

# ***InGaAsN: A Promising Material for Long Wavelength Vertical Cavity Lasers***

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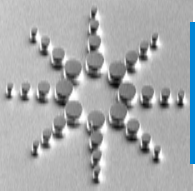


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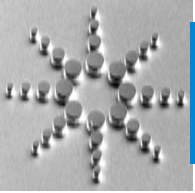
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# Outline

- **Motivation: Why 1300nm VCSEL?**
- **Brief VCSEL Tutorial**
- **Growth of InGaAsN**
- **Making VCSELs with InGaAsN**
- **Conclusions**





# Acknowledgements

## **At Agilent Labs:**

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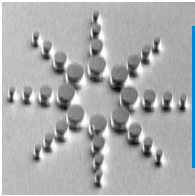
## **University of Wisconsin:**

L. J. Mawst, N. Tansu

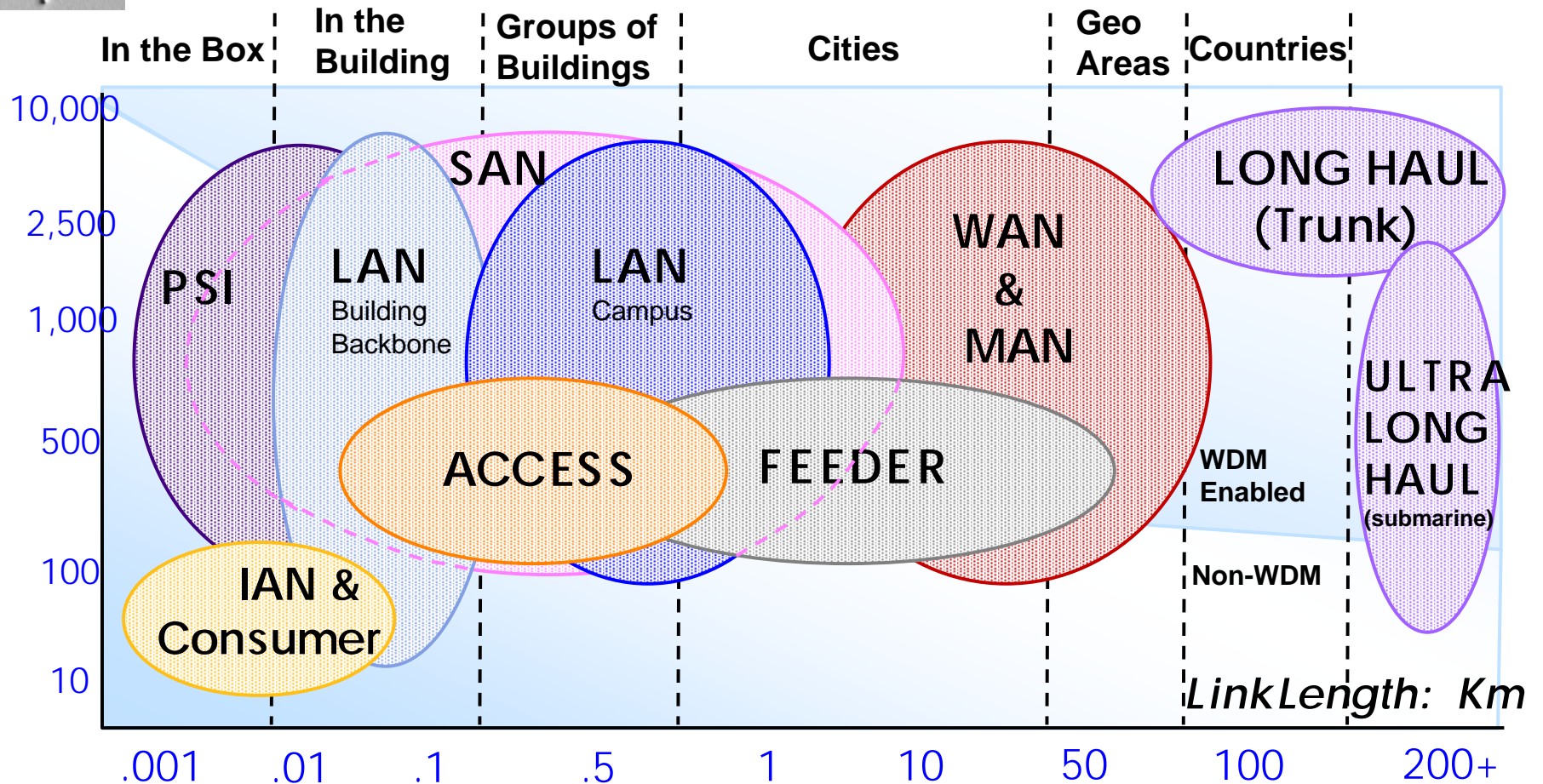
## **University of Berkeley:**

E. R. Weber, H. Feick, C. Kisielowski, P. Specht, R. Zhao





# Fiber Market Segments

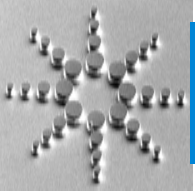


- SAN - Storage Area Network (Fiber Channel)
- IAN - Industrial Area Network
- LAN - Local Area Network: Building Backbone; Campus
- WAN - Wide Area Network
- PSI - Proprietary System Interconnect

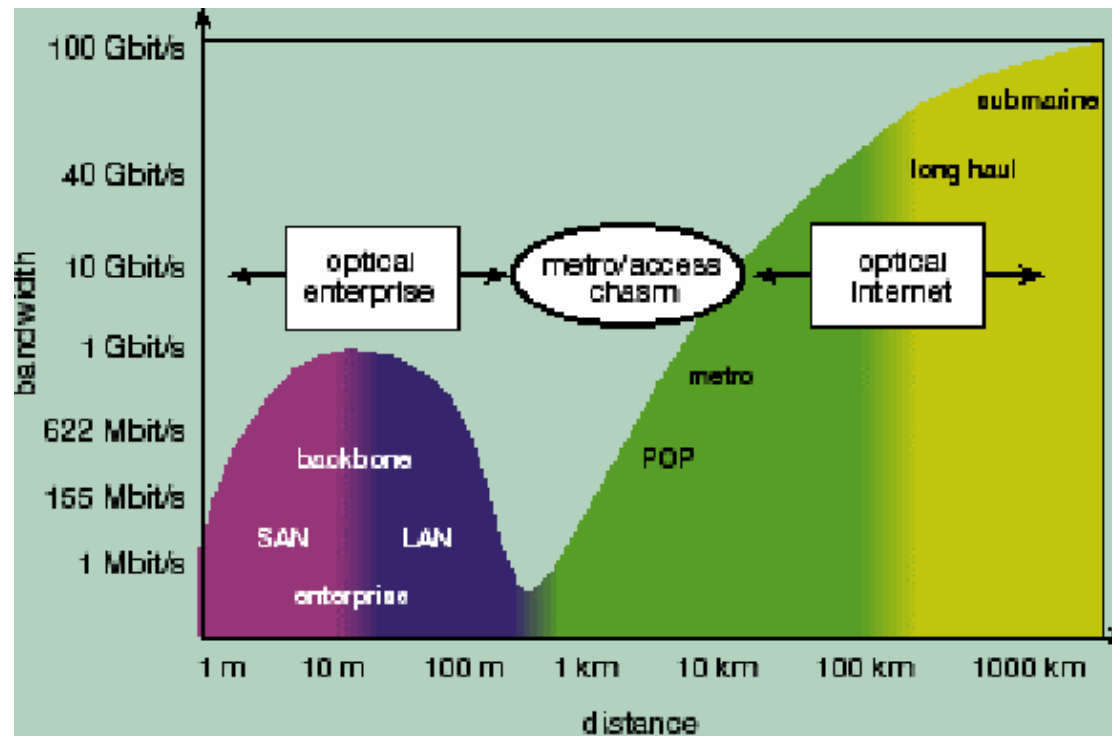
- MAN - Metropolitan Area Network
- FEEDER - Feeder Infrastructure

- LONG HAUL
- ULTRA LONG HAUL - Submarine Pump Lasers
- CONSUMER - CAN; Home Area Network (HAN); Automotive Area Network (AAN)





# Intermediate-Reach Bandwidth Chasm



***Bandwidth mismatch between the enterprise and long-haul networks***

***Low-cost, high bandwidth 1-10km link can eliminate the bottleneck***

*Chris Simoneaux , Picolight, Compound Semiconductor Magazine Volume 7 No. 5 (June 2001)*



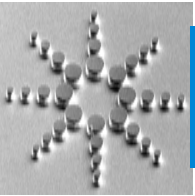
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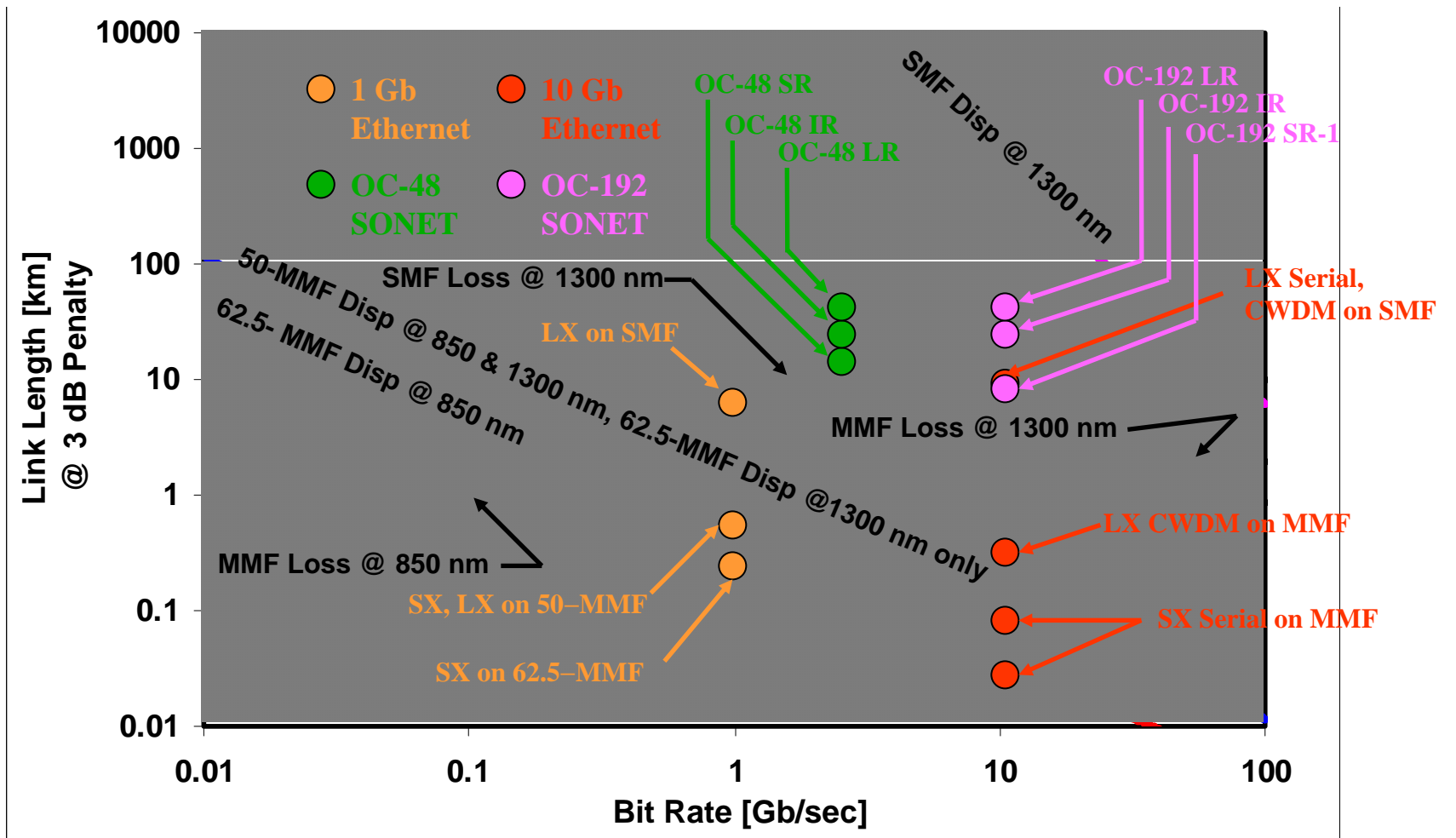
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# Telecom and Datacom Solution Space



D. W. Dolfi - 06/02

Note: SX = 850 nm wavelength  
 LX = 1300 nm wavelength  
 All SONET @ 1300 nm



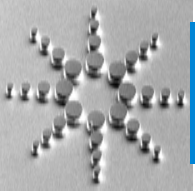
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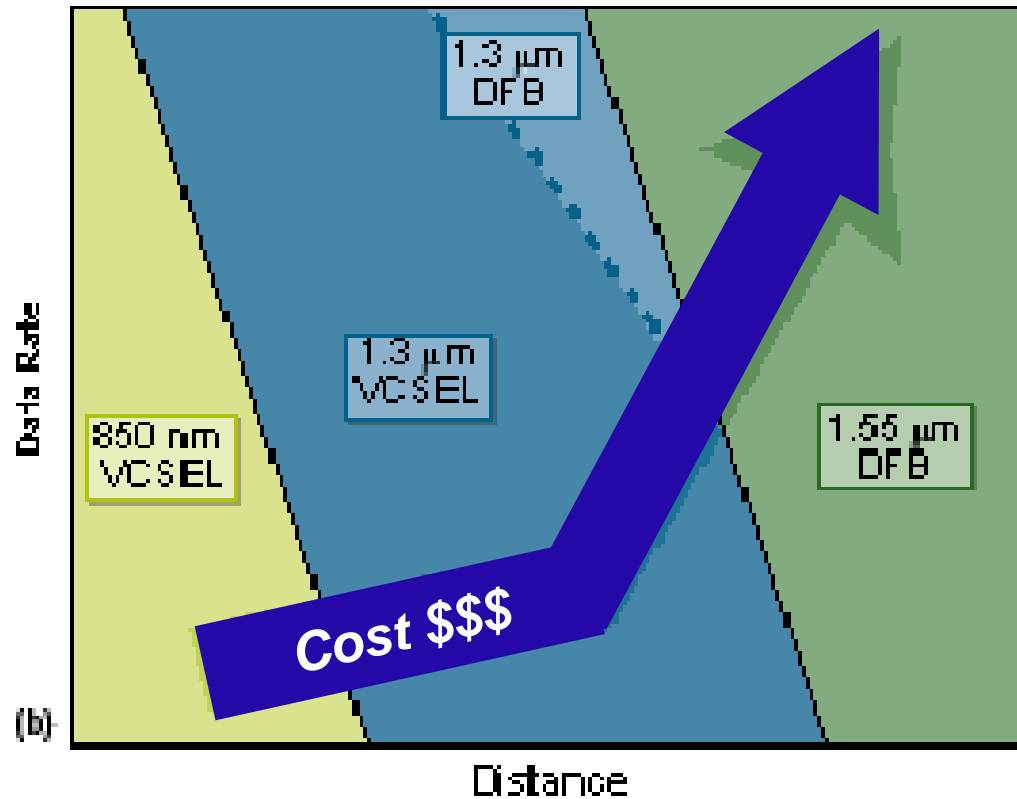
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Optical Interconnects &  
 Networks Department





# Why 1310 nm VCSEL?



**1310 nm VCSEL technology can introduce a kink in the cost curve.**

*M. Cowley, D. Kisker, etc. Cielo, Compound Semiconductor Magazine Volume 6 (2000)*



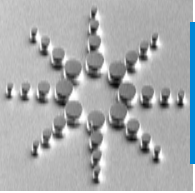
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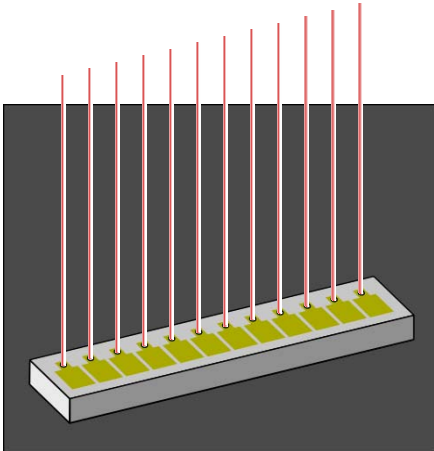
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# Agilent Parallel Optics Transceiver Module

World's First 12 x 2.5 GBd Products!

**850 nm VCSEL array technologies**



HFBR-712BP (Tx)



HFBR-722BP (Rx)

- Announced 11/00
- Full Production 11/01
- 12 x 2.5 GBd = 30 Gb/s
- 600 m (2200 MHz-km)

***The development of VCSEL operating at 1310 nm will extend these advantages into longer reach applications***

*Kirk Giboney, Agilent Technologies, (invited), LEOS, 2001*



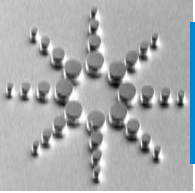
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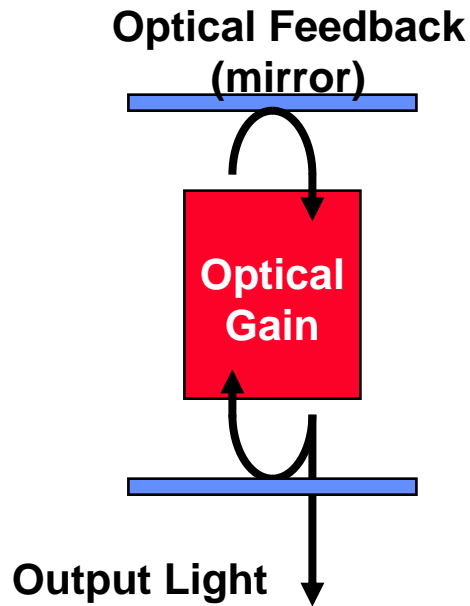


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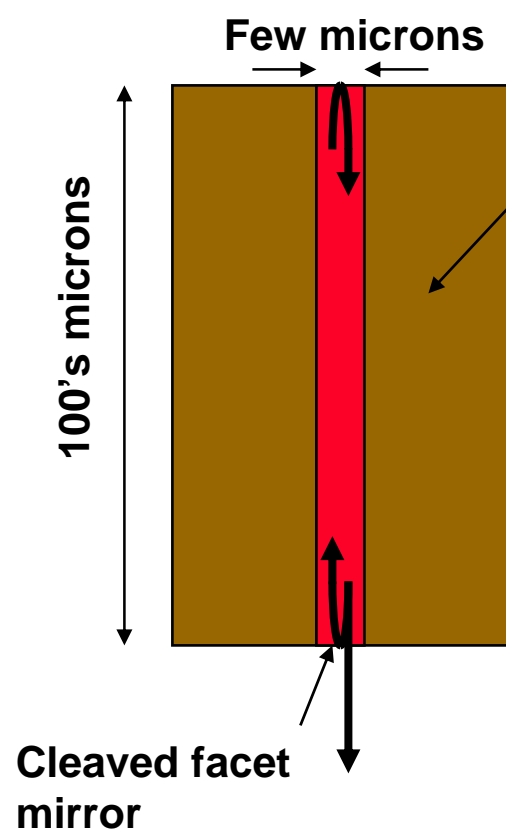


# 30-second Laser Tutorial

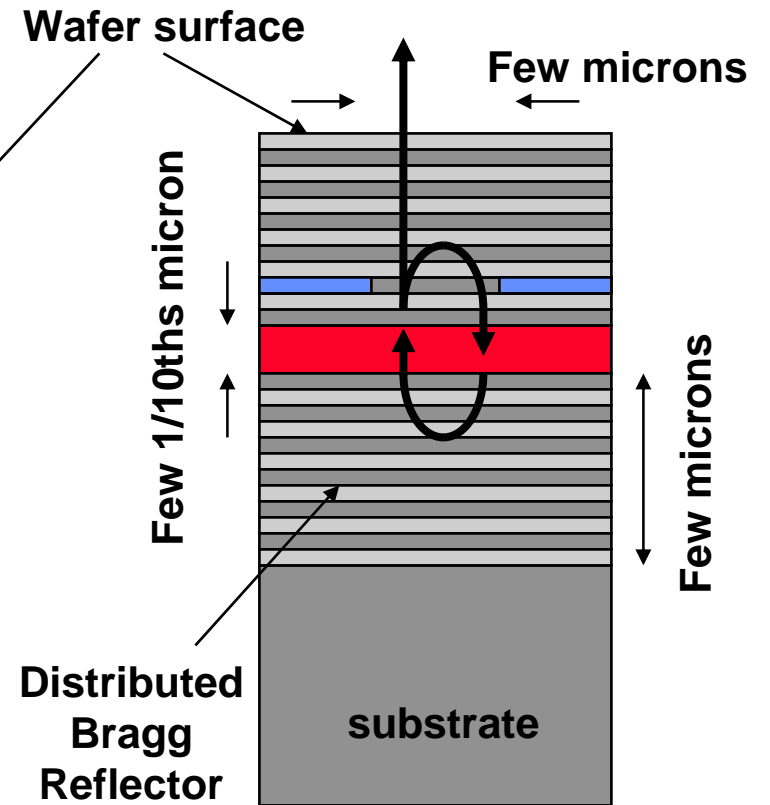
## Laser (Generic)

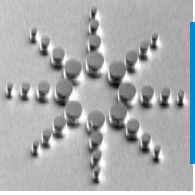


## Edge Emitting Laser

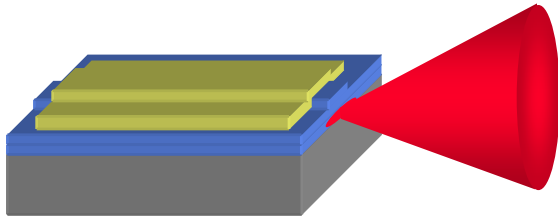


## Vertical Cavity Surface Emitting Laser



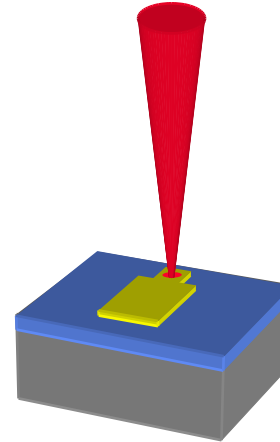


# Edge emitter vs VCSEL



## Fabry-Perot laser

- Edge emission
- Cleaved facets
- Asymmetric Far field
- Polarization locked
- High output power
- High current
- Linear arrays
- Simpler epi layer structure

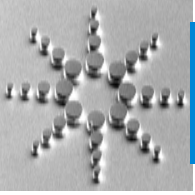


## VCSELS

- Surface emission
- LED like manufacturing
- On wafer probing
- Circular beam profile (sometimes)
- Lower output power
- Low current operation
- Low power consumption
- 2D arrays
- Complex epi layer structure

***VCSELS are very attractive when optical power requirement is low***





# 1300nm VCSEL Requirements

- **OBJECTIVE**

1300nm VCSELs for serial, parallel and CWDM applications.

- **Target Specification:**

*>1mW single mode @ 85°C*

*$\lambda_0$  1275nm ~ 1340nm*

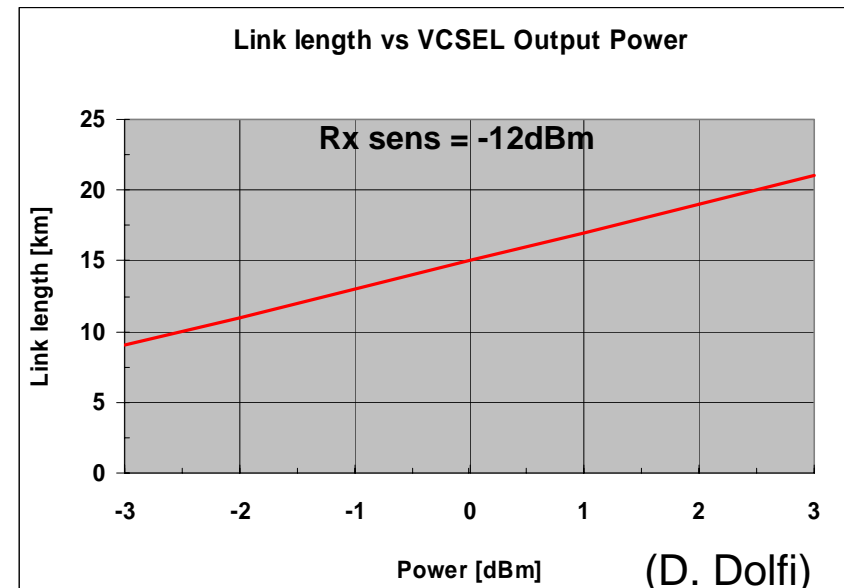
*Polarization locked*

*10 Gbps operation*

*RIN < -135dB/Hz*

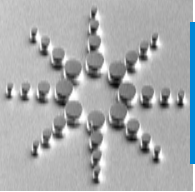
*Vop < 2V, Iop < 15mA*

*SMSR > 30dB*

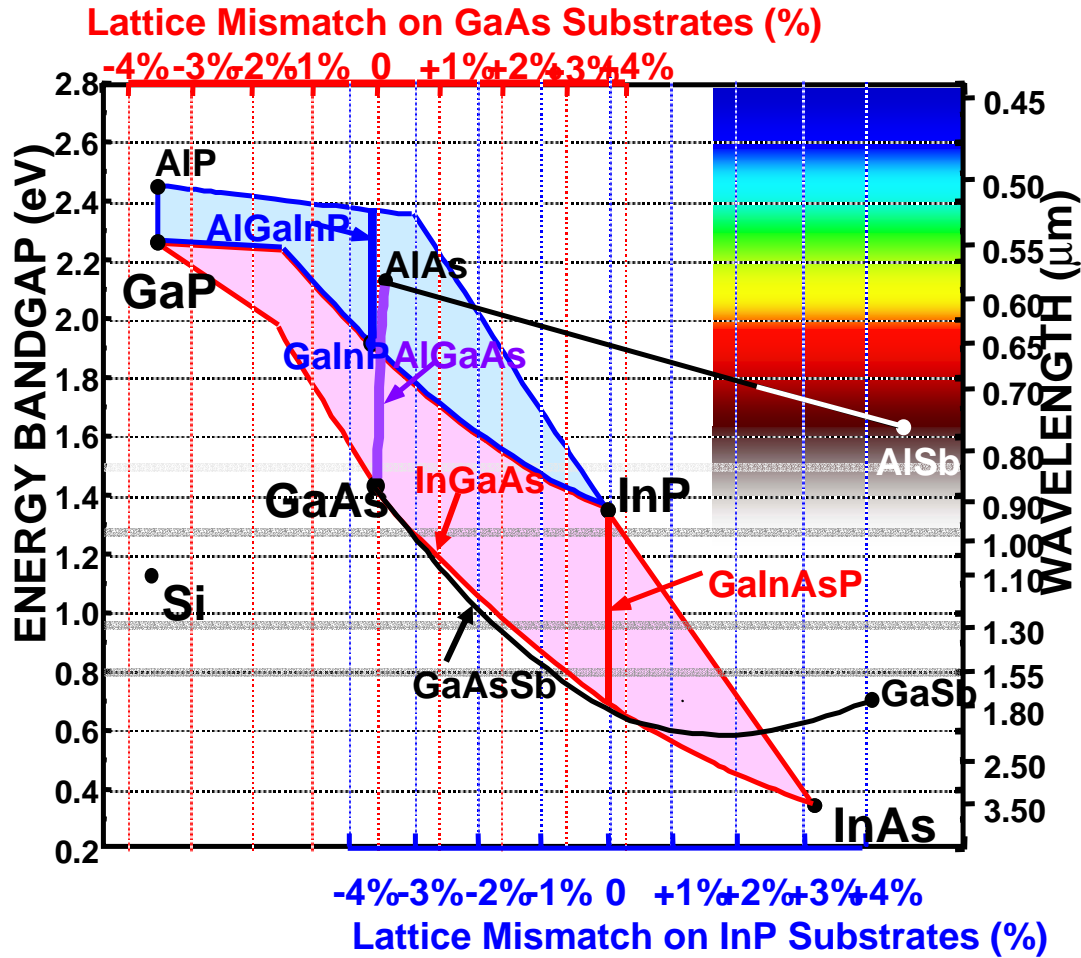


1300nm VCSELs enable lower cost per bit

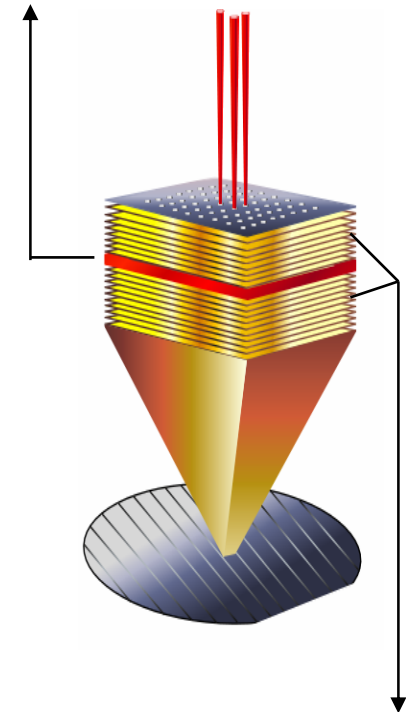




# The long wavelength VCSEL problem



*Best 1310 nm active region materials are lattice-matched to InP*



*Best DBR materials are lattice-matched to GaAs*

(R. Schneider, EMS, 2001)



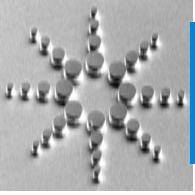
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# Approaches to long-wavelength VCSEL

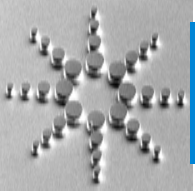
## *Multiple epi or intensive post-growth processing*

Wafer bonding (including optically-pumped versions)  
Hybrid VCSELs (dielectric mirrors)

## *Single epi growth*

new DBR materials on InP (metamorphic AlGaAs, AlGaAsSb, ...)  
new active materials on GaAs (InGaAsN, GaAsSb, quantum dots...)





# Why GaAs?

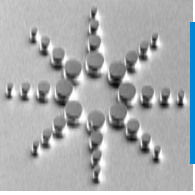
## Why GaAs ?

*Stand on the shoulders of proven 850 nm VCSEL technologies*

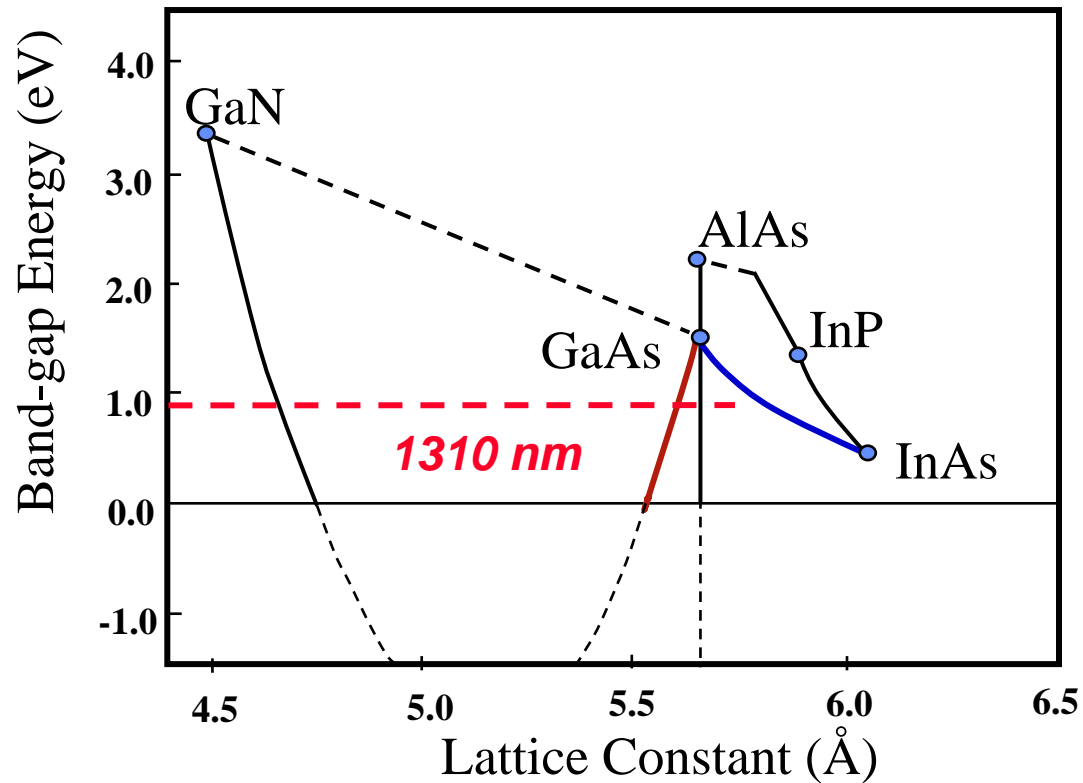
- Mature DBR mirror technology
  - AlGaAs/GaAs DBR
- Mature manufacturing infrastructure
- Readily available oxide confinement technology

*→ Need a suitable active region emitting at 1310 nm*





# Adding N to GaAs for Longer Wavelength



- **1310 nm emission can be easily achieved.**
- **“semi-metal” above certain N level**

(a) S. Sakai, et al, J. J. Appl. Phys. 32, p. 4413 (1993) (b) M. Kondow, et al., Jpn. J. Appl. Phys. Vol. 35, p. 1273 (1996)



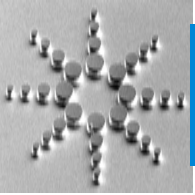
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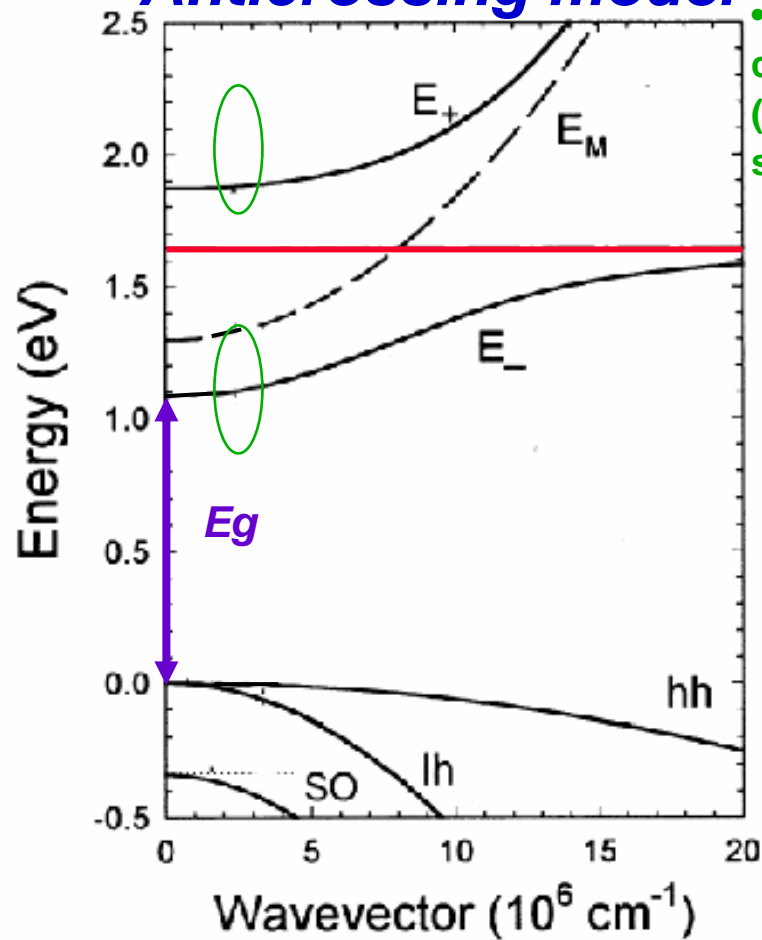


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# Mechanism for Bandgap Reduction

## Anticrossing model



• Splitting of conduction band ( $E_M$ ) to two subbands  $E_-$  and  $E_+$

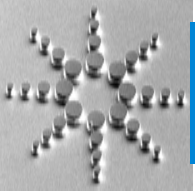
$E_N$ : localized impurity state

$$\Delta E_g(x) = bx(x-1)$$

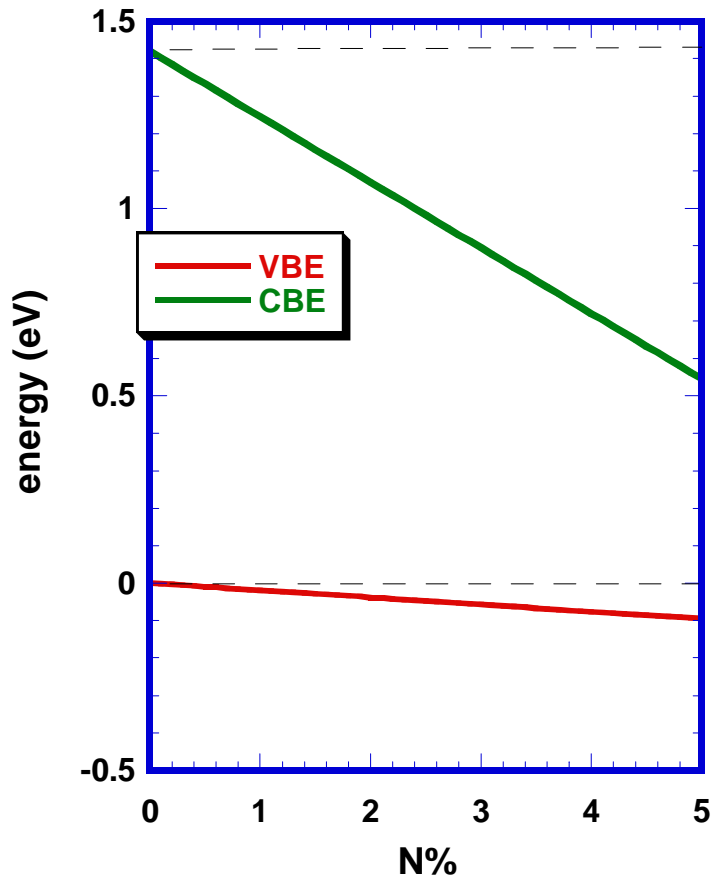
$$\Delta E \sim 150 \text{ meV}/\%N, b \sim 18$$

Ref. (1)W. Shan, etc. PRL. 82, p. 1221, 1999,(2) J. Hader, etc. ;APL. 77, p. 630, 2000





# GaAsN/GaAs QW?



- **GaAsN/GaAs:**  
**(I) type II QW**

$\Delta E_v = -0.019$  eV/N% (measured by XPS)

$\Delta E_c = -0.175$  eV/N%

$\Delta E_g = -0.156$  eV/N% (b~18)

(M. Kondow, et al., *Jpn. J. Appl. Phys. Vol. 35, p. 1273, 1996*)

- (II) Possibly type I, with small confinement**

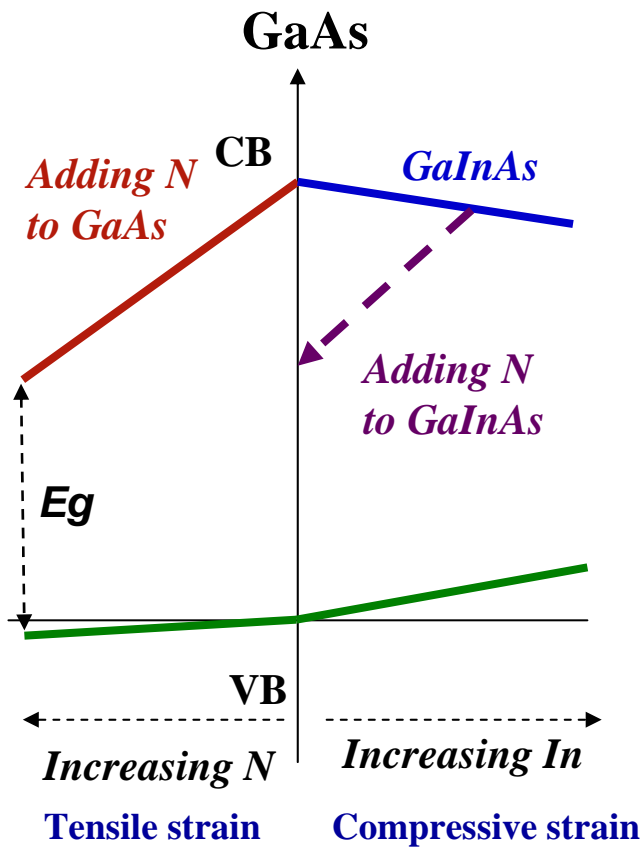
But the gain amplitudes, and gain bandwidth depend crucially on the value of the offset.

(J. Hader, et al, *Appl. Phys. Lett. 76, p. 3685, 2000*)



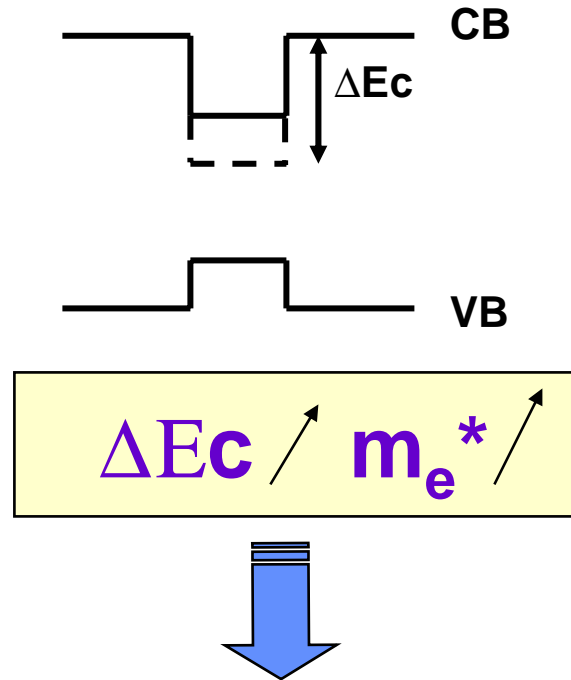


# InGaAsN: A Likely Solution



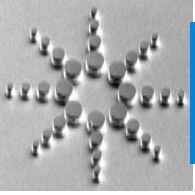
**Type I band alignment**

(M. Kondow, *et al.*, Jpn. J. Appl. Phys. Vol. 35, p. 1273, 1996)



- **Improved temperature performance**
- **Higher differential gain**

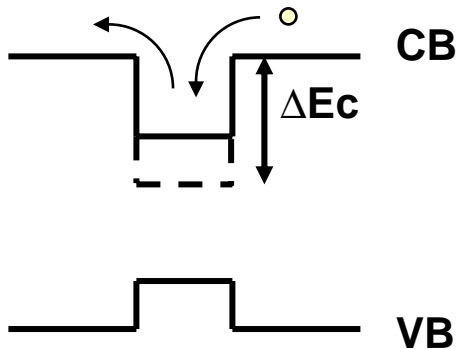




# InGaAsN: A Likely Solution

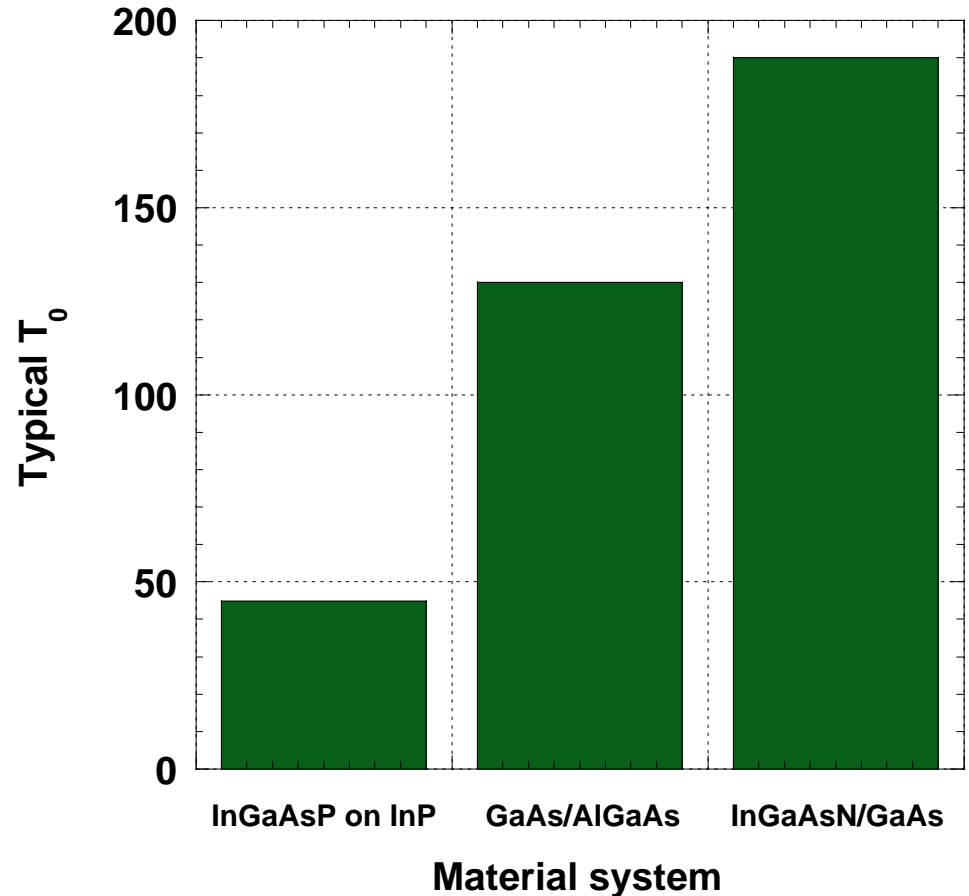
Characteristic Temperature “ $T_0$ ”

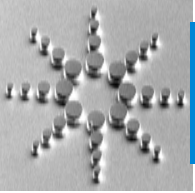
$$I_{th} \propto \exp\left(\frac{T}{T_0}\right)$$



**High  $T_0$  – uncooled operation – lower module cost**

$T_0$  of common laser materials





# InGaAsN Problems: Anneal Blueshift

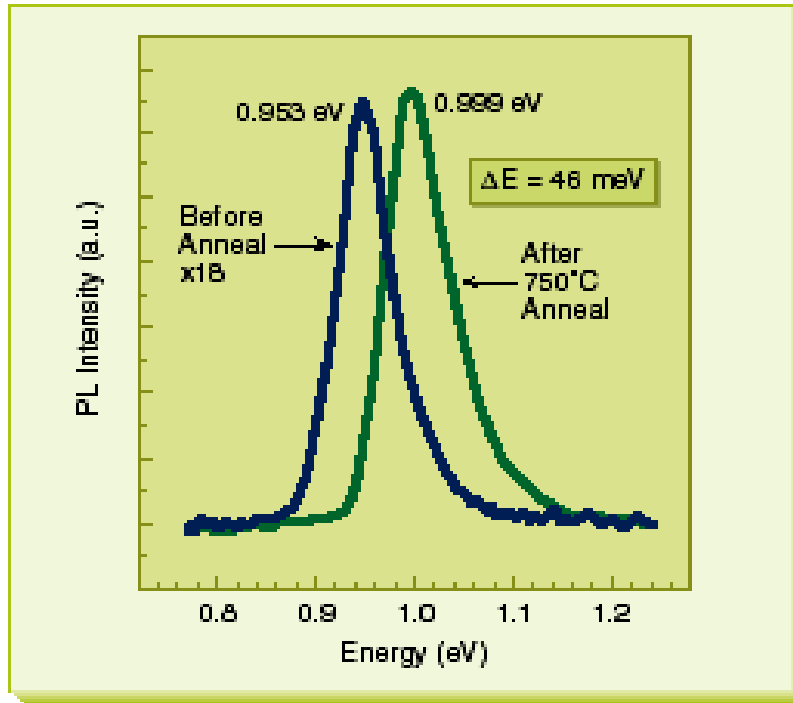


Figure 1. PL spectra of an  $\text{In}_{0.95}\text{Ga}_{0.05}\text{As}_{0.992}\text{N}_{0.018}$  MQW structure before (left) and after (right) annealing at 750°C.

Post-growth Anneal causes:

- **Improvement of luminescence efficiency**

- **Blueshift: not desirable**

- The as-grown material must be designed for longer wavelength emission.
- Wavelength control: significantly affect VCSEL performance

H. Riechert, *et al.* "Compound Semiconductor" 6, No. 5 (July 2000)



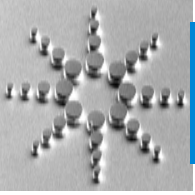
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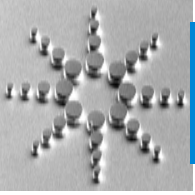


# Possible Causes of Blueshift

- (I) **J. Harris, Stanford University (2001)**  
decrease of blueshift with GaAsN barrier → **N outdiffusion**
- (II) **H. Riechert, Infineon technologies (2000)**  
shift in transition energy only if a) strain and b) N in group V lattice  
→ **strain enhanced N outdiffusion**
- (III) **K. Iga, (2001)**  
increase of blueshift with In composition → **In/Ga intermixing**
- (IV) **M. Kondow, Hitachi (2001)**  
blueshift : possibly caused by the bandgap shift in the InGaAsN itself →  
**bulk bandgap**

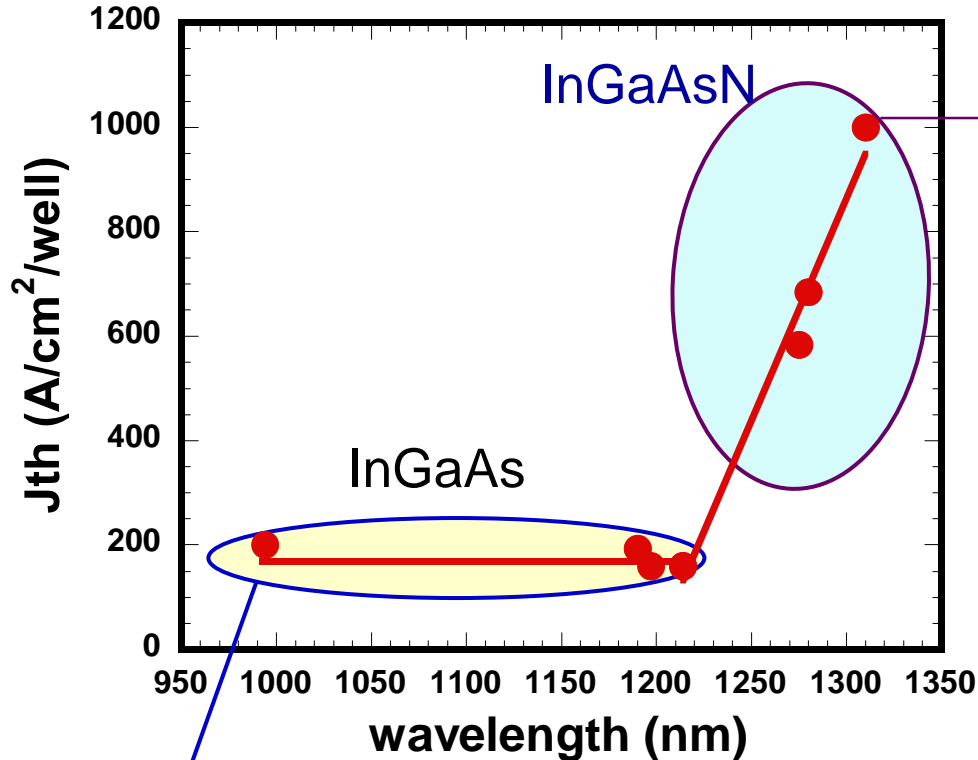
J. Harris, etc. SPIE, Photoic West (2001) H. Riechert, etc. "Compound Semiconductor" 6, No. 5 (July 2000)  
K. Iga, etc. J.J. Appl. Phys. 40 (2001) L1211, T. Kitatani, M. Kondow, etc., J. Cry. Growth 209 (2000) 345





# InGaAsN Problems: Nitrogen Penalty

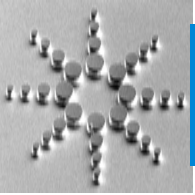
Broad Area Laser Threshold Current Density  
MOCVD InGaAs and InGaAsN, 50x500  $\mu\text{m}^2$



- Nitrogen penalty
- Carrier localization
  - 3D growth mode?
  - DMHy purity?

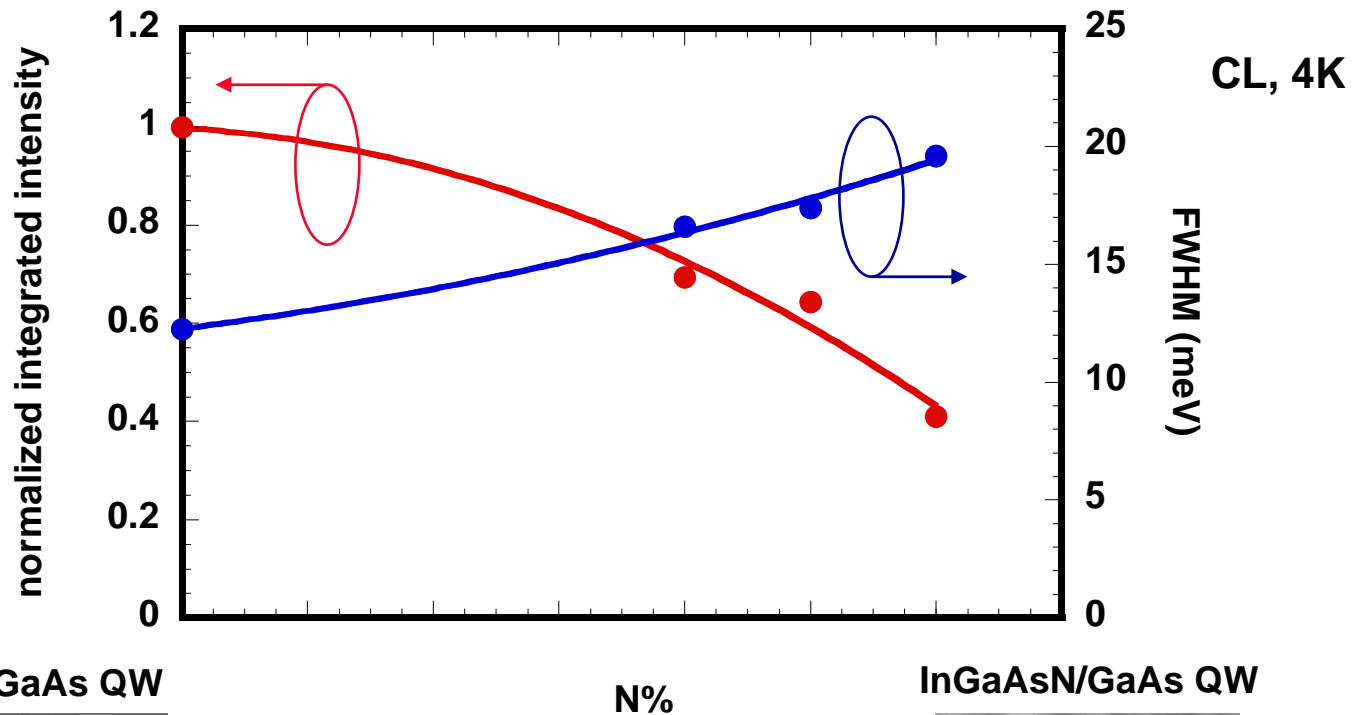
**Growth optimization:**  
Little or no strain penalty



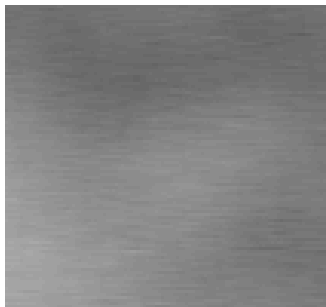


# InGaAsN Problems: Nitrogen Penalty

Cathodoluminescence Intensity and Spectral Width vs N fraction



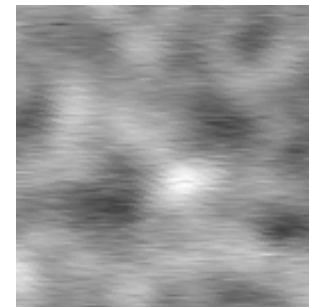
InGaAs/GaAs QW



40umx40um

N%

InGaAsN/GaAs QW



40umx40um



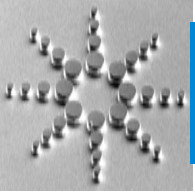
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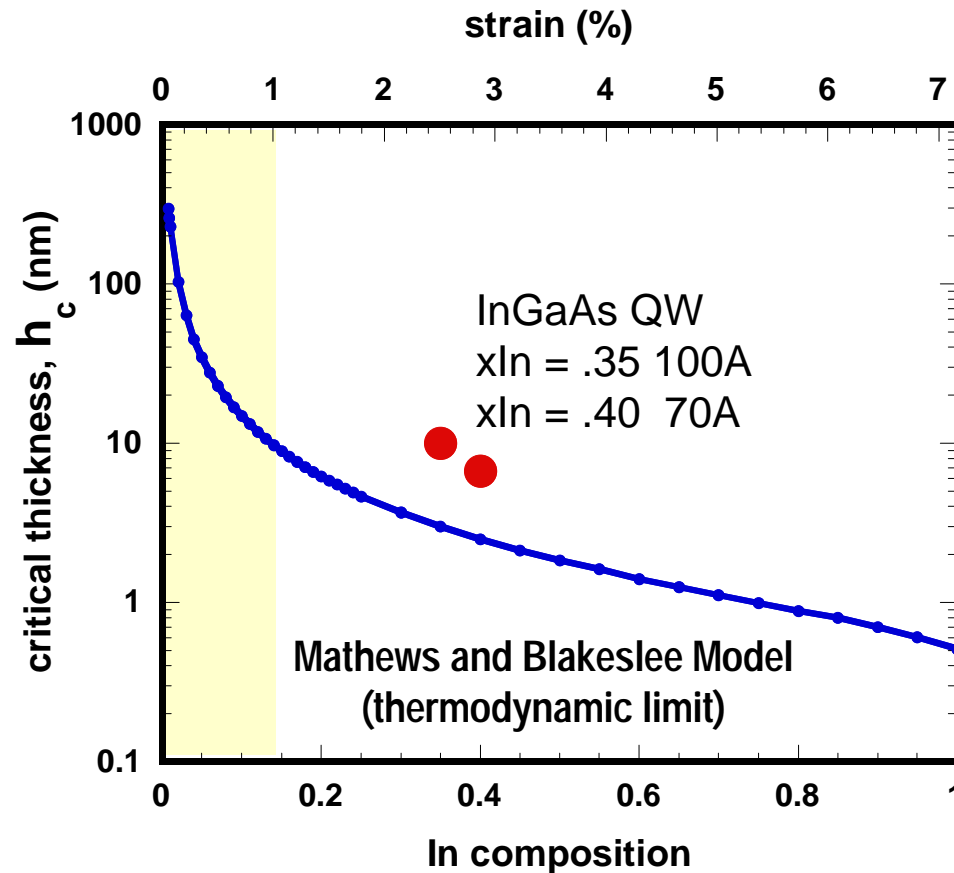
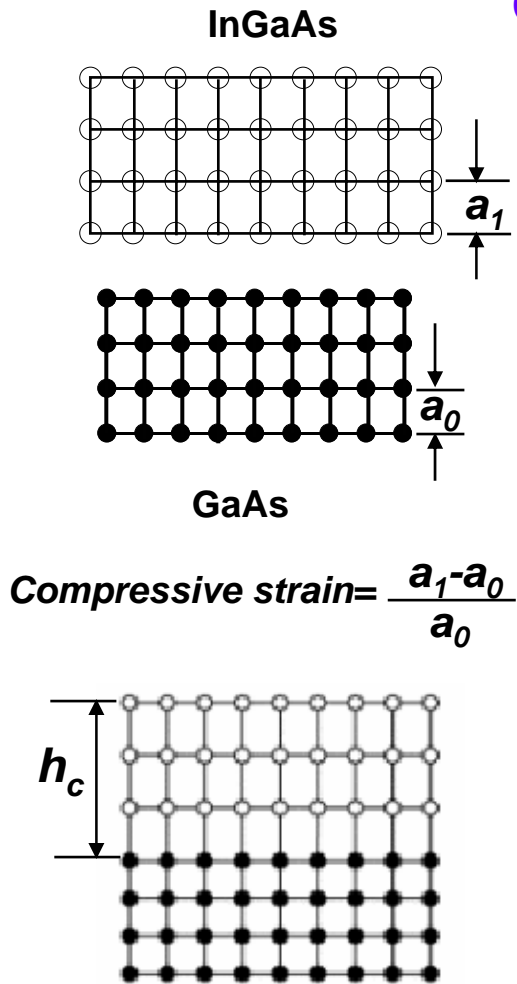


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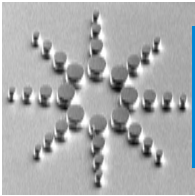
# InGaAsN Problems: Strain Limit

Can compensate N penalty by increasing In/N ratio, but...



Use kinetics to prevent the system from reaching equilibrium





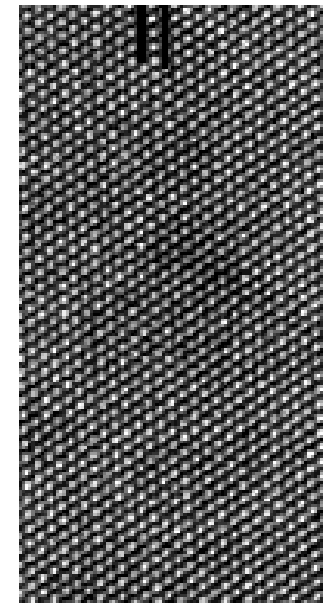
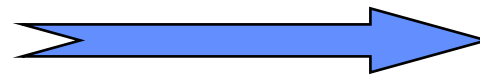
# Pushing the strain limit

TEM (transmission electron microscopy)

InGaAs/GaAs QW



*“high growth rate, low growth temp, high V/III  
→ suppress In migration*



InGaAs/GaAs QW  
Standard InGaAs Growth Conditions

InGaAsN/GaAs QW

D. Mars, Agilent; C. Kisielowski, C. Nelson, C. Song, X. Xu, P. Specht, E. Weber, Berkeley National Laboratory



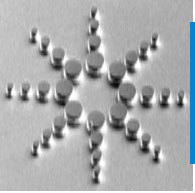
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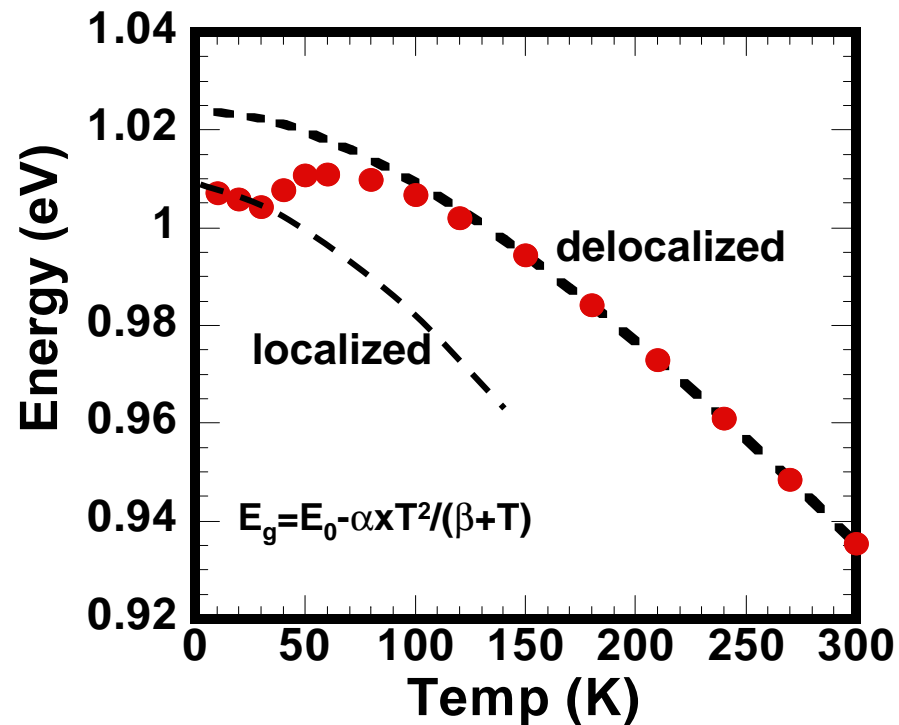


# InGaAsN Problems: Carrier Localization

*Low Temperature Photoluminescence Characterization:  
Evolution of peak position and linewidth shows evidence  
of carrier localization*

**Causes:**

- Band-tailing
- Local thickness fluctuation
- Local composition fluctuation



(H. Feick, E. R. Weber, Berkeley)



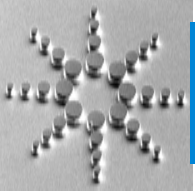
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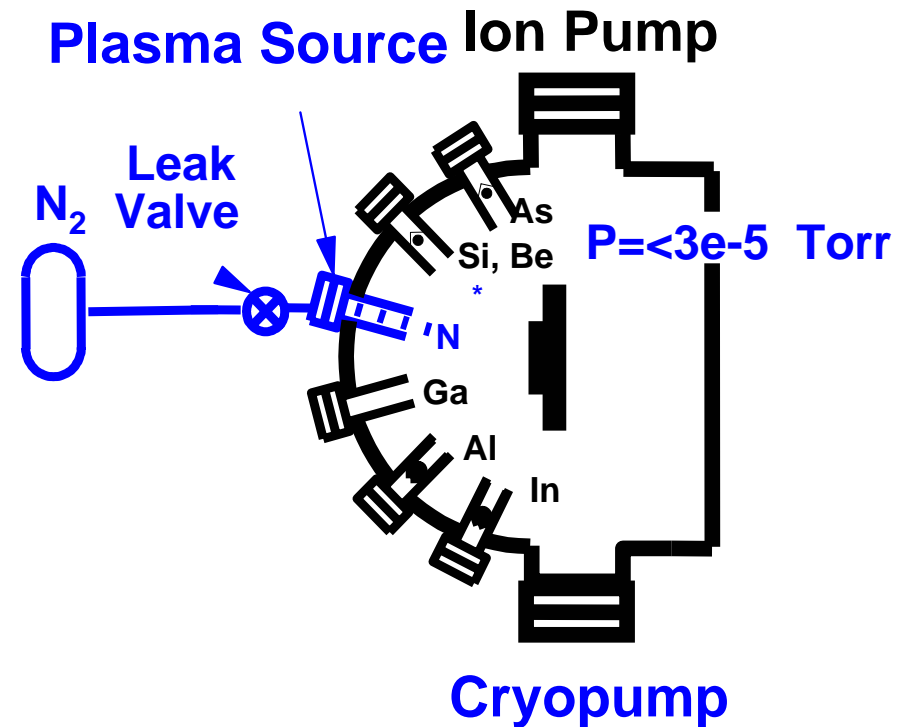
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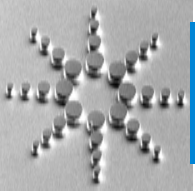


# Plasma-assisted MBE Growth of InGaAsN

## *Best results first achieved with MBE*

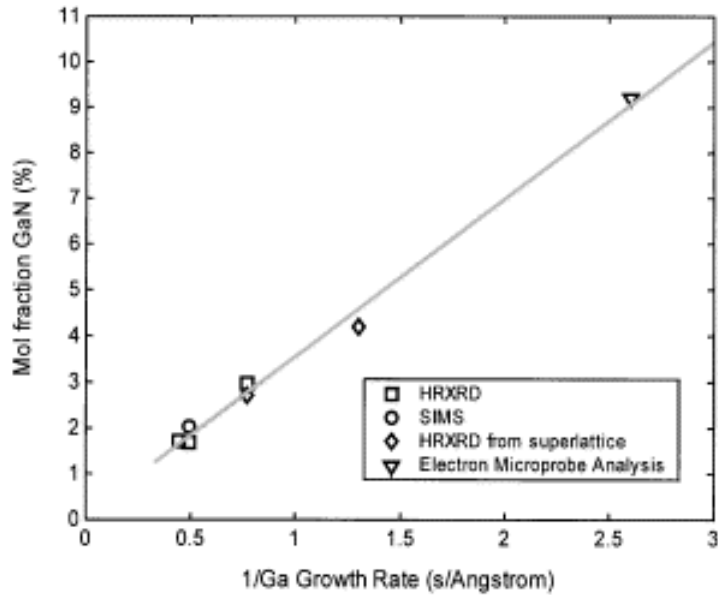
- Relatively simple growth mechanism
- Separable and linear influence of [In] and [N]
- In situ monitoring of growth behavior (RHEED)
- Sticking coefficient ~1 (for  $T < 520$  C)
- Plasma: ECR  $\rightarrow$  Rf



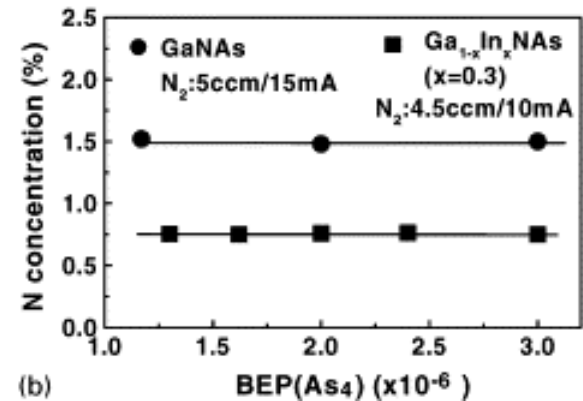
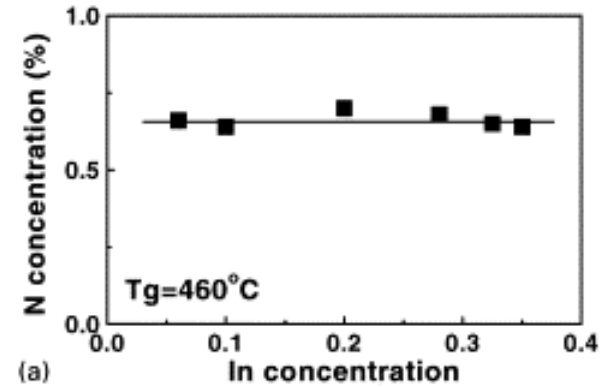


# MBE Growth of InGaAsN

N incorporation in MBE InGaAsN is well-behaved and controllable

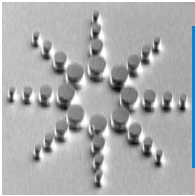


Spruyette, et al *J. Crystal Growth* v.227-228 p.506 2001



Pan, et al *J. Crystal Growth* v.227-228 p.516 2001

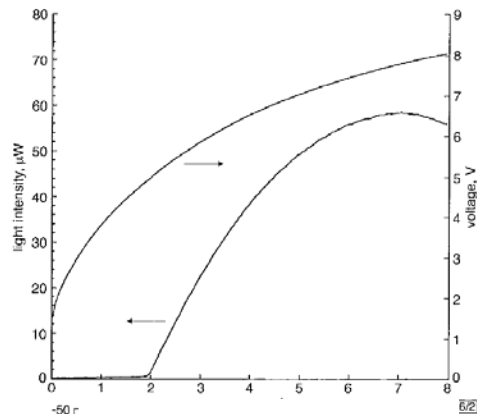




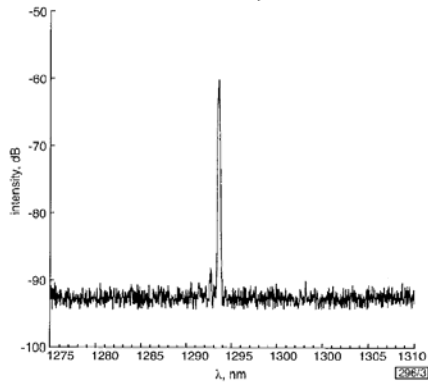
# MBE Growth of InGaAsN

MBE-grown material has led the way for InGaAsN VCSELS

First demonstration of RT CW 1.3 $\mu$ m  
 $\text{In}_{0.34}\text{Ga}_{0.66}\text{As}_{0.99}\text{N}_{0.01}$  QW VCSELS

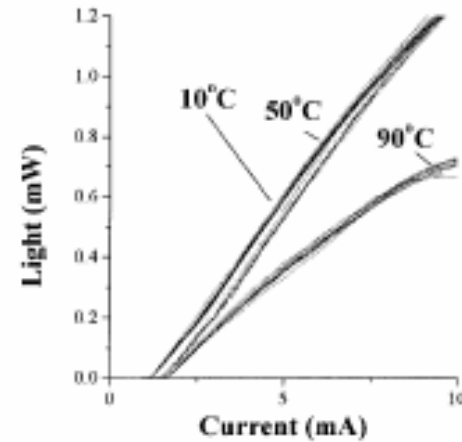


~58  $\mu$ W

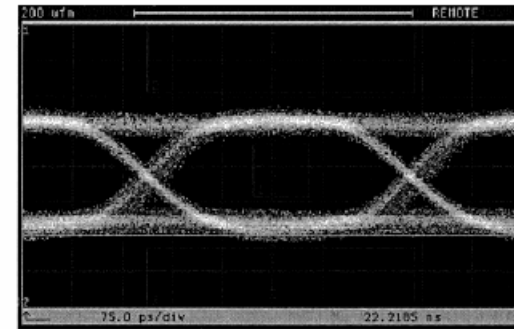


1294 nm

Recent "Commercial" Devices



~1 mW  
~1270nm



2.5Gb/s

TuW1 Fig. 2. Eye-diagram of a 1.3 micron VCSEL transmitted at 2.488 Gbps over 10 km of SM fiber.

Chirovsky, et. al., *OFC 2002 Tech Digest*  
TuW1, p 149-150.

Choquette, et.al., *Electron. Lett.* **36**, 1388-1390 (2000).



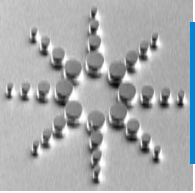
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Michael Leary

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# MOCVD InGaAsN growth

**MOCVD : high growth rate, desirable for VCSEL structure**

## ***Issues :***

### **(I) no well-established N source**

*NH<sub>3</sub> used for GaN*

Very high cracking temperature – incompatible with GaAs

*Dimethylhydrazine (DMHy)*

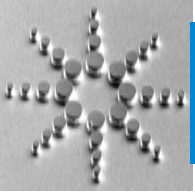
lower pyrolysis temperature compared to NH<sub>3</sub>

extremely low N incorporation, ~0.0001

Purity control not well developed

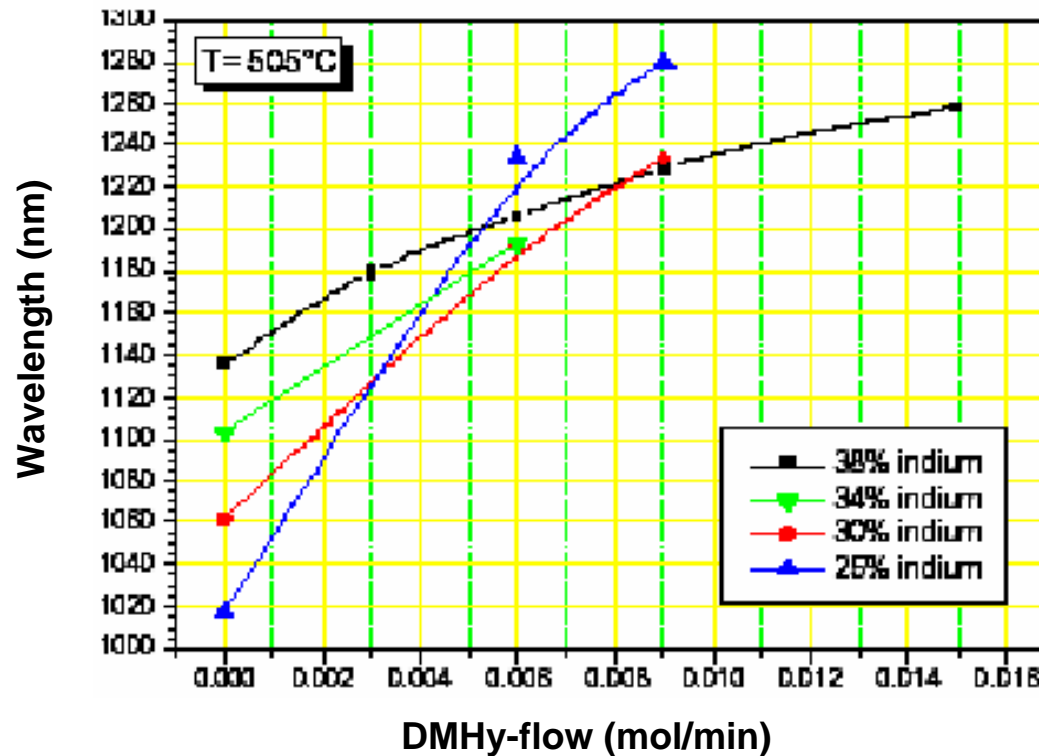
### **(II) complex gas phase reactions → dependence of N% on In/Ga ratio**





# MOCVD InGaAsN: In-N Interaction

*PL wavelength dependence on DMHy flow for different In fraction*



*(S. Illek, etc, Infineon technologies, IPRM, 2000)*



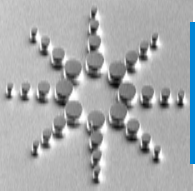
Agilent Technologies

Michael Leary

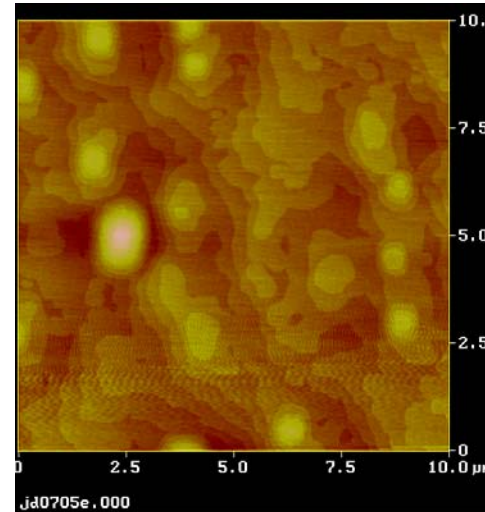
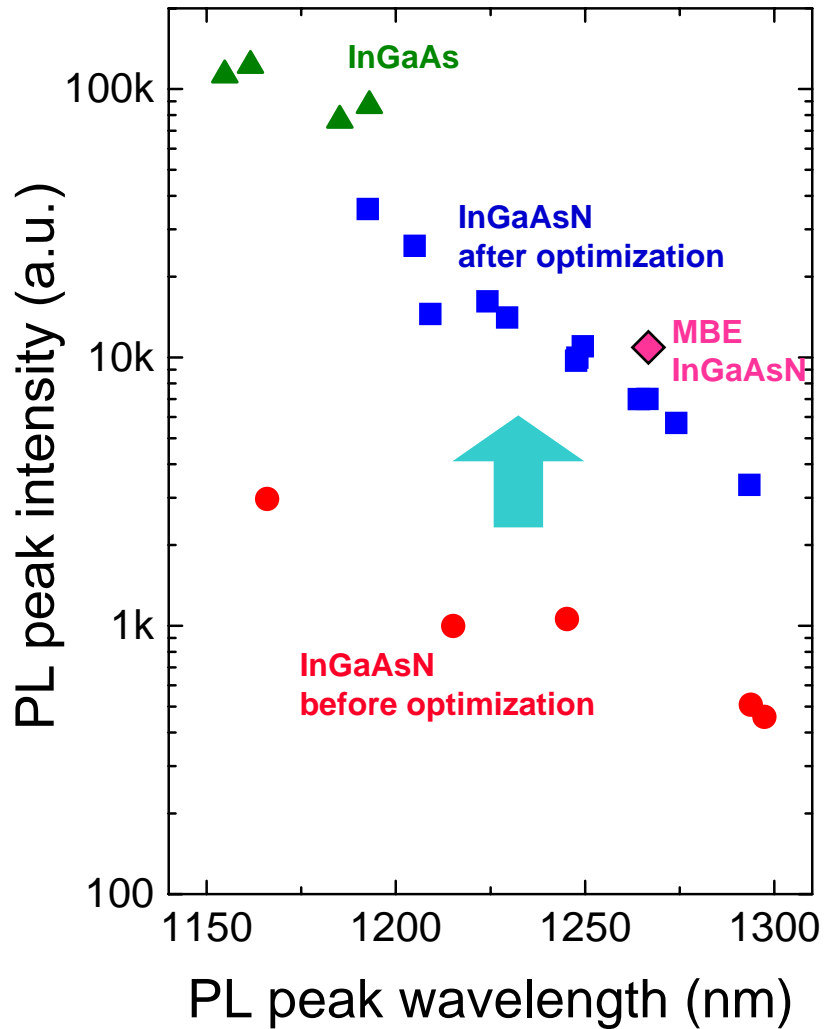
AVS Thin Film User's Group, June 19 2002



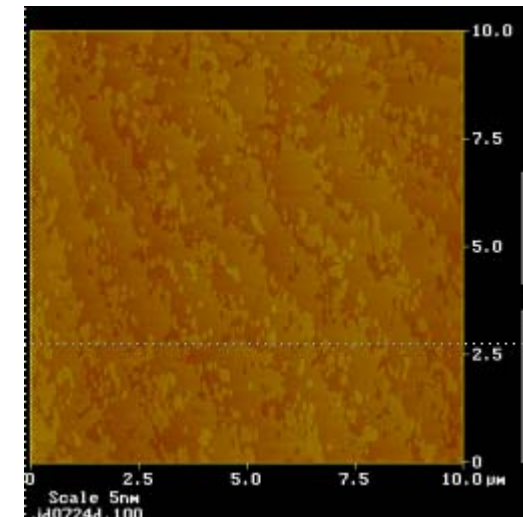
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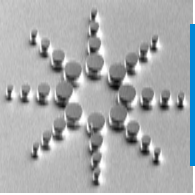


# MOCVD InGaAsN Growth Optimization

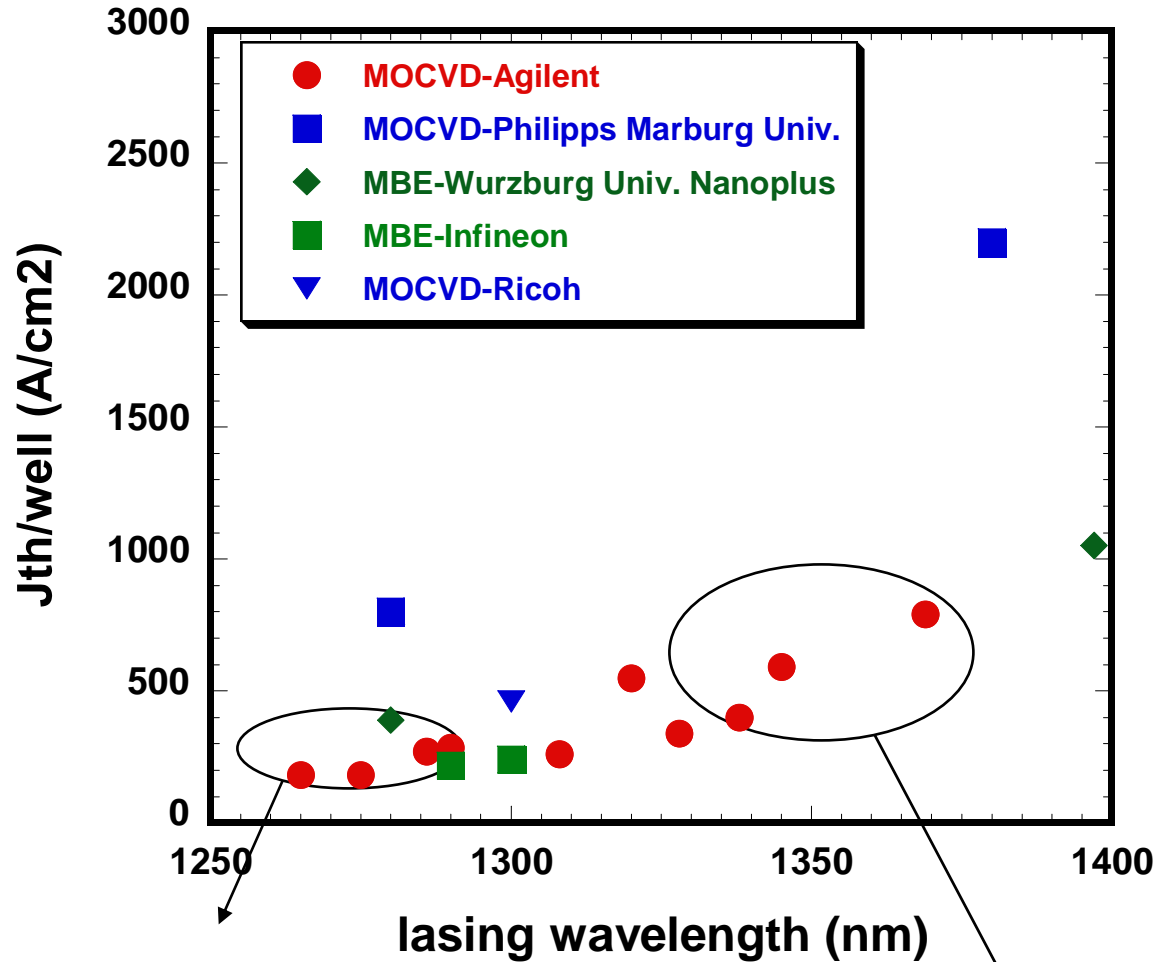


- Improvement of:*
- surface morphology
  - luminescence efficiency
  - thermal stability





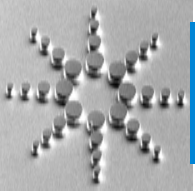
# InGaAsN Edge Emitting Laser Results



*Jth approaching best MBE data with  $T_0 \sim 180$  K*

*low Jth at long wavelength*





# 1300nm VCSEL Performance Requirements

- Link-Level Requirements

*$\lambda > 1260\text{nm}$  for 2.5Gb/s*

*$\lambda > 1290\text{nm}$  for 10Gb/s*

*Optical power into fiber  $> 0.5\text{mW}$*

*Low noise*

*Clean eye diagrams*

- Low-cost Wish List

*Excess power for easy coupling*

*Uncooled operation*

*Low electrical power dissipation*

*Low voltage operation*

*Scalability to other wavelengths*

*(CWDM, 1550nm)*

- Device-level requirements

***\*\*Output Power  $> 1\text{mW}$   
under all operating  
conditions\*\****

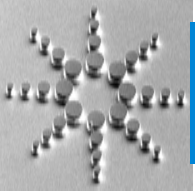
*4-6GHz Relaxation frequency*

*Single lateral mode*

*Operating voltage compatible with  
3.3V supply*

*Reliability*

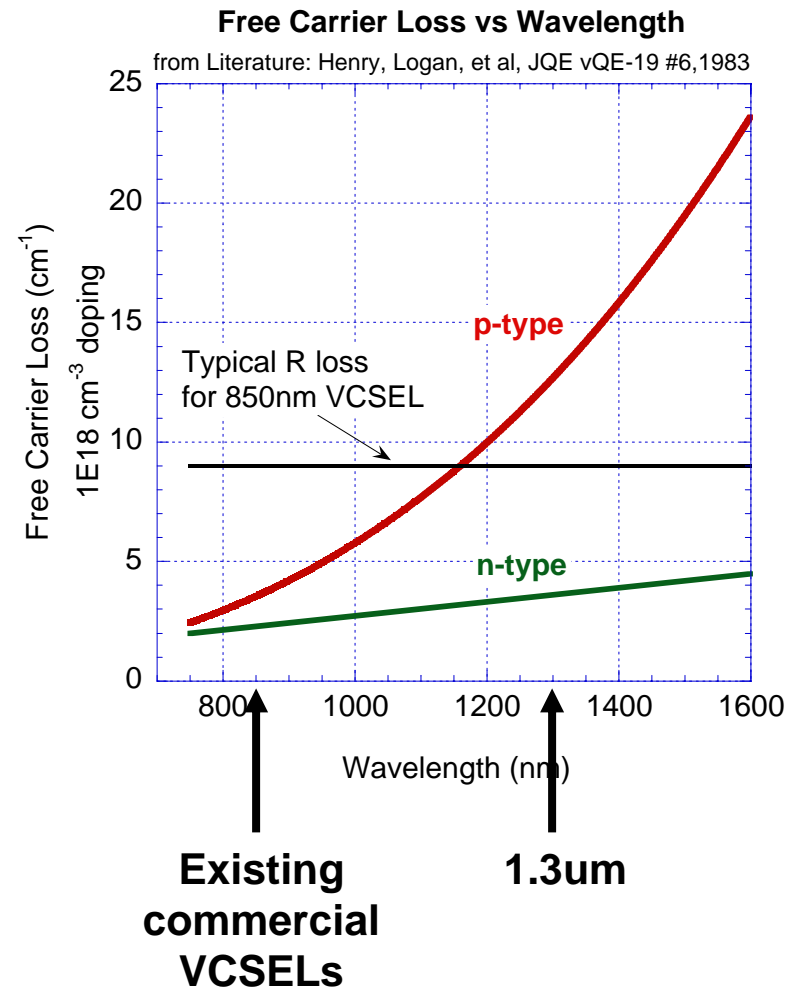


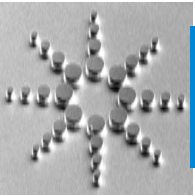


# The Long Wavelength VCSEL Problem

## Parasitic Losses

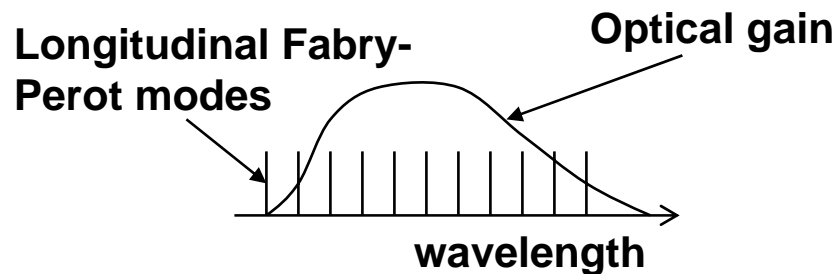
- *Small gain-interaction length in VCSELs*
- *Parasitic free carrier loss is dramatically higher at longer  $\lambda$*
- *Excess parasitic absorption hurts output power, efficiency*
- *Extreme measures for loss reduction will be necessary*





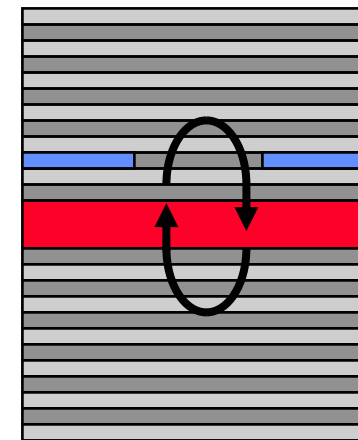
# Single Mode Lasers

## Edge Emitters

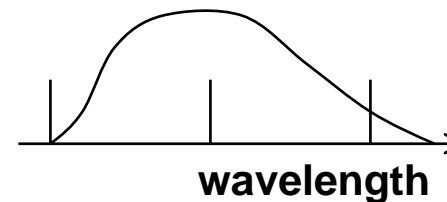


Requires mechanism to select single longitudinal cavity mode – DFB lasers, ~1000Å wide grating lines

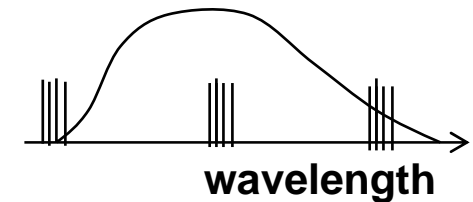
## VCSELs



### Longitudinal Fabry-Perot modes



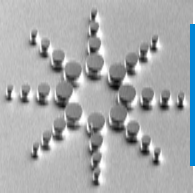
### Lateral “Fiber Modes”



**Lateral modes in VCSELs: Poor power coupling efficiency, mode competition noise**

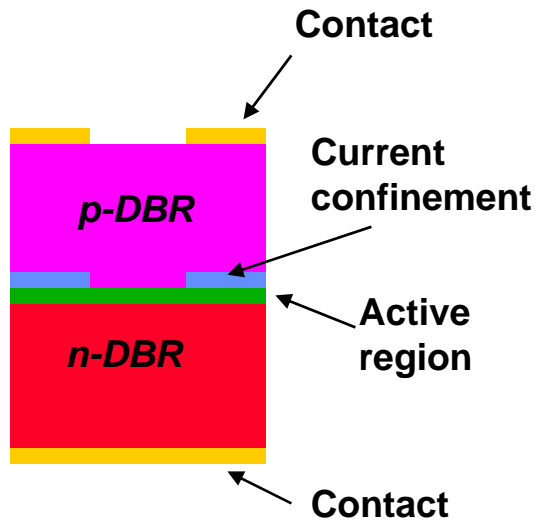
**Requirement for single lateral mode: Small current apertures**





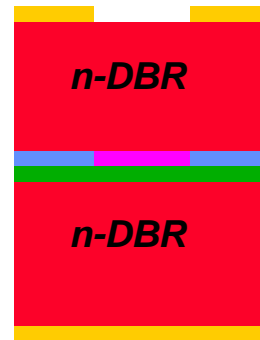
# 1300nm VCSEL Designs

Several options for reducing p-doping loss



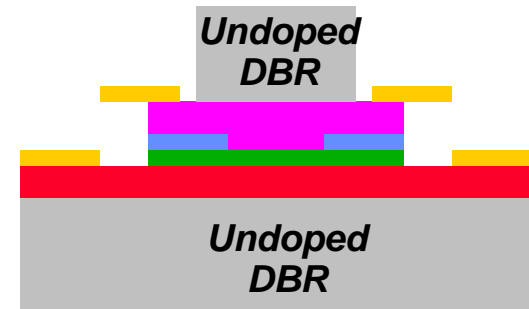
Conventional design with reduced p-doping

→ *Voltage penalty*



Tunnel Junction with n-DBR replacing p-DBR

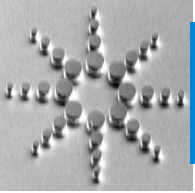
→ *High TJ voltage on GaAs*



Intracavity contacts with undoped or dielectric DBR

→ *High series resistance and nonuniform pumping*

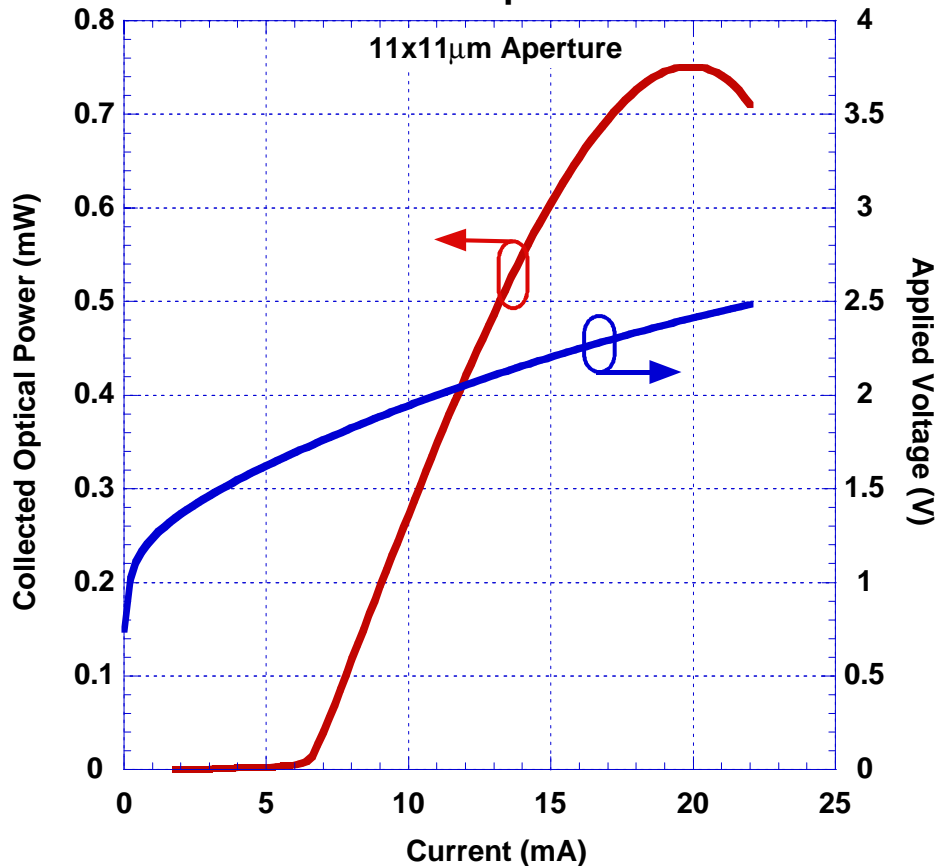




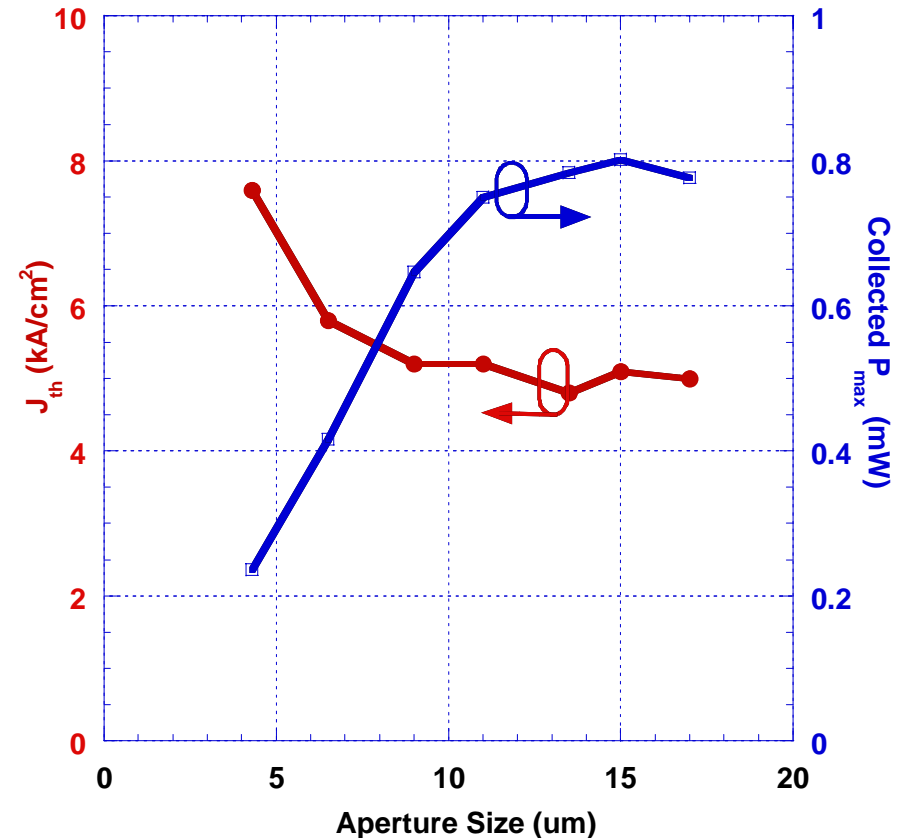
# Agilent MOCVD InGaAsN VCSEL Results

*World's First MOCVD 1300+ nm InGaAsN VCSELs*

MOCVD InGaAsN 1.305 $\mu$ m VCSEL  
CW Room Temperature L-I-V



1305nm InGaAsN MOCVD VCSELs



Agilent Technologies, LEOS 2001 Post-deadline



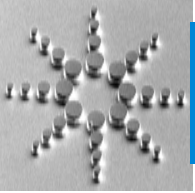
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# Summary

- **1300nm VCSELs are attractive for low-cost, high-bandwidth km-length links**
- **InGaAsN allows long-wavelength VCSELs to be made with established GaAs material technology**
- **Over the past several years, InGaAsN material quality and growth technology has improved dramatically**
- **MBE-grown InGaAsN VCSELs with adequate performance have been demonstrated**
- **MOCVD-grown InGaAsN laser performance is rapidly catching up**

