Applied Photonics

Christopher Kocot

G. P. Carey, R. Carico, T. Chung, R. Dato, J. J. Dudley, A. M. Earman, M.J. Finander, G. Giaretta, S. Hallstein, J.H. Hofler, M. Jansen, J. Krueger, S. Lim, A. Mooradian, G. Niven, Y. Okuno, F.G. Patterson, D. Sullivan, A. Tandon, A. Umbrasas,

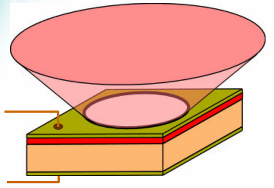
Novalux, Inc.
1220 Midas Way Sunnyvale, CA 94085 U.S.A.

XXXVI International School On The Physics
Of Semiconducting Compounds
June 9 – 15, 2007

Outline

- Vertical-Cavity Surface-Emitting Lasers
- Quantum Dot Lasers
- Tunable lasers
- VCSEL applications
- GaN LEDs
- NECSEL
- NECSEL applications

What exactly is a VCSEL? First look at it's cousins...

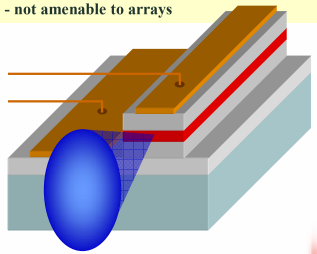


Light-Emitting Diode (LED)

- p-n junction device
- light emission from top surface
- large emitting area
- low current density
- on-wafer testing
- non-directional, non-coherent
- relatively slow (e.g., 155 Mbps)
- amenable to arrays

Edge-Emitting Laser Diode

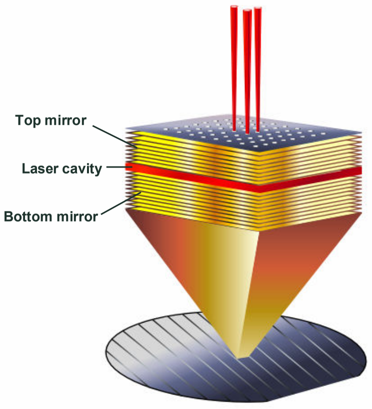
- p-n junction device
- light emission from cleaved/etched facet
- small emitting area
- high current density
- on-wafer testing not possible
- highly directional, coherent, elliptical beam
- can be designed for high speed
- not amenable to arrays



What exactly is a VCSEL?

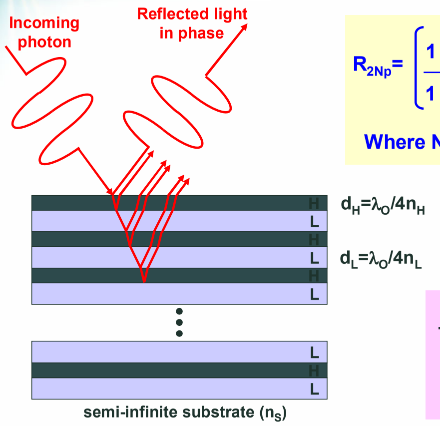
Vertical-Cavity Surface-Emitting Laser Diode (VCSEL)

- p-n junction device
- light emission from top surface
-small or large emitting area
-high current density (>1kA/cm^2)
- amenable to on-wafer testing
- amenable to 2D arrays
- circular beam
- can be designed for high speed operation



NOVALUX

Distributed Bragg Reflectors (DBRs) are key to re-orienting the laser cavity for surface emission...



$$R_{2Np}=\left(\frac{1-(n_S/n_O)(n_H/n_L)^{2Np}}{1+(n_S/n_O)(n_H/n_L)^{2Np}}\right)^2$$

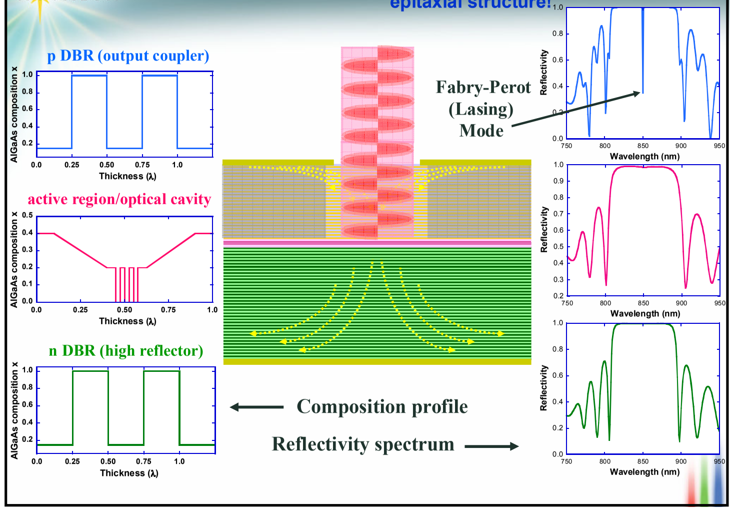
Where N_P = # of DBR periods

R increases as:

- **Np increases**
- **n_H/n_L increases**

NOVALUX

... but DBRs add great complexity to the epitaxial structure!



NOVALUX

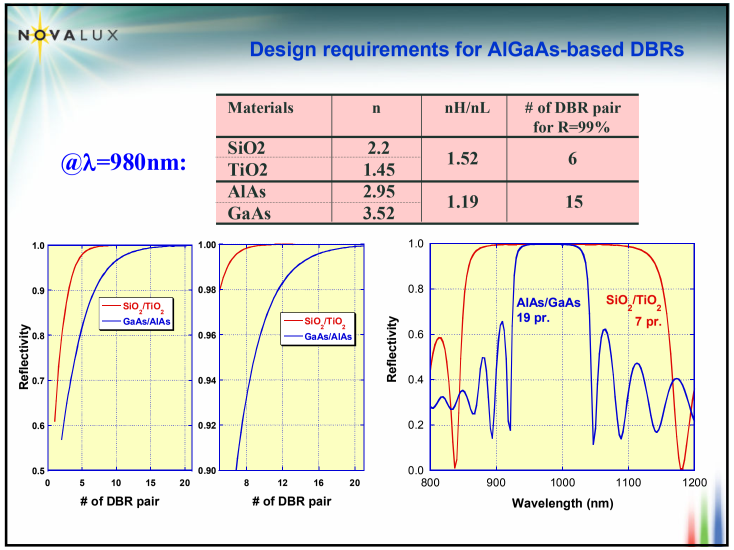
Materials and epitaxy issues are central to VCSEL development

- Development of epitaxy processes for AlGaAs-based 850nm VCSELs
- Native oxide technology for VCSELs
- New materials for new wavelengths and improved performance

NOVALUX

Materials and epitaxy issues are central to VCSEL development

- Development of epitaxy processes for AlGaAs-based 850nm VCSELs
  - epitaxial structure and process design requirements
  - epitaxy process technology
- Native oxide technology for VCSELs
- New materials for new wavelengths and improved performance

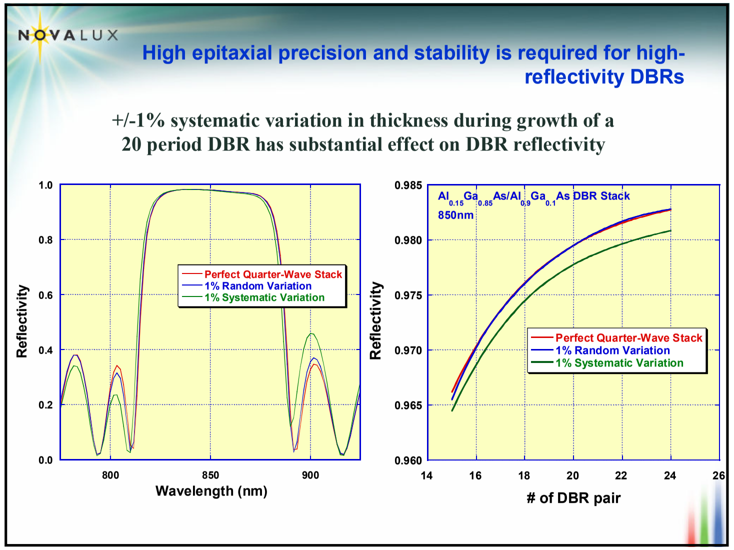


NOVALUX

Design requirements for AlGaAs-based DBRs

@λ=980nm:

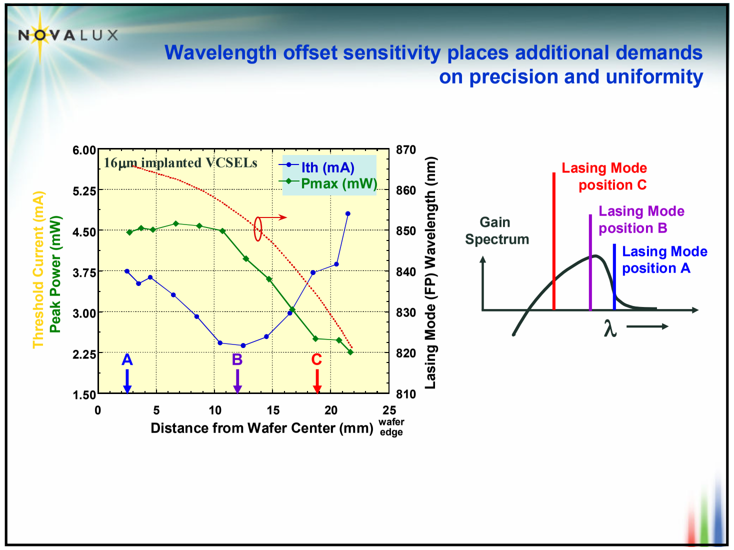
Materials	n	nH/nL	# of DBR pair for R=99%
SiO2	2.2	1.52	6
TiO2	1.45		
AlAs	2.95	1.19	15
GaAs	3.52		



NOVALUX

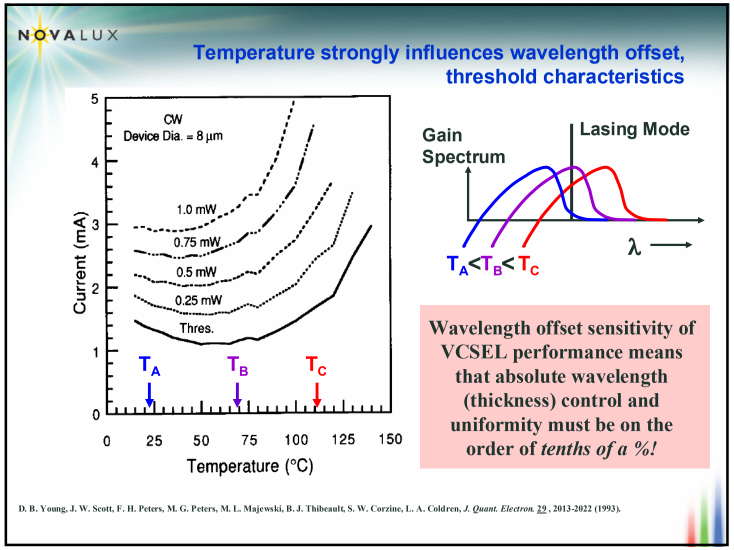
High epitaxial precision and stability is required for high-reflectivity DBRs

+/-1% systematic variation in thickness during growth of a 20 period DBR has substantial effect on DBR reflectivity



NOVALUX

Wavelength offset sensitivity places additional demands on precision and uniformity

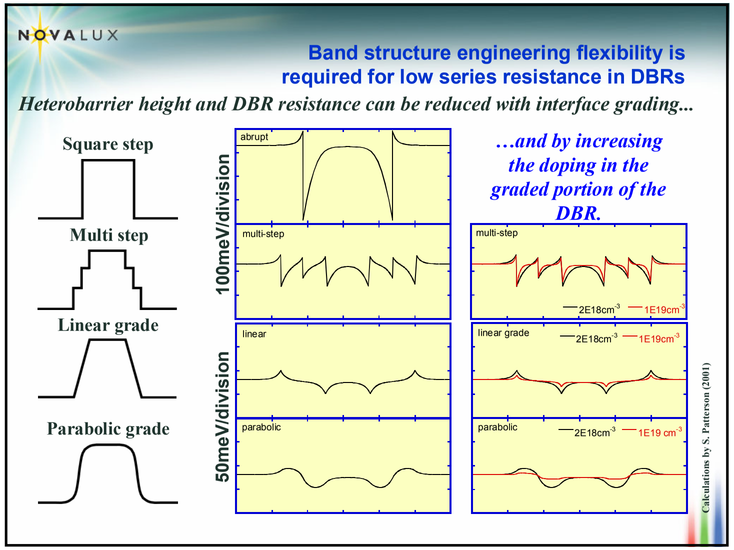


NOVALUX

Temperature strongly influences wavelength offset, threshold characteristics

Wavelength offset sensitivity of VCSEL performance means that absolute wavelength (thickness) control and uniformity must be on the order of *tenths of a %!*

D. B. Young, J. W. Scott, F. H. Peters, M. G. Peters, M. L. Majewski, B. J. Thibeault, S. W. Corzine, L. A. Coldren, *J. Quant. Electron.* 29 , 2013-2022 (1993).

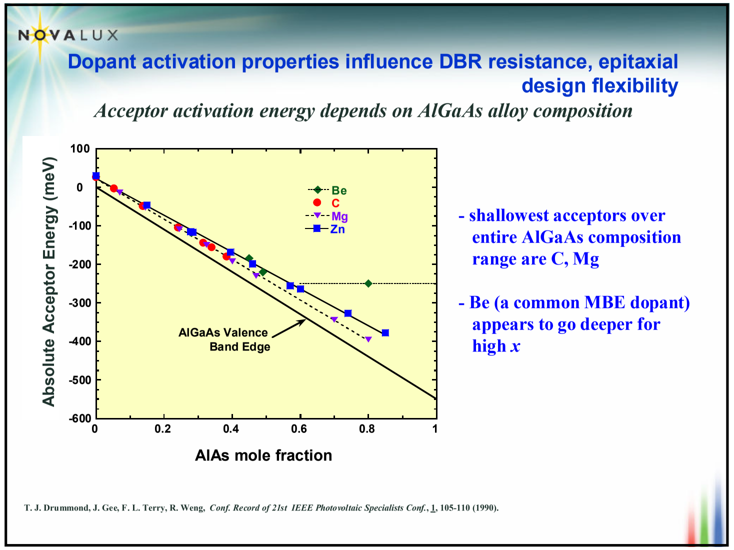

NOVALUX

Band structure engineering flexibility is required for low series resistance in DBRs

Heterobarrier height and DBR resistance can be reduced with interface grading...

...and by increasing the doping in the graded portion of the DBR.

Calculations by S. Patterson (2001)


NOVALUX

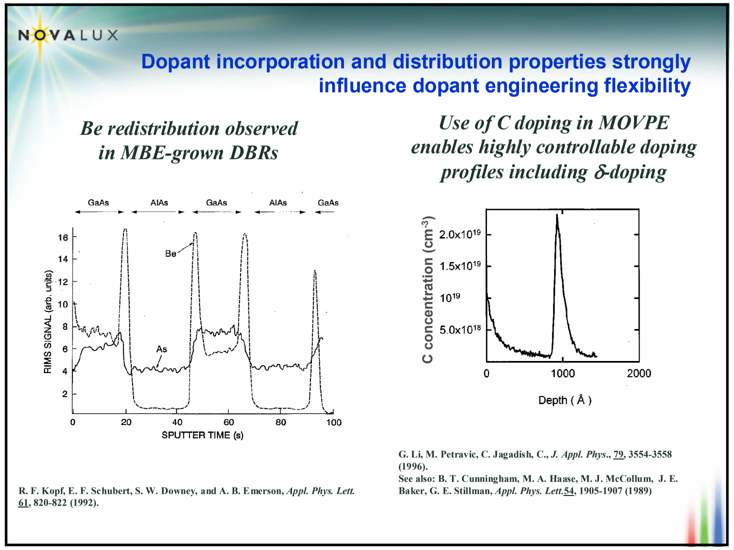
Dopant activation properties influence DBR resistance, epitaxial design flexibility

Acceptor activation energy depends on AlGaAs alloy composition

- shallowest acceptors over entire AlGaAs composition range are C, Mg

- Be (a common MBE dopant) appears to go deeper for high *x*

T. J. Drummond, J. Gee, F. L. Terry, R. Weng, *Conf. Record of 21st IEEE Photovoltaic Specialists Conf.*, 1, 105-110 (1990).


NOVALUX

Dopant incorporation and distribution properties strongly influence dopant engineering flexibility

Be redistribution observed in MBE-grown DBRs

R. F. Kopf, E. F. Schubert, S. W. Downey, and A. B. Emerson, *Appl. Phys. Lett.* 61, 820-822 (1992).

Use of C doping in MOVPE enables highly controllable doping profiles including δ-doping

G. Li, M. Petravic, C. Jagadish, C., *J. Appl. Phys.*, 79, 3554-3558 (1996).
See also: B. T. Cunningham, M. A. Haase, M. J. McCollum, J. E. Baker, G. E. Stillman, *Appl. Phys. Lett.* 54, 1905-1907 (1989)

NOVALUX

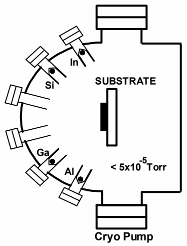
Summary of key epitaxy structure and process design requirements of VCSELs

- **Very stringent epitaxial uniformity and precision requirements:** ***to tenths of a percent!***
  - wavelength targeting depends directly on thickness control
  - cavity (FP) - gain wavelength offset strongly influences device characteristics
- **Epitaxial process must enable a high degree of epitaxial design flexibility**
  - continuous composition grading profiles required for low DBR resistance
  - modulation and delta doping capability required
    - high doping concentrations
    - controllable and stable dopant profiles

NOVALUX

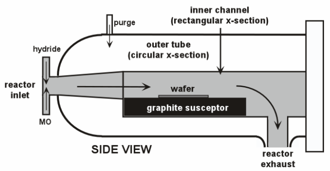
Epitaxial growth techniques for VCSELs

Molecular Beam Epitaxy



Process description:
- Ultra-high vacuum (base P<10^{-9} Torr)
- evaporation from heated effusion cells
- line-of-sight deposition beam
- composition, growth rate controlled by effusion cell temperature
- growth rate <1μm/hr

Metalorganic Vapor Phase Epitaxy



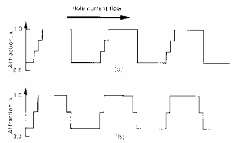
$AsH_3 + (CH_3)_3Ga \xrightarrow{heat} GaAs$ + byproducts

Process description:
- H_2 carrier gas
- low pressure: 0.1-1 atm.
- mass transport limited: composition and growth rate controlled by mass flow
- growth rate 1-4μm/hr

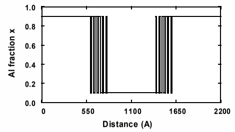
NOVALUX

Early MBE-grown VCSELs suffered from high series resistance associated with DBR heterobarriers

Stair-step and digital grading employed for MBE growth

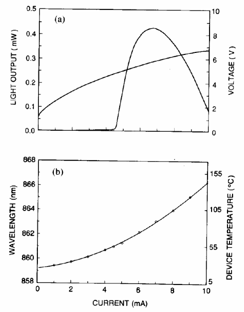


J. L. Jewell, J. P. Harbison, A. Scherer, Y. H. Lee and L. T. Florez, *IEEE J. Quant. Electron.* 27, 1332-1346 (1991).



R. S. Geels, S. W. Corzine, J. W. Scott, D. B. Young and L. R. Coldren, *IEEE Photon. Tech. Lett.*, 2, 234-236 (1990).

Operating voltages >4V; high resistance led to ohmic heating

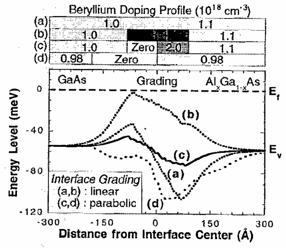


G. Hasnain, K. Tai, L. Yang, Y. H. Wang, R. J. Fischer, J. D. Wynn, B. Weir, N. K. Dutta, A. Y. Cho, *J. Quant. Electron.* 27, 1377 -1385 (1991)

NOVALUX

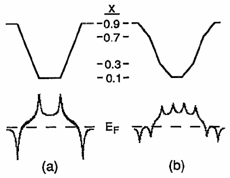
Early successful MBE work on resistance reduction by more sophisticated band structure engineering

Parabolic grading and modulation doping enables wallplug efficiency of 17%



M. G. Peters, B. J. Thibeault, D. B. Young, J. W. Scott, F. H. Peters, A. C. Gossard, and L. A. Coldren, Appl. Phys. Lett. 63, 3411-3413 (1993).

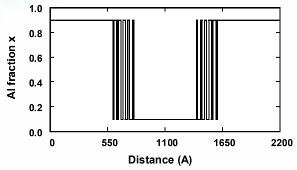
Piecewise approximation of parabolic grading by ramping effusion cell temperatures

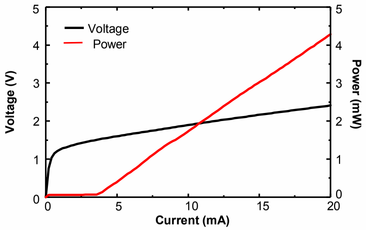


S. A. Chalmers, K. L. Lear, and K. P. Killeen, *Appl. Phys. Lett.* 62, 1585-1587 (1993)

NOVALUX

Digital linear grading combined with C doping in Gas-Source MBE provides low-voltage operation in 980nm VCSELs



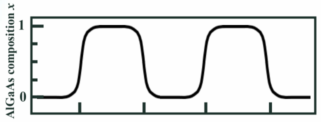


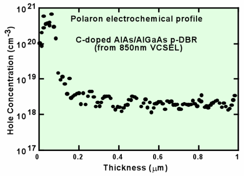
Despite demonstrated success, several difficulties slowed widespread VCSEL development and manufacturing using MBE:
- *adoption of continuous grading*
- *Be doping*
- *low throughput*

Y.M. Houng, M.R.T. Tan, B. W. Liang, S. Y. Wang, L. Yang, D. E. Mars, *Journal of Crystal Growth* 136, 216-220 (1994).

MOVPE readily enabled continuous interface grading, C doping and high throughput

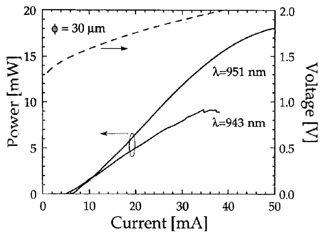
Continuous grading, high and controllable C doping are keys to low resistance p-DBRs by MOVPE





R. P. Schneider, Jr., J. A. Lott, K. L. Lear, K. D. Choquette, M. H. Crawford, S. P. Kilcoyne and J. J. Figiel, *IEEE J. Photon. Technol.* 6 1053-1055 (1994).

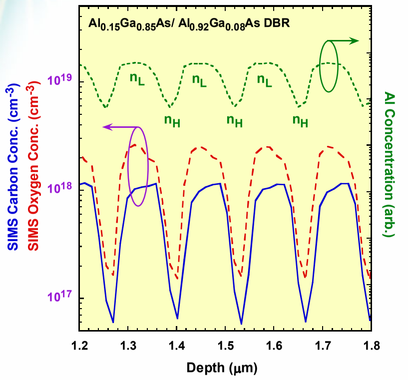
Vertical Cavity Surface Emitting Lasers With 21% Efficiency by Metalorganic Vapor Phase Epitaxy



K. L. Lear, R. P. Schneider, Jr., K. D. Choquette, S. P. Kilcoyne, J. J. Figiel and J. C. Zolper, *IEEE J. Photon. Technol.* 6 1053-1055 (1994).

Once high-performance VCSELs were demonstrated, MOVPE technology developed rapidly...

Intrinsic MOVPE materials properties depend strongly on Al composition



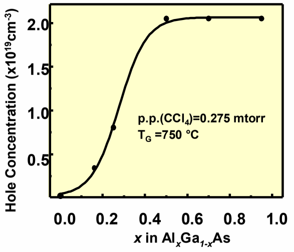
High C and O backgrounds can compromise n-doping in the n-DBR, reliability

Intrinsic C and O can be effectively controlled using higher V/III ratio in growth ambient

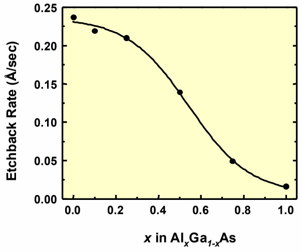
[see T. F. Kuech, D. J. Wolford, E. Veohoff, V. Deline, P. M. Mooney, R. Potemski, J. Bradley, *J. Appl. Phys.* 62, 632-643 (1987)]

Characteristics of C doping in MOVPE

C doping efficiency is extremely sensitive to Al mole fraction



C doping using CCl_4 or CBr_4 is subject to composition-dependent etchback



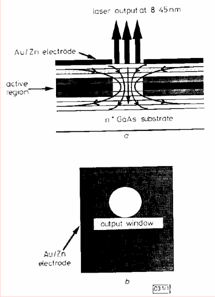
H. Q. Hou, B. E. Hammons, H. C. Chui, *Appl. Phys. Lett.* 70, 3600-3602 (1997).

Materials process issues for VCSEL fabrication

- **Development of epitaxy processes for AlGaAs-based 850nm VCSELs**
- **Materials process issues for VCSEL fabrication**
  - Proton implant technology for VCSELs
  - Native oxide technology for VCSELs
- **New materials for new wavelengths and improved performance**

Proton implantation enabled VCSEL process flexibility, planar geometries

First proton implant-confined VCSEL demonstrated 1990



Y. H. Lee, B. Tell, K. Brown-Goebeler, J. Jewell, J. V. Hove, *Electron. Lett.* 26, 710-711 (1990)

Implant-confined VCSELs continue to be a mainstay for mass-manufactured Gigabit VCSELs

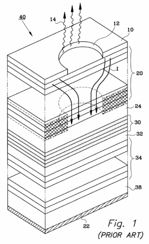
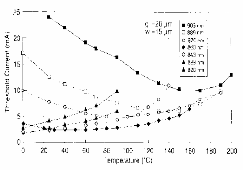


Fig. 1
(PRIOR ART)



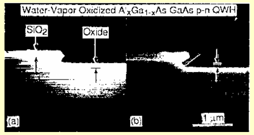
R. A. Morgan, M. K. Hibbs-Brenner, J. A. Lehman, E. L. Kalweit, R. A. Walterson, T. M. Marta, and T. Akinwande, *IEEE Photon. Tech. Lett.* 7, 1157-1159 (1995)

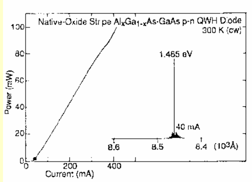
Drawbacks to proton implant technology for VCSELs

- **Index guiding is accomplished by "thermal lens"**
  - lack of design flexibility
  - thermal effects dominate
- **Lack of precision placement**
  - "straggle" limits vertical placement accuracy
  - maximum depth limited by equipment availability
  - aperture size limited to >8μm (process limitations)

Native oxide of AlAs enables unique process capabilities for diode lasers

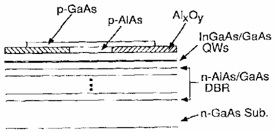
$2AlAs + 6H_2O \Rightarrow Al_2O_3$

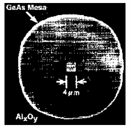


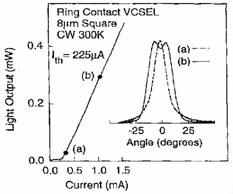


J. M. Dallesasse and N. Holonyak, Jr., *Appl. Phys. Lett.* 58, 394-396 (1991)

First oxide-confined VCSELs employed dielectric mirrors on the top side

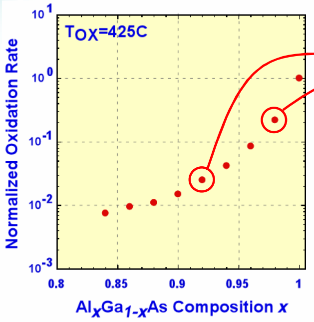


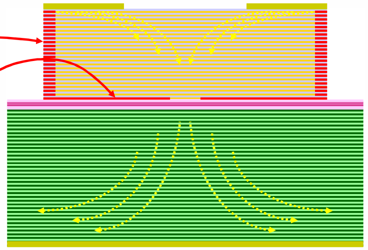


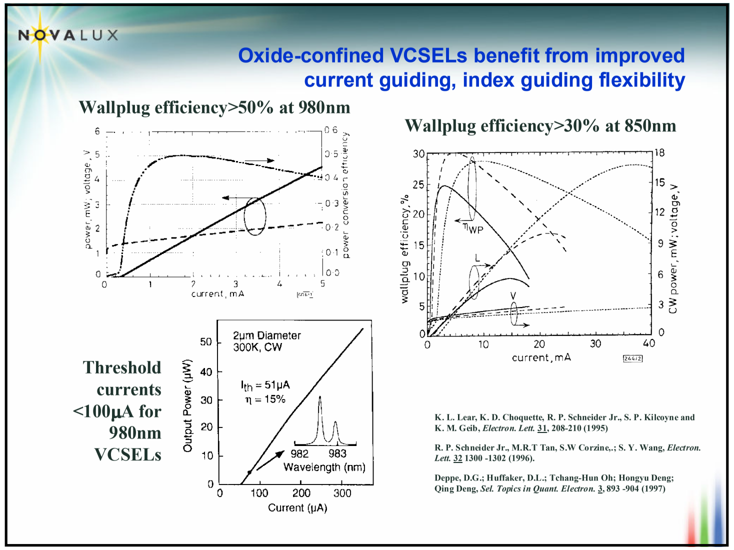


D. L. Huffaker, D. G. Deppe, K. Kumar, T. J. Rogers, *Appl. Phys. Lett.* 65, 97-99 (1994).

$Al_xGa_{1-x}As$ oxidation rate selectivity enables monolithic oxide-confined VCSEL design







Oxide-confined VCSELs benefit from improved current guiding, index guiding flexibility

Wallplug efficiency>50% at 980nm

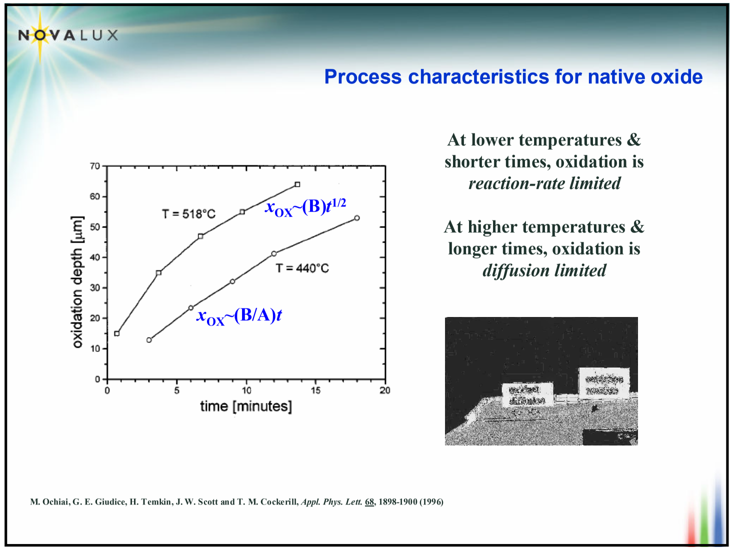
Wallplug efficiency>30% at 850nm

Threshold currents <100µA for 980nm VCSELs

K. L. Lear, K. D. Choquette, R. P. Schneider Jr., S. P. Kilcoyne and K. M. Geib, *Electron. Lett.* 31, 208-210 (1995)

R. P. Schneider Jr., M.R.T Tan, S.W Corzine,.; S. Y. Wang, *Electron. Lett.* 32 1300 -1302 (1996).

Deppe, D.G.; Huffaker, D.L.; Tchang-Hun Oh; Hongyu Deng; Qing Deng, *Sel. Topics in Quant. Electron.* 3, 893 -904 (1997)

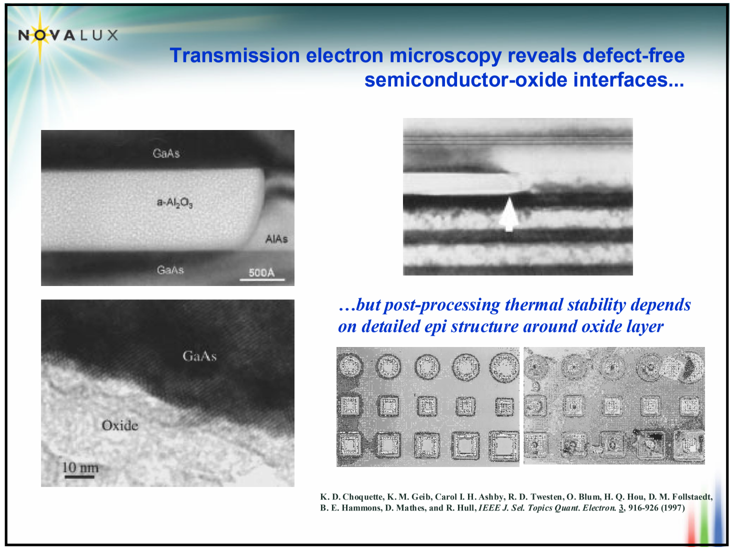


Process characteristics for native oxide

At lower temperatures & shorter times, oxidation is *reaction-rate limited*

At higher temperatures & longer times, oxidation is *diffusion limited*

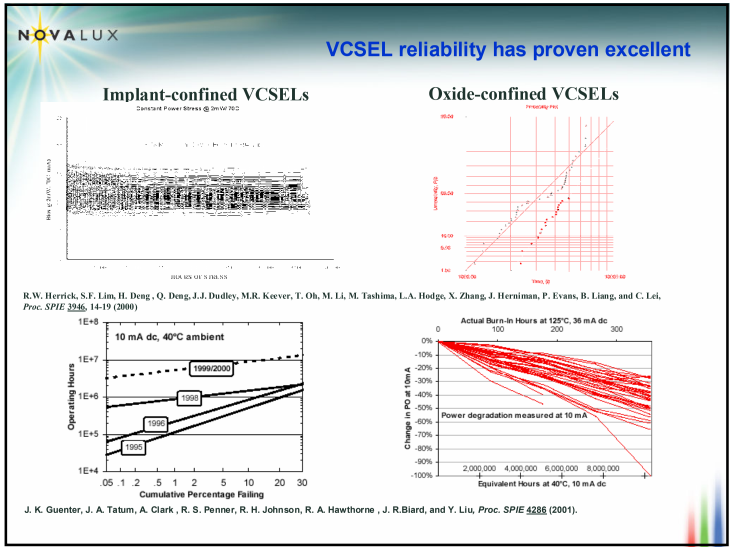
M. Ochiai, G. E. Giudice, H. Temkin, J. W. Scott and T. M. Cockerill, *Appl. Phys. Lett.* 68, 1898-1900 (1996)



Transmission electron microscopy reveals defect-free semiconductor-oxide interfaces...

…but post-processing thermal stability depends on detailed epi structure around oxide layer

K. D. Choquette, K. M. Geib, Carol I. H. Ashby, R. D. Twesten, O. Blum, H. Q. Hou, D. M. Follstaedt, B. E. Hammons, D. Mathes, and R. Hull, *IEEE J. Sel. Topics Quant. Electron.* 3, 916-926 (1997)



VCSEL reliability has proven excellent

Implant-confined VCSELs

Oxide-confined VCSELs

R.W. Herrick, S.F. Lim, H. Deng , Q. Deng, J.J. Dudley, M.R. Keever, T. Oh, M. Li, M. Tashima, L.A. Hodge, X. Zhang, J. Herniman, P. Evans, B. Liang, and C. Lei, *Proc. SPIE* 3946, 14-19 (2000)

J. K. Guenter, J. A. Tatum, A. Clark , R. S. Penner, R. H. Johnson, R. A. Hawthorne , J. R.Biard, and Y. Liu, *Proc. SPIE* 4286 (2001).

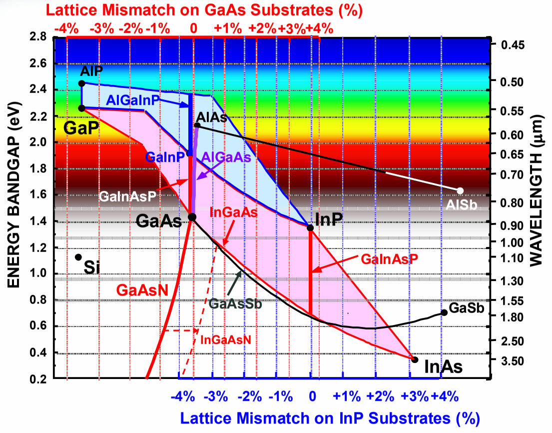
NOVALUX

New materials enable new wavelengths of operation

- Development of AlGaAs-based 850nm VCSELs by metalorganic vapor phase epitaxy (MOVPE)
- Native oxide technology for VCSELs
- New materials for new wavelengths and improved performance
  - short-wavelength VCSELs
    - GaInAsP near-IR
    - AlGaInP red
    - InGaN blue
  - long-wavelength (1.3-1.55μm) VCSELs

NOVALUX

Materials roadmap for III-V alloys

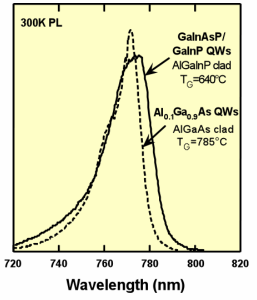


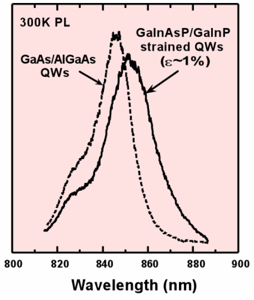
NOVALUX

GaInAsP-based QWs are promising alternatives to GaAs/AlGaAs for near-IR (780-850nm) devices

GaInAsP-based QWs should provide:

- greater engineering flexibility (including strained QWs, strain compensation and built-in etch selectivity)
- larger ΔE_C (=> better performance over T)
- improved reliability (?)

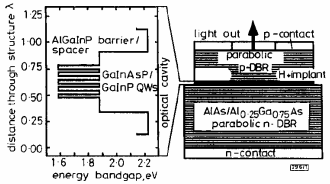


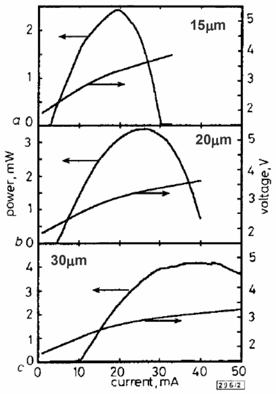


NOVALUX

Initial GaInAsP-based near-IR VCSELs

Epitaxial design includes AlGaInP confining layers for maximum ΔE_C on GaAs substrates

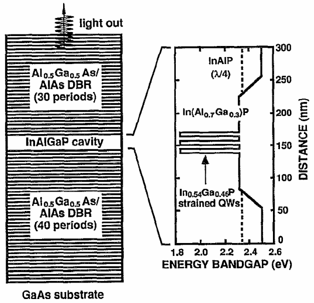




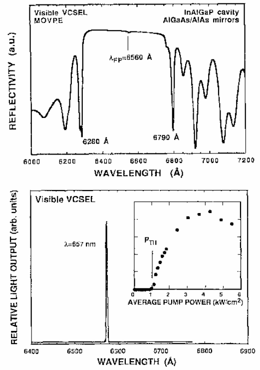
R.P. Schneider, Jr. and M. Hagerott-Crawford, *Electron. Lett.*, 31, 554-556 (1995).

AlGaInP-based Red VCSELs on GaAs substrates

Epitaxial structure includes strained InGaP/InAlGaP QWs and $Al_{0.5}Ga_{0.5}As$/AlAs DBRs



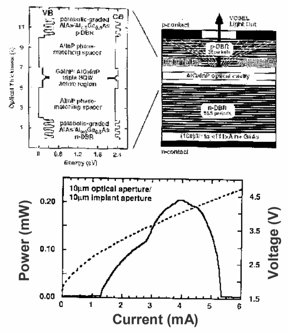
Reflectivity and optically-pumped lasing from initial red VCSELs



R. P. Schneider, Jr. R. P. Bryan, J. A. Lott, G. R. Olbright, *Appl. Phys. Lett.* 60, 1830-1832 (1992).

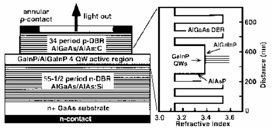
Room-temperature performance of AlGaInP red (660-690nm) VCSELs improved rapidly...

Initial cw implanted devices required relatively thick cavity design due to doping limitations

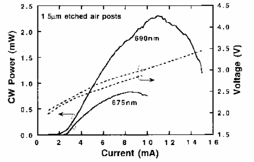


R. P. Schneider, Jr., K. D. Choquette, J. A. Lott, K. L. Lear, J. J. Figiel and K. J. Malloy, *IEEE Photon. Technol. Lett.*, 6, 313-316 (1994).

Refined doping, shorter cavity design...



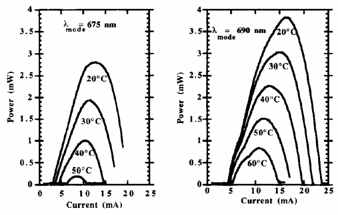
… results in >1mW output powers



R. P. Schneider, Jr., M. H. Crawford, K. D. Choquette, K. L. Lear, S. P. Kilcoyne, J. J. Figiel, *Appl. Phys. Lett.* 67, 329-331 (1995).

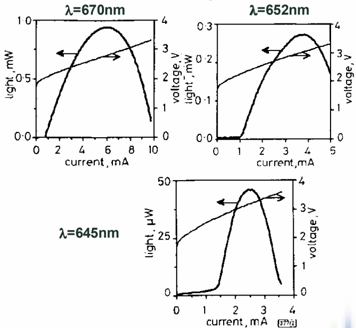
… however higher-temperature or shorter-wavelength performance remains inferior to AlGaAs VCSELs

Output power is extremely sensitive to ambient temperature



M. H. Crawford, R. P. Schneider, Jr., K. D. Choquette, K. L. Lear, *IEEE Photon. Technol. Lett.* 7, 724-726 (1995).

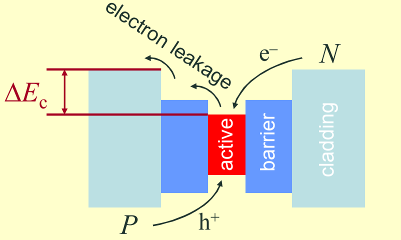
Output power is extremely sensitive to operational wavelength



K. D. Choquette, R. P. Schneider, Jr., M. H. Crawford, K. M. Geib, J. J. Figiel, *Electron. Lett.* 31, 1145-1146 (1995).

Principal limitation to AlGaInP performance is temperature-activated electron leakage

Electron Confinement



$I_{leak} \sim \exp[-\Delta E_c /kT]$

$\Rightarrow$ small ΔE_c:

- higher I_{th}
- worse over T

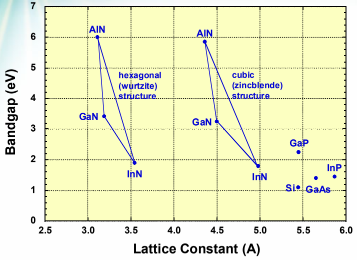
From S. W. Corzine, SPIE Class on GaN Lasers, 1999.

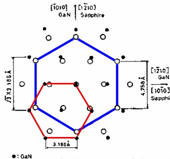
GaInP/AlGaInP heterostructures exhibit (relative to GaAs/AlGaAs):

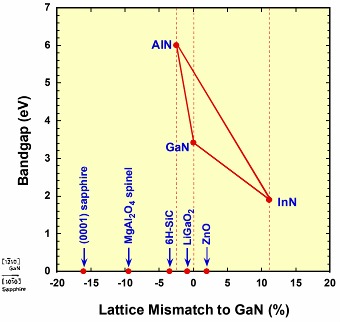
- **smaller ΔE_C (and decreasing ΔE_C with decreasing λ)**
- **higher thermal resistivity**
- **higher resistivity (poor p-dopant activation)**

NOVALUX

Blue-violet emission requires GaN-based materials… but lattice mismatch in this system is huge!





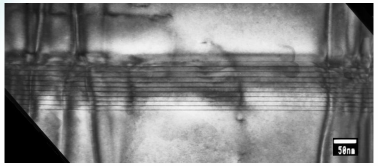


S. Nakamura and G. Fasol, *The Blue Laser Diode* (1997)

NOVALUX

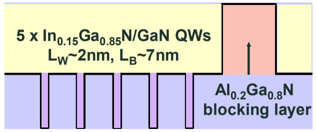
Despite large lattice mismatch and high dislocation densities, high optical efficiency is possible

Typical GaN heterostructures exhibit high dislocation densities (>10^8cm^{-3})…

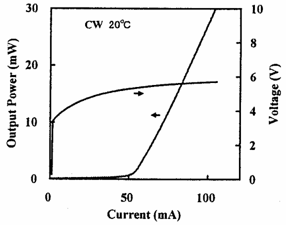


David Basile, Agilent Labs

Typical InGaN/GaN QW active:



…but robust, high-performance lasers have been realized



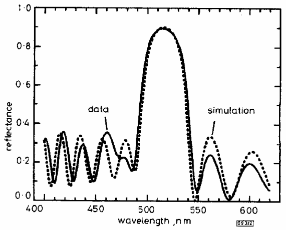
- λ : ~ 410 nm
- I_{th} : ~ 50 mA
- J_{th} : 3-5 kA/cm^2
- V_{th} : ~ 5 V
- P_{out} : > 30 mW

Nakamura, *et al. Jpn. J. Appl. Phys.*, 37, L1020 (1998)

NOVALUX

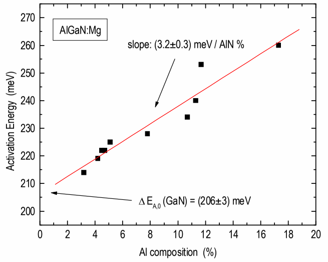
Large lattice mismatch and high resistivity complicates implementation of epitaxial DBRs

Initial report of GaN/AlN DBR required that spectrum be obtained from hexagonal *microdomain*



I. J. Fritz and T. J. Drummond, *Electron. Lett.*, 31, 68-69(1995).

Acceptor activation energy is >200meV for GaN, and increases rapidly with increasing AlN%

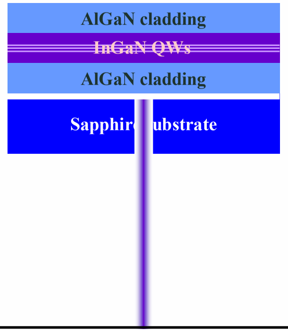


W. Götz, *Spring Meeting of the European Materials Research Society*, Strasbourg, 16-19 June 1998

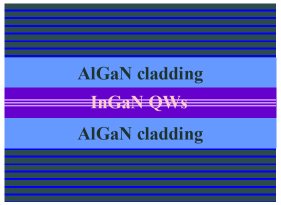
NOVALUX

Epitaxial liftoff combined with dielectric deposition provides best chance for forming laser resonator

High-power laser pulses are used to melt material at epi-sapphire interface and separates substrate from epi

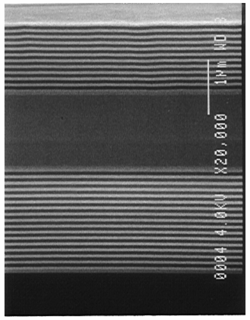


Resonator cavity is formed with dielectric stack on either side of the active

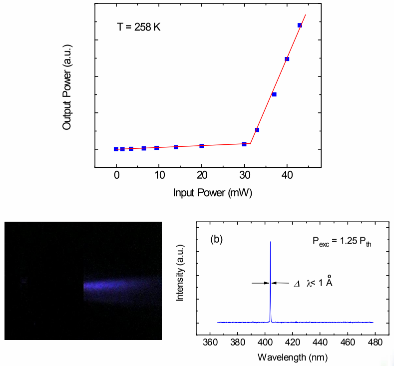


Demonstration of quasi-cw optically-pumped GaN-based violet VCSEL

SEM of completed resonator structure, with InGaN/GaN QW active region and dielectric DBRs



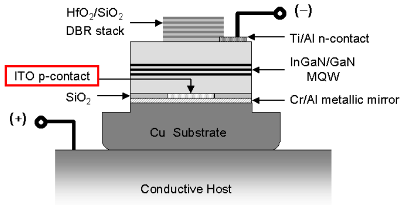
Lasing properties of InGaN-based VCSEL



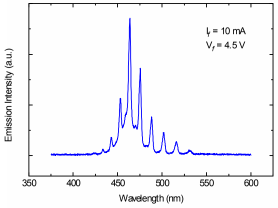
Y. K. Song, H. Zhou, M. Diagne, A. V. Nurmikko, R. P. Schneider, Jr.,, C. P. Kuo, M. R. Krames, R. S. Kern, C. Carter-Coman, F. A. Kish, *Appl. Phys. Lett.* 76 1662-1664 (2000).

Resonant cavity LED demonstrates additional building blocks for electrically-injected GaN VCSEL

ITO transparent contact enables current-spreading in LEDs; could also be used for VCSELs



Resonant-cavity LED exhibits well-defined microcavity mode spectrum



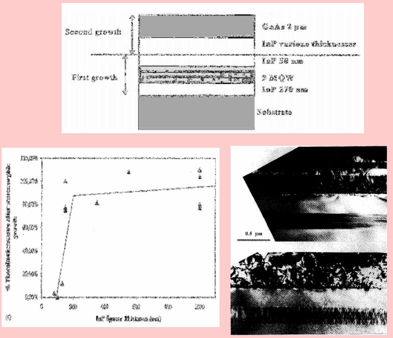
Y. K. Song, M. Diagne, H. Zhou, A. V. Nurmikko, R. P. Schneider, Jr., T. Takeuchi, *Appl. Phys. Lett.* 77 1744-1746 (2000).

The long-wavelength (1.3-1.55µm) VCSEL problem

- ***Fundamental problem related to alloy lattice-matching***
  - best DBR materials are lattice-matched to GaAs
    - InAlGaAs/InP materials system exhibits low Δn
  - best 1.3µm active region materials are lattice-matched to InP
    - InGaAsP/InP-based long-wavelength lasers are mature
  - no readily available oxide confinement technology on InP
    - AlInAs does not exhibit sufficiently high oxidation rate
- ***Many different approaches to long-λ VCSELs***
  - multiple epi or intensive post-growth processing
    - dielectric DBRs
    - wafer bonding (including optically-pumped versions)
  - single epi growth
    - new DBR materials on InP (metamorphic AlGaAs, AlGaAsSb, …)
    - new active materials on GaAs (InGaAsN, GaAsSb, quantum dots…)

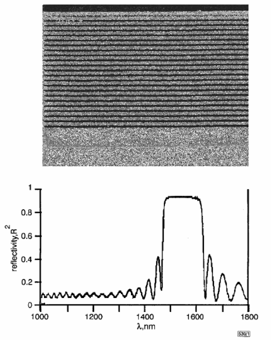
Metamorphic AlGaAs mirrors on InP substrates

Transition/buffer layer is key for eliminating defects in the active layer



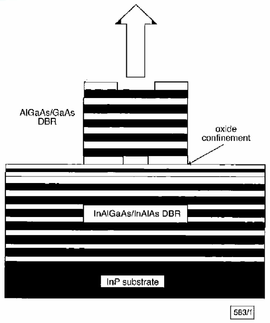
J. Boucart, F. Gaborit, C. Fortin, L. Goldstein, J. Jacquet, K. Leifer, *J. Crystal Growth,* 201-202, 1015-1019 (1999).

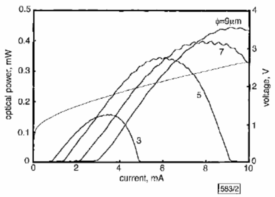
SEM, reflectivity spectra indicate high optical quality

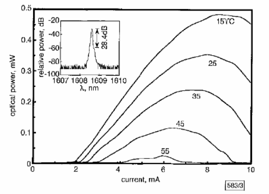


L. Goldstein, C. Fortin, C. Starck, A. Plais, J. Jacquet, J. Boucart, A. Rocher, C. Poussou, *Electron. Lett.*, 34, 268-270 (1998)

Continuous-wave 1.55µm VCSELs with metamorphic AlGaAs/GaAs DBR mirrors



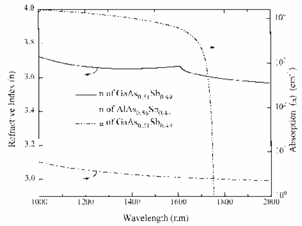




W. Yuen, G. S. Li, R. F. Nabiev, J. Boucart, P. Kner, R. J. Stone, D. Zhang, M. Beaudoin, T. Zheng, C. He, K. Yu, M. Jansen, D. P. Worland, C. J. Chang-Hasnain, *Electron. Lett.* 36, 1121 -1123 (2000)

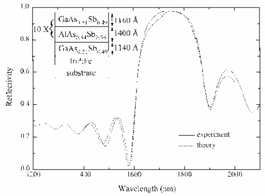
AlGaAsSb alloys offer largest index contrast for DBRs lattice-matched to InP substrates

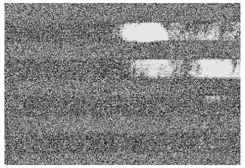
- GaAsSb/AlAsSb offers Δn~0.5 at λ~1550nm
- Sb alloy growth is best accomplished using MBE; MOVPE not yet developed
- interface grading and doping are more difficult in the AlGaAsSb quaternary materials system



O. Blum, I. J. Fritz, L. R. Dawson, A. J. Howard, T. J. Headley, J. F. Klem, T. J. Drummond, *Appl. Phys. Lett.* 66, 329-331 (1995)

Reflectivity and TEM reveal very high structural quality

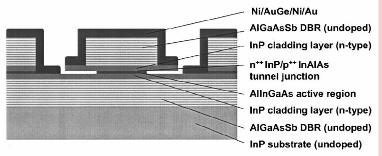




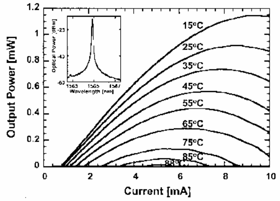
Demonstration of high-temperature, cw lasing from 1.55µm VCSELs with AlGaAsSb DBRs

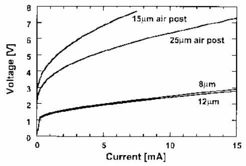
Very complex epitaxial and device structure grown by MBE:

- intracavity contacts and tunnel junctions are used to circumvent current injection in the DBRs
- InP cladding layers to improve thermal characteristics
- air-gap used for current constriction



S. Nakagawa, E. Hall, G. Almuneau, J. K. Kim, D. A. Buell, H. Kroemer, L. A. Coldren, *Appl. Phys. Lett.* 78, 1337-1339 (2001)

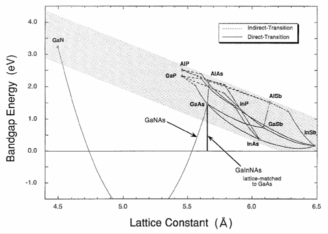




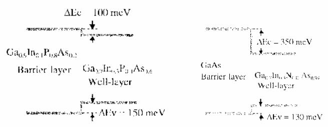
InGaAsN alloy system for long-wavelength (1.3µm) emission on GaAs substrates

Large bowing in GaNAs system raises possibility of long-λ emission

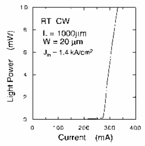
- N (tensile strain) compensates In (compressive) in InGaAsN QWs
- large lattice difference raises possibility of phase separation in alloys (growth difficulties)

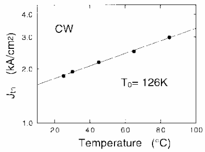


Predicted larger ΔE_C for InGaAsN/GaAs QWs

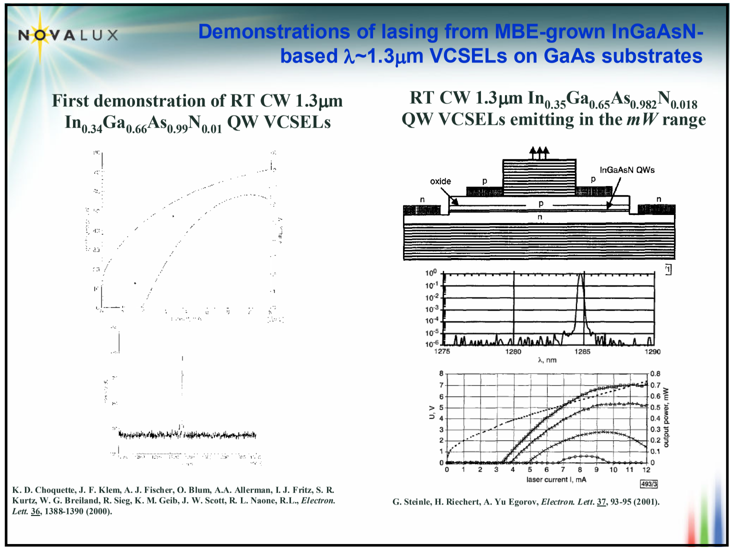


Early lasers exhibit high T_0, indicating improved electron confinement





M. Kondow, T. Kitatani, S. Nakatsuka, M.C. Larson, K. Nakahara, Y. Yazawa, M. Okai, K. Uomi, *IEEE J. Sel. Topics Quant. Electron.* 3, 719-730 (1997).



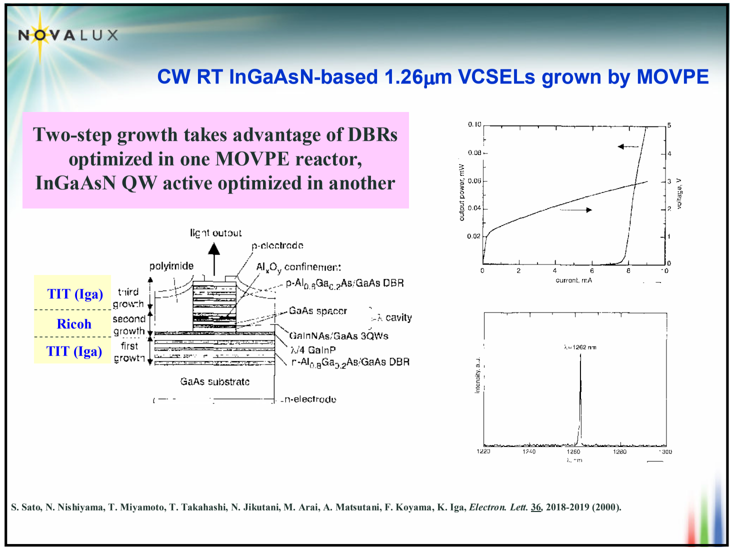
Demonstrations of lasing from MBE-grown InGaAsN-based λ~1.3μm VCSELs on GaAs substrates

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

RT CW 1.3μm $In_{0.35}Ga_{0.65}As_{0.982}N_{0.018}$ QW VCSELs emitting in the *mW* range

K. D. Choquette, J. F. Klem, A. J. Fischer, O. Blum, A.A. Allerman, I. J. Fritz, S. R. Kurtz, W. G. Breiland, R. Sieg, K. M. Geib, J. W. Scott, R. L. Naone, R.L., *Electron. Lett.* 36, 1388-1390 (2000).

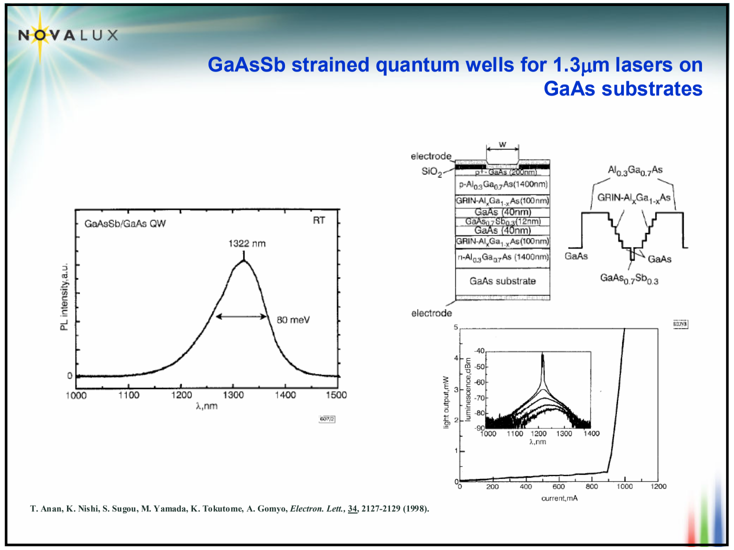
G. Steinle, H. Riechert, A. Yu Egorov, *Electron. Lett.* 37, 93-95 (2001).



CW RT InGaAsN-based 1.26μm VCSELs grown by MOVPE

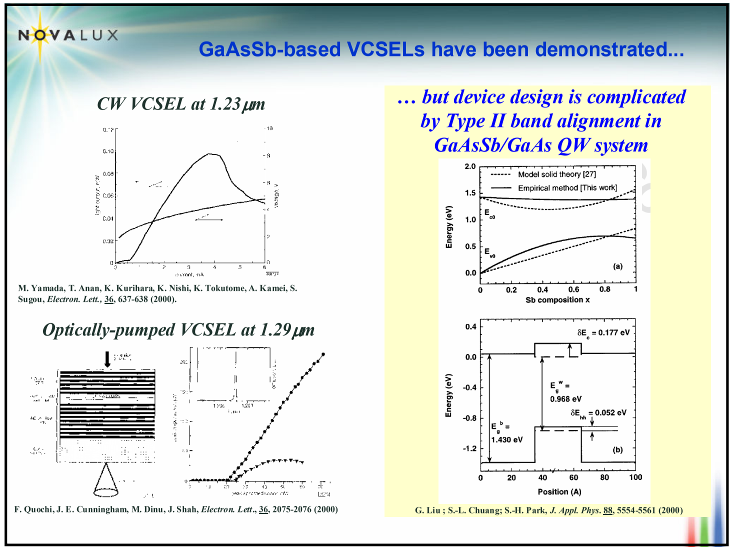
Two-step growth takes advantage of DBRs optimized in one MOVPE reactor, InGaAsN QW active optimized in another

S. Sato, N. Nishiyama, T. Miyamoto, T. Takahashi, N. Jikutani, M. Arai, A. Matsutani, F. Koyama, K. Iga, *Electron. Lett.* 36, 2018-2019 (2000).



GaAsSb strained quantum wells for 1.3μm lasers on GaAs substrates

T. Anan, K. Nishi, S. Sugou, M. Yamada, K. Tokutome, A. Gomyo, *Electron. Lett.*, 34, 2127-2129 (1998).



GaAsSb-based VCSELs have been demonstrated...

CW VCSEL at 1.23μm

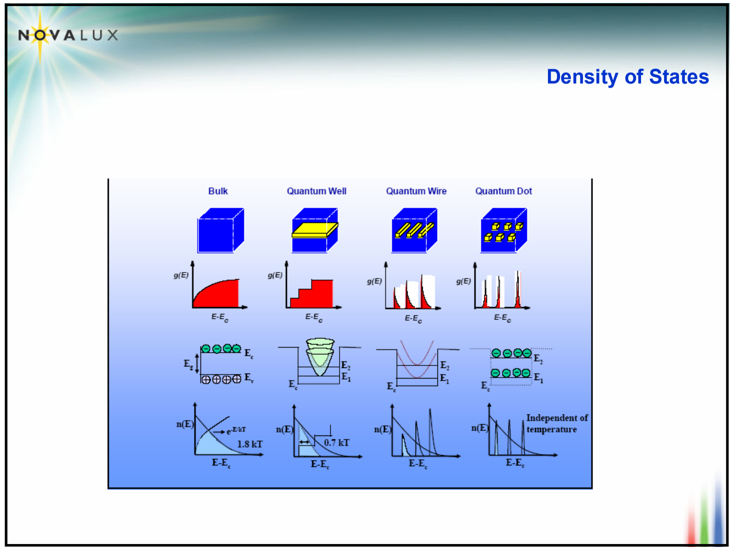
M. Yamada, T. Anan, K. Kurihara, K. Nishi, K. Tokutome, A. Kamei, S. Sugou, *Electron. Lett.*, 36, 637-638 (2000).

Optically-pumped VCSEL at 1.29μm

F. Quochi, J. E. Cunningham, M. Dinu, J. Shah, *Electron. Lett.*, 36, 2075-2076 (2000)

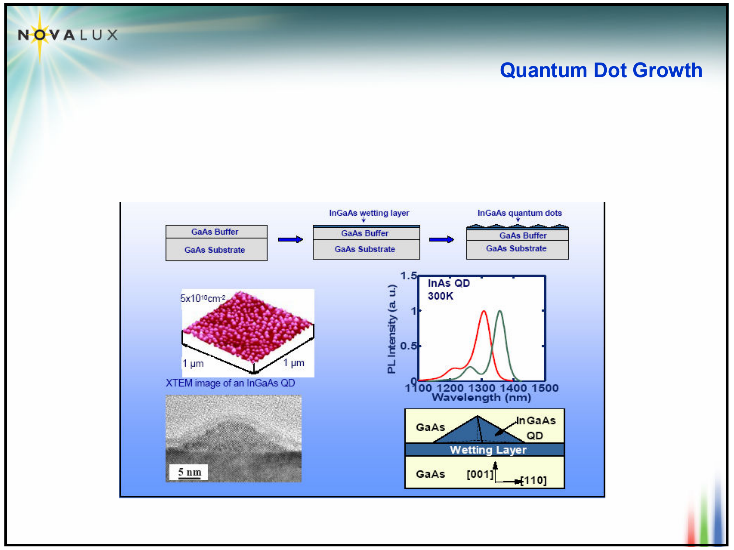
… but device design is complicated by Type II band alignment in GaAsSb/GaAs QW system

G. Liu ; S.-L. Chuang; S.-H. Park, *J. Appl. Phys.* 88, 5554-5561 (2000)



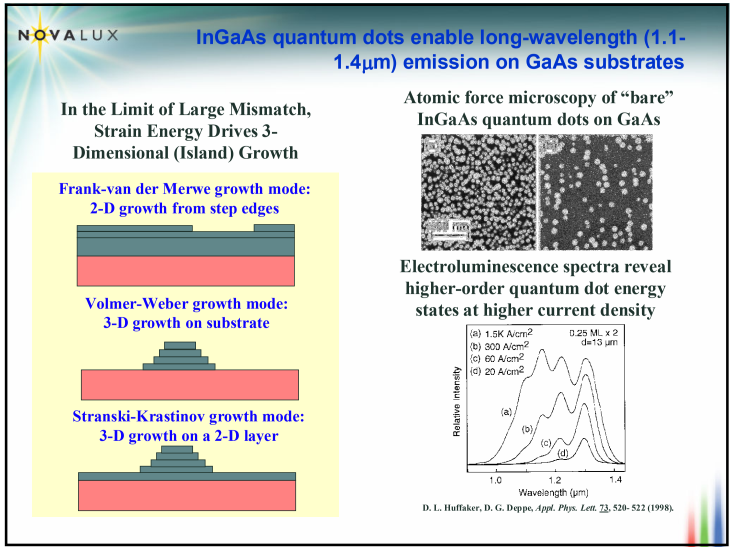
NOVALUX

Density of States



NOVALUX

Quantum Dot Growth



NOVALUX

InGaAs quantum dots enable long-wavelength (1.1-1.4μm) emission on GaAs substrates

In the Limit of Large Mismatch, Strain Energy Drives 3-Dimensional (Island) Growth

Frank-van der Merwe growth mode:
2-D growth from step edges

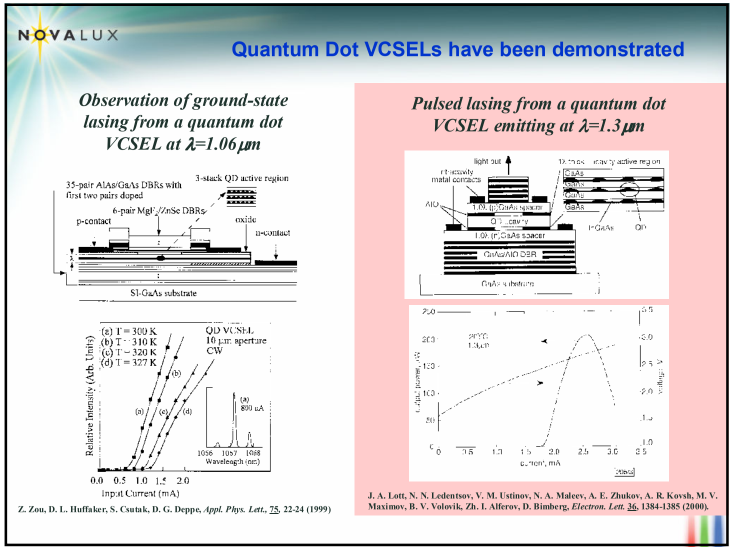
Volmer-Weber growth mode:
3-D growth on substrate

Stranski-Krastinov growth mode:
3-D growth on a 2-D layer

Atomic force microscopy of "bare" InGaAs quantum dots on GaAs

Electroluminescence spectra reveal higher-order quantum dot energy states at higher current density

D. L. Huffaker, D. G. Deppe, *Appl. Phys. Lett.* 73, 520- 522 (1998).



NOVALUX

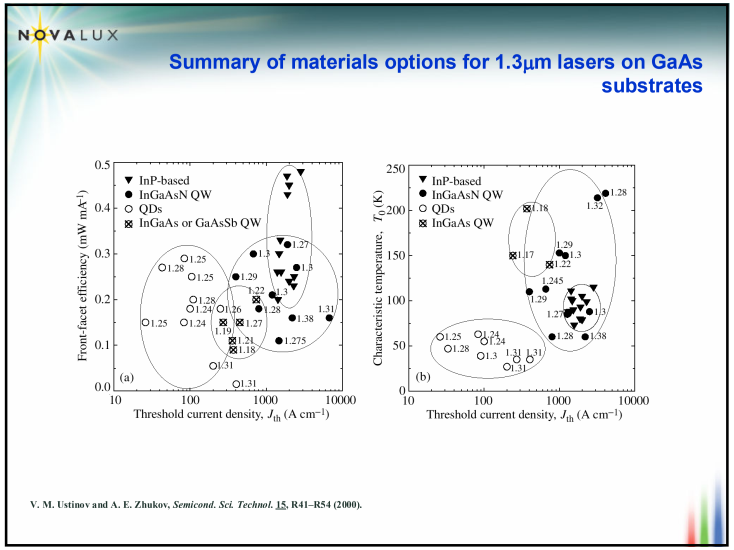
Quantum Dot VCSELs have been demonstrated

Observation of ground-state lasing from a quantum dot VCSEL at λ=1.06μm

Z. Zou, D. L. Huffaker, S. Csutak, D. G. Deppe, *Appl. Phys. Lett.*, 75, 22-24 (1999)

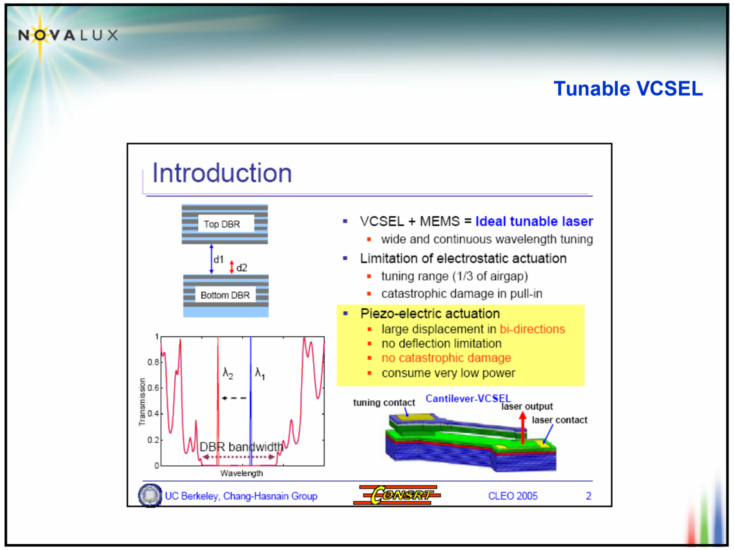
Pulsed lasing from a quantum dot VCSEL emitting at λ=1.3μm

J. A. Lott, N. N. Ledentsov, V. M. Ustinov, N. A. Maleev, A. E. Zhukov, A. R. Kovsh, M. V. Maximov, B. V. Volovik, Zh. I. Alferov, D. Bimberg, *Electron. Lett.* 36, 1384-1385 (2000).



Summary of materials options for 1.3µm lasers on GaAs substrates

V. M. Ustinov and A. E. Zhukov, *Semicond. Sci. Technol.* 15, R41–R54 (2000).

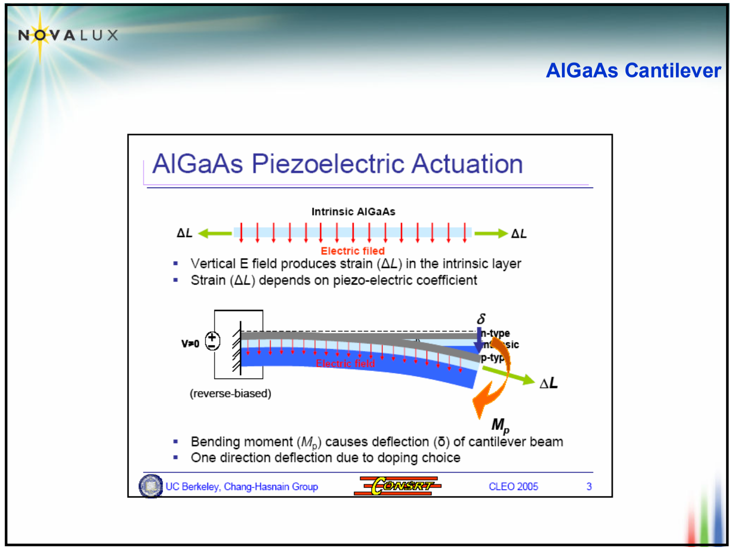


Tunable VCSEL

Introduction

- VCSEL + MEMS = **Ideal tunable laser**
  - wide and continuous wavelength tuning
- Limitation of electrostatic actuation
  - tuning range (1/3 of airgap)
  - catastrophic damage in pull-in
- Piezo-electric actuation
  - large displacement in bi-directions
  - no deflection limitation
  - no catastrophic damage
  - consume very low power

UC Berkeley, Chang-Hasnain Group CLEO 2005 2



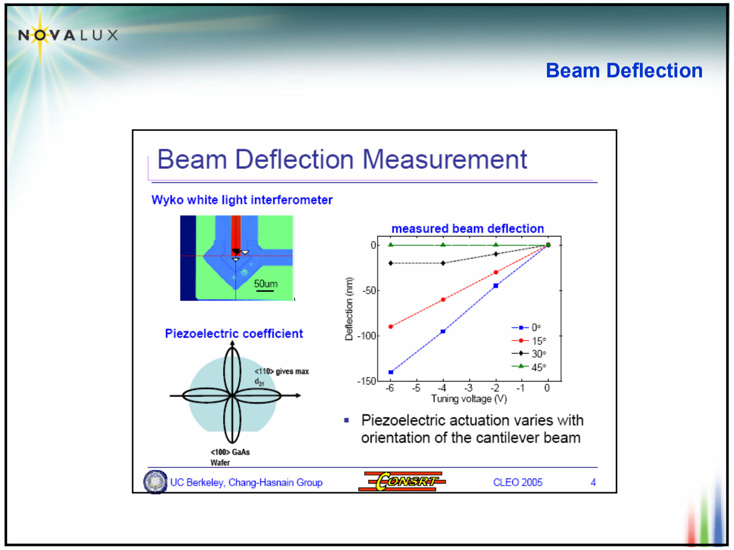
AlGaAs Cantilever

AlGaAs Piezoelectric Actuation

- Vertical E field produces strain (Δ*L*) in the intrinsic layer
- Strain (Δ*L*) depends on piezo-electric coefficient

- Bending moment (M_p) causes deflection (δ) of cantilever beam
- One direction deflection due to doping choice

UC Berkeley, Chang-Hasnain Group CLEO 2005 3



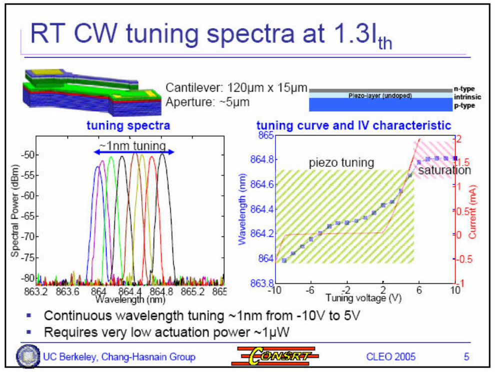
Beam Deflection

Beam Deflection Measurement

- Piezoelectric actuation varies with orientation of the cantilever beam

UC Berkeley, Chang-Hasnain Group CLEO 2005 4

Tunable VCSEL Spectra


RT CW tuning spectra at $1.3I_{th}$

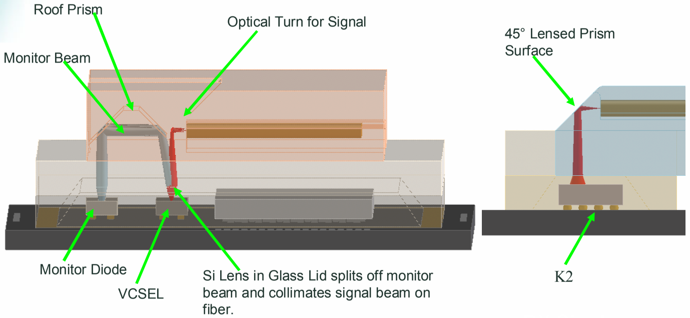
Cantilever: 120µm x 15µm
Aperture: ~5µm

- Continuous wavelength tuning ~1nm from -10V to 5V
- Requires very low actuation power ~1µW

UC Berkeley, Chang-Hasnain Group CLEO 2005 5

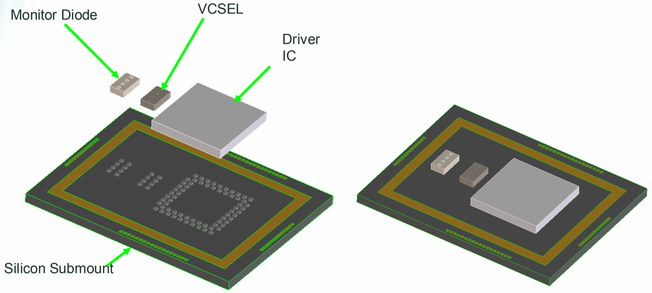
Hi-Speed Applications
Fiber-optics

Optical Turn with V-Groove

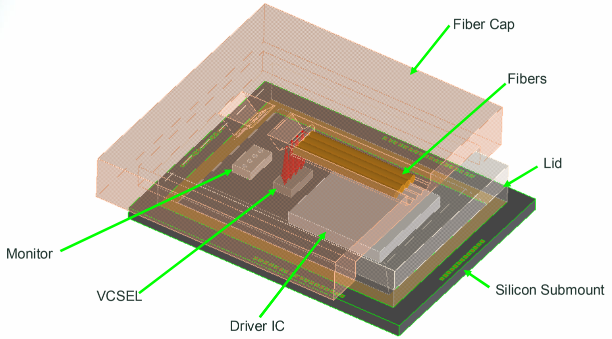


Si Lens in Glass Lid splits off monitor beam and collimates signal beam on fiber.

OSA Platform
VCSEL, Monitor, Driver IC Flipped to Si Submount



Optical Subassembly



Epi Design for 990nm VCSELS

		990nm	850nm
Mirror composition	nH:	GaAs	~20% AlGaAs
	nL:	~90%AlGaAs	~90% AlGaAs

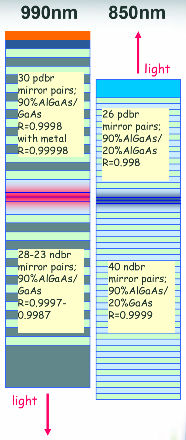
-higher contrast improves confinement, threshold, speed
-possible implications for resistance

		990nm	850nm
Reflectivity:		higher R for output side metal reflectivity contribution	

-higher reflectivity will lower threshold current density
(at expense of optical power)

		990nm	850nm
Active Region Design	QW:	InGaAs	GaAs
	barriers:	10%AlGaAs	26%AlGaAs
	other:	strain-compensation	

-InGaAs has better material gain (lower threshold densities); 990 wavelength
-strain-compensation to balance compressively strained InGaAs



Relaxation Frequency

$$\boxed{f_r^2 = \frac{v_g a}{V_m} \cdot \frac{\eta_i}{q}\left(I - I_{th}\right)} \quad = \left[\frac{v_g}{qL_{cav}}\right] \cdot \eta_i \cdot a \cdot \left(J - J_{th}\right)$$

Maximize differential gain, a (= dg/dN)

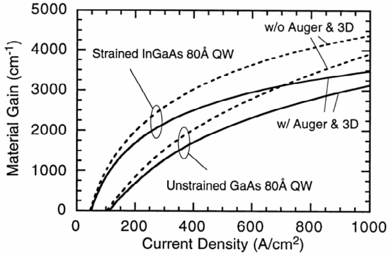
Increase $J - J_{th}$

Failure rate ~ J^3

Reduce Mode Volume

reduce L_{cav}

Why strained InGaAs



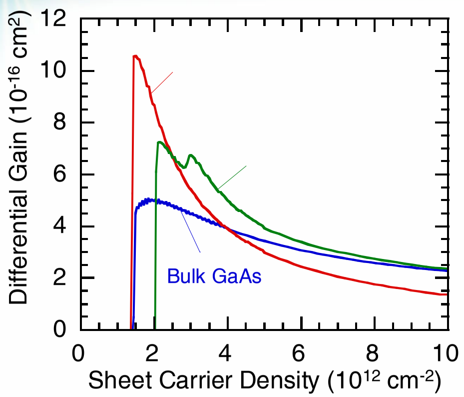
Higher gain

Lower N_{tr} over GaAs

Higher dg/dn

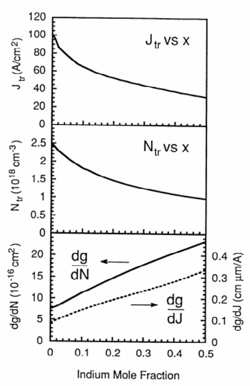
N close to N_{tr}

Enhancing the Differential Gain



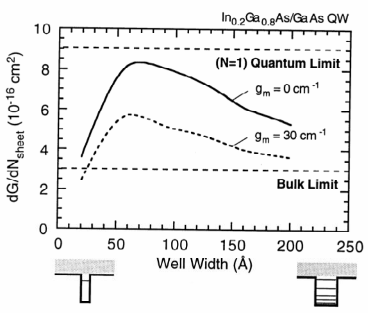
- **Reduce N_{th}**
  - No. of QWs
  - reduce loss
- **Strained QWs**

Quantum Well Composition



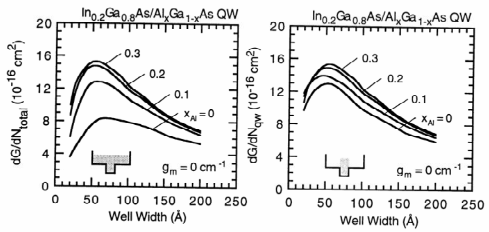
- **N_{tr} decreases with xIn**
- **J_{tr} decreases with xIn**
- **dg/dn increases with xIn**
- **Strain considerations**
  - critical thickness
  - ‹ 200 Å % per well

Quantum Well Width



- **Maximize dg/dn**
  - single level in QW
  - 50 - 65 Å well width depending on barrier

Effect of Barriers

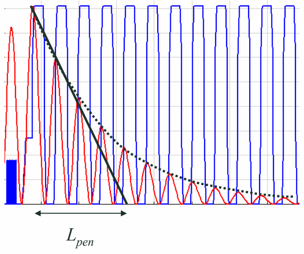


- **Use AlGaAs barriers to maximize dg/dn**
  - Reduce carriers in barrier region
  - dg/dn increase ~2x w/ $Al_{0.2}Ga_{0.8}As$ barriers

NOVALUX

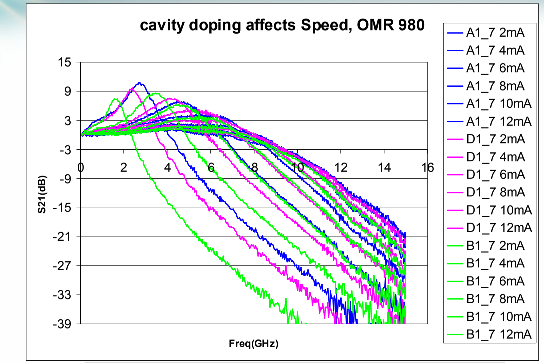
Reducing Mode Volume

- **Reduce field penetration depth**
  - Increase mirror contrast
  - AlAs/GaAs
    - Improved thermal design



NOVALUX

Cavity Doping

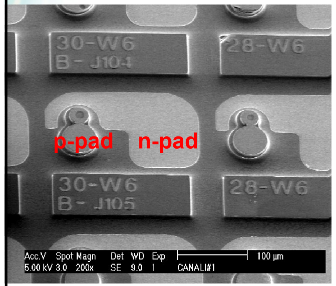


wafer	EPI	doping_A	doping_B	doping_C	doping_D(s
A	714A	17	17	40	40
B	711A	0	0	40	40
D	711C	0	0	17	40
C	710A	0	0	0	40

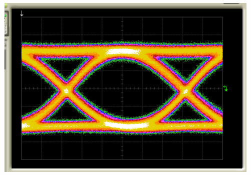
Rong Zhou, Sep. 25 03

NOVALUX

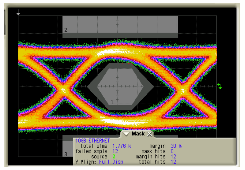
Orion Process



Pseudo-mesa devices (implant-isolated bondpad) for high-speed performance evaluation



8μm; 5 mA; 9.9 kA/cm^2; 25^{o}C; ER=~6.1 dB

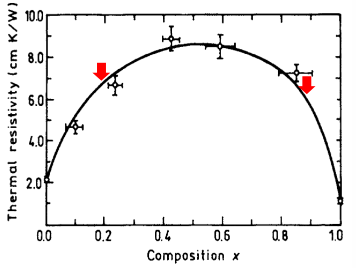


8μm; 5 mA; 9.9 kA/cm^2; 65^{o}C; ER=~7.3 dB

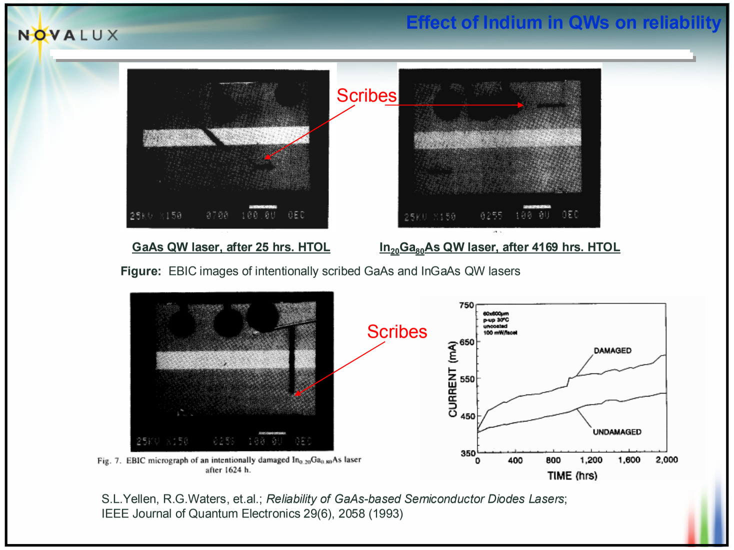
Eye mask has 30% margin included

NOVALUX

Thermal Resistance Dependence on Al Composition in AlGaAs



Thermal resistivity vs. aluminum composition x for $Al_xGa_{1-x}As$. Red arrows on the graph show typical compositions used in conventional 850nm VCSEL DBRs. Moving left arrow to GaAs provides ~3x improvement.



Effect of Indium in QWs on reliability

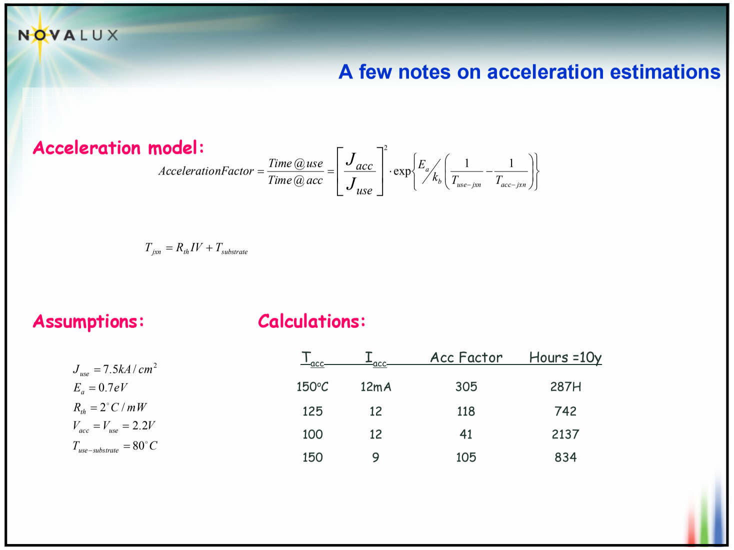
GaAs QW laser, after 25 hrs. HTOL

$In_{20}Ga_{80}As$ QW laser, after 4169 hrs. HTOL

Figure: EBIC images of intentionally scribed GaAs and InGaAs QW lasers

Fig. 7. EBIC micrograph of an intentionally damaged $In_{0.20}Ga_{0.80}As$ laser after 1624 h.

S.L.Yellen, R.G.Waters, et.al.; *Reliability of GaAs-based Semiconductor Diodes Lasers*; IEEE Journal of Quantum Electronics 29(6), 2058 (1993)



A few notes on acceleration estimations

Acceleration model:

$$AccelerationFactor = \frac{Time@use}{Time@acc} = \left[\frac{J_{acc}}{J_{use}}\right]^2 \cdot \exp\left\{ {E_a}/{k_b} \left(\frac{1}{T_{use-jxn}} - \frac{1}{T_{acc-jxn}} \right) \right\}$$

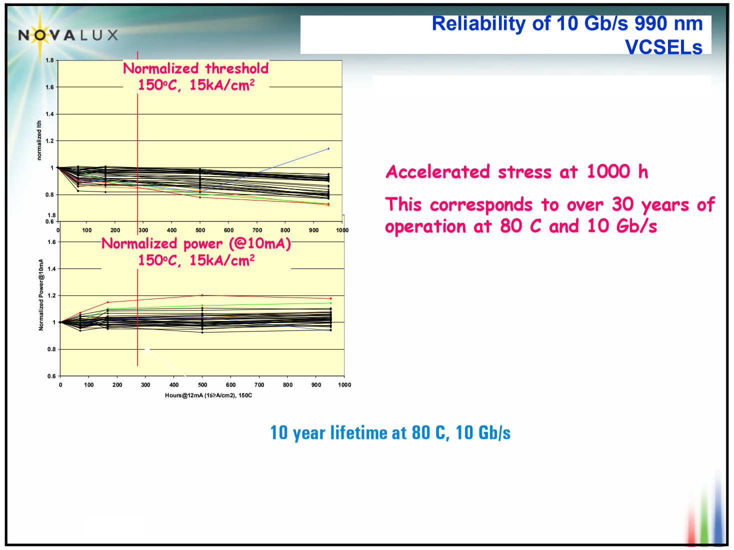
$$T_{jxn} = R_{th} IV + T_{substrate}$$

Assumptions:

$J_{use} = 7.5kA/cm^2$
$E_a = 0.7eV$
$R_{th} = 2^\circ C/mW$
$V_{acc} = V_{use} = 2.2V$
$T_{use-substrate} = 80^\circ C$

Calculations:

T_{acc}	I_{acc}	Acc Factor	Hours =10y
150°C	12mA	305	287H
125	12	118	742
100	12	41	2137
150	9	105	834

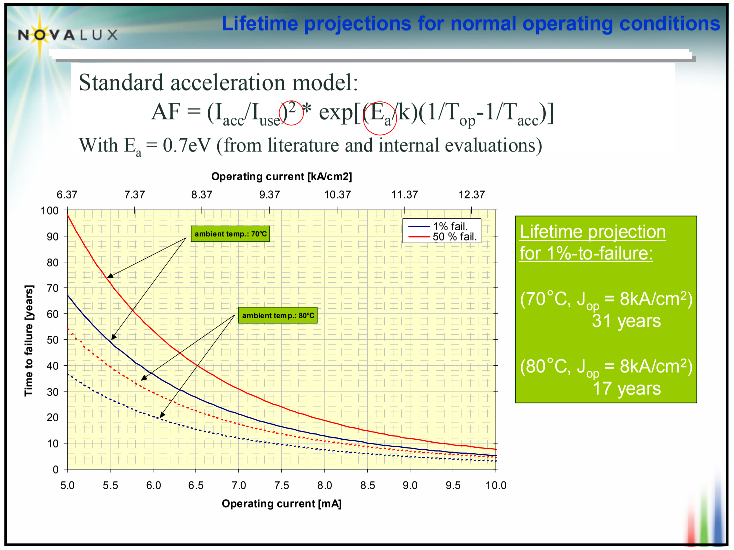


Reliability of 10 Gb/s 990 nm VCSELs

Accelerated stress at 1000 h

This corresponds to over 30 years of operation at 80 C and 10 Gb/s

10 year lifetime at 80 C, 10 Gb/s



Lifetime projections for normal operating conditions

Standard acceleration model:

$$AF = (I_{acc}/I_{use})^2 * \exp[(E_a/k)(1/T_{op} - 1/T_{acc})]$$

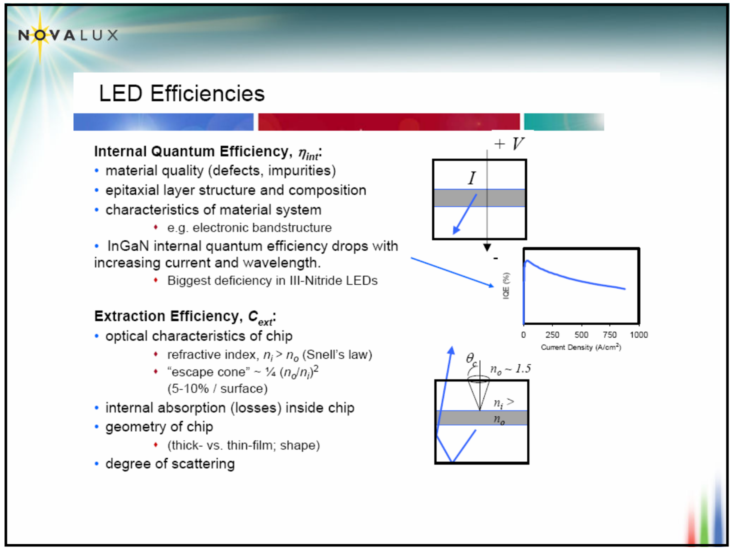
With E_a = 0.7eV (from literature and internal evaluations)

Lifetime projection for 1%-to-failure:

(70°C, J_{op} = 8kA/cm²) 31 years

(80°C, J_{op} = 8kA/cm²) 17 years

Sold State Lighting Applications



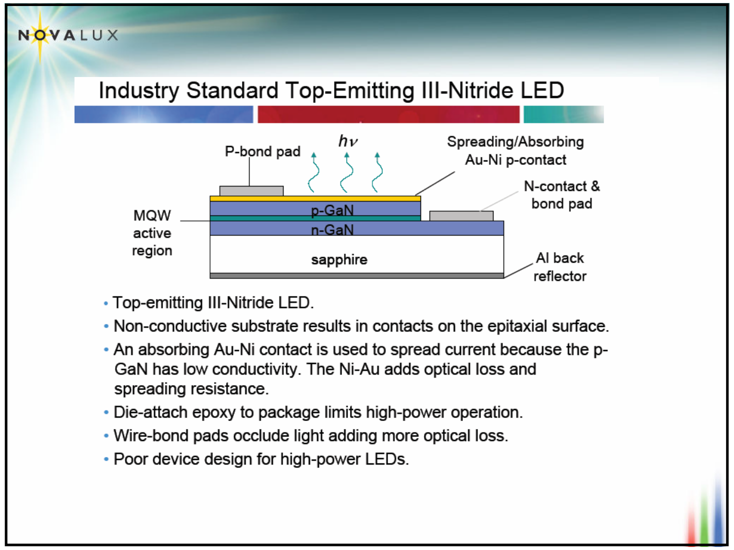
LED Efficiencies

Internal Quantum Efficiency, η_{int}:

- material quality (defects, impurities)
- epitaxial layer structure and composition
- characteristics of material system
  - e.g. electronic bandstructure
- InGaN internal quantum efficiency drops with increasing current and wavelength.
  - Biggest deficiency in III-Nitride LEDs

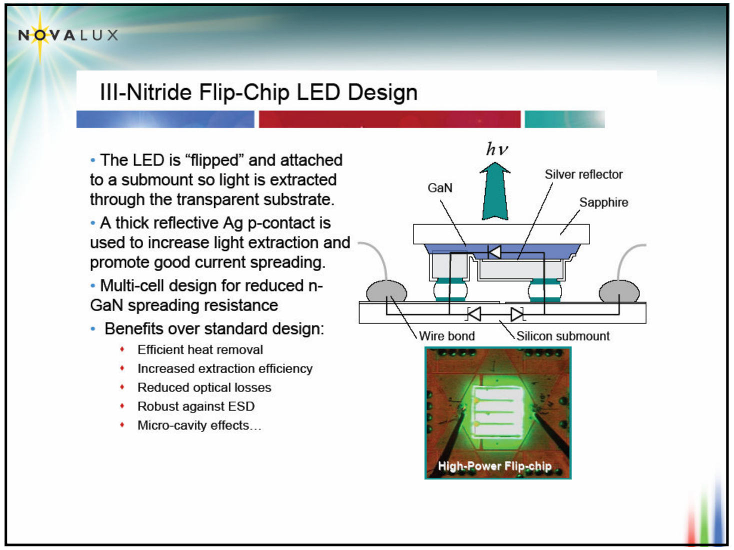
Extraction Efficiency, C_{ext}:

- optical characteristics of chip
  - refractive index, $n_i > n_o$ (Snell's law)
  - "escape cone" ~ ¼ $(n_o/n_i)^2$ (5-10% / surface)
- internal absorption (losses) inside chip
- geometry of chip
  - (thick- vs. thin-film; shape)
- degree of scattering



Industry Standard Top-Emitting III-Nitride LED

- Top-emitting III-Nitride LED.
- Non-conductive substrate results in contacts on the epitaxial surface.
- An absorbing Au-Ni contact is used to spread current because the p-GaN has low conductivity. The Ni-Au adds optical loss and spreading resistance.
- Die-attach epoxy to package limits high-power operation.
- Wire-bond pads occlude light adding more optical loss.
- Poor device design for high-power LEDs.



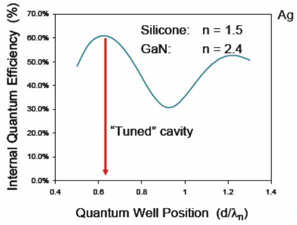
III-Nitride Flip-Chip LED Design

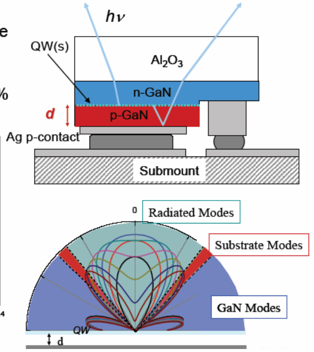
- The LED is "flipped" and attached to a submount so light is extracted through the transparent substrate.
- A thick reflective Ag p-contact is used to increase light extraction and promote good current spreading.
- Multi-cell design for reduced n-GaN spreading resistance
- Benefits over standard design:
  - Efficient heat removal
  - Increased extraction efficiency
  - Reduced optical losses
  - Robust against ESD
  - Micro-cavity effects…

NOVALUX

III-Nitride Flip-chip LED: Micro-Cavity Effects

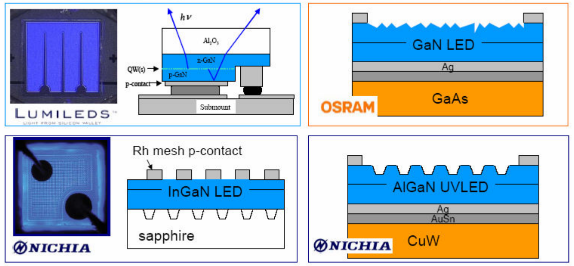
- The epi-layer thickness between the QW and Ag contact need to be controlled.
- Flip-Chip Extraction efficiency: 60 %





NOVALUX

High Extraction Efficiency III-Nitride LED Structures

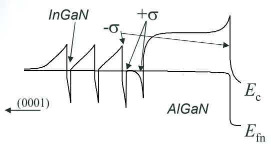


- Flip-chip with reflective electrodes
- Conventional with transparent electrode & scattering features
- Thin-film with reflective electrodes & scattering features
- All have extraction efficiencies ≥ 60%.

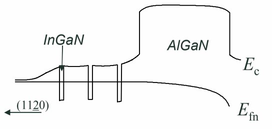
NOVALUX

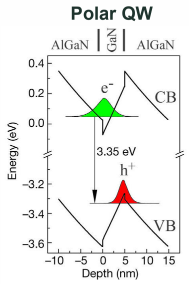
Motivation for non-*c*-axis III-nitride LEDs

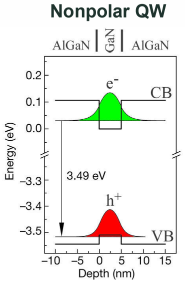
c-axis-oriented LED



a- or *m*-axis-oriented LED







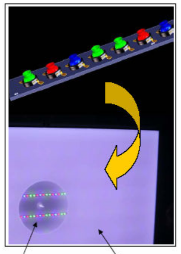
courtesy of M.D. Craven

See Steve DenBaars' invited talk on Monday morning

NOVALUX

SONY LED TVs: Qualia™ 005

First LED-based TV
August 2004



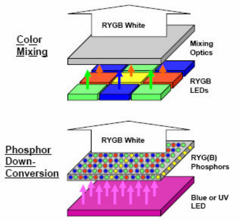
LED backlight

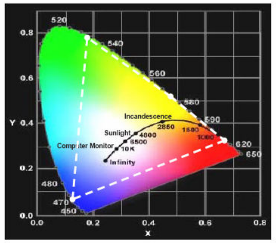
diffuser screen

- Triluminos™ LED backlight for LCD panel
- Ultra-high color gamut
  - ~ 100% NTSC
- 1920x1080 HD resolution
- LEDs eliminate motion artifacts
- No Hg
- Instant on

NOVALUX

Making White



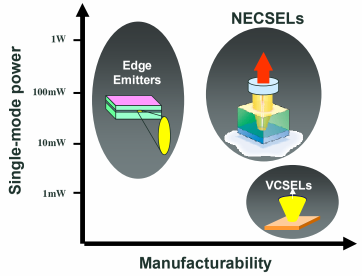


Images courtesy Jeff Tsao (Sandia National Labs).

Issues:
- Phosphor conversion
  - Quantum deficit, optical losses, new materials issues
- Color Mixing
  - Optical losses, color uniformity, color control circuits

NOVALUX

Types of Semiconductor Laser Technology



NECSEL Advantages
- High CW & pulsed output power with no damage
- Low cost manufacturing
- TEM_{00} beam
- Known good die: on-wafer testing
- Efficient nonlinear conversion (visible)
- Telcordia reliability of one million hours demonstrated for 980-nm devices

---

NOVALUX

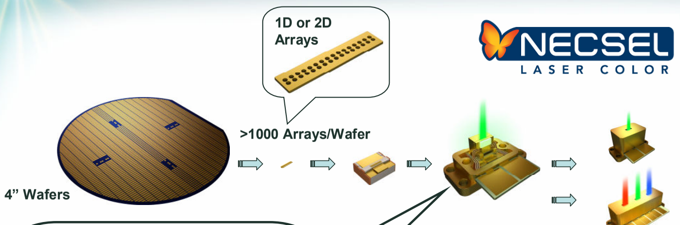
NECSEL Technology: What is it?

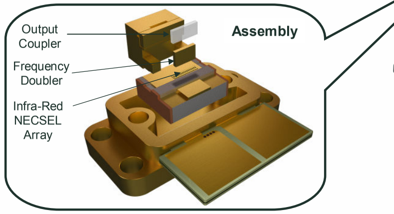
- Power scalable, efficient, highly manufacturable, low-cost surface emitting semiconductor diode lasers that behave like solid state lasers
- Simple, electrically pumped circular gain element

NOVALUX

What is a Novalux Necsel™ Laser?

NECSEL LASER COLOR

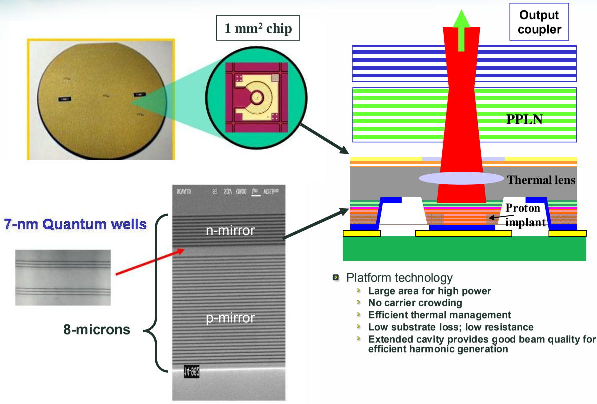




- **Mass Volume - Low Cost**
  - All components are wafer produced
  - Fully tested at wafer level (high yields)
  - Automated line assembly with flat/flat components & easy tolerances
  - Cost similar to UHP lamp at 1 million/year with higher cost compressibility
  - Validated by several CE companies

NECSEL Basic Technology

World-wide patented

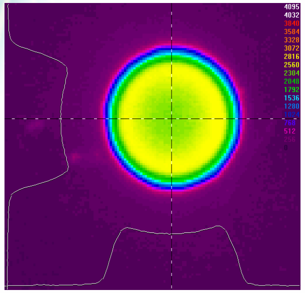


- Platform technology
  - Large area for high power
  - No carrier crowding
  - Efficient thermal management
  - Low substrate loss; low resistance
  - Extended cavity provides good beam quality for efficient harmonic generation

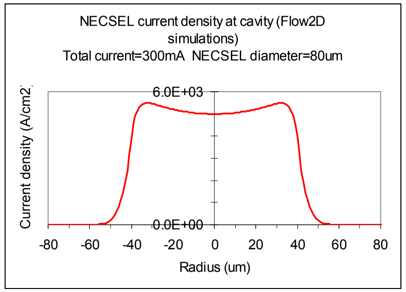
---

NECSEL Uniform Carrier Injection

Spontaneous emission

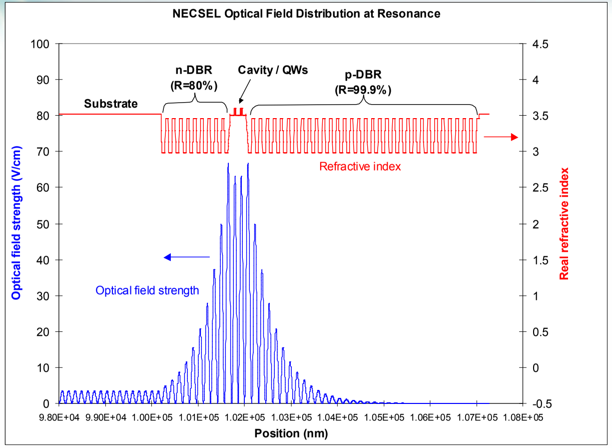


Modeled profile using finite element analysis



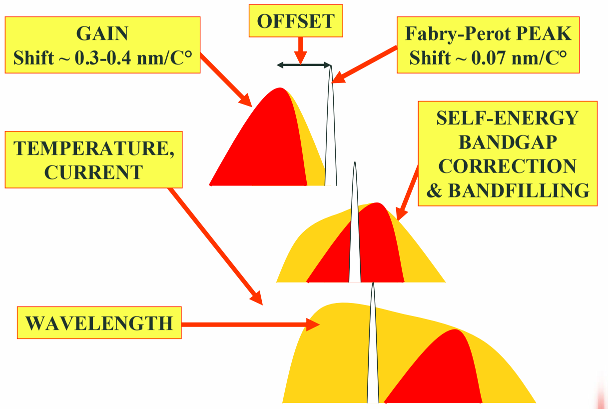
Spontaneous emission: intensity provides direct measure of current density
Current density (gain) variation across aperture is small

NECSEL structure similar to VCSELs

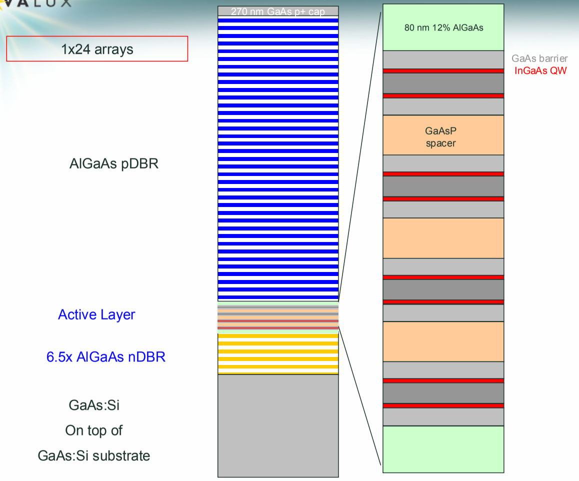


Electronic and Thermal Chirp of Gain through Fabry-Perot Wavelength

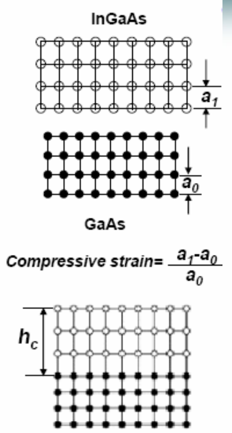
(CW and pulsed operation)



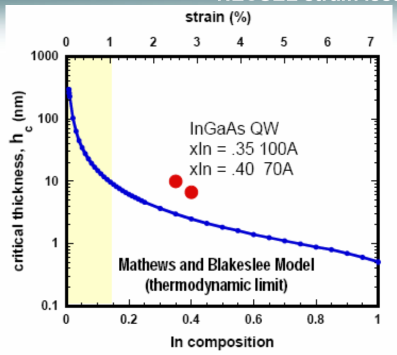
Typical Strained AL NECSEL Design



NECSEL strain issues



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



- Mathews Blakeslee model assumes system to be in thermodynamic equilibrium.
- In reality one can grow coherent layers beyond the “critical thickness” limit by using kinetics that prevent system from reaching equilibrium.

How does the system relieve or relax its strain

Different materials involved in the growth process, in the simplest case: **substrate** and **adsorbate** with identical crystal structure, but

lattice constants $\begin{cases} \sigma_A & \text{adsorbate} \\ \sigma_S & \text{substrate} \end{cases}$ **mismatch** $\varepsilon = \frac{\sigma_A - \sigma_S}{\sigma_S}$

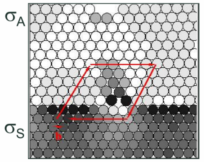
initial coherent growth enforced in first layers → species segregation/accumalation far from the substrate

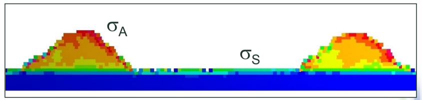
strain relaxation:

dislocations,
lattice defects

and/or

island and mound formation
hindered layered growth
self-assembled 3d structures





Ref: http://theorie.physik.uni-wuerzburg.de/~volkmann ~much, ~biehl

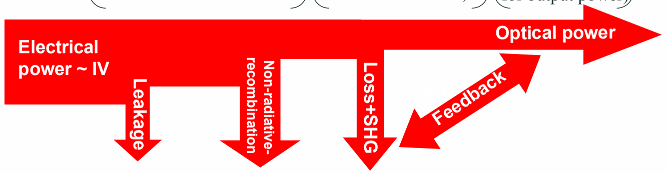
---

Consequences of strain on laser operation

$$\Gamma g = \alpha_i + \alpha_m + \alpha_{SHG}$$

$$P_{SHG} = \eta_{SHG} \eta_i \left(\frac{\alpha_m}{\alpha_i + \alpha_m + \alpha_{SHG}} \right) \frac{h\nu}{q} (I - I_{th})$$

Power output = (Internal efficiency → fraction of injected current that ends up as usable carriers in the active region) (Fraction of power allowed to escape laser cavity (depends on mirror transmission)) (Bias point above lasing threshold (external control for output power))



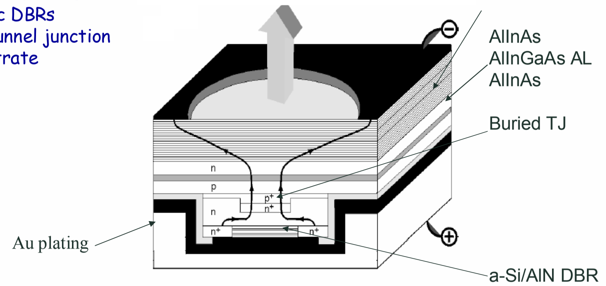
- Each loss mechanism reduces output power
- Island formation (3D) or dislocations lead to higher non-radiative recombination and poor material quality which result in:
  - higher threshold
  - lower gain

NECSEL Technology Comparison

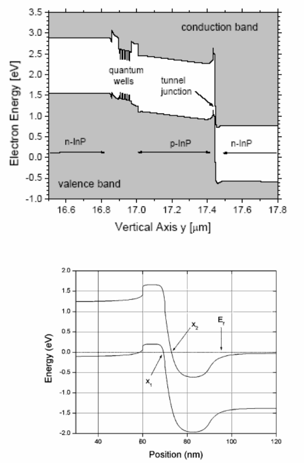
- **GaAs/InGaAs**
  - *Strained active*
  - Proton implantation available
  - Wavelength limited to < 1240 nm
  - Simple device fabrication
  - Robust substrate
  - May have better over temperature performance
  - Structure and fab similar to blue and green
  - Epitaxial DBR available
- **InP/AlInGaAs**
  - *Active region lattice-matched to InP substrate*
  - Wavelength = > 1260 nm available
  - Requires TJ
  - Requires dielectric DBR (on high reflectivity side)
  - Implantation difficult to implement
  - Brittle substrate
  - Higher gain

InP NECSEL Structure

Main Features:
AlInGaAs AL and DBRs
Dielectric DBRs
Buried Tunnel junction
InP substrate

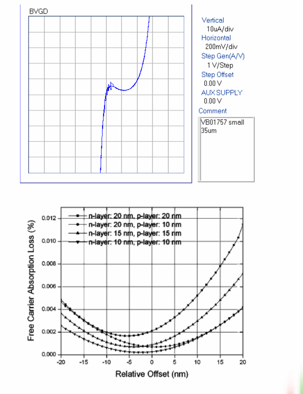


Band Diagram AL + TJ



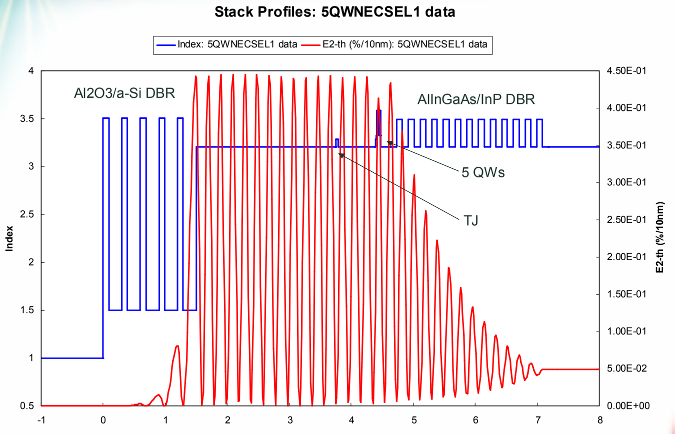
$$J \equiv J_p \left(\frac{V}{V_p}\right) \exp\left(1 - \frac{V}{V_p}\right)$$

$$V_P \approx \frac{(V_n + V_p)}{3}$$



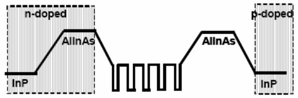
---

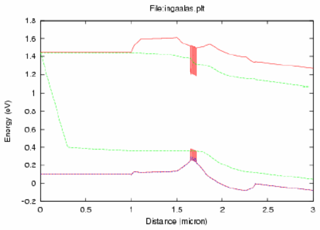
5 QW NECSEL Structure

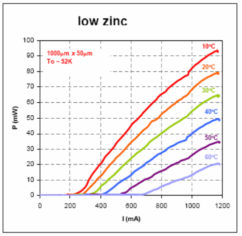


Non-optimized p-Doping Profile

T0 = 52 K



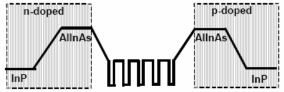


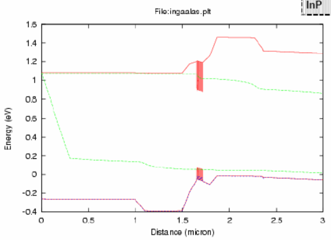


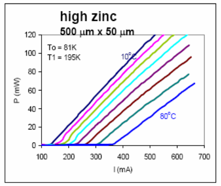
Ashish et al

Optimized p-Doping Profile

T0 = 81 K

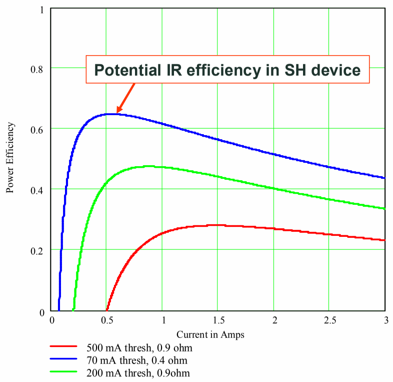




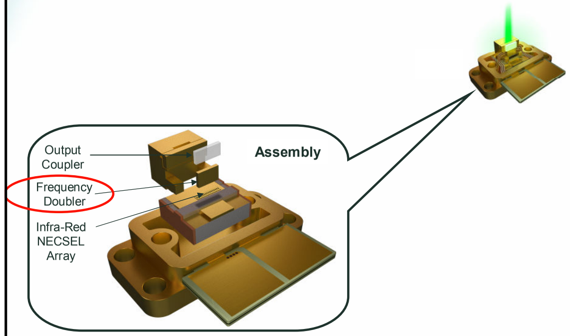


Ashish et al

Effect of Series Resistance and Threshold on IR Power Efficiency

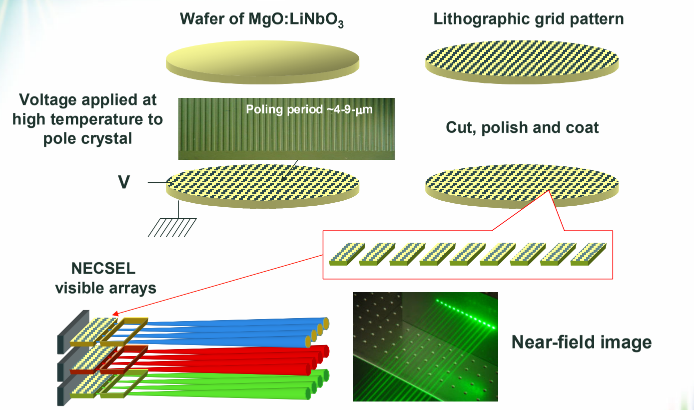


Nonlinear frequency conversion



NOVALUX

PPLN Wafer Scale Fabrication



NOVALUX

Nonlinear conversion efficiency in plane wave approximation

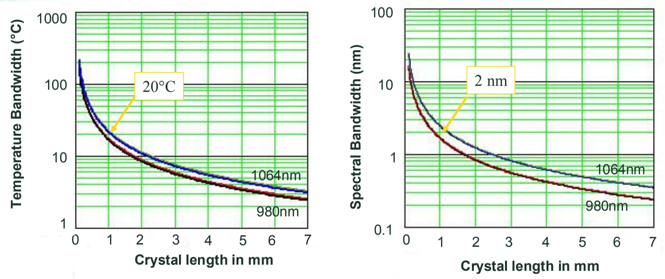
$$\eta \sim \frac{2\pi^2 d_{eff}^{\,2} l^2 I}{\lambda^2 n^3 \varepsilon_0 c}$$

Where

- d_{eff} is the nonlinear figure of merit (m/volt)
- l is the crystal length (m)
- I is the laser intensity (W/m^2)
- n is the refractive index (avg)
- c is the velocity of light (3x10^8 m/s)
- ε_0 is the permitivity in MKS (8.85x10^{-12} F/m)

NOVALUX

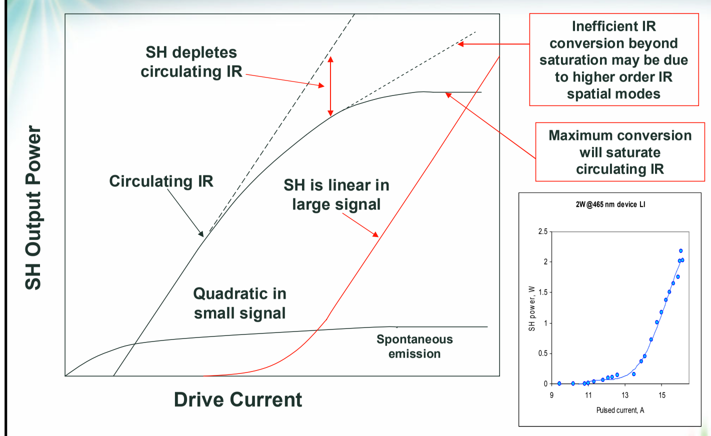
Temperature & Spectral Phase-Matching Bandwidths of PPLN as a Function of Crystal Length

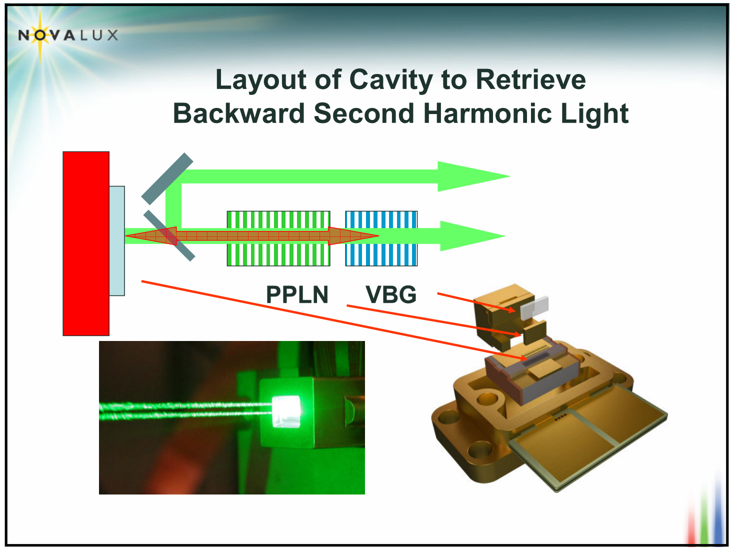


High intensity by pulsing allows shorter nonlinear crystals for more reliable wide temperature operating range.
Spectral chirp from pulsed operation helps reduce speckle

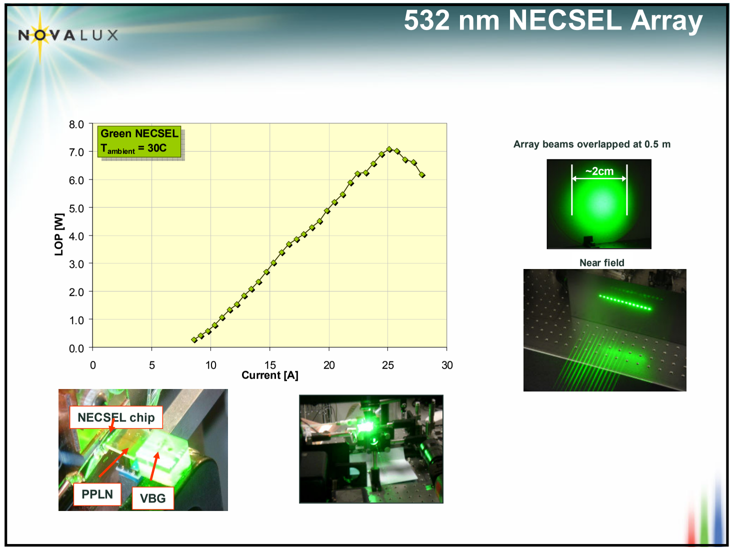
NOVALUX

Experiments to determine SH conversion efficiency



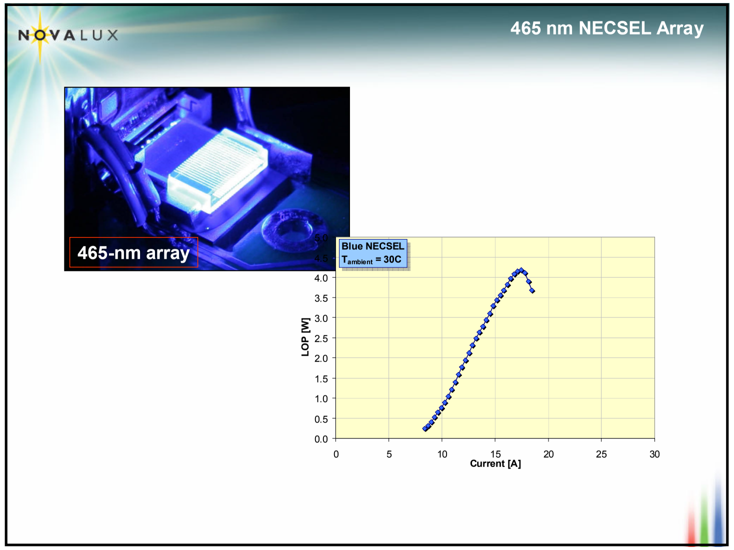


Layout of Cavity to Retrieve Backward Second Harmonic Light

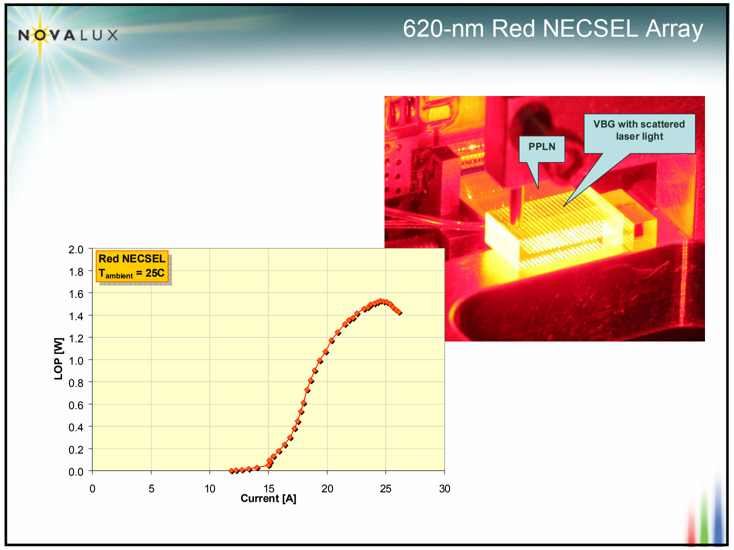


532 nm NECSEL Array

Array beams overlapped at 0.5 m



465 nm NECSEL Array



620-nm Red NECSEL Array

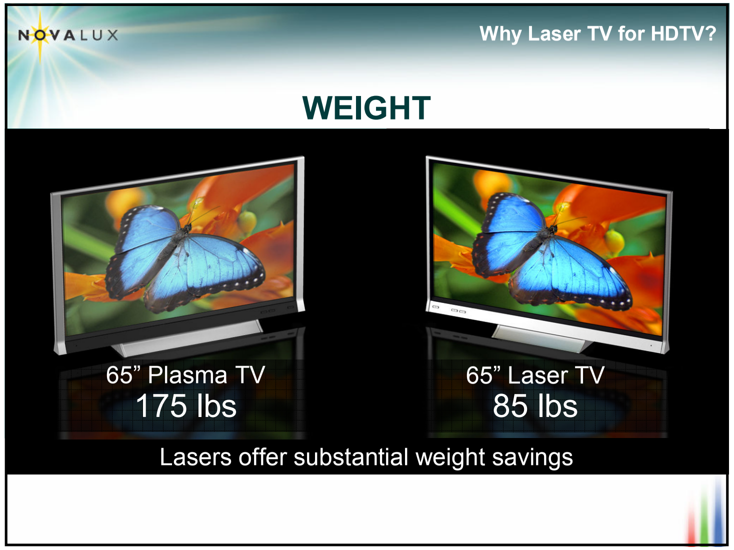
Why Laser TV for HDTV?

THIN

Hang it on a wall

65” Laser TV
< 8” depth

No more bulky rear projection architectures

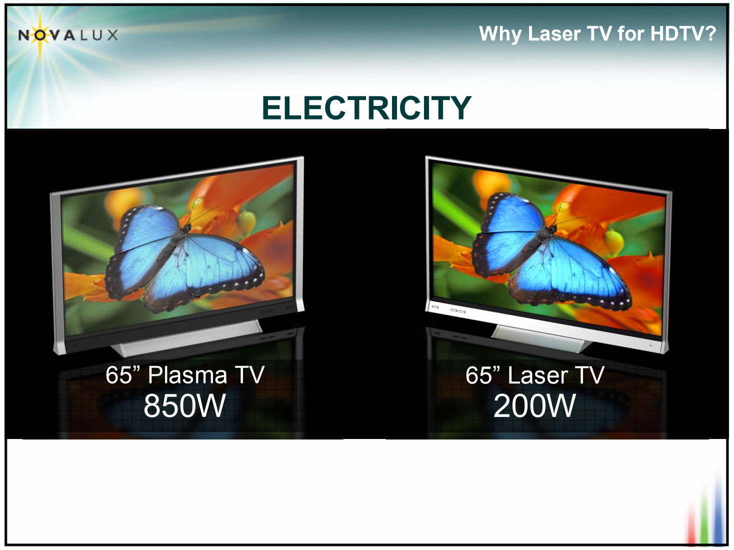


Why Laser TV for HDTV?

WEIGHT

65” Plasma TV	65” Laser TV
175 lbs	85 lbs

Lasers offer substantial weight savings



Why Laser TV for HDTV?

ELECTRICITY

65” Plasma TV	65” Laser TV
850W	200W

NOVALUX

Why Laser TV for HDTV?

CONSUMER COST

65” Plasma TV

$2X

65” Laser TV

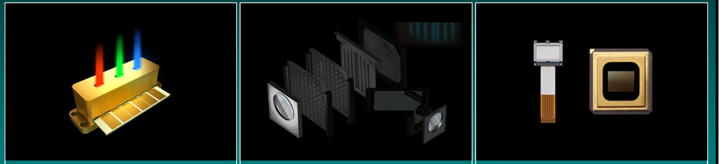
Laser TV has lowest cost for big screen & high resolution

NOVALUX

Why Lasers for MDTV?

COST

Lasers Provide Solutions



Never Needs Replacement	Fewer Optics	Smaller Microdisplays

NOVALUX

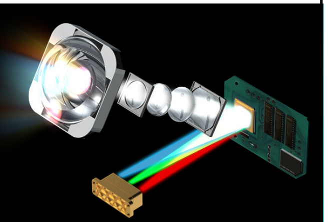
Why Lasers for MDTV?

COST

Fewer Optics Makes Simpler Light Engines Possible

Cost Decrease potential > 40%

DLP, 3LCD, and LCOS

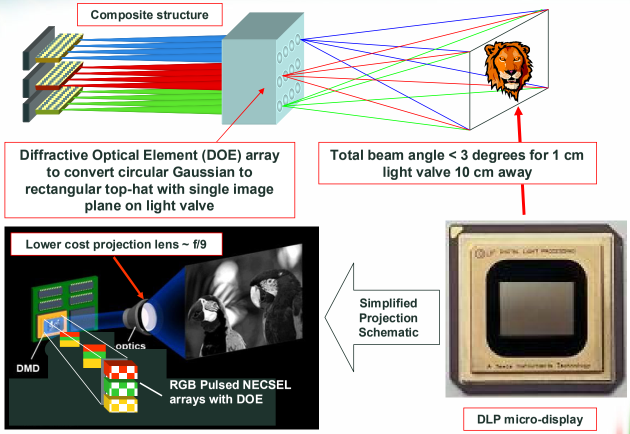


Reduces illumination optics, microdisplay, projection optics, & light source costs

---

NOVALUX

Diffractive Optical Light Engine Scheme (not to scale)



Composite structure

Diffractive Optical Element (DOE) array to convert circular Gaussian to rectangular top-hat with single image plane on light valve

Total beam angle < 3 degrees for 1 cm light valve 10 cm away

Lower cost projection lens ~ f/9

RGB Pulsed NECSEL arrays with DOE

Simplified Projection Schematic

DLP micro-display

NOVALUX

Why Lasers for MDTV?

RELIABILITY

Three light sources for MDTV: UHP, LEDs, & Lasers

Reliability has a “life time” aspect:

- **UHP Lamps** – “burn-out time” is 8,000 hours to 50% failure
- **LEDs** – “fade time” is 20,000 hours to 50% power
- **Lasers** – “life time” is the life of the TV at 100% original power

Reliability has an “endurance” aspect

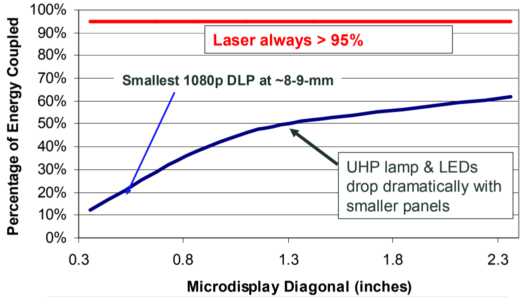
Lasers have constant power and constant wavelength over time & temperature

For the first time ever, your TV picture will never change!

NOVALUX

Laser Advantages: Etendue

- Compare coupling efficiency of lasers to UHP lamps with varying sizes of microdisplays
  - Unfortunately for the lamps (and LEDs), the trend is towards smaller (and therefore cheaper) panels



Lasers Enable Smaller Microdisplays
While Maintaining Brightness

NOVALUX

Comparison between NECSELs & LEDs for Projection Display

Comparison	NECSEL	LED
Brightness	> 10^5 W/mm^{2}str	0.2 W/mm^{2}str
Polarized output	Yes	No
Spectral width	~ 1 nm	10-20 nm
Visible efficiency	~ 10%	~ 20%
Scanning display	Yes	No
System optical efficiency	70-80%	~ 20-30%
Lifetime	> 30,000 hours at constant lumen output	~ 20K hours @ 50% lumen output
Light engine cost	Single RGB source with simple efficient optics	Requires more complex & costly optical train

Advantages of NECSELs for Display

- Lowest cost of TV
- Best color gamut
- Lowest screen gain
- No color shift
- Smallest micro-display
- Cheapest projection lens
- Polarized output
- Fiber delivery

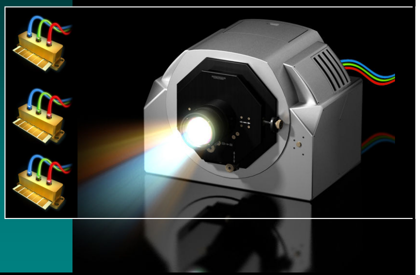
NOVALUX

How does Laser TV drive growth?

Lasers Enable D-Cinema

Group lasers to get to 20,000 lumens

Solves business model problem



Fiber-coupling can only be done with laser light sources

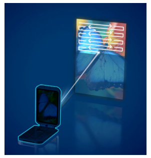
How does Laser TV drive growth?

Pocket Projection

Convenient
Versatile
Fun
Affordable
Small

How does Laser TV drive growth?

Mobile Projection

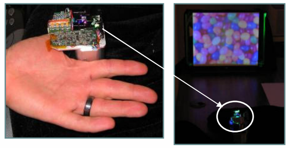


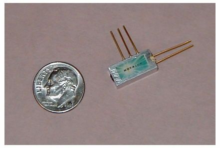
- •2D MEMS scanning projection
- •Single-emitter laser
- •Project anywhere
- •Battery friendly
- •Share instantly
- •All-in-one
- •Impromptu

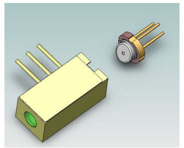
Pico Projector Green Laser

- Single-beam (TEM_{00}) GREEN laser
  - Wavelength: 532 +/- 2 nm
  - Power: > 50mW
  - Modulation Speed: Up to 100 MHz
  - Polarization: > 1000:1, perpendicular, S
  - M^2: < 1.3, TEM00 mode
- Small, low-cost package without TEC → ~ 0.5 cm^3
- Direct modulation of light output for scanning video
  - Up to 100MHz modulation
  - Fully arbitrary pulse-width, duty-factor, amplitude

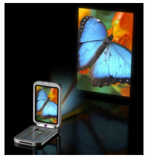
CES'06 Prototype Pico Projector





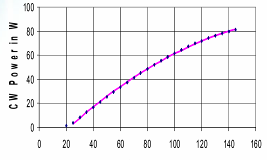


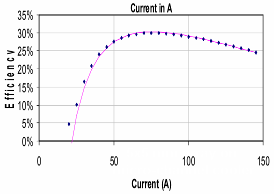
Future Embedded Projector

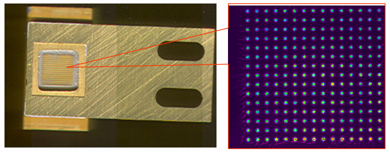


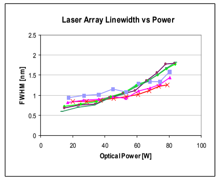
Performance of 5x5 mm VCSEL 2-D Arrays

225 emitters, ~ 978-nm, uniform parallel operation

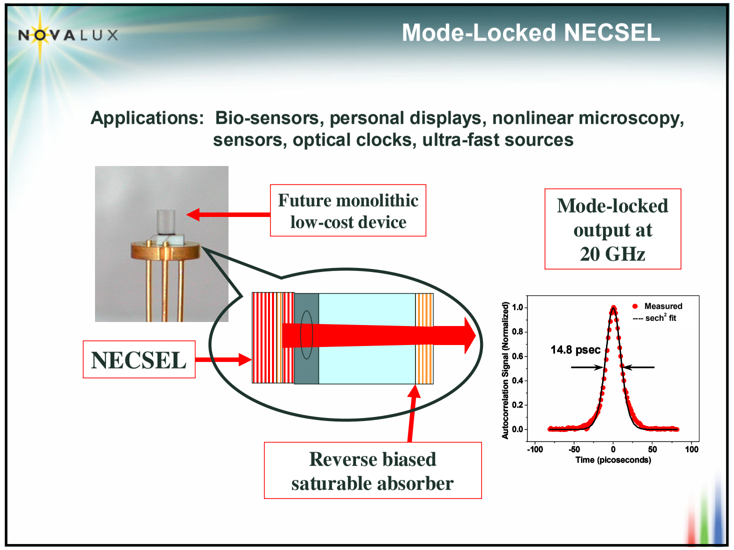








Applications include high power industrial lasers for materials processing, etc.



NOVALUX

Mode-Locked NECSEL

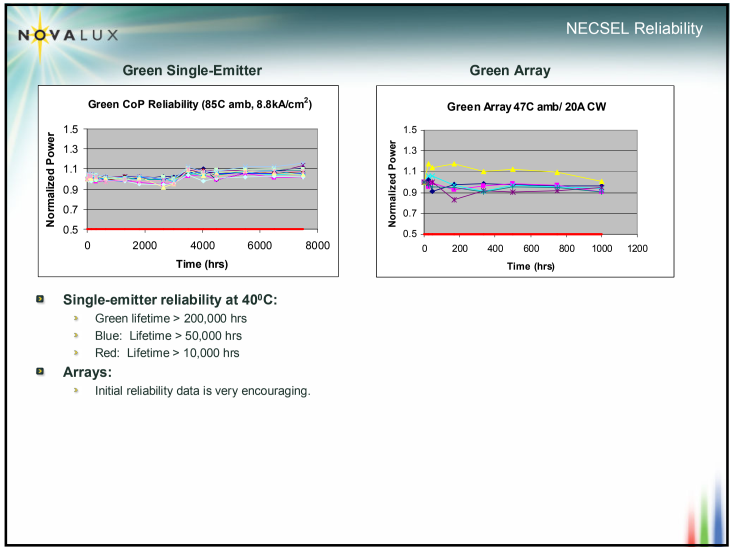
Applications: Bio-sensors, personal displays, nonlinear microscopy, sensors, optical clocks, ultra-fast sources

Future monolithic low-cost device

Mode-locked output at 20 GHz

NECSEL

Reverse biased saturable absorber



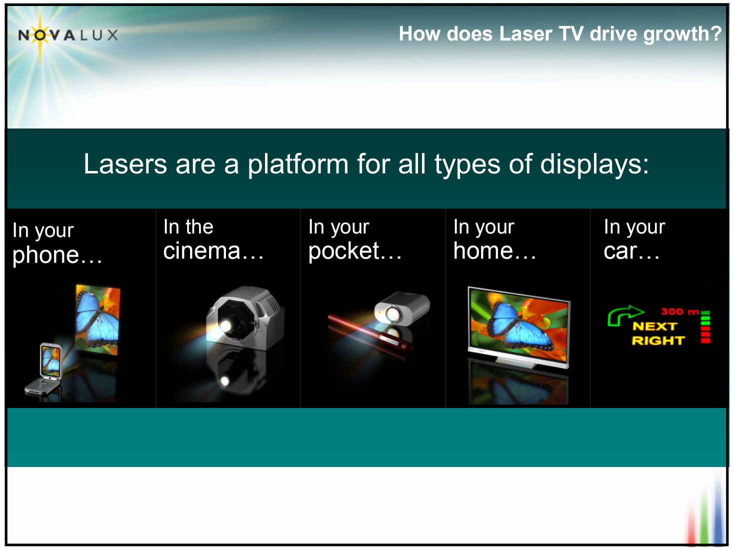
NOVALUX

NECSEL Reliability

Green Single-Emitter

Green Array

- **Single-emitter reliability at 40°C:**
  - Green lifetime > 200,000 hrs
  - Blue: Lifetime > 50,000 hrs
  - Red: Lifetime > 10,000 hrs
- **Arrays:**
  - Initial reliability data is very encouraging.



NOVALUX

How does Laser TV drive growth?

Lasers are a platform for all types of displays:

In your phone…

In the cinema…

In your pocket…

In your home…

In your car…

NOVALUX

NECSEL LASER COLOR

Thank You!

www.novalux.com
www.necsel.com