InGaAsN: A Promising Material for Long Wavelength Vertical Cavity Lasers

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Outline

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

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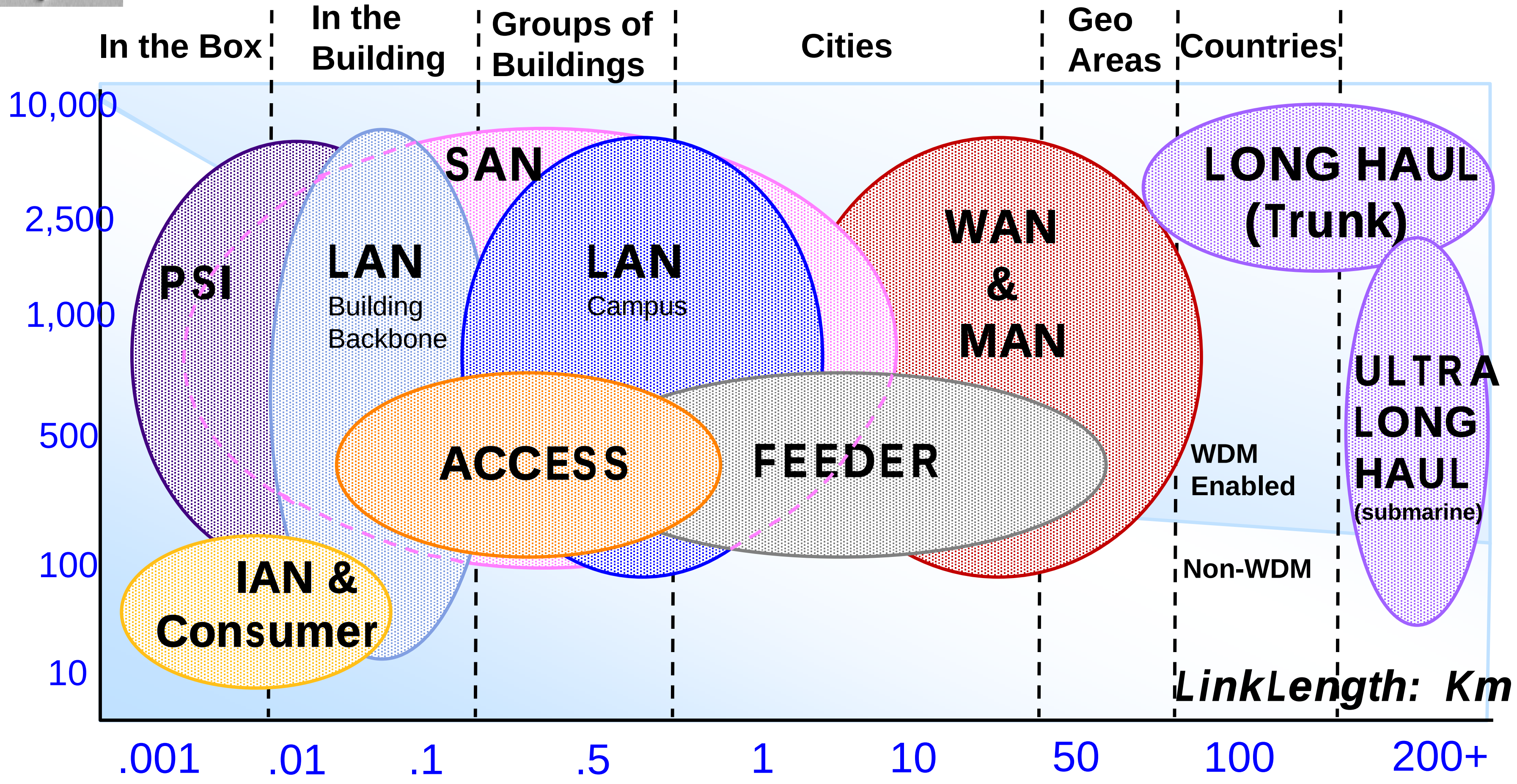
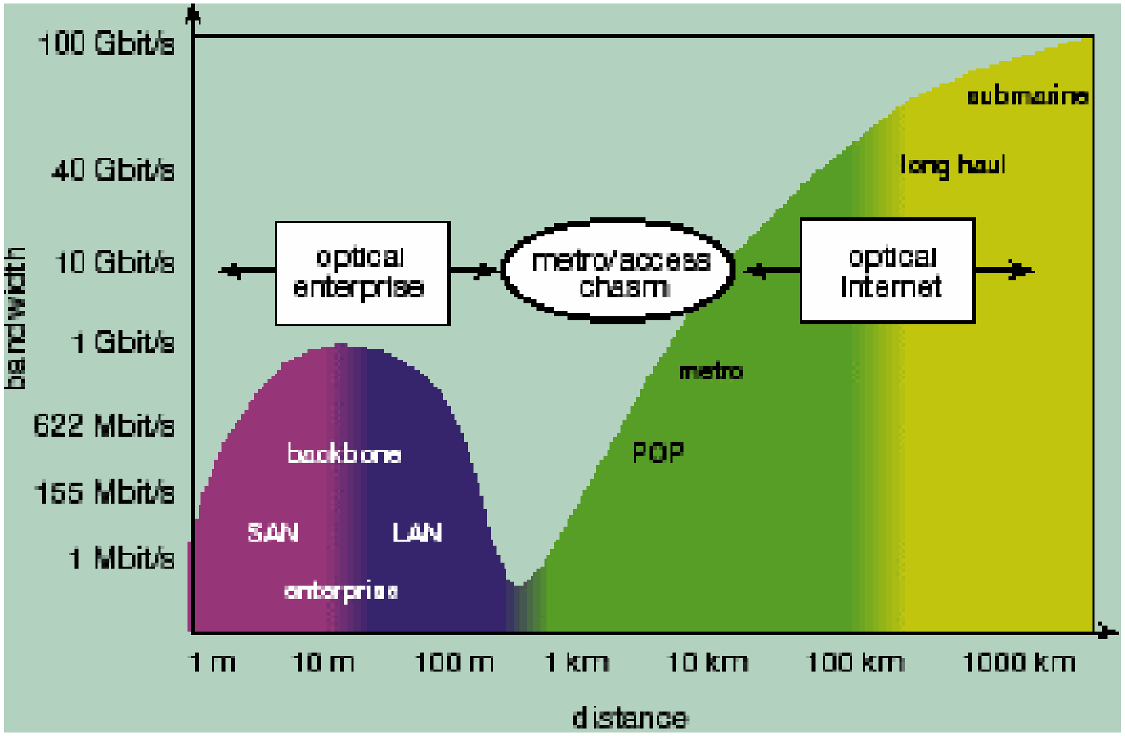
Fiber Market Segments



- 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

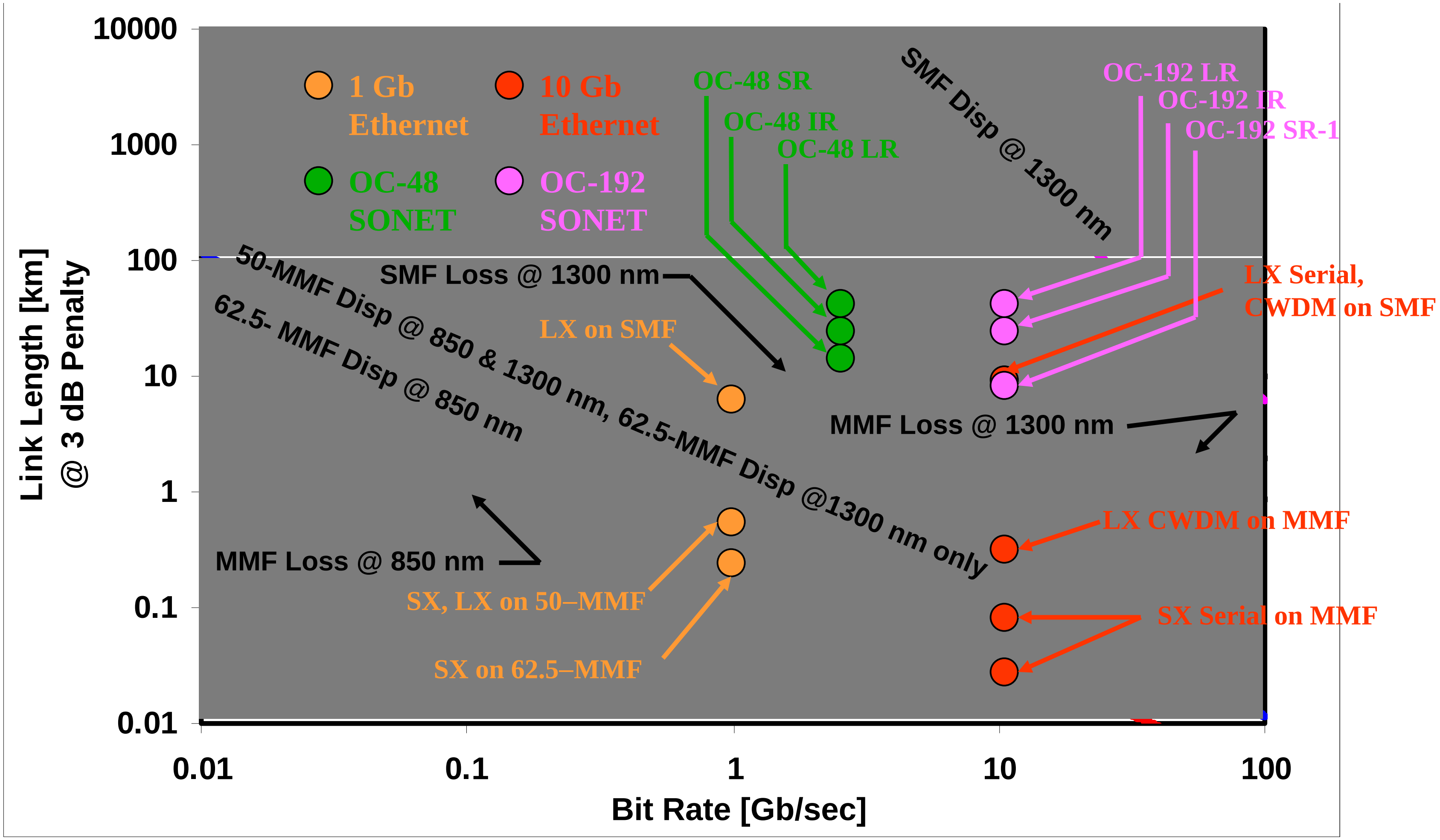


Bandwidth mismatch between the enterprise and long-haul networks

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

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

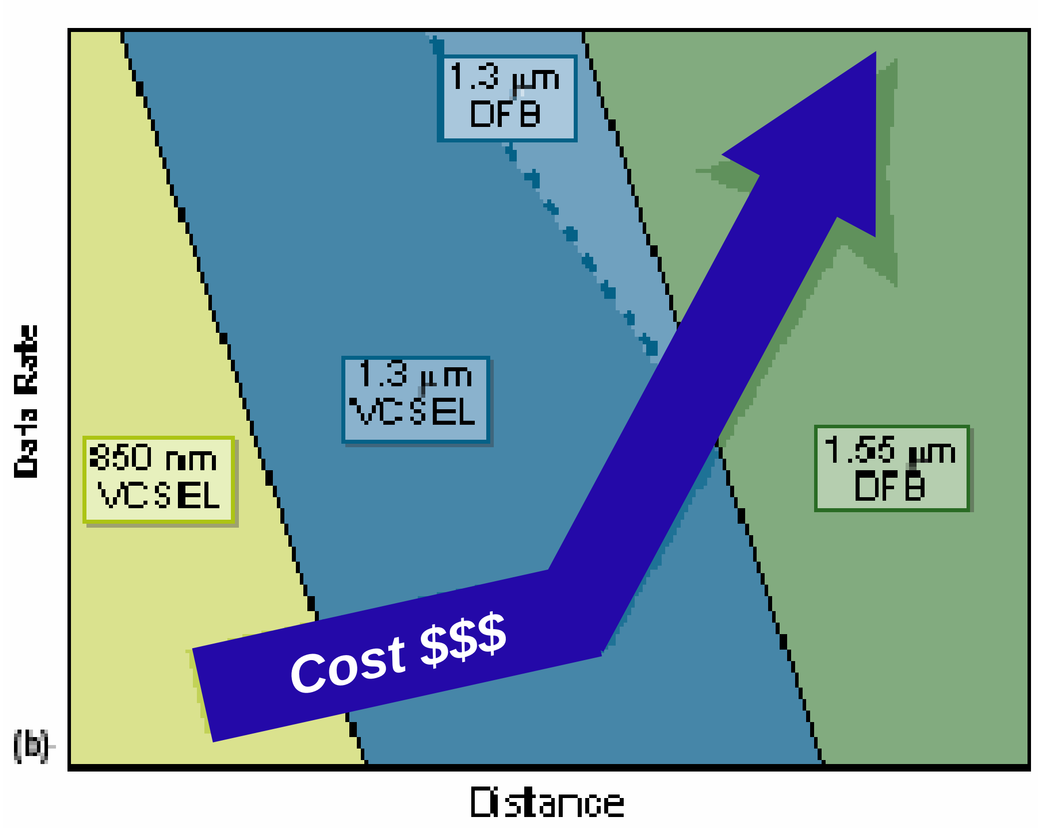
Telecom and Datacom Solution Space



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

D. W. Dolfi - 06/02

Why 1310 nm VCSEL?



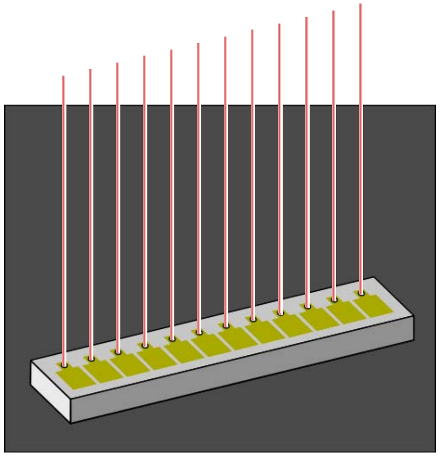
1310 nm VCSEL technology can introduce a kink in the cost curve.

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

Agilent Parallel Optics Transceiver Module

World's First 12 x 2.5 GBd Products!

850 nm VCSEL array technologies



- 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

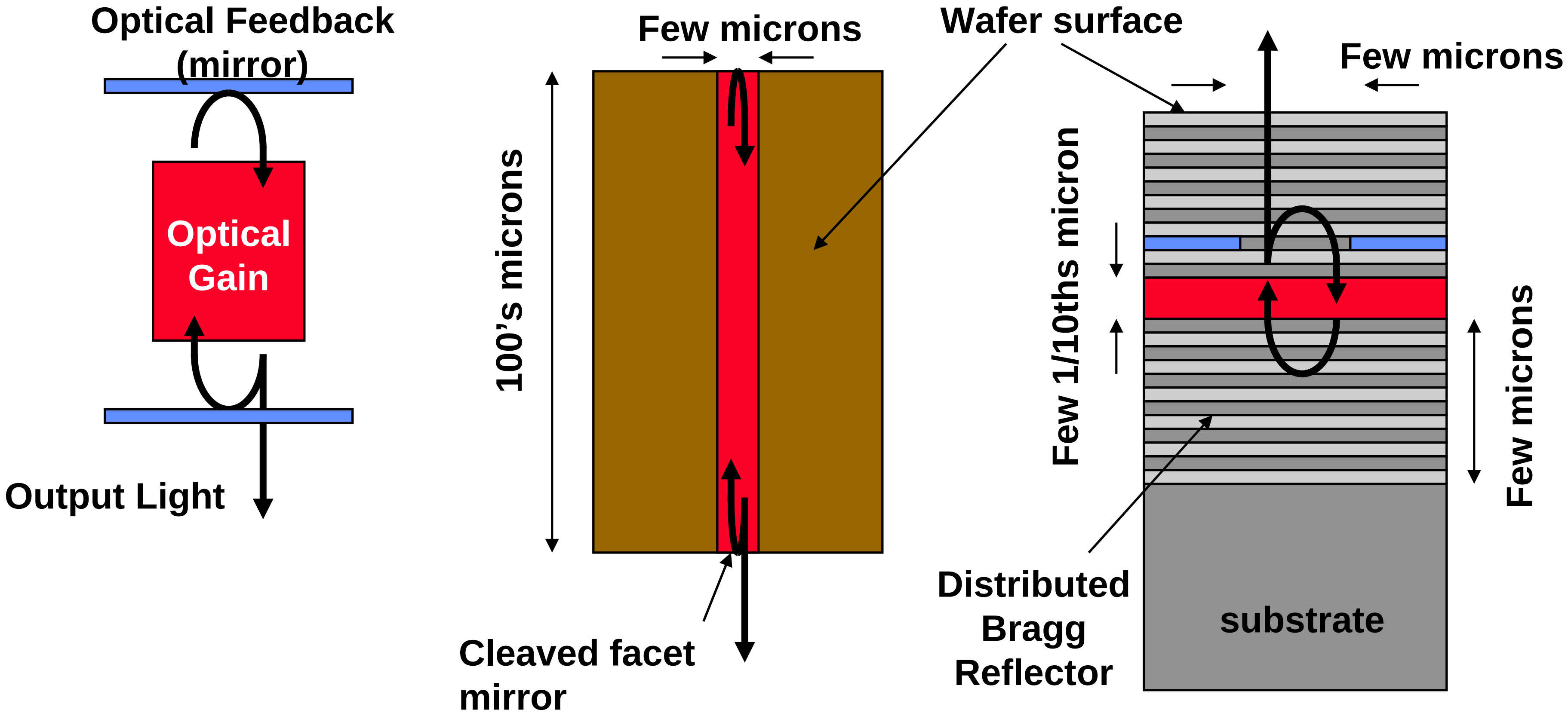
Kirk Giboney, Agilent Technologies, (invited), LEOS, 2001

30-second Laser Tutorial

Laser (Generic)

Edge Emitting Laser

Vertical Cavity Surface Emitting Laser



Optical Feedback (mirror)

Optical Gain

Output Light

Few microns

100's microns

Cleaved facet mirror

Wafer surface

Few microns

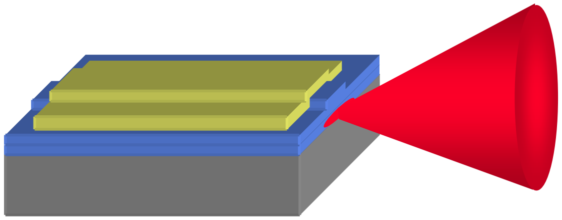
Few 1/10ths micron

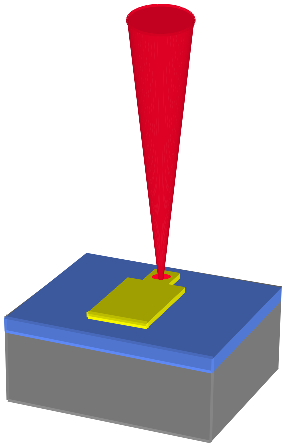
Few microns

Distributed Bragg Reflector

substrate

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

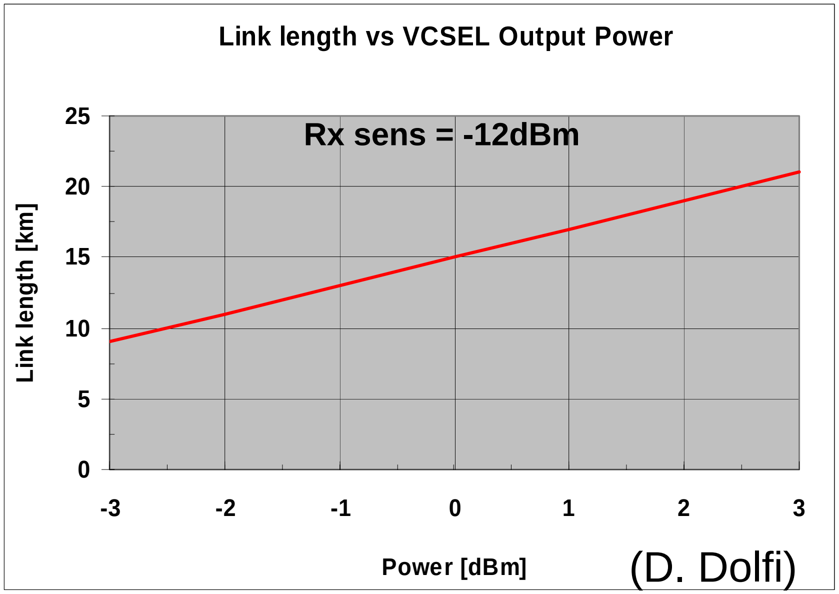
VCSELs
- Surface emission
- LED like manufacturing
- On wafer probing
- Circular beam profile (sometimes)
- Lower output power
- Low current operation
- Low power consumption
- 2D arrays
- Complex epi layer structure

VCSELs are very attractive when optical power requirement is low

1300nm VCSEL Requirements

- **OBJECTIVE**
  1300nm VCSELs for serial, parallel and CWDM applications.

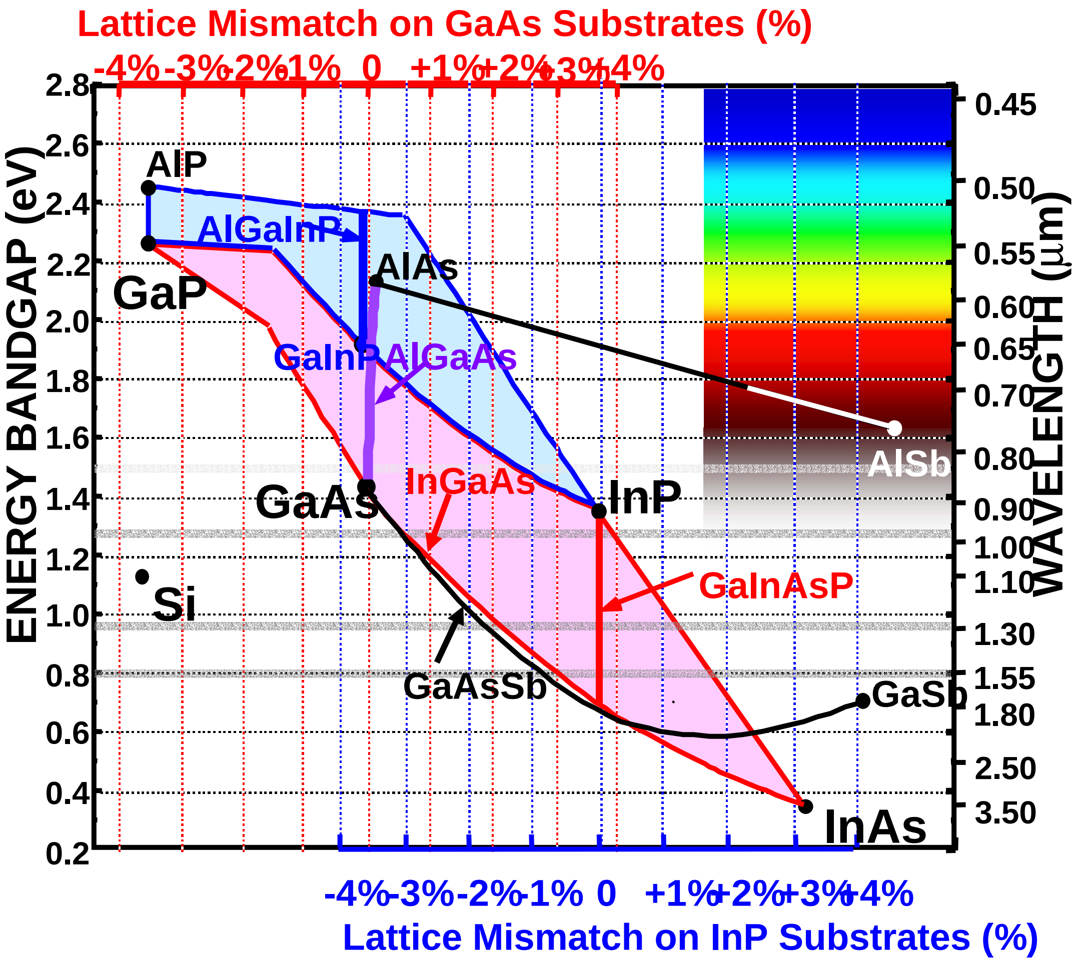
- **Target Specification:**
  - *>1mW single mode @ 85 ^oC*
  - *λ_0 1275nm ~ 1340nm*
  - *Polarization locked*
  - *10 Gbps operation*
  - *RIN < -135dB/Hz*
  - *Vop < 2V, Iop < 15mA*
  - *SMSR > 30dB*



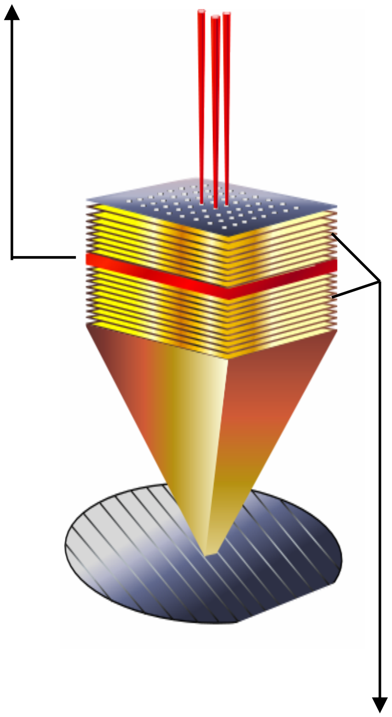
(D. Dolfi)

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)

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?

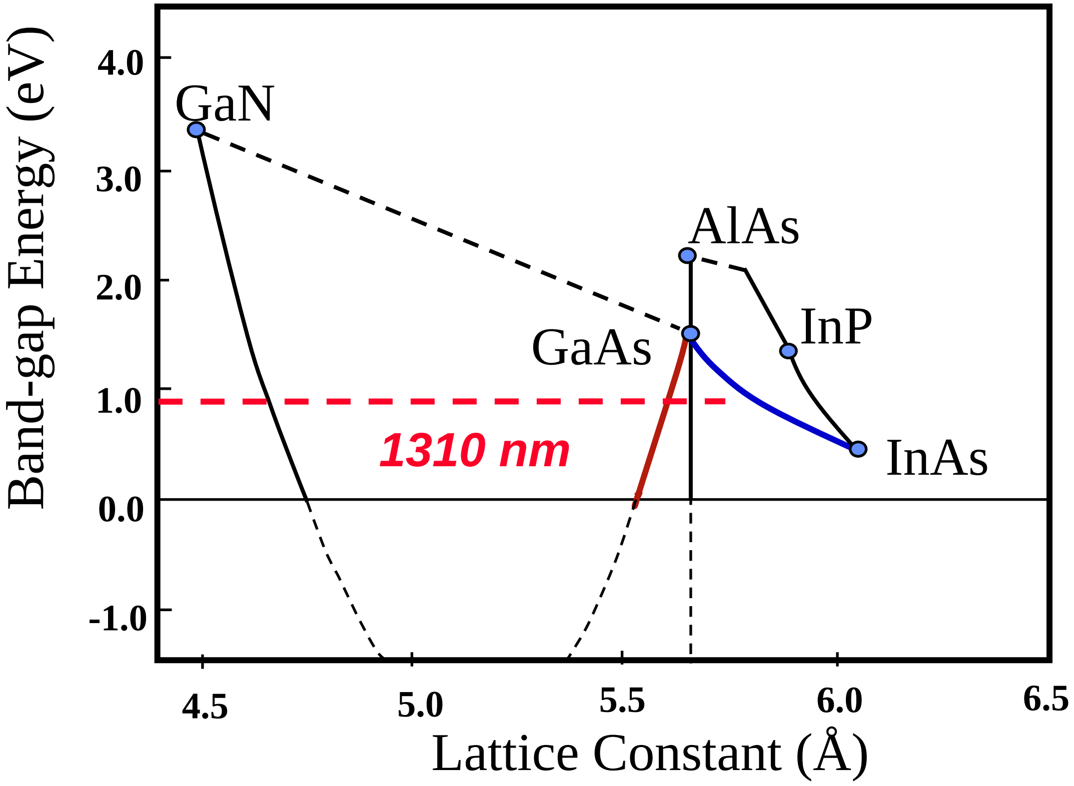
Why GaAs ?

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

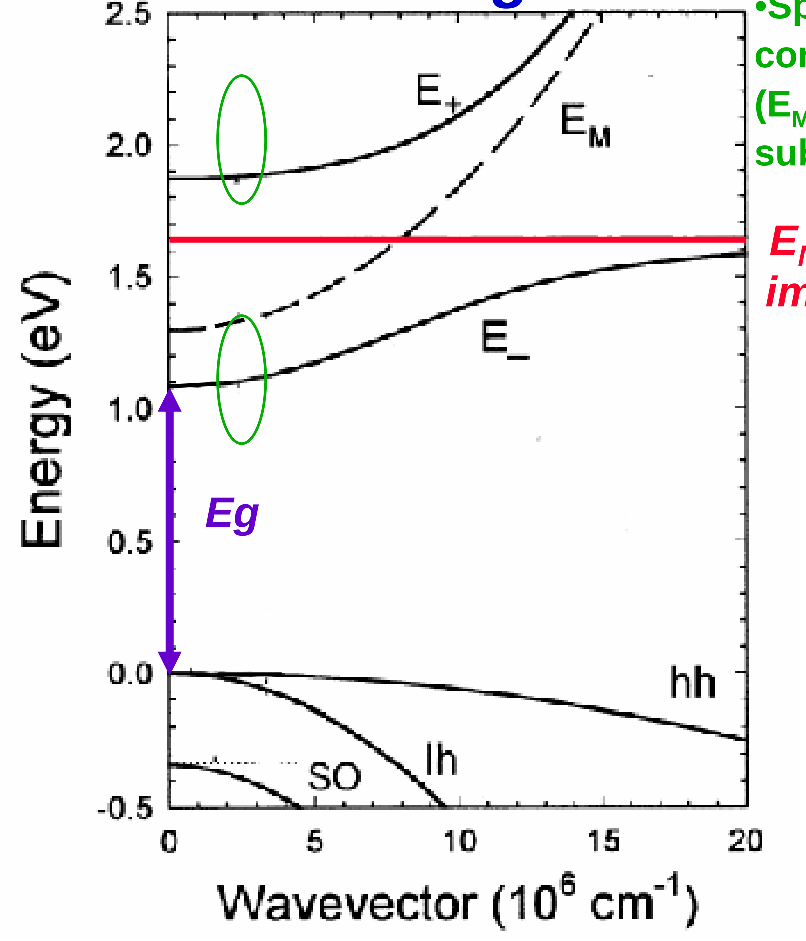


- *1310 nm emission can be easily achieved.*
- *“semi-metal” above certain N level*

(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)

Mechanism for Bandgap Reduction

Anticrossing model



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

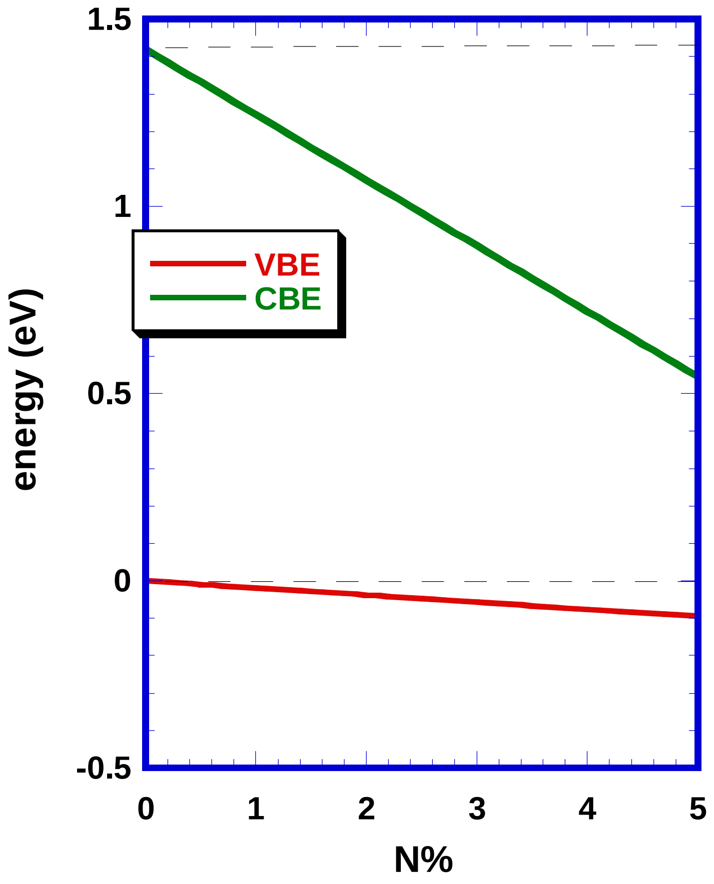
E_N : localized impurity state

ΔEg (x)=bx(x-1)

ΔE~150 meV/%N, b~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

ΔEv=-0.019 eV/N% (measured by XPS)
ΔEc=-0.175 eV/N%
ΔEg=-0.156 eV/N% (b~18)

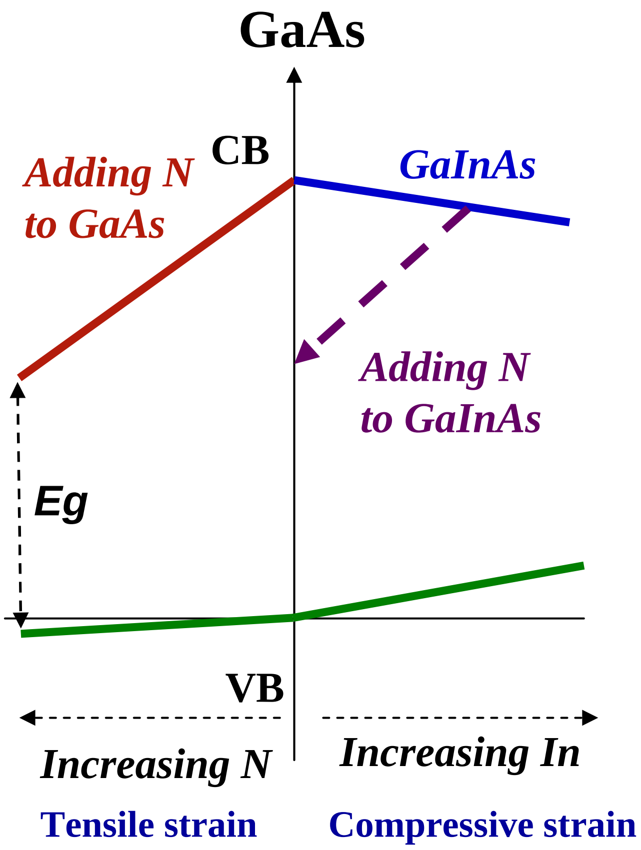
(M. Kondow, et al., Jpn. J. Appl. Phys. Vol. 35, p. 1273, 1996)

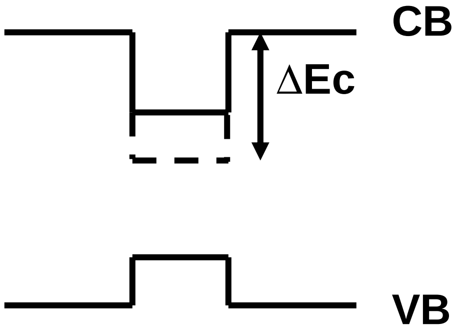
(II) Possibly type I, with small confinement

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





$\Delta E_c \nearrow \; m_e^* \nearrow$

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

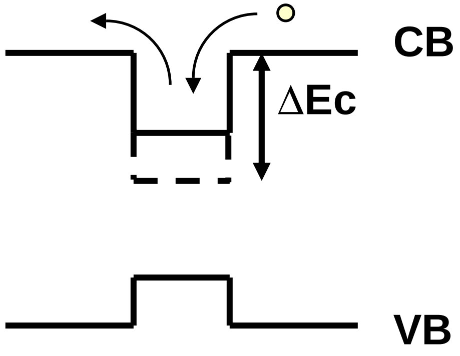
Type I band alignment

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

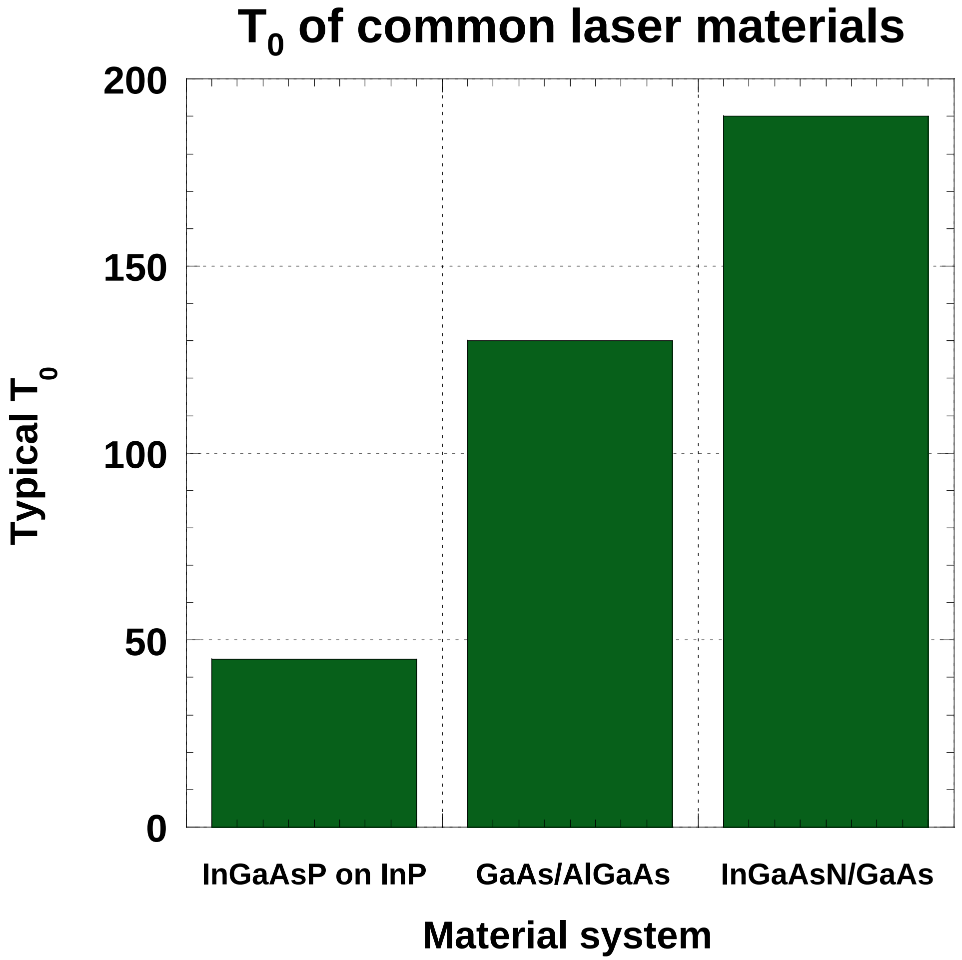
InGaAsN: A Likely Solution

Characteristic Temperature “T_0”

$$I_{th} \propto \exp\left({}^{T}\!/\!{}_{T_0} \right)$$



High T_0 – uncooled operation – lower module cost


T_0 of common laser materials

InGaAsN Problems: Anneal Blueshift

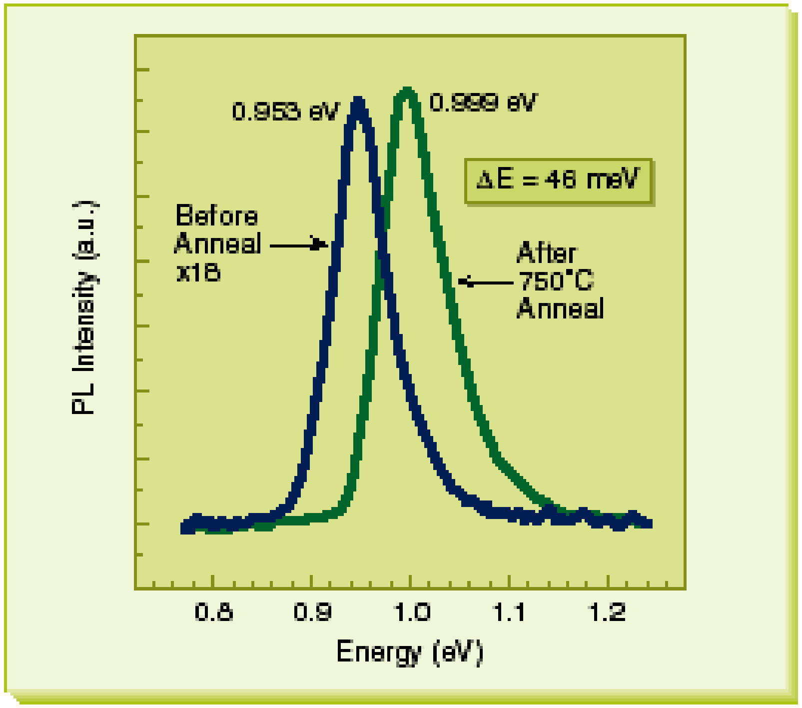


Figure 1. PL spectra of an $In_{0.35}Ga_{0.65}As_{0.982}N_{0.018}$ MQW structure before (left) and after (right) annealing at 750°C.

Post-growth Anneal causes:

- ***Improvement of luminescence efficiency***

- ***Blueshift: not desirable***

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

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

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

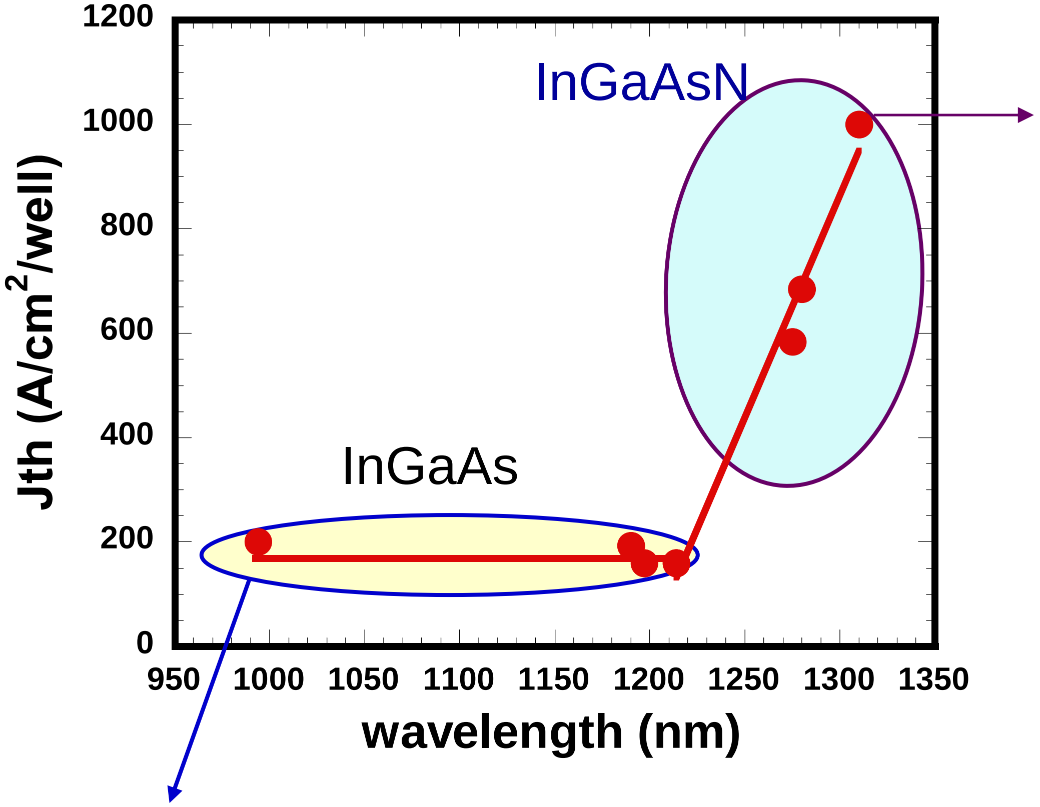
(III) **K. Iga, (2001)**
increase of blueshift with In composition→ In/Ga intermixing

(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 um^2



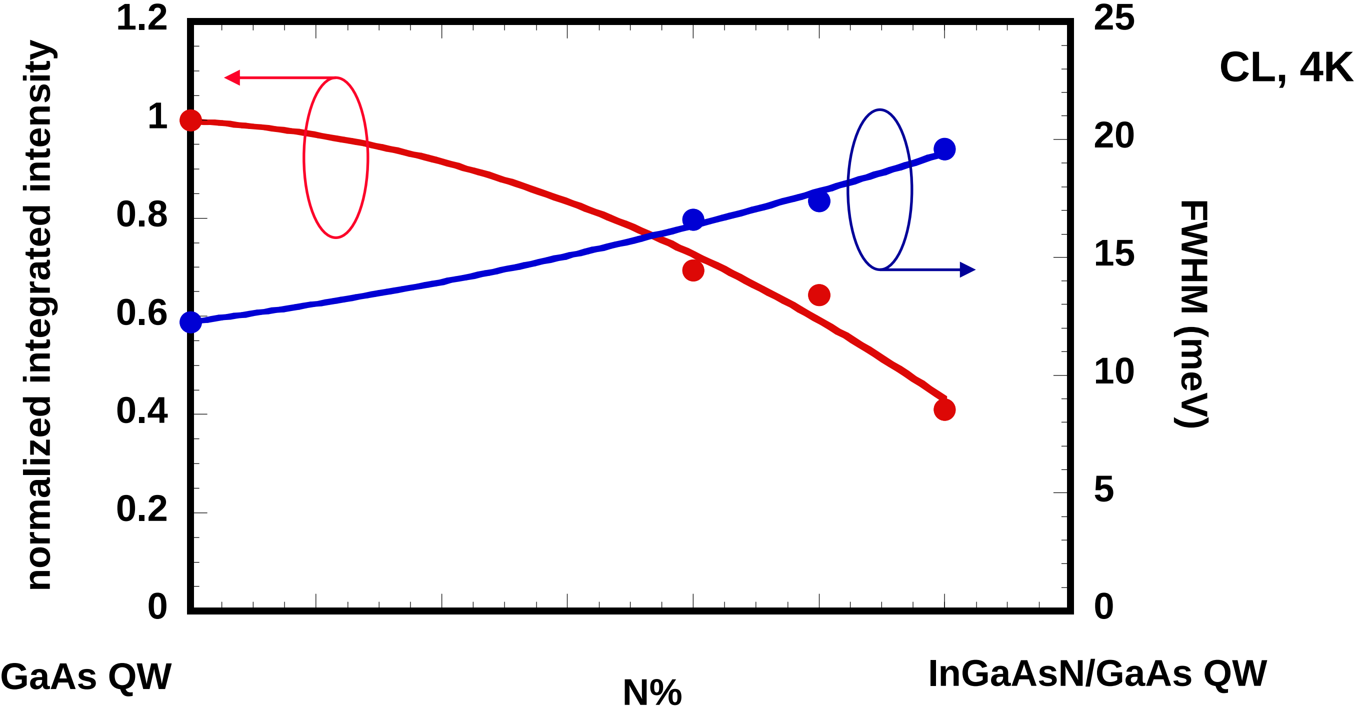
Nitrogen penalty

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

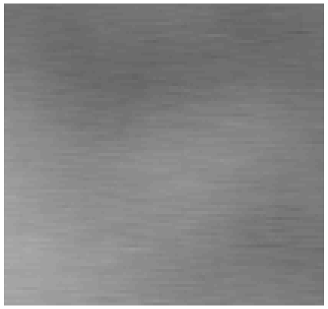
Growth optimization:
Little or no strain penalty

InGaAsN Problems: Nitrogen Penalty

Cathodoluminescence Intensity and Spectral Width vs N fraction

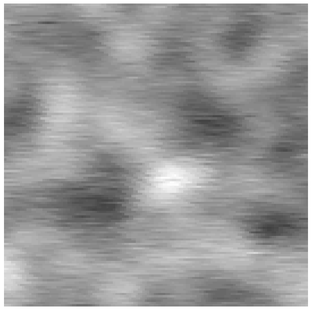


InGaAs/GaAs QW



40umx40um

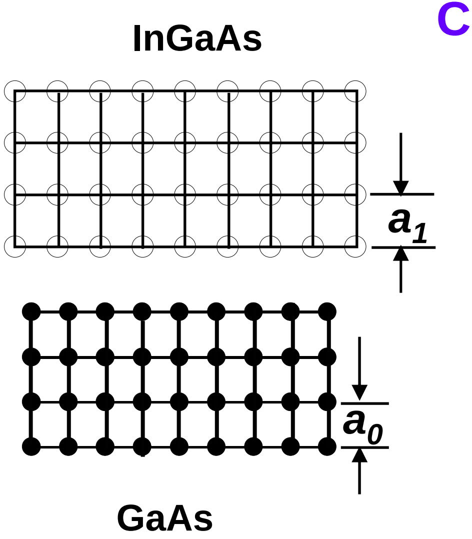
InGaAsN/GaAs QW



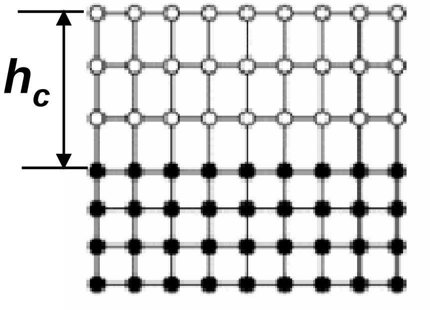
40umx40um

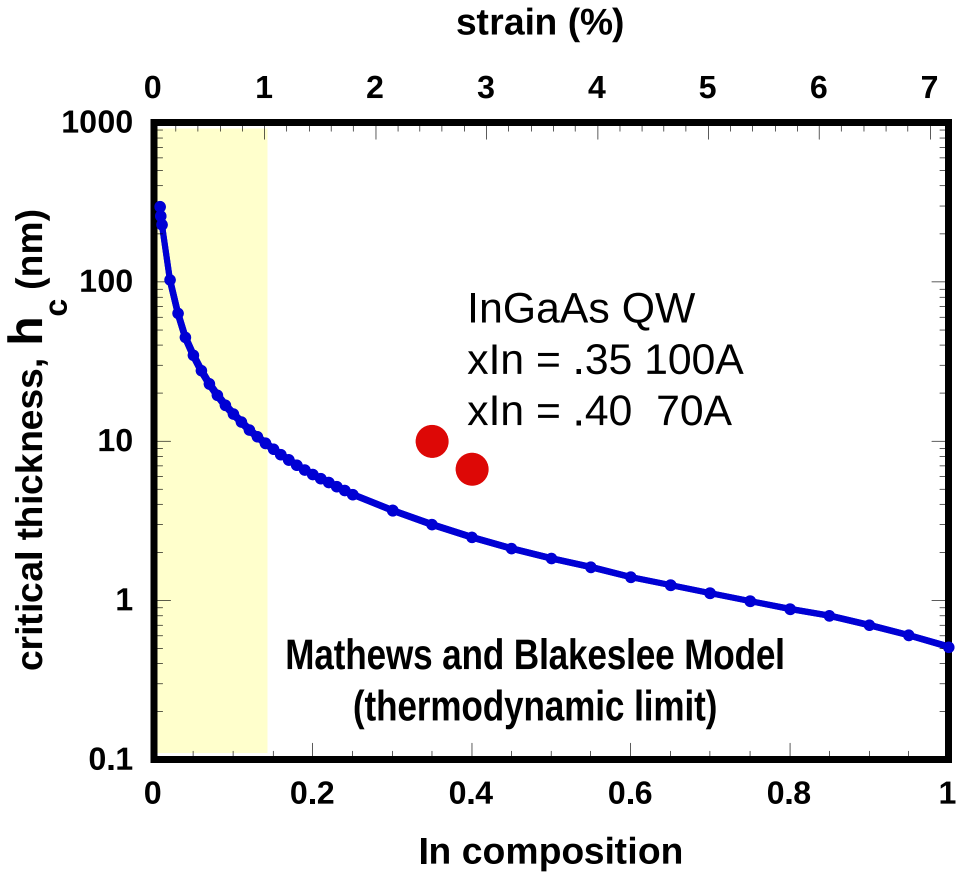
InGaAsN Problems: Strain Limit

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



Compressive strain= $\frac{a_1-a_0}{a_0}$





Use kinetics to prevent the system from reaching equilibrium

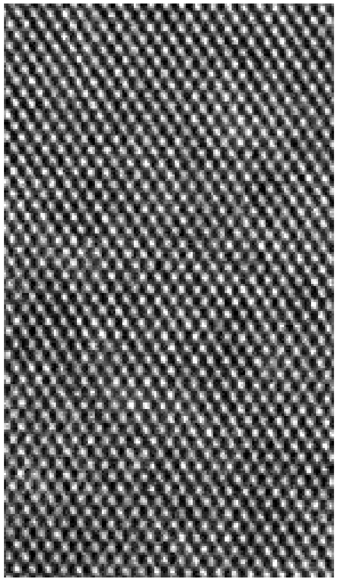
Pushing the strain limit

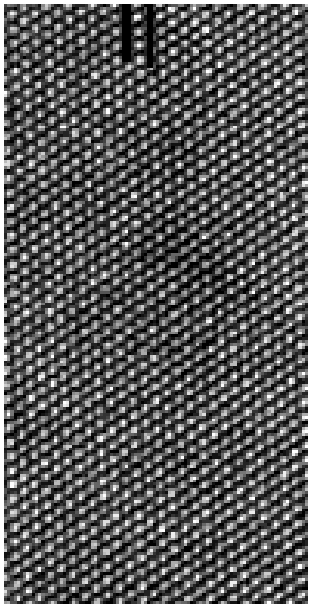
TEM (transmission electron microscopy)

InGaAs/GaAs QW
Standard InGaAs Growth Conditions

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

InGaAs/GaAs QW





InGaAsN/GaAs QW

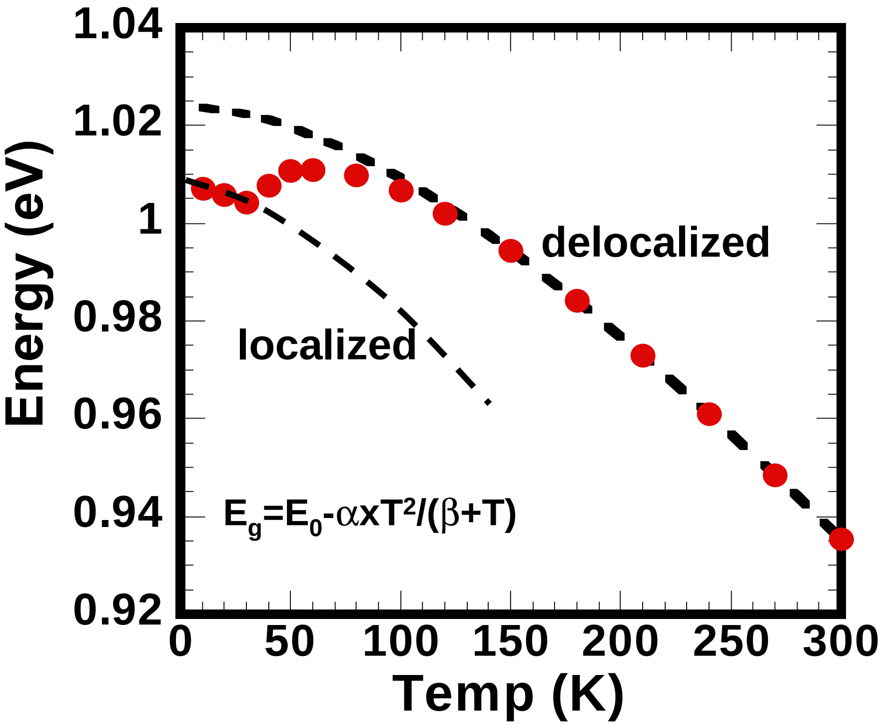
D. Mars, Agilent; C. Kisielowski, C. Nelson, C. Song, X. Xu, P. Specht, E. Weber, Berkeley National Laboratory

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

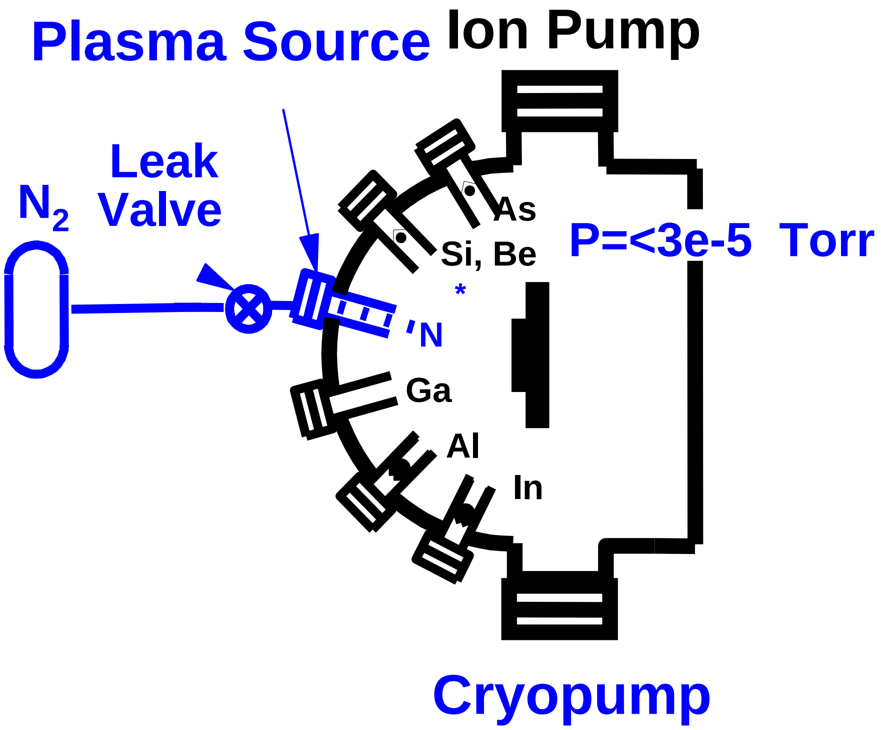


(H. Feick, E. R. Weber, Berkeley)

Plasma-assisted MBE Growth of InGaAsN

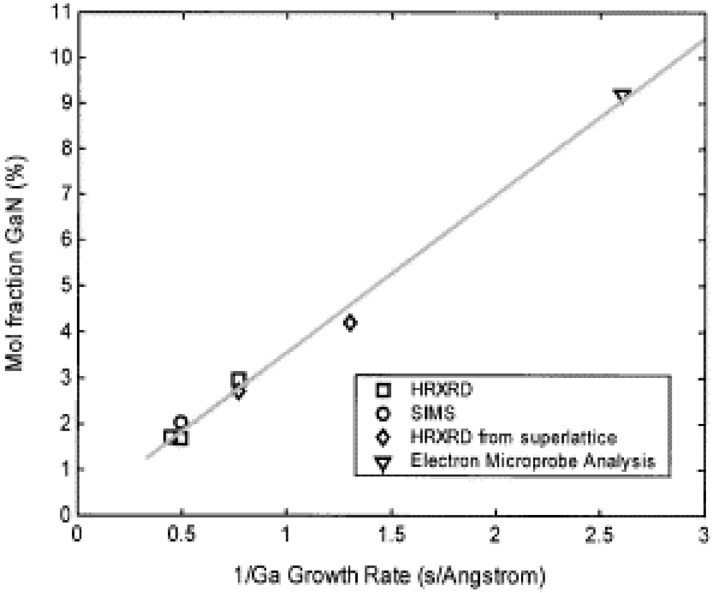
Best results first achieved with MBE

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

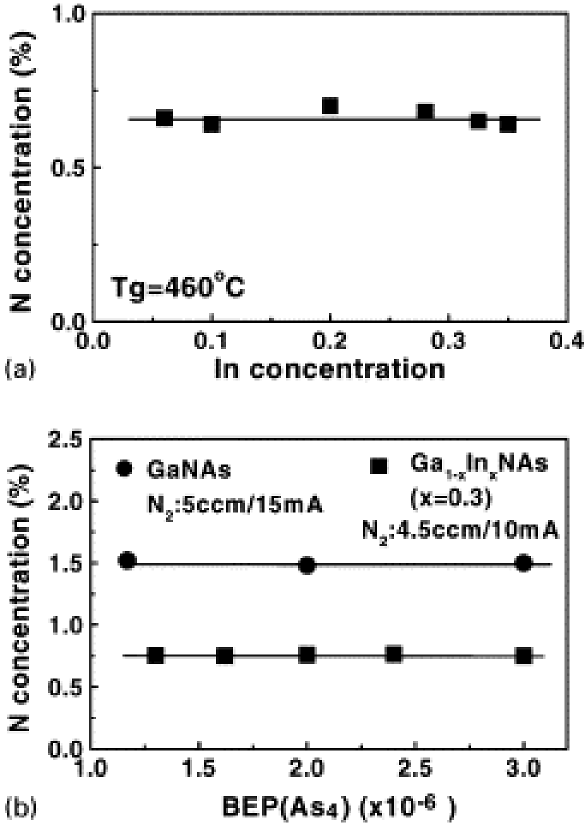


MBE Growth of InGaAsN

N incorporation in MBE InGaAsN is well-behaved and controllable



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

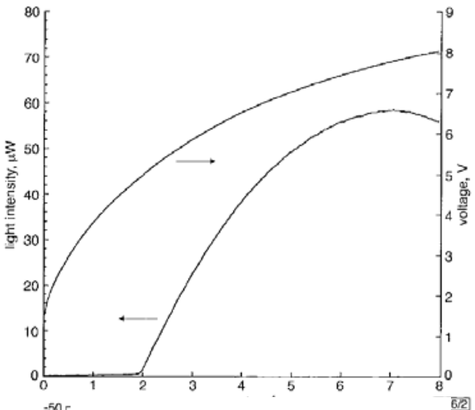


Pan, et al *J. Crystal Growth* v.227-228 p.516 2001

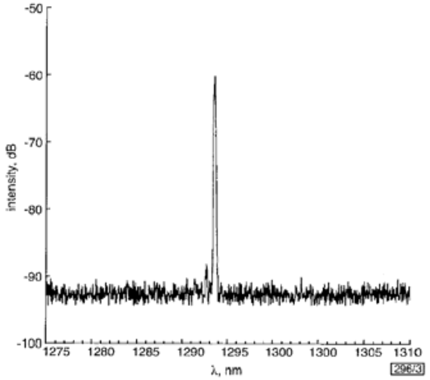
MBE Growth of InGaAsN

MBE-grown material has led the way for InGaAsN VCSELs

First demonstration of RT CW 1.3µm $In_{0.34}Ga_{0.66}As_{0.99}N_{0.01}$ QW VCSELs



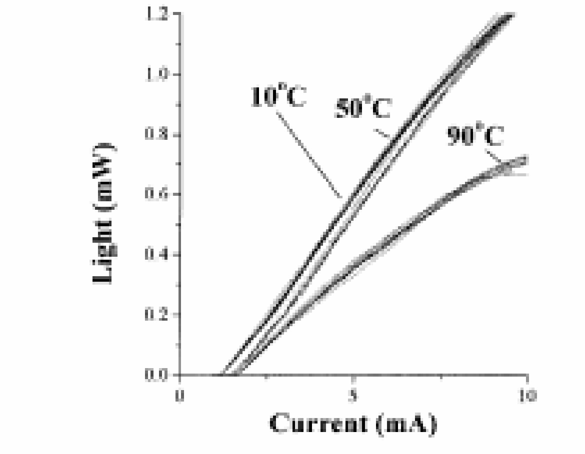
~58 µW



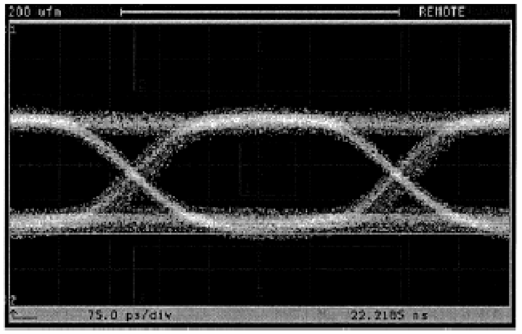
1294 nm

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

Recent "Commercial" Devices



~1 mW
~1270nm



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

2.5Gb/s

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

MOCVD InGaAsN growth

MOCVD : high growth rate, desirable for VCSEL structure

Issues :

(I) no well-established N source

NH_3 used for GaN

Very high cracking temperature – incompatible with GaAs

Dimethylhydrazine (DMHy)

lower pyrolysis temperature compared to NH_3

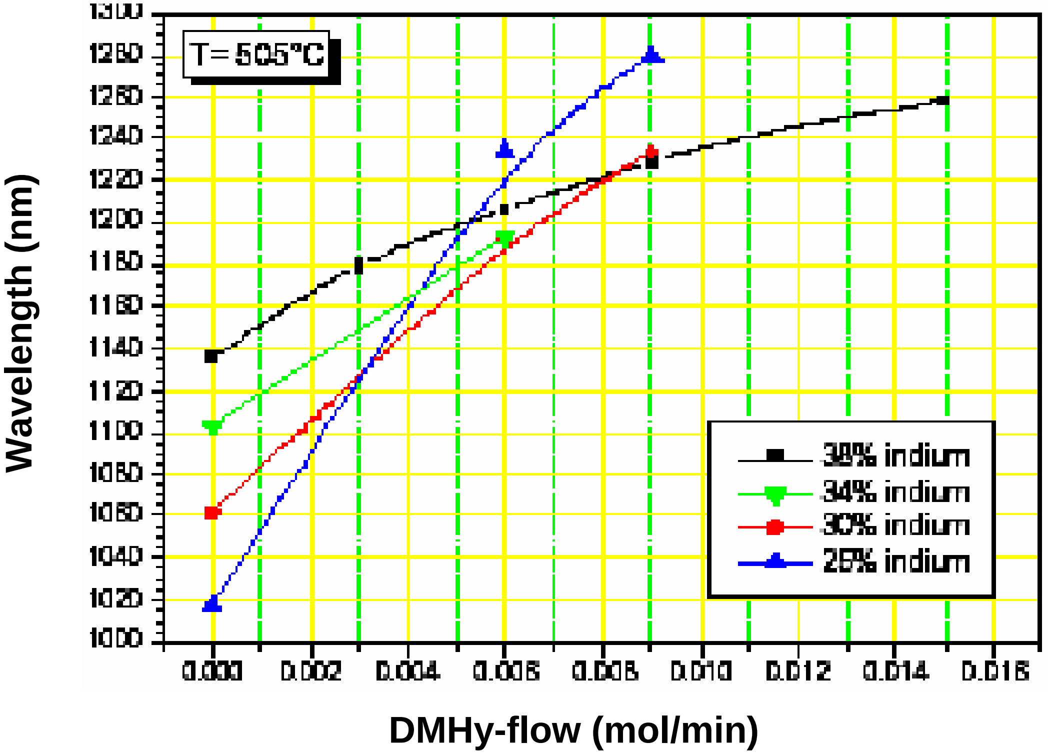
extremely low N incorporation, ~0.0001

Purity control not well developed

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

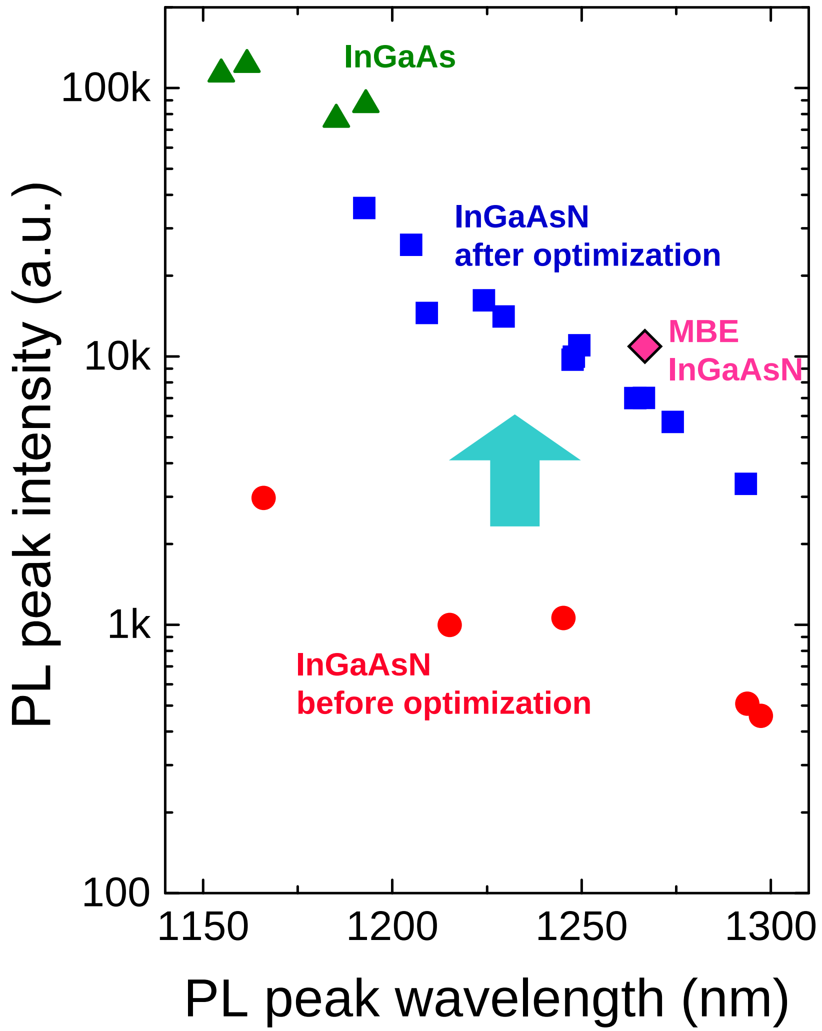
MOCVD InGaAsN: In-N Interaction

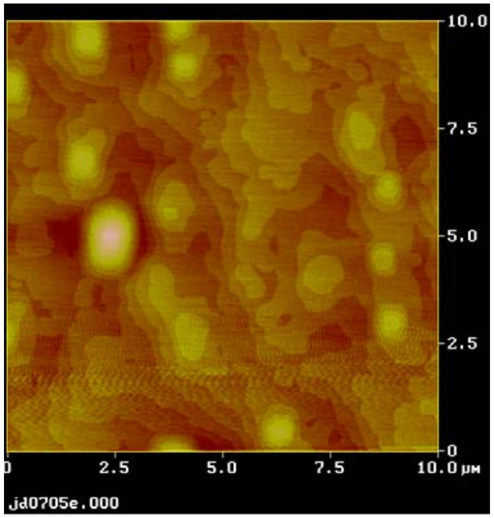
PL wavelength dependence on DMHy flow for different In fraction



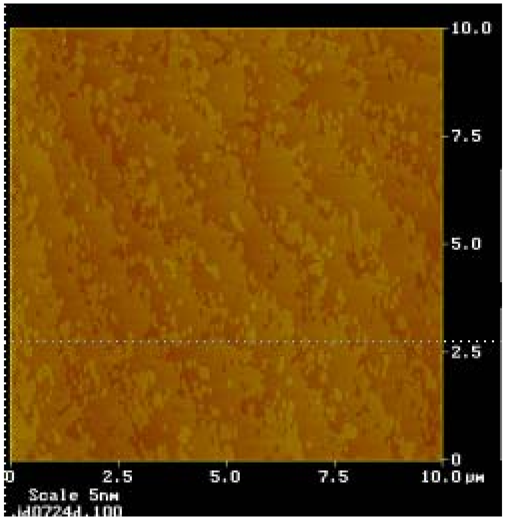
(S. Illek, etc, Infineon technologies, IPRM, 2000)

MOCVD InGaAsN Growth Optimization





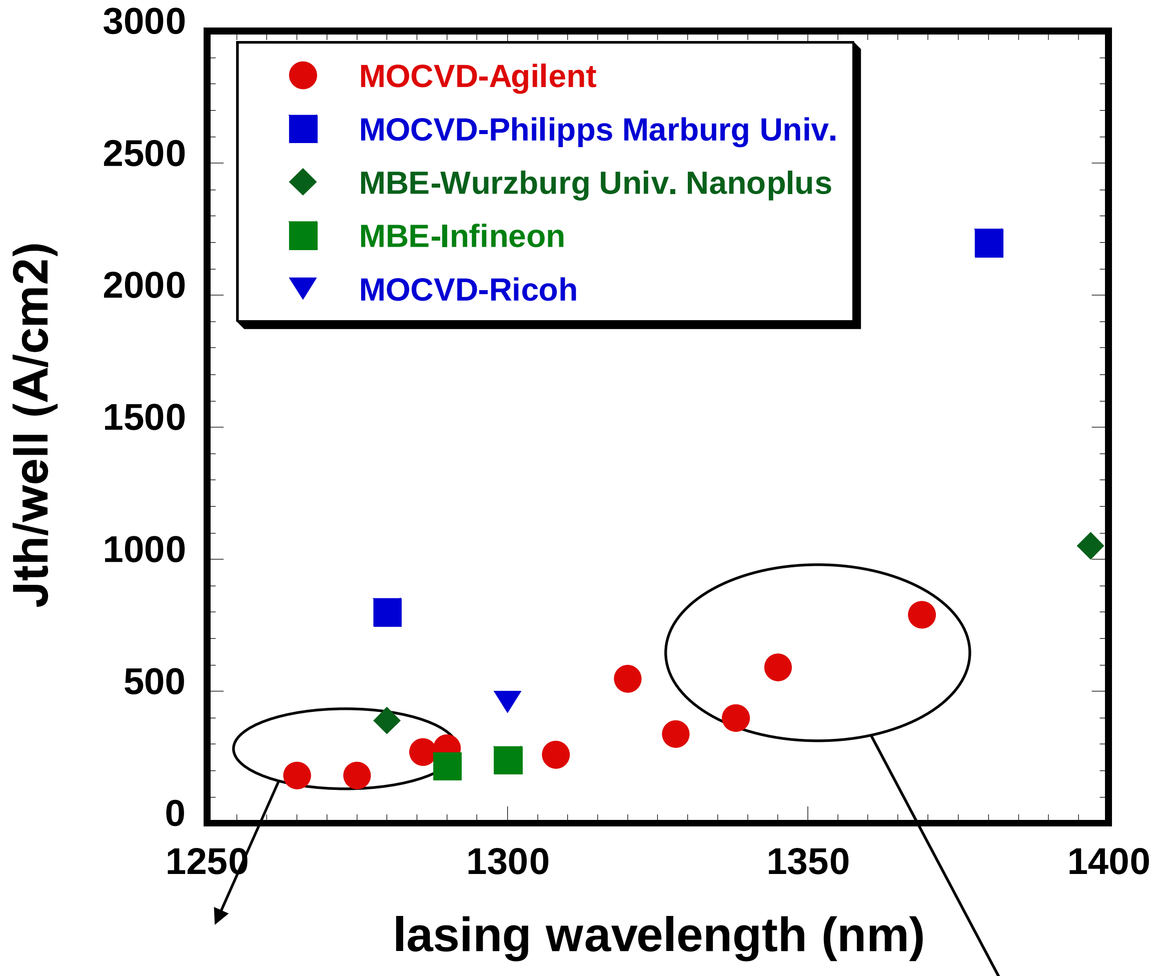
AFM surface profile



Improvement of:

- ***surface morphology***
- ***luminescence efficiency***
- ***thermal stability***

InGaAsN Edge Emitting Laser Results



Jth approaching best MBE data
with To~180 K

low Jth at long wavelength

1300nm VCSEL Performance Requirements

- Link-Level Requirements
  - *λ>1260nm for 2.5Gb/s*
  - *λ>1290nm for 10Gb/s*
  - *Optical power into fiber >0.5mW*
  - *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 > 1mW under all operating conditions*****
  - *4-6GHz Relaxation frequency*
  - *Single lateral mode*
  - *Operating voltage compatible with 3.3V supply*
  - *Reliability*

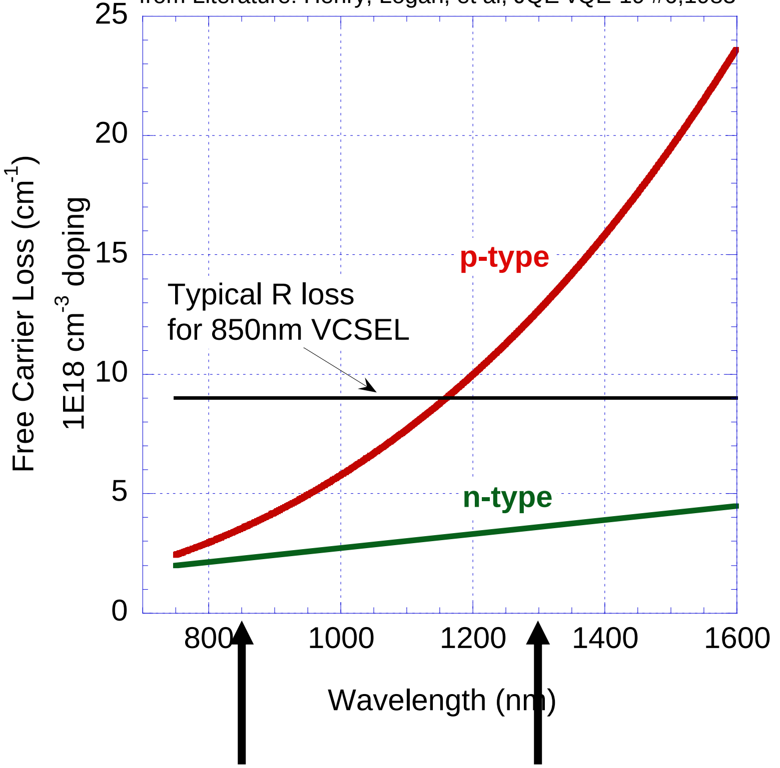
The Long Wavelength VCSEL Problem

Parasitic Losses

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

Free Carrier Loss vs Wavelength

from Literature: Henry, Logan, et al, JQE vQE-19 #6,1983

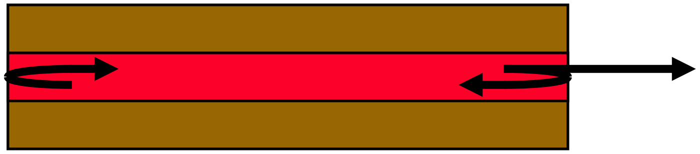


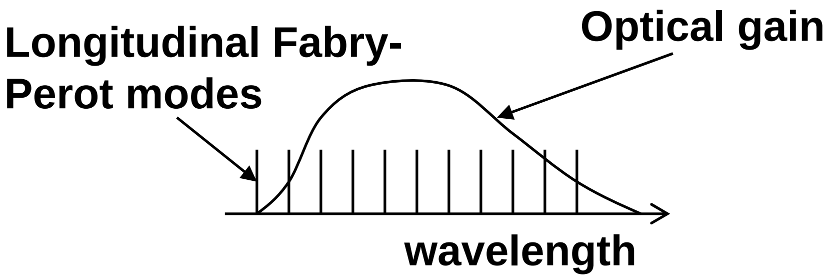
Existing commercial VCSELs

1.3um

Single Mode Lasers

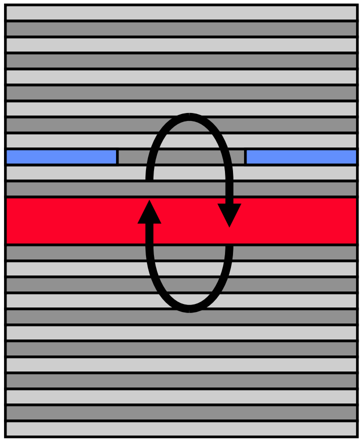
Edge Emitters

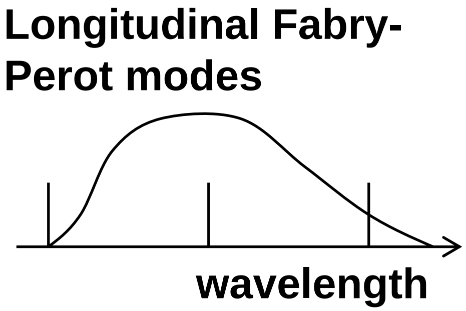


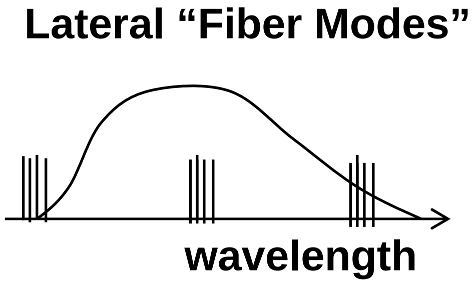


Requires mechanism to select single longitudinal cavity mode – DFB lasers, ~1000A wide grating lines

VCSELs





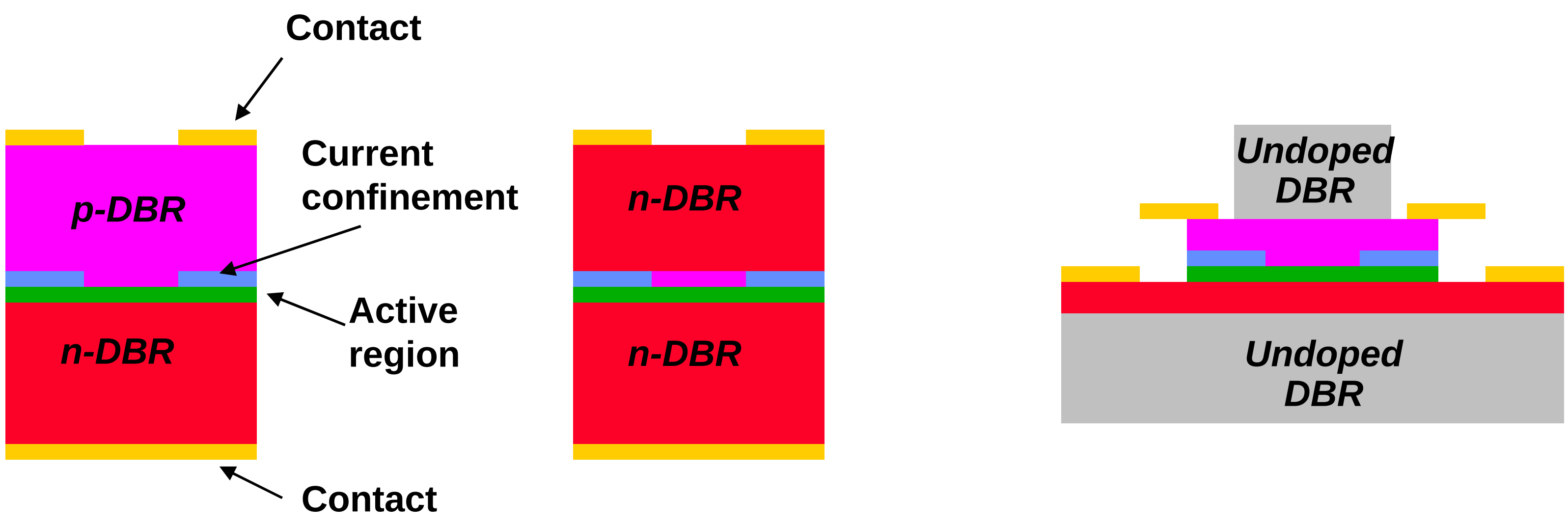


Lateral modes in VCSELs: Poor power coupling efficiency, mode competition noise

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

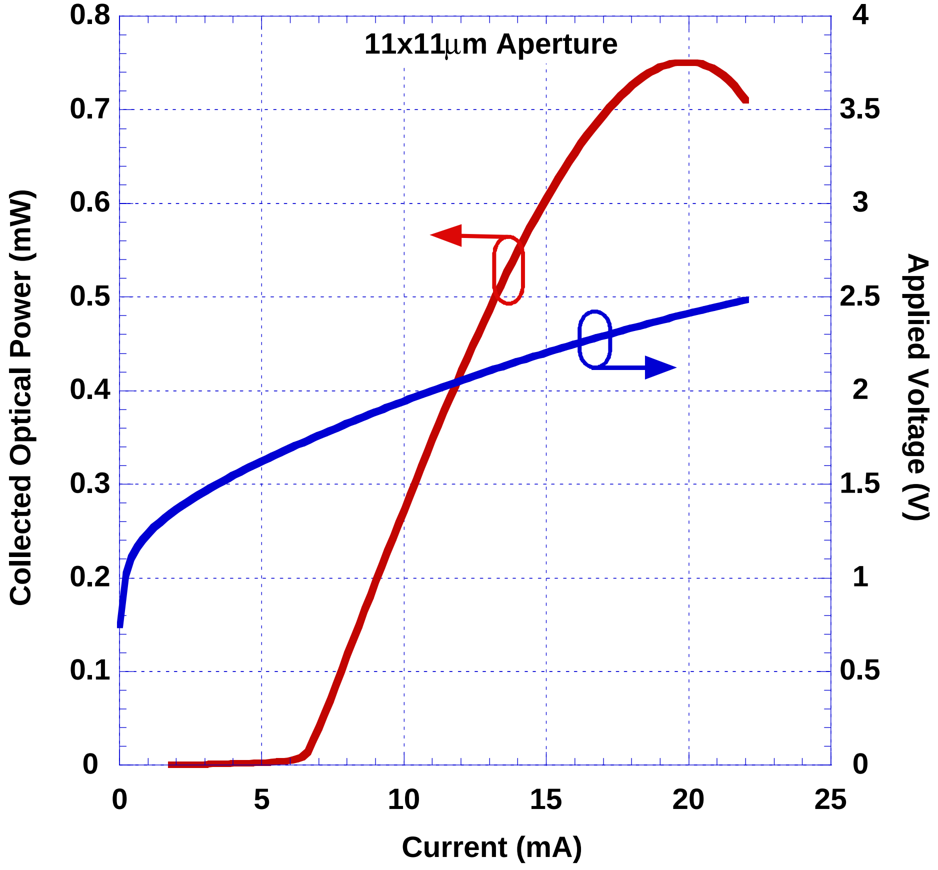
→ *High TJ voltage on GaAs*

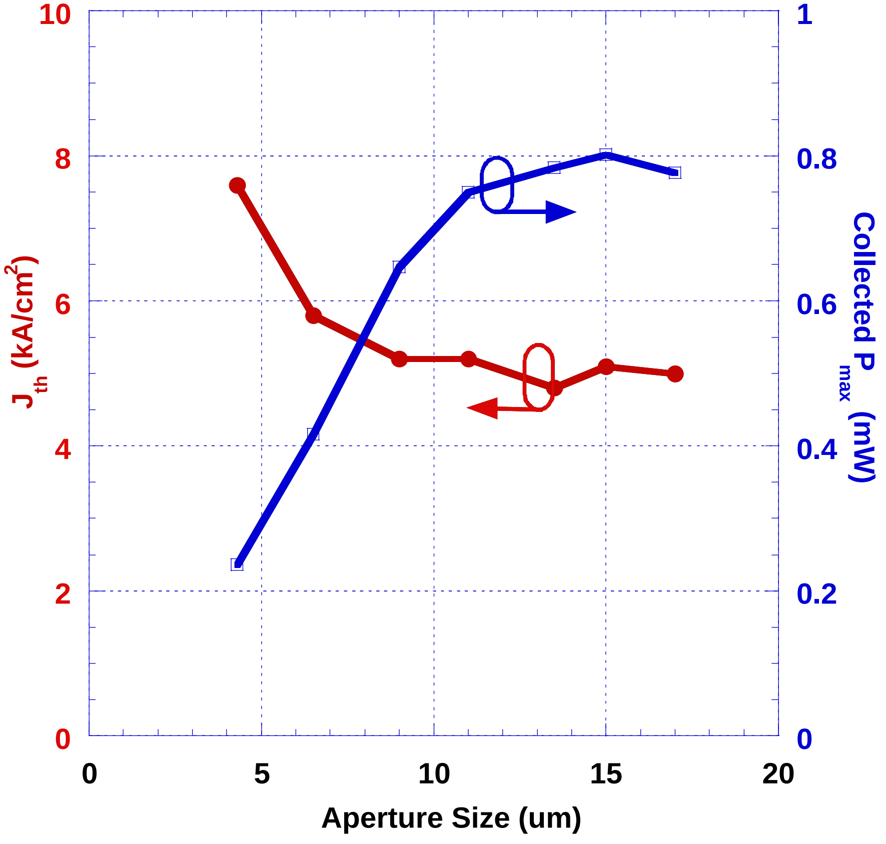
Intracavity contacts with undoped or dielectric DBR

→ *High series resitance and nonuniform pumping*

Agilent MOCVD InGaAsN VCSEL Results

World's First MOCVD 1300+ nm InGaAsN VCSELs


MOCVD InGaAsN 1.305µm VCSEL
CW Room Temperature L-I-V


1305nm InGaAsN MOCVD VCSELs

Agilent Technologies, LEOS 2001 Post-deadline

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