GaN Technology

Michael Shur ¹ and Asif Khan ²
¹ Rensselaer Polytechnic Institute, Troy, USA
http://nina.ecse.rpi.edu/shur/
² Department of EE, USC, SC 12110, USA

UV LED growth, Courtesy of SET, Inc.
Outline

• Nitride materials system
• Materials growth
• Device fabrication
• Nitride based electronics
• Nitride-based LEDs
• To explore further
AlInGaN Materials System

[Graph showing the relationship between Band Gap Energy (eV) and Lattice Constant (Å) for various materials including AlN, GaN, InN, sapphire (O sublattice), 6H-SiC, and ZnO.]

- AlN
- GaN
- InN
- Old value for InN
- sapphire (O sublattice)
- 6H-SiC
- ZnO

http://nina.ecse.rpi.edu/shur/
Nitride Advantages for Electronic Devices

**Properties**

- High mobility
- High saturation velocity
- High sheet carrier concentration
- High breakdown field

- Decent thermal conductivity
- Growth on SiC substrate
- Chemical inertness
- Good ohmic contacts
- No micropipes
- SiO$_2$/AlGaN and SiO$_2$/GaN good quality interfaces

**Advantages**

- High power
- Heat handling capability
- Reliability
- Insulated Gate

http://nina.ecse.rpi.edu/shur/
**Figure of Merit**
for high frequency/high power

\[
CFOM = \frac{\chi \varepsilon_0 \mu v_s E_B^2}{(\chi \varepsilon_0 \mu v_s E_B^2)_{\text{silicon}}}
\]

\(\chi\) is thermal conductivity

\(E_B\) is breakdown field

\(\mu\) is low field mobility

\(v_s\) is saturation velocity

\(\varepsilon_0\) is dielectric constant

\(\text{Si, GaAs, 6H-SiC, 4H-SiC, GaN}\)
Energy gaps of nitrides compared with spectral sensitivity of human eye

![Graph showing energy gaps of AlN, GaN, and InN compared to human eye response spectrum.](http://nina.ecse.rpi.edu/shur/)
Problems to Solve

- Aging
- Substrates
- Current slump
- Cost
- Yield
- Manufacturability
## Basic parameters of InN, GaN, and AlN at 300 K

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>GaN</th>
<th>AlN</th>
<th>InN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice constant, $c$</td>
<td>Å</td>
<td>5.186</td>
<td>4.982</td>
<td>5.693</td>
</tr>
<tr>
<td>Lattice constant, $a$</td>
<td>Å</td>
<td>3.189</td>
<td>3.112</td>
<td>3.533</td>
</tr>
<tr>
<td>Band gap energy, $E_g$</td>
<td>eV</td>
<td>3.339a</td>
<td>6.2</td>
<td>1.97</td>
</tr>
<tr>
<td>Effective electron mass, $m_e$</td>
<td>$m_0$</td>
<td>0.19b (∥)</td>
<td>0.33c (∥)</td>
<td>0.11b (∥)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.17b (⊥)</td>
<td>0.25c (⊥)</td>
<td>0.10b (⊥)</td>
</tr>
<tr>
<td>Effective heavy hole mass, $m_{hh}$</td>
<td>$m_0$</td>
<td>1.76c (∥)</td>
<td>3.53c (∥)</td>
<td>1.56b (∥)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.61c (⊥)</td>
<td>10.42c (⊥)</td>
<td>1.68b (⊥)</td>
</tr>
<tr>
<td>Effective light hole mass, $m_{lh}$</td>
<td>$m_0$</td>
<td>1.76c (∥)</td>
<td>3.53c (∥)</td>
<td>1.56b (∥)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.14c (⊥)</td>
<td>0.24c (⊥)</td>
<td>0.11b (⊥)</td>
</tr>
<tr>
<td>Piezoelectric constant, $e_{31}$</td>
<td>C/m²</td>
<td>-0.33</td>
<td>-0.48</td>
<td>-0.57</td>
</tr>
<tr>
<td>Piezoelectric constant, $e_{33}$</td>
<td>C/m²</td>
<td>0.65</td>
<td>1.55</td>
<td>0.97</td>
</tr>
<tr>
<td>Spontaneous polarization, $P_{∥}$</td>
<td>C/m²</td>
<td>-0.029</td>
<td>-0.081</td>
<td>-0.032</td>
</tr>
<tr>
<td>Radiative recombination coefficient</td>
<td>cm³/s</td>
<td>$4.7 \times 10^{-11}$</td>
<td>$1.8 \times 10^{-11}$</td>
<td>$5.2 \times 10^{-11}$</td>
</tr>
<tr>
<td>Refraction index at 555 nm</td>
<td></td>
<td>2.4</td>
<td>2.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Absorption coefficient at the photon energy $hν \approx E_g$</td>
<td>$10^5$ cm⁻¹</td>
<td>1</td>
<td>3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

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Nitrides: Hetero epitaxy and homoepitaxy

- Substrates
- MOCVD
- MBE
- PALE
- HVPE
- Strain energy band engineering
## Substrates for III-Nitride Epi

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Lattice constant (Angstroms)</th>
<th>Thermal Conductivity W/cm-K</th>
<th>Thermal expansion coefficient ($10^{-6}$ 1/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN</td>
<td>a = 3.189 c = 5.185</td>
<td>1.3</td>
<td>5.59 3.17</td>
</tr>
<tr>
<td>AlN</td>
<td>a = 3.112 c = 4.982</td>
<td>3.2</td>
<td>4.2 5.3</td>
</tr>
<tr>
<td>6H SiC</td>
<td>a = 3.08 c = 15.12</td>
<td>3.6 - 4.9</td>
<td>4.2 4.68</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>a = 3.073 c = 10.053</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Sapphire</td>
<td>a = 3.252 c = 5.213</td>
<td>0.5</td>
<td>7.5 8.5</td>
</tr>
<tr>
<td>Si</td>
<td>a = 5.4301</td>
<td>1.5</td>
<td>3.59</td>
</tr>
<tr>
<td>GaAs</td>
<td>a = 5.6533</td>
<td>0.5</td>
<td>6</td>
</tr>
</tbody>
</table>

LiGaO$_2$, ZnO
Substrate Comparison

- **Sapphire**: poor crystal structure match, large thermal expansion mismatch, poor thermal conductivity.
- **SiC** has high thermal conductivity and close lattice match in the c-plane.
  - But, also has: a different c-axis, relatively large thermal expansion mismatch and chemical mismatch at the interface.
- **GaN and AlN** bulk crystals have the same crystal structure, excellent chemical match, high thermal conductivity, and the same thermal expansion but are difficult to produce presently (will this change?).
- **LEO and HVPE GaN** films allow fabrication of “quasi-bulk” substrates. Temporary solution until bulk substrates become available?

From MRS Fall 2000 tutorial by M. S. Shur and L. J. Schowalter

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Bulk GaN and AlN substrates have become available!

- North Coast Crystals, Inc.: Commercial Scale Production of Bulk, Polycrystalline Group III Nitrides
- Sanders, bulk nitrides (ATP)
- High Pressure Research Center in Warsaw
- Bulk GaN and AlN at TDI, Inc.
- Sakai: Combining the ELO technology on MOVPE templates, thick GaN layers (up to 500µm) Samsung
- Sumimoto (GaN)
- Crystal IS (AlN)
- NCSU (AlN)
- Kansas State: sublimation (AlN)

When large area high quality AlN and GaN will become available? Which devices will emerge to take advantages of bulk substrates?
High 2DEG mobility for homoepitaxial GaN


> 60,000 cm²/V-s at low T
GaN-based HFETs on bulk GaN substrates

GaN-based HFETs on bulk AlN substrates


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LEO (Lateral Epitaxial Overgrowth) material

Defect free GaN

SiO₂ (for defect blocking)

Dislocated material

Dislocation density $10^9 - 10^{10}$ cm$^{-2}$ for regular material
$10^4 - 10^7$ for the LEO material
Nitrides, SiC, SiO$_2$

- Solid-state solutions and hetero-structures based on AlN/SiC/-InN/GaN have been demonstrated.
- GaN devices on SiC substrates demonstrated superior performance.
- GaN devices on Si have been demonstrated.
- SiO$_2$ forms excellent interface with AlGaN*

Epitaxial films

- **MOCVD**
  - Lateral Epitaxial Overgrowth
- **MBE**
- **Hydride VPE**
  
  Gallium transport by chloride formation
  
  \[ 2\text{HCl}(g) + 2\text{Ga}(l) \rightarrow 2\text{GaCl}(g) + \text{H}_2(g) \quad T = 800 \degree C \]

  Reaction with chloride formation
  
  \[ \text{GaCl}(g) + \text{NH}_3(g) \rightarrow \text{GaN}(s) + \text{HCl}(g) + \text{H}_2(g) \quad T = 700 \degree C \]
Nichia Two-Flow MOCVD Process for High Quality Epitaxial GaN

After Nakamura

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MOCVD

- N2
- H2
- PH3
- DETe/H2
- TMGa
- TMAI
- TMIn
- Cp2Mg

- Mass flow controller
- Pressure controller
- Bubbler bypass valve
- Run/Vent valve
- 3-way valve

MOCVD reactor

Process exhaust

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Molecular Beam Epitaxy

Electron Cyclotron Resonance Cracker

N₂

Magnets

RHEED screen

Pyrometer

Solid source

Pulsed Atomic Layer Epitaxy


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MOCVD AlN vs PALE AlN

Conventional MOCVD

PALE

J. P. Zhang, et.al, accepted for publication in Appl. Phys. Lett.
XRD study of MOCVD & PALE AlN

J. P. Zhang, et.al, accepted for publication in Appl. Phys. Lett,

http://nina.ecse.rpi.edu/shur/
STRAIN ENERGY BAND ENGINEERING QUATERNARY ALLOYS

- Independent control of band offset and Lattice Mismatch
- Quantification of bulk, piezo, spontaneous polarization doping contributions

<table>
<thead>
<tr>
<th>Al&lt;sub&gt;x&lt;/sub&gt;In&lt;sub&gt;y&lt;/sub&gt;Ga&lt;sub&gt;1-x-y&lt;/sub&gt;N</th>
<th>n-GaN</th>
<th>i-GaN</th>
<th>AlN</th>
<th>SiC</th>
</tr>
</thead>
</table>

$\Delta a/a \%$

$\Delta E_g = 0.25 \text{ eV}$
$\Delta E_g = 0.45 \text{ eV}$
$\Delta E_g = 0.86 \text{ eV}$

Al fraction, %
SIMS and X-ray

Electron microprobe analysis agrees with SIMS

X-ray (0006) peaks

(Al- alloy composition 12%)
PL and lattice constant

- Lattice mismatch and band-offset vs. In- composition

**ROOM TEMPERATURE PHOTOLUMINESCENCE**

- **Normalized PL Intensity**
- **Photon Energy (eV)**
- **In Molar Fraction (%)**
- **Δc (Angstroms)**
- **ΔE_g (eV)**

- For Al = 9% and Al = 12%

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SURFACE AND INTERFACE QUALITY

*RMS versus IN*

TEM

AFM

*(Al- alloy composition 12%)*
Fabrication
Typical Process Flow in GaN device fabrication

Epitaxial Wafer

Wafer Cleaning

Lithography

Mesa Etching

Metallization

Lithography

Mesa Etching

Metallization

Lithography

Dielectric Deposition

Annealing

Probe Contact Metallization

Multiple
Process Flow

Ultra-Sonic Rinse

Organic Cleaning
UNCLEANED SAMPLE

Acidic Cleaning
CLEANED SAMPLE

Pre-Baking
PR Coating
PhotoResist
Sample

Exposure

Post-Bake

Develop

http://nina.ecse.rpi.edu/shur/
Etching

Mesa Etching of GaN & Alloys

Di-electric Dry Etching

Etching

http://nina.ecse.rpi.edu/shur/
Metallization

Contact Metallization
Ti, Al, Ni, Au etc

Rapid Thermal Annealing
from 20 deg C to 1000 deg C in seconds

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Surface passivation

To dicing / packaging or on-wafer testing

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Ti/Al/Ti/Au Ohmic Contacts to n-AlInGaN


http://nina.ecse.rpi.edu/shur/
Pd/Au Ohmic Contacts to p-type GaN

• Pd (5 nm)/Au (10 nm) pads deposited with e-beam.
• This thickness results in nearly 70% transparency for visible wavelengths
• A 30 second RTA anneal at 400° C in an oxygen ambient
• Contact resistance $1 \times 10^{-4} \Omega \text{cm}^{-2}$ at 300 K
• $1.5 \times 10^{-6} \Omega \text{cm}^2$ (at 550 K).

After A. Lunev, Vinamra Chaturvedi, Ashay Chitnis, Grigory Simin, Jinwei Yang and M. Asif Khan

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GaN-based Schottky Barriers


Gallium Nitride Schottky Barrier Diode Operated to 500°C
( Furukawa Electric )
GaN-based p-n junctions


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GaN p-n junctions on SiC substrates

Pt contact
Al contact
p-type GaN
N-type GaN
Buffer layer
SiC substrate

GaN p-n junctions on LEO material

\[ P = 10^{18} \text{ cm}^{-3} \quad N = 5 \times 10^{16} \text{ cm}^{-3} \]

\[ S = 2 \times 20 \mu \text{m} \]

Reverse leakage current \( 9 \times 10^{-7} \text{ A/cm}^2 \) in the LEO GaN
Reverse leakage current \( 9 \times 10^{-4} \text{ A/cm}^2 \) in the non-LEO GaN

Band diagrams of FETs below threshold

Si

SiC

GaAs

GaN

http://nina.ecse.rpi.edu/shur/
Doped Channel GaN-based FET Operation at 750 °C

Device Applications

Reported state-of-art performance of III-N HFETs

- RF-power levels: 5...11 W/mm
- Peak drain current: 1...1.5 A/mm

Critical issues with III-N HFETs

- Gate leakage current: $10^{-3}$-$10^{-5}$ A/mm
- Current collapse (RF performance degradation)
- Long term stability and parameter drift
Current collapse in AlGaN/GaN HFETs: Pulsed measurements of “return current”


http://nina.ecse.rpi.edu/shur/
HFET, MOSHFET, and MISHFET

HFET
MOSHFET
MISHFET

Gate current, A

1x10^-16
1x10^-14
1x10^-12
1x10^-10
1x10^-8
1x10^-6
1x10^-4

Gate voltage, V

-14 -12 -10 -8 -6 -4 -2 0 2

Drain current, mA/mm

500
400
300
200
100
0

MOSHFET - SiO_2 (\varepsilon = 3.9, 100 \text{ A})
MISHFET - Si_3N_4 (\varepsilon = 7.5, 100 \text{ A})

X. Hu, A. Koudymov, G. Simin, J. Yang, M. Asif Khan, A. Tarakji, M. S. Shur and R. Gaska

http://nina.ecse.rpi.edu/shur/
Resolving the issues: 
AlGaInN, gate dielectrics, InGaN channel

Reducing the gate leakage current (10^4 - 10^6 times)

Reducing current collapse, 
Improving carrier confinement

Combining the advantages

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**AlInGaN/InGaN/GaN DHFET concept:**

**improved carrier confinement and strain management**

- Better 2DEG confinement
- Constant field in the QW region
- Strain compensation

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AlInGaN-InGaN-GaN
DHFET characteristics

SIMS profiles
AlGaN-InGaN-GaN DHFET: Carrier confinement and current collapse reduction

Pulsed transfer curves
Pulsed "return" currents

Pulsed drain current, A/mm
Gate pulse amplitude, V

Pout, dbm; Gain, dB

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Si₃N₄ /AlGaN/InGaN/GaN MISDHFET DC & RF characteristics

- Low Gate leakage current (as in MOS/MIS HFETs)
- No current collapse (as in DHFET)
- Stable DC and RF performance (7.5 W/mm)
Breakdown voltage and offset gate

MOSHFET Switch


http://nina.ecse.rpi.edu/shur/
Comparison with SiC and GaN Diodes


MG-MOSHFET point is from G. Simin, X. Hu, N. Ilinskaya, A. Kumar, A. Koudymov, J. Zhang, M. Asif Khan, R. Gaska and M. S. Shur, A 7.5 kW/mm² current switch using AlGaN/GaN Metal-Oxide-Semiconductor Heterostructure Field Effect Transistors on SiC Substrates (EL-2000).

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Power devices - applications and ratings


http://nina.ecse.rpi.edu/shur/
GaN Microwave Detector


http://nina.ecse.rpi.edu/shur/
Measured Detector Responsivity


http://nina.ecse.rpi.edu/shur/
Photonic Nitride Devices

• Solid State Lighting
• UV LEDs
Importance of Solid State Lighting

• 21% of electric energy use in lighting
• Half of this energy can be saved by switching to solid-state lighting
  Projected savings from solid-state lighting $115 billion by year 2020
• Solid-state lighting expected to reach lifetimes exceeding 100,000 hours
• LEDs are the most efficient sources of colored light in visible spectral range.
• White phosphor-conversion LEDs surpassed incandescent lamps in performance
Benefits of LED Lighting

An improvement of luminous efficiency by 1% may save 2 billions dollars per year.

LED Penetration(%)

Energy Savings 100TWh/yr

Cost Savings $10B/yr

Data from R. Haitz, F. Kish, J. Tsao, and J. Nelson

“Low Investment Model”

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Solid State Lighting Efficiency (lm/W)

Flickers
Cannot be dimmed
Losses in ballast
Noisy

http://nina.ecse.rpi.edu/shur/
Cool LED Light – saving cooling costs

Light and heat percentages for lighting sources
Schematic of band gap alignment in AlInGaN LEDs.

(a) DH-based structure with two wide-band-gap cladding layers; radiative transitions occur between donor-acceptor pairs (after S.Nakamura et al., J. Appl. Phys. 76, 8189, 1994);
(b) SQW structure with asymmetric confining layers; radiative transitions occur between quantum-confined levels of electrons and holes (after S.Nakamura et al., Jpn. J. Appl. Phys. 34, L1332, 1995)
Nitrides for Blue, White and UV emitters
A Note on Carborundum.

To the Editors of Electrical World:

Sirs,—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

New York, N. Y.

H. J. Round.
Emissive and Electrical Characteristics


http://nina.ecse.rpi.edu/shur/
Current-voltage characteristics of AlGaAs, AlGaInP, and AlInGaN-based high brightness LEDs


http://nina.ecse.rpi.edu/shur/
Chip structure of AlInGaN/Al₂O₃ LED

AlInGaN/SiC LED

Au Top Electrode

p-GaN Contact Layer

InGaN/AlGaN DH

n-GaN Contact Layer

Shorting Ring

Insulating Buffer Layer

n-SiC Transparent Substrate

Ni Back Electrode


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High power AlInGaN Flip-Chip LED


http://nina.ecse.rpi.edu/shur/
Shaped Chips: semi-spherical

http://nina.ecse.rpi.edu/shur/
Light Extraction: TIP-LEDs from LumiLeDs


http://nina.ecse.rpi.edu/shur/
WHITE SOLID-STATE LAMP
## CRI for White Light

\[
K = 683 \text{ lm/W} \times \frac{\int_{380}^{780} V(\lambda)S(\lambda)d\lambda}{\int_{0}^{\infty} S(\lambda)d\lambda},
\]

<table>
<thead>
<tr>
<th>Spectral Range</th>
<th>Temperature (K)</th>
<th>Efficacy (lm/W)</th>
<th>General CRI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full (Planckian)</strong></td>
<td>2856</td>
<td>17</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>4870</td>
<td>79</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>6504</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td><strong>380 nm-780 nm (trimmed-Planckian)</strong></td>
<td>2856</td>
<td>154</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>4870</td>
<td>196</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>6504</td>
<td>193</td>
<td>100</td>
</tr>
<tr>
<td><strong>430 nm-660 nm (trimmed-Planckian)</strong></td>
<td>2856</td>
<td>334</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>4870</td>
<td>320</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>6504</td>
<td>305</td>
<td>95</td>
</tr>
</tbody>
</table>

Optimization of White Polychromatic Semiconductor Lamp

Approach: Find the global maxima of the objective function for different values of $\sigma$.

$$F_\sigma(\lambda_1, \ldots, \lambda_n, I_1, \ldots, I_n) = \sigma K + (1 - \sigma) R_a$$


http://nina.ecse.rpi.edu/shur/
Phase distribution for a dichromatic white lamp with the 30-nm line width of the primary sources and 4870 K color temperature

(after Žukauskas et al., Appl. Phys. Lett. 80, 2002).
Optimal boundaries of the phase distribution for 4870-K white-light sources containing 2, 3, 4, and 5 primary sources with the 30-nm line widths

(after Žukauskas et al., Appl. Phys. Lett. 80, 2002). Crosses mark the points that are suggested for highest reasonable CRI for each number of the primary sources.
InGaN based luminescence conversion white LED

Phosphor layer

InGaN chip

White light from blue emission of AlInGaN LED (465 nm) and yellow emission of cerium-doped garnet with different peak wavelength positions

## MULTICHIP LED: 2 chip LEDs

<table>
<thead>
<tr>
<th>Color Temperature (K)</th>
<th>Wavelength (nm)/Intensity</th>
<th>$K$ (lm/W)</th>
<th>$R_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda_1/I_1$</td>
<td>$\lambda_2/I_2$</td>
<td></td>
</tr>
<tr>
<td>2856</td>
<td>450/0.157</td>
<td>580/0.843</td>
<td>492</td>
</tr>
<tr>
<td>4870</td>
<td>450/0.325</td>
<td>572/0.675</td>
<td>430</td>
</tr>
<tr>
<td>6504</td>
<td>450/0.399</td>
<td>569/0.601</td>
<td>393</td>
</tr>
</tbody>
</table>

Optimized spectral power distributions

http://nina.ecse.rpi.edu/shur/
Variation of the peak wavelength with general CRI for solid-state lamps composed of 2, 3, 4, and 5 primary LEDs with the 30-nm line widths

(after A. Žukauskas et al., Proc. SPIE 4425, 2001)
# Nichia UV LEDs

<table>
<thead>
<tr>
<th>Type (mm)</th>
<th>Product Number</th>
<th>Peak Wavelength (nm)</th>
<th>Optical Power Output (µW)</th>
<th>Forward Voltage Vf (V) Typ.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ5</td>
<td>NSHU550</td>
<td>375</td>
<td>700</td>
<td>3.5</td>
</tr>
<tr>
<td>Φ5</td>
<td>NSHU590</td>
<td>375</td>
<td>700</td>
<td>3.5</td>
</tr>
</tbody>
</table>

After [http://www.nichia.co.jp/product/led.html](http://www.nichia.co.jp/product/led.html)
### Nichia White LEDs

<table>
<thead>
<tr>
<th>Type (mm)</th>
<th>Product Number</th>
<th>Luminous Intensity (cd)</th>
<th>Forward Voltage (Vf)</th>
<th>Directivity (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ3</td>
<td>NSPW300BS</td>
<td>3.2</td>
<td>3.6</td>
<td>25°</td>
</tr>
<tr>
<td>Φ3</td>
<td>NSPW310BS</td>
<td>1.5</td>
<td>3.6</td>
<td>60°</td>
</tr>
<tr>
<td>Φ3</td>
<td>NSPW312BS</td>
<td>2.2</td>
<td>3.6</td>
<td>35°</td>
</tr>
<tr>
<td>Φ3</td>
<td>NSPW315BS</td>
<td>0.78</td>
<td>3.6</td>
<td>70°</td>
</tr>
<tr>
<td>Φ5</td>
<td>NSPW500BS</td>
<td>6.4</td>
<td>3.6</td>
<td>20°</td>
</tr>
<tr>
<td>Φ5</td>
<td>NSPW510BS</td>
<td>1.8</td>
<td>3.6</td>
<td>50°</td>
</tr>
<tr>
<td>Φ5</td>
<td>NSPW515BS</td>
<td>0.48</td>
<td>3.6</td>
<td>70°</td>
</tr>
<tr>
<td>4.6</td>
<td>NSPW5F50BS</td>
<td>0.3</td>
<td>3.6</td>
<td>140/120°</td>
</tr>
</tbody>
</table>
# Nichia Blue LEDs

<table>
<thead>
<tr>
<th>Product Number</th>
<th>Luminous Intensity (cd)</th>
<th>Forward Voltage Vf (V)</th>
<th>Directivity $2\theta \frac{1}{2}$ (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSPB300A</td>
<td>2.3</td>
<td>3.6</td>
<td>4 15°</td>
</tr>
<tr>
<td>NSPB310A</td>
<td>1.2</td>
<td>3.6</td>
<td>4 30°</td>
</tr>
<tr>
<td>NSPB320BS</td>
<td>0.7</td>
<td>3.6</td>
<td>4 45°</td>
</tr>
<tr>
<td>NSPB500S</td>
<td>3.5</td>
<td>3.6</td>
<td>4 15°</td>
</tr>
<tr>
<td>NSPB510S</td>
<td>1.5</td>
<td>3.6</td>
<td>4 30°</td>
</tr>
<tr>
<td>NSPB520S</td>
<td>0.8</td>
<td>3.6</td>
<td>4 45°</td>
</tr>
<tr>
<td>NSPB636AS</td>
<td>0.55</td>
<td>3.6</td>
<td>4 70°/30</td>
</tr>
</tbody>
</table>
Applications (for 250 nm – 340 nm)
Sensing and beyond

- Environmental protection
- Homeland security
- Biology
- Medicine
- Medical sterilization
- Bio-agent detection
- Water and air purification
- Solid-state white lighting
- Short-range secure communications
- Dense data storage
- Ballistic missile defense
- To be emerged

UV-LED Based Fluorimeter with Integrated Lock-in Amplifier (after Prof. Zukauskas, U of V, Lithuania)

Applications of U of V/RPI/SET quadrichromatic Versatile Solid-State Lamp: Phototherapy of seasonal affective disorder at Psychiatric Clinic of Vilnius University

http://nina.ecse.rpi.edu/shur/
Existing and proposed UV LED based bio detection systems

UV-LED Based Fluorimeter with Integrated Lock-in Amplifier (after Prof. Zukauskas, U of V, Lithuania)

Anthrax Bacteria

From Introduction to Biological Agent Detection Equipment for Emergency First Responders, U.S. Department of Justice Office of Justice Programs National Institute of Justice.

http://nina.ecse.rpi.edu/shur/
Medical Applications: Example

• Seasonal affective disorder affects many people (up to 10%) in the northern latitudes

• Bright white light is known to treat SAD

• The exact mechanism of treatment is not known

• Optimization of Spectral Power Distribution might help treatment

Applications of U of V/RPI/SET quadrichromatic Versatile Solid-State Lamp: Phototherapy of seasonal affective disorder at Psychiatric Clinic of Vilnius University
Multiple Quantum Well (50% Al Molar Fraction) Photoluminescence on SiC and Bulk AlN

ArF excimer laser (pulse duration 8 ns) emitting at 193 nm (6.42 eV) was used for the generation of carriers above the band gap of AlN (6.2 eV) so that both the wells and the barriers have been photoexcited. The structures were also excited selectively by 4-ns-long pulses of the fifth harmonic of Nd:YAG laser radiation at 213 nm (5.82 eV), which generates carriers only in the quantum well material.

PL signal from MQWs on bulk AlN is approximately 28 times stronger compared to the structure grown over SiC.

Photoluminescence spectra of Al0.5Ga0.5N/AlN MQWs deposited on bulk AlN. Solid curve represents the spectrum of spontaneous emission detected in the direction perpendicular to the sample surface; dotted and dashed curves correspond to the spectra measured from the sample edge along the direction of a 30 \( \mu \text{m} \) wide stripe, which length was 400 \( \mu \text{m} \) and 440 \( \mu \text{m} \), respectively. The excitation wavelength was 213 nm.


http://nina.ecse.rpi.edu/shur/
AlInGaN-based UV LEDs on Sapphire Substrates


http://nina.ecse.rpi.edu/shur/
AlInGaN-based UV LEDs on Sapphire Substrates

**Improve light extraction**

**Control current crowding**

![Graph showing output power vs wavelength for different LED structures and pump currents.](http://nina.ecse.rpi.edu/shur/)


http://nina.ecse.rpi.edu/shur/
10 mW 325 nm UV LED on Sapphire


http://nina.ecse.rpi.edu/shur/
Sub-milliwatt power 285 nm Emission UV LED on Sapphire.

- **Rs~70-80 Ω**

- **285.5 nm**

- **200 mA pulsed pumping 500 ns, 10 kHz**

- **RT pulse 500 ns, 0.5%**


http://nina.ecse.rpi.edu/shur/
285 nm Emission UV LED
Low temperature performance

285 nm Emission UV LED
Time resolved electroluminescence

70 mA current pulse
1000 ns, 20 kHz


http://nina.ecse.rpi.edu/shur/
Milliwatt power 278 nm UV LED on Sapphire. Modified design


http://nina.ecse.rpi.edu/shur/
Thermal and current crowding management

Square geometry  Inter-digitated fingers  LED arrays


http://nina.ecse.rpi.edu/shur/
278 nm / 325 nm LED comparison

278 nm Emitting LED
3 mW
1 A pulsed

325 nm Emitting LED
10 mW
1 A pulsed


http://nina.ecse.rpi.edu/shur/
SAW Oscillator/Photodetector

BASICS OF SURFACE ACOUSTIC WAVE DELAY-LINE OSCILLATOR

Velocity change

\[ \frac{\Delta f}{f} = \left( \frac{\Delta V}{V} \frac{L_{UV}}{L} \right) \]

Amplitude condition

Gain > Loss

Phase condition

\[ \frac{2\pi f L}{V} + \phi = 2m\pi \]
Response to Artificial Light Sources and Sunlight

SOME of LED WEB SITES

- http://www.misty.com/people/don/led.html
- http://ledmuseum.home.att.net/
- http://www.nichia.com/
- http://www.cree.com/
- http://www.s-et.com
- http://www.oida.org/
- http://safeco2.home.att.net/laser.htm
Conclusions

- Materials properties of wide band semiconductors are superior for applications in high power, high temperature electronics
- All device building blocks demonstrated
- Record breaking microwave power performance achieved
- Strain Energy Band Engineering - Strain and Band Offset Control using quaternary and ternary heterostructures augmented using SiO$_2$ and Si$_3$N$_4$ allow us to obtain superior HFET performance
- Nitrides hold promise of solid state lighting
- Nitride deep UV emitters and detectors have been demonstrated