GaInNAs: A new Material in the Race for Long Wavelength VCSELs

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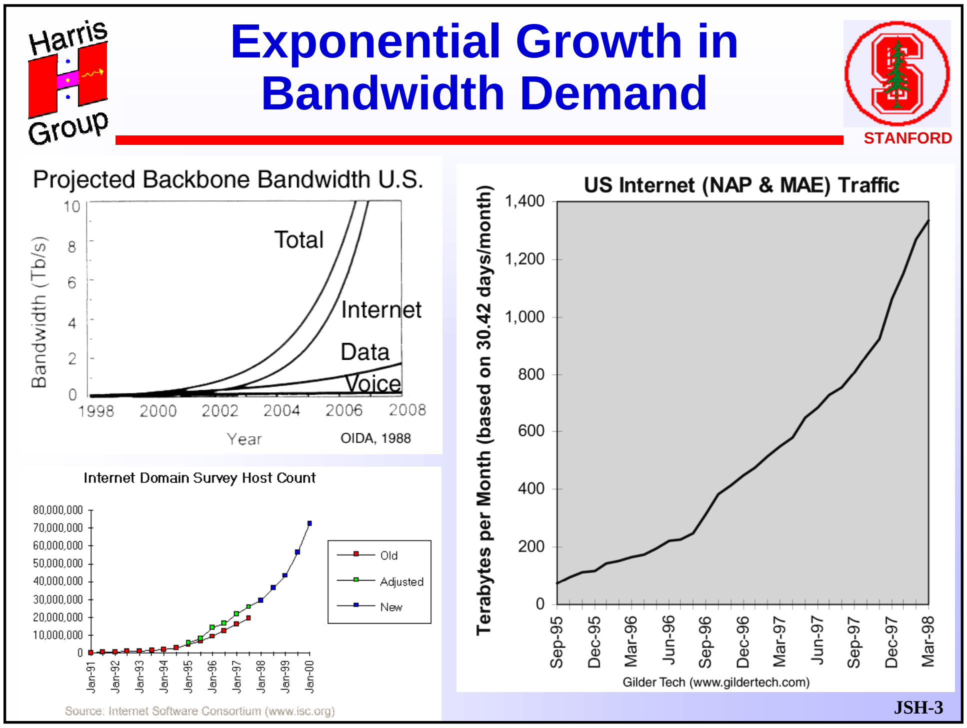
Outline

- **Introduction**
- **The Choices**
- **GaInNAs/GaAs Material Properties**
- **Work at Stanford**
  - **MBE Growth**
  - **Edge-emitting lasers**
  - **Pulsed broad area VCSELs**
  - **CW oxide-confined VCSELs**
- **GaInNAs as an Enabling Technology**
- **Summary**

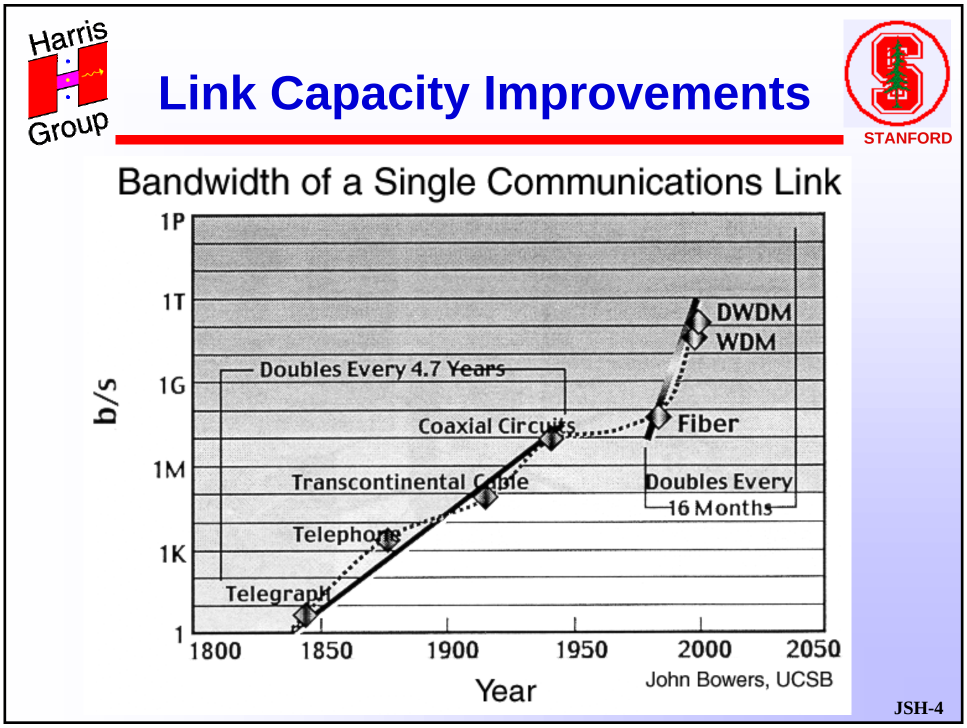


Exponential Growth in Bandwidth Demand

OIDA, 1988

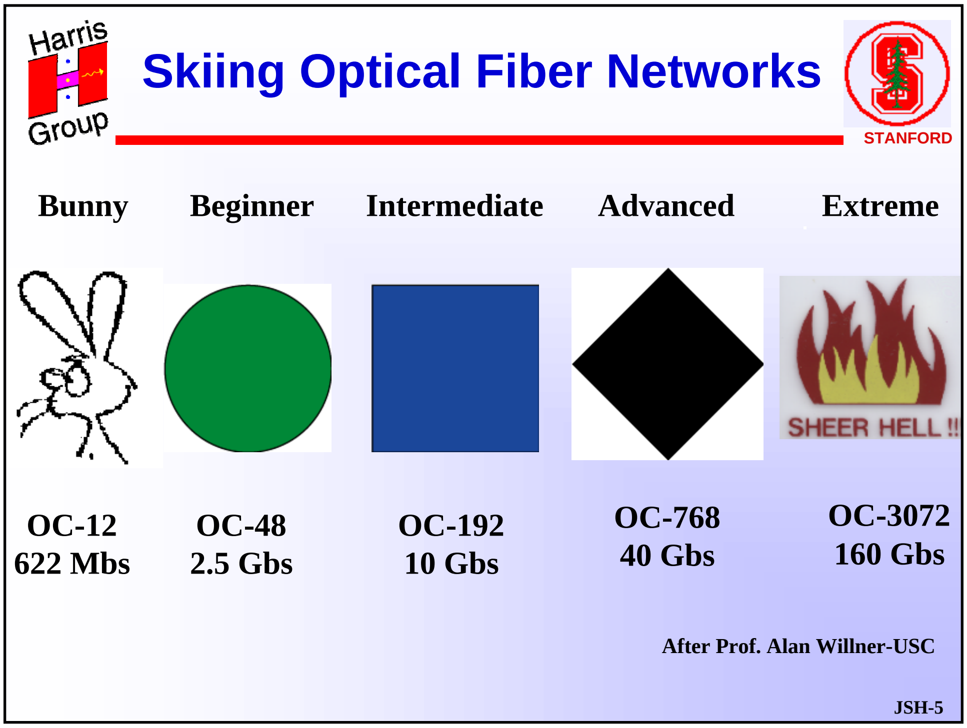
Source: Internet Software Consortium (www.isc.org)

Gilder Tech (www.gildertech.com)



Link Capacity Improvements

John Bowers, UCSB



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Skiing Optical Fiber Networks

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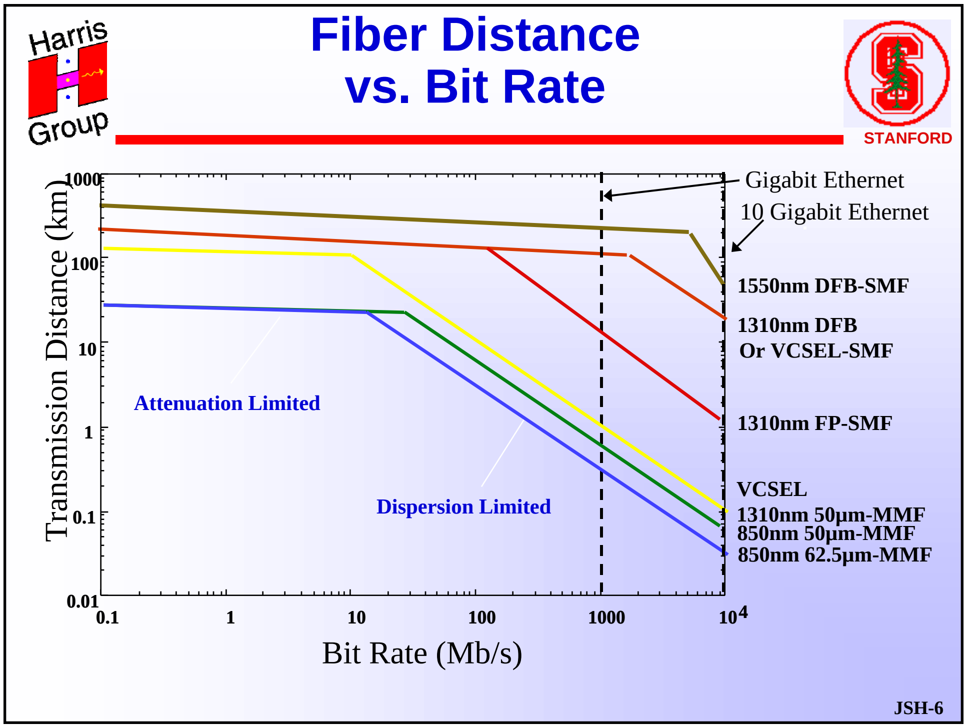
Bunny	Beginner	Intermediate	Advanced	Extreme
OC-12 622 Mbs	OC-48 2.5 Gbs	OC-192 10 Gbs	OC-768 40 Gbs	OC-3072 160 Gbs

After Prof. Alan Willner-USC



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Fiber Distance vs. Bit Rate

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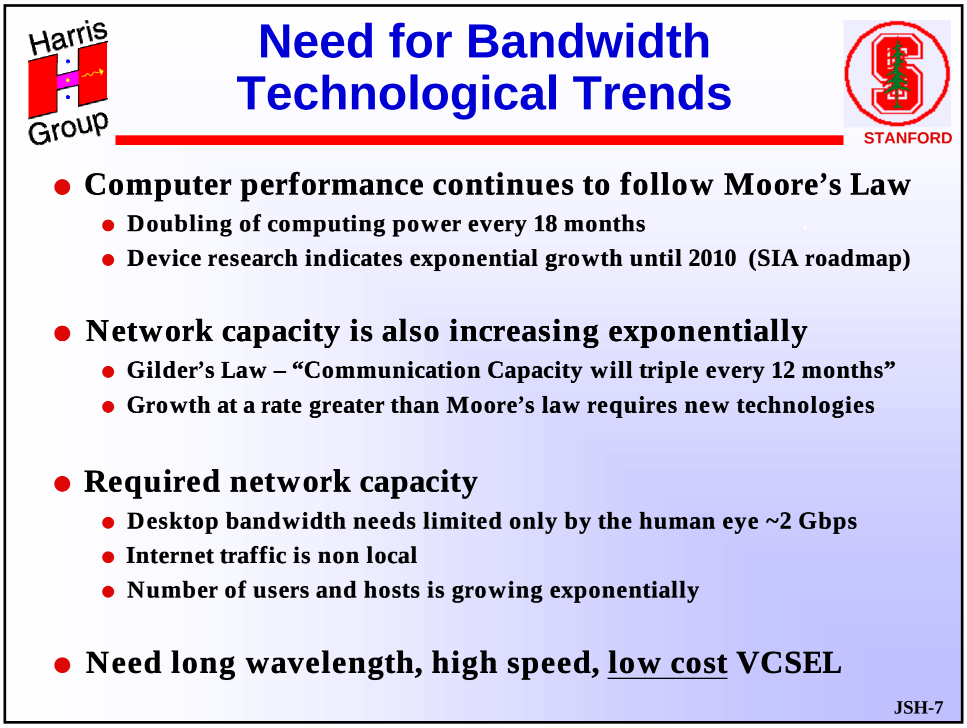

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Need for Bandwidth
Technological Trends

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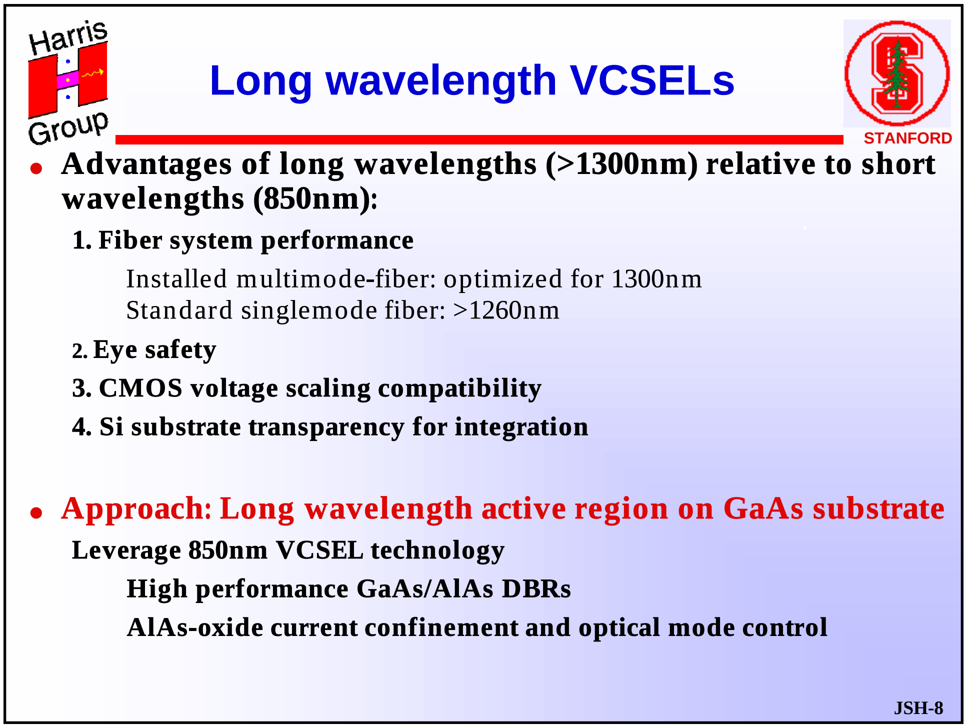
- **Computer performance continues to follow Moore's Law**
  - **Doubling of computing power every 18 months**
  - **Device research indicates exponential growth until 2010 (SIA roadmap)**
- **Network capacity is also increasing exponentially**
  - **Gilder's Law – "Communication Capacity will triple every 12 months"**
  - **Growth at a rate greater than Moore's law requires new technologies**
- **Required network capacity**
  - **Desktop bandwidth needs limited only by the human eye ~2 Gbps**
  - **Internet traffic is non local**
  - **Number of users and hosts is growing exponentially**
- **Need long wavelength, high speed, <u>low cost</u> VCSEL**

JSH-7



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Long wavelength VCSELs

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- **Advantages of long wavelengths (>1300nm) relative to short wavelengths (850nm):**

1. Fiber system performance

Installed multimode-fiber: optimized for 1300nm
Standard singlemode fiber: >1260nm

2. Eye safety

3. CMOS voltage scaling compatibility

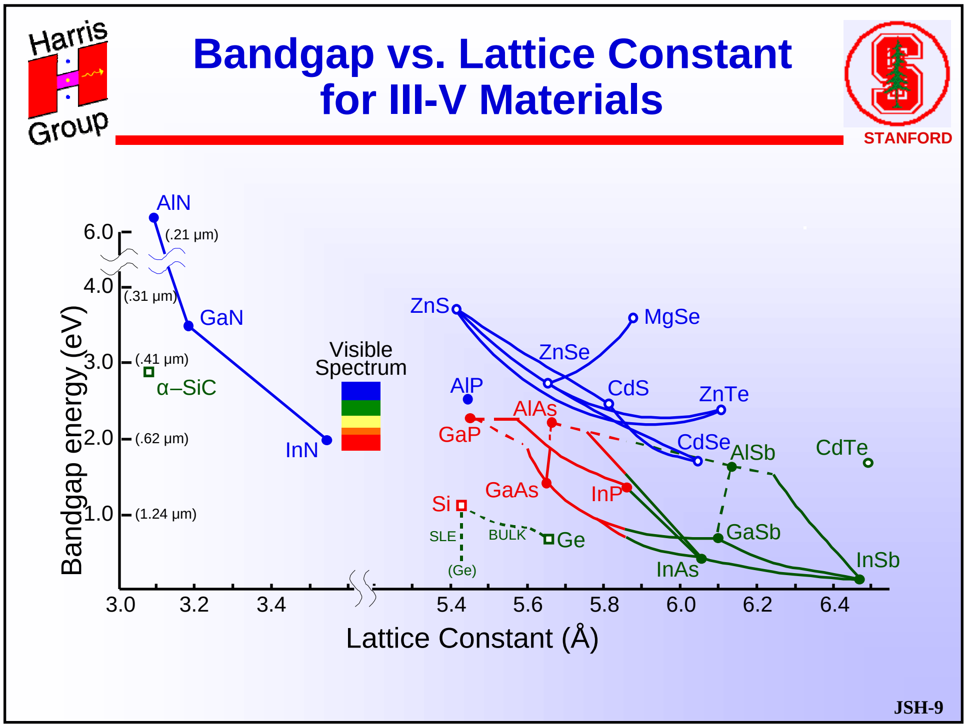
4. Si substrate transparency for integration

- **Approach: Long wavelength active region on GaAs substrate**

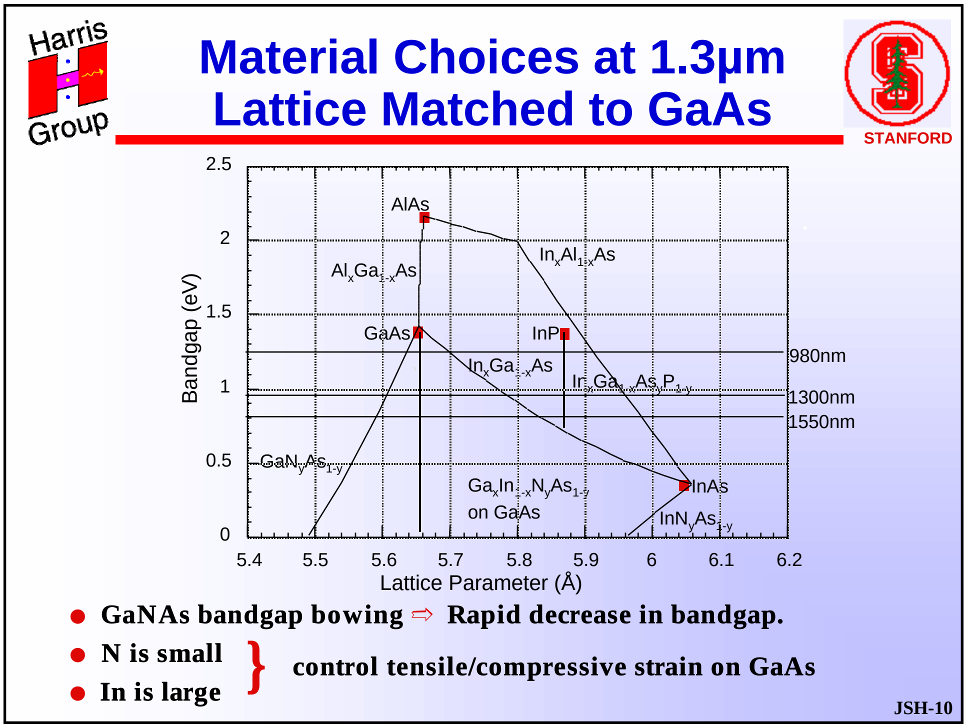
Leverage 850nm VCSEL technology

High performance GaAs/AlAs DBRs
AlAs-oxide current confinement and optical mode control

JSH-8

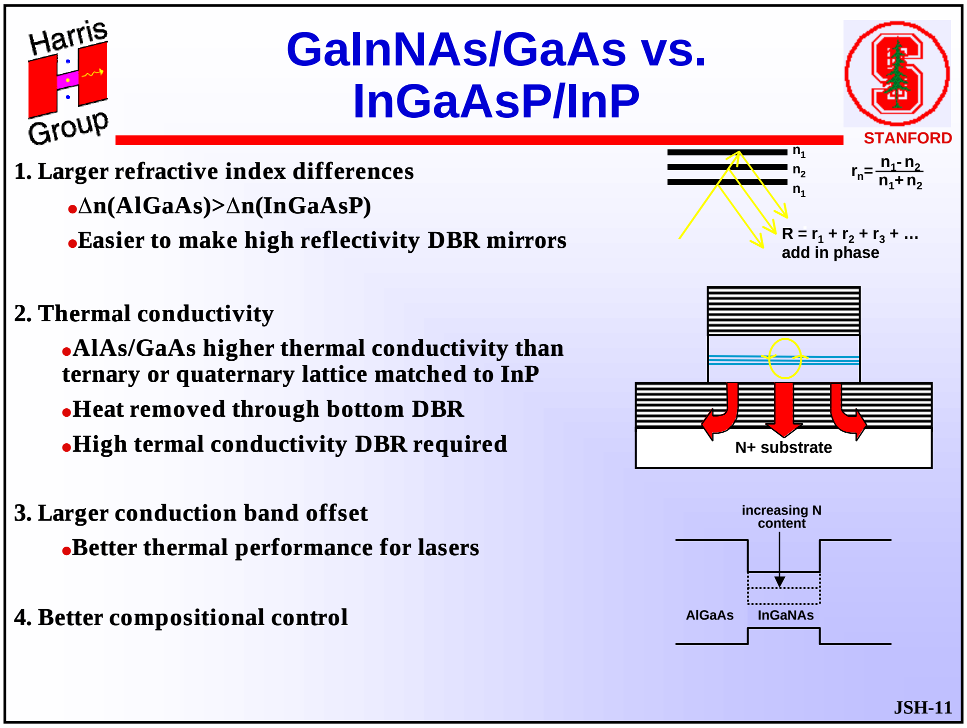


Bandgap vs. Lattice Constant for III-V Materials



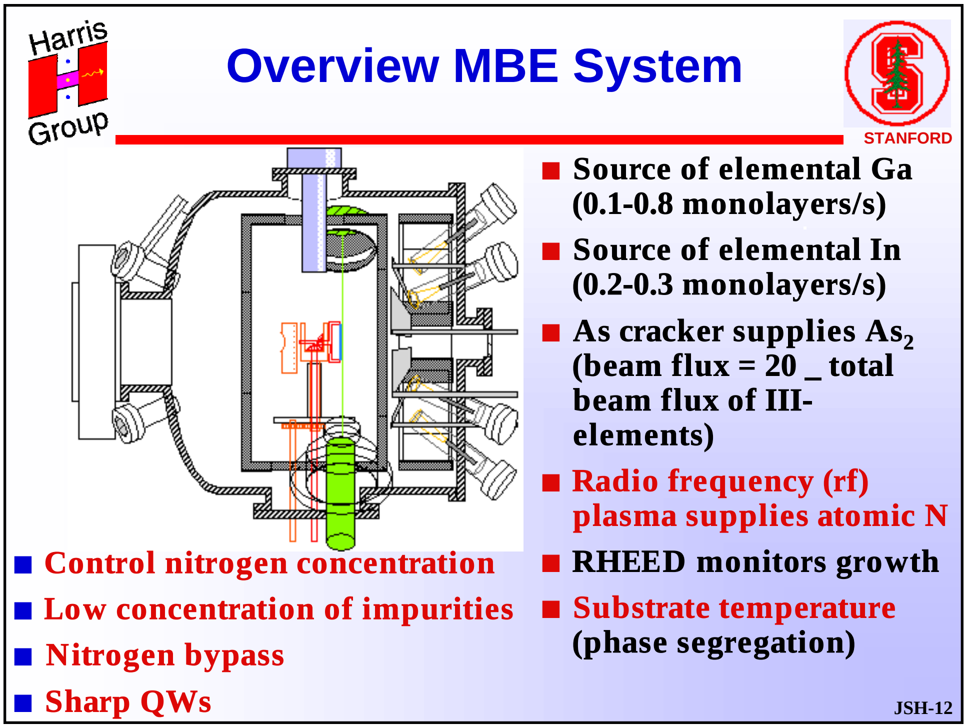
Material Choices at 1.3µm Lattice Matched to GaAs

- **GaNAs bandgap bowing ⇨ Rapid decrease in bandgap.**
- **N is small** } **control tensile/compressive strain on GaAs**
- **In is large**



GaInNAs/GaAs vs. InGaAsP/InP

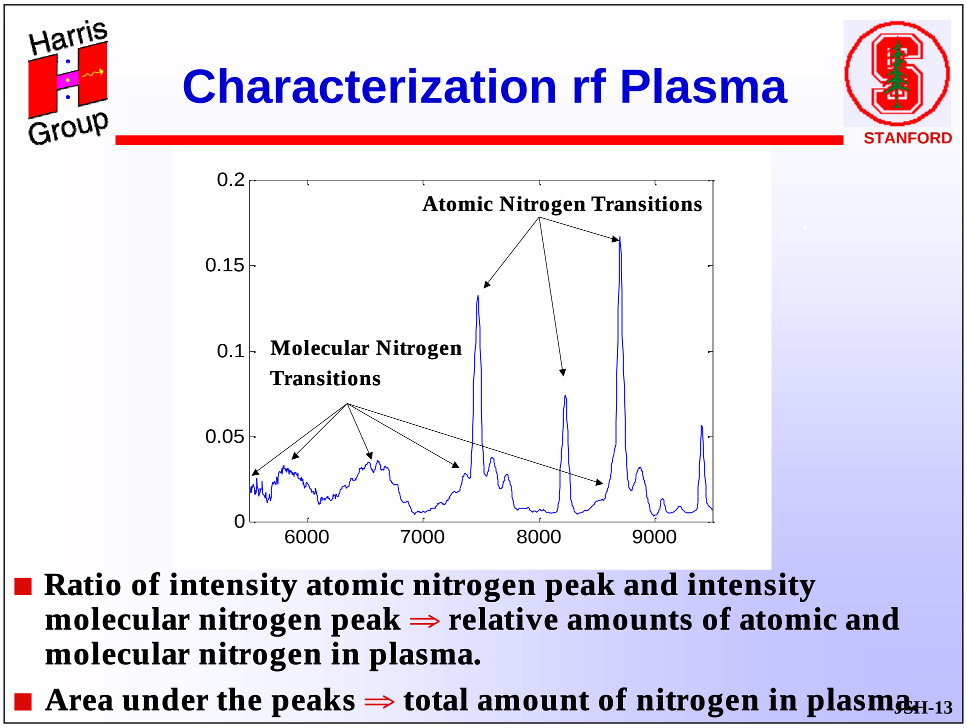
1. Larger refractive index differences
   - Δn(AlGaAs)>Δn(InGaAsP)
   - Easier to make high reflectivity DBR mirrors
2. Thermal conductivity
   - AlAs/GaAs higher thermal conductivity than ternary or quaternary lattice matched to InP
   - Heat removed through bottom DBR
   - High termal conductivity DBR required
3. Larger conduction band offset
   - Better thermal performance for lasers
4. Better compositional control



Overview MBE System

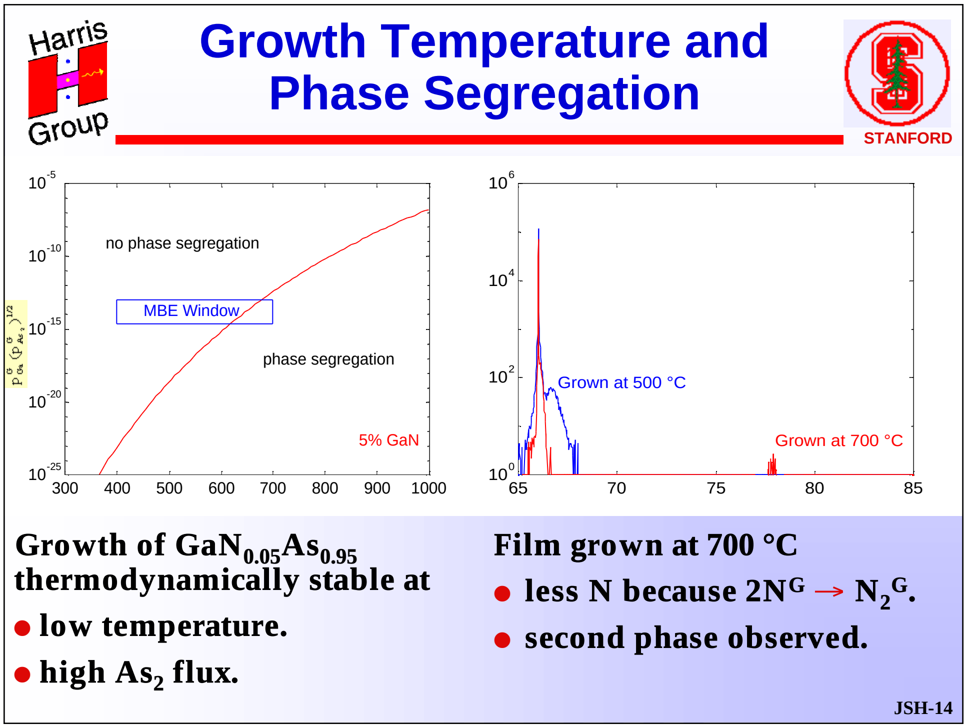
- Source of elemental Ga (0.1-0.8 monolayers/s)
- Source of elemental In (0.2-0.3 monolayers/s)
- As cracker supplies As_2 (beam flux = 20 _ total beam flux of III-elements)
- Radio frequency (rf) plasma supplies atomic N
- RHEED monitors growth
- Substrate temperature (phase segregation)

- Control nitrogen concentration
- Low concentration of impurities
- Nitrogen bypass
- Sharp QWs



Characterization rf Plasma

- Ratio of intensity atomic nitrogen peak and intensity molecular nitrogen peak ⇒ relative amounts of atomic and molecular nitrogen in plasma.
- Area under the peaks ⇒ total amount of nitrogen in plasma.



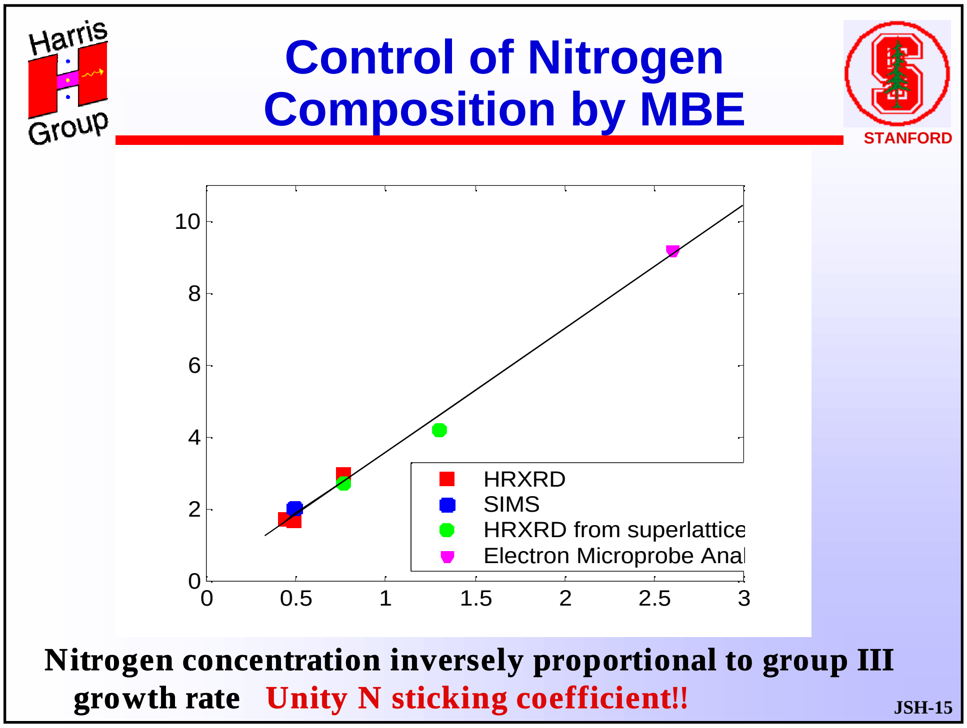
Growth Temperature and Phase Segregation

Growth of $GaN_{0.05}As_{0.95}$ thermodynamically stable at

- low temperature.
- high As_2 flux.

Film grown at 700 °C

- less N because $2N^G \rightarrow N_2^G$.
- second phase observed.



Control of Nitrogen Composition by MBE

Nitrogen concentration inversely proportional to group III growth rate **Unity N sticking coefficient!!**

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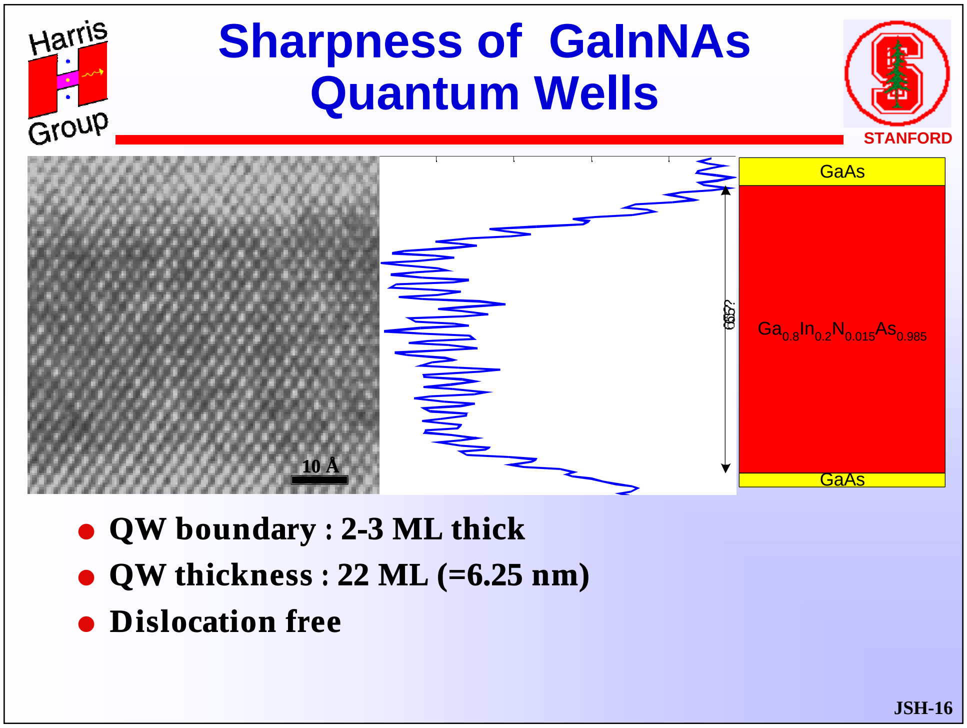

Sharpness of GaInNAs Quantum Wells

- **QW boundary : 2-3 ML thick**
- **QW thickness : 22 ML (=6.25 nm)**
- **Dislocation free**

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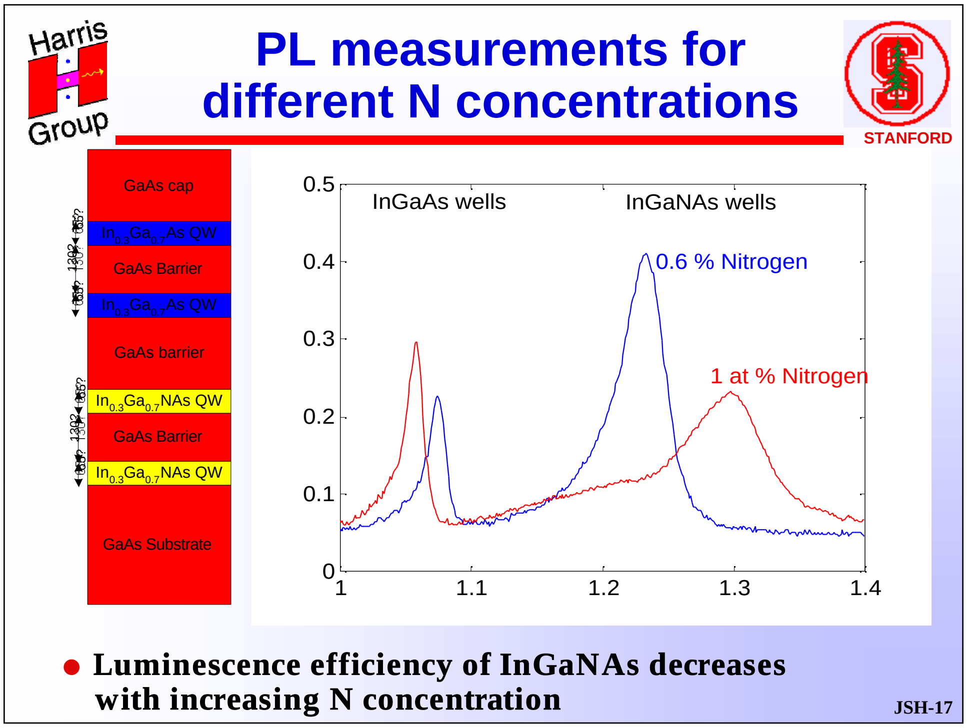

PL measurements for different N concentrations

- Luminescence efficiency of InGaNAs decreases with increasing N concentration

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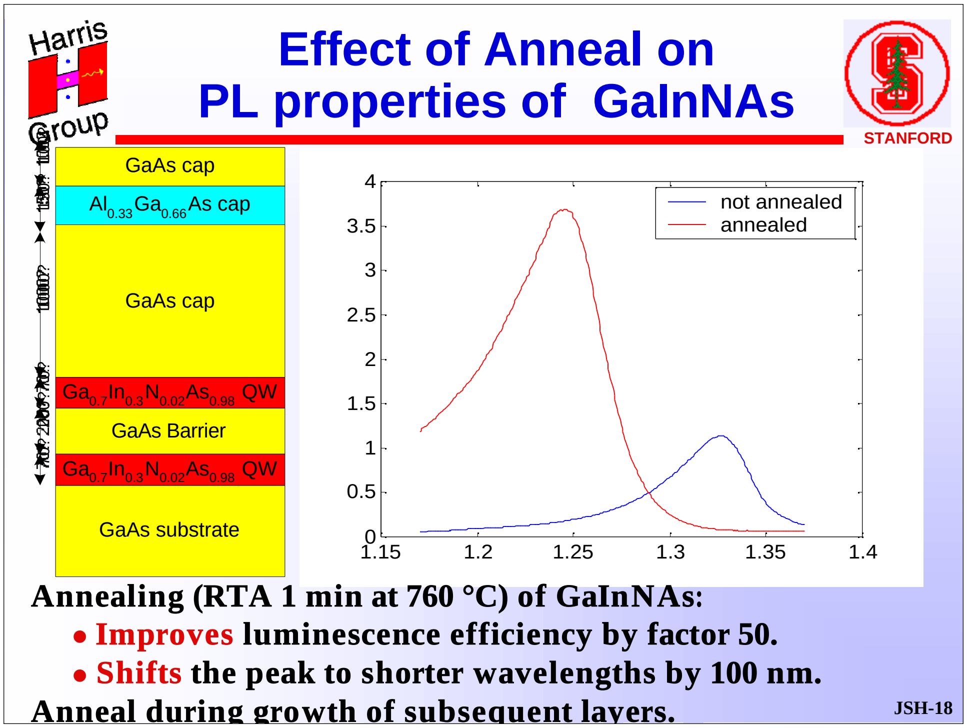

Effect of Anneal on PL properties of GaInNAs

Annealing (RTA 1 min at 760 °C) of GaInNAs:

- **Improves luminescence efficiency by factor 50.**
- **Shifts the peak to shorter wavelengths by 100 nm.**

Anneal during growth of subsequent layers.

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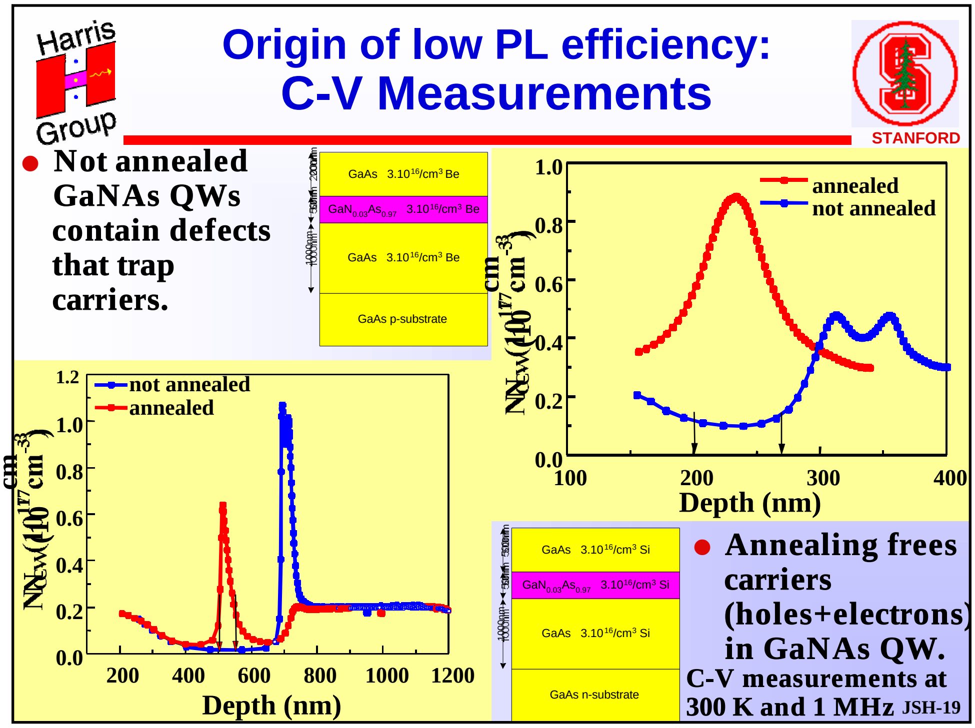

Origin of low PL efficiency: C-V Measurements

- Not annealed GaNAs QWs contain defects that trap carriers.

GaAs 3.10^{16}/cm^3 Be
$GaN_{0.03}As_{0.97}$ 3.10^{16}/cm^3 Be
GaAs 3.10^{16}/cm^3 Be
GaAs p-substrate

GaAs 3.10^{16}/cm^3 Si
$GaN_{0.03}As_{0.97}$ 3.10^{16}/cm^3 Si
GaAs 3.10^{16}/cm^3 Si
GaAs n-substrate

- Annealing frees carriers (holes+electrons) in GaNAs QW.

C-V measurements at 300 K and 1 MHz

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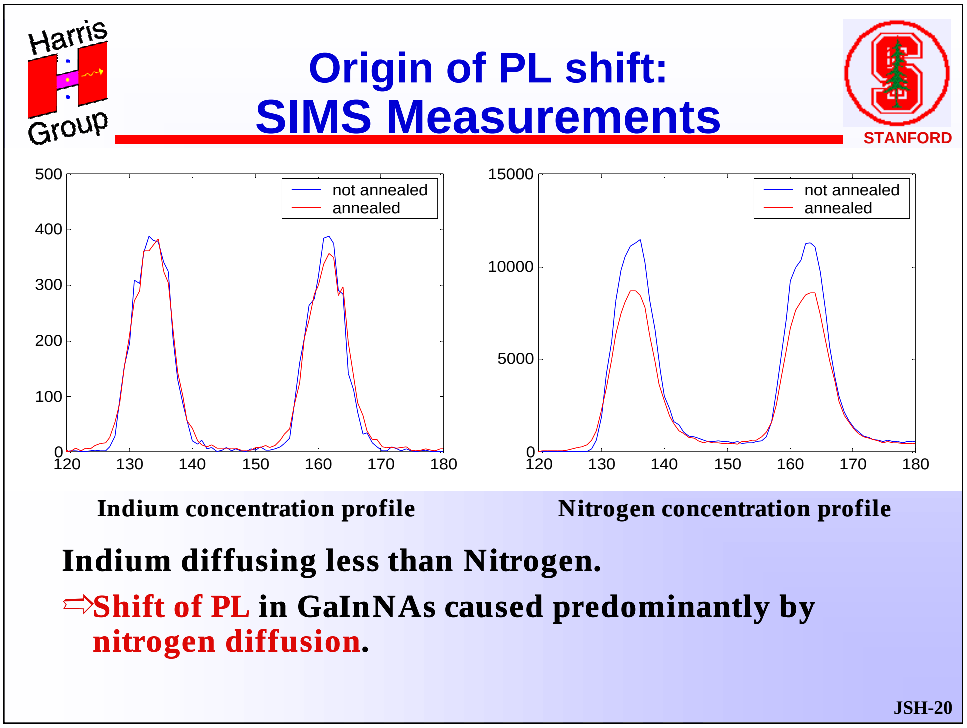

Origin of PL shift: SIMS Measurements

Indium concentration profile

Nitrogen concentration profile

Indium diffusing less than Nitrogen.

⇨Shift of PL in GaInNAs caused predominantly by nitrogen diffusion.

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Origin of low PL efficiency: Interstitial Nitrogen

- Channeling combined with Nuclear Reaction Analysis (NRA) to determine location of nitrogen.
- $^{14}N + ^{3}He \rightarrow ^{16}O$ + proton.
- 2.5 MeV ^{3}He analysis beam
- 1.5 MeV protons detected

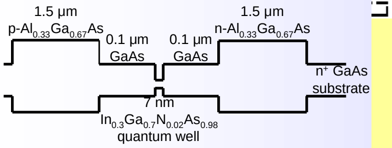
Counts	Aligned <100>	Unaligned	Ratio
Not annealed	102	390	0.262 ± 0.03
Annealed	59	369	0.160 ± 0.02

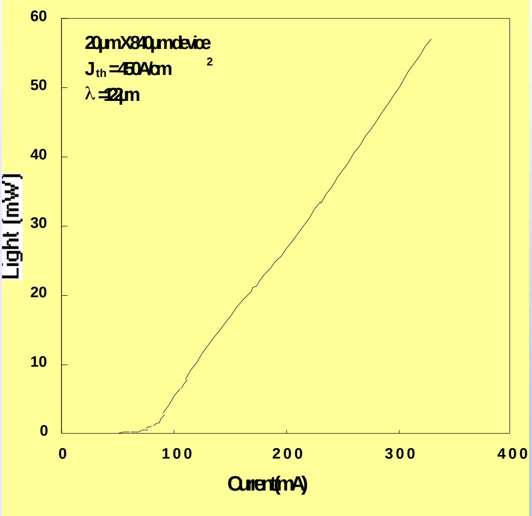
$\chi_{min} = 0.06$
for RBS channeling

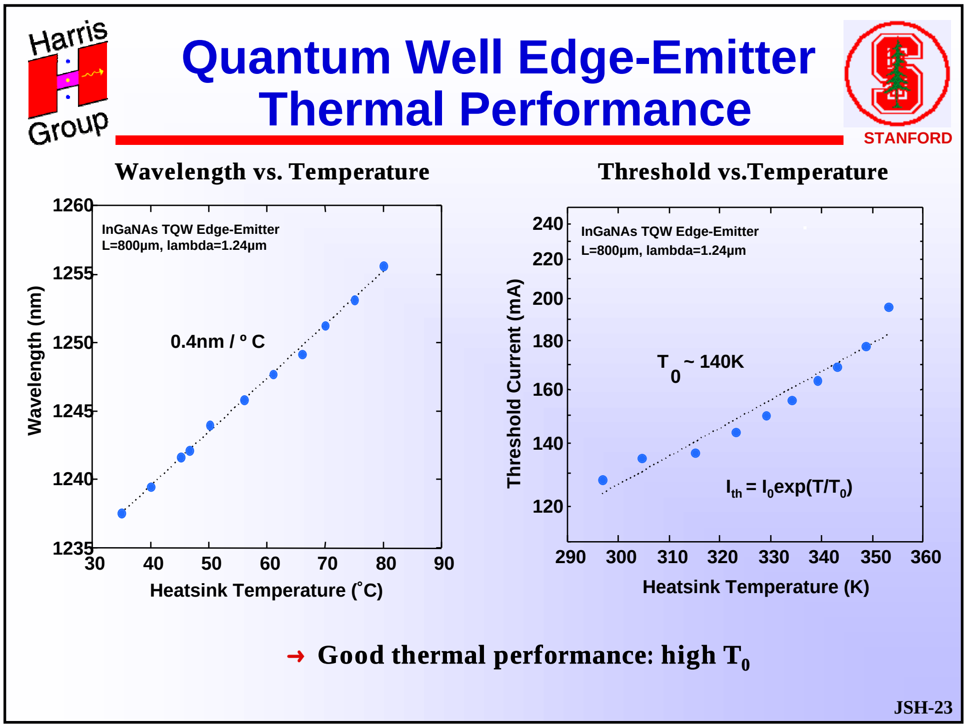
- Nitrogen is not all substitutional.
- Amount of non-substitutional Nitrogen is decreased by annealing.

In-plane Laser Results

- Broad area diode laser
- 70 Å Single QW laser
- $J_{th} = 450\ A/cm^2$





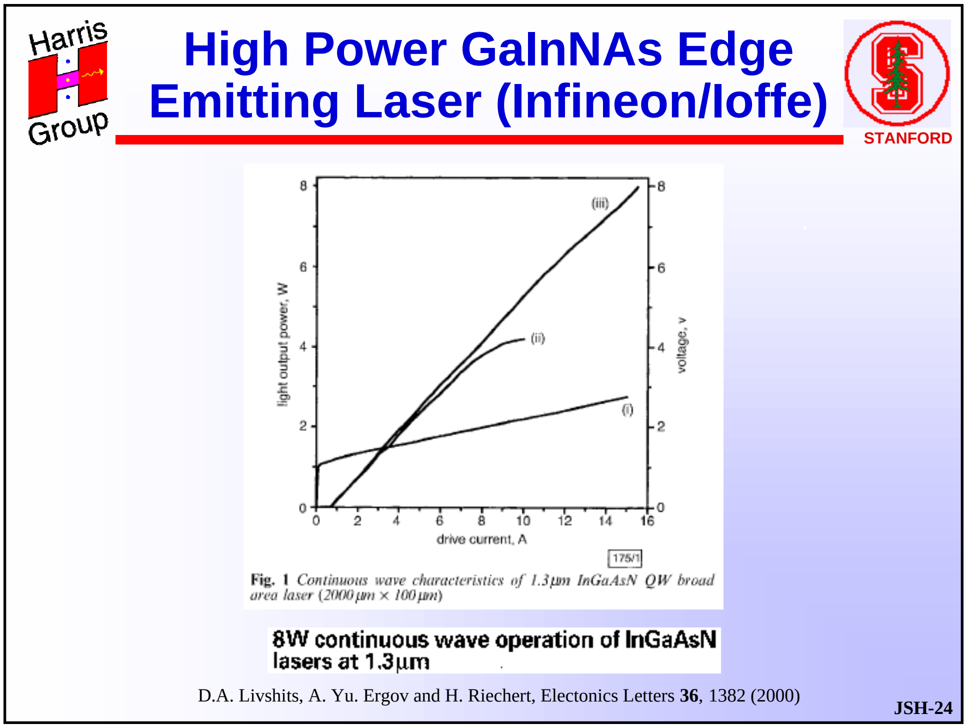


Quantum Well Edge-Emitter Thermal Performance

Wavelength vs. Temperature

Threshold vs.Temperature

→ **Good thermal performance: high T_0**

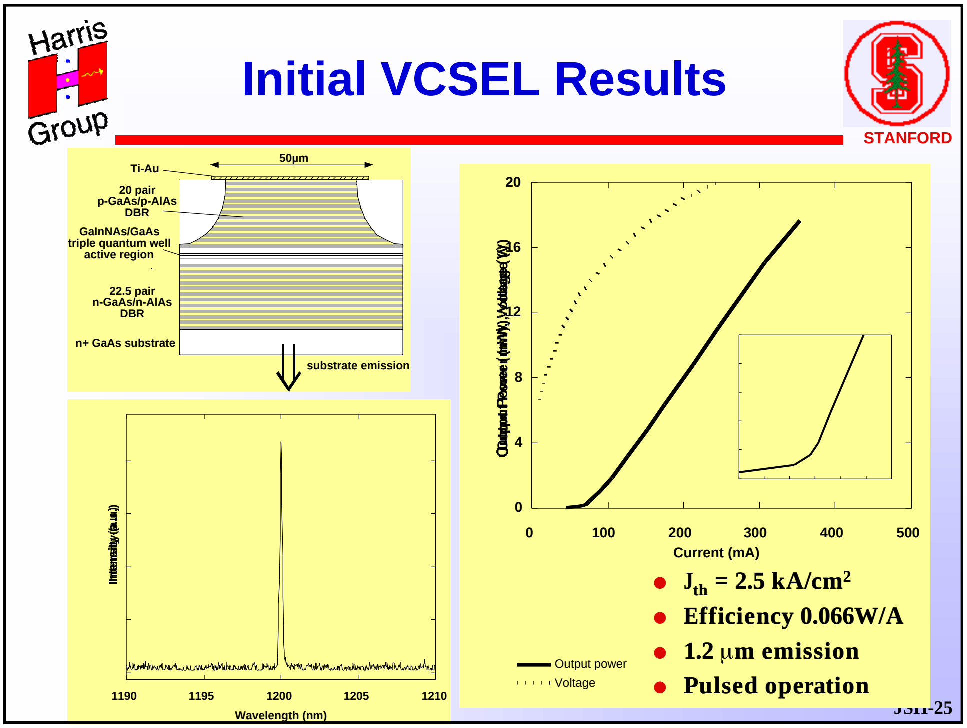


High Power GaInNAs Edge Emitting Laser (Infineon/Ioffe)

Fig. 1 *Continuous wave characteristics of 1.3µm InGaAsN QW broad area laser (2000µm × 100µm)*

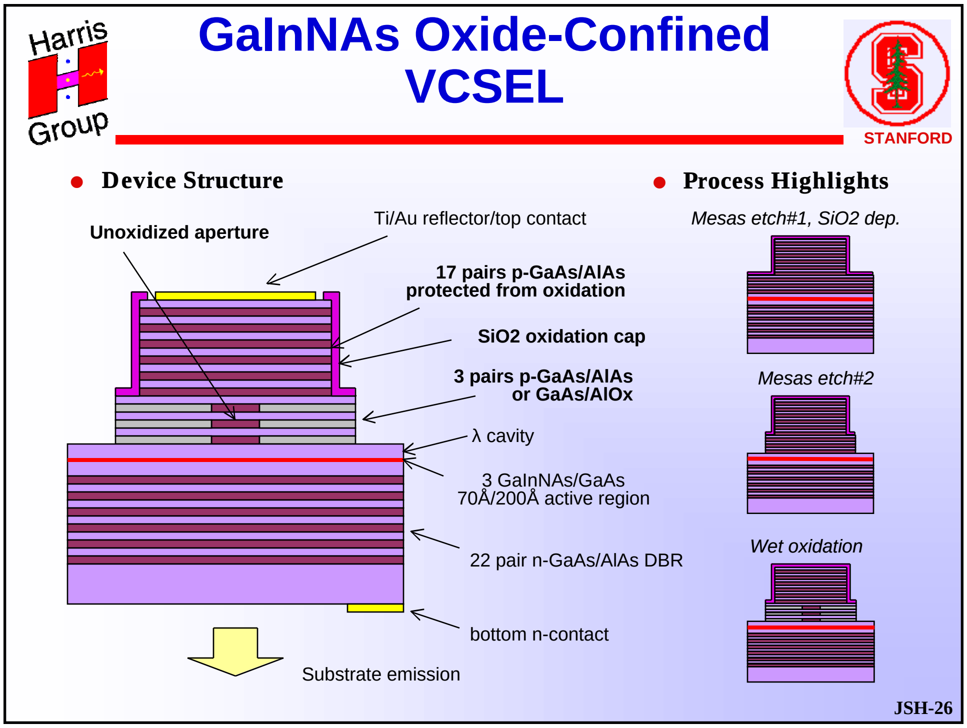
8W continuous wave operation of InGaAsN lasers at 1.3µm

D.A. Livshits, A. Yu. Ergov and H. Riechert, Electonics Letters **36**, 1382 (2000)



Initial VCSEL Results

- J_{th} = 2.5 kA/cm^2
- Efficiency 0.066W/A
- 1.2 μm emission
- Pulsed operation



GaInNAs Oxide-Confined VCSEL

- **Device Structure**

Unoxidized aperture

Ti/Au reflector/top contact

17 pairs p-GaAs/AlAs protected from oxidation

SiO2 oxidation cap

3 pairs p-GaAs/AlAs or GaAs/AlOx

λ cavity

3 GaInNAs/GaAs 70Å/200Å active region

22 pair n-GaAs/AlAs DBR

bottom n-contact

Substrate emission

- **Process Highlights**

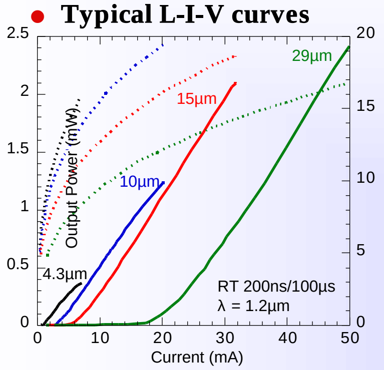
Mesas etch#1, SiO2 dep.

Mesas etch#2

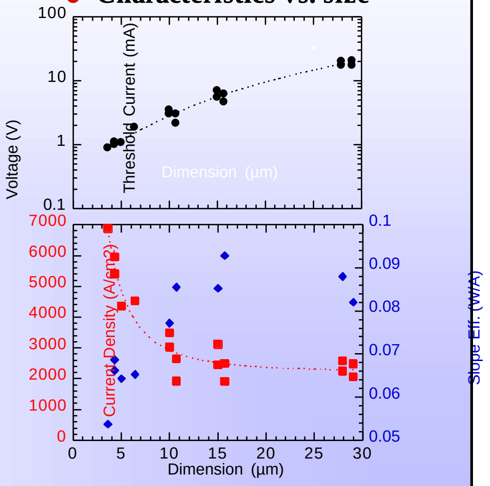
Wet oxidation

Oxide-confined GaInNAs VCSEL pulsed characteristics

- Typical L-I-V curves



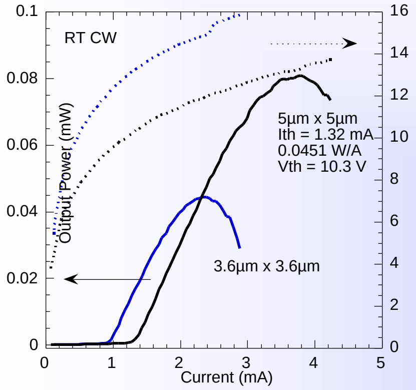
- Characteristics vs. size



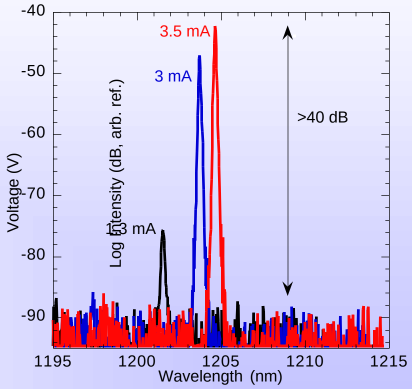
- 3.6 - 29 µm square apertures
- 0.9 - 20 mA threshold current
- Current density down to 2 kA/cm²
- Slope Efficiency up to 0.09 W/A

Oxide-confined GaInNAs VCSEL Room Temp. CW Operation

Output Power vs Current

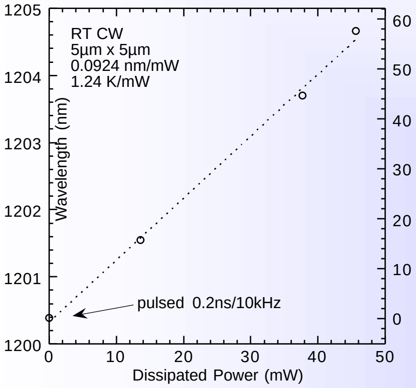


Spectra (5µm x 5µm)



- 5µm aperture: 1.3 mA threshold current; 3.6µm: < 1 mA
- CW operation in spite of very high voltage drop (~9V) in top mirror

Oxide-Confined VCSEL: CW Thermal Analysis



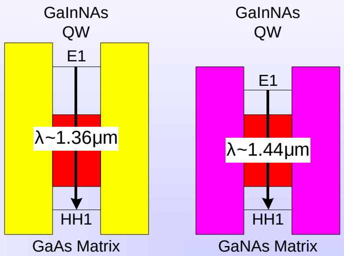
- **~60°K temperature rise at peak power**
- **Thermal Impedance $Z_T \propto$ 1/diameter**
- **Z_T (5µm) = 1.24 K/mW ($Z_{T,\ 50\mu m\ etched\ pillar}$ = 0.36 K/mW)**
- **$Z_{T(5\mu m)}$ / $Z_{T(50\mu m)}$ = 3.6**
- **$I_{th(5\mu m)}$ / $I_{th(50\mu m)}$ = 1/50**
- **Reduce dissipated power in pDBR for higher output power**

Challenge for Long wavelength GaInNAs

- **Post annealing process is required to improve material quality after growth**
- **Nitrogen out-diffuses from quantum wells**
- **Emission spectrum blue-shifts due to nitrogen loss**

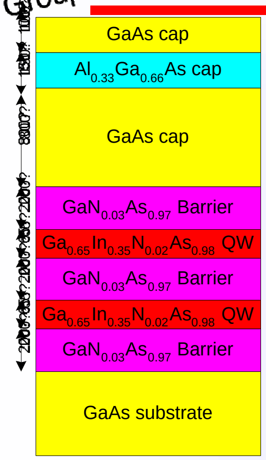
Advantages of GaNAs Barrier

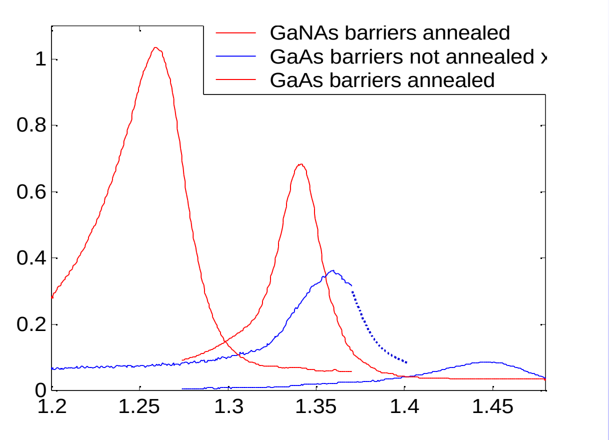
- **Decreased carrier confinement ⇨ Emission at longer wavelengths.**



- **Decreased nitrogen out-diffusion during the anneal ⇨ less shift of peak energy during anneal (65 meV versus 74 meV).**
- **Strain compensation possible (GaAsN tensile / GaInNAs compressive).**

GaAsN Barrier PL Measurements





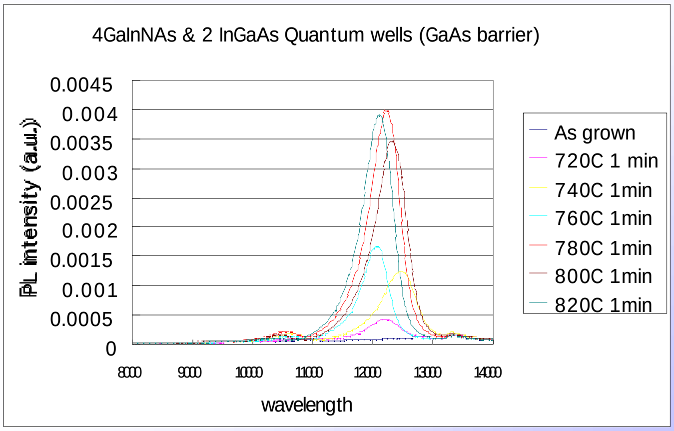
Use of GaNAs barriers instead of GaAs barriers results in:

- **PL peak at 1.44µm instead of 1.36µm for not annealed sample.**
- **PL peak at 1.34µm instead of 1.26µm for annealed sample.**

GaAs Barrier GaInNAs Quantum Well

- 4 $Ga_{0.65}In_{0.35}N_{0.033}As_{0.967}$ quantum wells and 2 InGaAs quantum wells were grown
- GaAs Barriers between Quantum wells
- As grown sample : PL peak at 1.286μm
- Annealed at 780°C(Highest PL intensity) : PL peak at 1.222μm
- PL blue-shift : 64nm

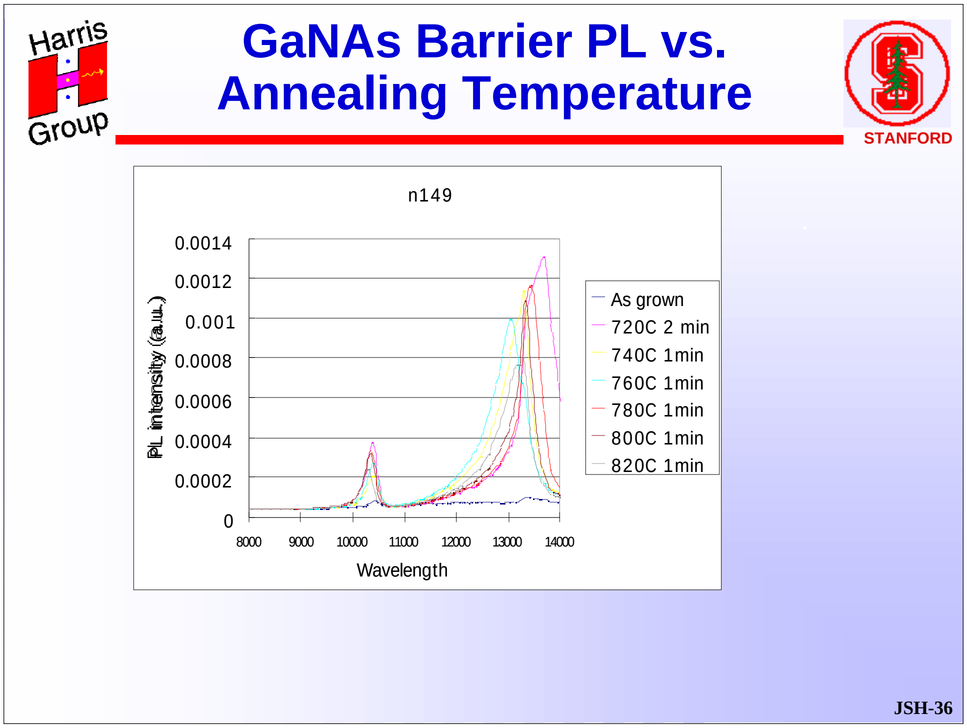
GaAs Barrier PL vs. Annealing Temperature

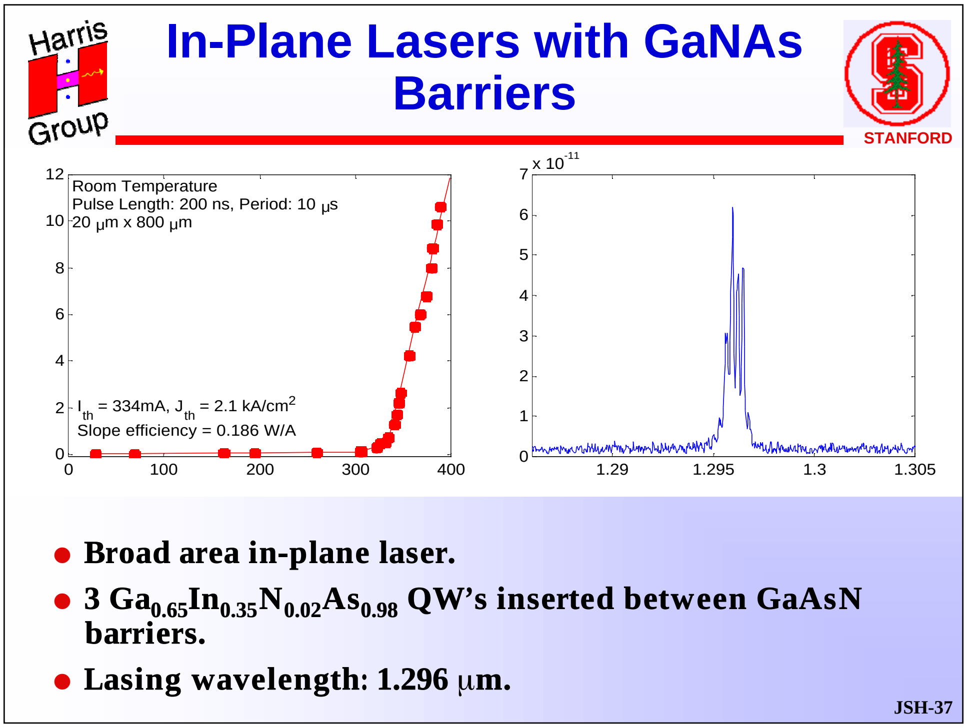


GaNAs Barrier GaInNAs Quantum Well

- 4 $Ga_{0.65}In_{0.35}N_{0.033}As_{0.967}$ quantum wells and 2 InGaAs quantum wells were grown
- GaNAs Barriers between Quantum wells
- As grown sample : PL peak at 1.336μm
- Annealed at 780°C(Highest PL intensity) : PL peak at 1.368μm
- PL red-shift : 32nm

GaNAs Barrier PL vs. Annealing Temperature



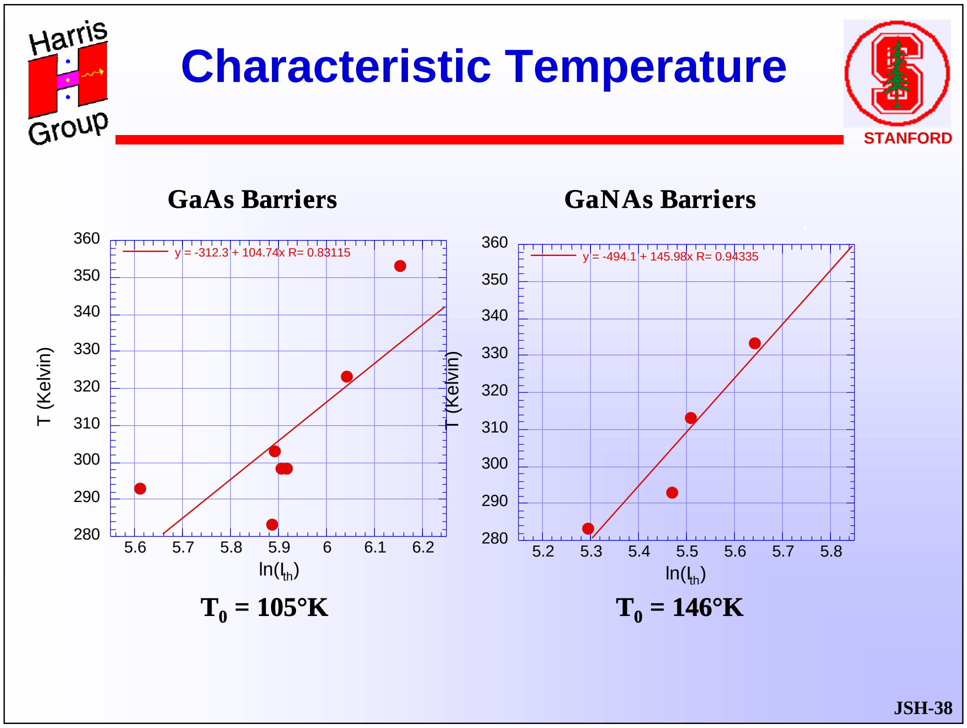


In-Plane Lasers with GaNAs Barriers

Room Temperature
Pulse Length: 200 ns, Period: 10 μs
20 μm x 800 μm

I_{th} = 334mA, J_{th} = 2.1 kA/cm^2
Slope efficiency = 0.186 W/A

- **Broad area in-plane laser.**
- **3 $Ga_{0.65}In_{0.35}N_{0.02}As_{0.98}$ QW's inserted between GaAsN barriers.**
- **Lasing wavelength: 1.296 μm.**



Characteristic Temperature

GaAs Barriers

T_0 = 105°K

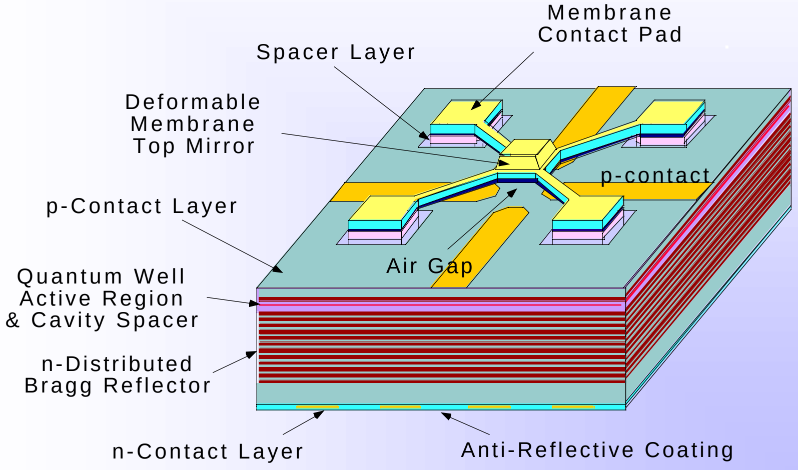
GaNAs Barriers

T_0 = 146°K

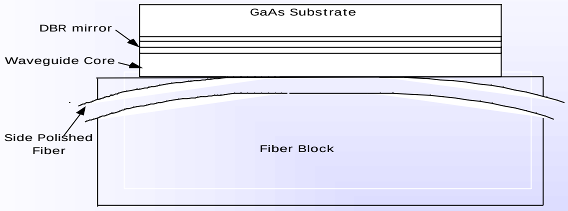
GaInNAs: an Enabling Technology

- Many low cost photonic devices utilize vertical cavity configuration on GaAs substrates
    - They don’t operate at communications wavelengths
- Significant technology base for GaAs based modulators, detectors, tunable lasers, free space optical interconnects
    - Require long wavelength QW active regions that are lattice matched to GaAs

Tunable VCSELs for Switching and WDM

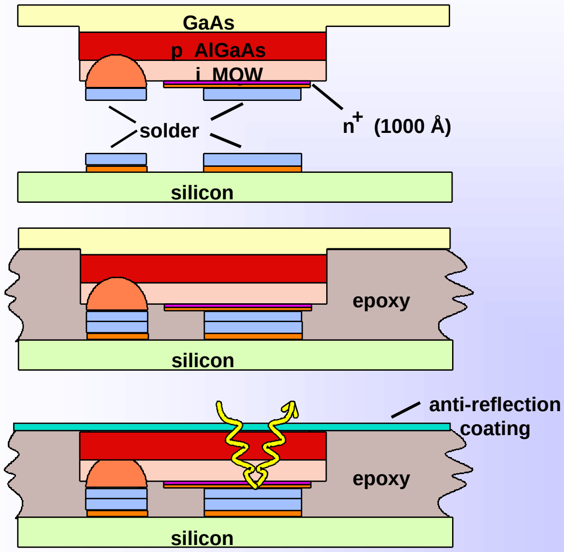


In-Line Waveguide Coupled Semiconductor Active Devices



- Low insertion loss
- Coupling controlled by active region length
- Simple, low-cost bonding
- Applicable to detectors, lasers and switches

Quantum Well Modulators Solder-Bonded to Si ICs



K. W. Goossen et al., IEEE Photonics Tech. Lett. 7, 360 - 362 (1995)

Summary

- GaInNAs/GaAs is a promising material for long wavelength VCSELs
  - All epitaxial single-step growth
  - High T_0 active layer with high-contrast thermally-conductive mirrors
  - Easily controlled composition by MBE
- Demonstrated low threshold, RT, CW GaInNAs VCSELs
  - ~1 mA threshold current, 0.05 W/A slope efficiency at λ=1.2µm
  - Peak output power limited by p-DBR resistance (~9V at I_{th})
  - Demonstrated edge emitting lasers at 1.3µm and PL beyond 1.3µm
  - GaInNAs is the best candidate for low cost, 1.3 µm VCSELs
- Future work
  - Rebuilding two chamber MBE system for high thruput, graded interface, C-doped mirrors and VCSEL growth
  - Extend GaInNAs active QW material to tunable sources, modulators, semiconductor optical amplifiers, optical IC interconnects
  - Apply GaInNAs active devices to Si optical interconnects

Conclusion 2!!!

The GOOD NEWS

GaInNAs is easier to grow by MBE

than by MO-CVD

The BAD NEWS

Grading & multiple Al composition GaAs/AlAs mirrors are difficult to grow by MBE

Some would say this is

(BAD NEWS)^2