GaN Technology

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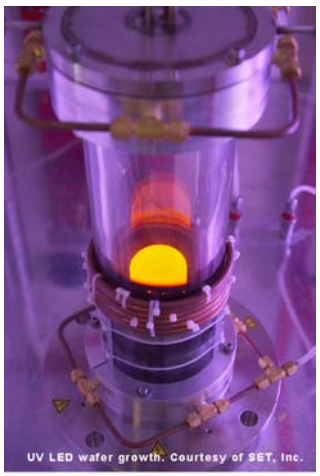
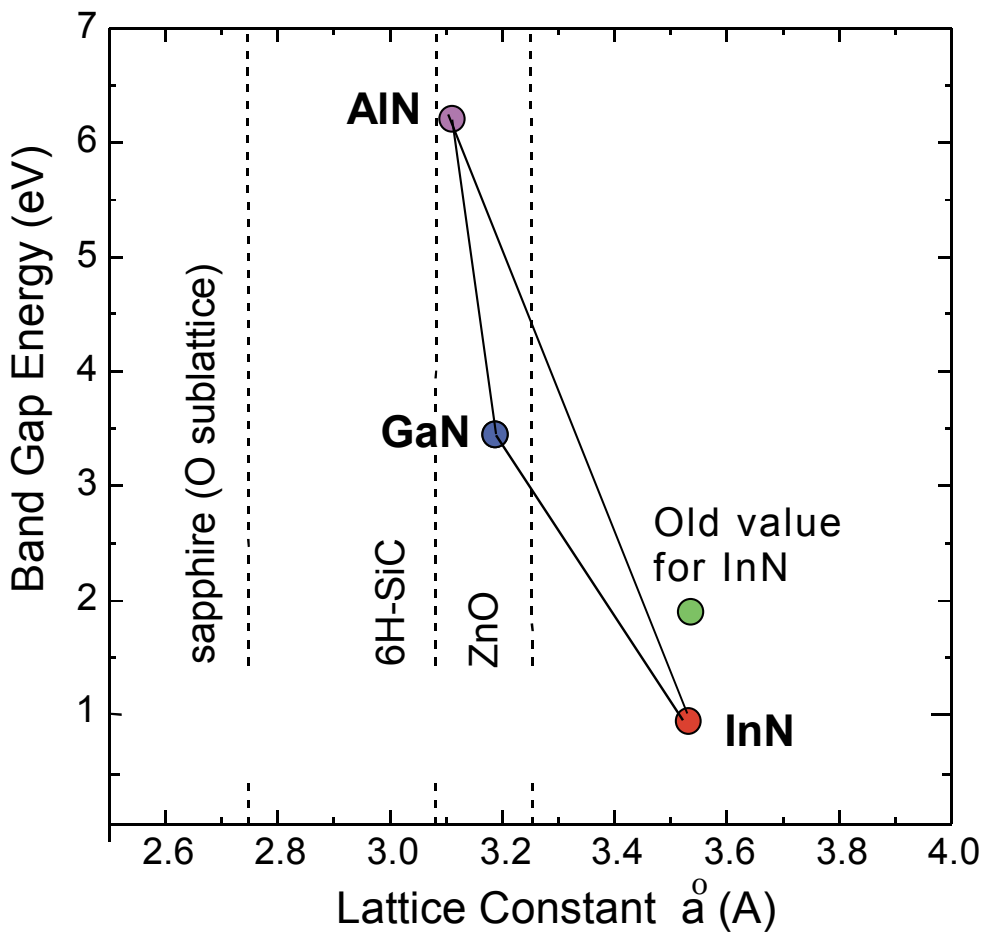


UV LED growth, Courtesy of SET, Inc.

Outline

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

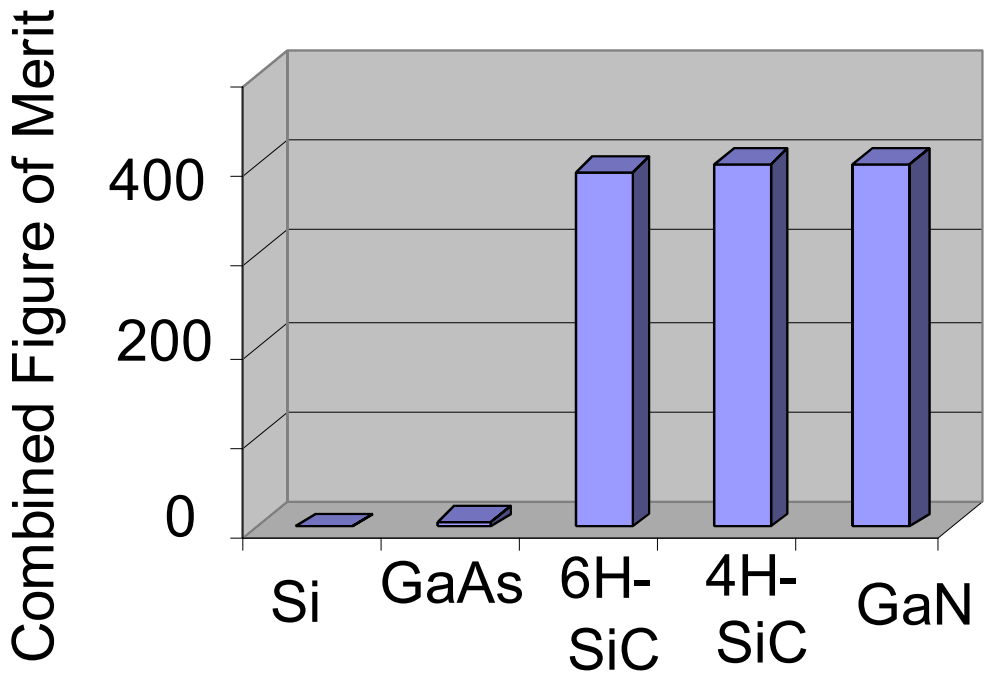
AlInGaN Materials System



Nitride Advantages for Electronic Devices

Properties		Advantages
•High mobility •High saturation velocity •High sheet carrier concentration •High breakdown field	→	**High power**
•Decent thermal conductivity •Growth on SiC substrate	→	**Heat handling capability**
•Chemical inertness •Good ohmic contacts •No micropipes	→	**Reliability**
•SiO_2/AlGaN and SiO_2/GaN good quality interfaces	→	**Insulated Gate**

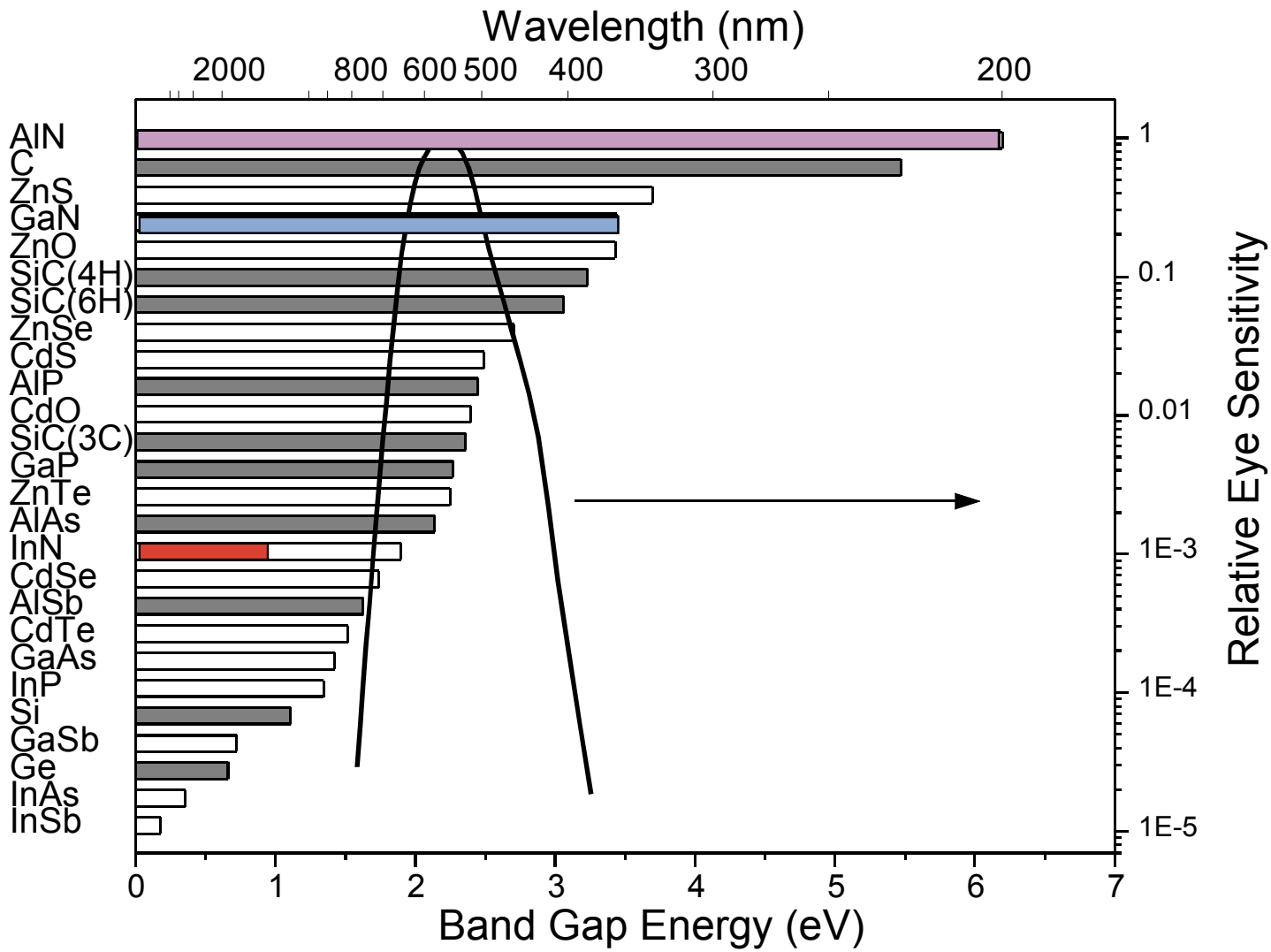
Figure of Merit for high frequency/high power



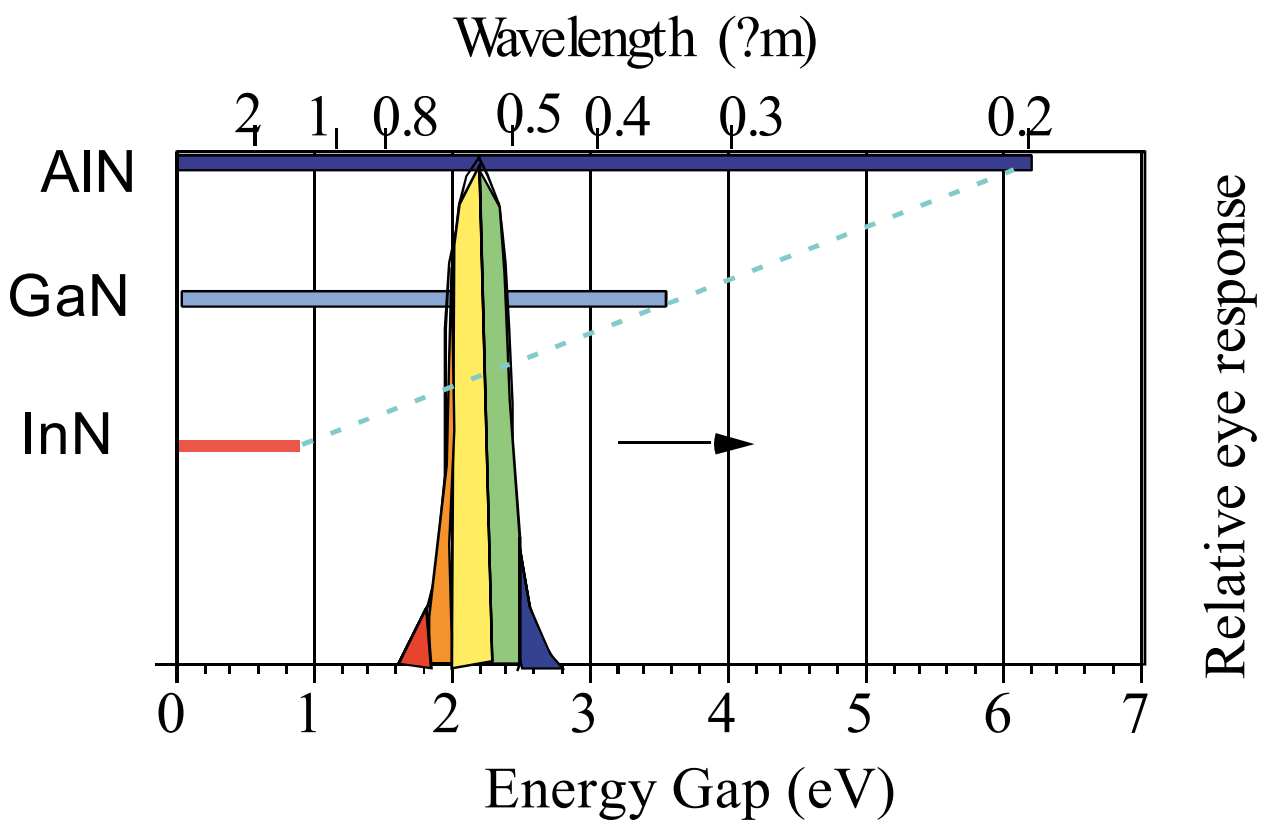
$$CFOM = \frac{\chi \varepsilon_o \mu v_s E_B^2}{\left(\chi \varepsilon_o \mu v_s E_B^2\right)_{silicon}}$$

χ is thermal conductivity
E_B is breakdown field
μ is low field mobility
v_s is saturation velocity
ε_o is dielectric constant

SEMICONDUCTOR MATERIALS SYSTEMS FOR LIGHT EMITTERS



Energy gaps of nitrides compared with spectral sensitivity of human eye



Problems to Solve

- Aging
- Substrates
- Current slump
- Cost
- Yield
- Manufacturability

Basic parameters of InN, GaN, and AlN at 300 K

Parameter	Units	GaN	AlN	InN
Lattice constant, c	Å	5.186	4.982	5.693
Lattice constant, a	Å	3.189	3.112	3.533
Band gap energy, E_g	eV	3.339[a]	6.2	1.97
Effective electron mass, m_e	m_0	0.19[b] (‖) 0.17[b] (⊥)	0.33[c] (‖) 0.25[c] (⊥)	0.11[b] (‖) 0.10[b] (⊥)
Effective heavy hole mass, m_{hh}	m_0	1.76[c] (‖) 1.61[c] (⊥)	3.53[c] (‖) 10.42[c] (⊥)	1.56[b] (‖) 1.68[b] (⊥)
Effective light hole mass, m_{lh}	m_0	1.76[c] (‖) 0.14[c] (⊥)	3.53[c] (‖) 0.24[c] (⊥)	1.56[b] (‖) 0.11[b] (⊥)
Piezoelectric constant, e_{31}	C/m^2	-0.33	-0.48	-0.57
Piezoelectric constant, e_{33}	C/m^2	0.65	1.55	0.97
Spontaneous polarization, $P_{\parallel}$[d]	C/m^2	-0.029	-0.081	-0.032
Radiative recombination coefficient[e]	cm^3/s	4.7×10^{-11}	1.8×10^{-11}	5.2×10^{-11}
Refraction index at 555 nm		2.4	2.1	2.8
Absorption coefficient at the photon energy $h\nu \approx E_g$	$10^5\ cm^{-1}$	1	3	0.4

From M. E. Levinshtein, S. L. Rumyantsev, and M. S. Shur, Editors, "Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN, and SiGe", John Wiley and Sons, ISBN 0-471-35827-4, New York (2001)

Nitrides: Hetero epitaxy and homoepitaxy

- Substrates
- MOCVD
- MBE
- PALE
- HVPE
- Strain energy band engineering

Substrates for III-Nitride Epi

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

$LiGaO_2$, 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?

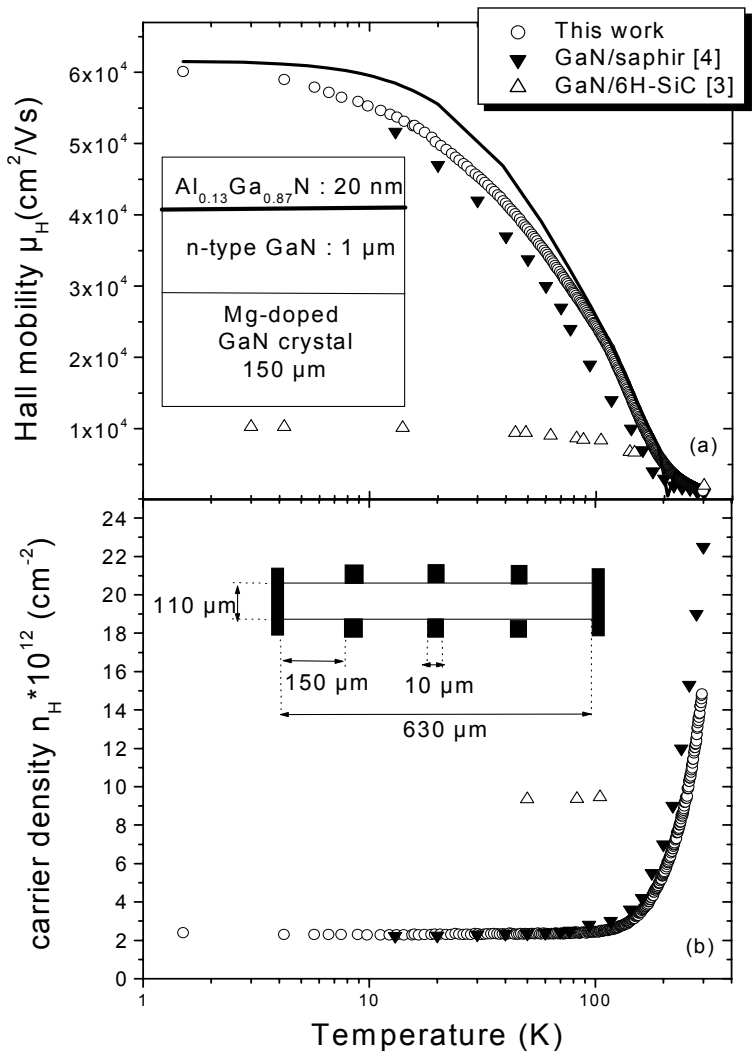
From MRS Fall 2000 tutorial by M. S. Shur and L. J. Schowalter

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?

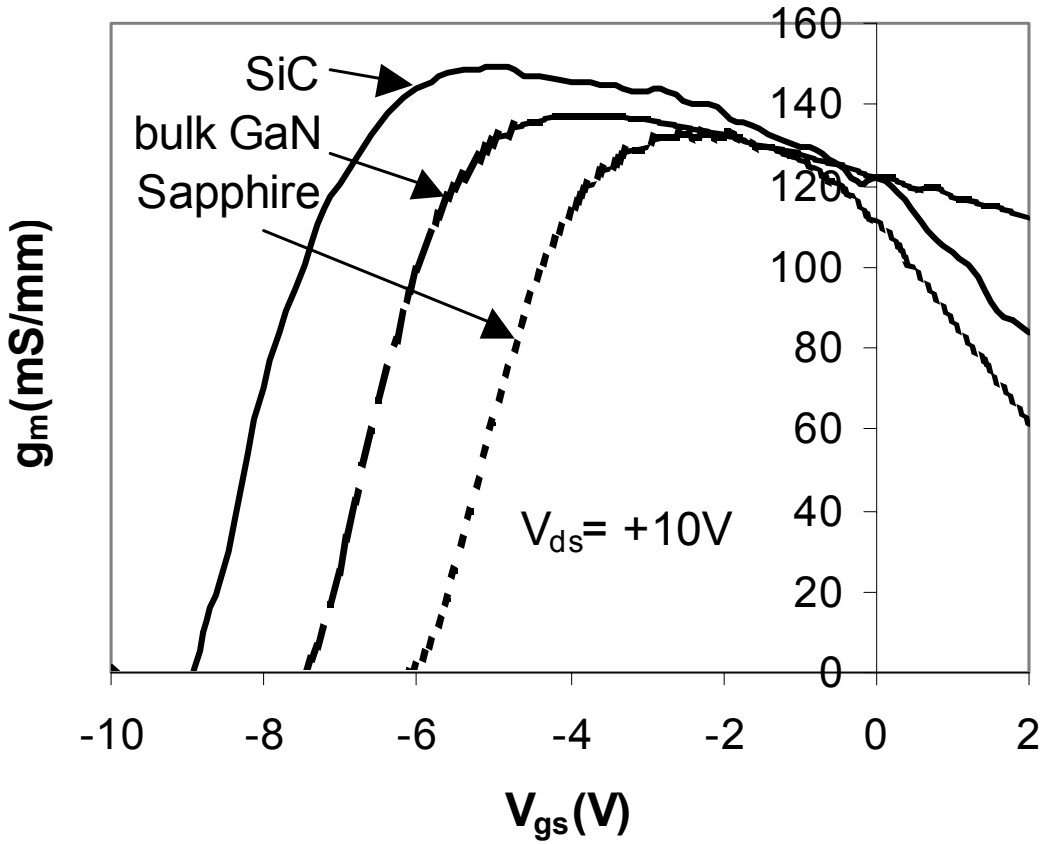
High 2DEG mobility for homoepitaxial GaN



E. Frayssinet, W. Knap, P. Lorenzini, N. Grandjean, J. Massies, C. Skierbiszewski, T. Suski, I. Grzegory, S. Porowski, G. Simin, X. Hu, M.Asif Khap, M. Shur, R. Gaska, and D. Maude, Applied Physics Letters, October 16, 2000; R. Gaska, J. W. Yang, A. Osinsky, Q. Chen,M. Asif Khan, A. O. Orlov, G. L. Snider, M. S. Shur, Appl. Phys. Lett., Feb. 1999

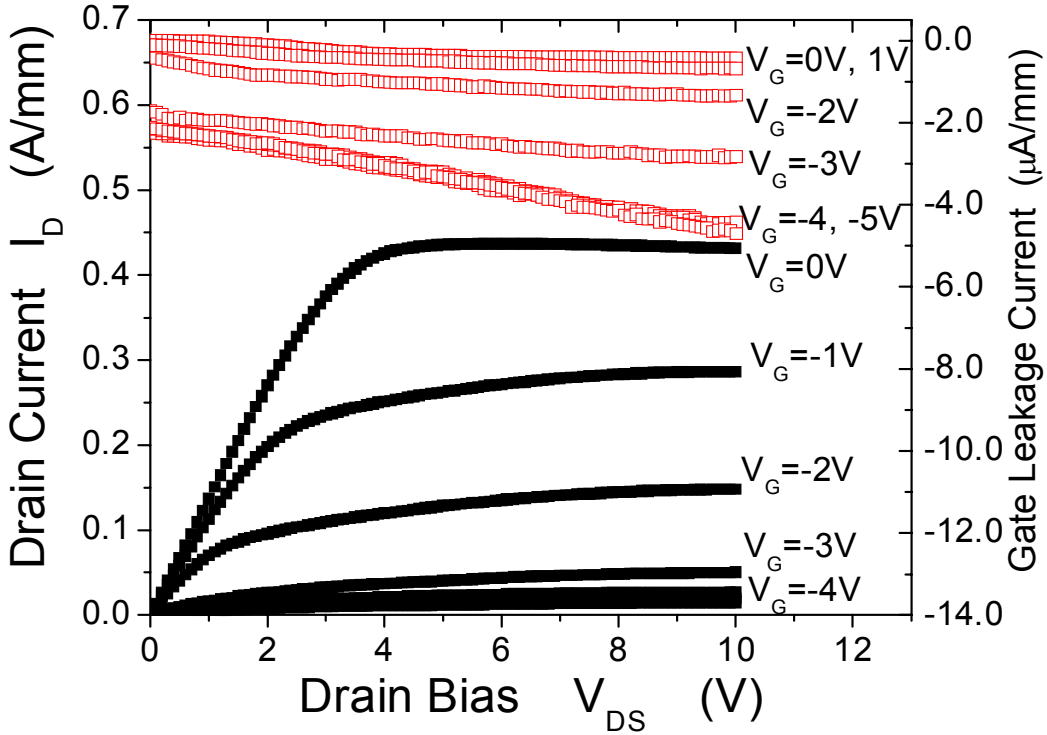
$>$ 60,000 cm^2/V-s at low T

GaN-based HFETs on bulk GaN substrates



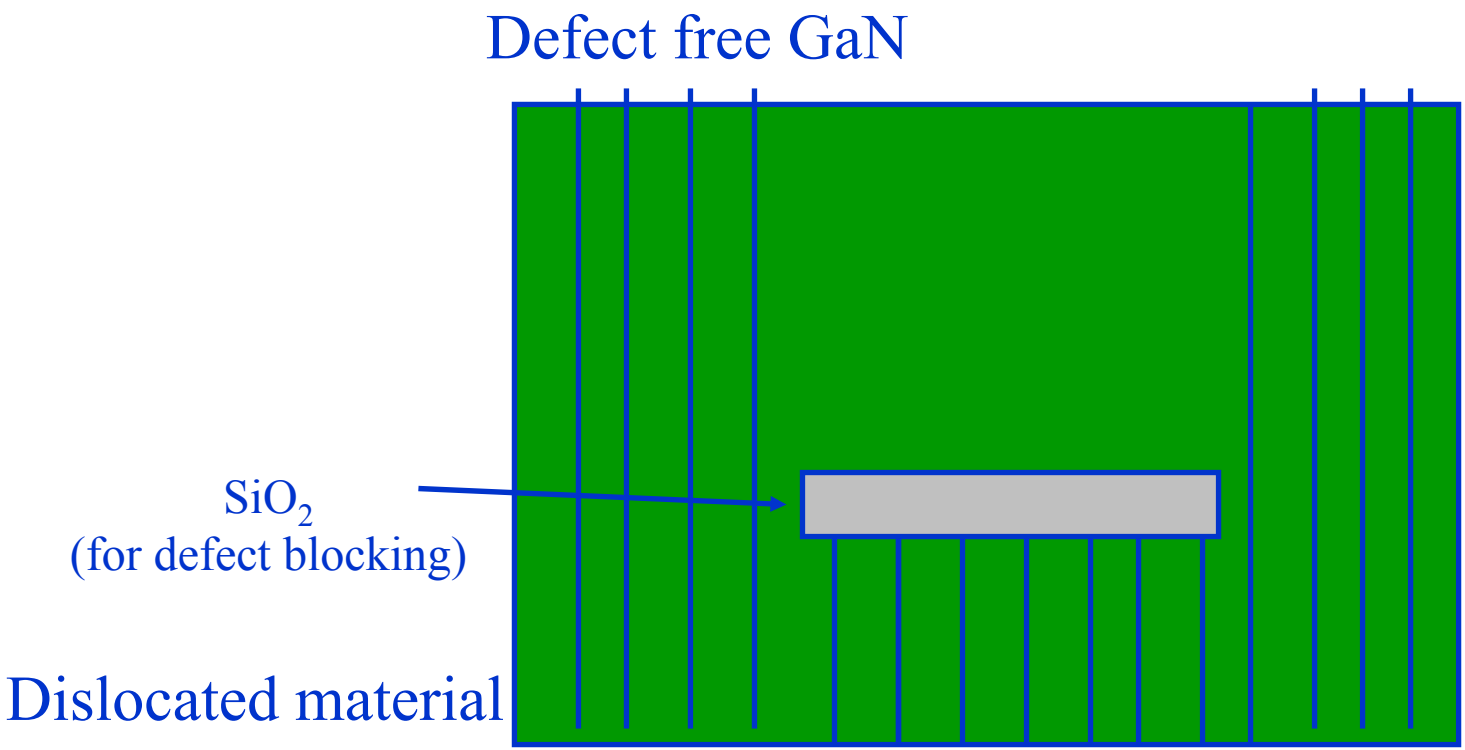
From M. Asif Khan and J. W. Yang, W. Knap, E. Frayssinet, X. Hu and G. Simin, P. Prystawko, M. Leszczynski, I. Grzegory, S. Porowski, R. Gaska, M. S. Shur, B. Beaumont, M. Teisseire, and G. Neu, GaN-AlGaN Heterostructure Field Effect Transistors Over Bulk GaN Substrates, Appl. Phys. Lett. 76, No. 25, pp. 3807, 3809, 19 June (2000)

GaN-based HFETs on bulk AlN substrates



X. Hu, J. Deng, N. Pala, R. Gaska, M. S. Shur, C. Q. Chen, J. Yang, S. Simin, and A. Khan, C. Rojo, L. Schowalter, AlGaN/GaN Heterostructure Field Effect Transistor on Single Crystal Bulk AlN, submitted to APL

LEO (Lateral Epitaxial Overgrowth) 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***

*M. A. Khan, X. Hu, G. Simin, A. Lunev, R. Gaska and M. S. Shur, Novel AlGaN/GaN Metal-Oxide-Semiconductor Field Effect Transistor, IEEE Electron Device Letters, vo. 21, No. 2, pp. 63-65, February, 2000

Epitaxial films

- MOCVD
  - Lateral Epitaxial Overgrowth
- MBE
- Hydride VPE

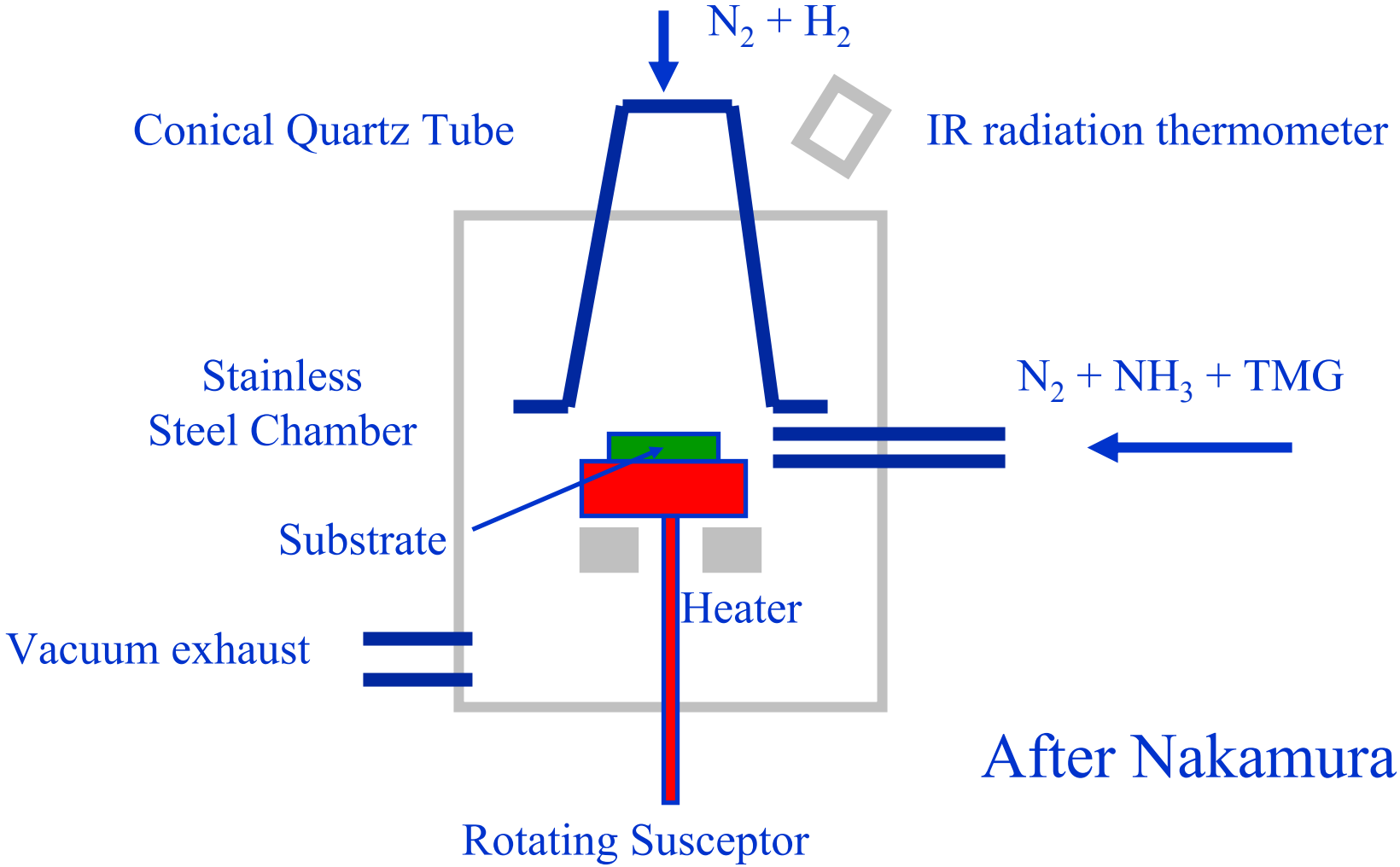
  Gallium transport by chloride formation

  $2HCl(g) + 2Ga(l) \rightarrow 2GaCl(g) + H_2(g)$ T = 800 °C

  Reaction with chloride formation

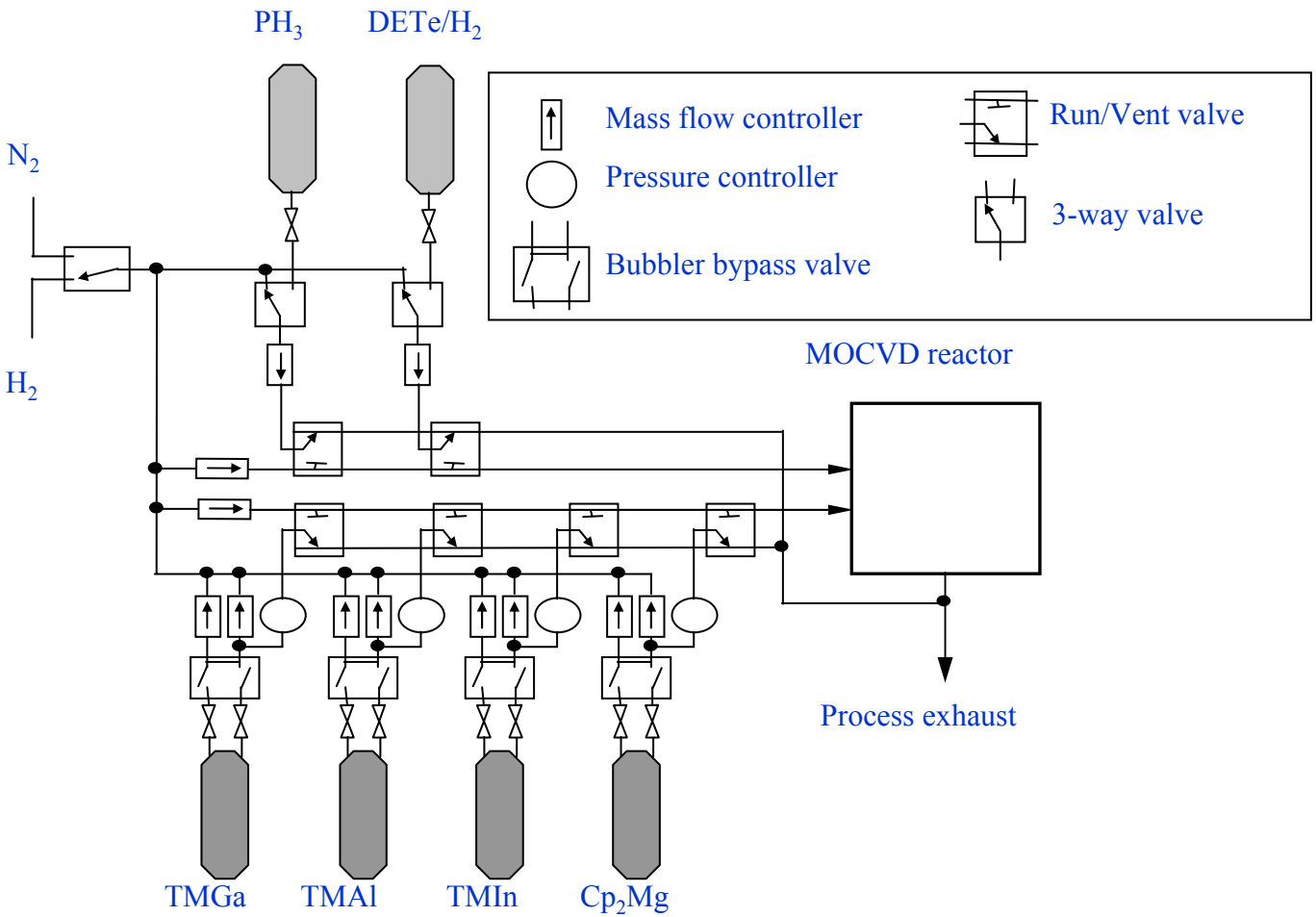
  $GaCl(g) + NH_3(g) \rightarrow GaN(s) + HCl(g) + H_2(g)$ T = 700 °C

Nichia Two-Flow MOCVD Process for High Quality Epitaxial GaN

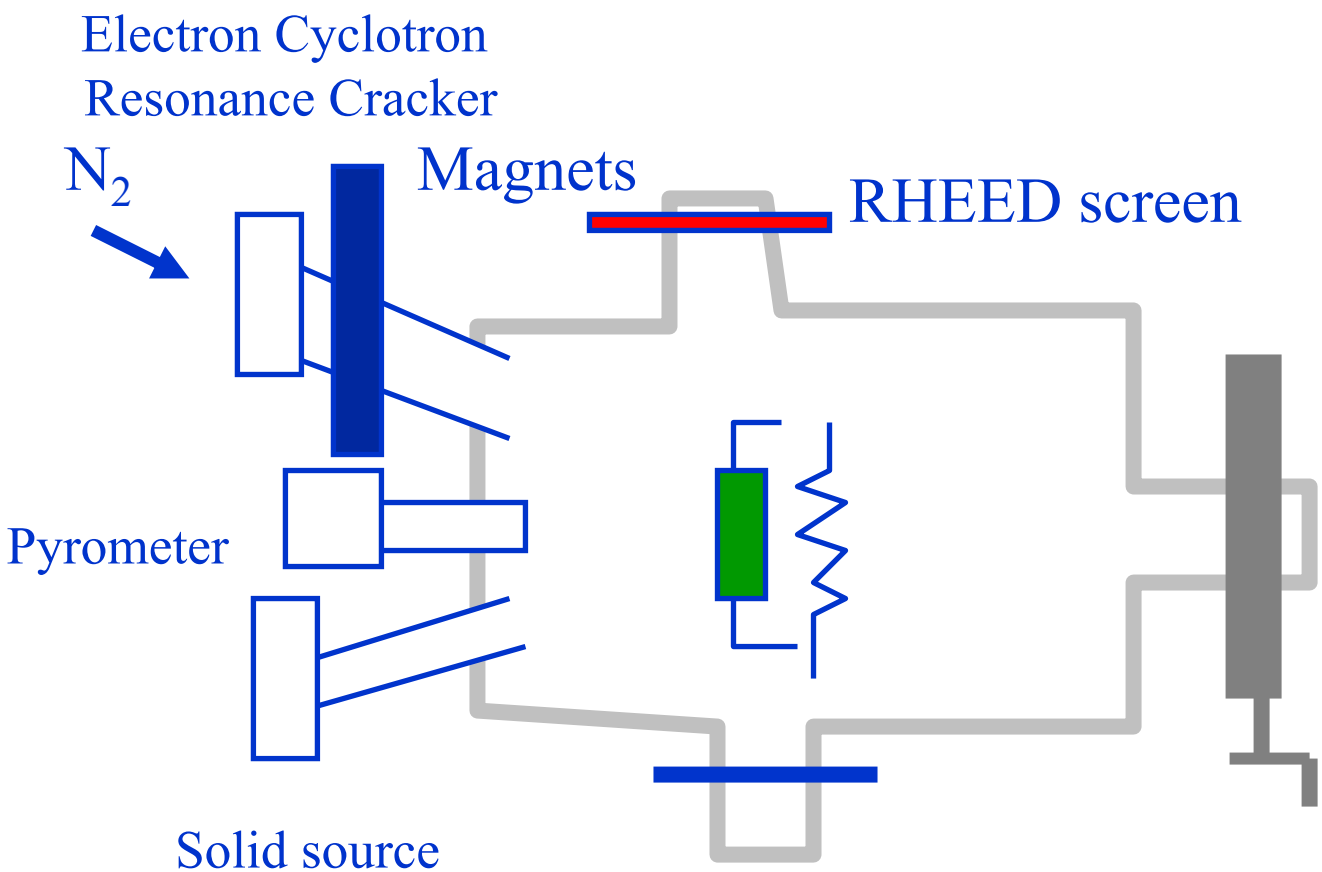


After Nakamura

MOCVD

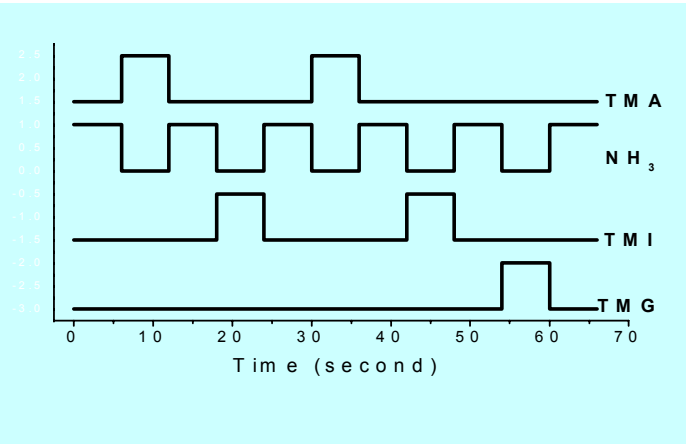

PH3
DETe/H2
N2
H2
Mass flow controller
Pressure controller
Bubbler bypass valve
Run/Vent valve
3-way valve
MOCVD reactor
Process exhaust
TMGa
TMAl
TMIn
Cp2Mg

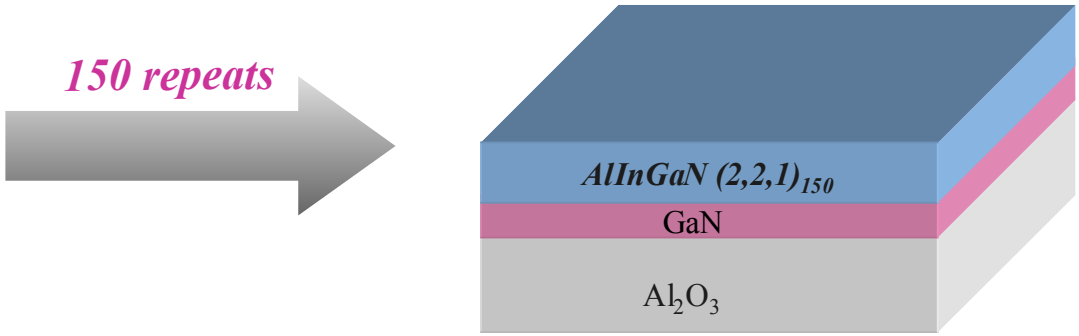
Molecular Beam Epitaxy



After Morkoc et al., J. Appl. Phys. 76 (3), p. 1363 (1991)

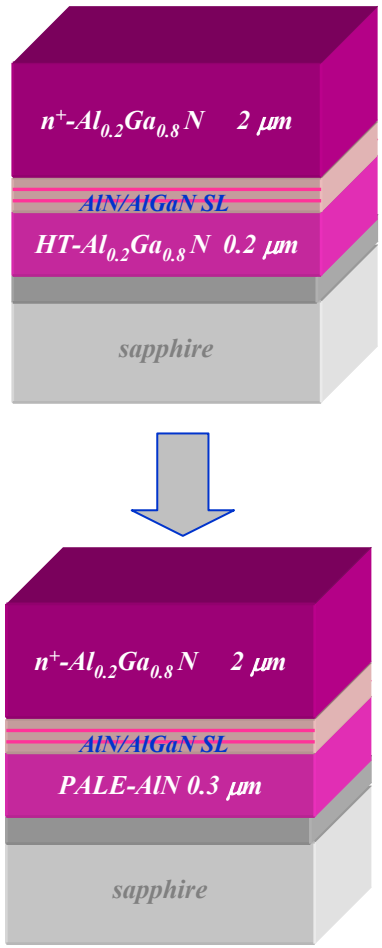
Pulsed Atomic Layer Epitaxy

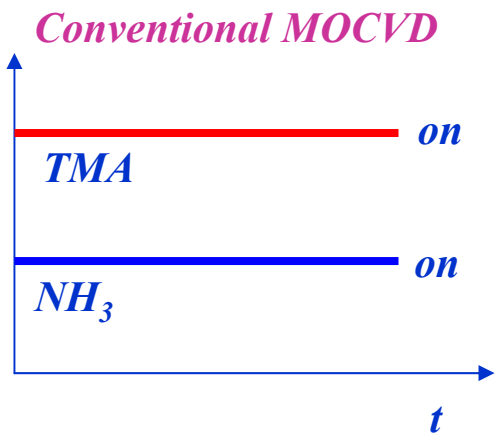


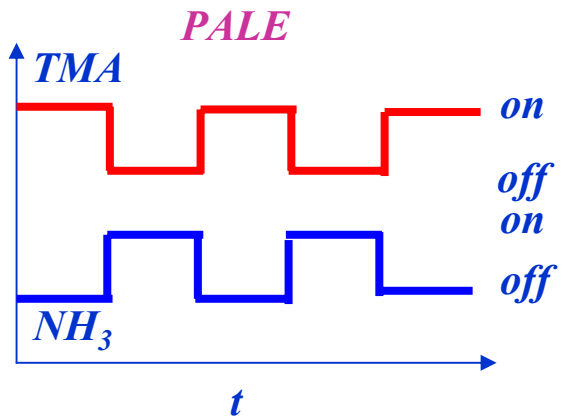


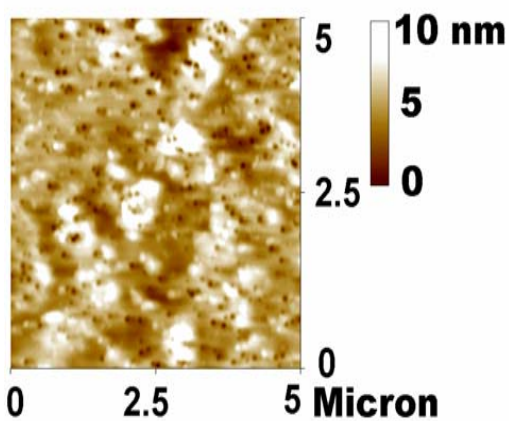
Khan et. al. "Lattice and Energy Band Engineering in AlInGaN/GaN Heterostructure " Appl. Phys. Lett ***76****, (2000) 1161.*
Zhang et. al. "Pulsed atomic Layer Epitaxy of Quaternary AlInGaN Layers" Appl. Phys. Lett. ***79****, (2001) 925.*

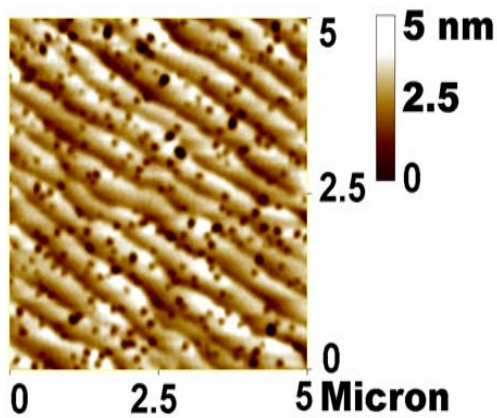
MOCVD AlN vs PALE AlN









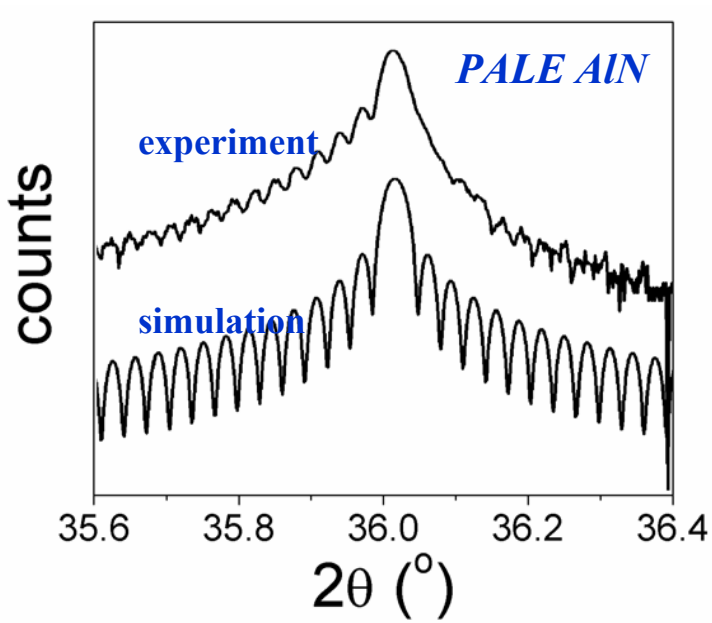


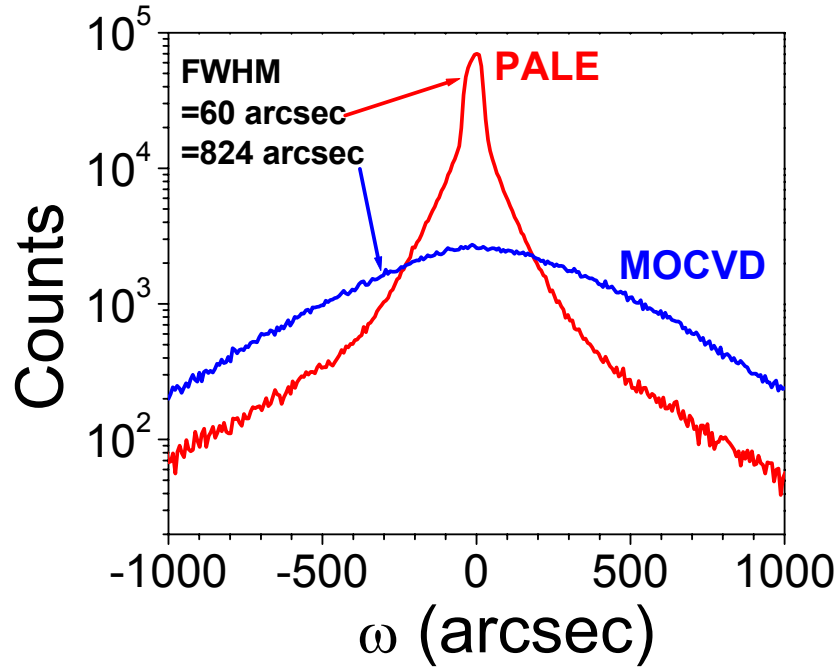
MOCVD AlN **PALE AlN**

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

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

XRD study of MOCVD & PALE AlN

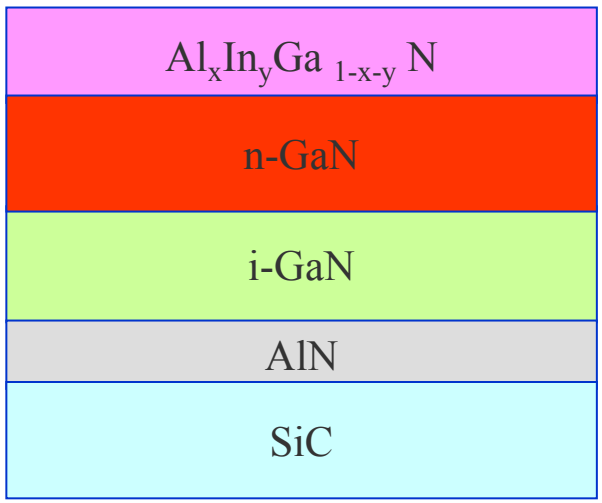


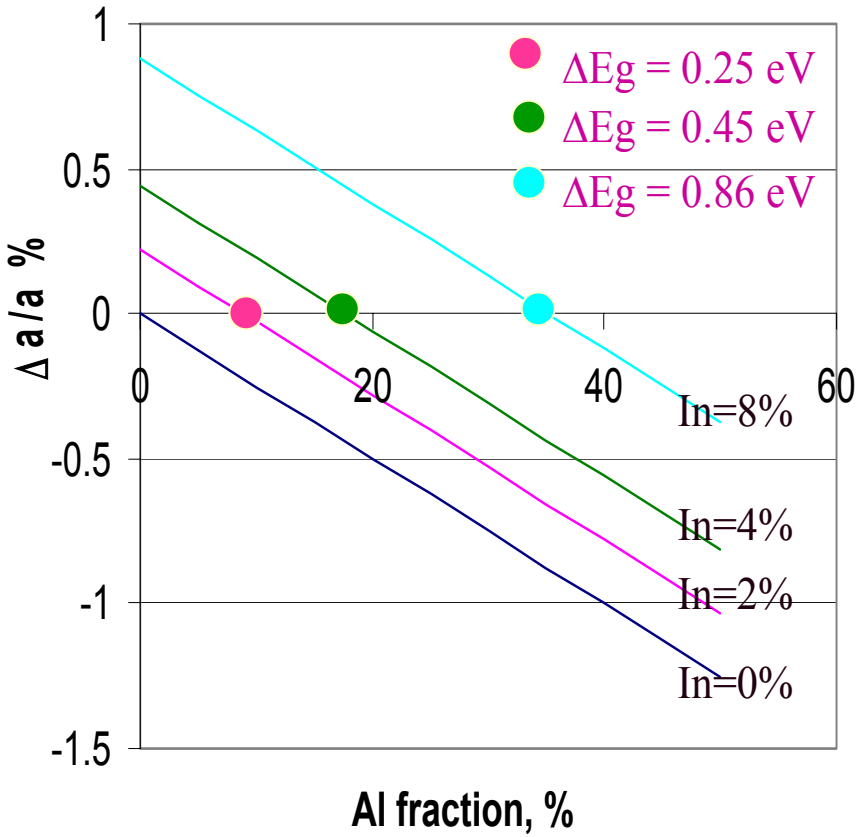


J. P. Zhang, et.al, accepted for publication in Appl. Phys. Lett,

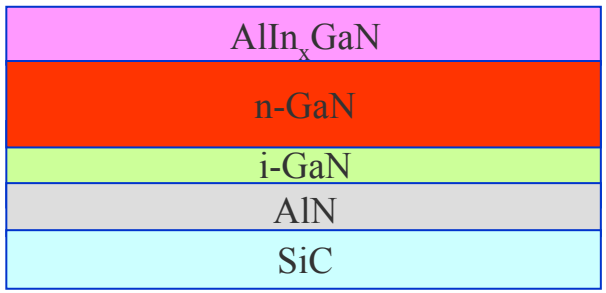
STRAIN ENERGY BAND ENGINEERING QUATERNARY ALLOYS

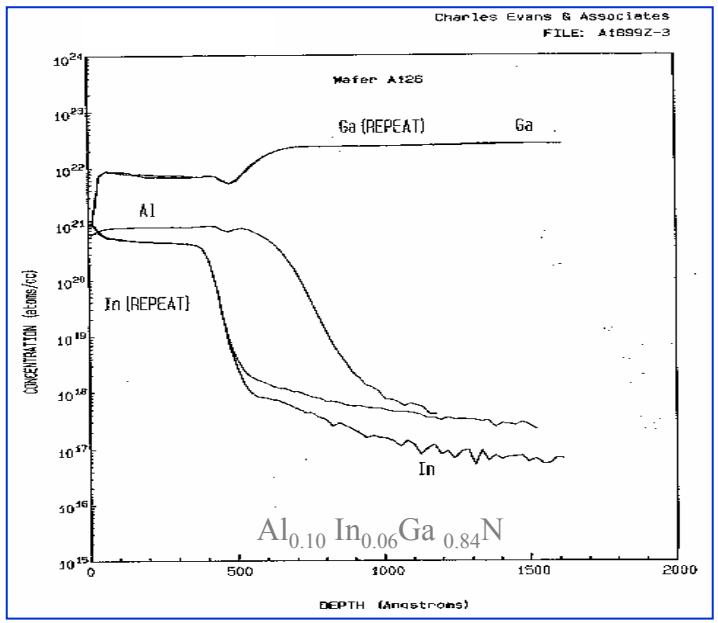
- Independent control of band- offset and Lattice Mismatch
- Quantification of bulk, piezo, spontaneous polarization doping contributions





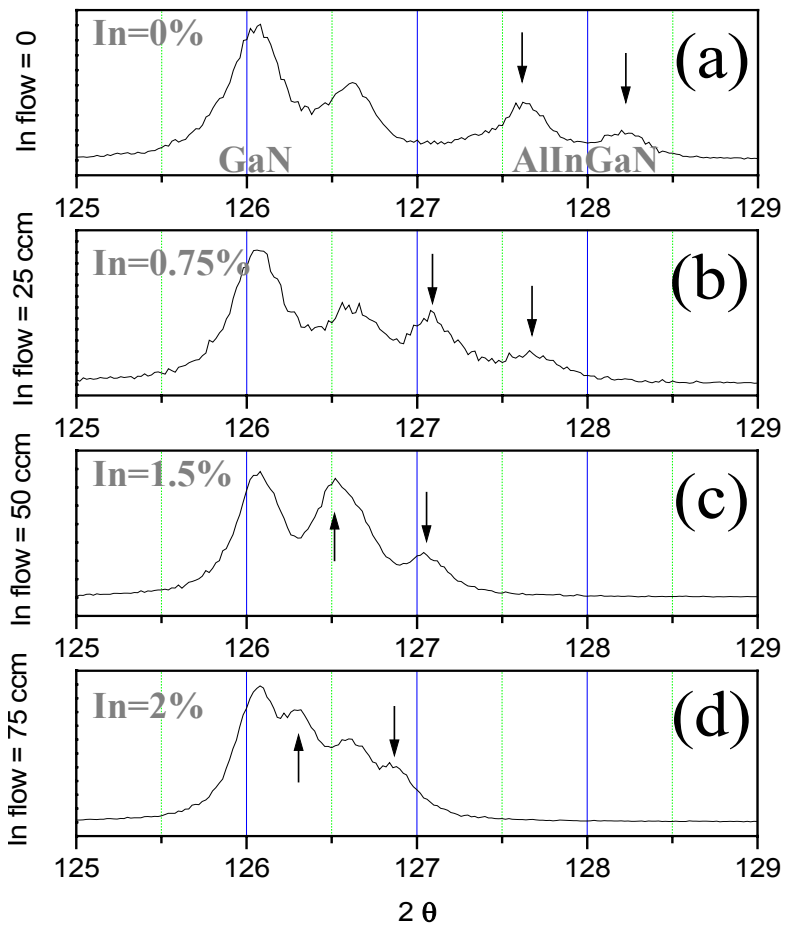
SIMS and X-ray





Electron microprobe analysis agrees with SIMS

(Al- alloy composition 12%)

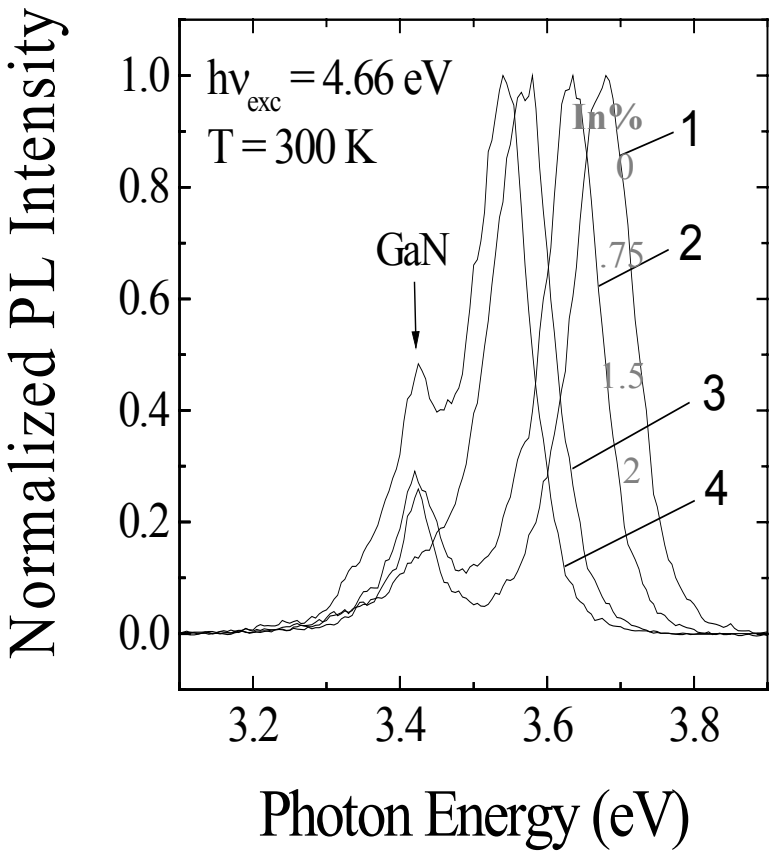


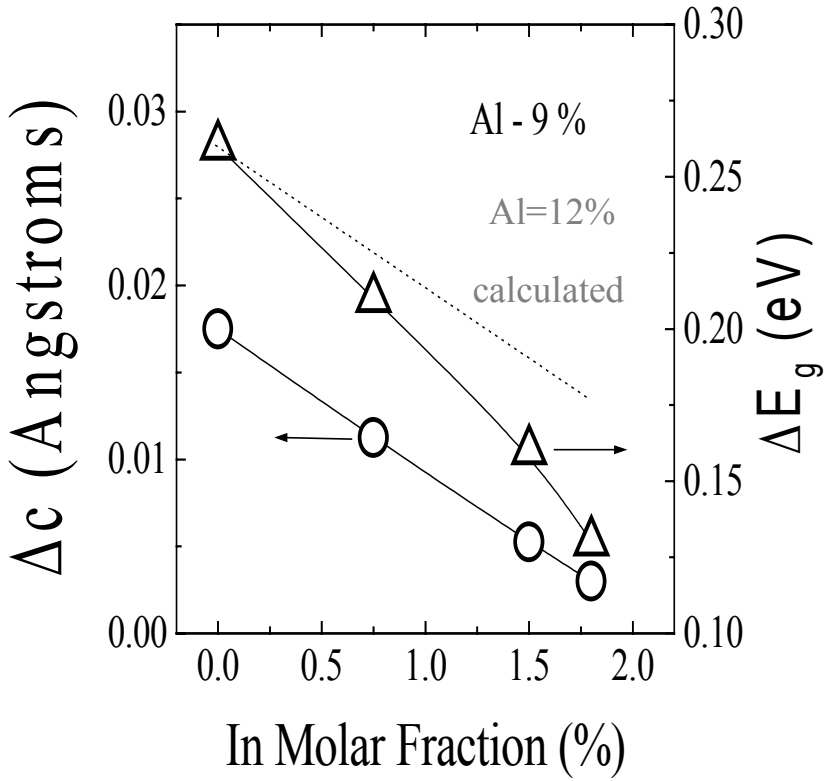
X-ray (0006) peaks

PL and lattice constant

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

ROOM TEMPERATURE PHOTOLUMINESCENCE

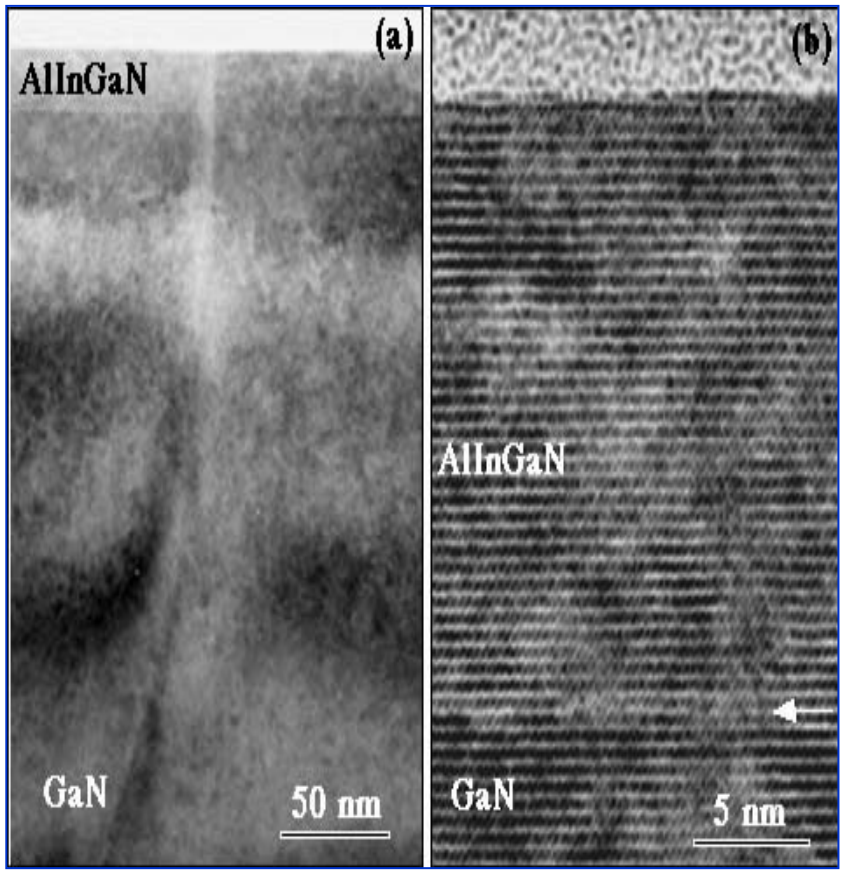




SURFACE AND INTERFACE QUALITY

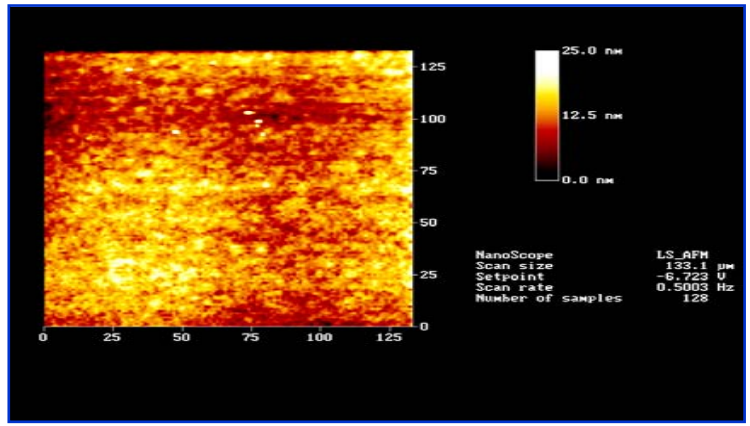
RMS versus IN

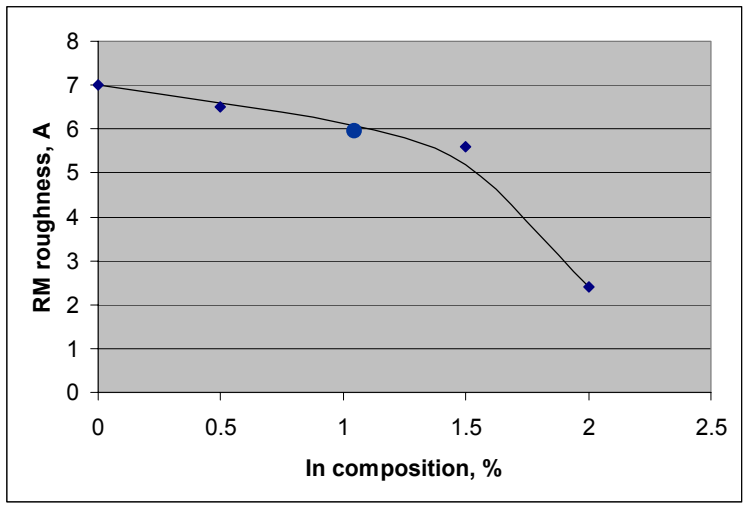
TEM



(Al- alloy composition 12%)

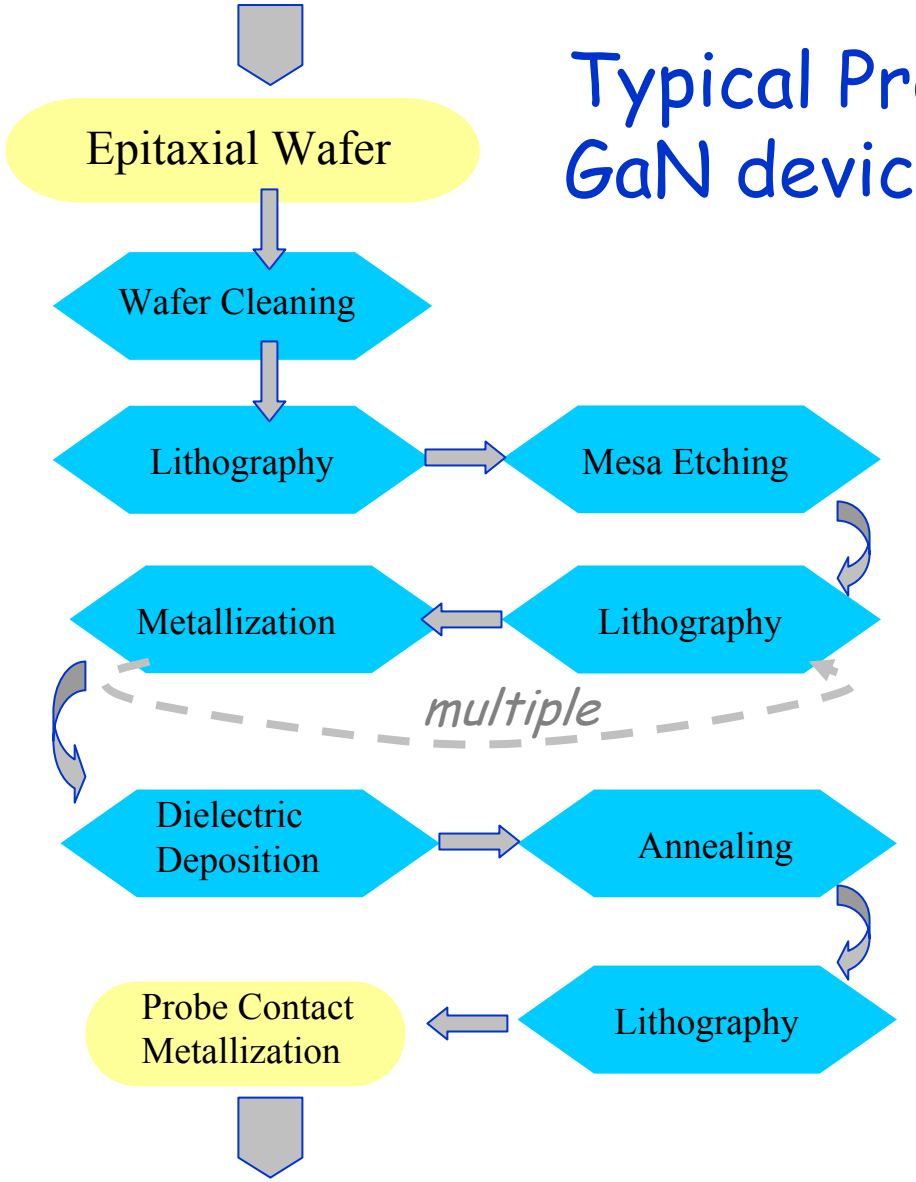
AFM



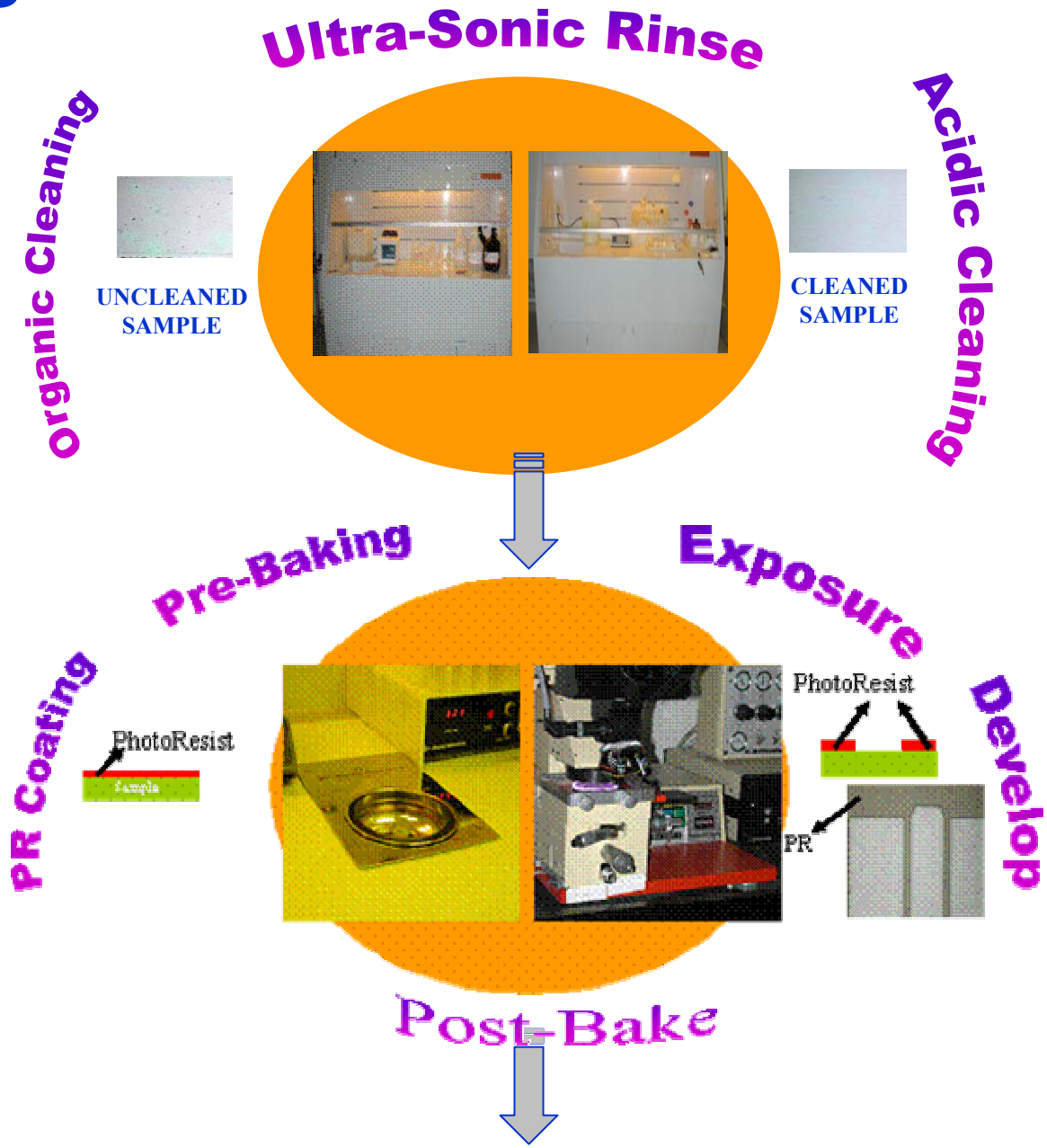


Fabrication

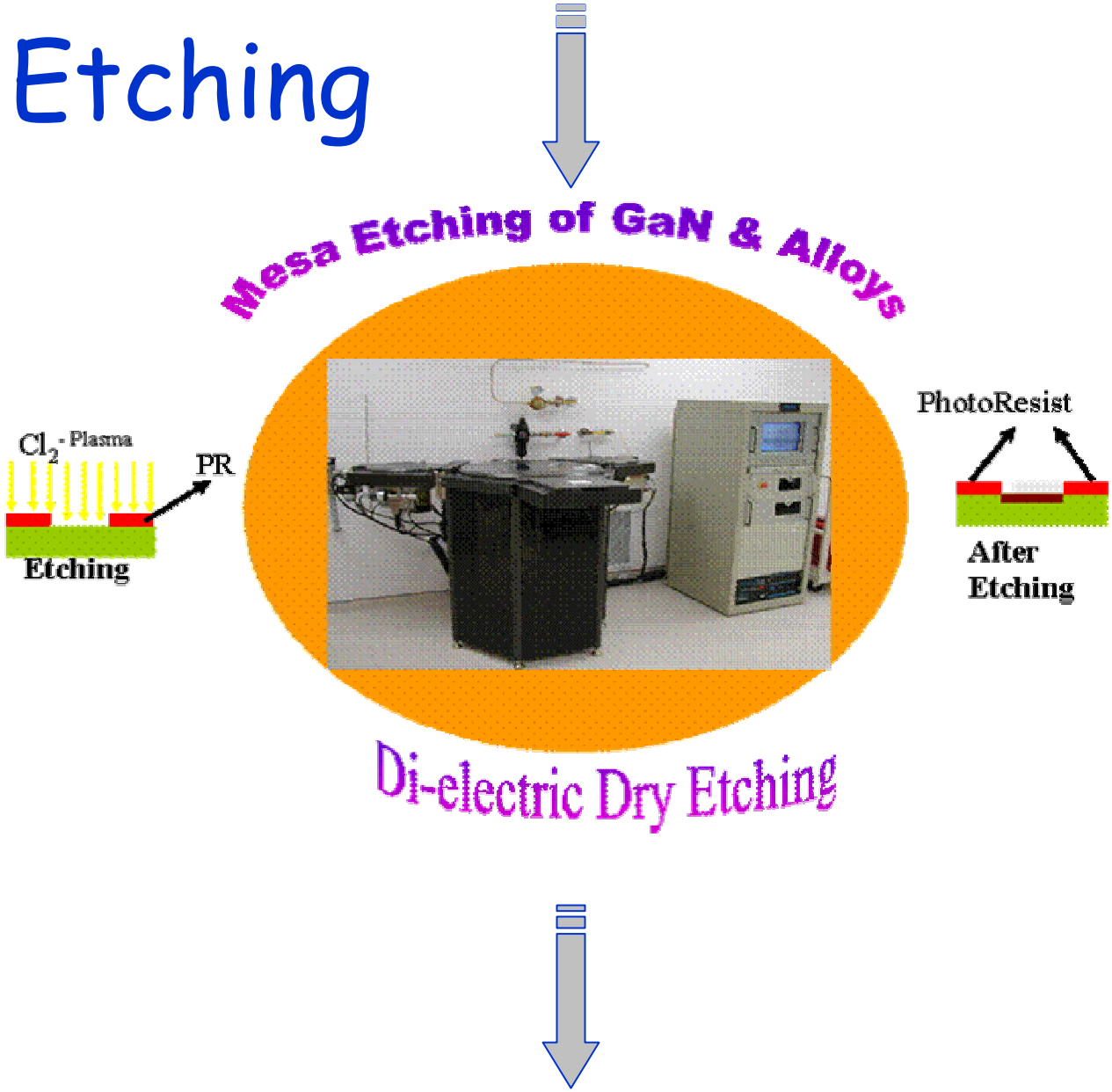
Typical Process Flow in GaN device fabrication



Process Flow



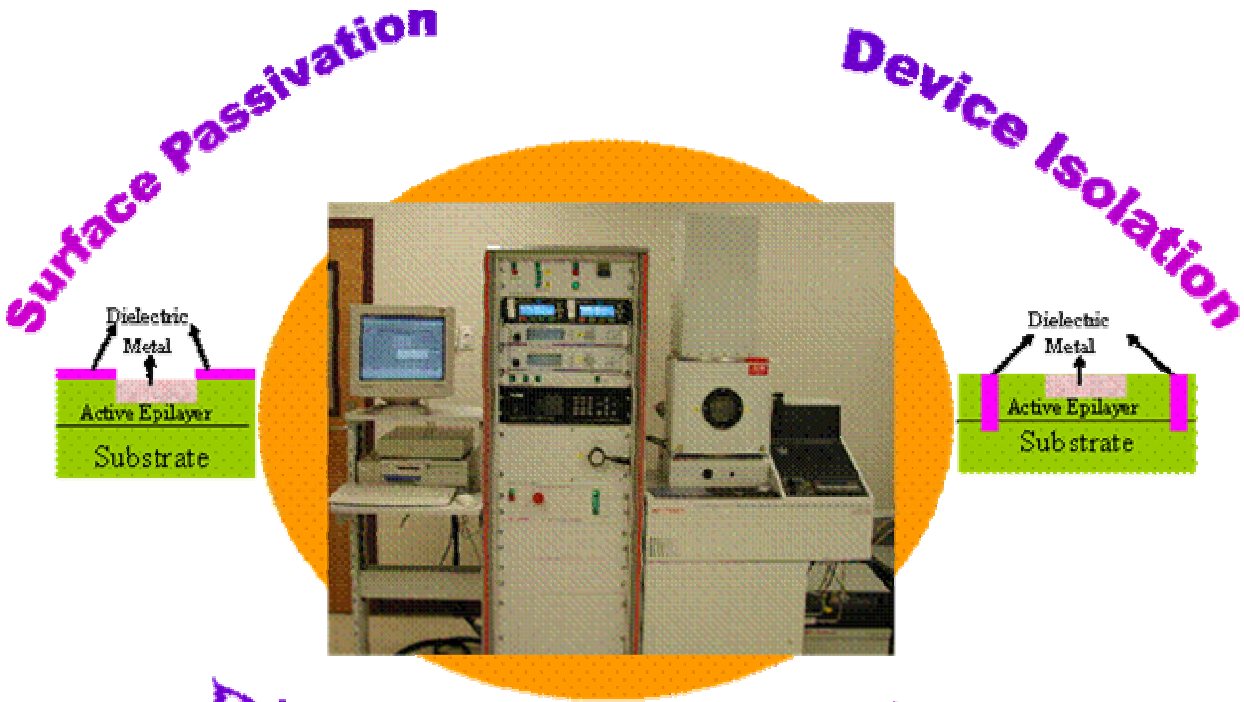
Etching


Mesa Etching of GaN & Alloys
Cl_2 - Plasma
PR
Etching
PhotoResist
After Etching
Di-electric Dry Etching

Metallization

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

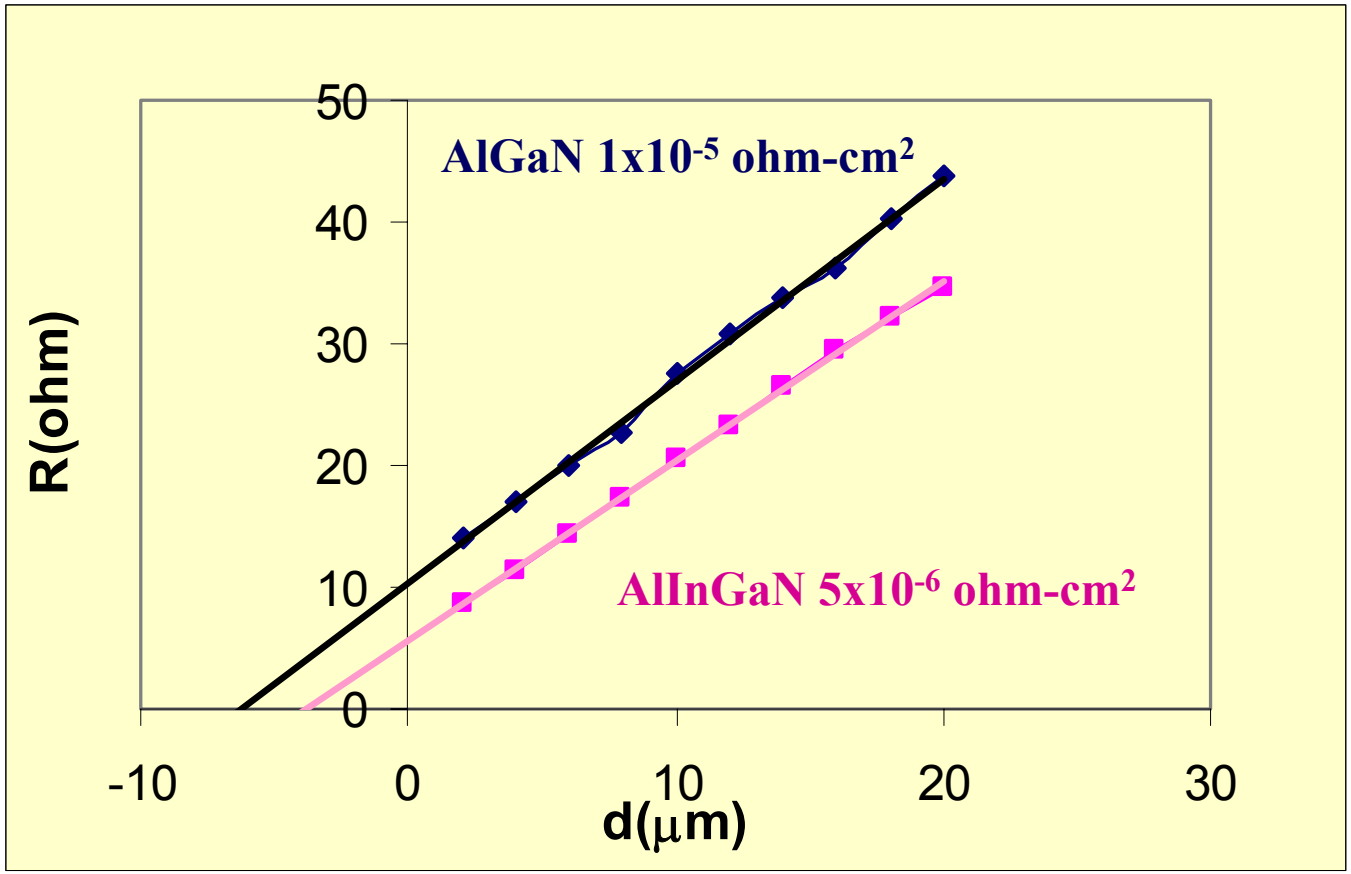
Surface passivation



Di-electric Deposition

To dicing /packaging or on-wafer testing

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



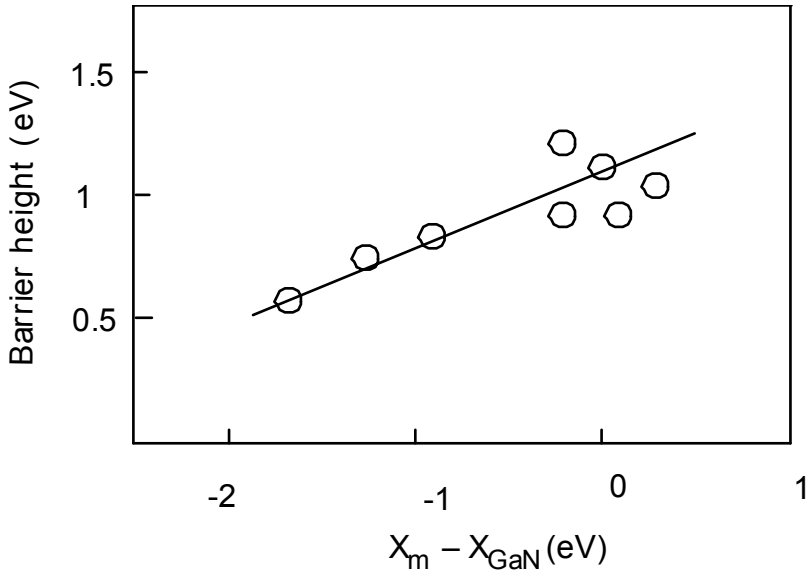
After M. Asif Khan, M. S. Shur, and R. Gaska, Strain Energy Band Engineering in AlGaInN/GaN Heterostructure Field Effect Transistors, presented at GaAs-99 Proceedings, October 4, 1999

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 x 10^{-4} Ωcm^{-2} at 300 K
- 1.5 x $10^{-6} \Omega cm^2$ (at 550 K).

After A. Lunev, Vinamra Chaturvedi, Ashay Chitnis, Grigory Simin, Jinwei Yang and M. Asif Khan
R. Gaska, and M. S. Shur, Low-Resistivity Pd/Au Ohmic Contacts to p-GaN for Heterostructure Bipolar Transistors and Light Emitting Diodes, ICSRM-99, October 10-15, 1999

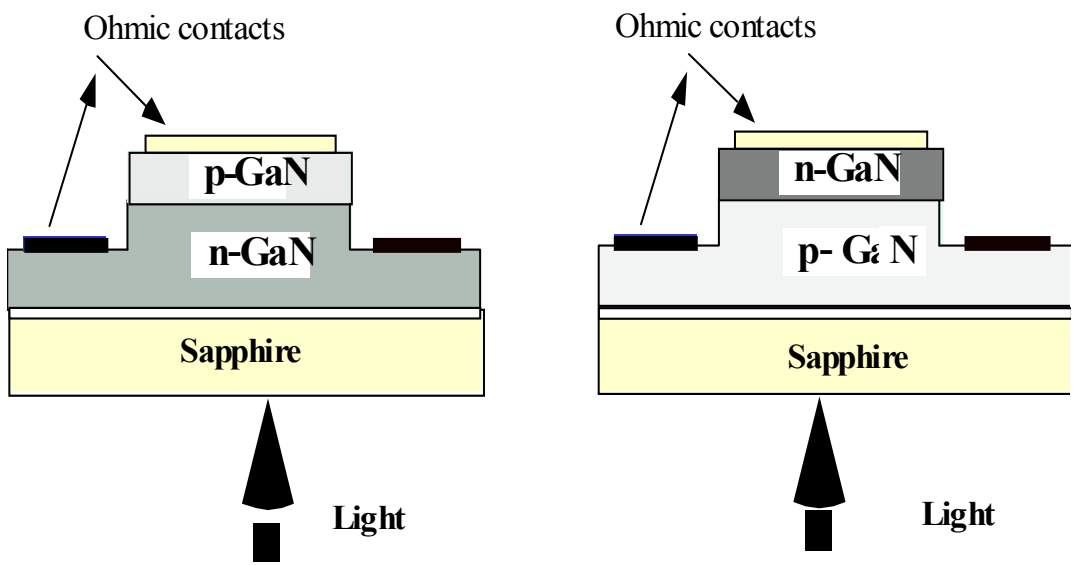
GaN-based Schottky Barriers



After T. U. Kampen and W. Mönch, Metal Contacts on GaN, MIJ-NRS, Vol. 1, Article 4, 12/20 (1997)

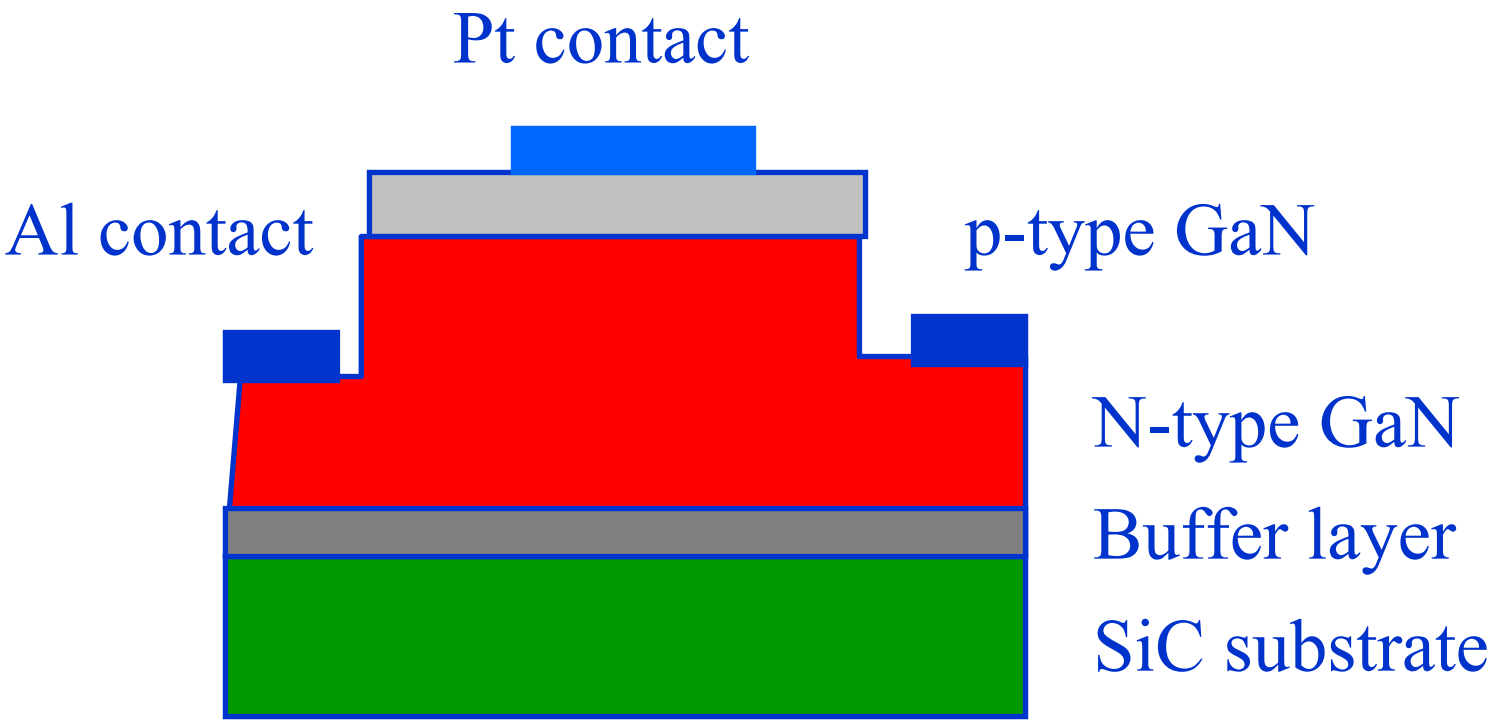
Gallium Nitride Schottky Barrier Diode Operated to 500°C
(Furukawa Electric)

GaN-based p-n junctions



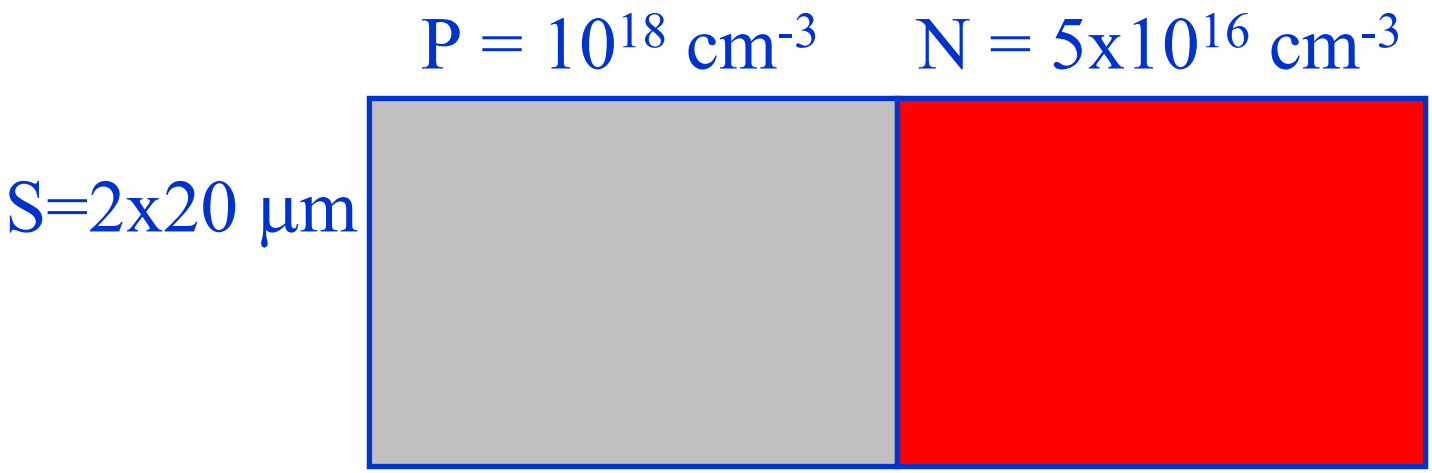
After Q. Chen, M. A. Khan, C. G. Sun, and J. W. Yang, Electronics Letters, 31, p. 1781 (1995)

GaN p-n junctions on SiC substrates



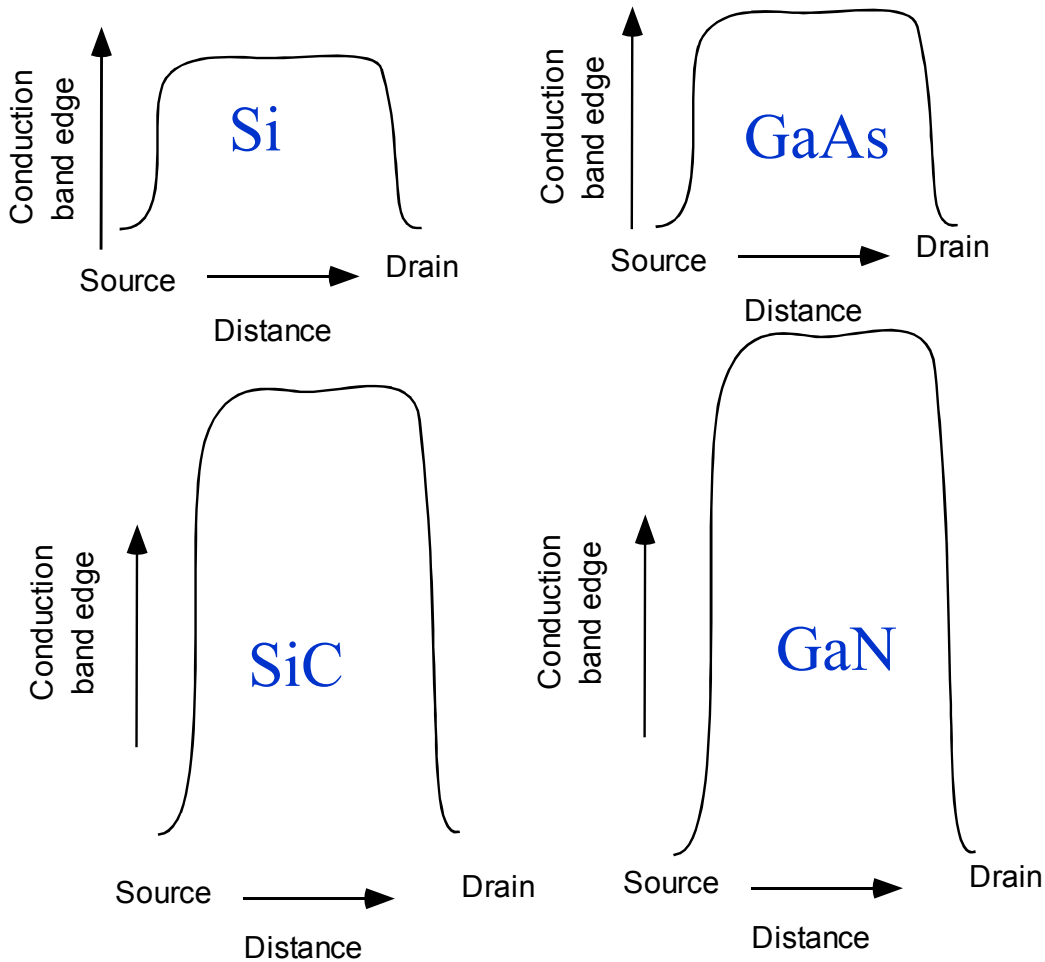
See V. Dmitriev, *MRS Internet J. Nitride Semicond. Res.* ***1***, 29(1996).

GaN p-n junctions on LEO material

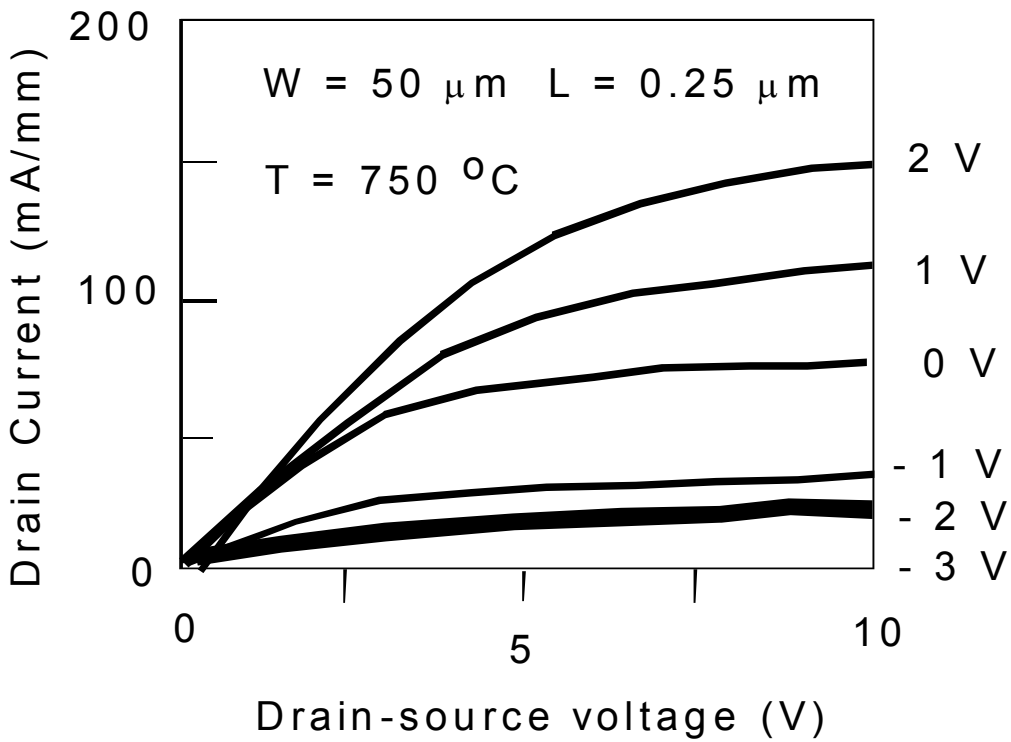


Reverse leakage current 9x 10^{-7} A/cm^{-2} in the LEO GaN
Reverse leakage current 9x 10^{-4} A/cm^{-2} in the non-LEO GaN
(After P. Kozodoy et al. Appl. Phys. Lett. 73(7), 975 (1998)

Band diagrams of FETs below threshold



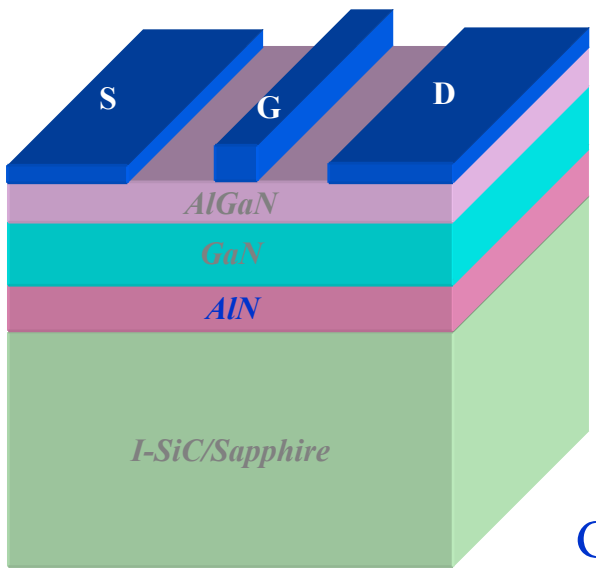
Doped Channel GaN-based FET Operation at 750 °C



After M. Kamp, GaN workshop continues the substrate search, III-Vs Review, Vol. 11, No 6, pp. 42-44 (1998)

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

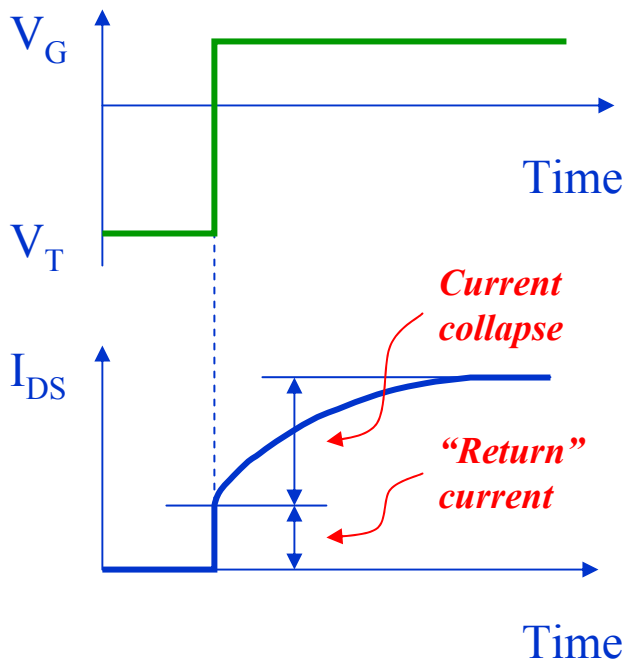
- Critical issues with III-N HFETs

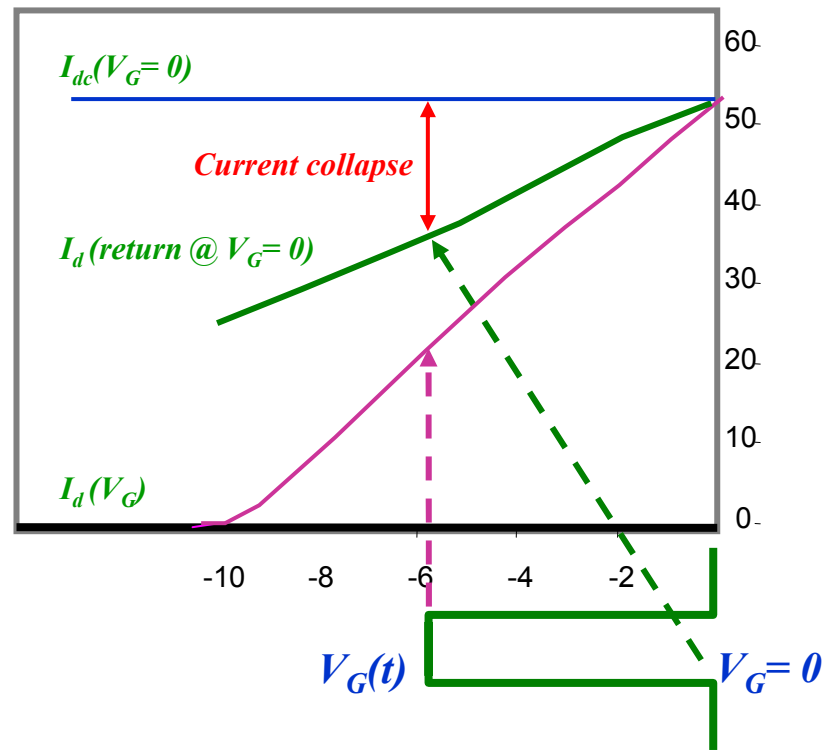
Gate leakage current: 10^{-3}-10^{-5} A/mm

Current collapse (RF performance degradation)

Long term stability and parameter drift

Current collapse in AlGaN/GaN HFETs: Pulsed measurements of "return current"

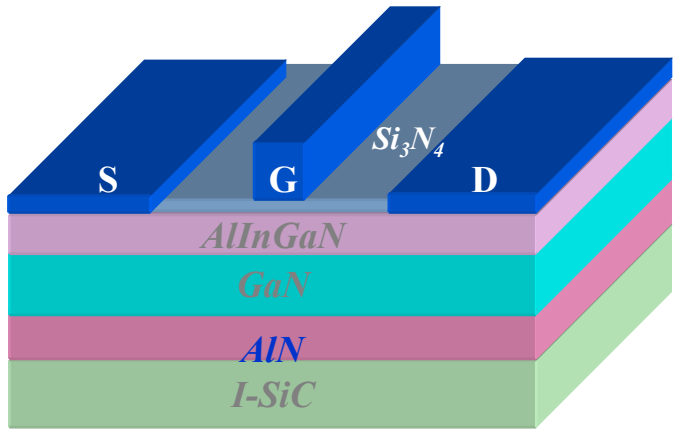


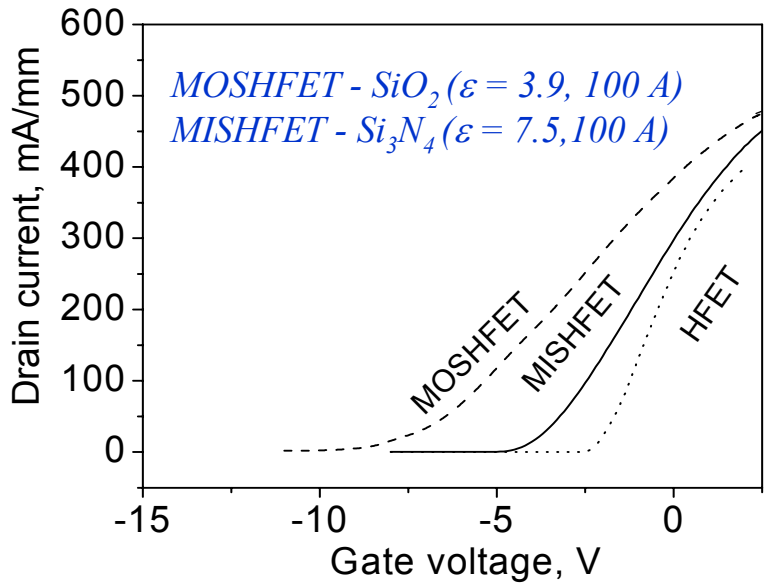


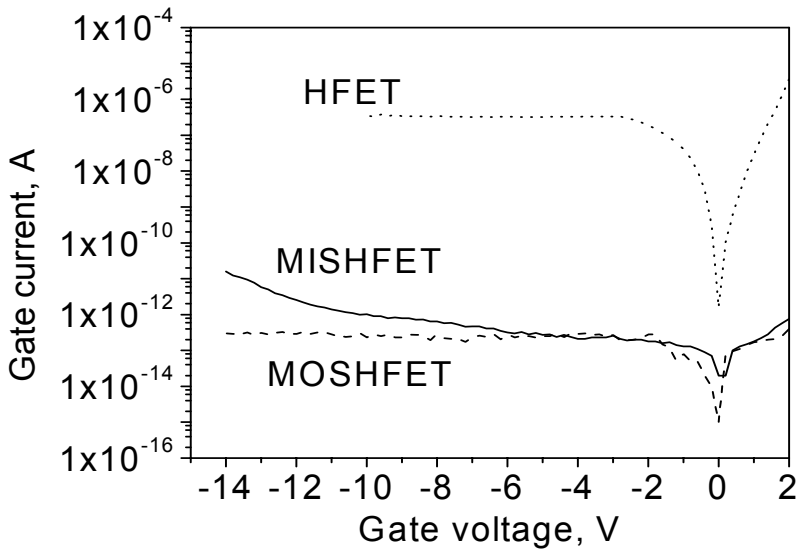
A. Tarakji, G. Simin, N. Ilinskaya, X. Hu, A. Kumar, A. Koudymov, J. Zhang, and M. Asif Khan, M.S. Shur and R. Gaska, Appl. Phys. Lett., 78, N 15, pp. 2169-2171 (2001)

G. Simin, A. Koudymov, A. Tarakji , X. Hu, J. Yang and M. Asif Khan, M. S. Shur and R. Gaska APL October 15 2001

HFET, MOSHFET, and MISHFET

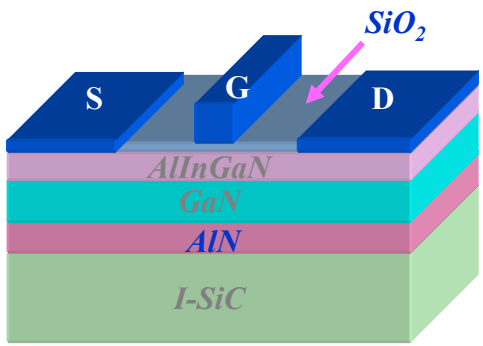






X. Hu, A. Koudymov, G. Simin, J. Yang, M. Asif Khan, A. Tarakji, M. S. Shur and R. Gaska
Appl. Phys. Lett, v.79, p.2832-2834 (2001)

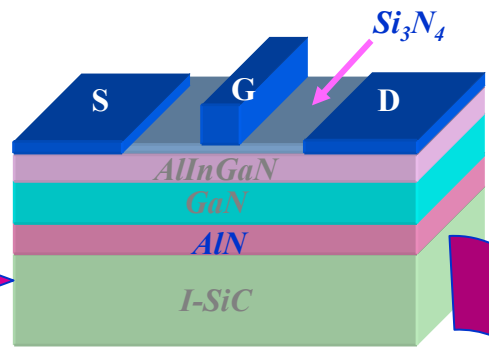
Resolving the issues:
AlGaInN, gate dielectrics, InGaN channel



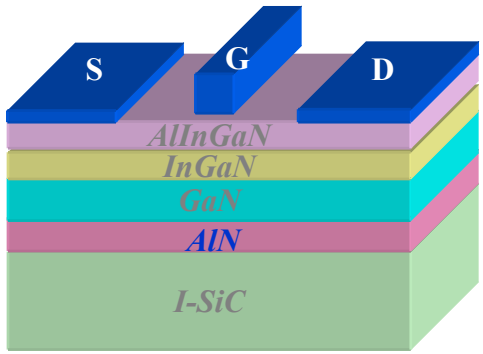
Reducing the gate leakage current (10^4 - 10^6 times)

MOSHFET (SiO_2)

MISHFET Si_3N_4

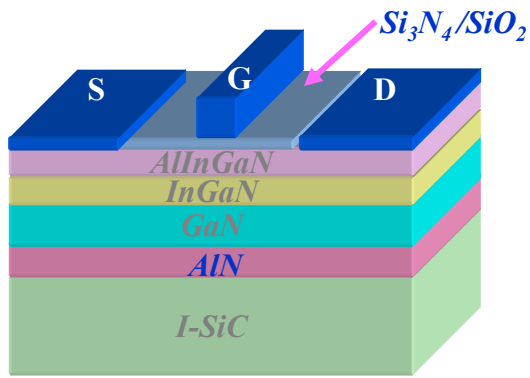


Reducing current collapse,
Improving carrier confinement



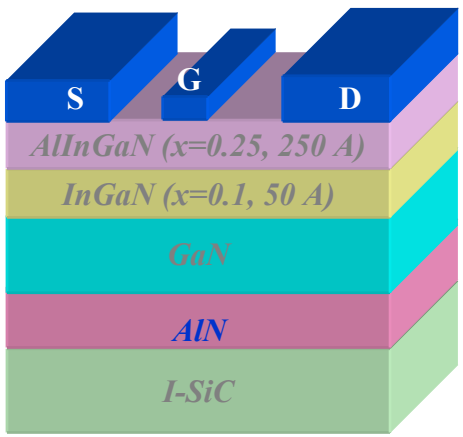
AlGaN/ InGaN GaN DHFET

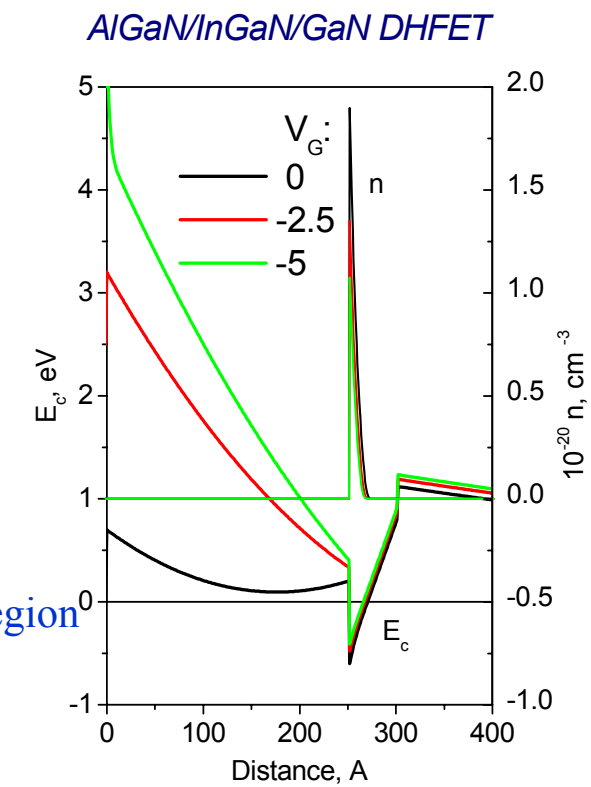
Combining the advantages

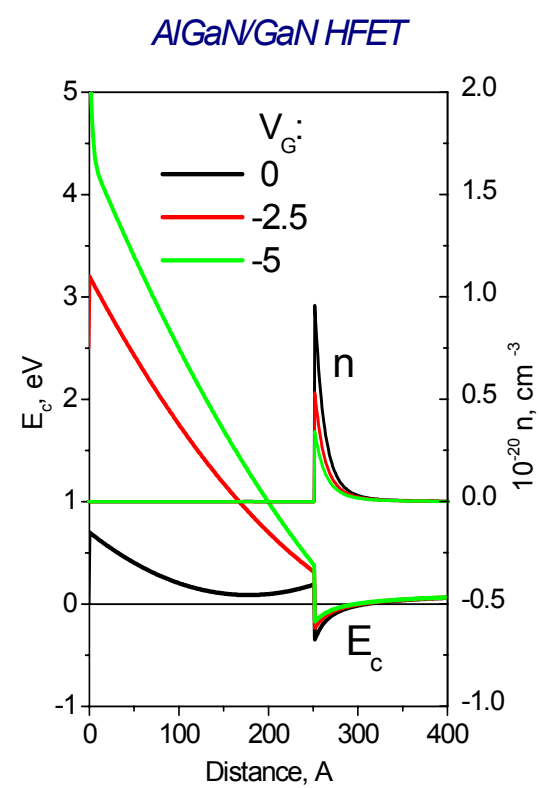


MISDHFET

AlInGaN/InGaN/GaN DHFET concept: improved carrier confinement and strain management



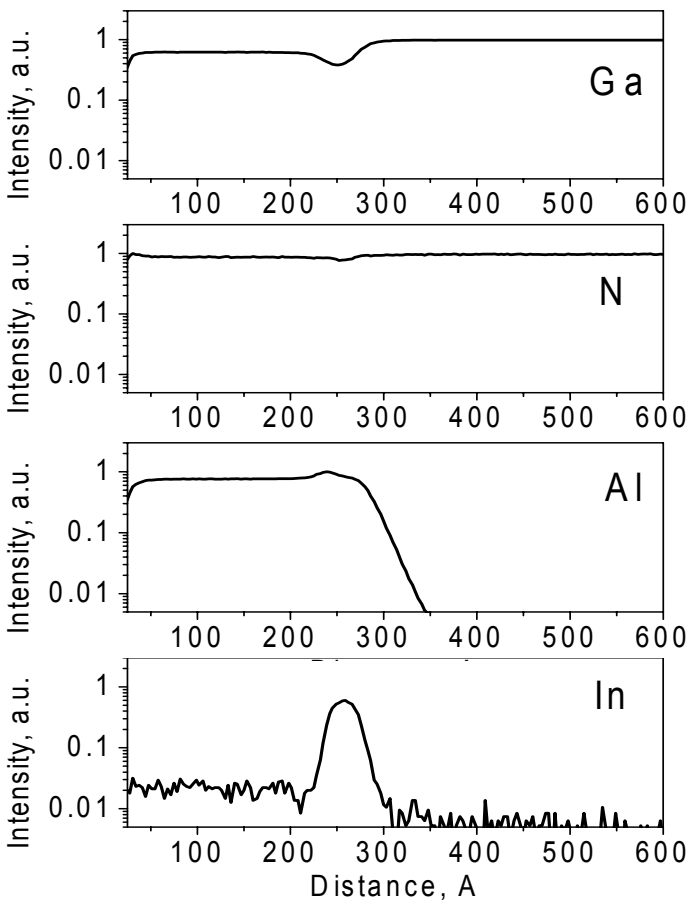




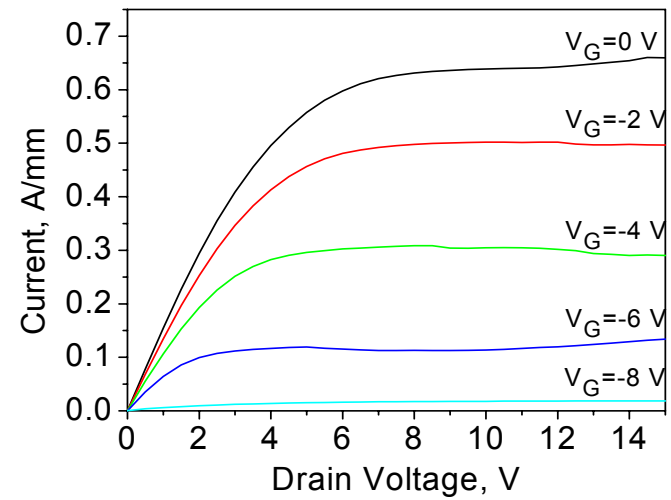
- Better 2DEG confinement
- Constant field in the QW region
- Strain compensation

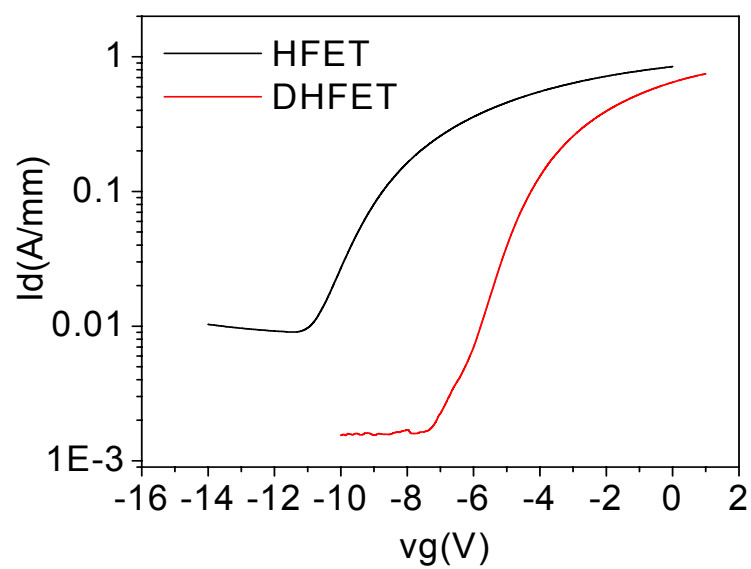
G. Simin et.al. AlGaN/InGaN/GaN Double Heterostructure Field-Effect Transistor Jpn. J. Appl. Phys. Vol.40 No.11A pp.L1142 - L1144 (2001)

AlInGaN-InGaN-GaN DHFET characteristics

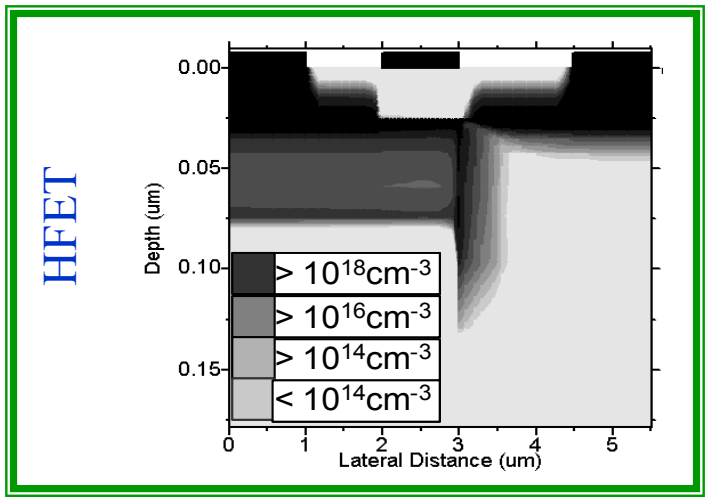


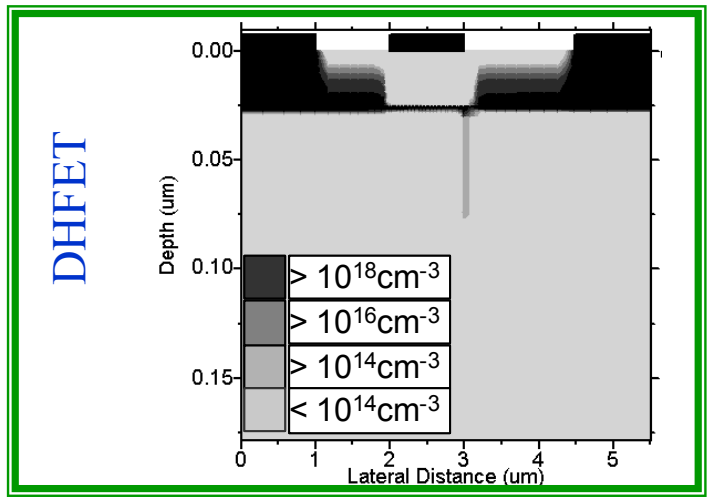
SIMS profiles

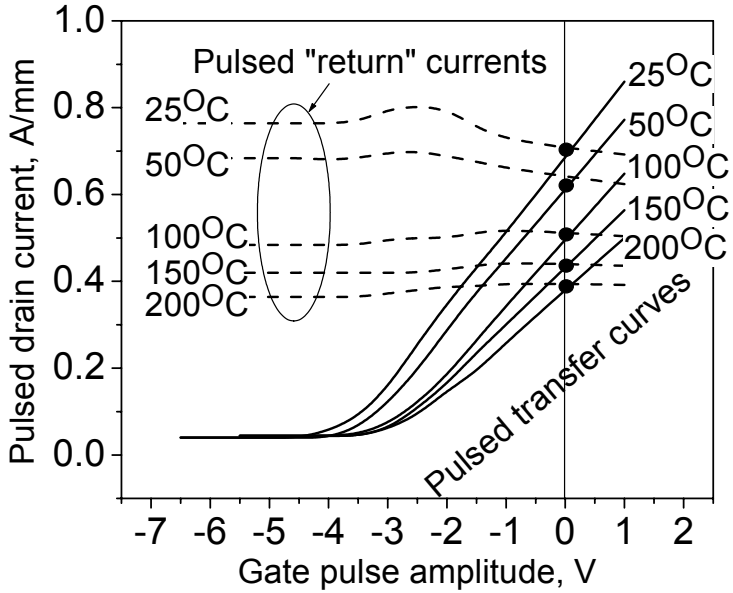


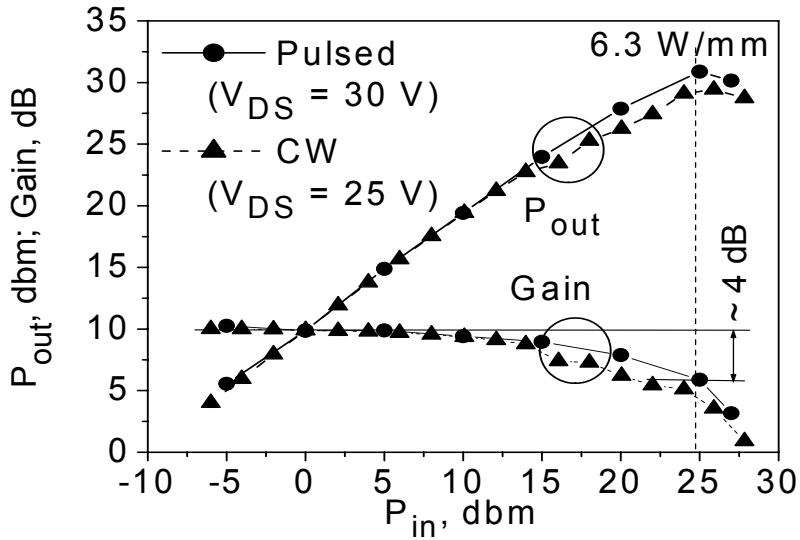


AlGaN-InGaN-GaN DHFET:
Carrier confinement and current collapse reduction

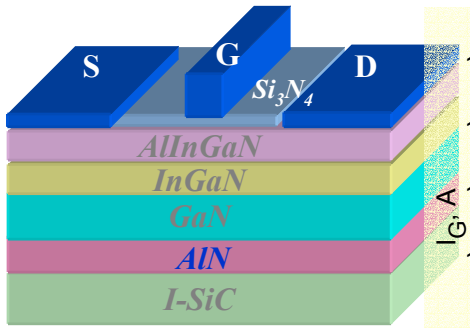


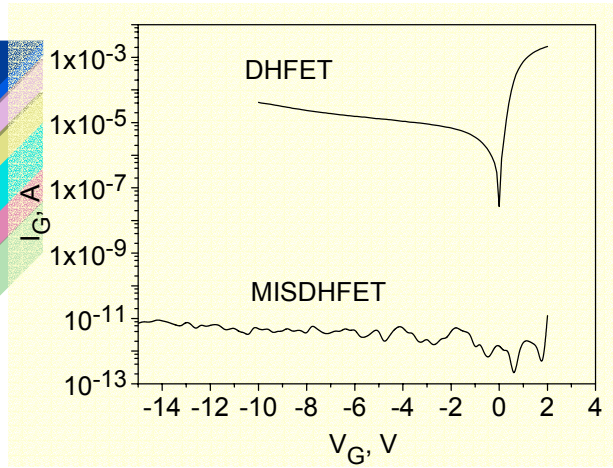


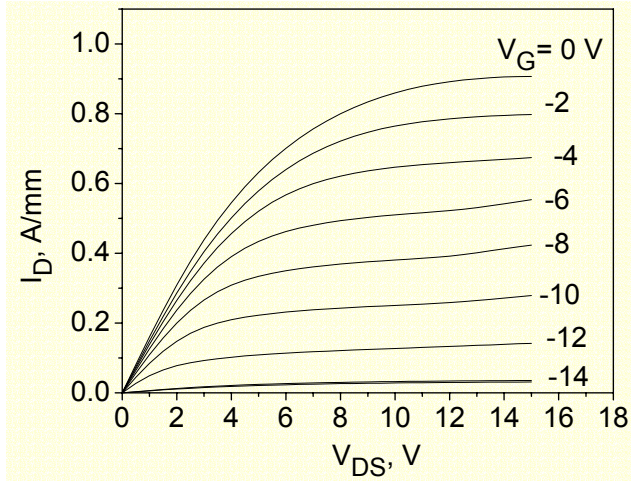




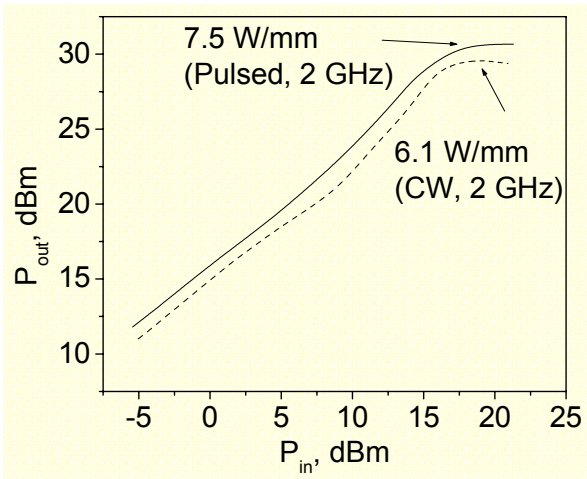
Si_3N_4 /AlGaN/InGaN/GaN MISDHFET DC & RF characteristics

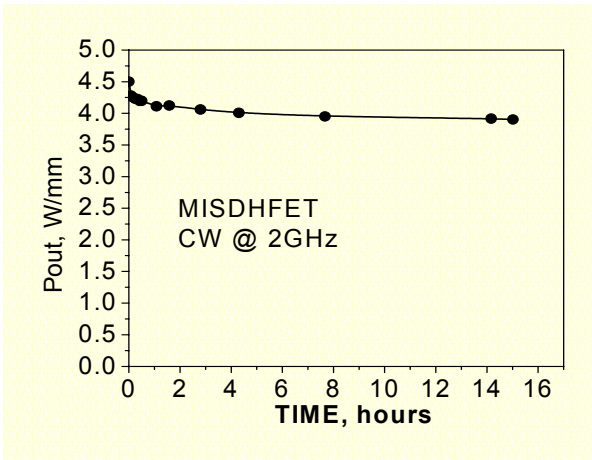




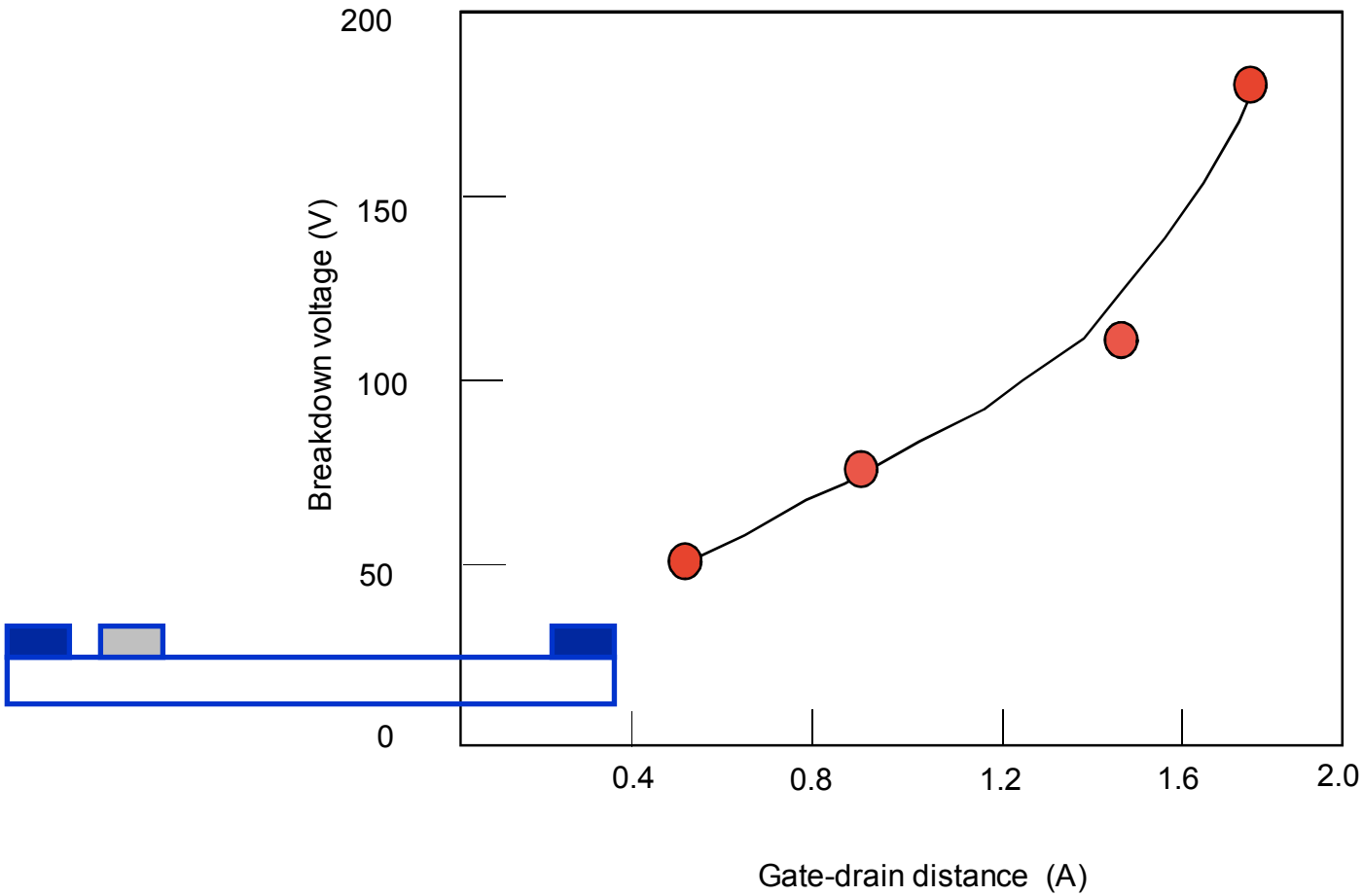


- **Low Gate leakage current (as in MOS/MIS HFETs)**
- **No current collapse (as in DHFET)**
- **Stable DC and RF performance (7.5 W/mm)**



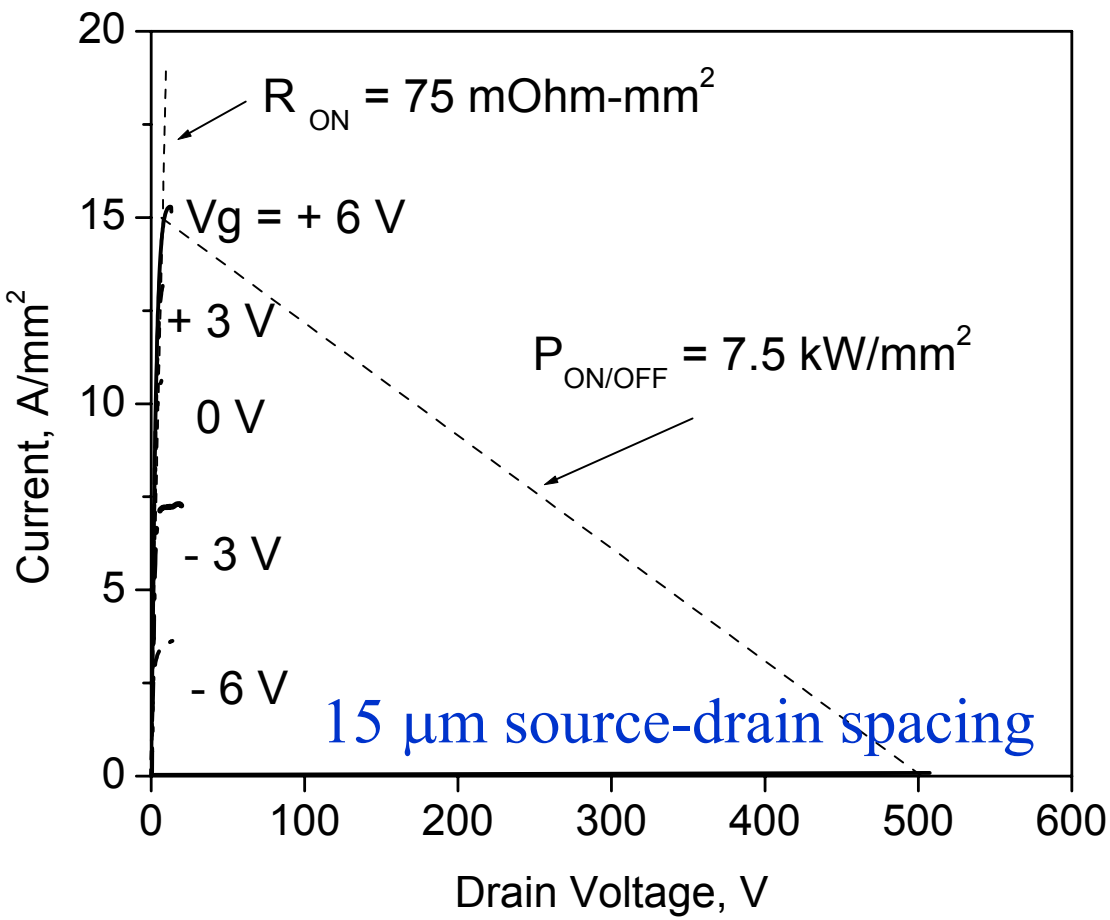


Breakdown voltage and offset gate



From R. Gaska, Q. Chen, J. Yang, A. Osinsky, M. Asif Khan, and Michael S. Shur, AlGaN/GaN Heterostructure FETs with Offset Gate Design, Electronics Letters, 33, No. 14, pp. 1255-1257, 3 July (1997)

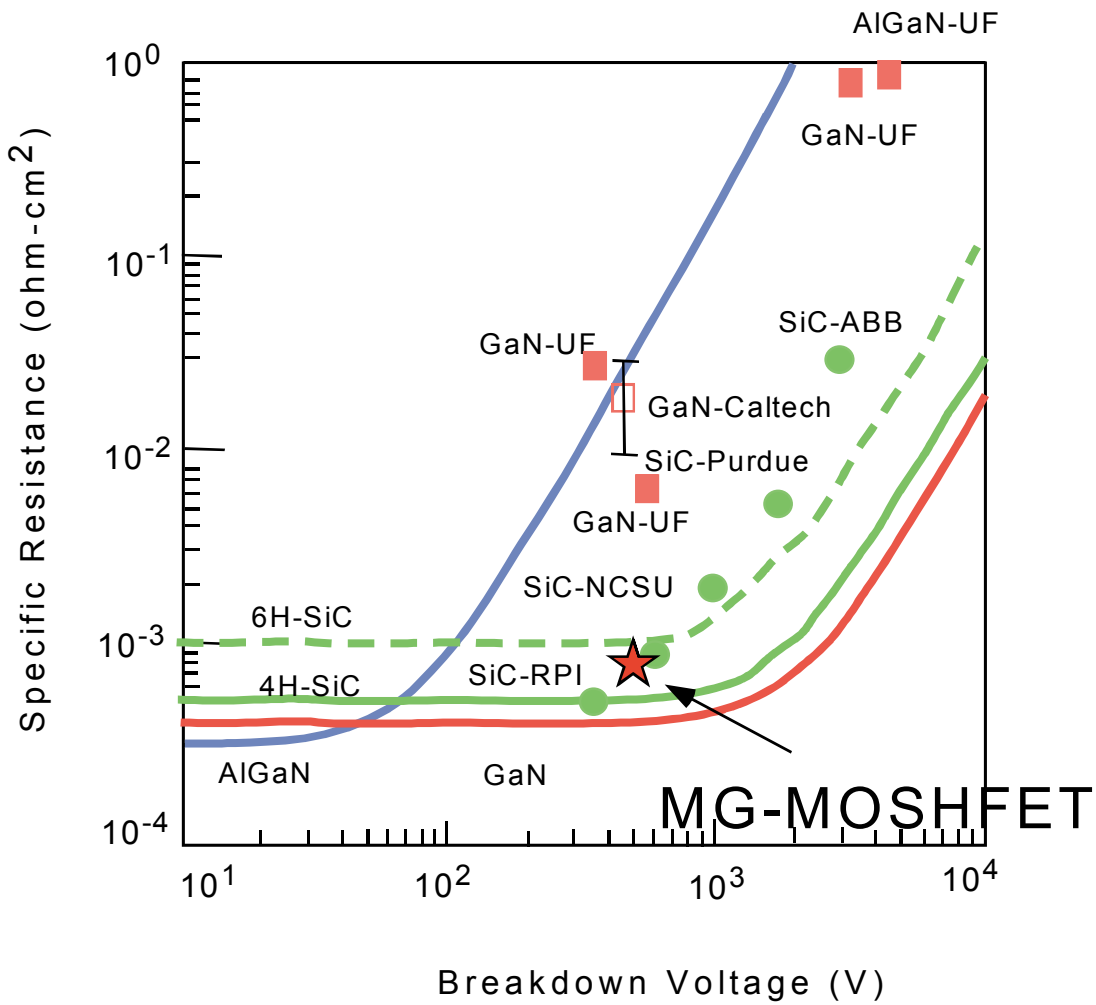
MOSHFET Switch



After 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, Electronics Letters. Vol. 36, pp. 2043 –2044, Nov. 2000

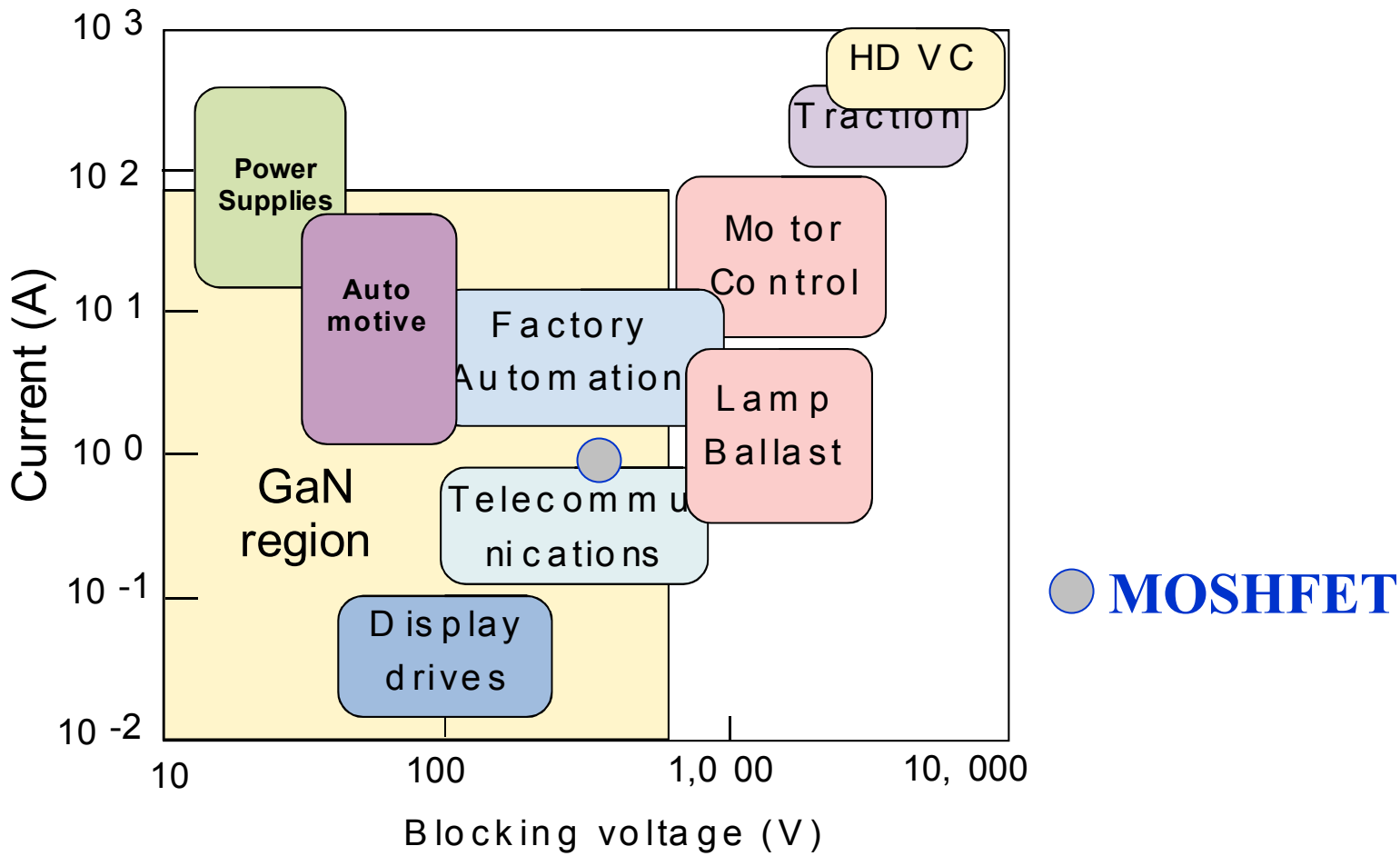
Comparison with SiC and GaN Diodes

From S. J. Pearton et al. GaN Electronics for High Power, High Temperature Applications, Interface, Vol. 9, No. 2, pp. 34-39 (2,000)



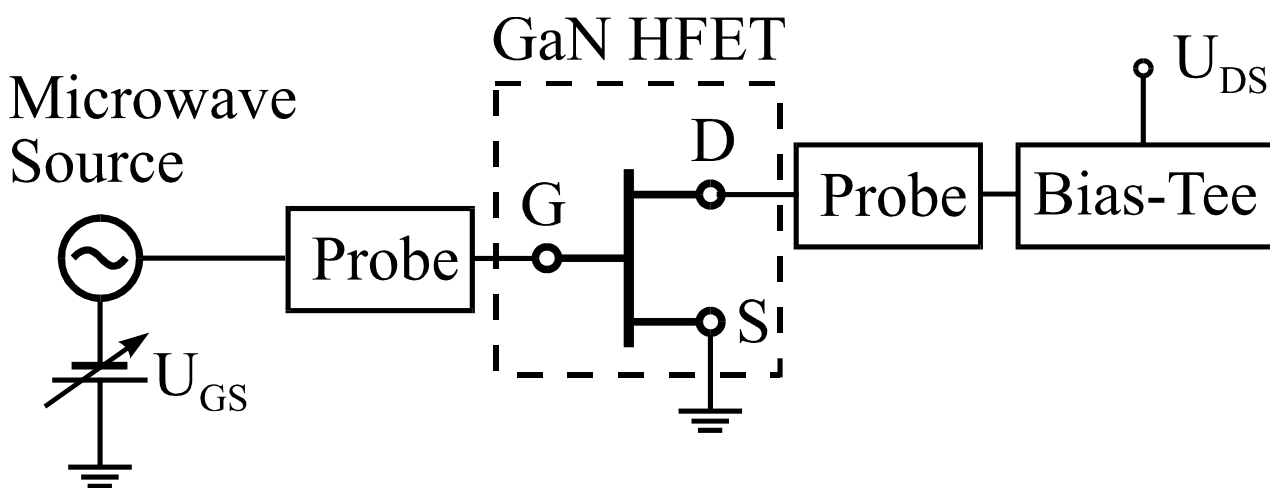
MG-MOSHFET point is from G. Simin, X. Hu, N. Ilinskaya, A. Kumar, A. Koudymov, J. Zhang, M.Asif Khan, R. Gaska and M. S. Shur, A 7.5 kW/mm2 current switch using AlGaN/GaN Metal-Oxide-Semiconductor Heterostructure Field Effect Transistors on SiC Substrates (EL-2000).

Power devices - applications and ratings



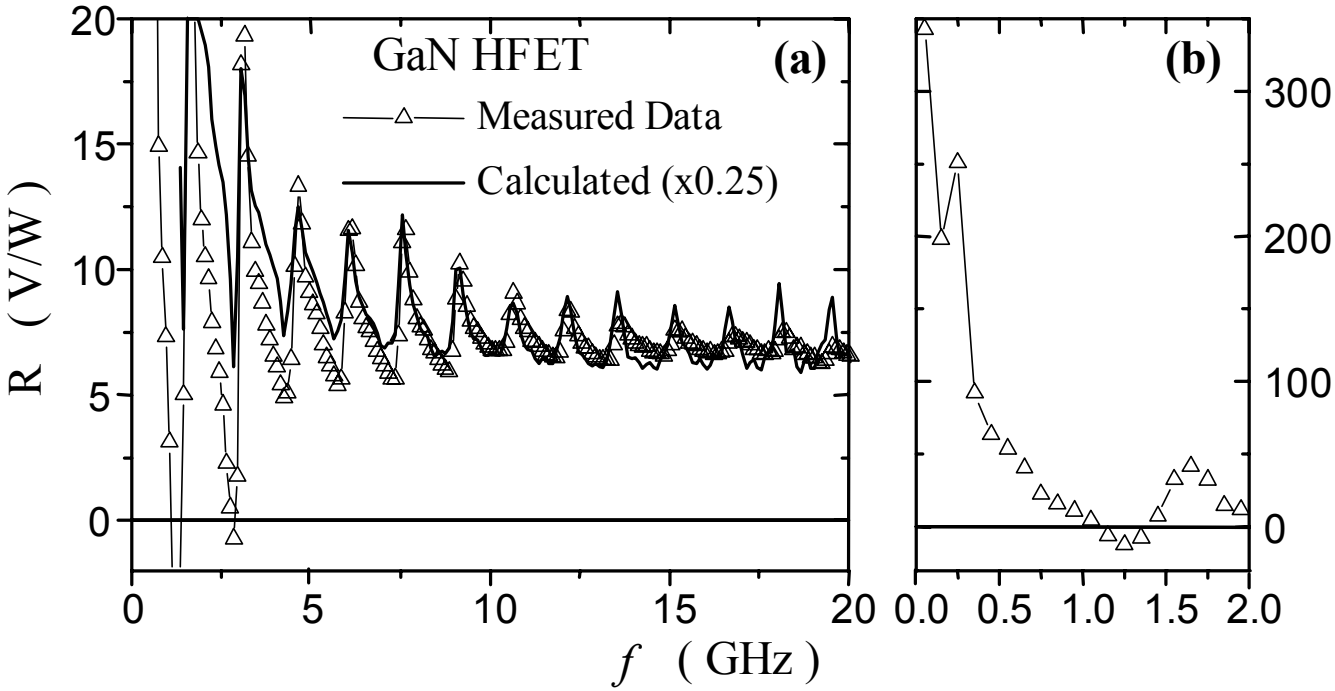
Data from B. J. Baliga, IEEE Trans., ED-43, p. 1717 (1996)

GaN Microwave Detector



From J. Lu, M. S. Shur, R. Weikle, and M. I. Dyakonov, Detection of Microwave Radiation by Electronic Fluid in AlGaN/GaN High Electron Mobility Transistors, in Proceedings of Sixteenth Biennial Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits, Ithaca, New York, Aug. 4-6 (1997), pp. 211-217

Measured Detector Responsivity



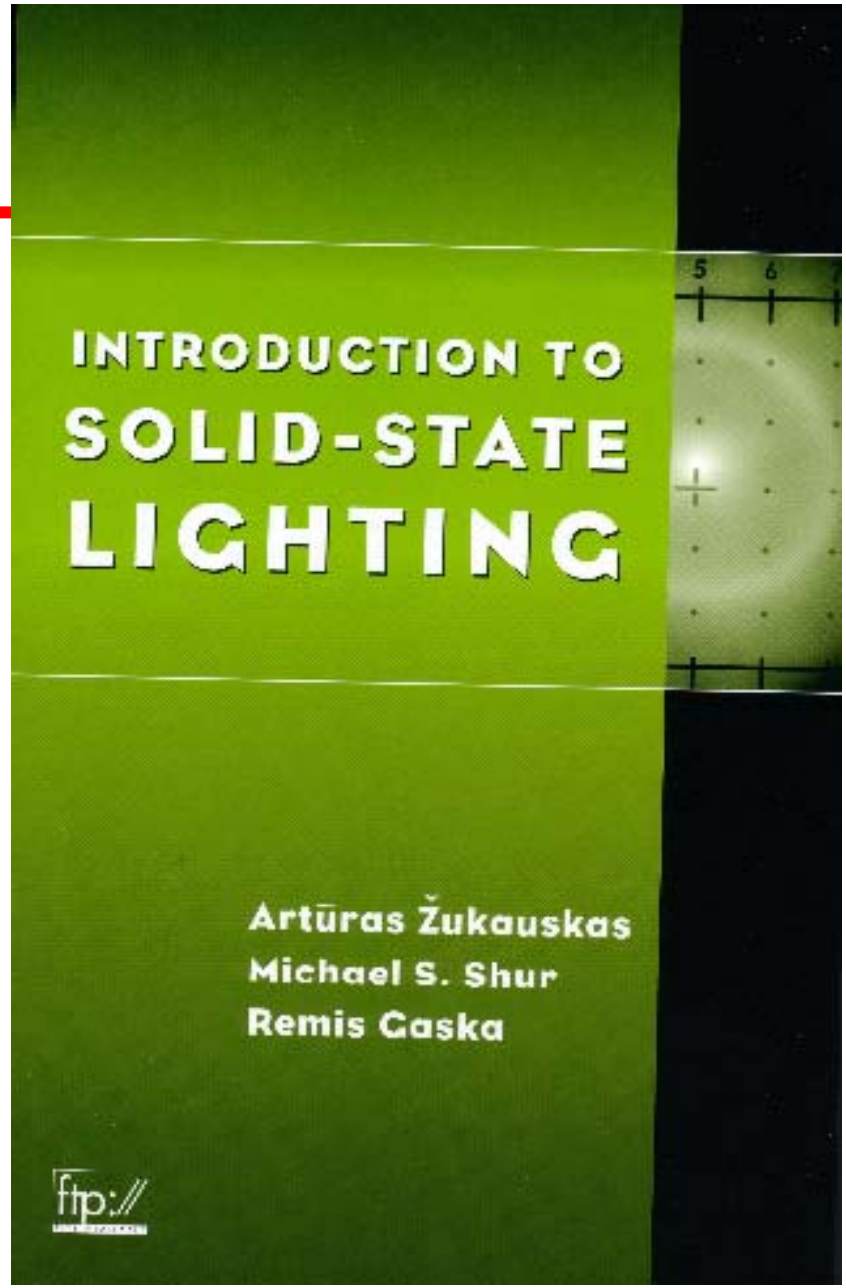
From J. Lu, M. S. Shur, R. Weikle, and M. I. Dyakonov, Detection of Microwave Radiation by Electronic Fluid in AlGaN/GaN High Electron Mobility Transistors, in Proceedings of Sixteenth Biennial Conference on Advanced Concepts in High Speed Semiconductor Devices and Circuits, Ithaca, New York, Aug. 4-6 (1997), pp. 211-217

Photonic Nitride Devices

- Solid State Lighting
- UV LEDs

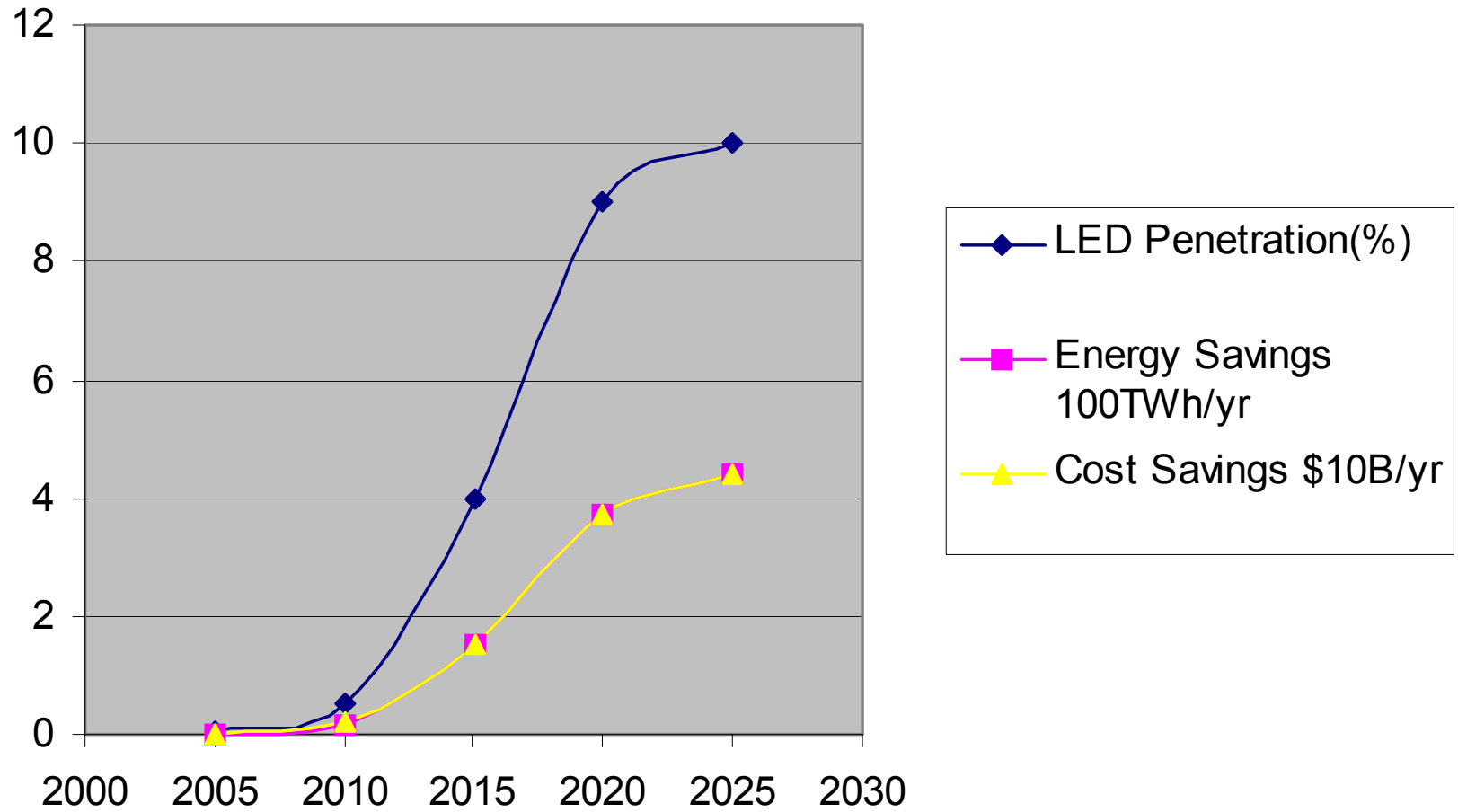
Importance of Solid State Lighting

- 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.

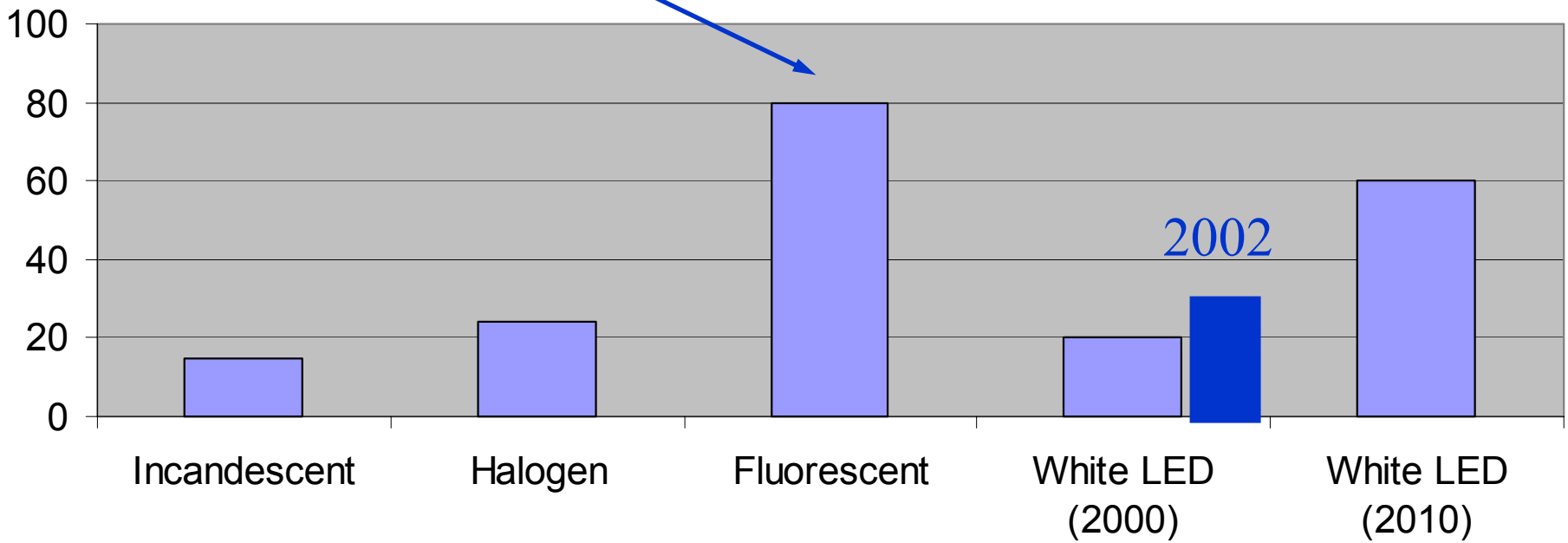


"Low Investment Model"

Data from R. Haitz, F. Kish, J. Tsao, and J. Nelson
Innovation in Semiconductor Illumination: Opportunities for National Impact (2000)

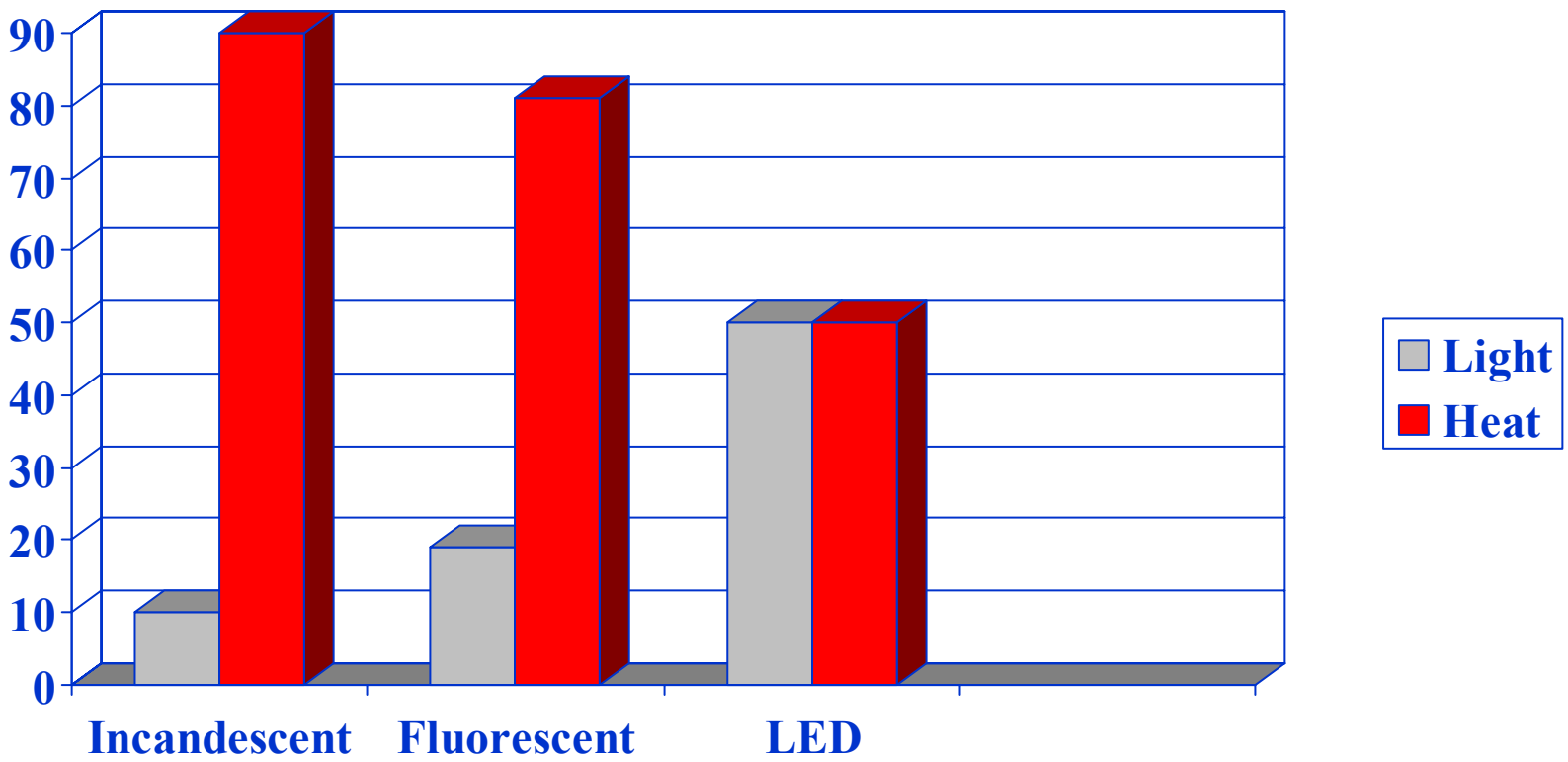
Solid State Lighting Efficiency (lm/W)

Flickers
Cannot be dimmed
Losses in ballast
Noisy

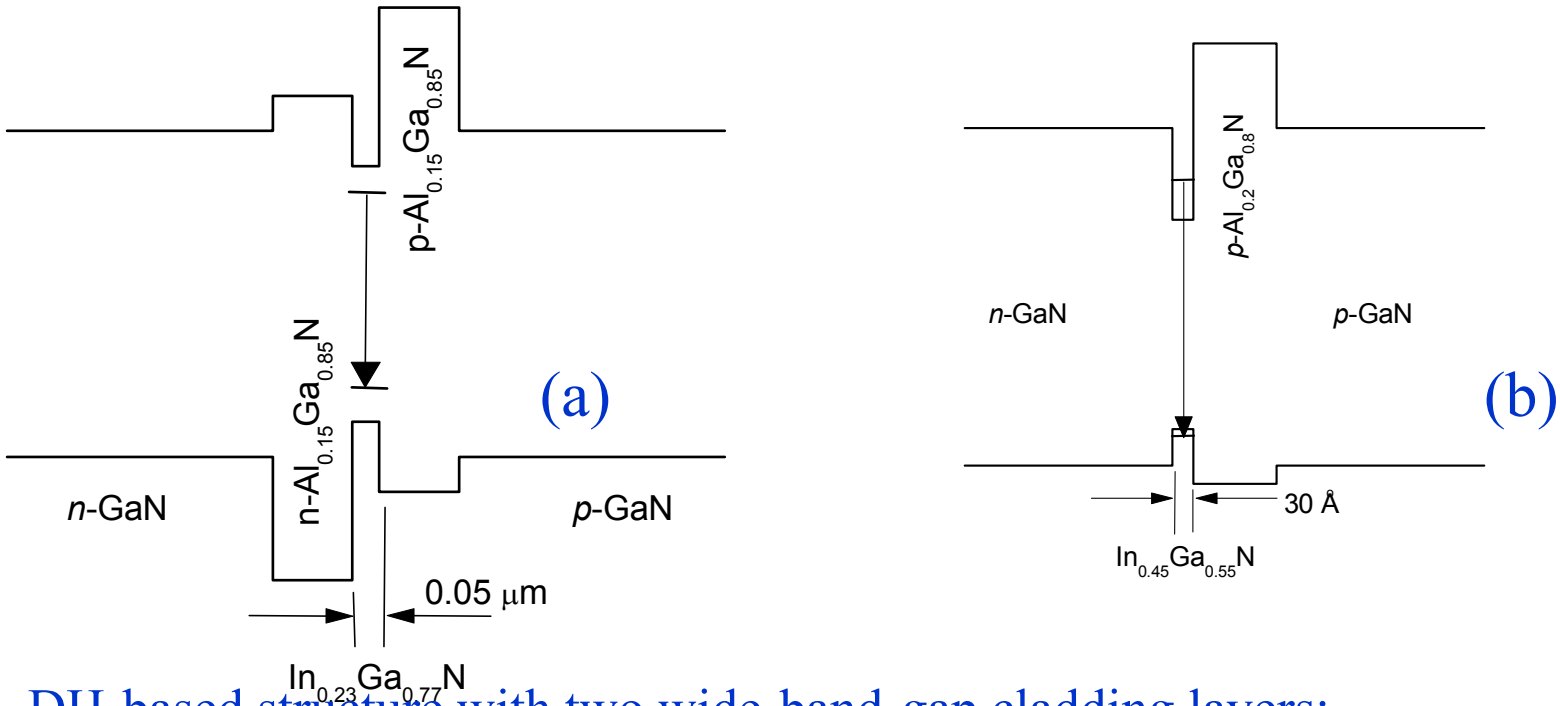


Cool LED Light – saving cooling costs

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

First LED (1907)

A Note on Carborundum.

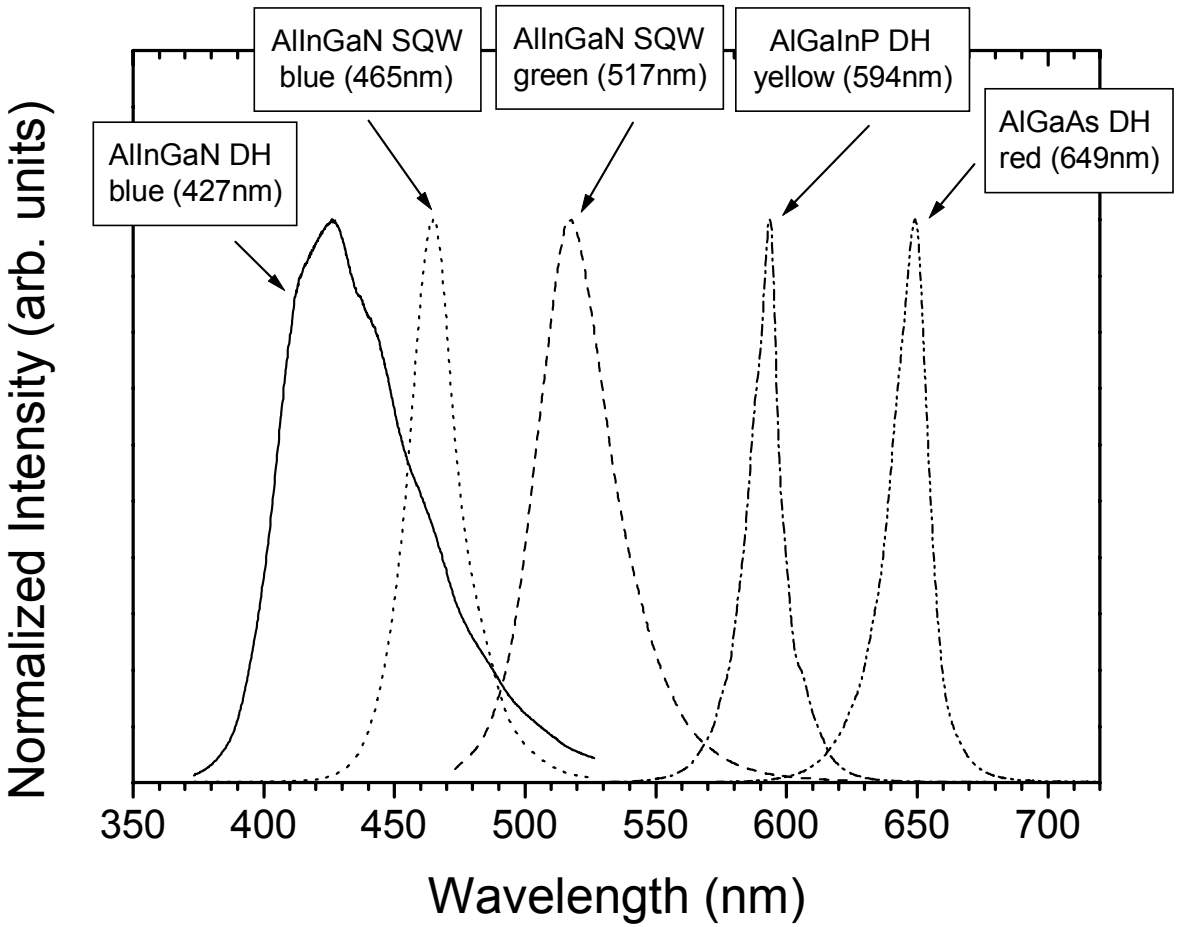
To the Editors of Electrical World:

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.

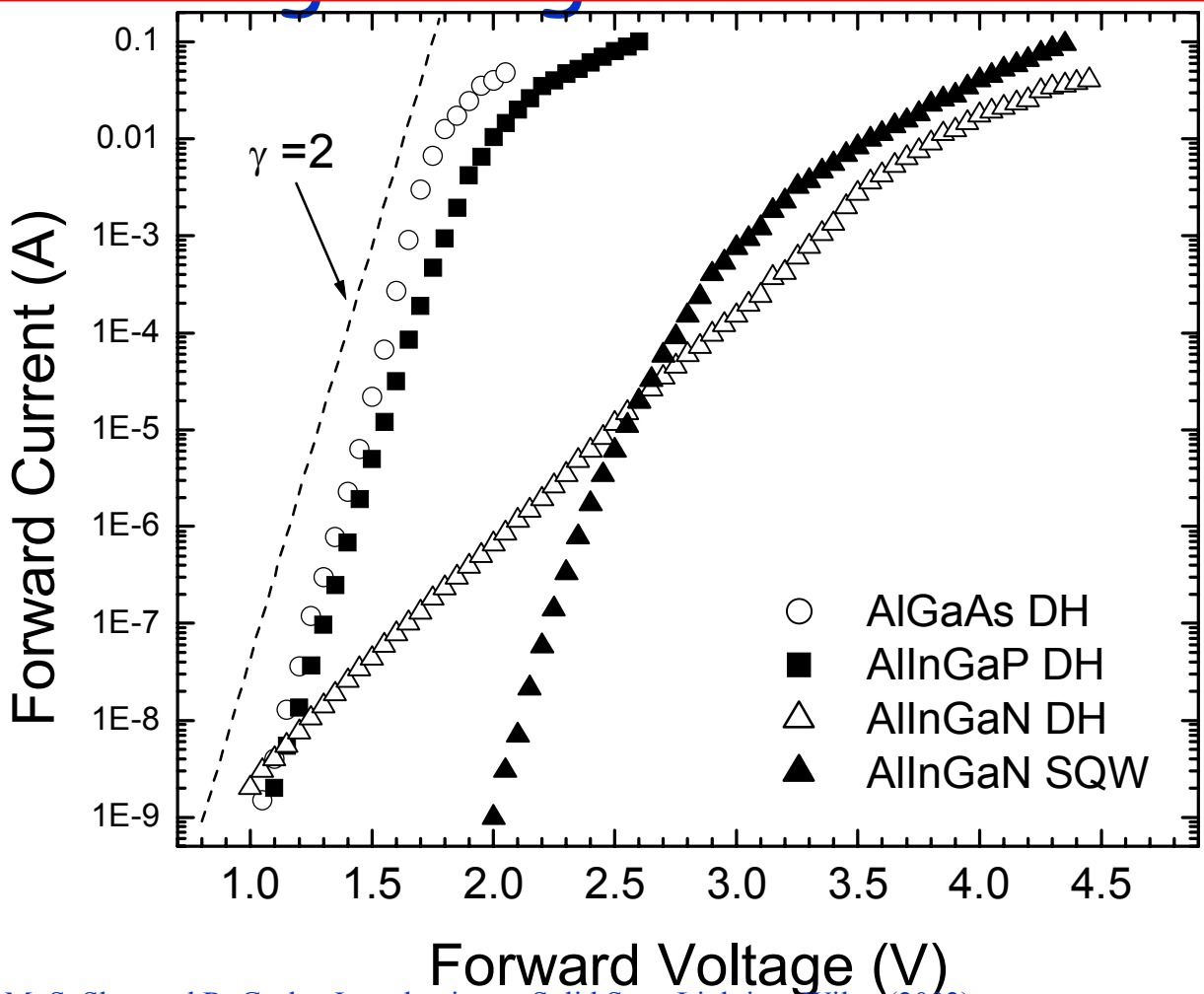
NEW YORK, N. Y. H. J. ROUND.

Emissive and Electrical Characteristics



From A. Zukauskas, M. S. Shur and R. Gaska, Introduction to Solid State Lighting, Wiley (2002)

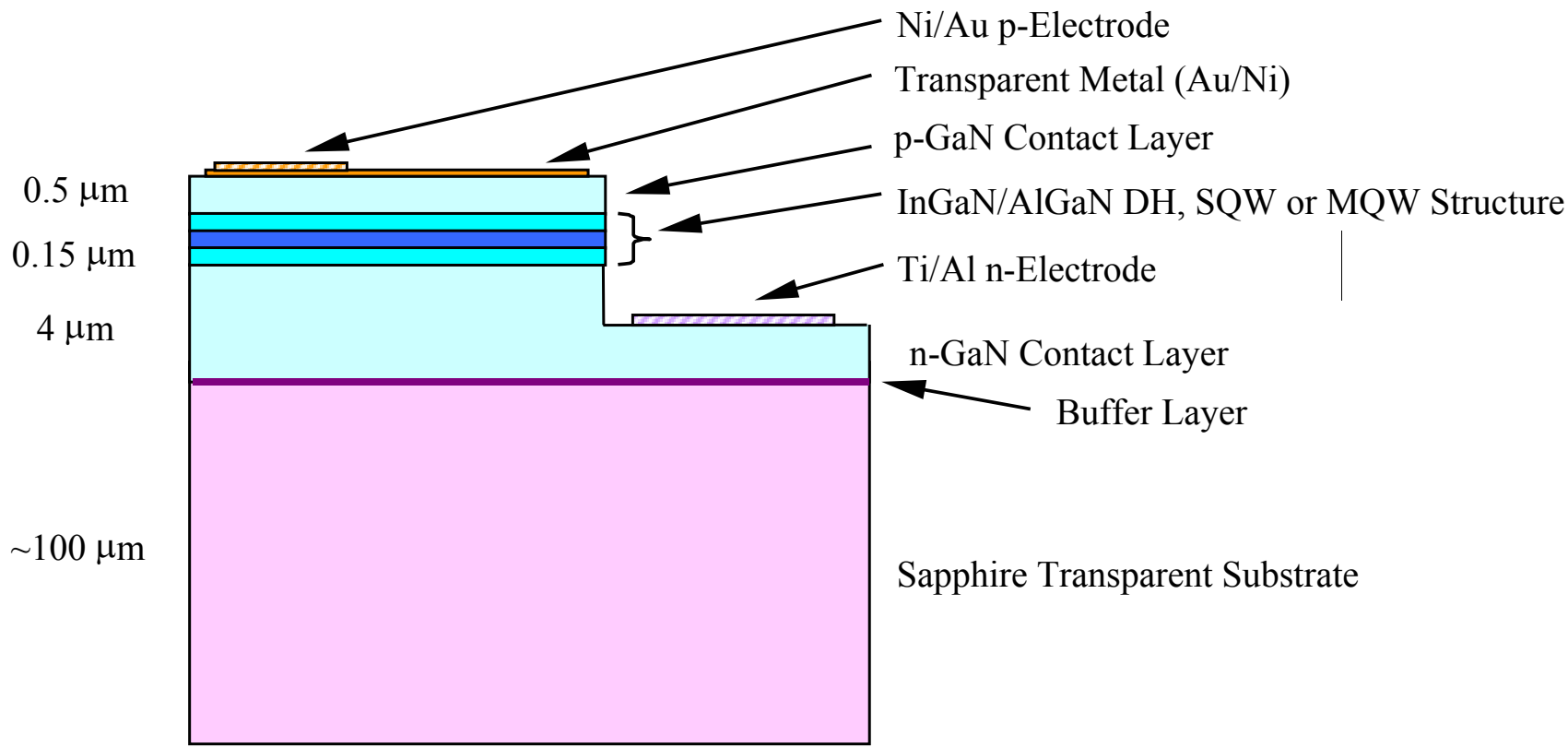
Current-voltage characteristics of AlGaAs, AlGaInP, and AlInGaN-based high brightness LEDs



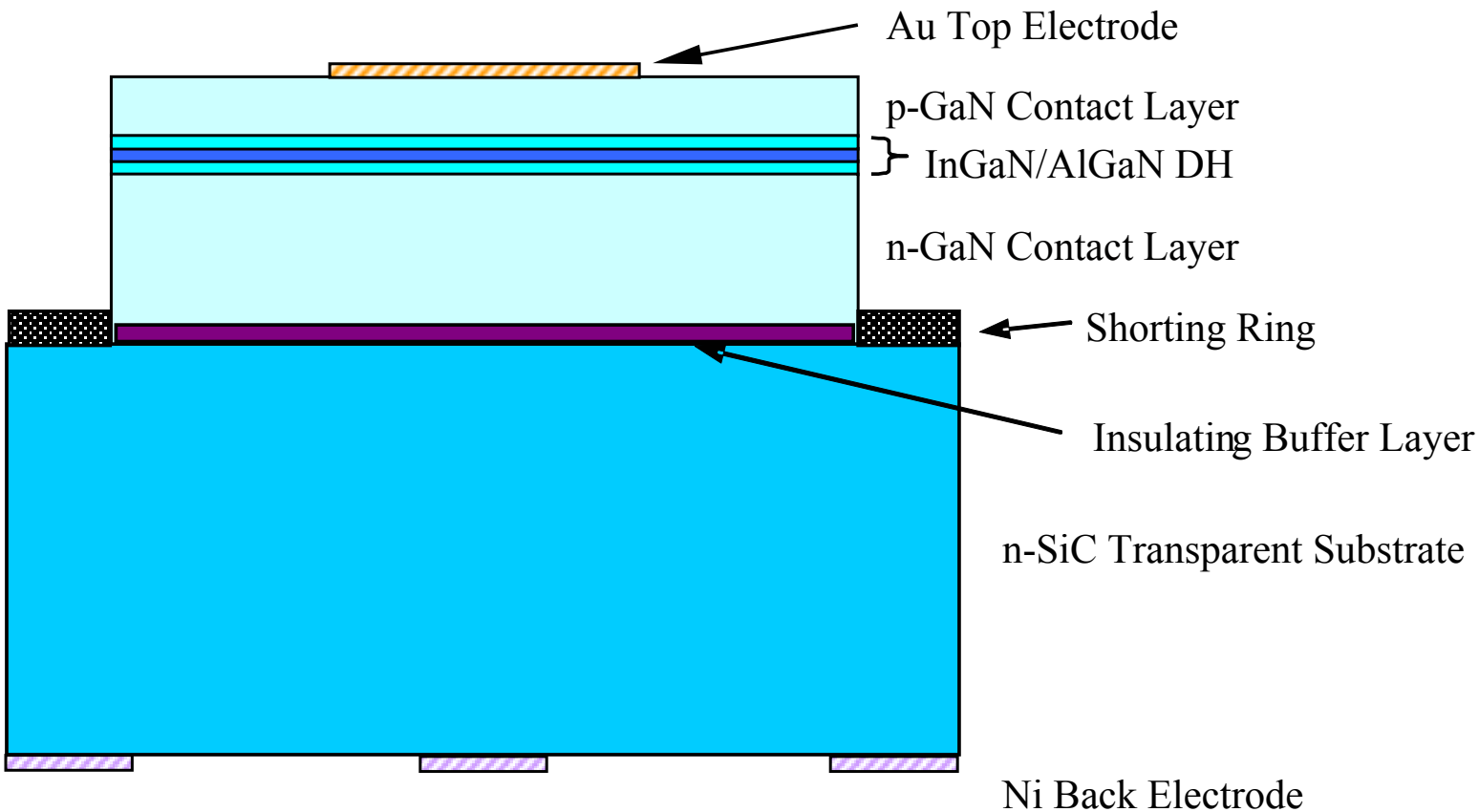
From A. Zukauskas, M. S. Shur and R. Gaska, Introduction to Solid State Lighting, Wiley (2002)

Chip structure of AlInGaN/Al_2O_3 LED

(after S.Nakamura and G. Fasol, *The Blue Laser Diode: GaN Based Light Emitters and Lasers,* Springer, Berlin, 1997).

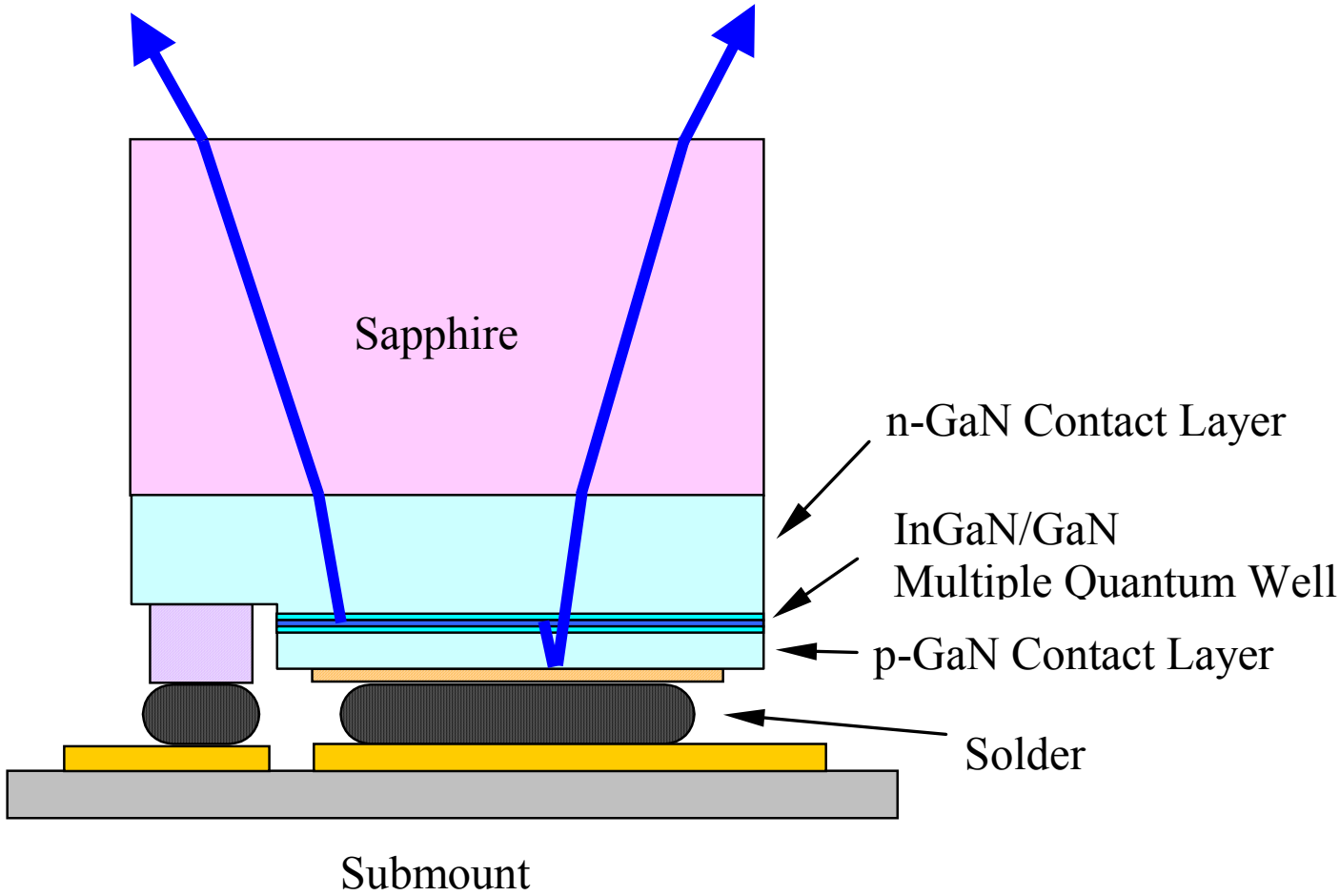


AlInGaN/SiC LED



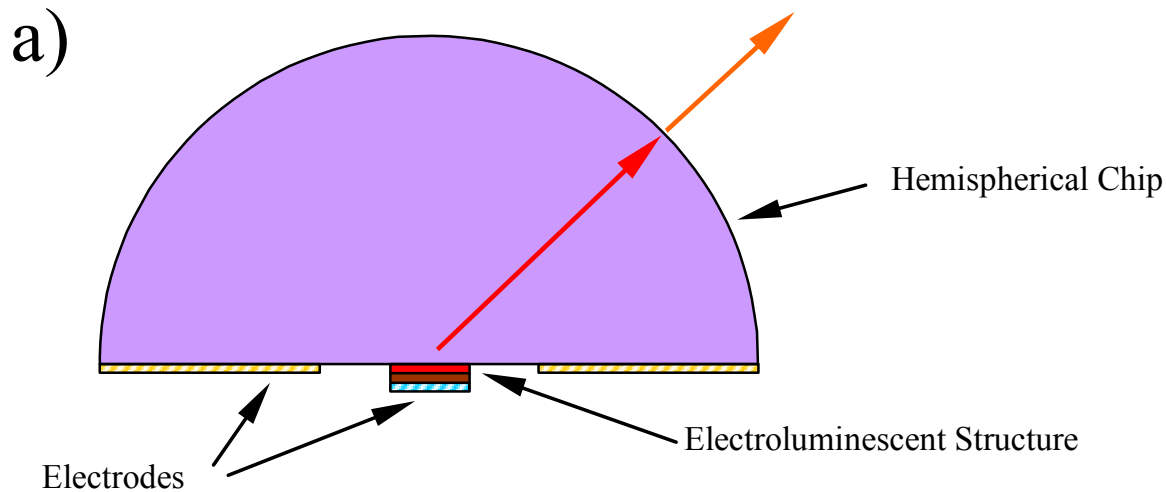
(after J.A.Edmond *et al., Proc. SPIE* **3002**, 2, 1997).

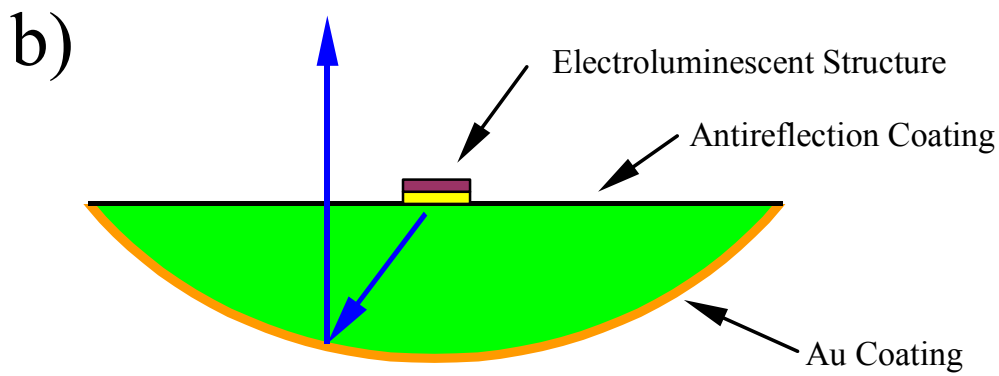
High power AlInGaN Flip-Chip LED



After J. J. Wieret *et al.*, *Appl. Phys. Lett.* **78,** 3379, 2001.

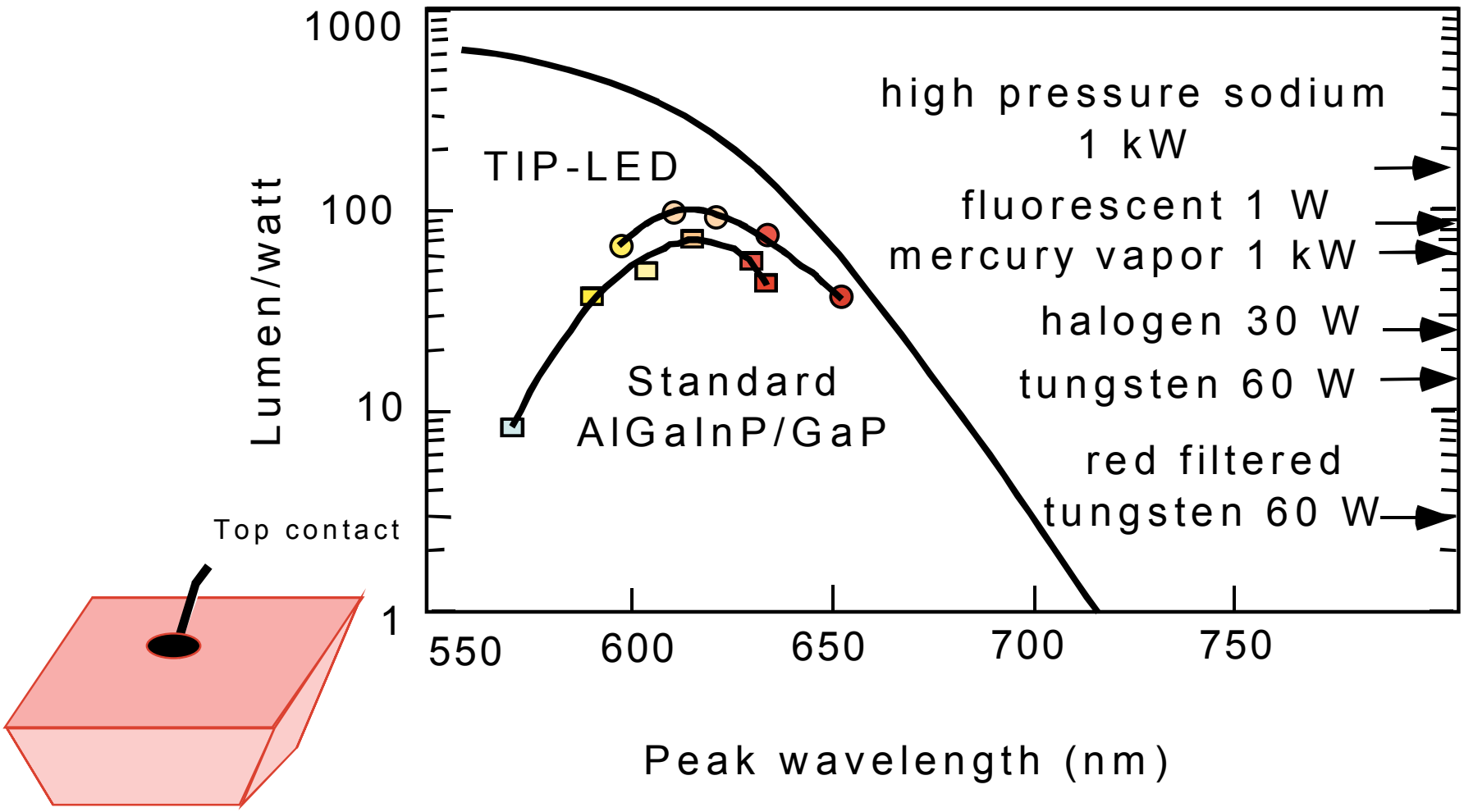
Shaped Chips: semi-spherical





From A. Zukauskas, M. S. Shur and R. Gaska, Introduction to Solid State Lighting, Wiley (2002)

Light Extraction : TIP-LEDs from LumiLeDs



After M.O. HOLCOMB *et al.* (2001), Compound Semiconductor **7**, 59, 2001).

WHITE SOLID-STATE LAMP

CRI for White Light

$$K = 683\ \mathrm{lm/W} \times \int_{380}^{780} V(\lambda) S(\lambda) d\lambda \Big/ \int_{0}^{\infty} S(\lambda) d\lambda \ ,$$

Spectral Range	Temperature (K)	Efficacy (lm/W)	General CRI
Full (Planckian)	2856	17	100
	4870	79	100
	6504	95	100
380 nm-780 nm (trimmed-Planckian)	2856	154	100
	4870	196	100
	6504	193	100
430 nm-660 nm (trimmed-Planckian)	2856	334	95
	4870	320	95
	6504	305	95

From A. Zukauskas, M. S. Shur and R. Gaska, Introduction to Solid State Lighting, Wiley (2002)

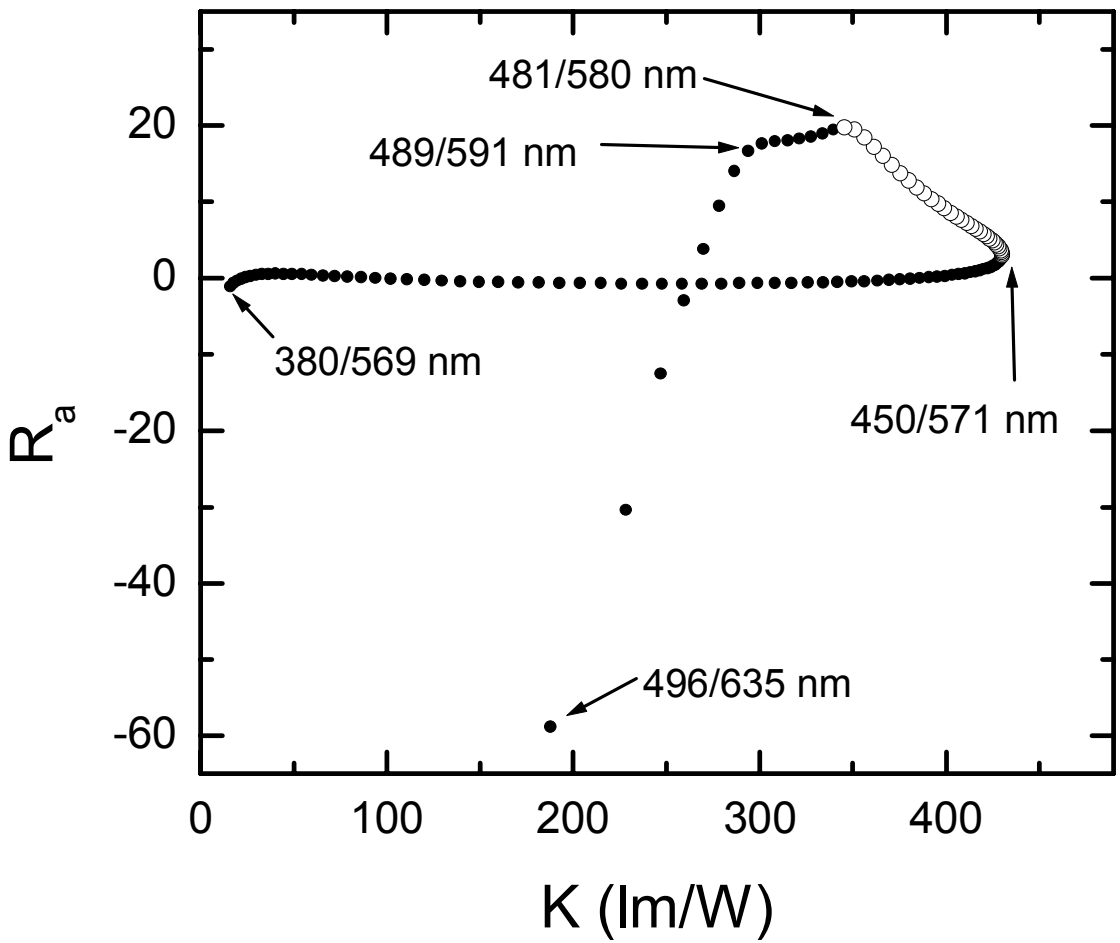
Optimization of White Polychromatic Semiconductor Lamp

Approach: Find the global maxima of the objective function for different values of σ.

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

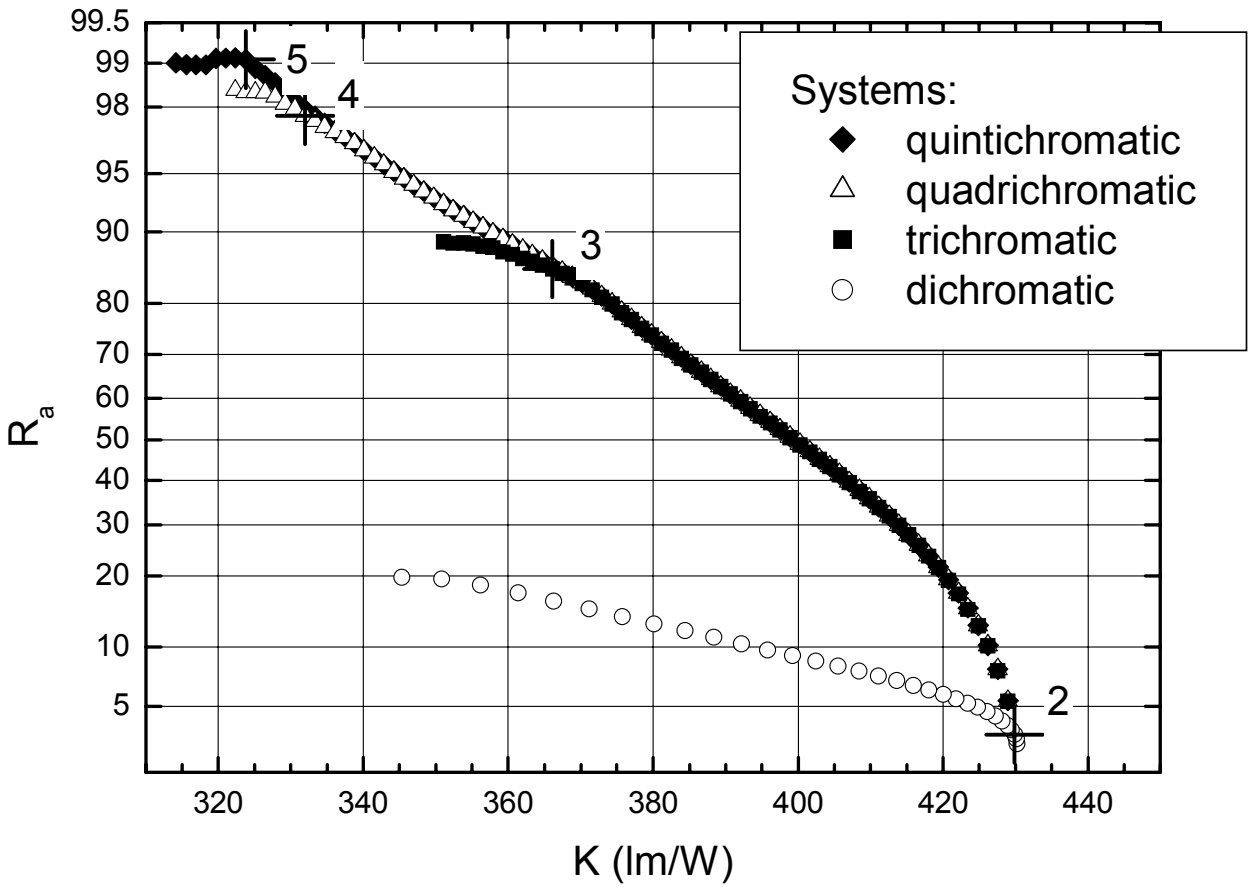
From A. Zukauskas, M. S. Shur and R. Gaska, Introduction to Solid State Lighting, Wiley (2002)

Phase distribution for a dichromatic white lamp with the 30-nm line width of the primary sources and 4870 K color temperature



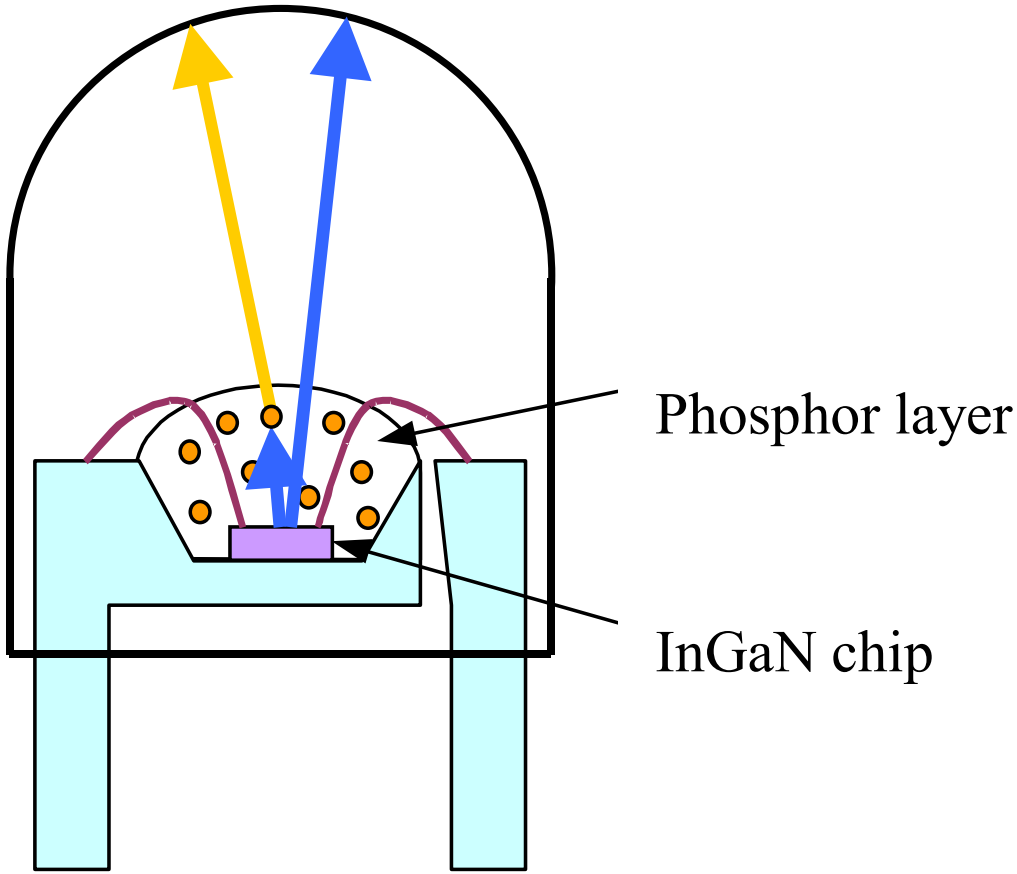
(after Žukauskas *et al.,* Appl. Phys. Lett. **80**, 2002).

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



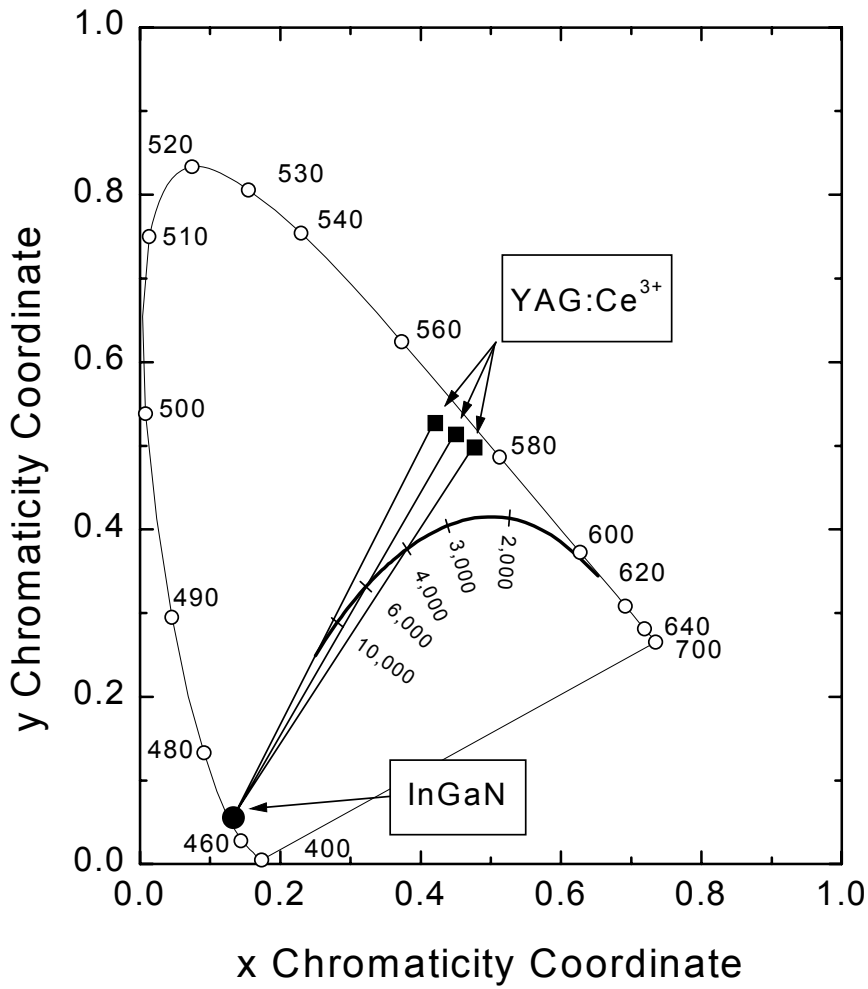
(after Žukauskas *et al.,* Appl. Phys. Lett. **80**, 2002). Crosses mark the points that are suggested for highest reasonable CRI for each number of the primary sources.

InGaN based luminescence conversion white LED



(after S.Nakamura and G.Fasol, *The Blue Laser Diode: GaN Based Light Emitters and Lasers,* Springer, Berlin, 1997)

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



From A. Zukauskas, M. S. Shur and R. Gaska, Introduction to Solid State Lighting, Wiley (2002)

MULTICHIP LED: 2 chip LEDs

Color Temperature (K)	Wavelength (nm)/Intensity		K (lm/W)	R_a
	λ_1/I_1	λ_2/I_2		
2856	450/0.157	580/0.843	492	-13
4870	450/0.325	572/0.675	430	3.0
6504	450/0.399	569/0.601	393	9.5

From A. Zukauskas, M. S. Shur and R. Gaska, Introduction to Solid State Lighting, Wiley (2002)

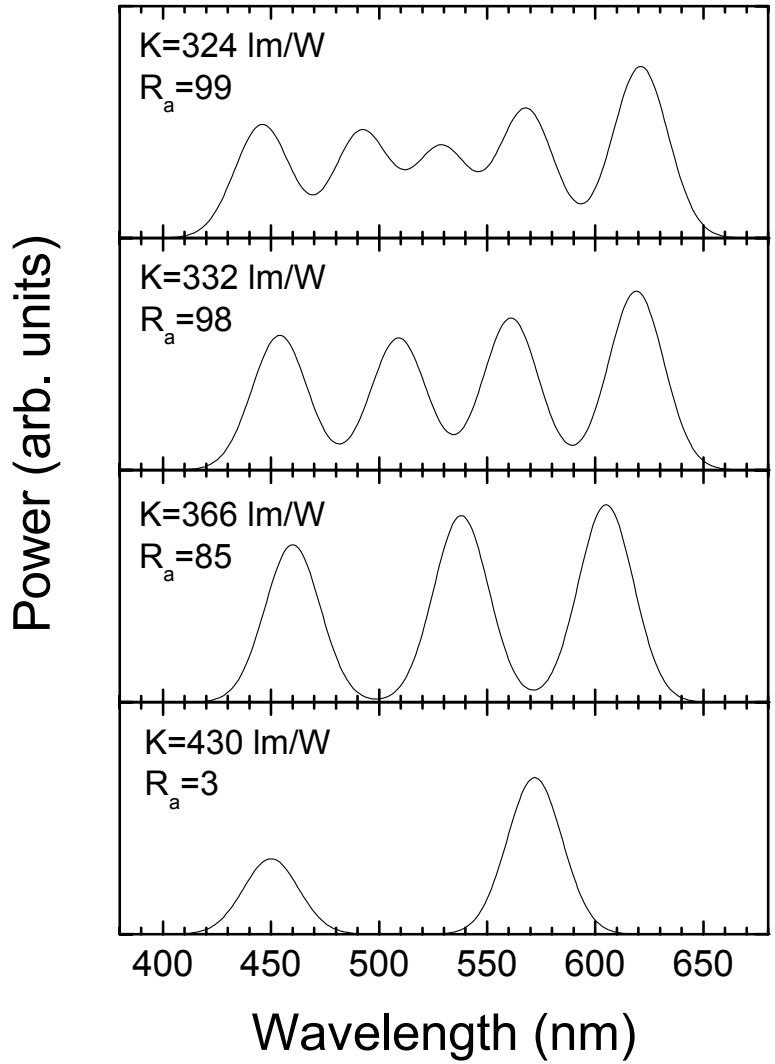
Optimized spectral power distributions

5 LEDs

4 LEDs

3 LEDs

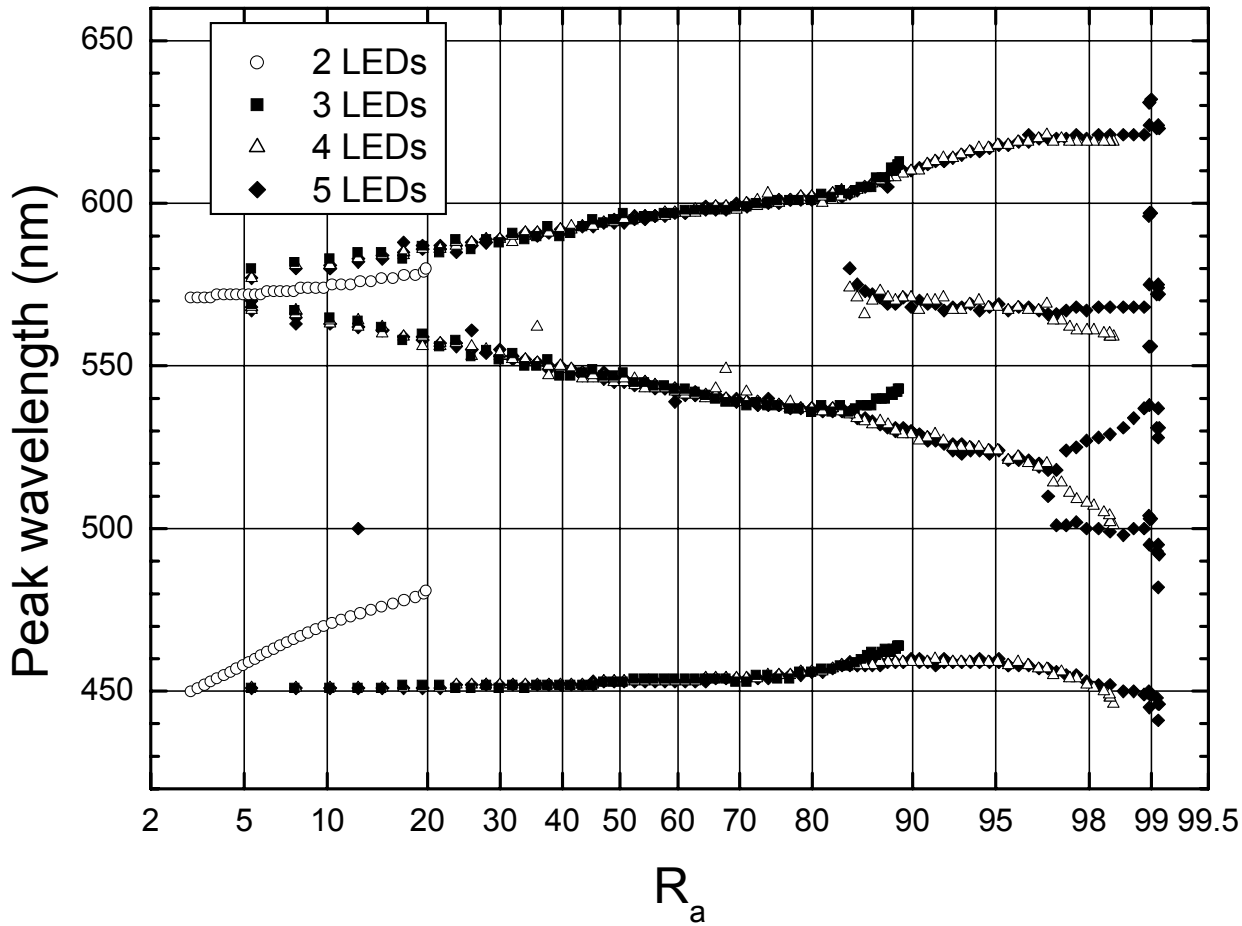
2 LEDs



After
A.Žukauskas *et al.*, *Appl. Phys. Lett.* **80**, 2002.

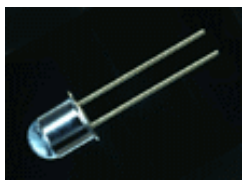
From A. Zukauskas, M. S. Shur and R. Gaska, Introduction to Solid State Lighting, Wiley (2002)

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



Type (mm)	Product Number	Peak Wavelength (nm)	Optical Power Output (μW)	Forward Voltage Vf (V) Typ.
Φ5	NSHU550	375	700	3.5
Φ5	NSHU590	375	700	3.5

After http://www.nichia.co.jp/product/led.html

Nichia White LEDs

Type (mm)	Product Number	Luminous Intensity (cd)	Forward Voltage Vf (V) Typ.	Directivity 2θ ½ (degree)
Φ3	NSPW300BS	3.2	3.6	25°
Φ3	NSPW310BS	1.5	3.6	60°
Φ3	NSPW312BS	2.2	3.6	35°
Φ3	NSPW315BS	0.78	3.6	70°
Φ5	NSPW500BS	6.4	3.6	20°
Φ5	NSPW510BS	1.8	3.6	50°
Φ5	NSPW515BS	0.48	3.6	70°
4.6	NSPWF50BS	0.3	3.6	140/120°

Nichia Blue LEDs

Product Number	Luminous Intensity (cd)	Forward Voltage Vf (V) Typ.	Max.	Directivity 2θ ½ (degree)
NSPB300A	2.3	3.6	4	15°
NSPB310A	1.2	3.6	4	30°
NSPB320BS	0.7	3.6	4	45°
NSPB500S	3.5	3.6	4	15°
NSPB510S	1.5	3.6	4	30°
NSPB520S	0.8	3.6	4	45°
NSPB636AS	0.55	3.6	4	70°/30

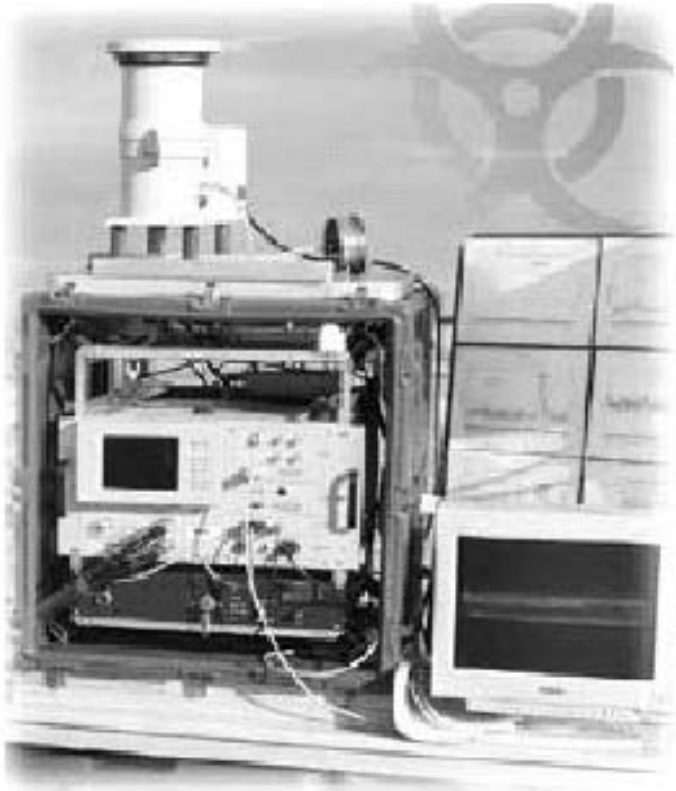
Applications (for 250 nm – 340 nm) Sensing and beyond

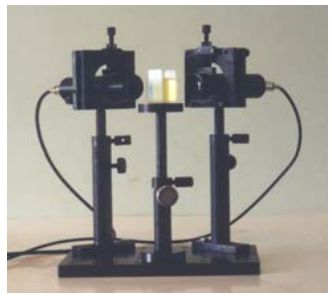
- Environmental protection
- Homeland security
- Biology
- Medicine
- Medical sterilization
- Bio-agent detection
- Water and air purification
- Solid-state white lighting
- Short-range secure communications
- Dense data storage
- Ballistic missile defense
- <u>To be emerged</u>

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

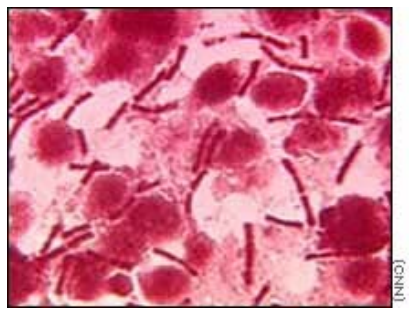
Existing and proposed UV LED based bio detection systems





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

Anthrax Bacteria

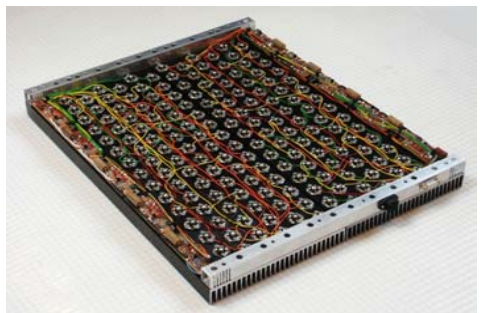


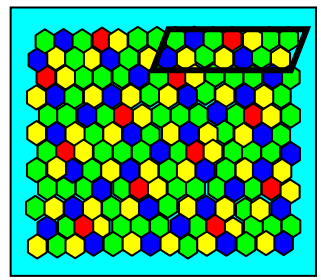
From Introduction to Biological Agent Detection Equipment for Emergency First Responders, U.S. Department of Justice Office of Justice Programs National Institute of Justice.

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



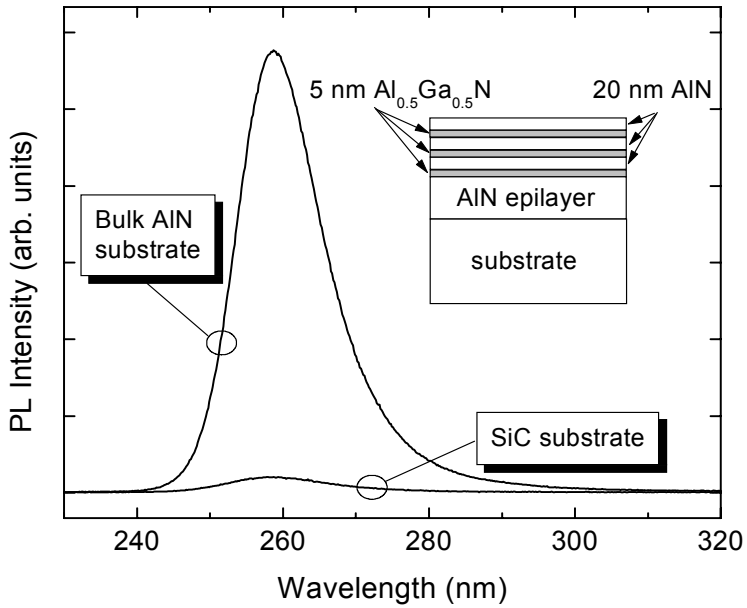


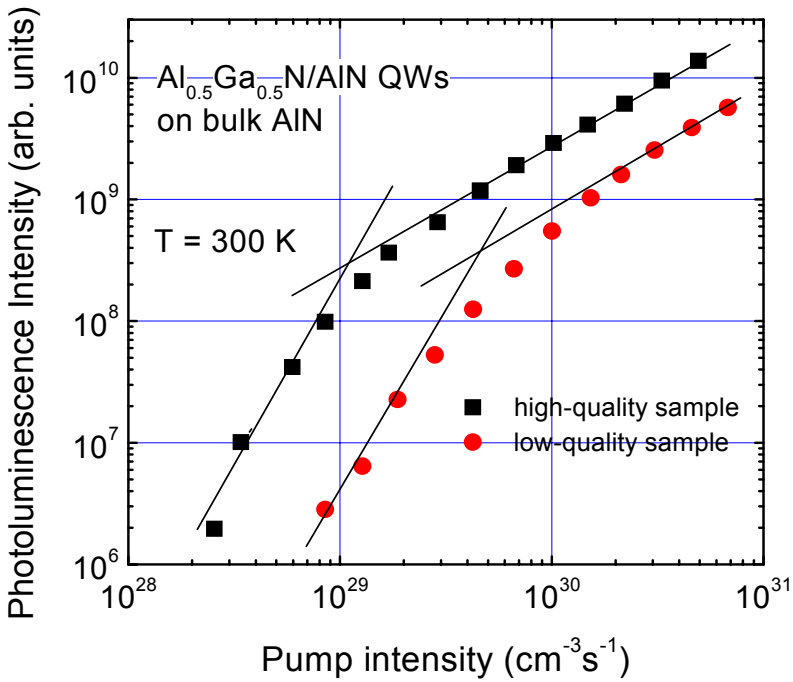
Multiple Quantum Well (50% Al Molar Fraction) Photoluminescence on SiC and Bulk AlN

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.

From R. Gaska, C. Chen, J. Yang, E. Kuokstis, A. Khan, G. Tamulaitis, I. Yilmaz, M. S. Shur, J. C. Rojo, L. Schowalter, . Deep-ultraviolet emission of AlGaN/AlN quantum wells on bulk AlN, accepted at APL

AlN/AlGaN Room Temperature Photoluminescence



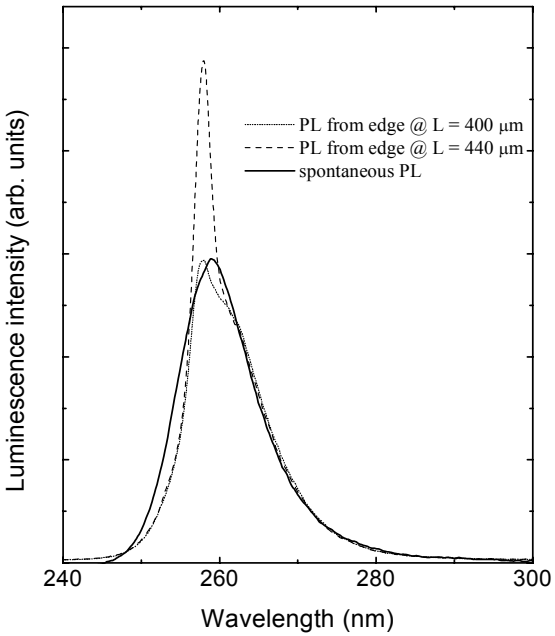


PL signal from MQWs on bulk AlN is approximately 28 times stronger compared to the structure grown over SiC.

PL signal from MQWs on bulk AlN for AlN/$Al_{0.5}Ga_{0.5}N$ QWs with 20 nm barriers and: 5 nm QWs; 2 nm QWs

From R. Gaska, C. Chen, J. Yang, E. Kuokstis, A. Khan, G. Tamulaitis, I. Yilmaz, M. S. Shur, J. C. Rojo, L. Schowalter, . Deep-ultraviolet emission of AlGaN/AlN quantum wells on bulk AlN, accepted at APL

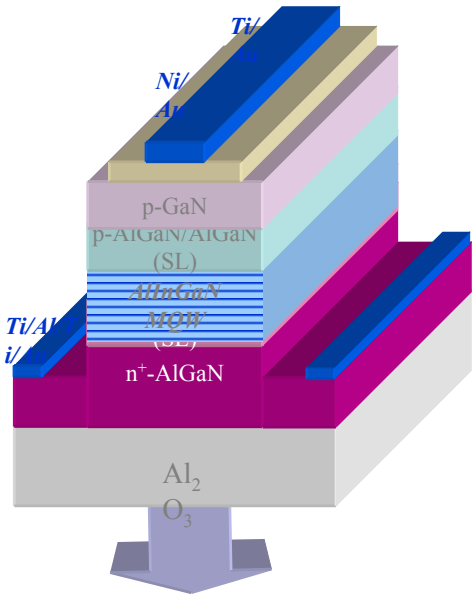
Stimulated Emission

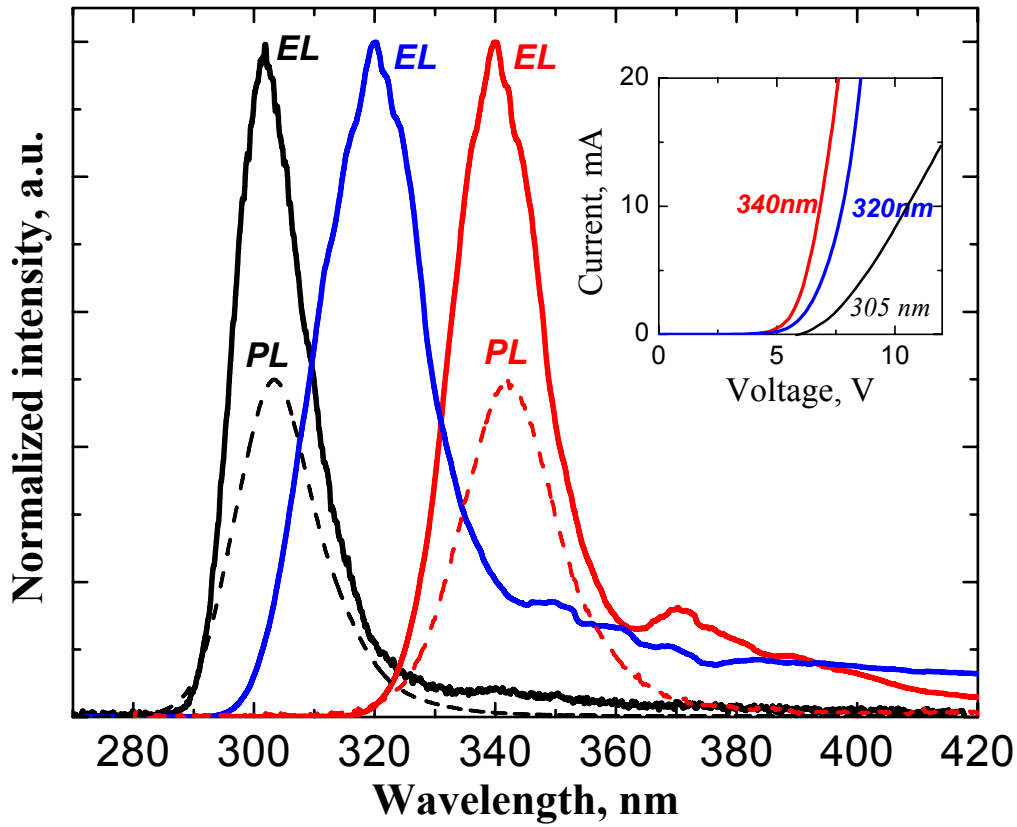


Photoluminescence spectra of Al0.5Ga0.5N/AlN MQWs deposited on bulk AlN. Solid curve represents the spectrum of spontaneous emission detected in the direction perpendicular to the sample surface; dotted and dashed curves correspond to the spectra measured from the sample edge along the direction of a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

From R. Gaska, C. Chen, J. Yang, E. Kuokstis, A. Khan, G. Tamulaitis, I. Yilmaz, M. S. Shur, J. C. Rojo, L. Schowalter, . Deep-ultraviolet emission of AlGaN/AlN quantum wells on bulk AlN, accepted at APL

AlInGaN-based UV LEDs on Sapphire Substrates



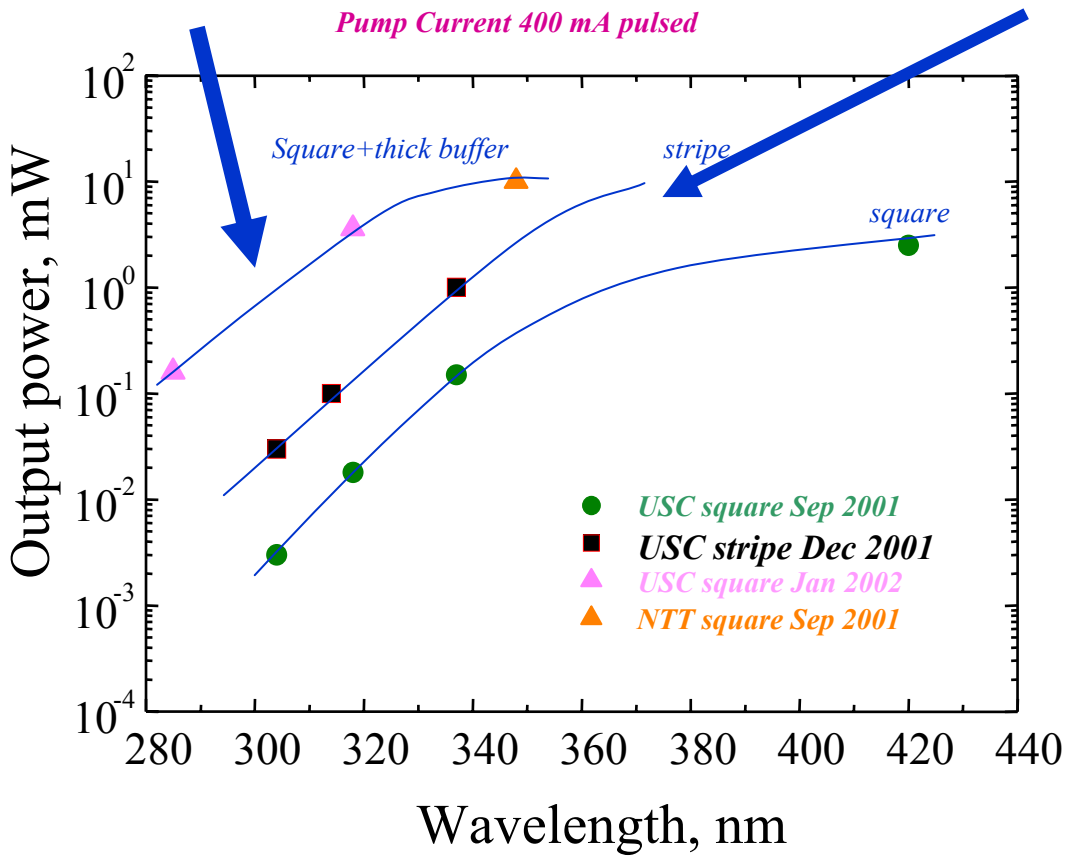


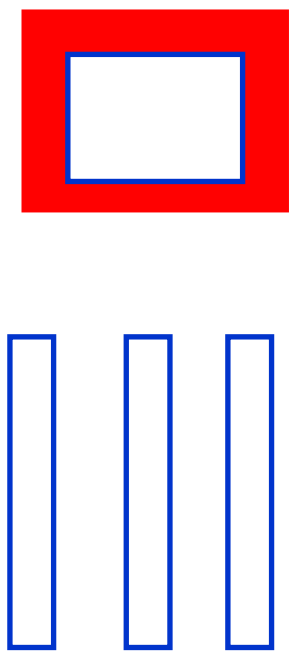
M. Asif Khan, Vinod Adivarahan, Jian Ping Zhang, Changqing Chen, Edmundas Kuokstis, Ashay Chitnis, Maxim Shatalov, Jin Wei Yang, Grigory Simin Stripe Geometry Ultraviolet Light Emitting Diodes at 305 nanometers using quaternary AlInGaN multiple quantum wells, Jpn. J. Appl. Phys. Vol. 40 (2001) pp. L 1308-L 1310

AlInGaN-based UV LEDs on Sapphire Substrates

Improve light extraction

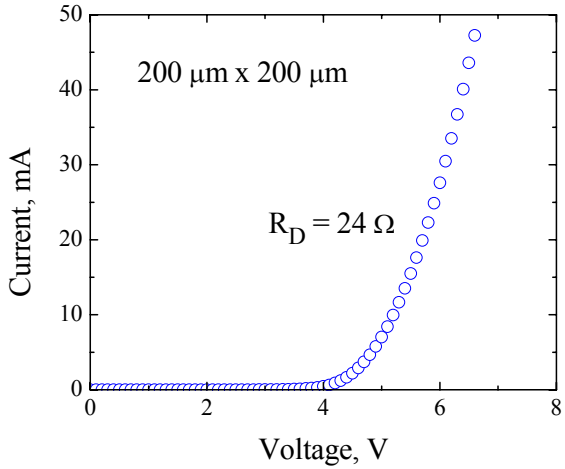
Control current crowding

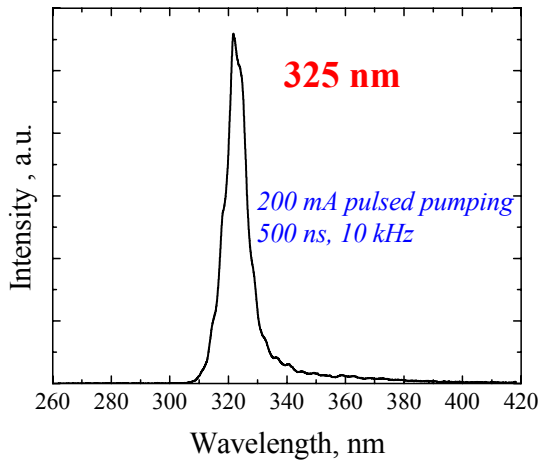


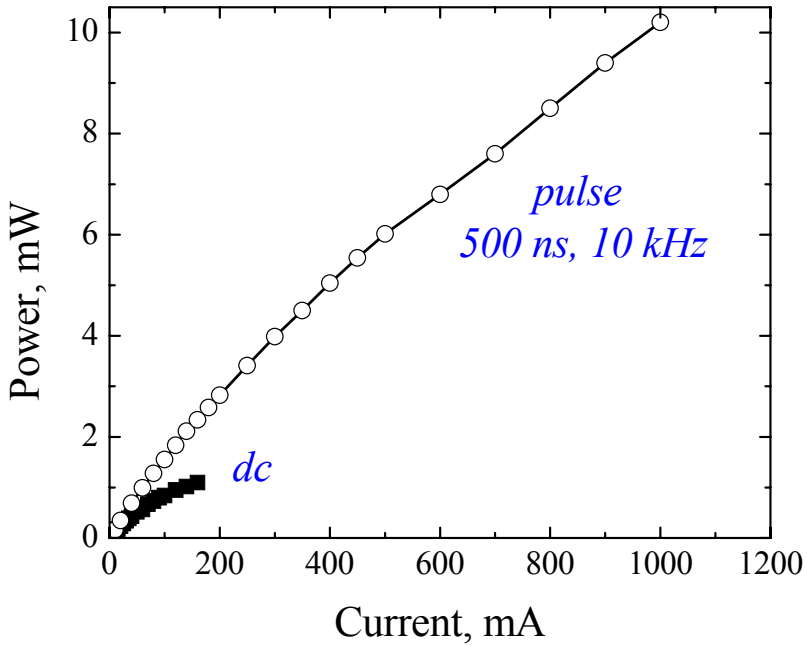


M. Shatalov, G. Simin, V. Adivarahan, A. Chitnis, S. Wu, R. Pachipulusu, K. Simin, J. P. Zhang, J. W. Yang, and M. Asif Khan . Lateral Current Crowding in Deep UV Light Emitting Diodes over Sapphire Substrates. Jpn. J. Appl. Phys. Vol. 41 (2002) pp. 5083-5087 Part 1, No. 8, August 2002

10 mW 325 nm UV LED on Sapphire

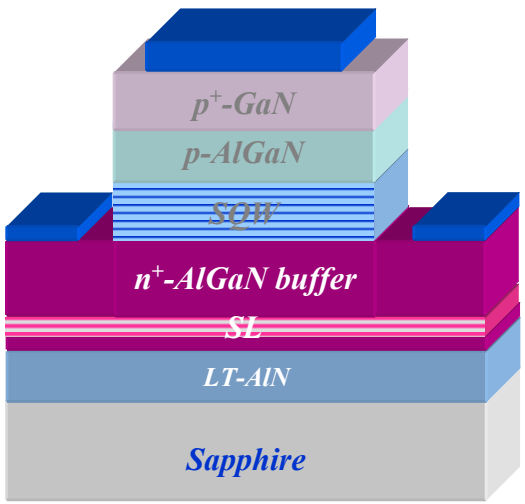


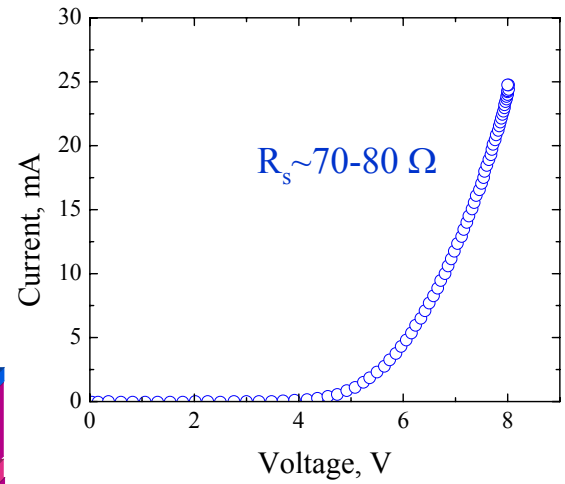


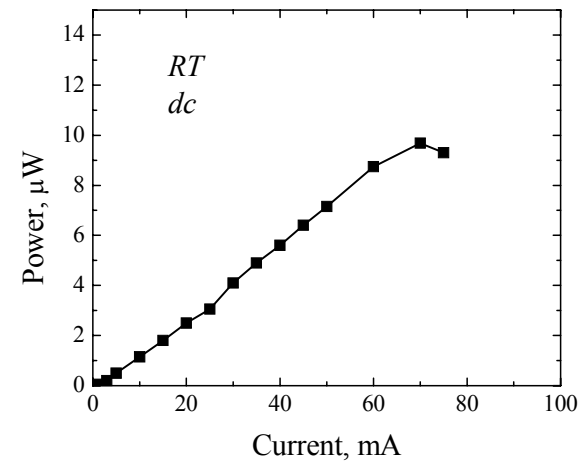


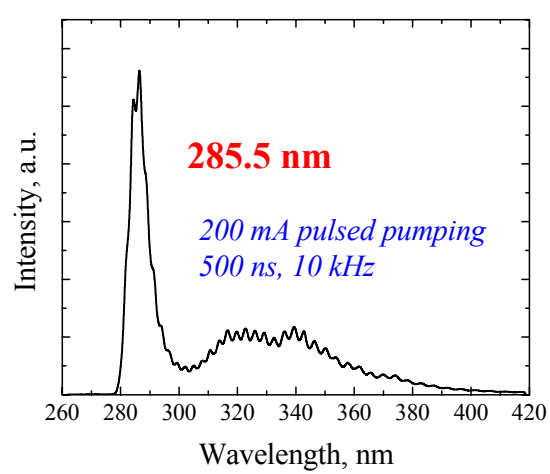
A. Chitnis, J. P. Zhang, V. Adivarahan, M. Shatalov, S. Wu, R. Pachipulusu, V. Mandavilli, and M. Asif Khan
Improved performance of 325-nm emission AlGaN ultraviolet light-emitting diodes. Appl. Phys. Lett., 82, pp. 2565-2567 (2003)

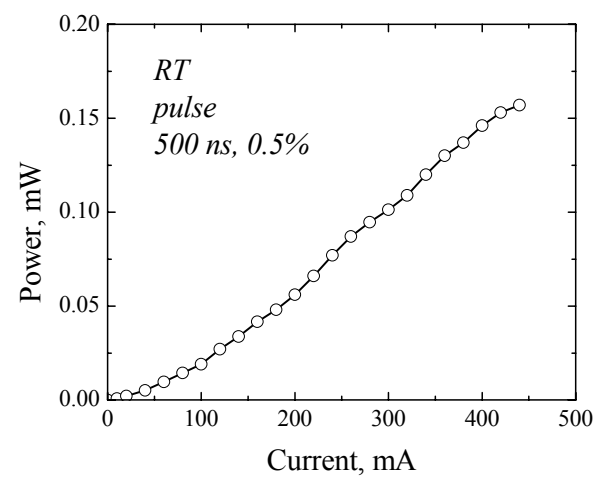
Sub-milliwatt power 285 nm Emission UV LED on Sapphire.







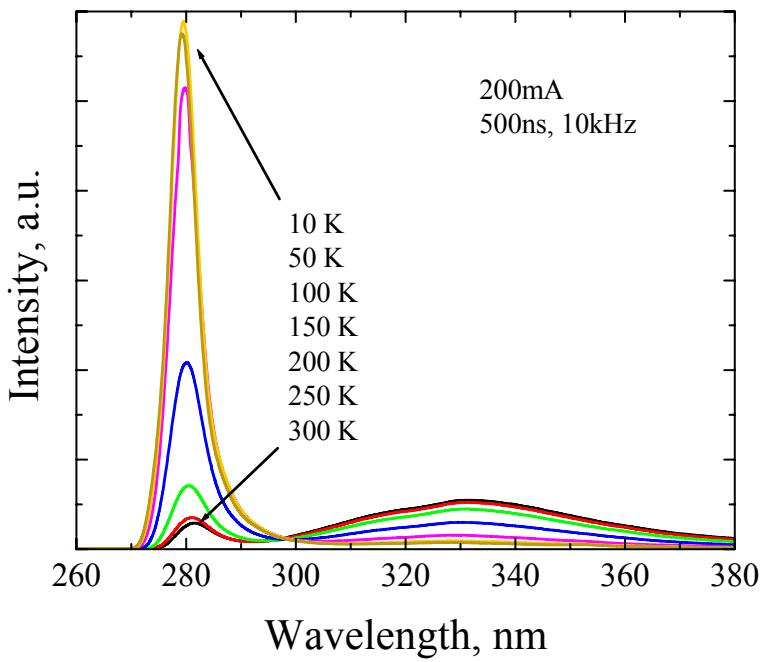


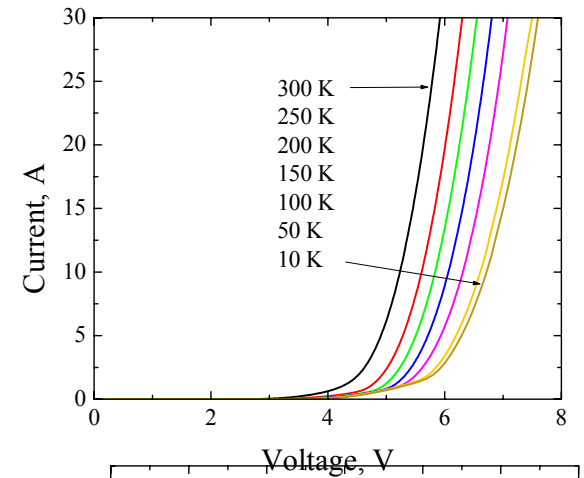


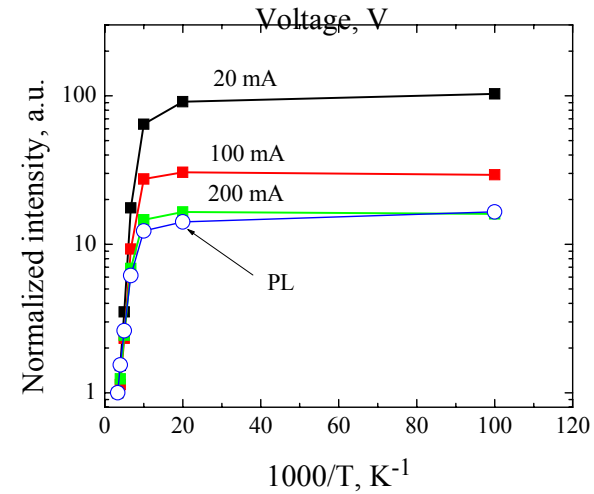
V. Adivarahan et al., Jpn. J. Appl. Phys. Lett., ***41****, L435 (2002)*

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

285 nm Emission UV LED
Low temperature performance





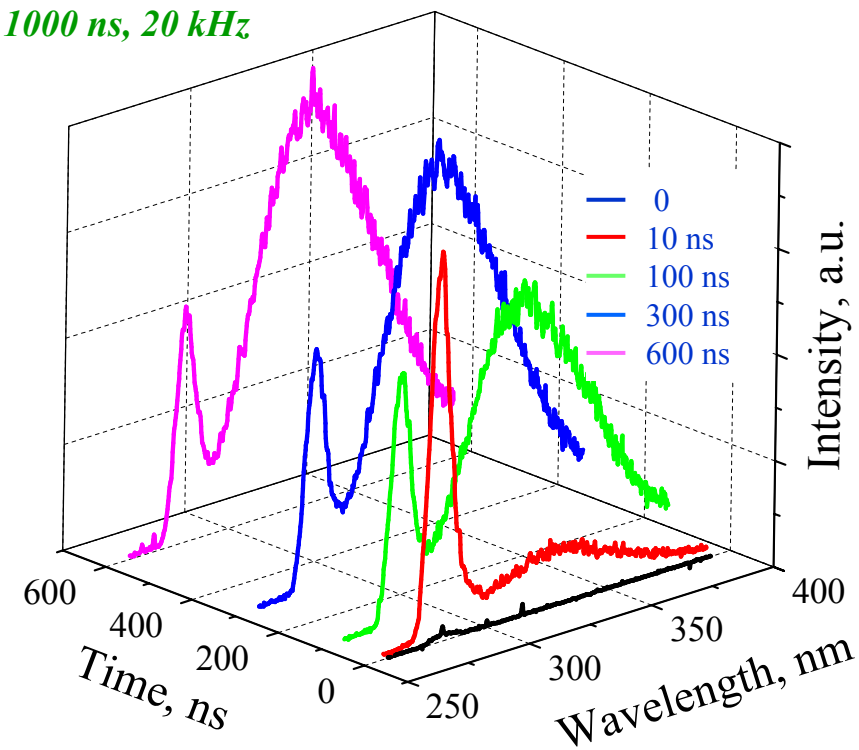


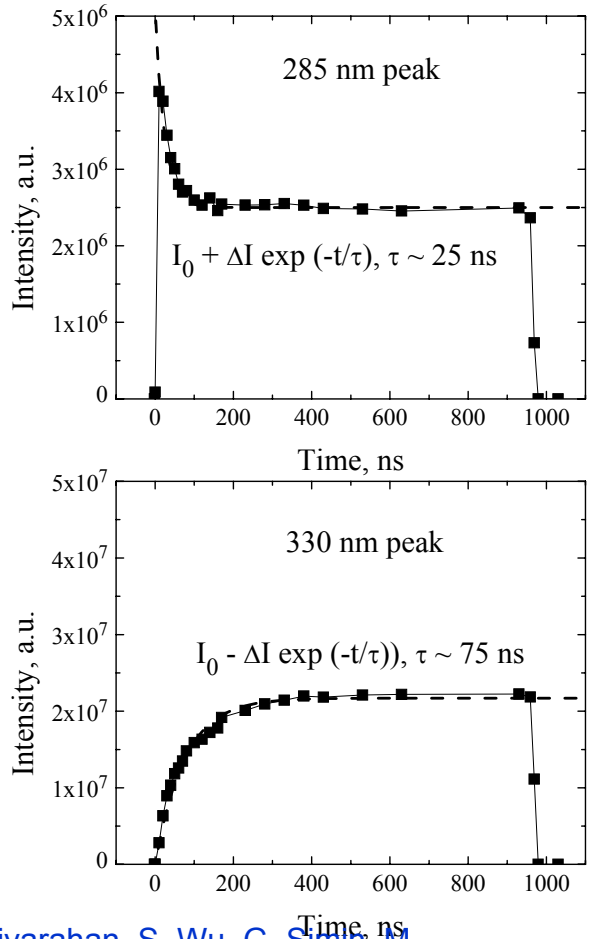
A. Chitnis, R. Pachipulusu, V. Mandavilli, M. Shatalov, E. Kuokstis, J. P. Zhang, V. Adivarahan, S. Wu, G. Simin, and M. Asif Khan. Low-temperature operation of AlGaN single-quantum-well light-emitting diodes with deep ultraviolet emission at 285 nm. APL, 81, 2938-2940 (2002)

285 nm Emission UV LED

Time resolved electroluminescence

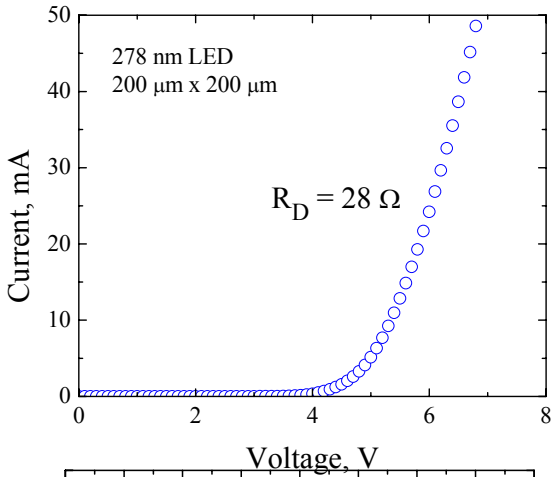
70 mA current pulse
1000 ns, 20 kHz

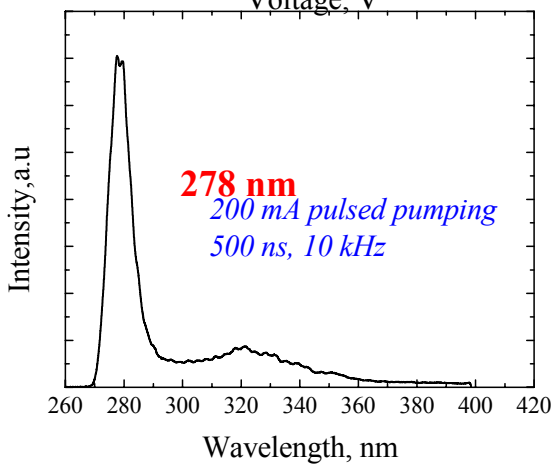


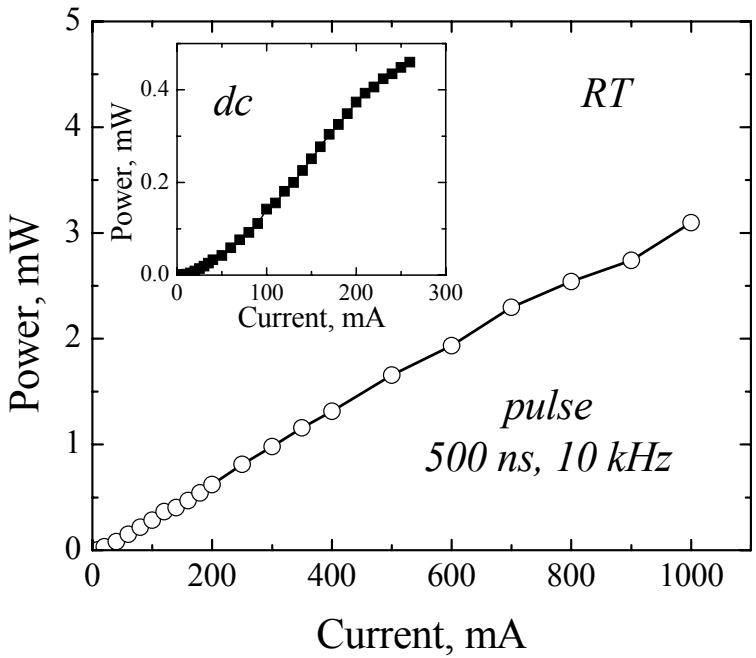


M. Shatalov, A. Chitnis, V. Mandavilli, R. Pachipulusu, J. P. Zhang, V. Adivarahan, S. Wu, G. Simin, M. Asif Khan, G. Tamulaitis, A. Sereika, I. Yilmaz, M. S. Shur and R. Gaska, Time-resolved electroluminescence of AlGaN-based light-emitting diodes with emission at 285 nm, Appl. Phys. Lett. 82, Issue 2, pp. 167-169 (2003)

Milliwatt power 278 nm UV LED on Sapphire. Modified design



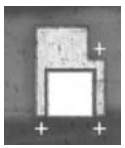




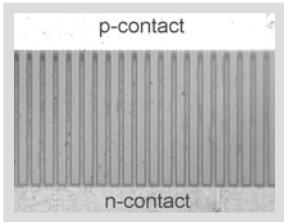
J. P. Zhang, A. Chitnis, V. Adivarahan, S. Wu, V. Mandavilli, R. Pachipulusu, M. Shatalov, G. Simin, J. W. Yang, and M. Asif Khan, Milliwatt power deep ultraviolet light-emitting diodes over sapphire with emission at 278 nm, Appl. Phys. Lett. 81, 4910-4912 (2002)

Thermal and current crowding management

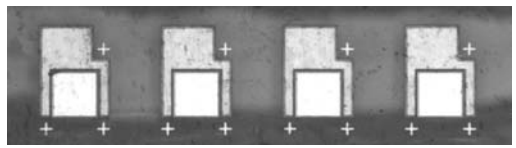
Square geometry

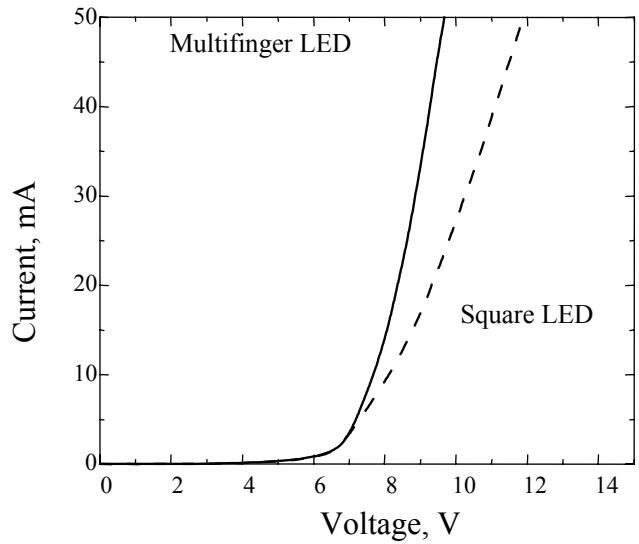


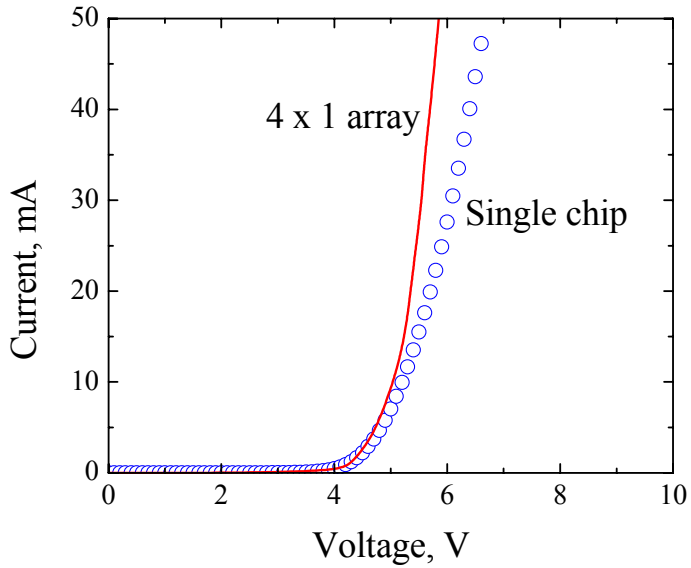
Inter-digitated fingers



LED arrays







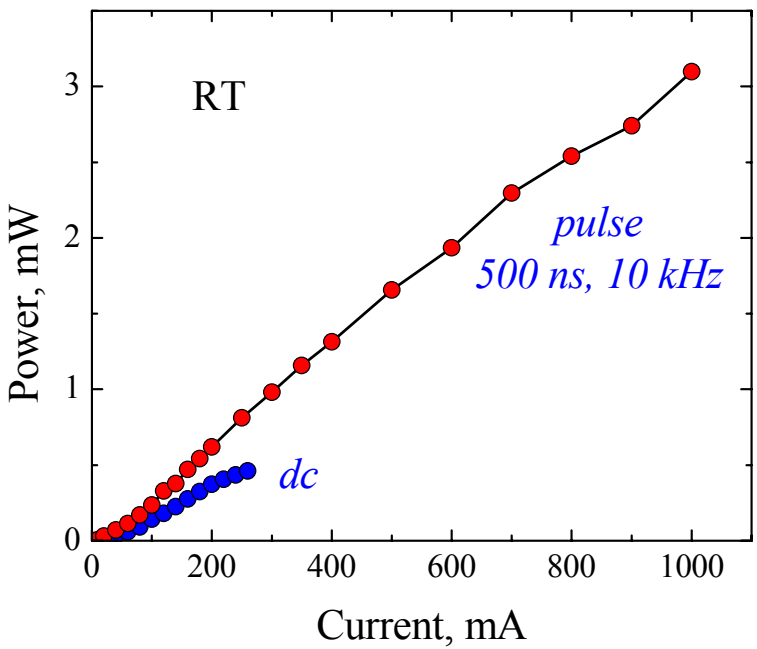
A. Chitnis et al., Jpn. J. Appl. Phys. Lett., ***41****, L320 (2002)*

278 nm / 325 nm LED comparison

278 nm Emitting LED

3 mW

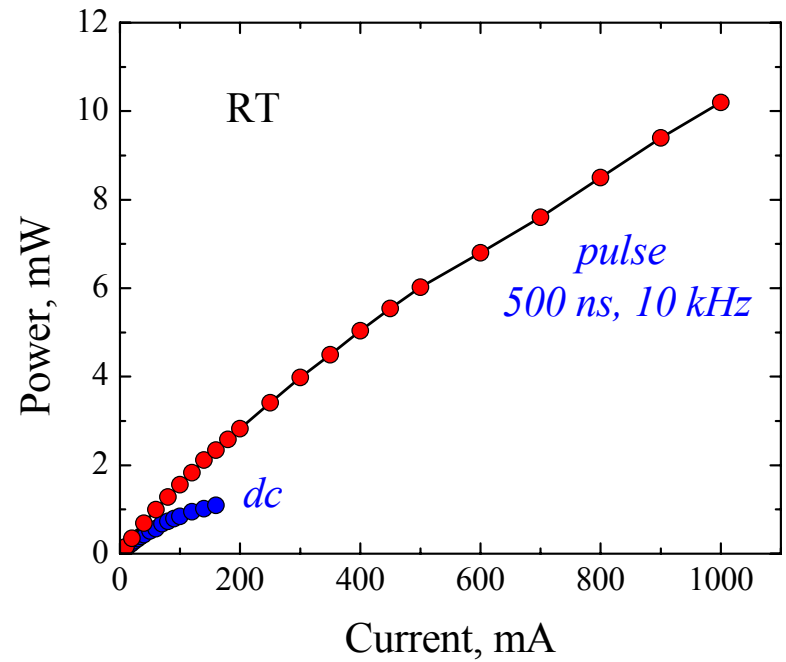
1 A pulsed



325 nm Emitting LED

10 mW

1 A pulsed



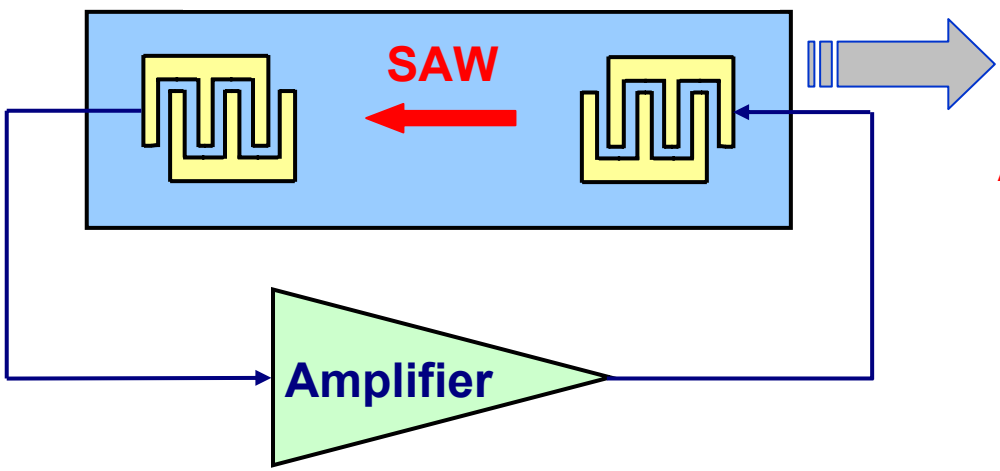
J. P. Zhang, A. Chitnis, V. Adivarahan, S. Wu, V. Mandavilli, R. Pachipulusu, M. Shatalov, G. Simin, J. W. Yang, M. Asif Khan, Milliwatt Power Deep Ultraviolet Light Emitting Diodes over Sapphire with Emission at 278 nm. APL vol. 81, No. 26, pp. 4910-4912 (2002) ; A. Chitnis, J. P. Zhang, V. Adivarahan, M. Shatalov, S. Wu, R. Pachipulusu, V. Mandavilli, M. Asif Khan. Improved performance of 325-nm emission AlGaN ultraviolet light-emitting diodes. APL vol. 82, No. 16, pp. 2565-2567 (2003)

SAW Oscillator/Photodetector

BASICS OF SURFACE ACOUSTIC WAVE DELAY-LINE OSCILLATOR

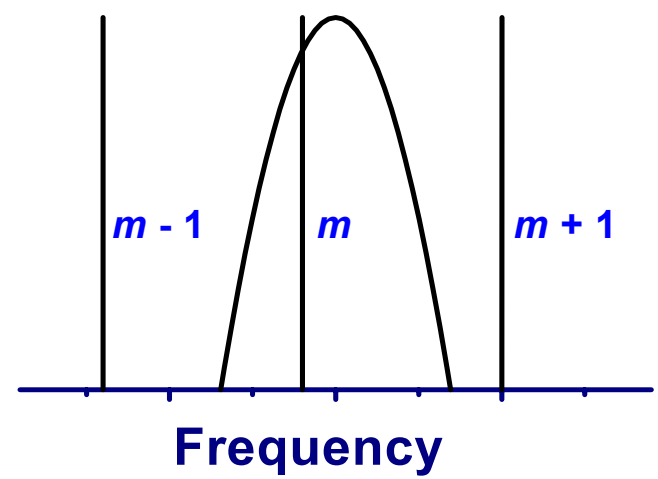
$$\frac{\Delta f}{f} = \left(\frac{\Delta V}{V} \frac{L_{UV}}{L} \right)$$

Velocity change



Amplitude condition

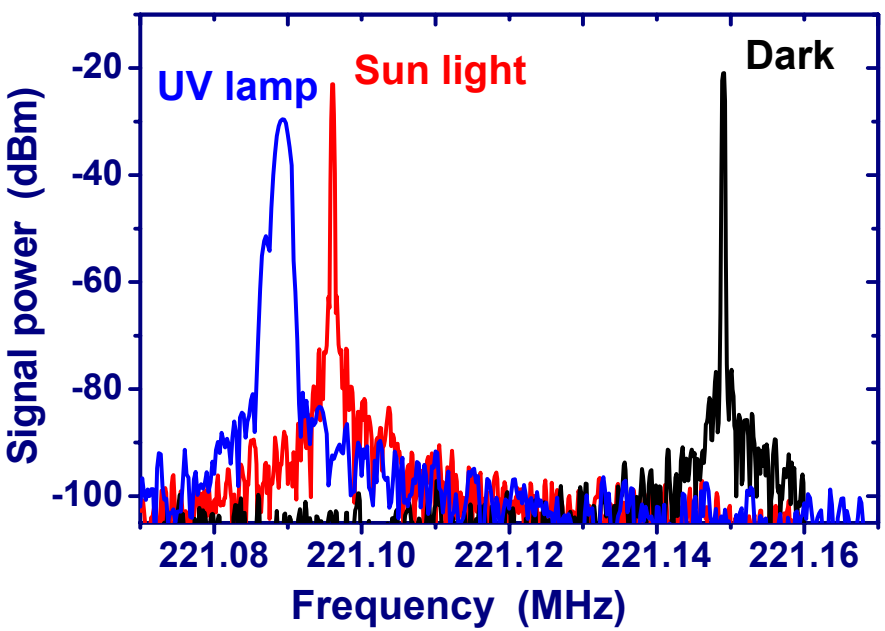
Gain > Loss

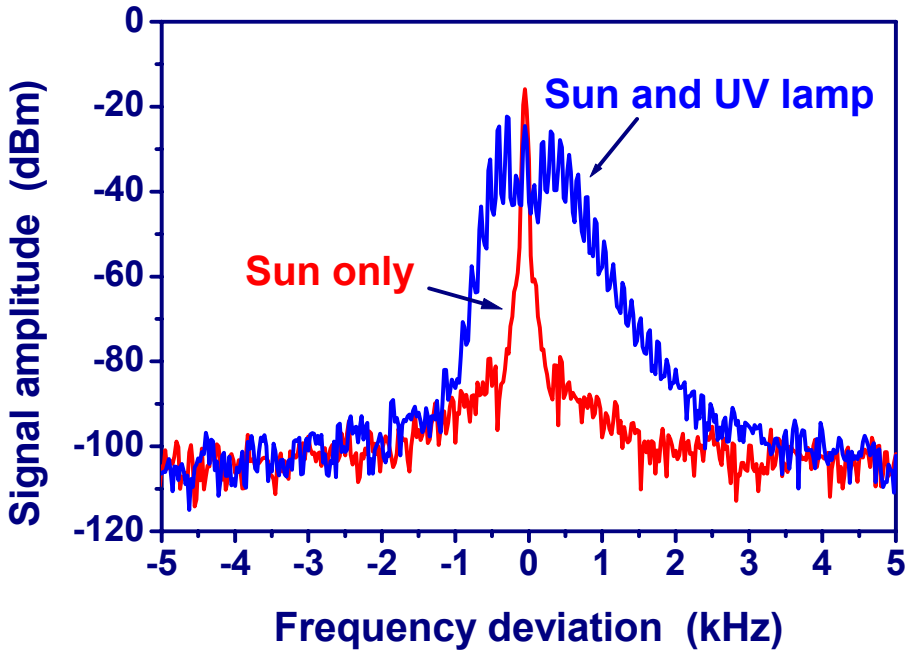


Phase condition

$$\frac{2\pi f L}{V} + \phi = 2m\pi$$

Response to Artificial Light Sources and Sunlight





D. Ciplys, R. Rimeika, M.S. Shur, R. Gaska, A. Sereika, J. Yang, M. Asif Khan, "Radio frequency response of GaN-based SAW oscillator to UV illumination by the Sun and man-made source", Electronics Letters, vol. 38, no. 3, pp. 134-135, 2002

SOME of LED WEB SITES

- http://www.misty.com/people/don/led.html
- http://www.luxeon.com/index.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 for 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_3N_4 allow us to obtain superior HFET performance
- Nitrides hold promise of solid state lighting
- Nitride deep UV emitters and detectors have been demonstrated