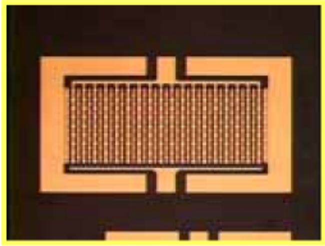
Basics of III-nitride-based devices

Light emitters

LEDs
- Homo and Hetero-epitaxy
- LED chip design and characterization
- UV LED Development

Microwave Devices

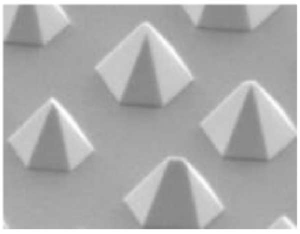


GaN HEMT

- High power, high frequency transistors development *(For communications)*

UV detectors

- Device design, epi-growth and performance

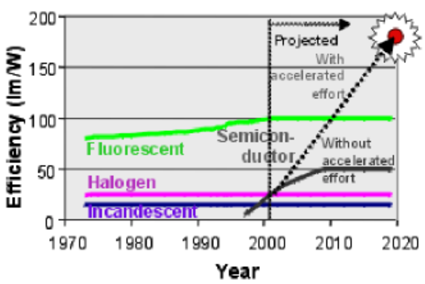


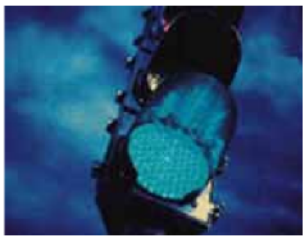
Other important nitride devices include laser diodes, HBT， power devices, various harsh-environmental sensors, mems, bio-related stuff as well as novel applications.

Solid State Lighting

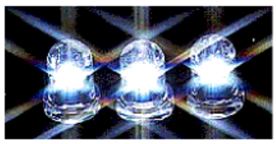
VS.

Some Advantages:
- Operating Life (10× Incandescent, 5× Halogen)
- Durability
- Compactness
- Cool Operation
- Directional
- Efficiency (~3× less electricity used)
- Better Color Rendition (Dimmable)
- Use of the semiconductor infrastructure



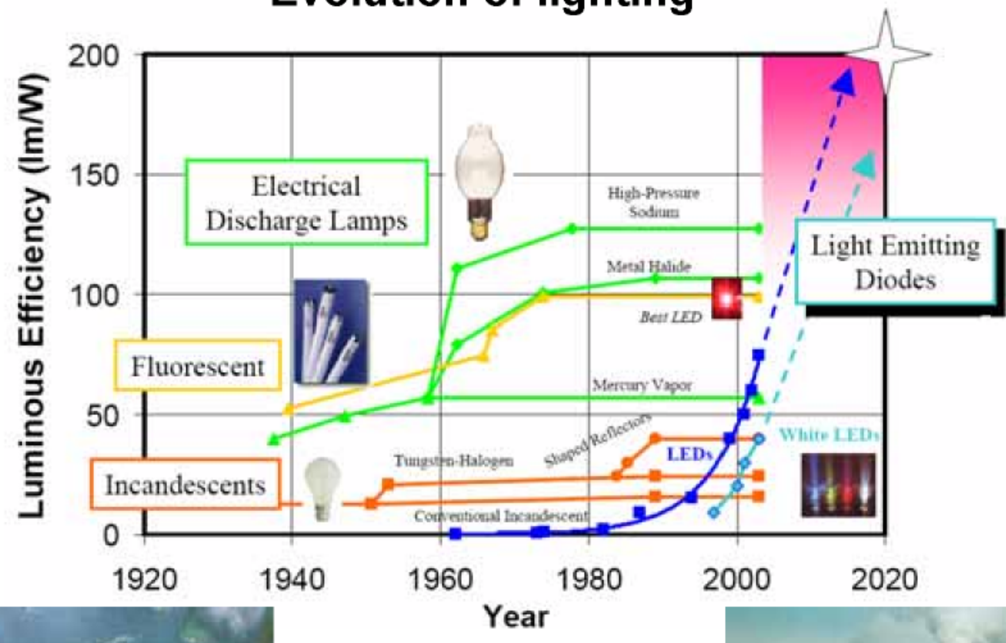


Signals / Signs



White Lighting

Evolution of lighting



SSL saves energy, $$$, and benefits environments

LED performance

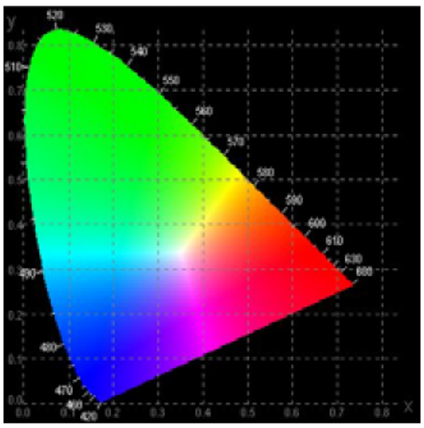
- Total luminous flux
- Luminous intensity
- Color (CCT, CRI)
- Electrical (voltage, current, power)
- Life testing/estimating

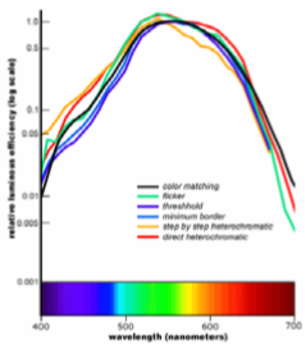
And others……

$$\eta int = \frac{\#\text{ of photons emitted from active region per second}}{\#\text{ of electrons injected in to LED per second}} = \frac{Pint / (hv)}{I / e}$$

$$\eta extr = \frac{\#\text{ of photons emitted into free space per second}}{\#\text{ of photons emitted from active region per second}} = \frac{P / (hv)}{Pint / (hv)}$$

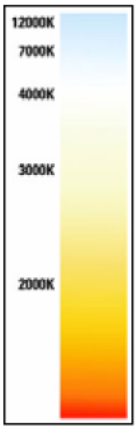
External quantum effi.=Internal quantum effi. x light extrac. effi.





Color LED: mW vs. White LED: Lumen
Wall-plug efficiency vs. luminous efficiency
Color temperature vs. color rendering index
Internal quantum efficiency vs. external quantum efficiency

- Candela (cd) = lm/sr, a LED with high mcd doesn't mean it must be efficient.
- Lumen involves the spectral sensitivities of human eyes.

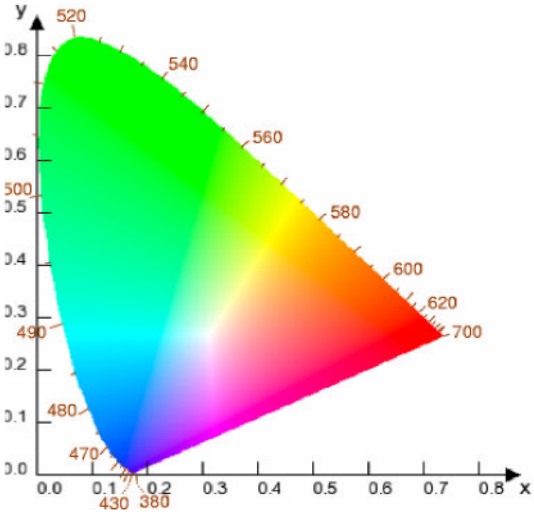


Color temperature

When we say a lamp has a Color Temperature of 3000 Kelvins, it means a glowing metal at 3000 Kelvins would produce light of about the same color as the lamp. Instead, if the metal is heated to 4100 Kelvins, it will produce a much whiter light. Direct sunlight corresponds to about 5300 Kelvins while daylight, which has the blue from the sky mixed in, is typically 6000 Kelvins or above. A standard incandescent lamp has a filament at 2700 Kelvins, and therefore (by definition) a Color Temperature of 2700 Kelvins.

Color Rendering Index

The three "primary" colors are dubbed "X," "Y," and "Z." If we are merely concerned about color and not about brightness, we can specify just the relative strengths of these three colors, denoted by x, y and z. Since x + y + z must add up to 1 (i.e. 100%) just providing x and y is sufficient to specify lamp color; the z value is implied. Lamp color can then be represented on a two-dimensional plot of x and y.



A typical product on the market

sr = 2 π (1 - cos(θ /2))

1 cd = 1 lm/sr

Application notes:

• The total light output (luminous flux) of a 40-watt incandescent light bulb is about 500 lm, while that of a 40-watt fluorescent tube is about 2300 lm.

• **Question**: How bright is an IR LED?
Answer: 0 mcd.

• when buying LEDs for illuminating purposes - a 2000 mcd 30° LED puts out just as much light as an 8000 mcd LED with a 15° viewing angle. (The angle is half in both width and height, so the beam is *four* times as bright.) This is one of the reasons that ultra-bright LEDs are often "water clear", to keep the light going in one direction and not diffuse it all over the place.

SPECIFICATIONS FOR NICHIA **WHITE** LED

MODEL : **NSPW500BS**

1.SPECIFICATIONS

(1) Absolute Maximum Ratings (Ta=25°C)

Item	Symbol	Absolute Maximum Rating	Unit
Forward Current	I_F	30	mA
Pulse Forward Current	I_{FP}	100	mA
Reverse Voltage	V_R	5	V
Power Dissipation	P_D	120	mW
Operating Temperature	T_{opr}	-30 ~ + 85	°C
Storage Temperature	T_{stg}	-40 ~ +100	°C
Soldering Temperature	T_{sld}	265°C for 10sec.	

I_{FP} Conditions : Pulse Width ≦ 10msec. and Duty ≦ 1/10

(2) Initial Electrical/Optical Characteristics (Ta=25°C)

Item		Symbol	Condition	Min.	Typ.	Max.	Unit
Forward Voltage		V_F	I_F=20[mA]	-	3.6	4.0	V
Reverse Current		I_R	V_R= 5[V]	-	-	50	µA
Luminous Intensity	Rank T	Iv	I_F=20[mA]	11000	12600	15500	mcd
	Rank S	Iv	I_F=20[mA]	7800	9200	11000	mcd
	Rank R	Iv	I_F=20[mA]	5520	6400	7800	mcd

∗ Luminous Intensity Measurement allowance is ± 10%.

Color Ranks (I_F=20mA,Ta=25°C)

	Rank a0			
x	0.280	0.264	0.283	0.296
y	0.248	0.267	0.305	0.276

	Rank b1			
x	0.287	0.283	0.330	0.330
y	0.295	0.305	0.360	0.339

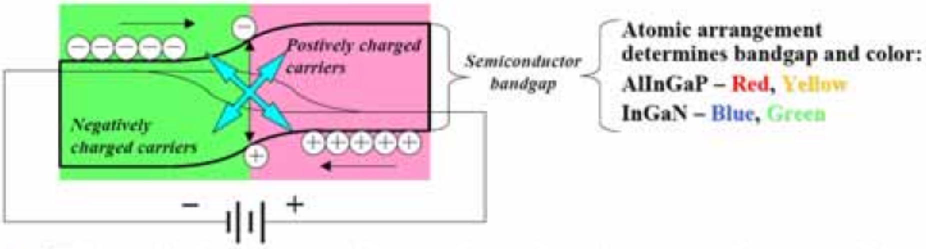
	Rank b2			
x	0.296	0.287	0.330	0.330
y	0.276	0.295	0.339	0.318

	Rank c0			
x	0.330	0.330	0.361	0.356
y	0.318	0.360	0.385	0.351

∗ Color Coordinates Measurement allowance is ± 0.01.

∗ One delivery will include up to two consecutive color ranks and three luminous intensity ranks of the products. The quantity-ratio of the ranks is decided by Nichia.

What is a light emitting diode?



- With applied voltage positive and negative charge carriers recombine
- Energy may be released as light or heat
- Fundamentally a non-destructive process

Internal Efficiency x Extraction Efficiency = External Efficiency

- Material Quality
- Layer Structure and composition

- Geometry of Chip
- Absorption Losses in Chip

For a single PN junction LED, The external efficiency is limited by:

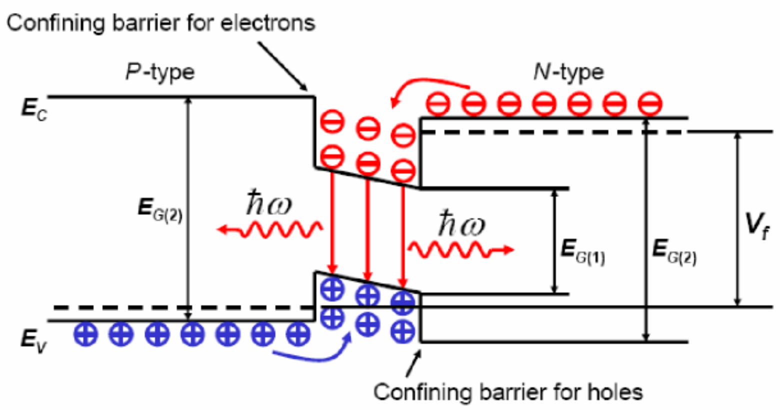
- Full internal reflection at the semiconductor surface

Typically, not more than 1-2 % of emitted light can leave a flat-surface diode. Refraction coefficient for semiconductors is large (n = 3.5 for GaAs) and the critical angle is very small.

- Reabsorption within the diode

Up to 90 % of emitted light may be re-absorbed

Double-heterojunction light emitting diode



Important advantages

(1) $$\hbar\omega \cong E_{G(1)} < E_{G(2)}$$

Therefore, outer layers are transparent and don't absorb the emitted light.

There is **no reabsorption**.

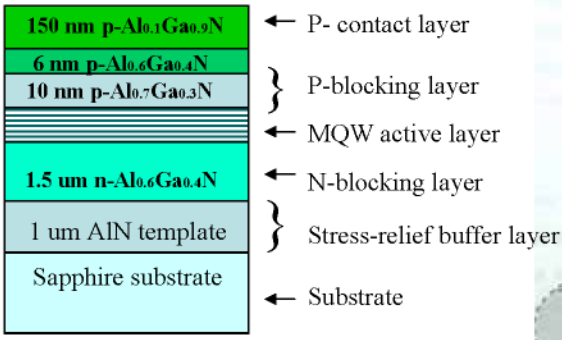
(2)

Due to the barriers, injected electrons and holes **are confined** in the inner layer.

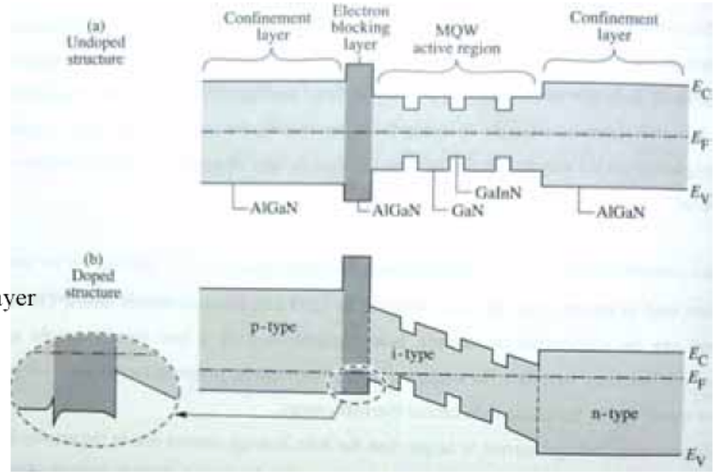
Therefore, **heavy injection** (accumulation of large number of electrons and holes) in the inner layer is possible.

This strongly **improves the internal recombination efficiency** (decreases the radiative-recombination time, increases **maximum frequency**)

InGaN-based light emitting diode

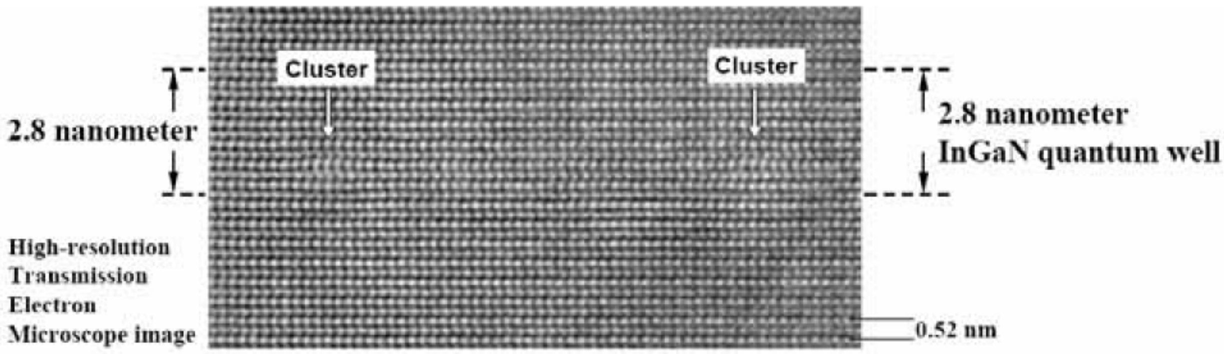


Schematic of a UV-LED epilayer

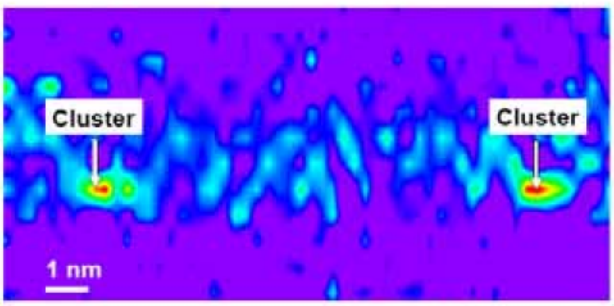


• Electron Blocking Layers are required to prevent electron escape at high injection current densities
• LEDs emit slightly different colors at different temperatures. They also emit different colors at different currents, especially white LEDs which depend on phosphors to change the colored light of the die to white light

Nanoscale In-clustering in InGaN light generation region



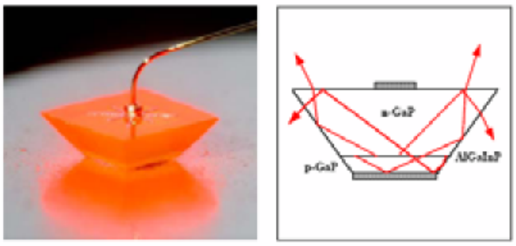
False-color image emphasizing changes in spacing of atomic columns



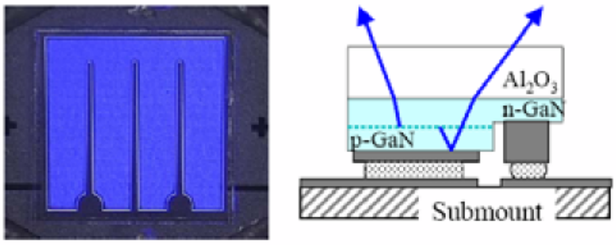
ncem
J.R. Jinschek & Ch. Kisielowski
National Center for Electron Microscopy (NCEM) Lawrence Berkeley National Lab. (LBNL) Berkeley, CA

Light extraction from LEDs

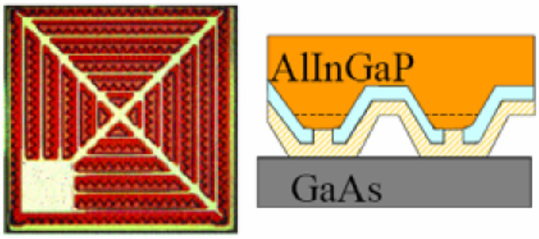
Lumileds AlGaInP/GaP Truncated-Inverted-Pyramid LED



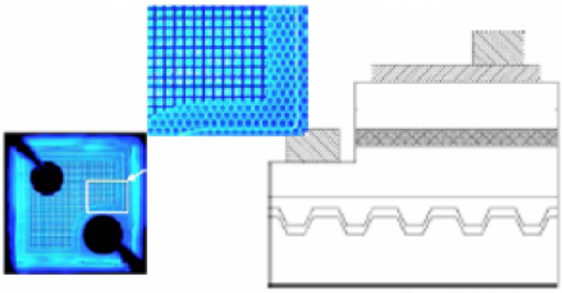
Lumileds AlInGaN Flip-Chip LED



OSRAM AlGaInP Micro-mirror LED

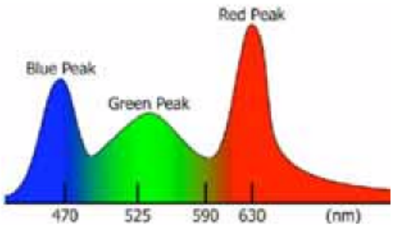


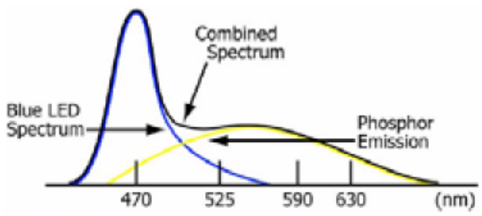
Nichia AlInGaN patterned substrate and mesh electrode LED



- Total internal reflection at the semiconductor air interface reduces the external quantum efficiency.

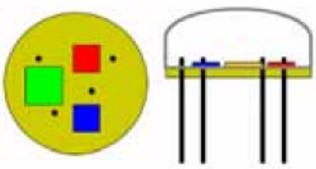
How to make white light?





Multi-LED:

Mix light from multiple LEDs of different color



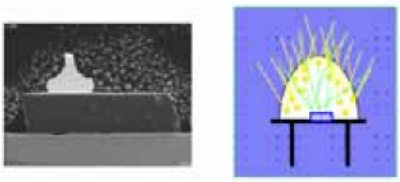
Potentially Higher Efficiency

Color Control Needed

Color Tuneability Possible

LED + Phosphors:

Use blue or near-UV LED to pump a mixture of phosphors



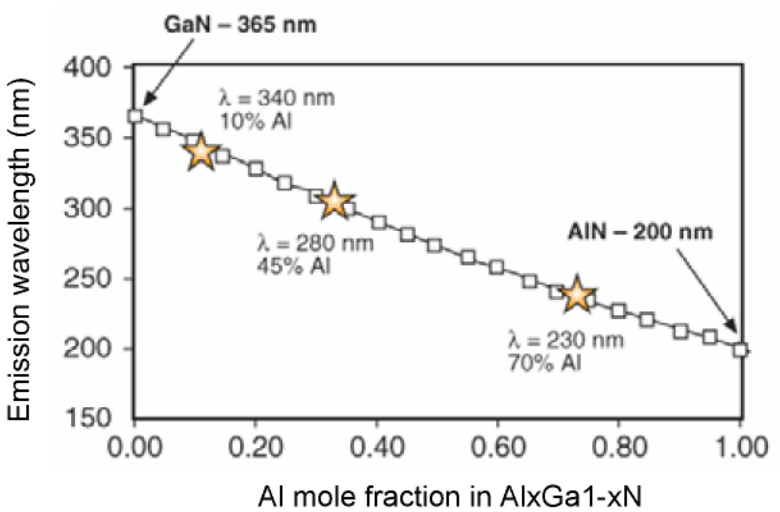
Efficiency May Be Lower

Color Control Easier

Tuneability Not Possible

Blue or UV requires use of gallium nitride (GaN) based material

Challenges for making high brightness UV-LED

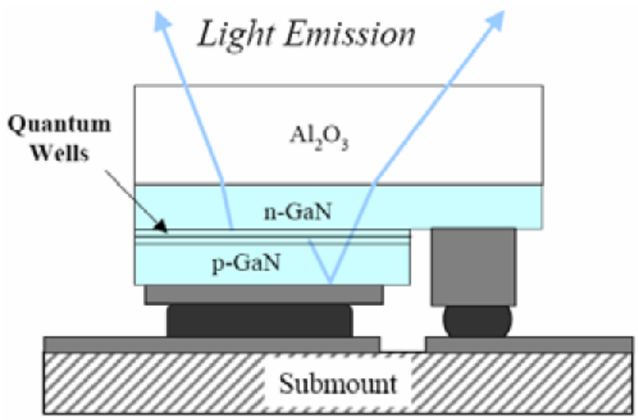


LED internal quantum efficiency η :

- AlInGaP-based red/yellow: ~100%
- State-of-the-art GaN blue: ~60-80%
- The best 280 nm UV today: ＜2%

1. **Low dopant activation in high-Al alloys, poor ohmic contacts**
2. **Minimal carrier localization effects in AlGaN as opposed to in InGaN alloys, high nonradiative recombination rates**
3. **Strain-induced cracking, high dislocation density (lack of good substrates), rough epi morphology**
4. **Strong polarization fields which further lowers the radiative recombination efficiency.**

Flip-chip III-nitride blue/UV LED

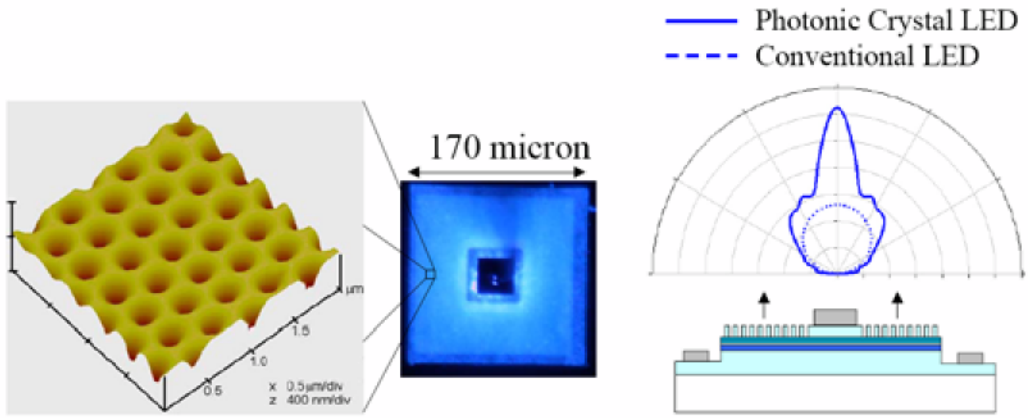


Advantages of flip-chip design:

- Better thermal management.
- Better light extraction
- Low absorption due to transparent substrate

SET flip-chip UV LED design

Photonic LEDs for better light extraction



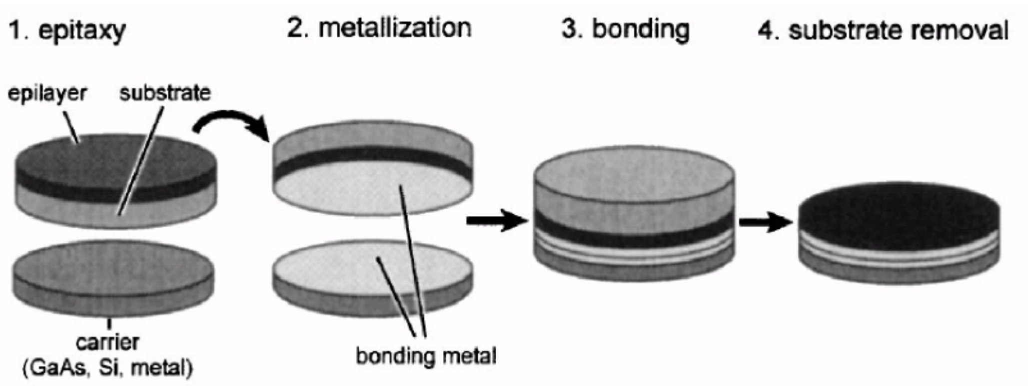
250 nanometer holes etched into GaN.

Top-view of a Photonic Crystal LED

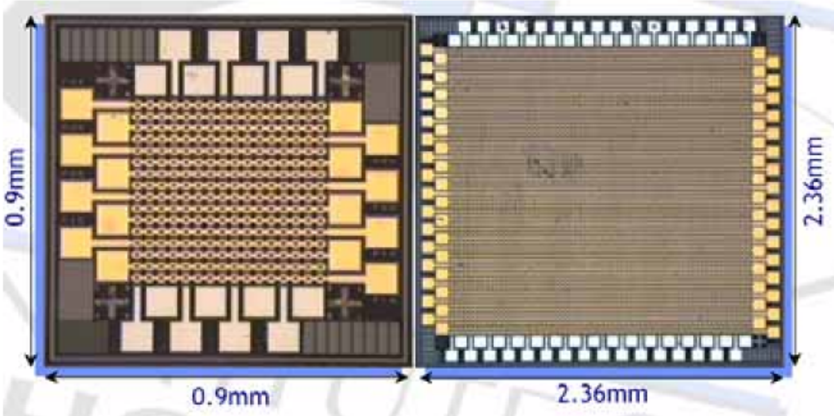
Light intensity vs. angle. The Photonic Crystal LED's light emission is narrow.

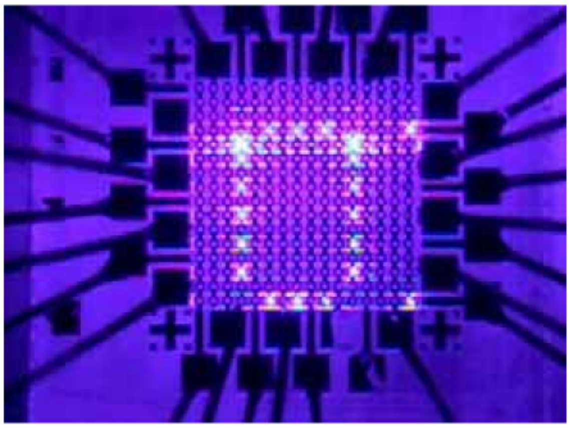
If designed correctly photonic crystal LEDs can be directional (increased brightness). However, the approach is quite costly !

Thin film LED technology



- **Nice thermal management**
- **The bonding metal also has good reflectivity.**





Blue-LED arrays and micro-display

Unfortunately, until now Nichia is still the only company which can mass produce GaN lasers

LASER DIODEs

*The products comply with RoHS Directive except for LD Slot Module. (December 2005)

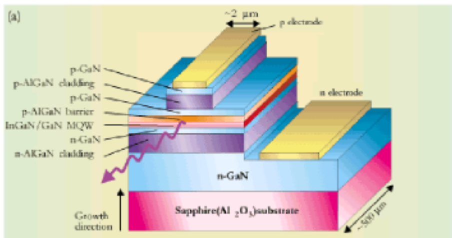
Edge-emitting blue laser is on the market, but there is still a long way to go for vcsels.

The photo might not exactly be the same as the original.

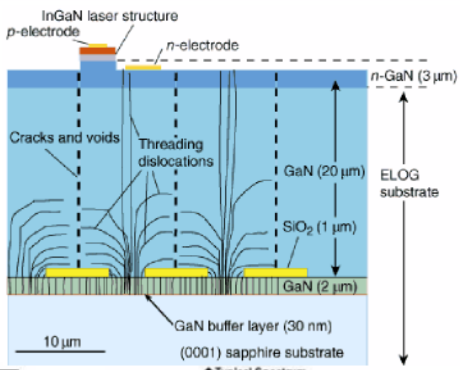
(As of August 2004)

Marketed Products

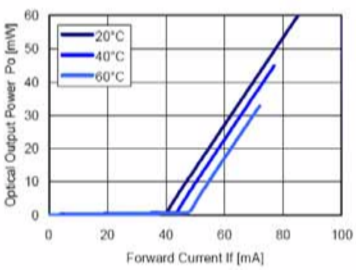
Part Number	Peak Wave-length [nm]	Optical Output Power [mW]	Threshold Current [mA]	Operating Current [mA]	Operating Voltage [V]	Monitor Current [mA]	Photo Diode	Package	FDA Accession Number
NDHV310APC	400-415	60	40	85	4.6	0.3	With	Φ5.6CAN Cathode Common	0112221-09
NDHB510APA	440-450	50	35	120	5.5	-	with	φ5.6CAN Cathode Common	0112221-19



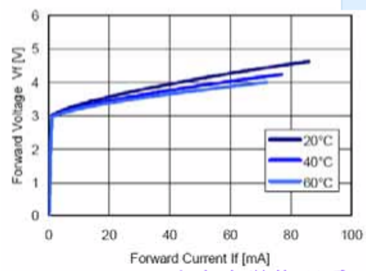
Typical structure of an edge-emitting blue multiple quantum well (MQW) diode laser. **(a)** Schematic of the layered heterostructure for electronic and optical confinement, with electrical contacts.



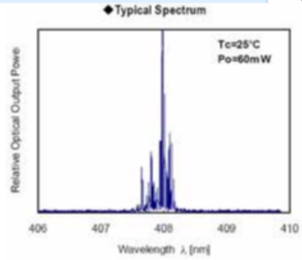
◆Optical Output Power vs. Forward Current

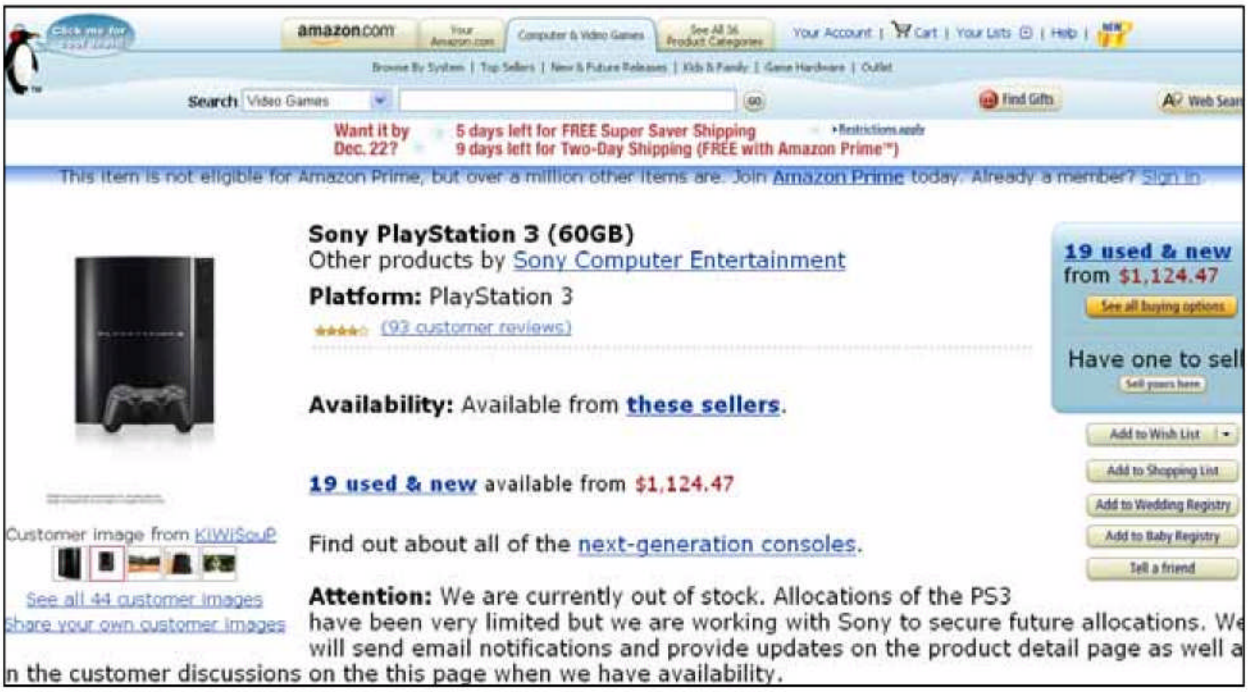


◆Forward Voltage vs. Forward Current



◆Typical Spectrum





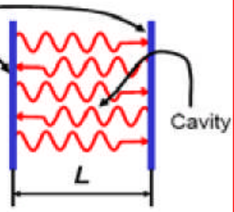
PS3 is based on GaN violet laser.
Finally it is out after several delays, but out of stock right now!

NECESSARY CONDITIONS FOR LASING

- High concentration of excess electrons and holes
  - Excess electrons and holes should be **provided externally**
    - \- **heavy electrical injection** (pumping)
- For photons, **gain should be ≥ losses**
  - Gain is proportional to the concentration of electrons and holes
    - \- the concentration should exceed a **threshold value** !
- High **positive feedback** for photons

Reflective mirrors

Mirrors
- Provide positive feedback
- Define propagation direction
- Select a set of wavelengths



***L* - cavity length**

Light is enhanced (positive feedback)
in the case of the **constructive interference**
(if the **standing wave** is formed in the cavity)

$$L = N\frac{\lambda}{2n_1}$$

THRESHOLD CURRENT

For a diode to operate as a laser, **gain should exceed loss**.
Above the **threshold** should be:
- Excess electron and hole concentration
- Electron and hole injection (pumping)
- **Electric current**

Threshold current - the current at which gain equals loss

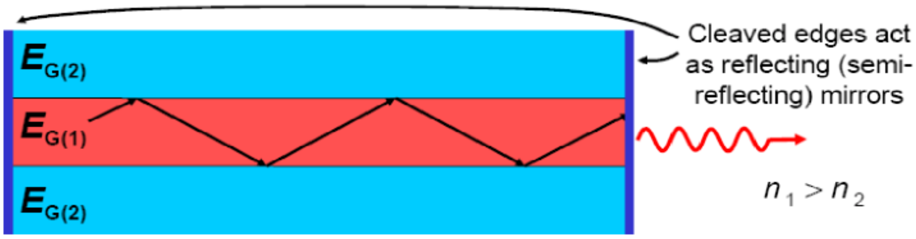
Due to large currents for the heavy injection and small active-region size, an operating laser diode can be strongly overheated.
Cooling is essential.

Important aim of laser-diode design - to reduce the threshold current (and therefore to fight overheating)

DESIGN OF A SEMICONDUCTOR LASER DIODE

In principle, a simple *p-n* junction may operate as a laser.
However, a double-heterostructure laser diode is much more effective.

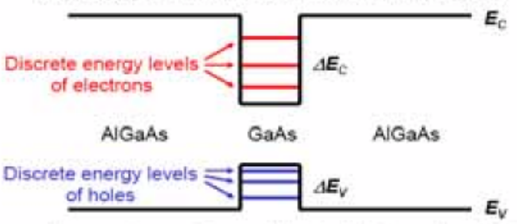
Edge-emitting diode:
Long (~ **300 μm**) and thin double-heterostructure light-emitting diode.



- **Advantage**: acts as a light guide in the lateral direction
- Would-be disadvantage for a diode: re-absorption
  However, the **re-absorption is favourable for lasing** !
- **Favourable** for lasing also are:
  Confinement of electrons and holes - efficient recombination
  Confinement and enhancement of light

QUANTUM WELLS (*)

We consider **two sequential heterojunctions** (a double heterostructure).
For example, AlGaAs/GaAs/AlGaAs.
The inner layer (GaAs) is **very thin** (2 - 20 nm);
its energy gap is smaller than that in the outer layers.



Because the quantum well is very thin (typically less than 10-20 nm),
the motion of electrons and holes is **quantized**.
Instead of continuous energy spectra,
there are **discrete energy levels** for both electrons and holes.
A quantum well can be very effectively used as the active region of semiconductor laser diodes.

ADVANTAGES OF QUANTUM-WELL LASER DIODES (*)

- Very small active volume - efficient recombination
- Easy to create large densities of electrons and holes of the same energy
- Smaller non-radiative losses

Due to the above - much lower (10 times !) threshold current

Also:

- The threshold current is less sensitive to temperature - more stable performance
- Emission wavelength can be easily designed

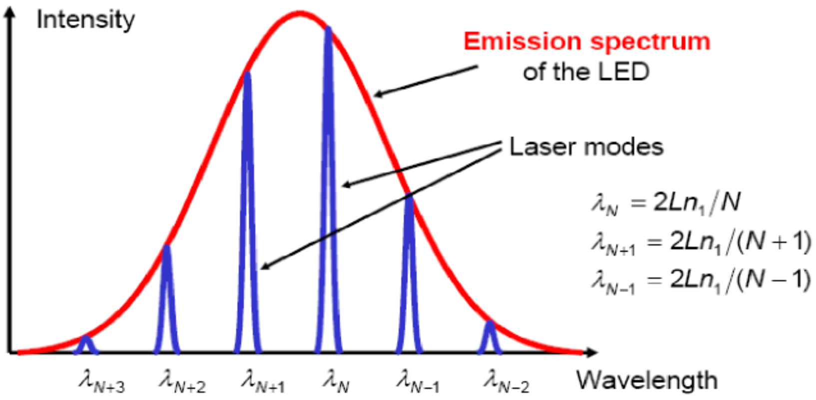
WHY SEMICONDUCTOR LASER DIODES ARE SO ATTRACTIVE FOR OPTICAL- FIBRE COMMUNICATIONS

- Easy and fast (below 1 ns) direct internal modulation
- Reasonably small working voltages
- Easy coupling to optical fibres (due to a parallel beam)

EMISSION SPECTRUM OF LASER DIODES

Cavity length (size of the active region) $L \approx 300\ \mu m$

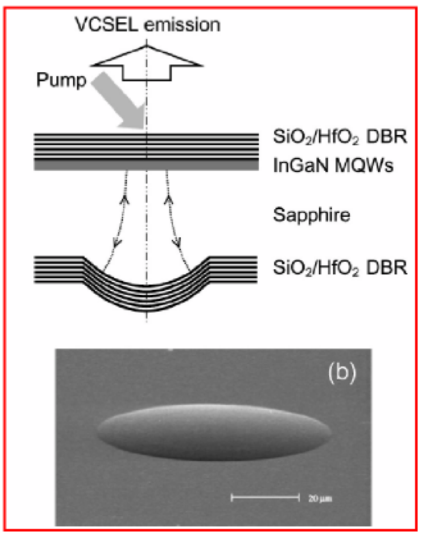
$n_1 \approx 3.5$; $\lambda = 2Ln_1/N$; for $\lambda = 1000$ nm, $N \approx 2000$



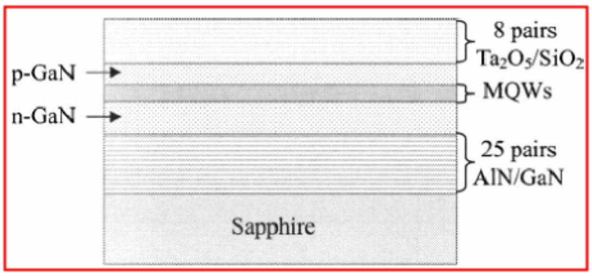
Constructive interference in the cavity
selects a **discrete set** of narrow laser lines (modes)
from the **original** LED emission spectrum

VCSELs (Vertical Cavity Surface Emitting Lasers)

A VCSEL is a semiconductor laser diode in which light propagates normal to the epitaxial layer.
No cleaving is required for VCSEL mirrors, which are formed from multiple layers of epitaxially grown or otherwise deposited thin films.



The most important advantages of VCSELs are on-wafer testing, and batch-processing fabrication. Other advantages includes low drive current and small thermal budgets. However, compared with edge-emitting laser, VCSEL usually has relatively smaller output due to shorter resonant cavity.



AlGaN/GaN high electron mobility transistor (HEMT)


COVER STORY

The Toughest Transistor Yet

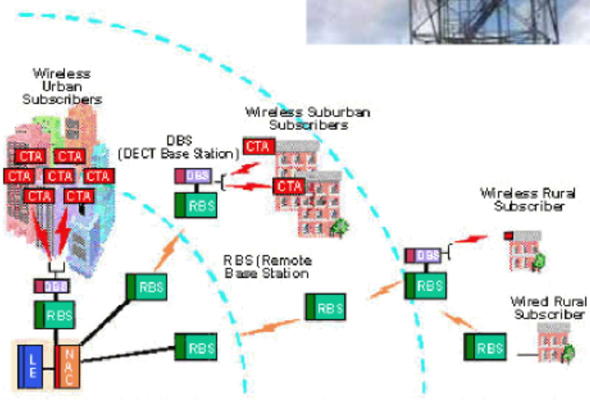
From broadband wireless to compact radars, countless future scenarios depend on the high power and high frequencies that only gallium nitride can deliver

BY LESTER F. EASTMAN
Cornell University

& UMESH K. MISHRA
University of California at Santa Barbara

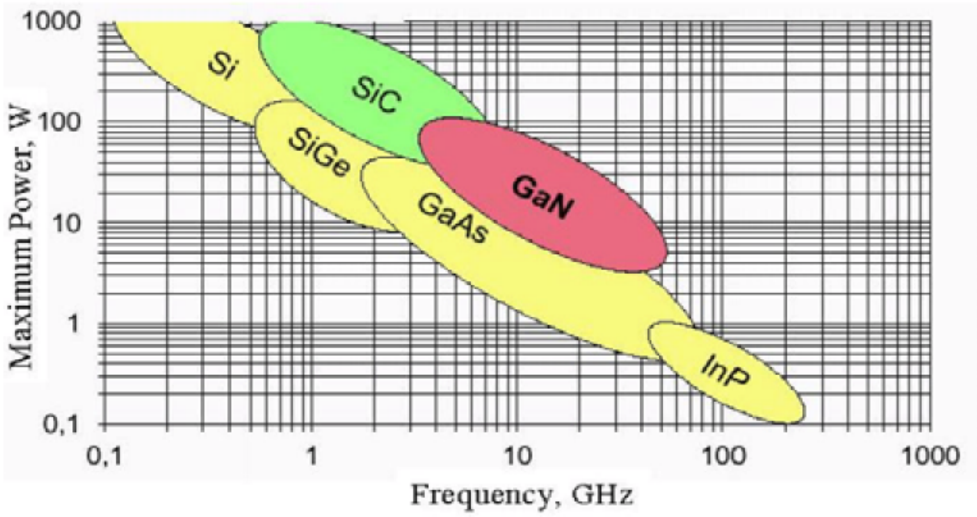
Where are High-Power Microwaves Needed (Besides in Ovens)?

- RADAR applications
  - Military
  - Commercial applications
- Wireless network infrastructure
  - Conventional (1-2 GHz)
  - Local Multipoint Distribution Service (LMDS) (28 GHz).
- Satellite Communications (12.4-30 GHz)

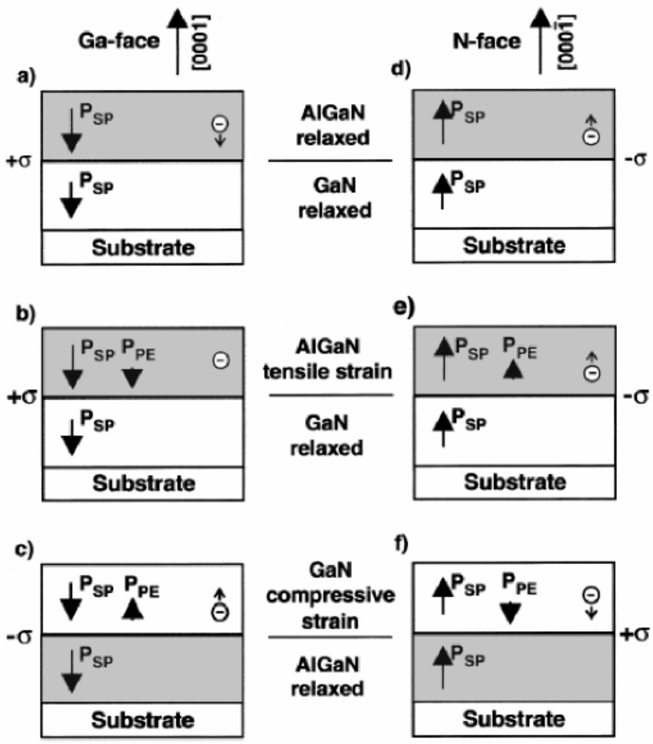


Why GaN is superior for micro-wave power application?

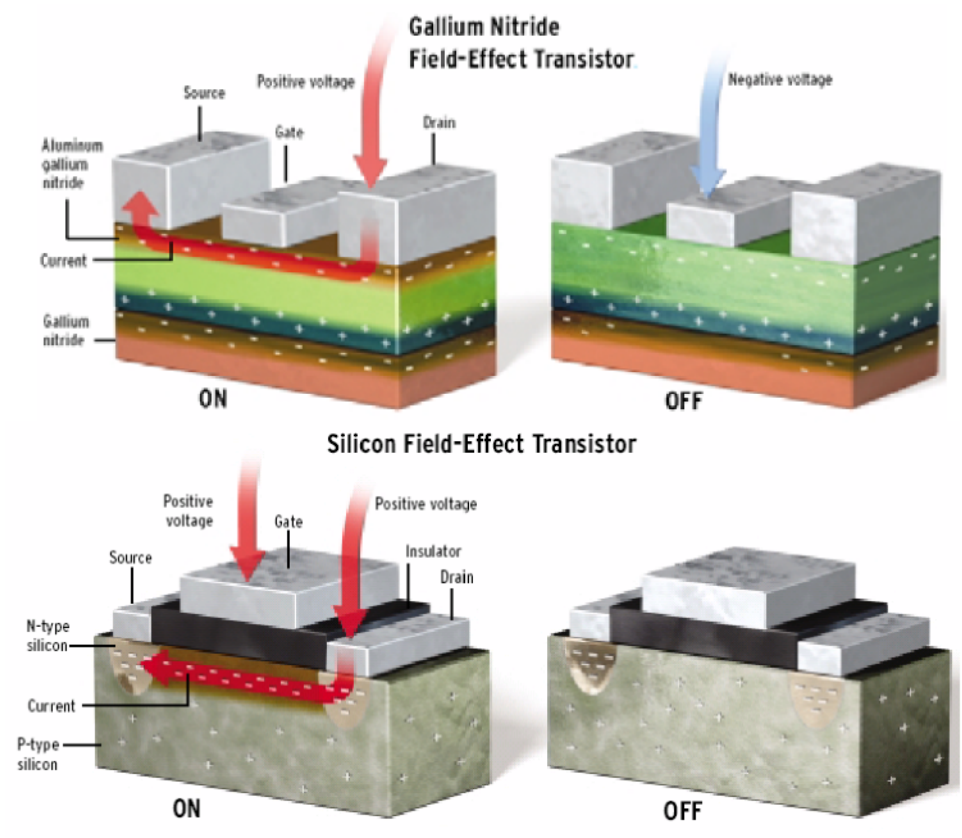
	GaAs	InP	GaN	SiC
Band-gap, Eg (eV)	1.43	1.34	3.39	3.26
Saturation velocity Vs (m/s) @ 300K	10^5	0.9×10^5	2.7×10^5	2×10^5
Critical breakdown field Ea (MV/m)	40	50	330	200
Relative dielectric constant, r (static)	12.8	12.5	8.9	10
Piezoelectric constant, e14 (C/m 2)			-0.035	0.375
Thermal conductivity, (W/m K) @RT	50	69	170	380



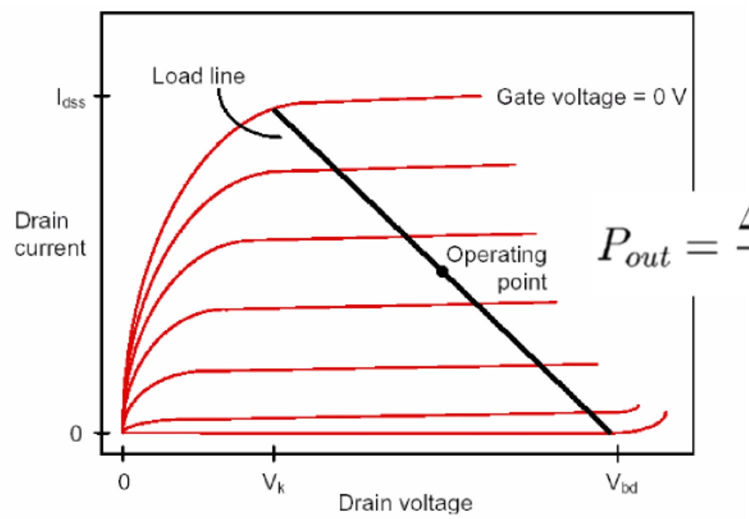
Formation of 2DEG at AlGaN/GaN heterojunction interface



How AlGaN/GaN HEMT works?



What is important for a HEMT epilayer?
— sheet resistance and breakdown voltage

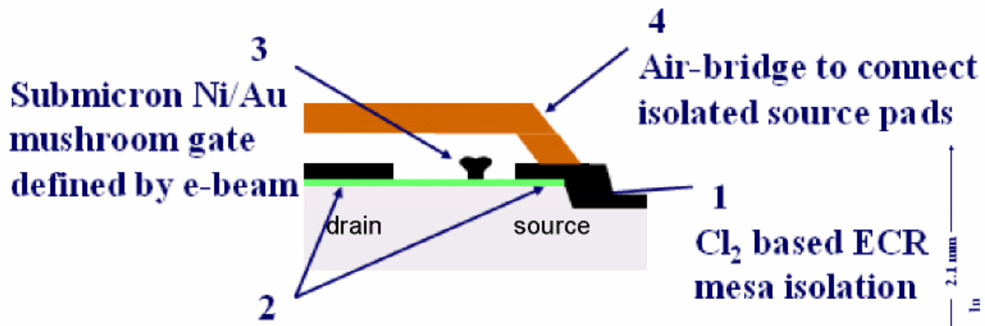


$$P_{out} = \frac{\Delta V \Delta I}{8}$$

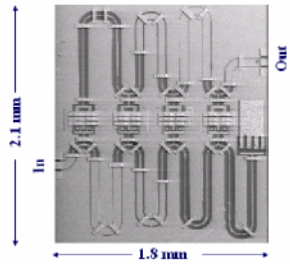
Operation of a transistor as an amplifier

By maximizing both V and I, which can be done by increasing the breakdown voltage and also at the same time increasing the maximum current that can be delivered by the transistor, we can improve high power performance. Gallium nitride is a material system ideally suited to do all of this.

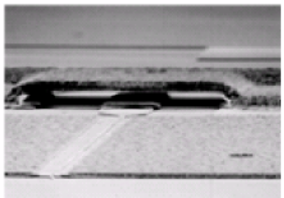
Fabrication of AlGaN/GaN HEMT transistors

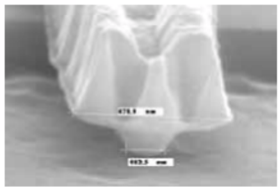


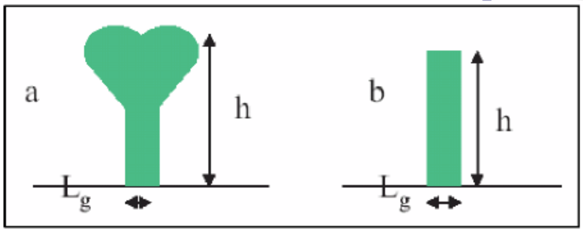
Ti/Al/Ti/Au ohmic contact annealed at 800 C
(0.3-0.6 Ω.mm)



SEM photo



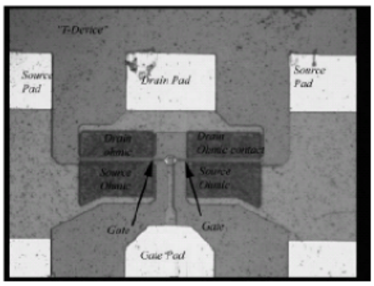




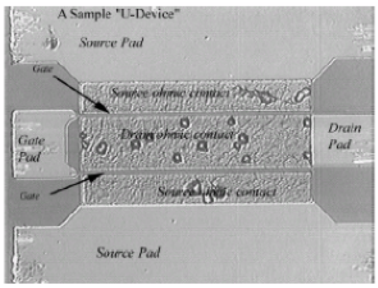
0.3um gate with ft>30GHz for x-band (8-12GHz)
SD spacing 3.5um, SG spacing 1um

A mushroom gate has the same foot print as a rectangular gate B) but at the same time has a larger area of cross section

Small periphery and large periphery devices

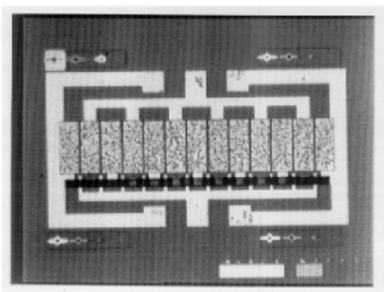


T device

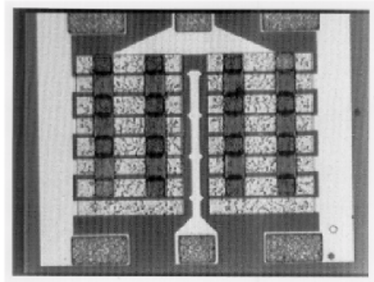


U device

These devices are ready to be probed by co-planar waveguide probe (or Cascade probe)



Parallel fingers

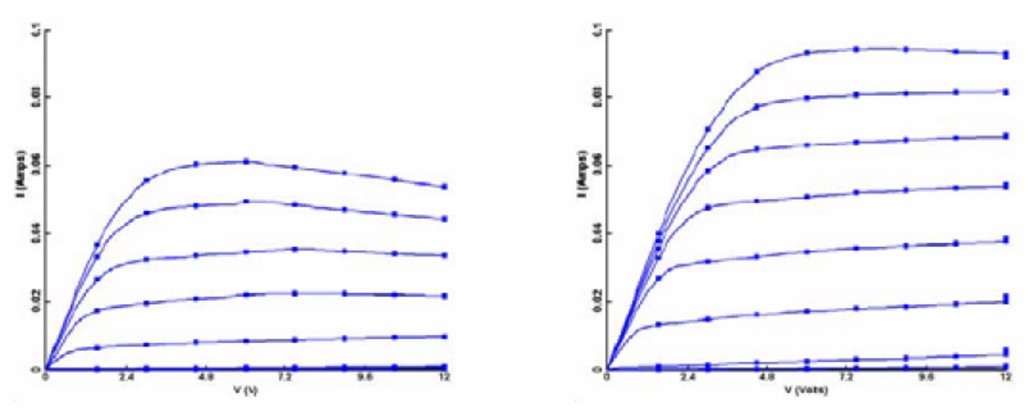


Fishbone

Large periphery devices with gate length up to cm-size has been fabricated.

Trade-off in scale-up: phase lag and potential drop and thermal removal.

DC measurement



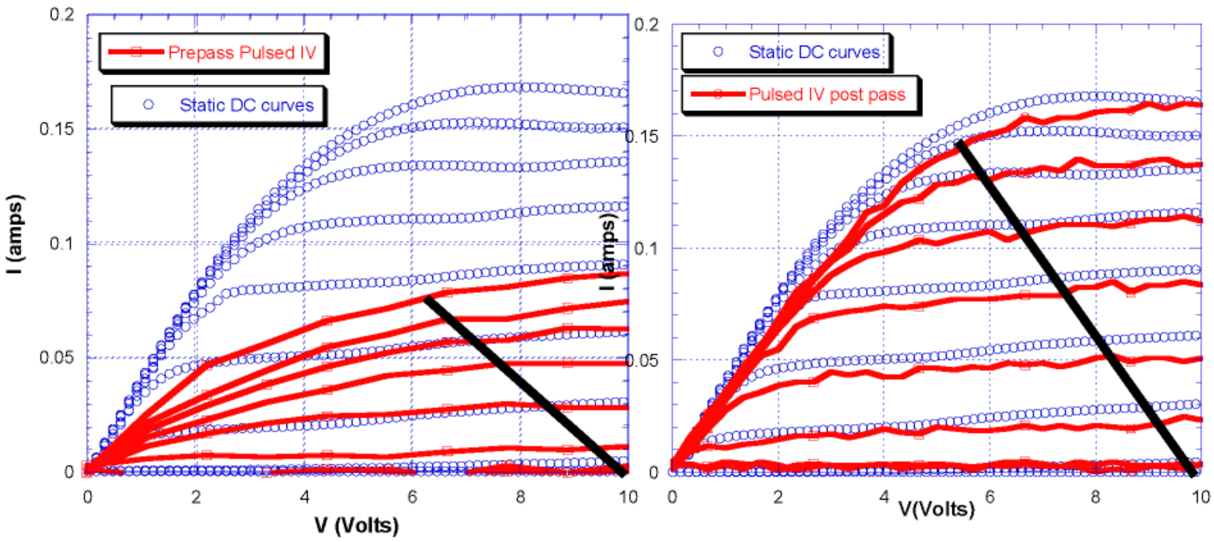
(a) Sapphire substrate transistor IV curves

(b) SiC substrate transistor IV curves

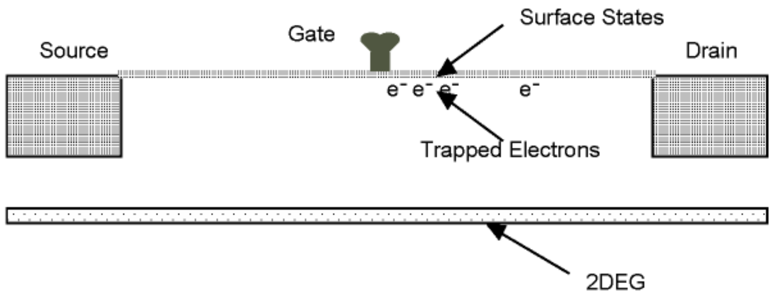
If DC is not good, RF is certainly bad!

Epi-layer on SiC substrate has smaller dislocation dislocation and SiC substrate has much better thermal conductivity. Therefore, most companies follow the SiC development trend.

Current collapse or RF slump

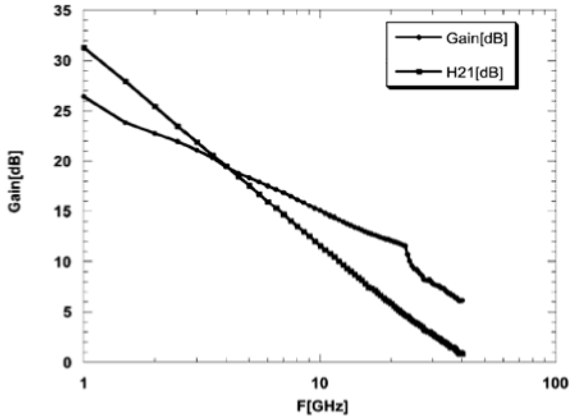


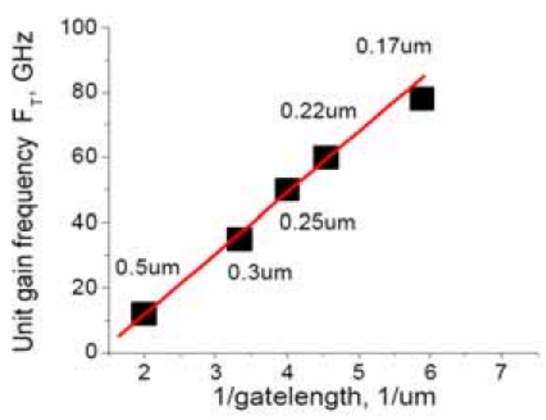
- **Expected power is less than predicted power due to RF dispersion**
- **Pulsing gate with 100 ns pulse we plot the i-v curves to get conditions similar to RF**
- **Mitigate the problem by using PECVD Si_3N_4**

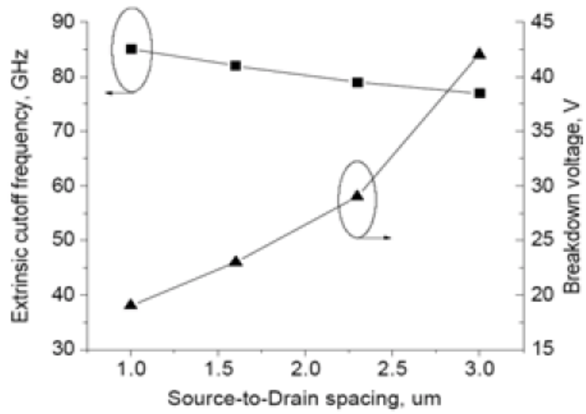


III族氮化物半导体系列讲座（二）　　© 2006 南京大学物理系　　陆海，hailu@nju.edu.cn

Small Signal measurement

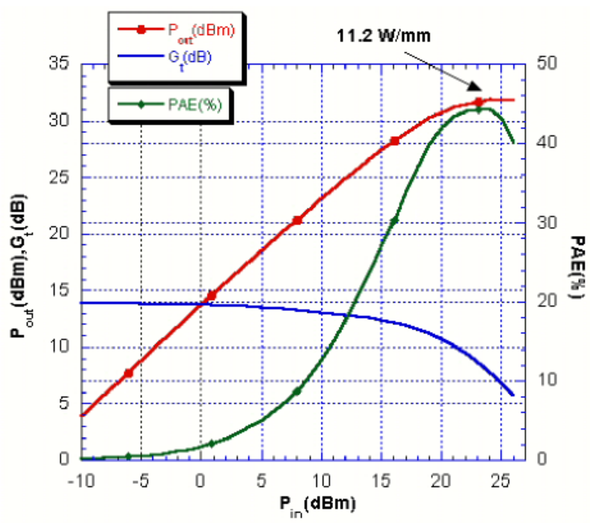


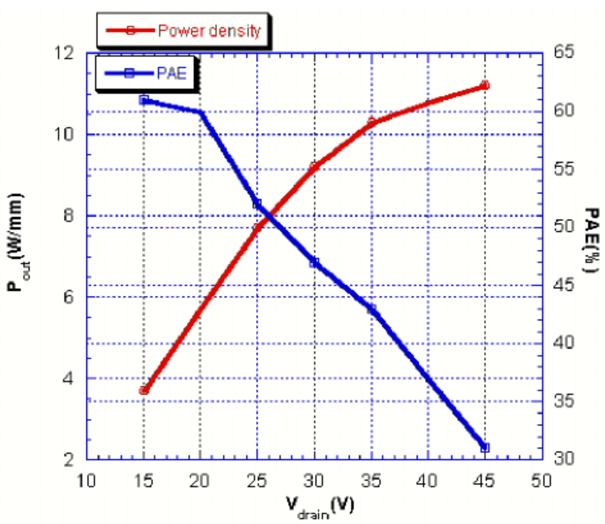




A typical small-signal result obtained by HRL. With 0.25 um gate, the current gain cut-off and max. power gain cut-off frequency are 40 and 90 GHz respectively.

State-of-the-art result in year 2002

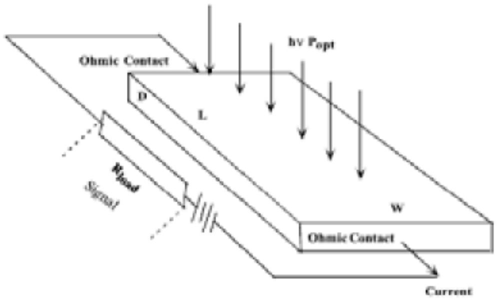


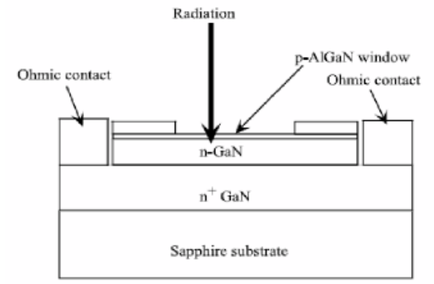


Power sweep at drain bias = 45V, gate bias = -3.5V, 10GHz.
The result was achieved by Vinny Tiak in 2002, a student of Lester Eastman.

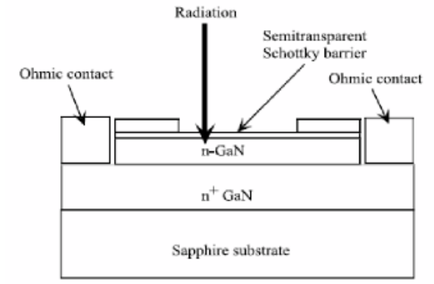
Nitride-based UV detectors

The solar-blind region (260-280nm) is due to ozone layer absorption.





P-n junction detector- Front illuminated



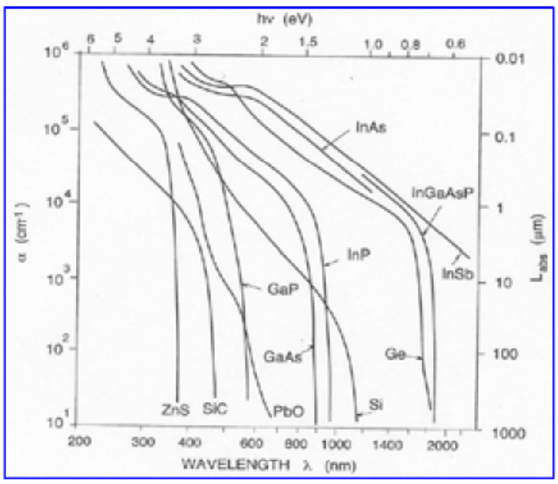
Schottky Barrier detector- Front illuminated

Three basic types of photo detectors:
- photo-conductive detector
- pn junction detector
- Schottky barrier detector

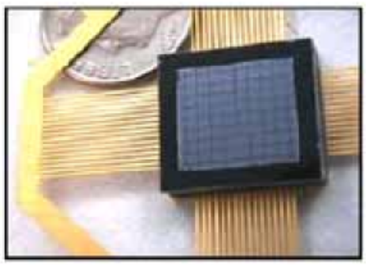
Other configurations include MSM, PIN, APD, phototransistor……

Important definitions

- Quantum efficiency η: Ratio of the number of electrons collected to the number of photons incident.
- Responsivity: current out divided by optical power incident.
- Gain: Photovoltaic (PN and PIN) No; Photoconductive Yes; Avalanche APD Yes



Direct gap in semiconductors: α ~1/μm
Indirect gap in semiconductors α ~0.01/μm

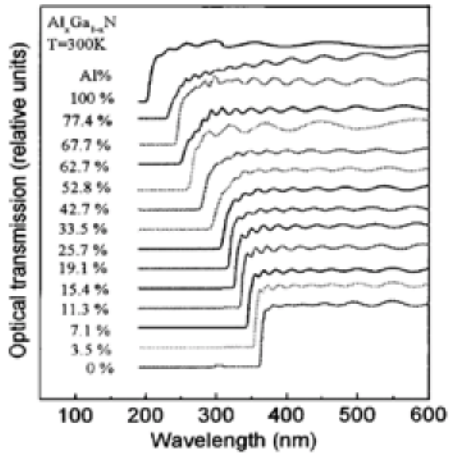


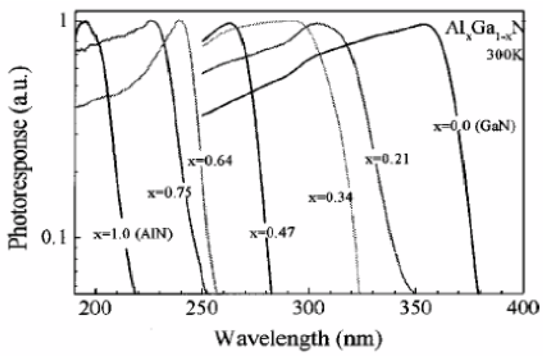
Size of Detector Chip

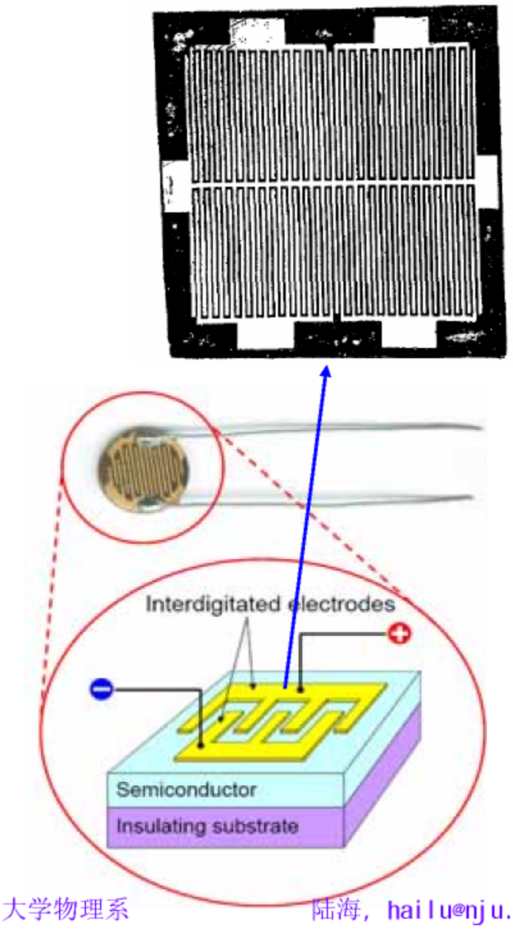
SMALL SIZE	PARAMETER	LARGE SIZE
LOWER	SENSITIVITY	HIGHER
FASTER	SPEED OF RESPONSE	SLOWER
LOWER	DARK CURRENT	HIGHER
LOWER	COST	HIGHER

There are many trade-offs in photodetector design.

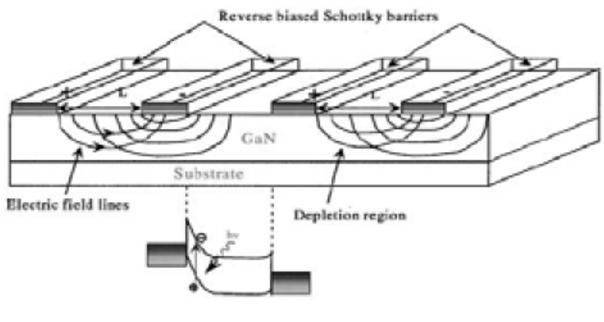
AlGaN photoconductors







AlGaN MSM photodetectors



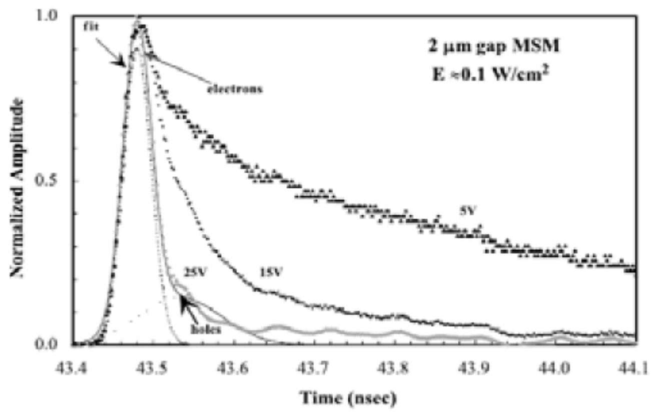
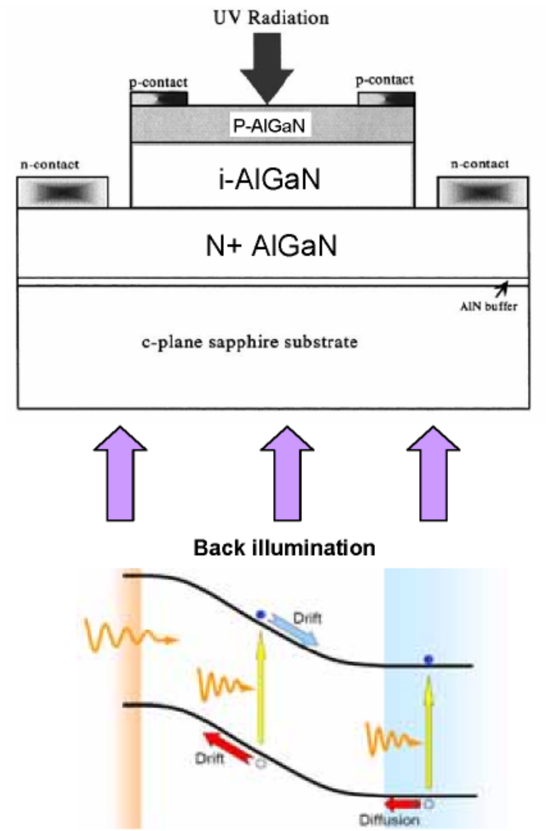


Fig. 51. Time-domain response of an MSM detector at various bias voltages for a 2 mm gap spacing. For a bias voltage of 25 V and without the hole response, 90–10% decay time is about 200 ps. Courtesy of Prof. J.C. Campbell (University of Texas, Austin).

MSM structure has following advantages:
- no p doping required.
- ease of growth and fabrication
- high speed and large bandwidth

But it suffers from high leakage and poor noise performance, in addition, bias is normally required.

Nitride-based PIN photodetectors



The choice of the PIN photodiode design for solar-blind UV detectors is driven by its intrinsic advantages:

1) a very low dark current due to large potential barrier;
2) a high speed of operation;
3) a high impedance suitable for FPA readout circuitry;
4) a direct control of the quantum efficiency and speed through the control thickness of the intrinsic layer;
5) the device can operate under low bias.

There are two modes of operation for photodiodes: 1) photovoltaic (operation under no bias) and 2) photoconductive (operation under reverse bias).

For photodiode, the response speed is limited by three factors:

1. Diffusion of carriers,
2. Drift time in the depletion region,
3. Capacitance of the depletion region.