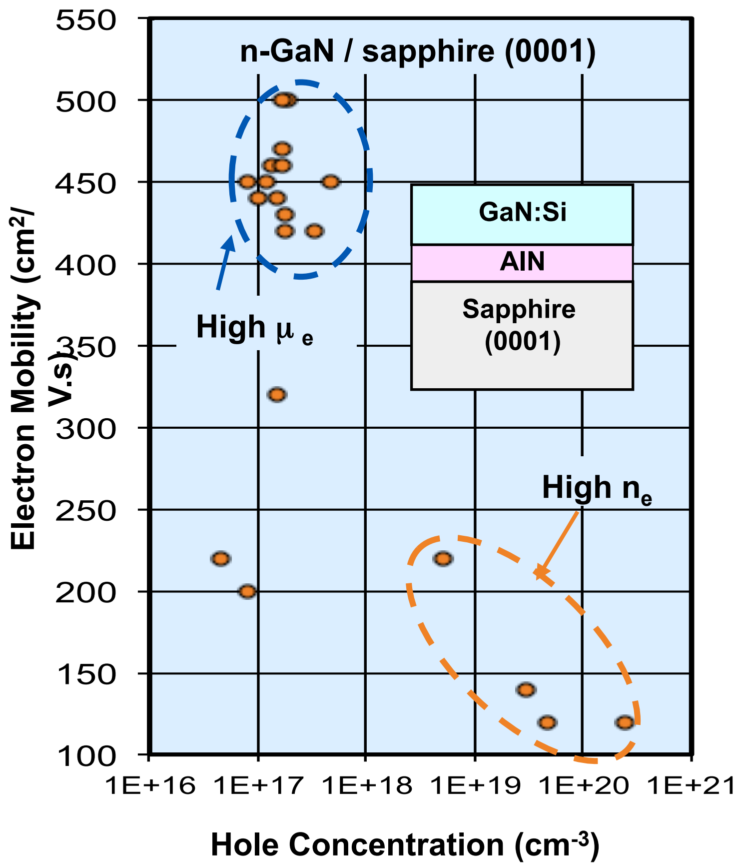
It has been found that wurtzite AlN and GaN films grow epitaxially on SrTiO3(111) by the use of PLD. The epitaxial relationship has been determined to be nitrides(0001) || SrTiO3(111) and nitrides [10–10] || [11–2]SrTiO3. The in-plane alignment is rotated by 30 along the c-axis from that expected by the notion of lattice matching. It has been also found that AlN grown on SrTiO3 is dilated by 0.4% in the normal direction to the surface due to the lattice mismatch and the smaller thermal contraction during cooling down from the growth temperature

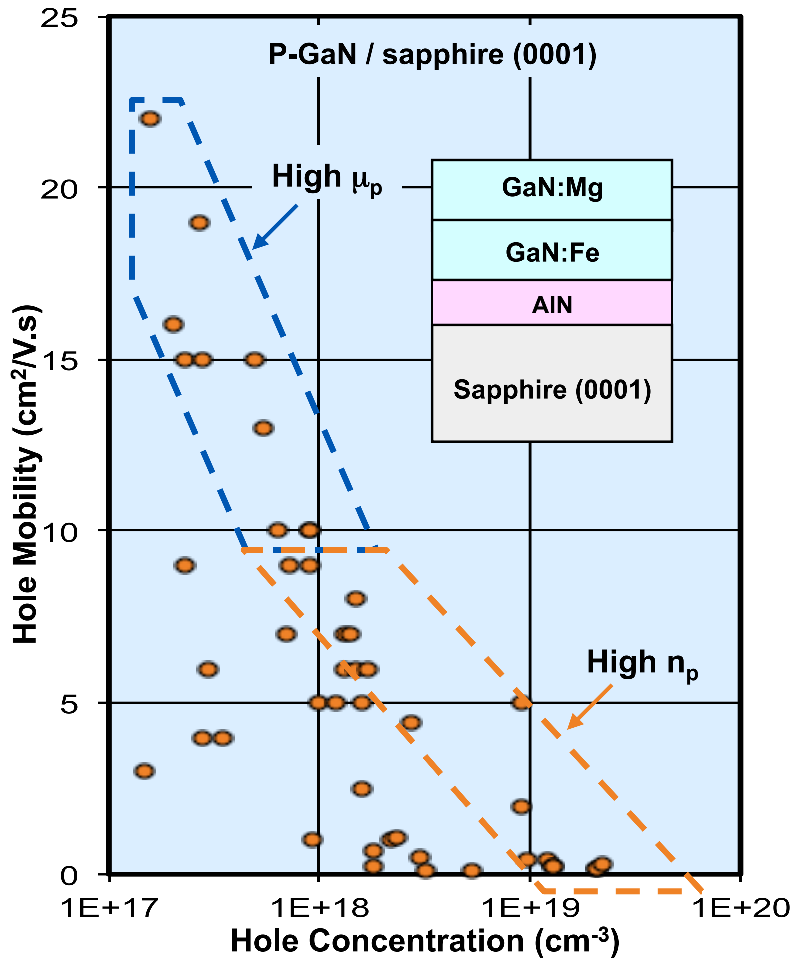
GIXD 2q-f curves of the AlN/SrTiO3 structure for

a) STO-101 and
b) STO11-2

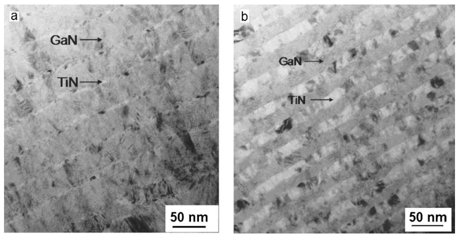


Courtesy of the University of Tokyo

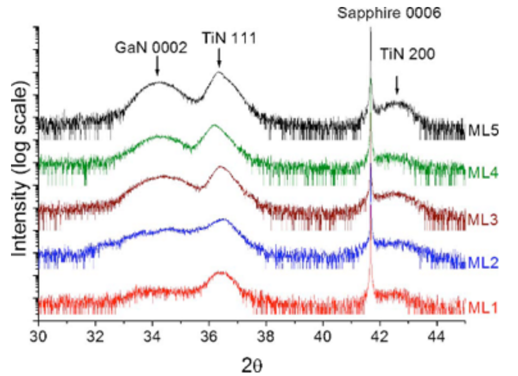

n-GaN / sapphire (0001)
Electron Mobility (cm²/ V.s)
Hole Concentration (cm⁻³)
550
500
450
400
350
300
250
200
150
100
1E+16
1E+17
1E+18
1E+19
1E+20
1E+21
High μ e
High ne
GaN:Si
AlN
Sapphire (0001)


P-GaN / sapphire (0001)
Hole Mobility (cm²/V.s)
Hole Concentration (cm⁻³)
25
20
15
10
5
0
1E+17
1E+18
1E+19
1E+20
High μp
High np
GaN:Mg
GaN:Fe
AlN
Sapphire (0001)

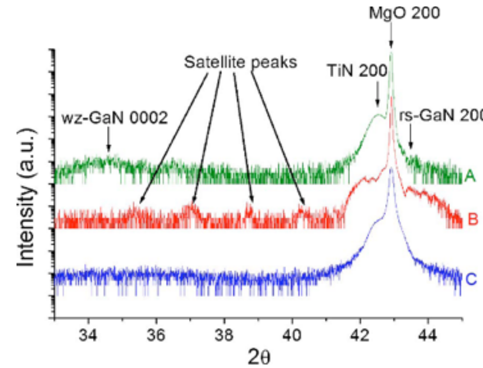
Growth of TiN/GaN metal/semiconductor multilayers by reactive pulsed laser deposition



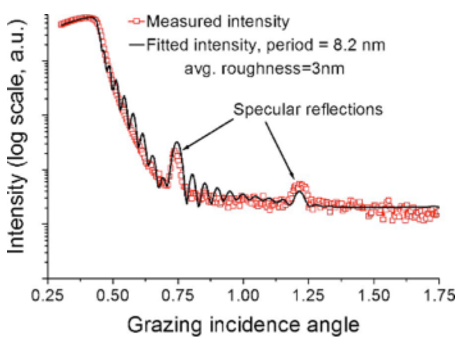
Cross-sectional TEM images of (a) a TiN (5 nm)/GaN(30 nm) multilayer grown on a (0001) sapphire substrate and (b) a TiN (20 nm)/GaN (variable thickness) multilayer grown on a (100) MgO substrate.



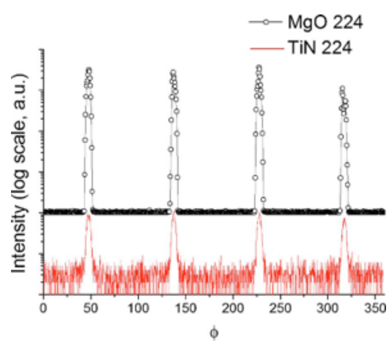
w-2θ symmetric θ-2θ x-ray scans obtained from the TiN-GaN multilayers grown on sapphire with periods of (a) ML1, λ=3.4 nm, (b) ML2, λ=6.8 nm, (c) ML3, λ=15.9 nm, (d) ML4, λ=19.1 nm, and (e) ML5, λ=22.5 nm.



w-2θ & x-ray scans obtained from three different period TiN–GaN multilayers grown on MgO(100) substrate. The multilayer or superlattice period is given as A=18.4 nm (with TiN=12.2 nm/GaN =6.2 nm), B=5.5 nm (with TiN=4.3 nm/GaN=1.2 nm), and C=2.4 nm (with TiN=1.4 nm/GaN=1.0 nm)

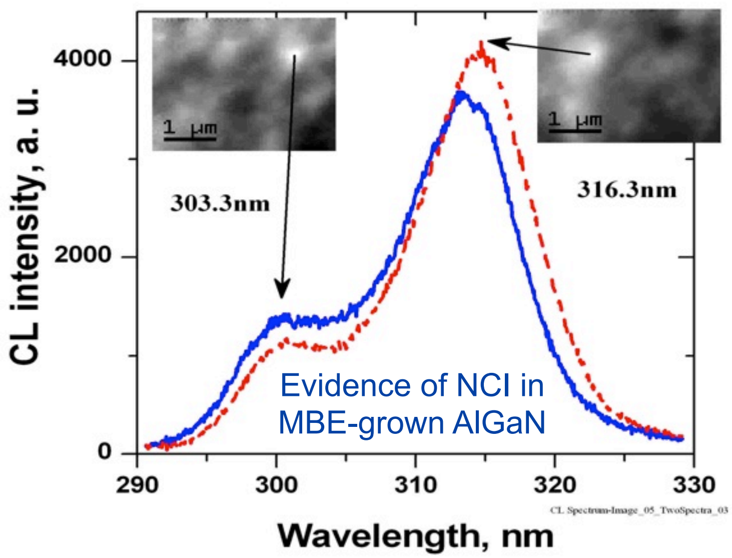


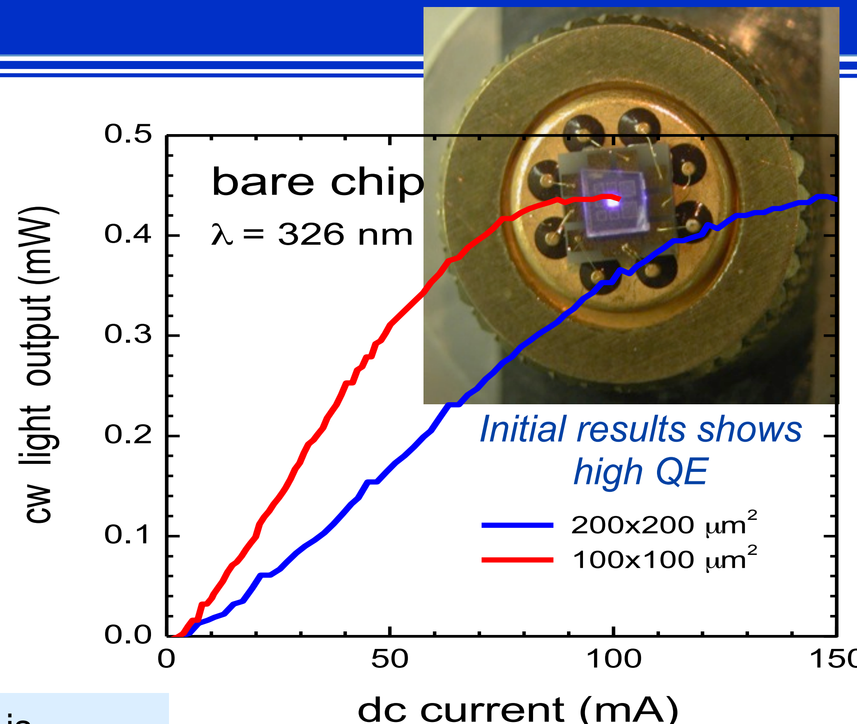
X-ray reflectivity spectra and the fitted data for sample ML2.



X-ray phi scans about MgO 224 and TiN 224 reflections of a 2.35 µm thick TiN(1.4 nm)/GaN(1 nm) multilayer grown on MgO.

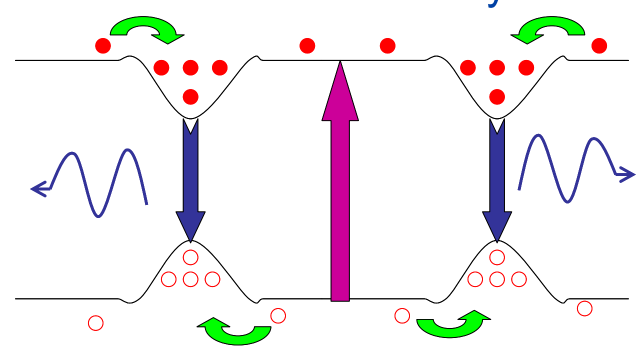
High Efficiency AlGaN-based UV-LEDs Nano-compositional inhomogeneity (NCI)



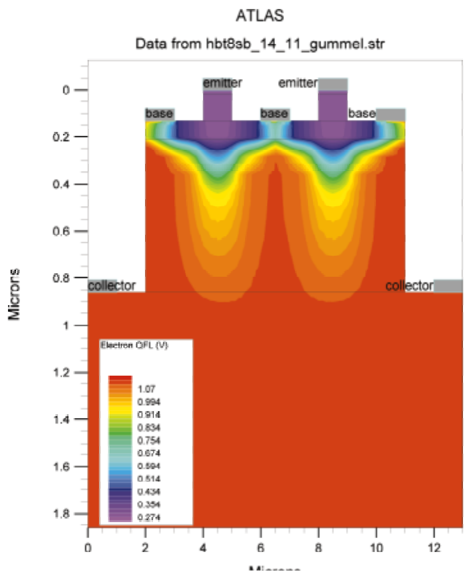


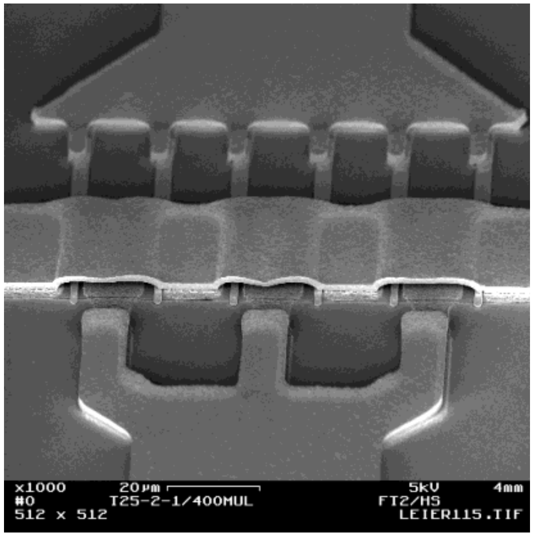
Compositional inhomogeneity in InGaN-based LEDs is known to enhance blue/green emission by increasing carrier localization High growth temperatures required for AlGaN-based UV LEDs make In incorporation difficult. Recent work at Army Research Lab have shown dramatic improvement in UV-LED efficiency by creating Nano-compositional inhomogeneities in AlGaN active layer.

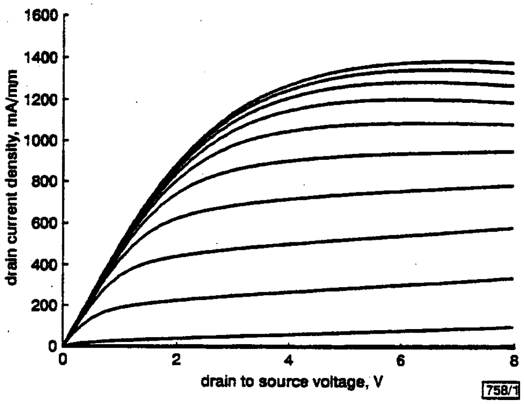
Carrier Localization by NCI



III-Nitride: Device Modeling, Processing and Characterization







RT μ_n (cm^2/V.s)	n_s x10^{13} (cm^{-2})	Gate (mm)	I_{ds}max (mA/mm)	I_{dss} (mA/mm)	G_m (mS/mm)	f_T (GHz)	f_{max} (GHz)	V Break-down (V)
1210	**1.5**	**0.25**	**1397**	**1300**	**218**	**67**	**136**	**18**