Solid State Lighting: Synergisms with Office of Science Materials Programs

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Sandia National Laboratories

OUTLINE

- Brief overview of prospects & promise of SSL
  - National Initiative
  - Grand Challenge LDRD at Sandia
- BES-supported activities at Sandia provided core capabilities
- Other NS applications of nitride materials science

Will only discuss inorganic materials and devices here.

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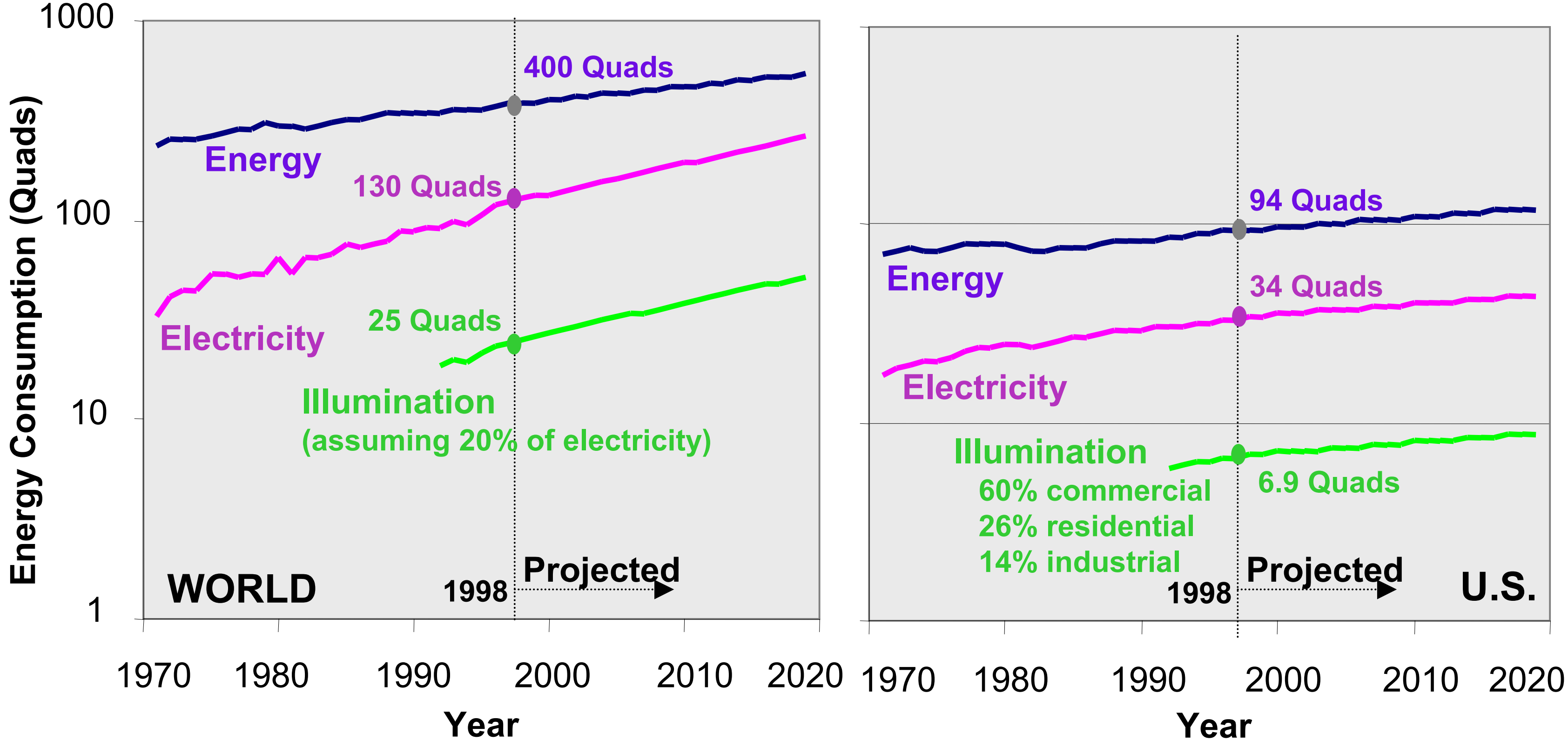
Major motivation for SSL is energy savings: lighting is large fraction of energy consumption



~20% of U.S electricity consumption is for general illumination

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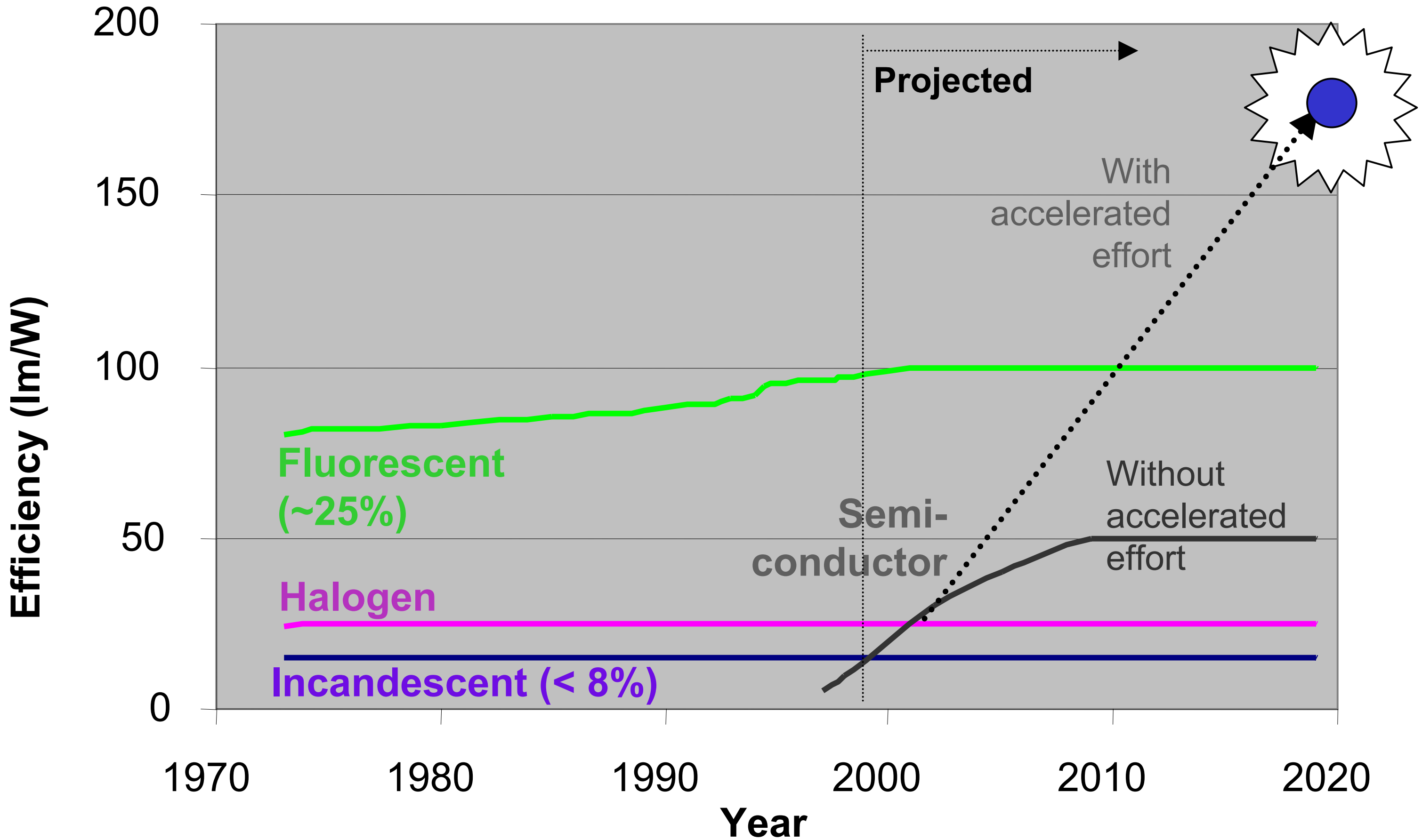
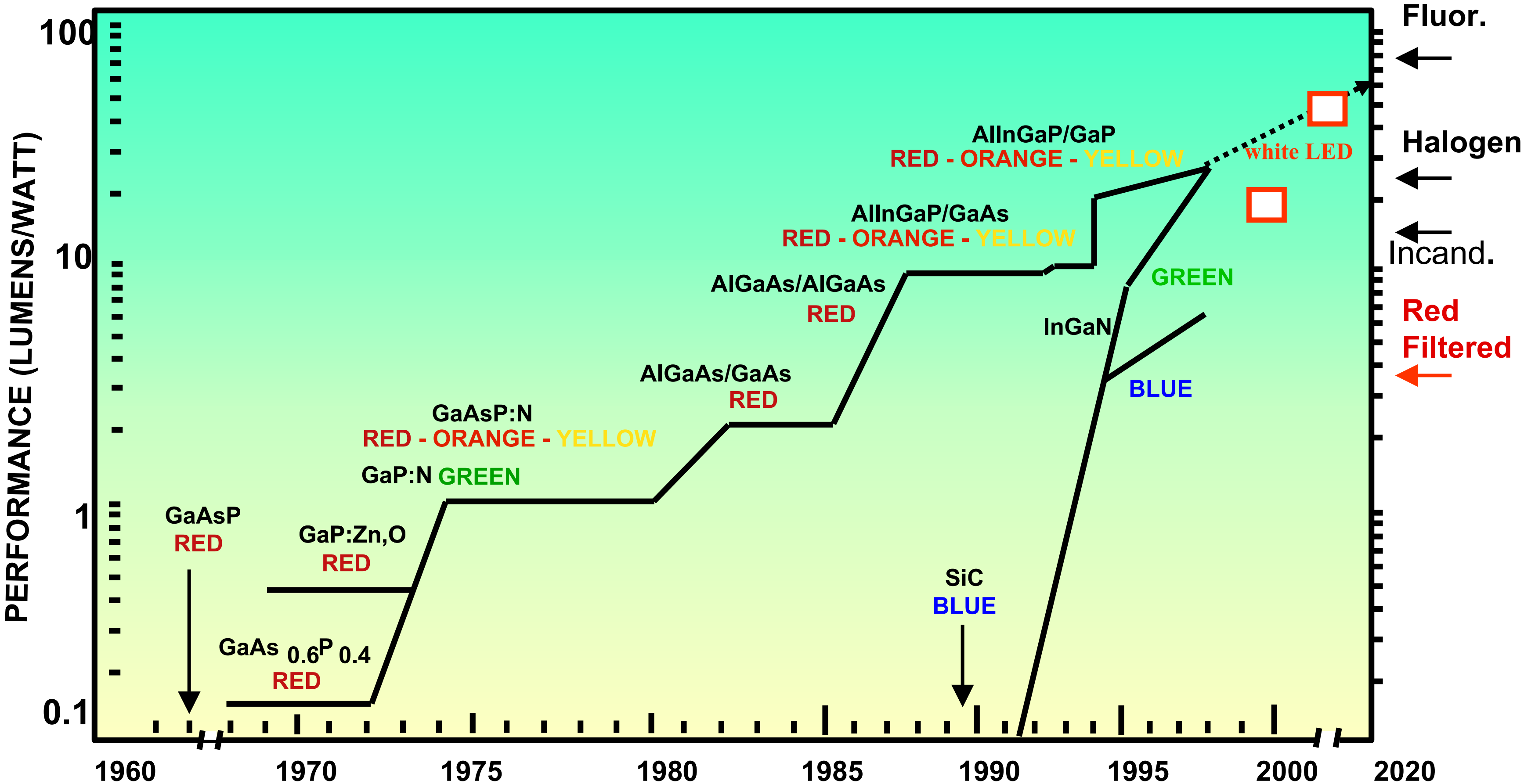
Conventional lighting is relatively inefficient



Energy efficiencies of conventional lighting sources leave ample opportunities for energy savings. (700 lm/W max @ 550 nm)

However, LEDs have been increasing in efficiency (and dropping in cost) at phenomenal rates



RED: lm/W has improved at 30X/decade, cost has decreased at 10X/decade.
BLUE: A new player thanks to Nitride-based materials.

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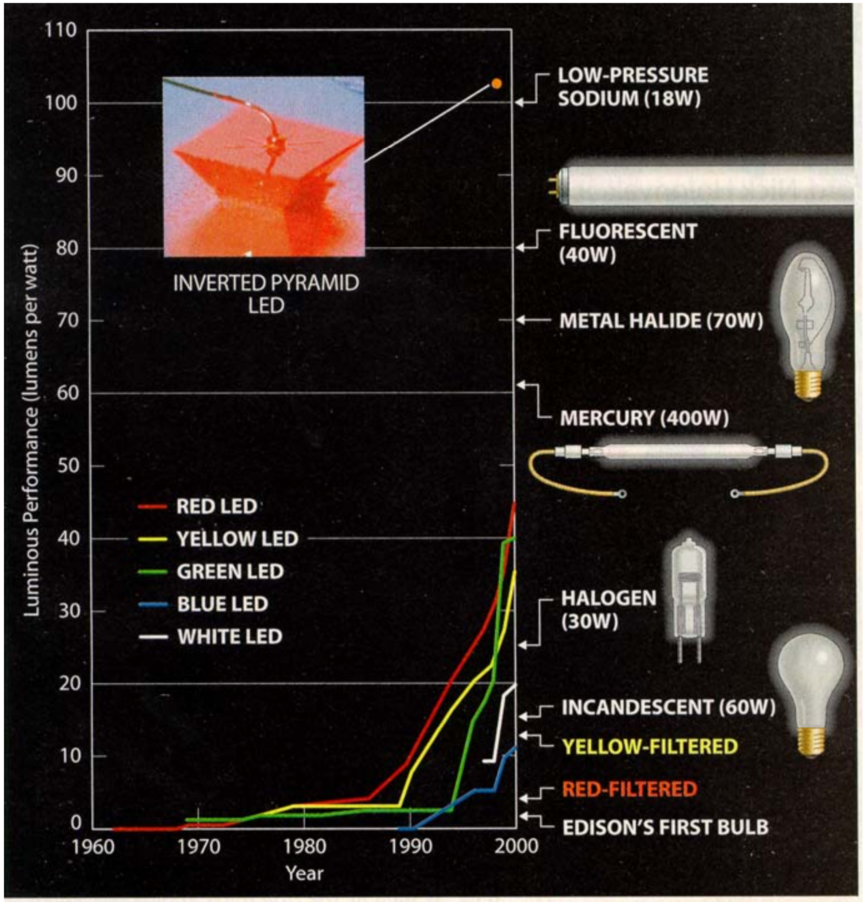
Red LEDs have recently exceeded fluorescents in efficacy



LIGHT-EMITTING DIODES have steadily improved and now outperform many other kinds of lights; the best is a prototype red-orange inverted pyramid LED.

Feb. 2001 Scientific American

Specialty applications are currently driving advances

Red LEDs 10X more efficient than
red-filtered incandescents

LED Bulbs Getting Green Light in County

Traffic: Old stoplight variety is being replaced with cost-effective ones that last longer and use 90% less electricity.

By CATHERINE BLAKE
SPECIAL TO THE TIMES

The red and green stoplights may seem a little brighter these days, but local cities aren't playing a holiday trick on you. Some stoplights are indeed more radiant, and they won't be taken down once Christmas is over.

For the past few years, cities across California have replaced energy-draining incandescent bulbs in traffic signals with a longer-lasting light technology, called LED, that uses 90% less electricity. And in the face of today's increasingly volatile power markets, many local cities are applying for a state grant to help them change thousands more in coming years.

Although most drivers won't likely notice the difference, upon close inspection the LEDs, or light-emitting diodes, give stoplights a pinpoint look, with rows and rows of small dots instead of a soft glow. These bulbs are consistently bright, with a darker hue.

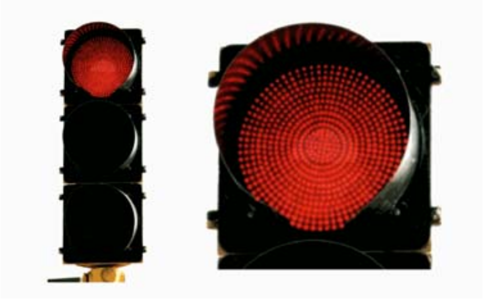
In contrast, incandescent lights are strongest in the center and the light fades around the edges. When LEDs are shut off, there is no afterglow.

Most importantly, considering the threats of rolling blackouts, a light-emitting diode uses only 10% of the electricity. If the entire state exchanged its 4 million incandescent stoplights for LED bulbs, the cumulative savings would be $95 million a year, ac-

Please see ENERGY, B5

MEL MELCON / Los Angeles Times

LED traffic light, replacing incandescent bulb, lasts 10 years and uses 90% less electricity.



QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

Big Hairy Audacious Goal is replacing 50% of lighting with SSL.

Decrease by 50% the global amount of electricity used for lighting.

Decreasing by 10% the total global consumption of electricity.

Global reductions of 1100 Billion kWh/year of electricity, or $100B/year.

Freeing over 125 GW of electric generating capacity for other uses, saving about $50B in construction costs.

Reducing global carbon emissions by 200M tons/year.

High Investment Economic Model

	Year	2005	2010	2015	2020	2025
LED Penetration	%	0.05	2	12	30	55
Energy Savings per year	TWh/yr	2	67	330	720	1100
Energy Cost Savings per year	$B/yr	0.2	7	33	72	110
Energy Generating Capacity Savings	GW	0.2	8	38	82	125

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Community consensus on need for a National Lighting Initiative

- **Focus is to perform the R&D to overcome technical roadblocks**
- **Primary motivator is energy savings:**
- **Strategic planning document prepared at joint OIDA/DOE/Sandia workshop in Albuquerque in Oct., 2000, recommends**
  - **a National Initiative be funded at $50M/yr for 5-10 years**
  - **Industry, Academia, and National Labs collaborate**
  - **(Report is available)**
- **Several economic studies on the effect of a government funded program predict a substantial return on investment.**
- **Full day workshop at National Academy of Sciences will occur March 26, 2001**

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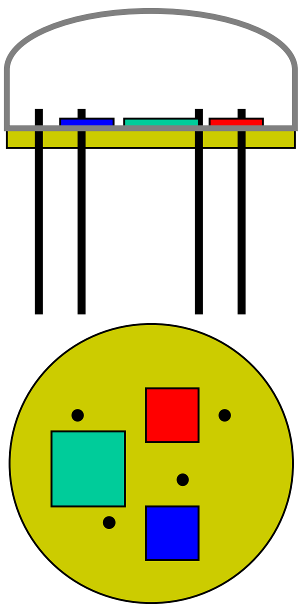
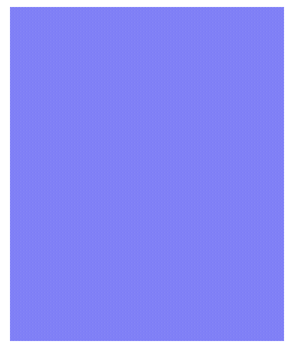
How do you make a white LED?

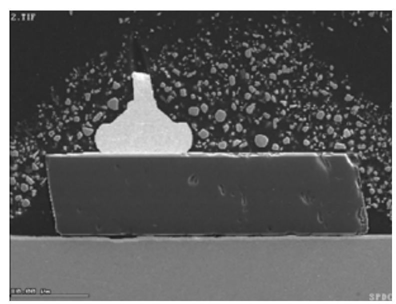
A. Multi-chip LED

(w/ control circuitry)

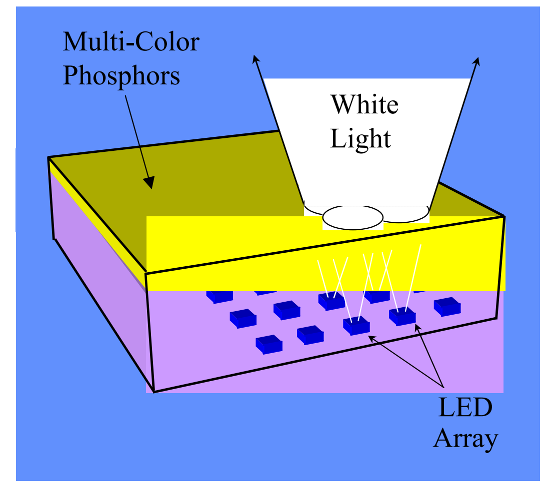


B. Blue LED + Phosphor(s)





C. UV LED + Phosphors



High Control

High CRI

High Cost

Low Control (Stability)

Low CRI

Low Cost

Moderate Control (Stability)

Moderate CRI

Moderate Cost

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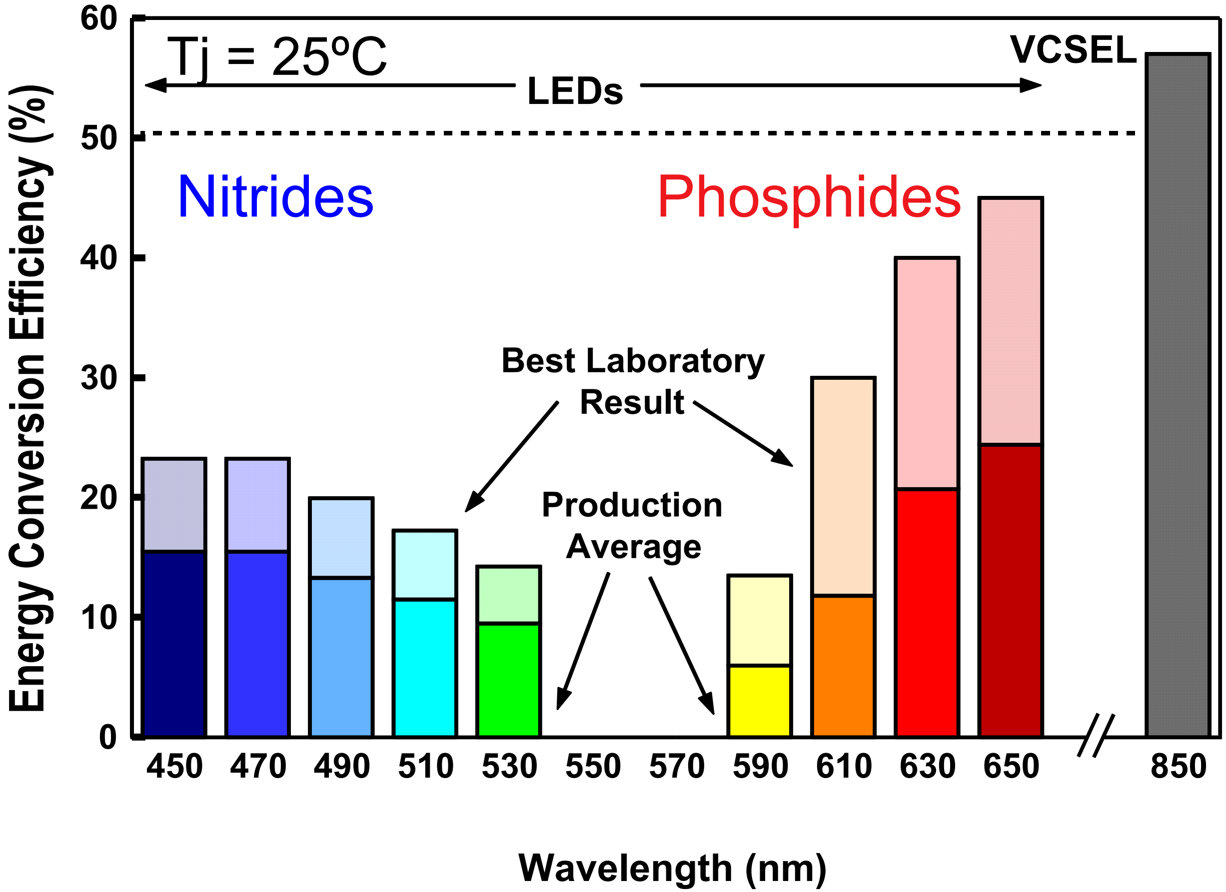
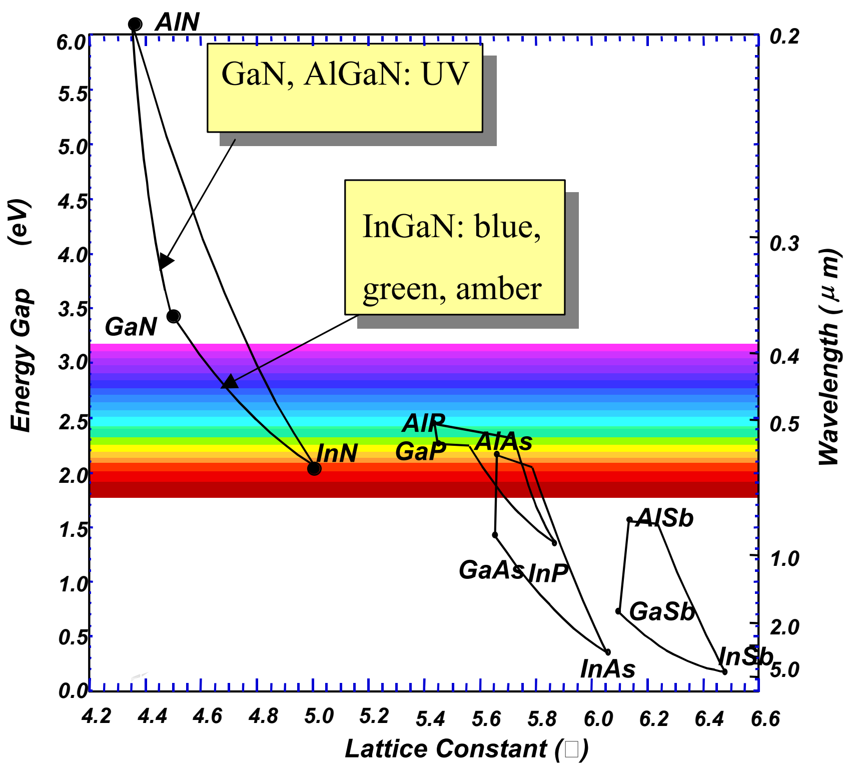
NEED TO: (1) Close the gap in green, and
(2) achieve 50% efficiency across the visible



DETAILS: OIDA Strategic Plan

GaN, InGaN, and AlGaN materials provide longer wavelength emission



But nitrides have challenges:

- •No lattice-matched substrate (dislocations)
- •AlGaN not lattice-matched to GaN (dislocations and cracking)
- •Mg p-type doping problematic (poor activation, high resistance)
- •Highly non-linear growth (poor control)
- •High T, high pressure growth (poor stability)

Optical & electrical properties dependent on defect concentrations

White LED market drivers and research needs

Brightness & Efficiency: **Increase radiative recombination, light extraction.**

Fundamental material, device, and optical physics.

Nitride materials new and little understood:

- **no native substrates (very high dislocation densities)**
- **highly non-linear, irreproducible growth. Edisonian understanding**

Cost: **Reproducibility, reactor scale-up, efficient chemical usage.**

Growth chemistry, reactor design, and *in-situ* process monitoring.

Reliability: **Longevity of LEDs at higher operating currents.**

Defect physics, physics and chemistry of electrical contacts, and physics of packaging materials.

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•Sandia has built up considerable expertise in these R&D areas, ***substantially due to long-running BES programs.***

•Sandia plans to participate in the SSL National Initiative. Consensus of OIDA Workshop study is that NL's basic research will be crucial.

•We are jumpstarting work on SSL-related issues with a Grand Challenge LDRD.

FY01 funding = $1.1M
Req. FY02 funding = $2.3M

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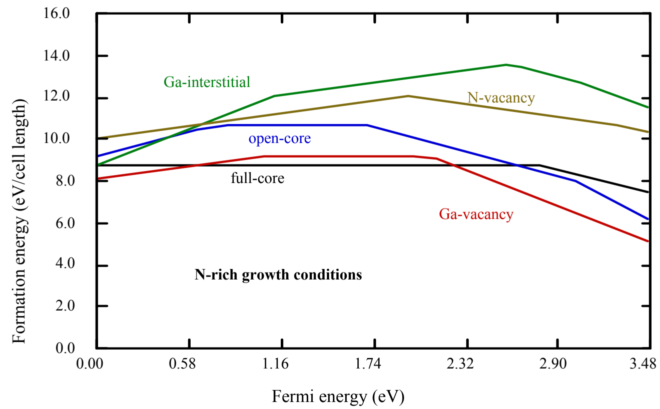
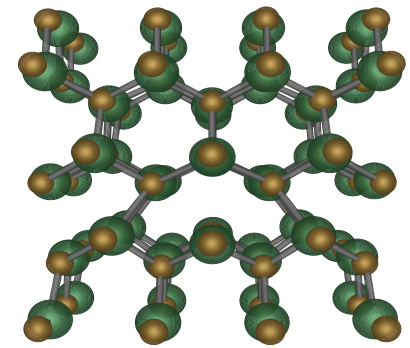
Part II: Synergistic Activities under BES

A few highlights of BES-supported basic R&D commensurate with goals of Solid State Lighting

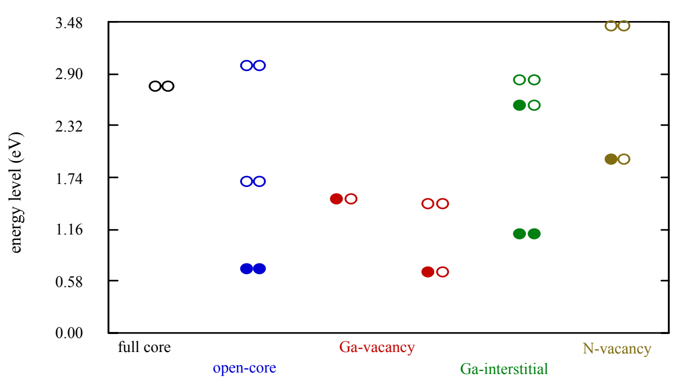
- Fundamental materials physics
- Growth chemistry and reactor physics
- In-situ monitoring and stress-engineering
- Semiconductor nanoclusters as engineered phosphors

Defect levels in the gap and formation energy vs. Fermi level for several candidate edge-dislocation core structures in GaN using DFT

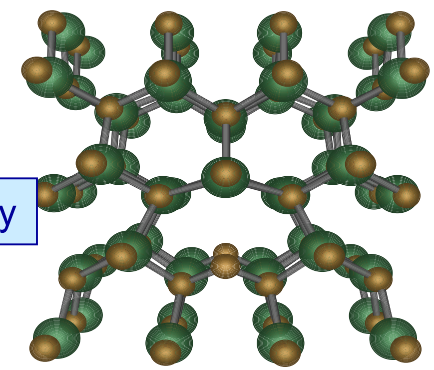




Full-core



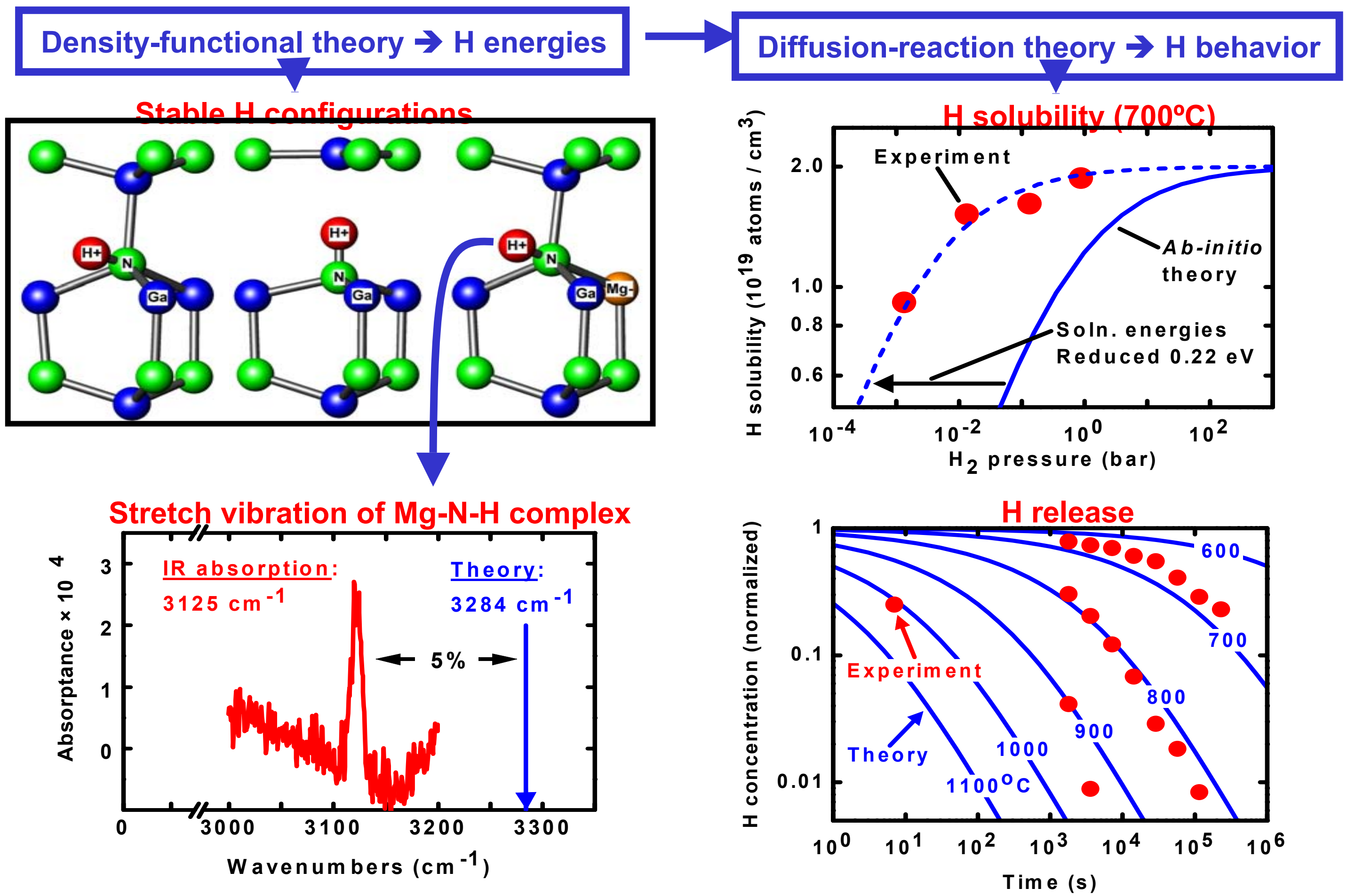
Ga-vacancy



Deep levels can act as non-radiative recombination centers

Can they be passivated? Can you control with growth T?

New predictive understanding of H in Mg-doped GaN (for p-type doping)



Allows understanding of H-dynamics. Must drive out passivating H without deconstructing surface. Uniroyal using this data for anneals. Will examine e-beam to activate Mg-doping.

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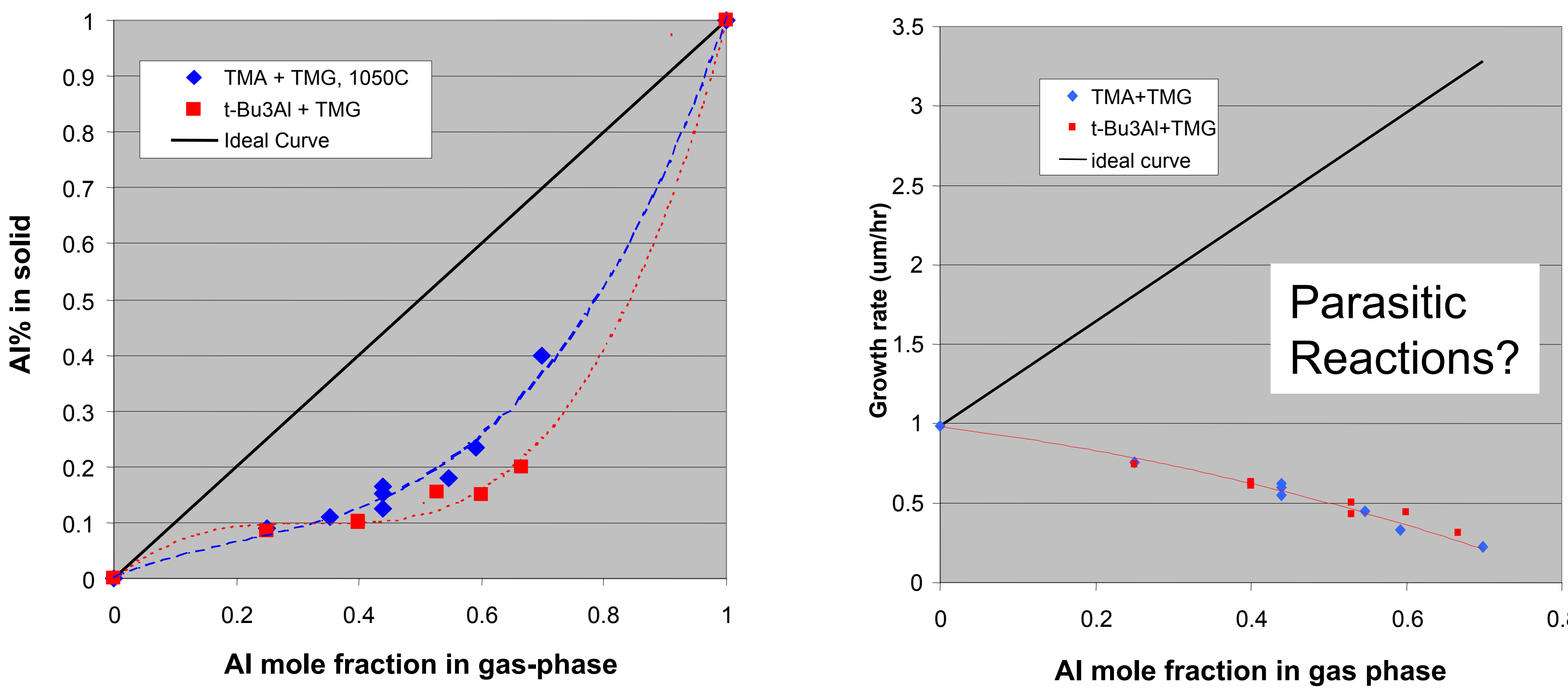
AlGaN composition and growth rate exhibit highly non-linear behavior

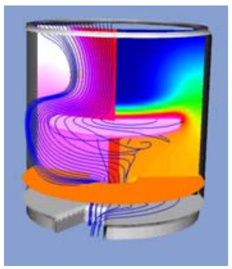


VERY LITTLE IS UNDERSTOOD. To control, need:

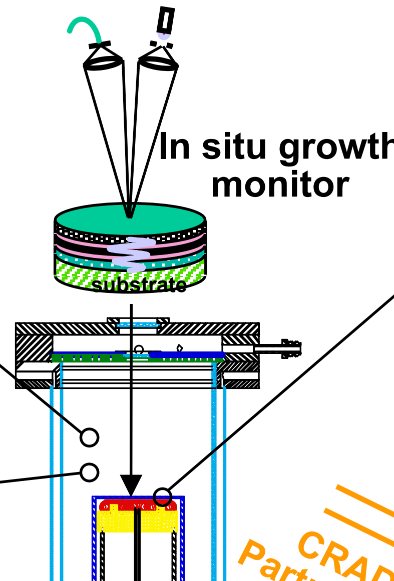
- fundamental understanding of growth chemistry
- better in-situ monitoring

Chemical Vapor Deposition (CVD) Sciences

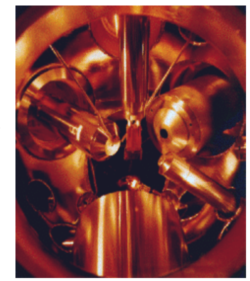
We have developed experimental tools and theoretical techniques that provide an understanding of the fundamental mechanisms of CVD. This research has had a clear impact on CVD Science, and the U.S. technology base through collaboration and commercialization.



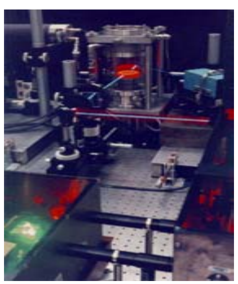
Reactor models



Rotating-disk CVD reactor

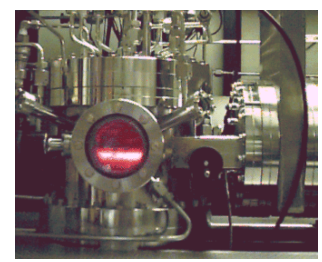


UHV surface science



Gas-phase diagnostics

CRADA Partnerships



Commercial CVD reactor designs

Over 250 licenses of Surface Chemkin software; in situ monitor probes have been commercialized by three companies; research collaborations with 11 companies in the U. S. semiconductor industry.

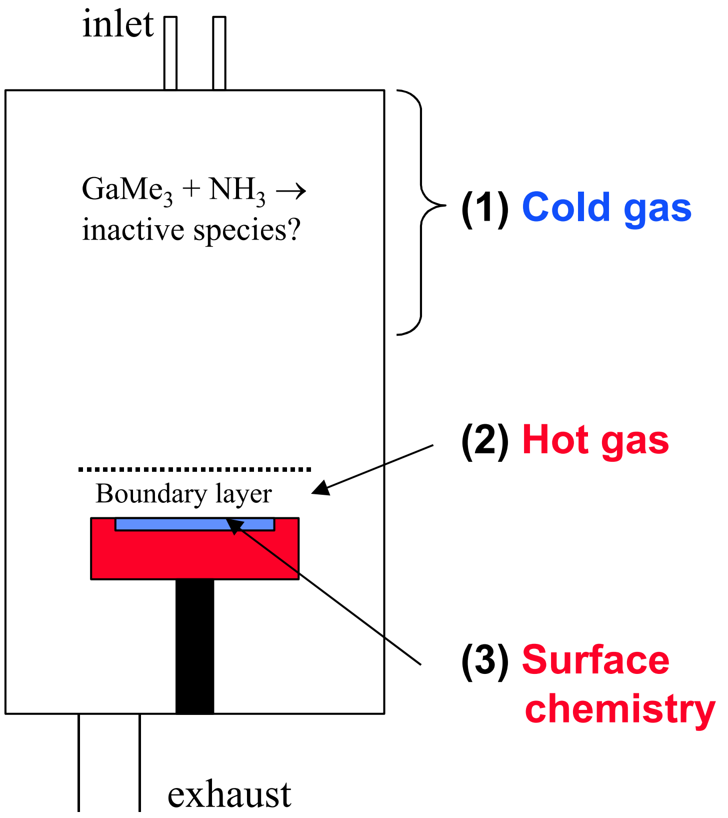
Searching for origin of parasitic reactions

Detailed reactor-scale experiments:

- AlGaN Growth rate vs. total Flow & spin rate
- full-scale reactor modeling with Spin/Chemkin

In situ studies to search for particulate formation

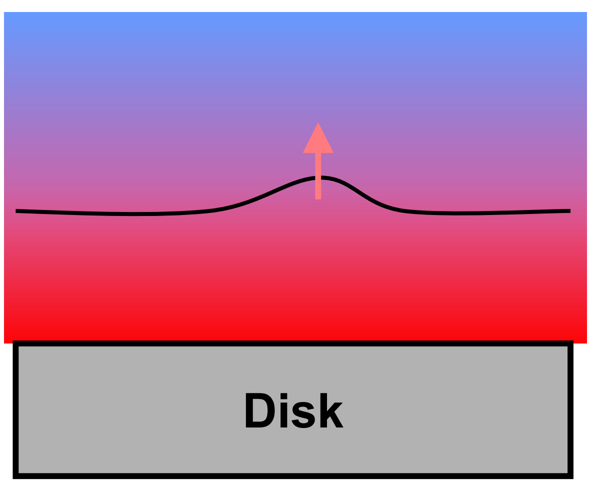
- laser light scattering
- Mass quadrupole spectrometer reaction analysis

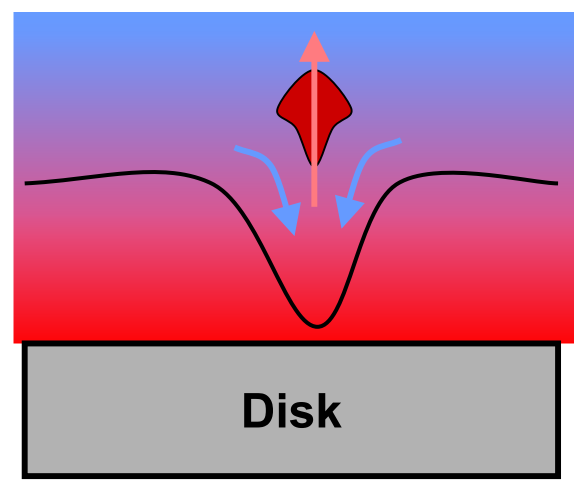


Origin of buoyancy instabilities
(exacerbated by high pressure, high T of GaN growth)

Hot, low-density gas that ventures into cold, high density region experiences an upward buoyancy force

Hot bubble erupts, and cold gas is pulled into hot layer, shutting down buoyant forces

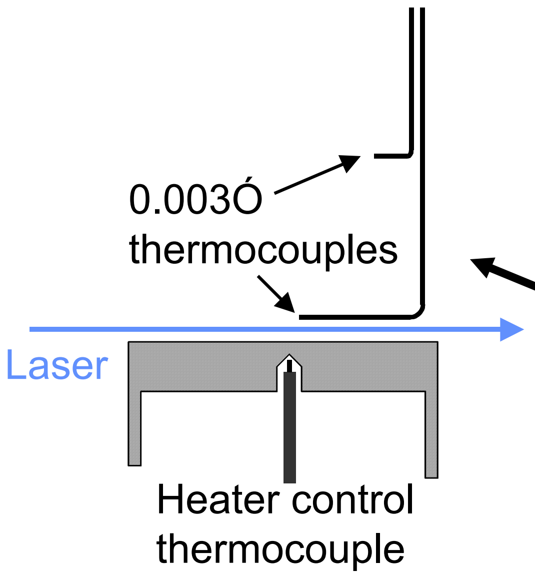


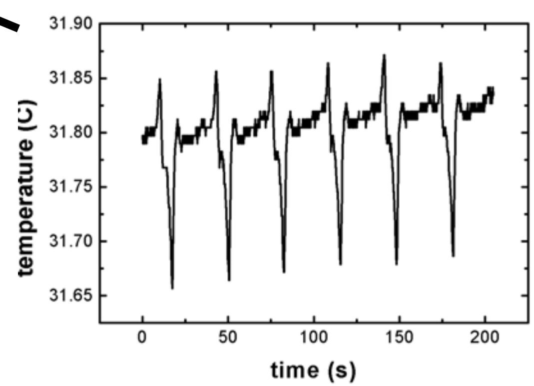


Theoretical analysis suggests that stability is characterized by a “mixed Rayleigh number”

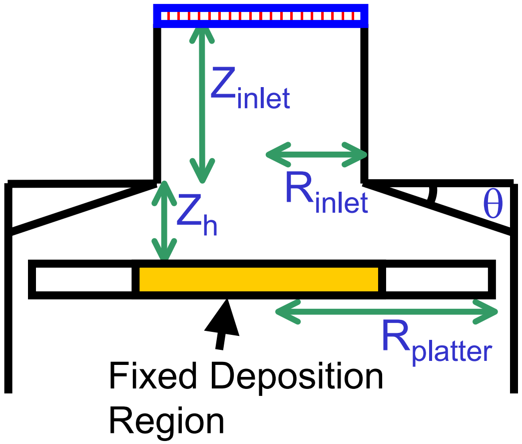
$$\Gamma = \frac{g\Delta TH}{T\kappa\omega}$$

- Thermocouple T(t) measurements
- Mirage dT(t)/dz measurements
- Test for Γ dependence on reactor height, H, Temperature gradient, disk spin rate, ω, and thermal diffusivity, κ (gas type, temperature, pressure)
- use Γ for reactor scale-up and operation over wide parameter range





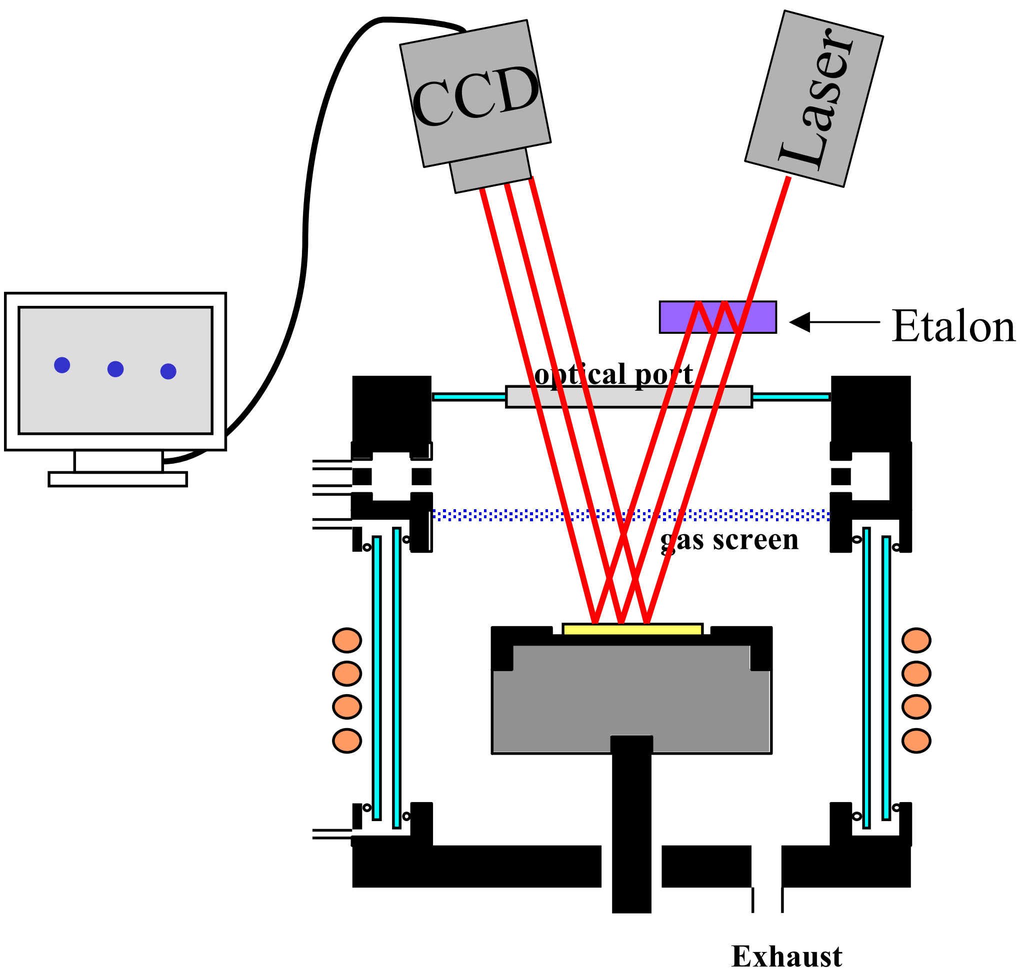
Optimization of reactor design for efficiency and film thickness (comp., etc.) uniformity



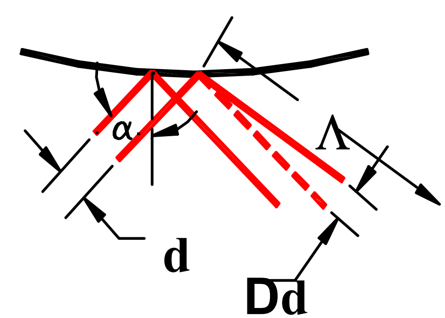
- Optimize geometric configuration based on simple sticking coefficient model for growth.
- Leverage ongoing programs in the MP algorithms group at Sandia
- SALSA (fluid flow) and DAKOTA (parameter optimization) codes
- Can include nitride chemistry in future

Numerical modeling gives scalable reactor design

Schematic drawing of an in-situ stress monitor (MOSS) implemented on a CVD reactor



"MOSS":
Multi-beam
Optical
Stress
Sensor



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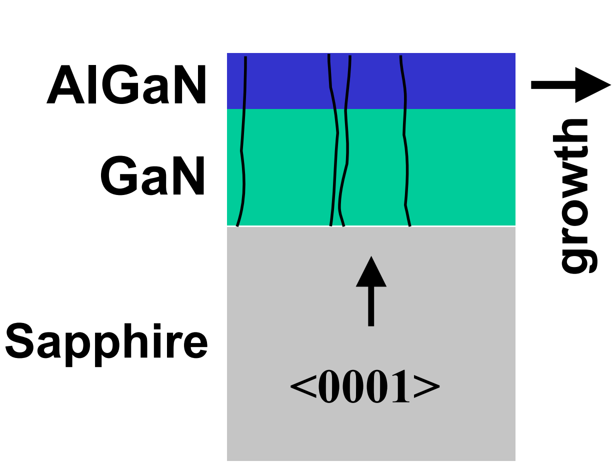
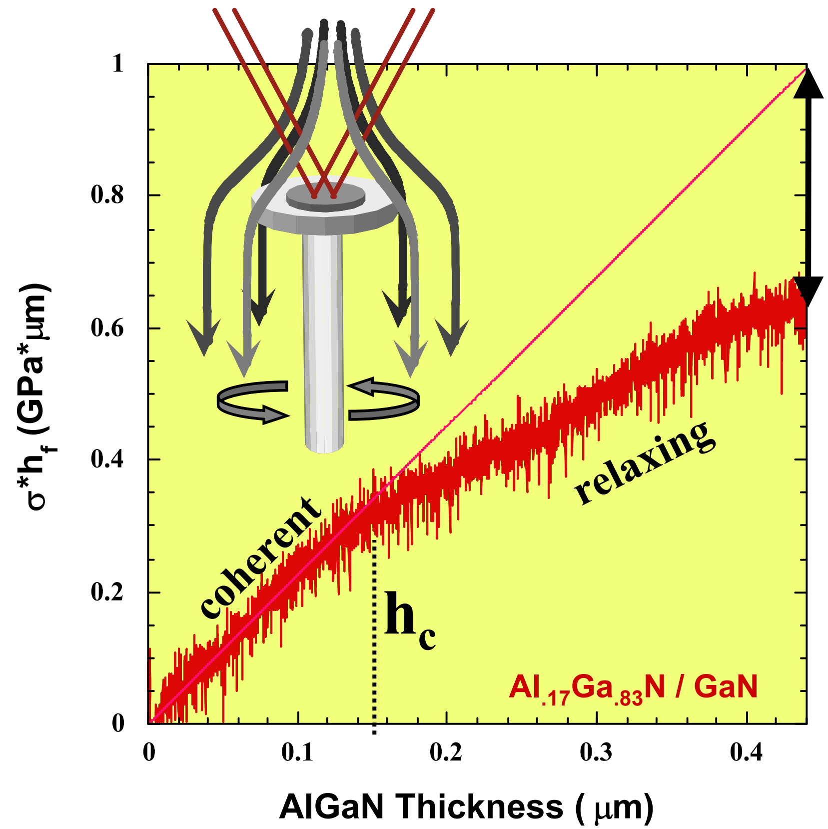
Stress-Induced Failure of III-Nitride Heterostructures



Sandia's approach: characterize stress evolution in real-time during MOCVD growth using our Multi-beam Optical Stress Sensor (MOSS).

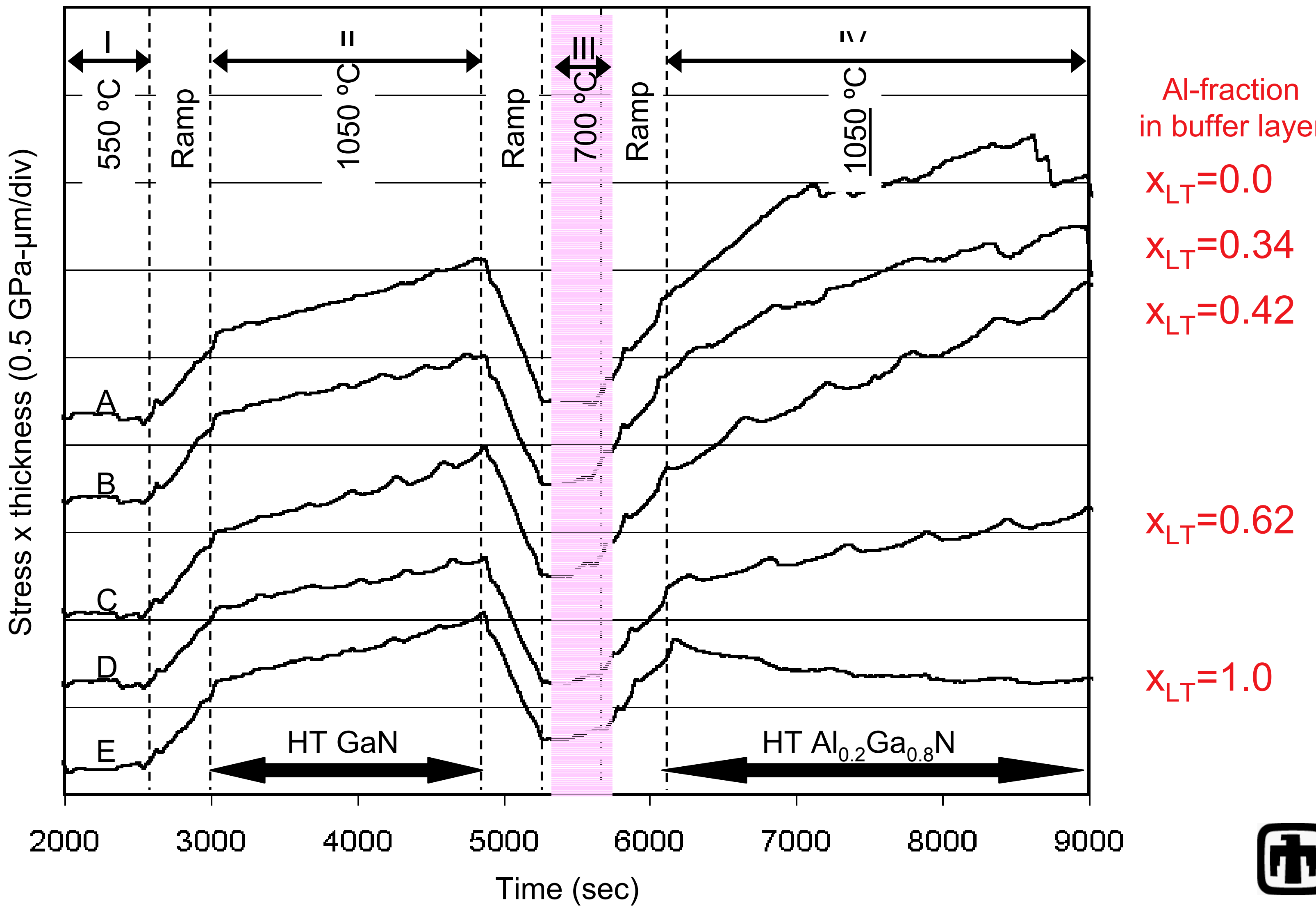


AlGaN/GaN: *tensile*-strained heteroepitaxy in *hexagonal* crystals

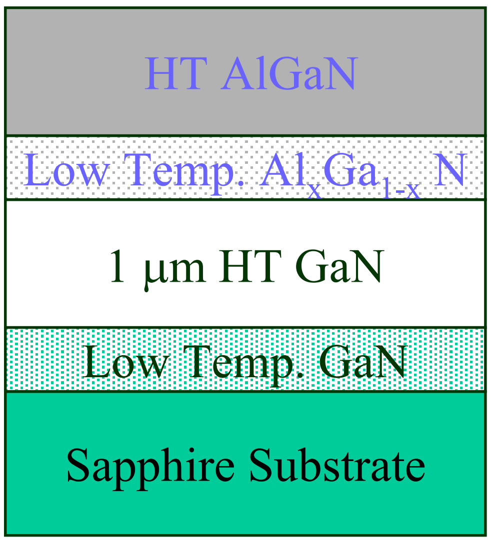
- FRACTURE HAPPENS! But:

  When do cracks occur?
  What are the fracture energetics?
  How much strain do cracks relieve?
  How do cracks and dislocations interact?
  Can we avoid fracture?

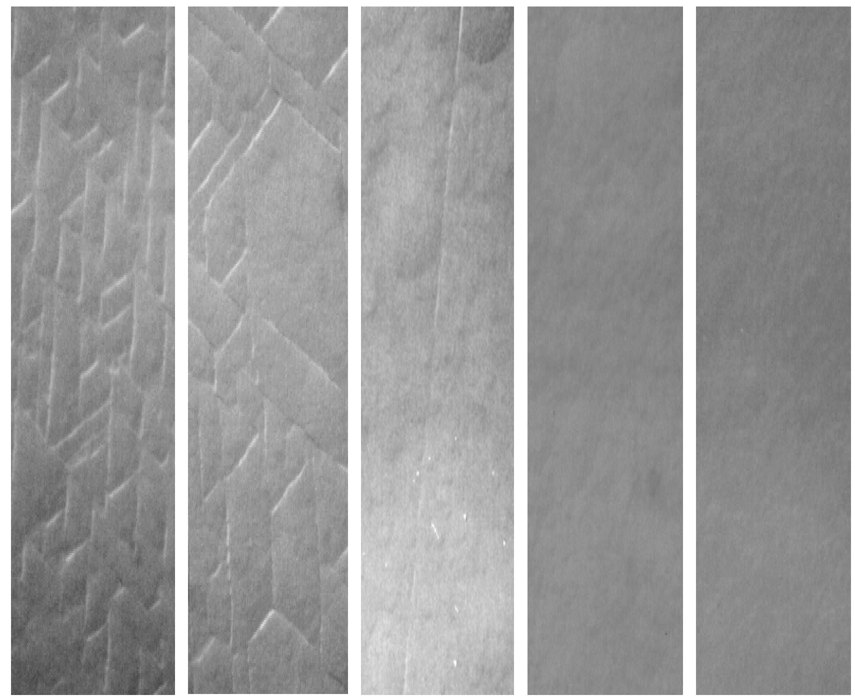
Al content of LT interlayer affects stress in subsequent AlGaN layer



Control and Elimination of Cracking of AlGaN Using Low-Temperature AlGaN Interlayers

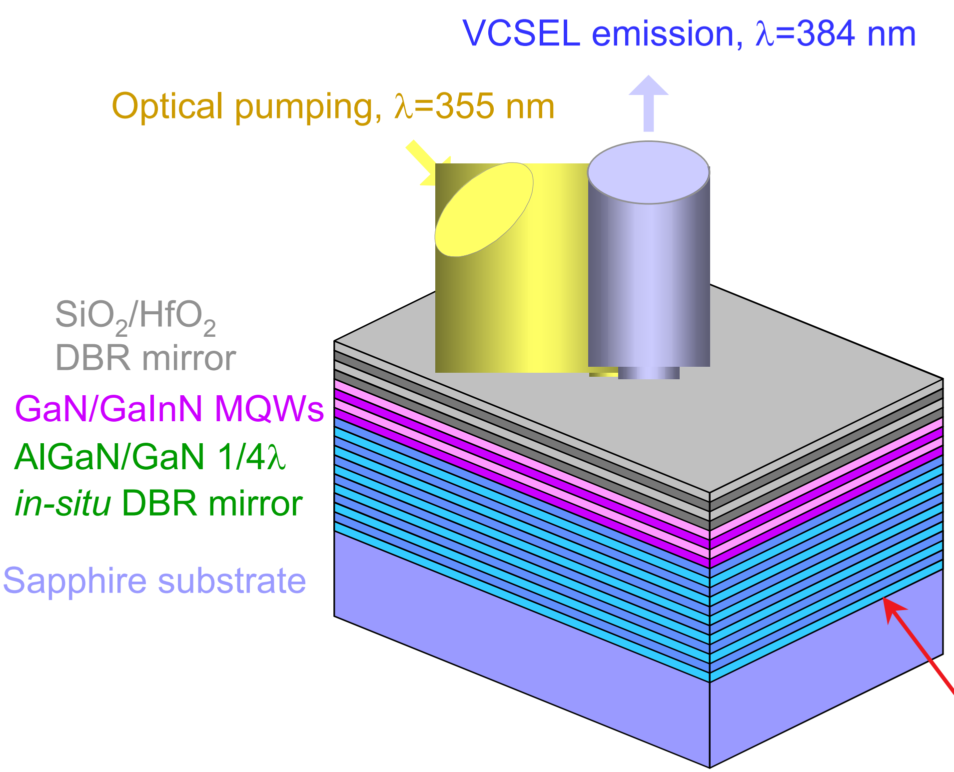


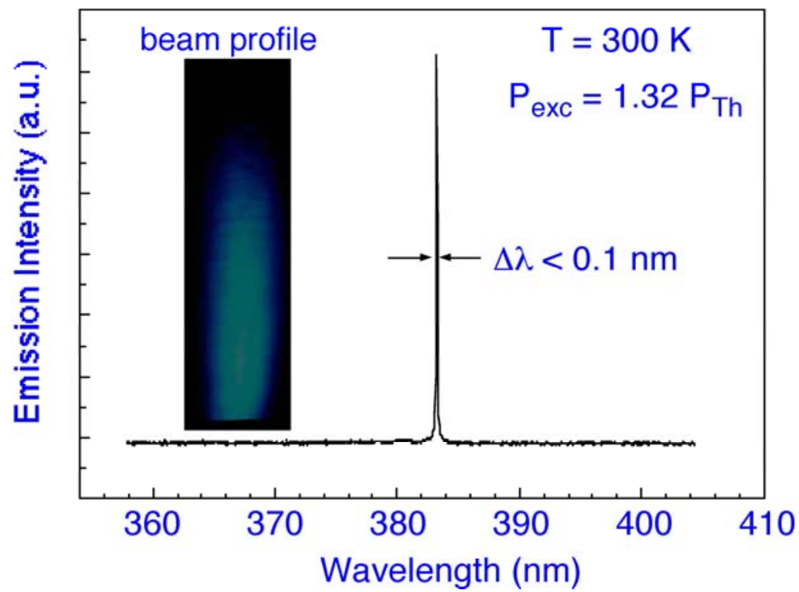
h_g=0.10 μm h_g=0.43 μm h_g=0.38 μm h_g=3.0 μm h_g=∞



(A) x_{LT}=0 (B) x_{LT}=0.34 (C) x_{LT}=0.42 (D) x_{LT}=0.62 (E) x_{LT}=1

Stress engineering enabled world's first UV semiconductor laser, a photo-pumped CW InGaN UV VCSEL, at λ = 384 nm





Thick 60-period DBR mirror enabled by insertion of 4 LT-AlN stress relief layers

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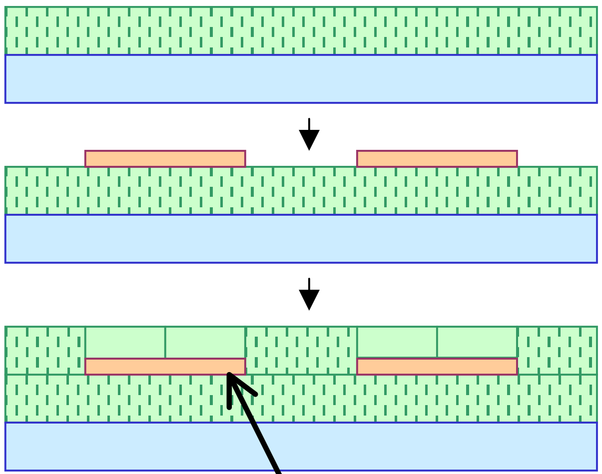
Growth on sapphire or SiC substrates yields high dislocation densities Epitaxial Lateral Overgrowth (ELO) has partly solved the problem

ELO Process

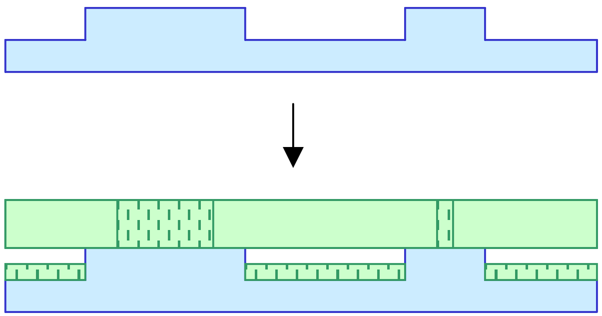


Advantages:
- Low threading dislocation density over overgrown region
- Has increased operating time of blue emitters

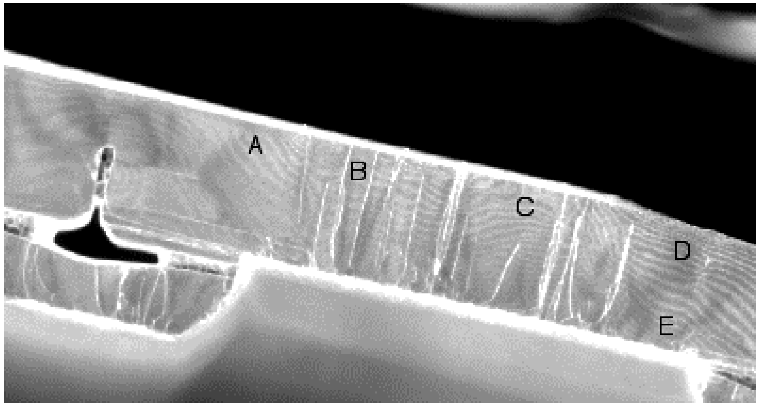
Problems:
- Stress over SiO_2 leads to wing tilt and TDs at edge of mask
- Concerns that autodoping effects lead to leaky substrate material

Cantilever Epitaxy (CE): New Approach to Lateral Overgrowth

CE Process



1) Pattern substrate
2) Grow GaN
   250 Å LT GaN NL
   0.4 mm HT GaN at 1050 ºC
   Grow cantilevers at 1100 ºC

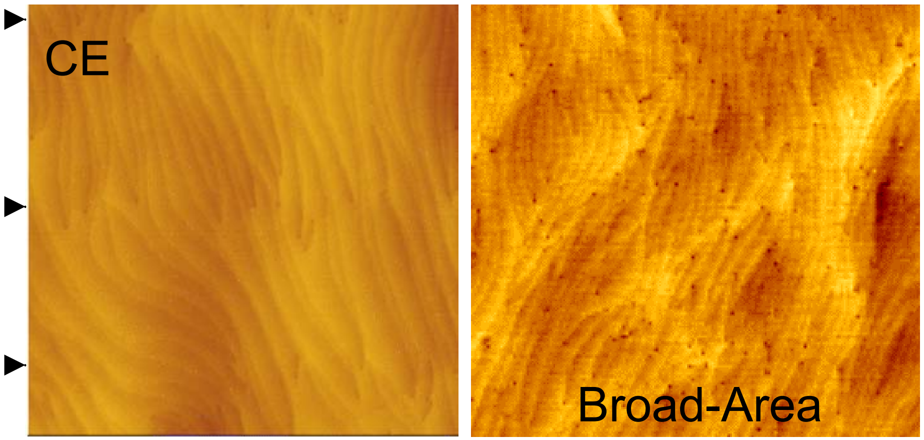


Advantages:
- No SiO_2 masks:
- few VTDs along coalescence.
- Only one GaN growth.

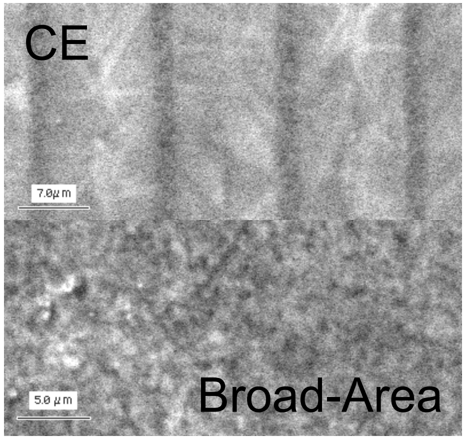
Problems:
- VTDs sometimes over center of supports.

Cantilever Epitaxy Can Improve Structural and Optical Properties of GaN Over Whole Wafer

AFM: 5x5 mm Dots=dislocations



Cathodoluminescence



Cantilevers are virtually VTD-free, including coalescence front.

VTDs are greatly reduced over support.

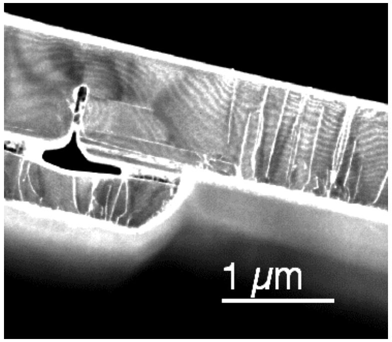
CE with 1 mm supports, 20 mm cantilevers, expect:

Whole wafer: $<5\times10^{7}$ VTD/cm^{2}

Cantilever only: $<5\times10^{6}$ VTD/cm^{2}

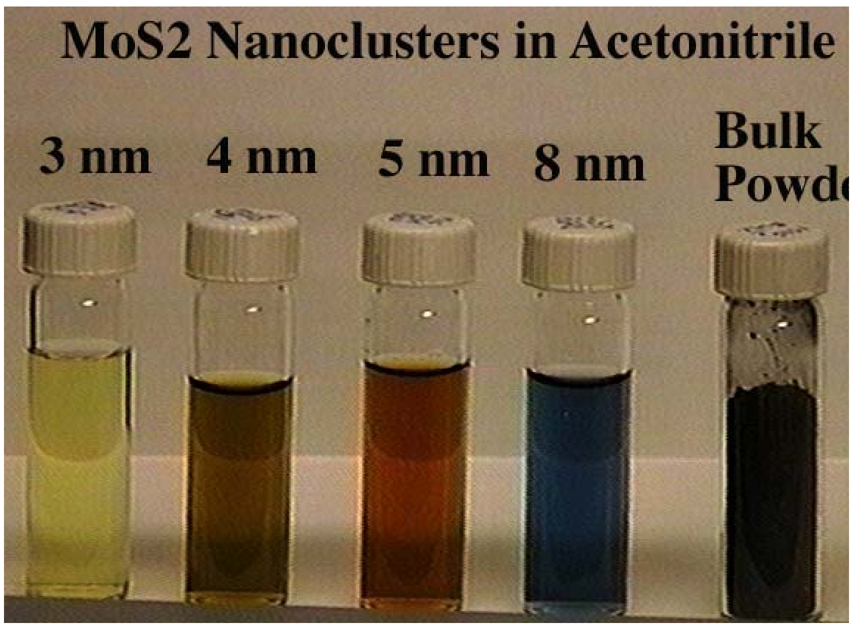
(Broad Area growth: 10^{9}-10^{10} VTD/cm^{2})

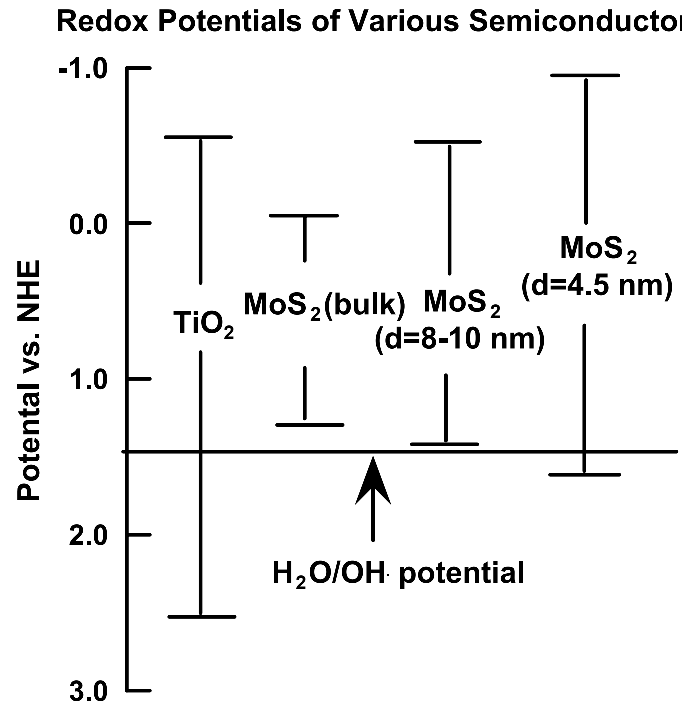
TEM



Quantum Size Effects control the optical and electronic properties of Indirect Semiconductor Nanoclusters

Example: MoS_2





By adjusting the size alone, the conductance and valence band energy levels can be shifted allowing new types of photocatalytic behavior to occur

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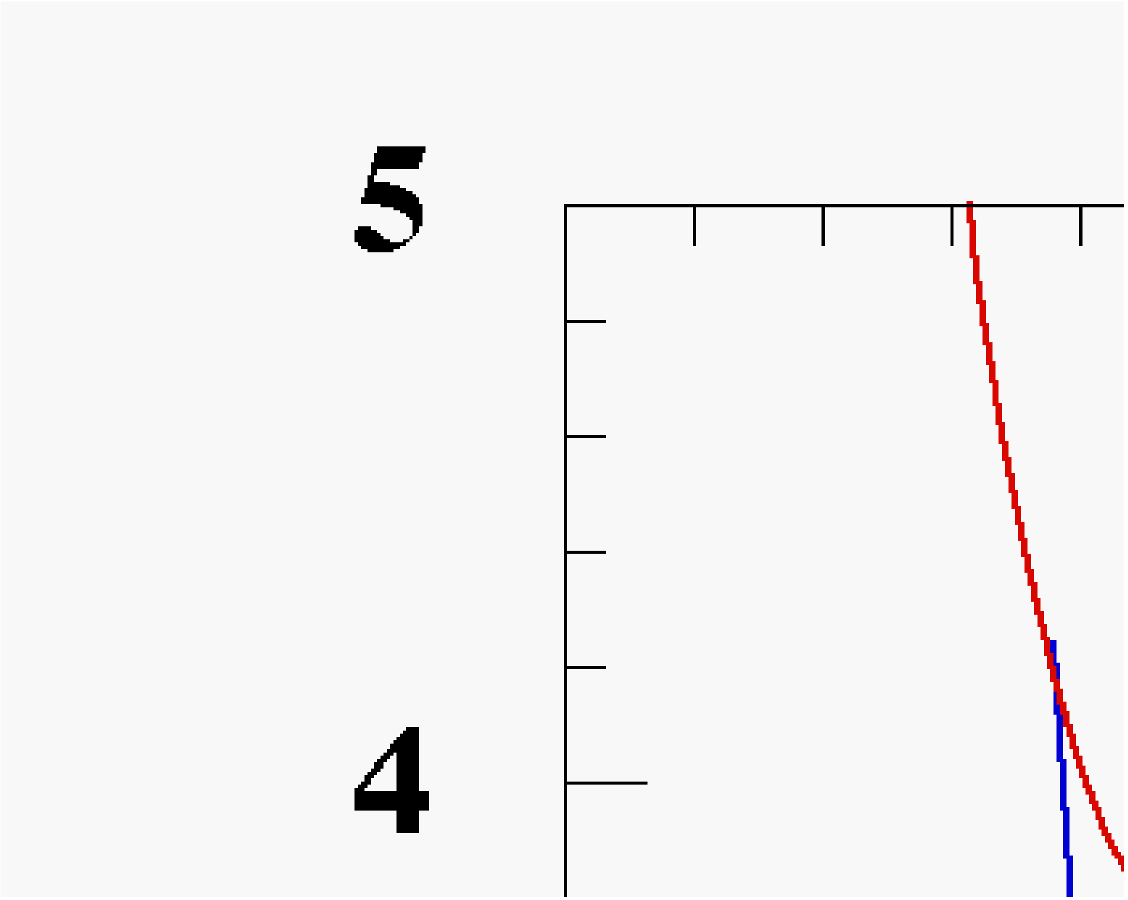
Nanocrystals may have advantages over conventional phosphors



3.0 nm CdS particles with and without a ZnS surface coating

- optical properties are tunable by size
- PL efficiency can be improved by surface coatings

PART III: SSL has significant synergisms with other projects directly aligned with National Security needs

Large band-gaps of nitrides suited to three technological application areas of vital importance to national security:

semiconductor optoelectronics in the UV

- compact fluorescence-based chem-bio sensors (to detect WMD)
- solar-blind 240-280 nm detectors for missile tracking
- 300-360 nm detectors for combustion control

high-temperature electronics for hostile environments

- low weight, local monitoring of jet engines in aircraft, cruse missiles
- “in-hole” electronics for oil well drilling

high-power electronics at high frequencies

- high-efficiency, low-weight satellite communications
- high-power, low-noise **synthetic aperture radar (SAR),** and active decoys and jamming

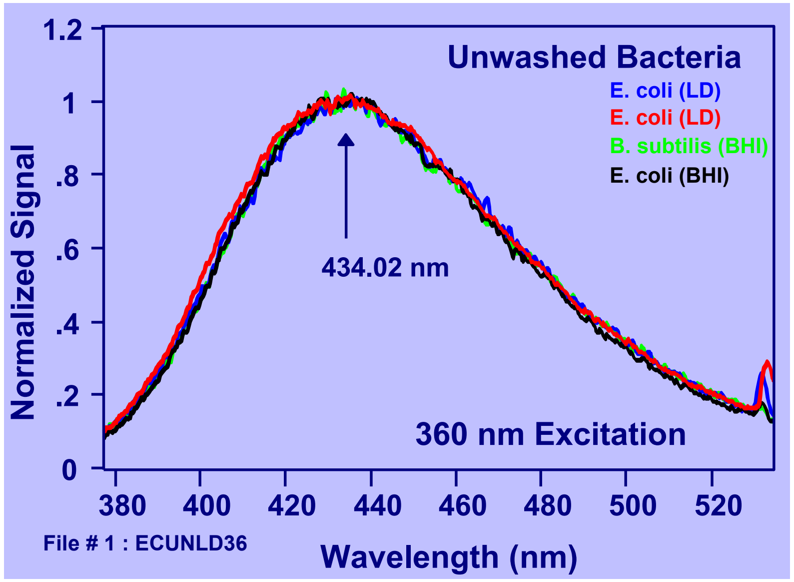
NS applications for UV LEDs and VCSELs- - fluorescence-based detection of WMD

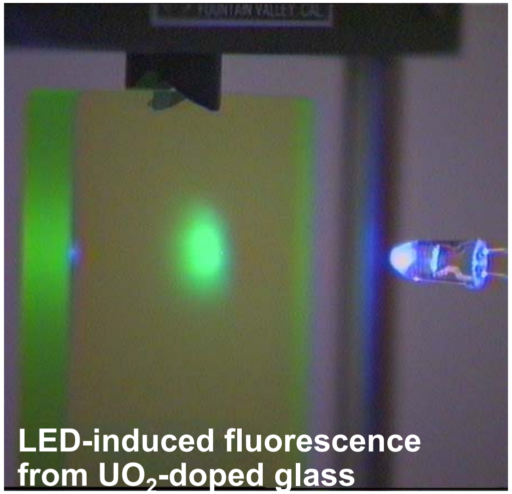
Focus: nitride UV emitters/detectors for
- **Inorganics (UO_2)**
- **Organics (micro-organisms)**

Funding: LDRD plus 3-letter agency

354 nm and 357.5 nm LEDs demonstrated in fluorescence measurements

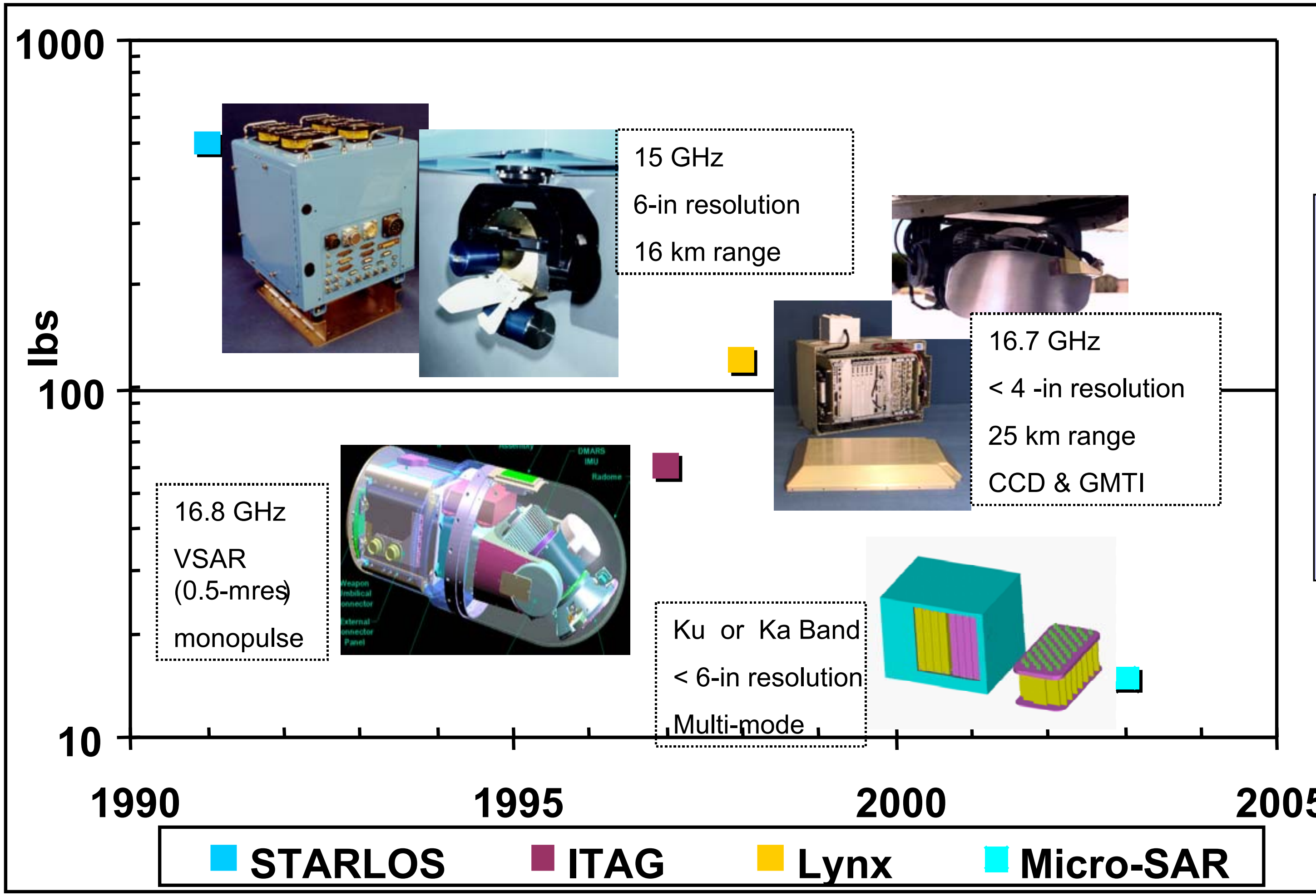
VCSELs are much preferred for this application





LED-induced fluorescence from UO_2-doped glass

High power electronics for low weight Synthetic Aperture Radar (SAR)



Low weight, high resolution enabled by high power density of GaN

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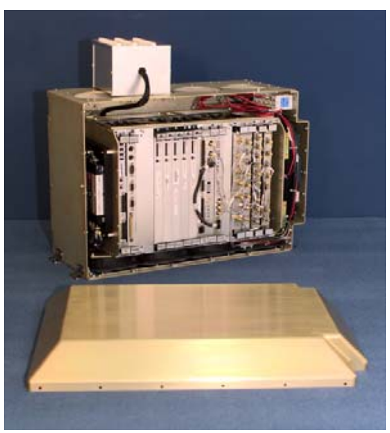
Reduced weight is crucial for UAV field applications

Predator UAV

I-GNAT UAV

Prowler II UAV

Antenna Assembly



Radar Electronics Assembly

Lighter weight

↓

Smaller UAV

↓

Less vulnerable target

GaN HEMTs have 10X power density of InP. Enables:

- **replacement of TWTs**
- **electronically scanned antennas**

Summary

Breakthroughs in fundamental materials science and technology will be required for the vision of Solid State Lighting to become a reality.

Considerable expertise in the key S&T areas required has been developed at the national laboratories, ***substantially due to long-running BES programs.***

These areas include:

- Fundamental materials physics & defect physics
- Growth chemistry and reactor physics
- In-situ monitoring and stress-engineering
- Semiconductor nanoclusters

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