INTEGRATION AND APPLICATION OF EPITAXIAL SYSTEMS: III/V ON SILICON FOR OPTOELECTRONICS

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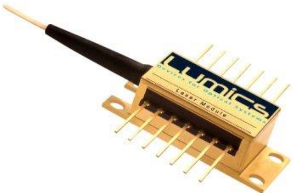
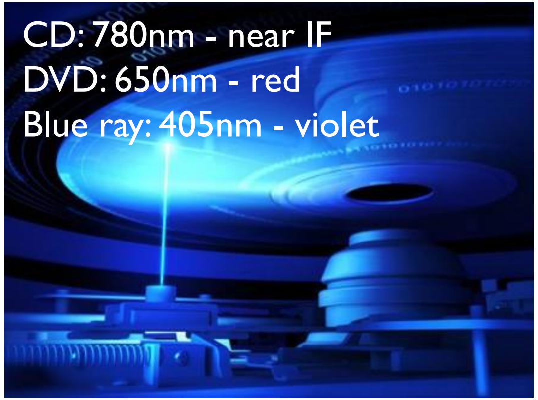
WHY III/V ON SILICON?

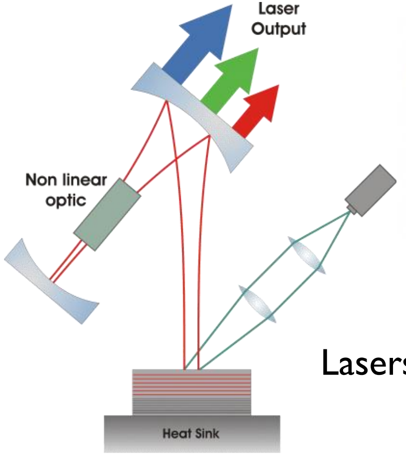
III/V APPLICATION

Telecommunication
Local Area Network
Back-Plane

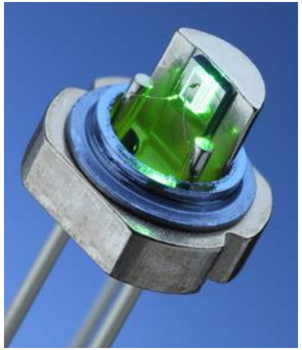


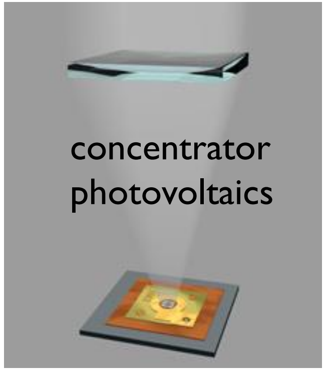
- HEMTs (radar, mobile phone switch, low noise amplifier, ...)
- HBT (mobile phone power amplifier, ...)
- detectors
- ...





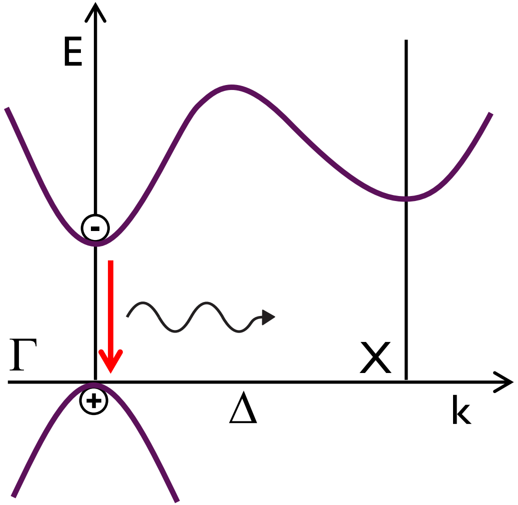
Lasers & LEDs





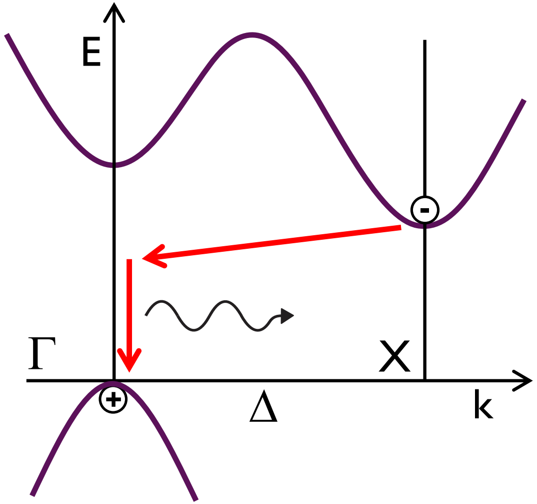
BAND STRUCTURE: K-SPACE

III/V direct semiconductor



→ perfect for optoelectronic

indirect semiconductor



Silicon & Germanium

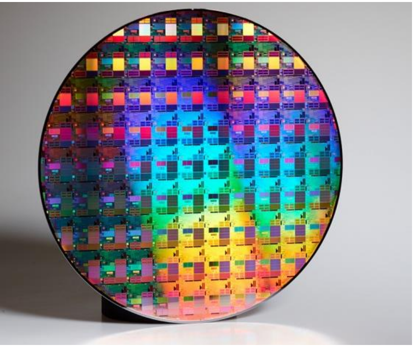
- phonon-mediated recombination
- long recombination lifetime [ms]
- Auger recombination & free-carrier absorption crucial for lasing

→ poor light emitter

→ good for electronics!

BENEFIT OF SI-BASED TECHNOLOGY

16nm Node TSMC



Advantage of Silicon

- easy to purify/handle/manufacture
- good thermal/mechanical properties
- cheap!

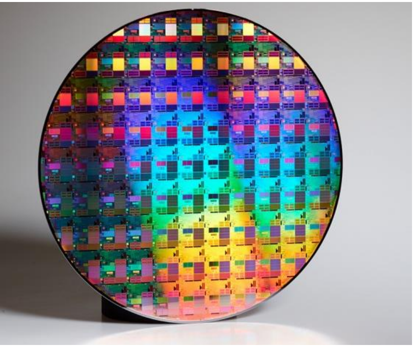
Advantage of SiO_2

- interface quality: Gate stack
- good insulator
- effective diffusion barrier
- high etching selectivity

→ **highly developed Micro-Technology!**

III/V ON SILICON

+



Optoelectronic Integrated Circuits (OEIC) & Silicon Photonics

- combine the advantages of Silicon (ICs) & III/V (optics)

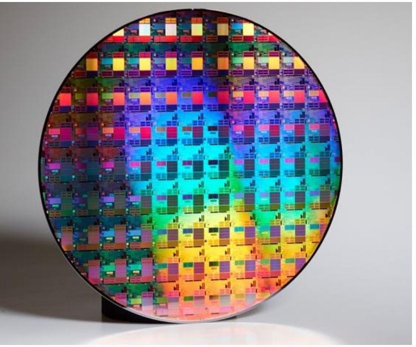
→ large field of new applications

Profit from the low Si substrate price

- pseudo III/V substrate
  - LED production at lower cost
  - multi-junction solar cells
  - …

III/V ON SILICON

+



Optoelectronic Integrated Circuits (OEIC) & Silicon Photonics

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Unpredictable potential!!!

Profit from the low Si substrate price

- pseudo III/V substrate
  - LED production at lower cost
  - multi-junction solar cells
  - …

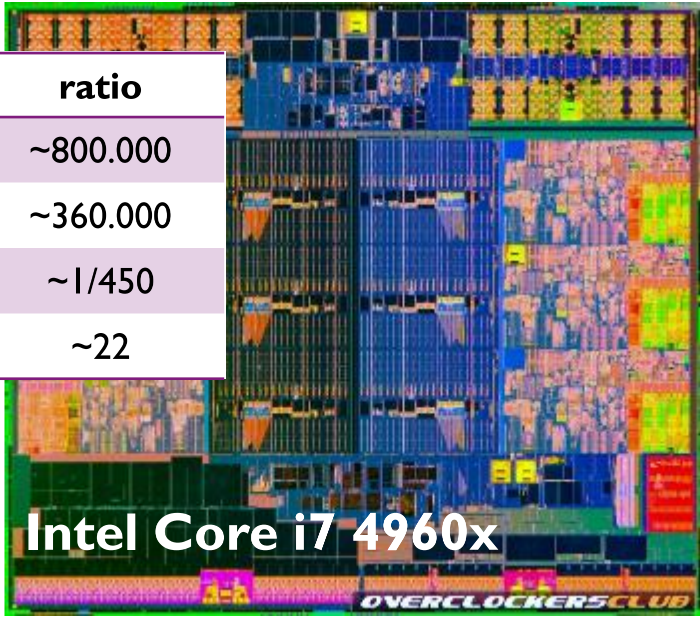
EXAMPLE:
ADVANTAGE OF OPTICAL DATA TRANSMISSION ON INTEGRATED CIRCUITS!

SI-TECHNOLOGY: INTEGRATED CIRCUITS

"The numbers of transistors doubles every 18 months" ***1965 Gordon Moore***

Year	1971	2013	ratio
Transistor	2.300	1.860.000.000	~800.000
Speed (Hz)	10.800	3.900.000.000	~360.000
Gate length (nm)	10.000	22	~1/450
Area (mm²)	12	257	~22

Scaling down from 10µm to 22nm!



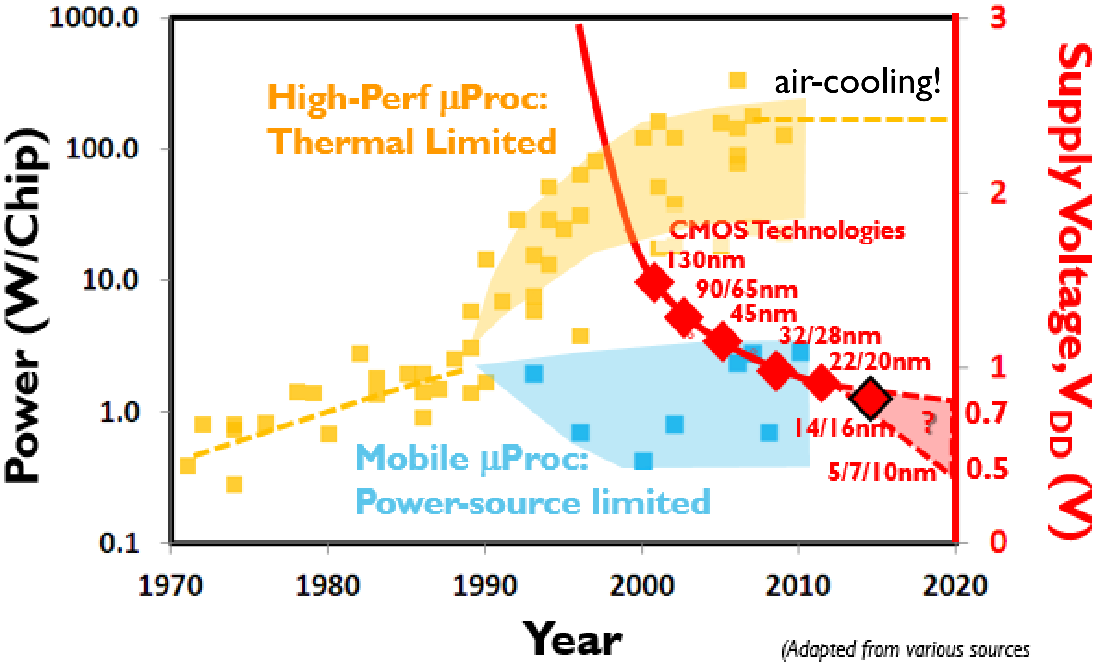
First commercially available microprocessor

POWER DENSITY

Power consumption

$$P_{static} \sim V_{DD} * I_{off}$$

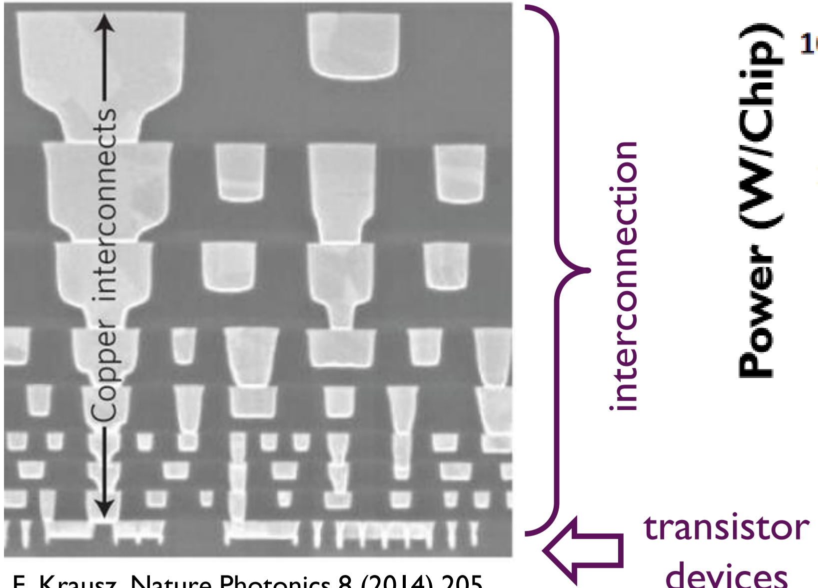
$$P_{dyn.} \sim f * C_{cap} * V_{DD}^2$$



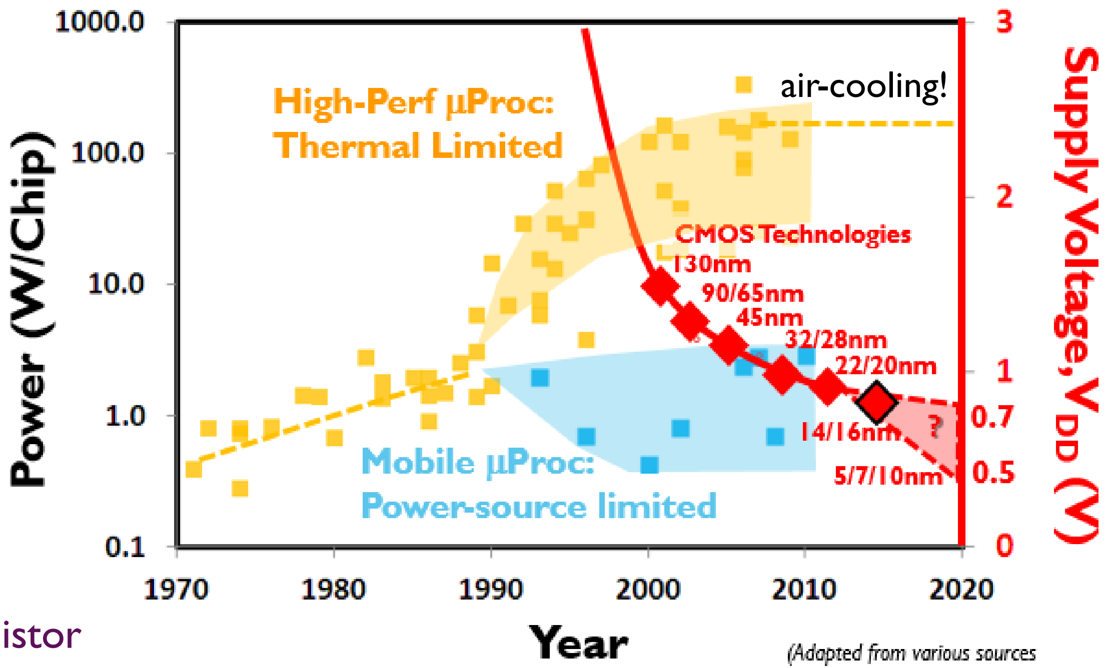
(Adapted from various sources
Includes T. Masuhara, IEEE-SSCM 2013)

POWER DENSITY

cross section of a ICs



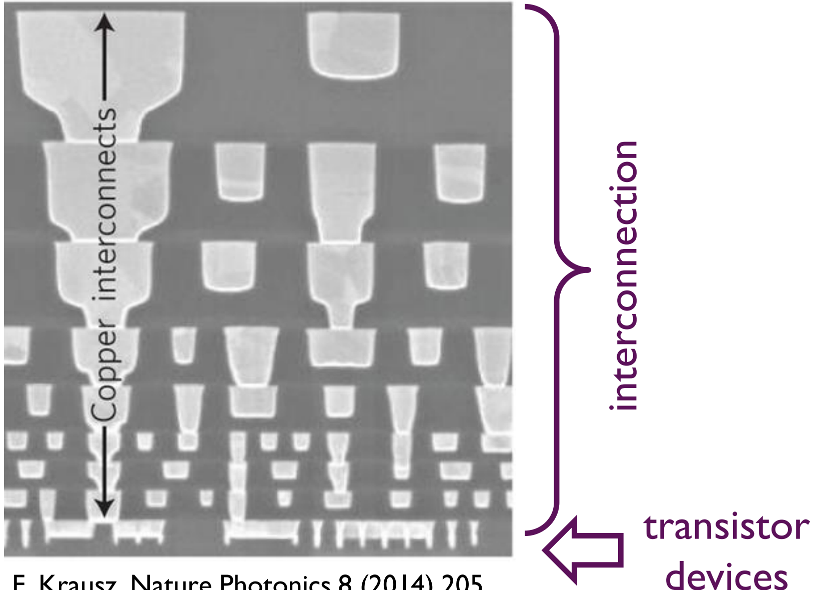
F. Krausz, Nature Photonics 8 (2014) 205



(Adapted from various sources Includes T. Masuhara, IEEE-SSCM 2013)

ELECTRICAL INTERCONNECTION

cross section of a ICs



F. Krausz, Nature Photonics 8 (2014) 205

Drawbacks of "pure" electrical interconnections in Si-technology

- power dissipation
- RC delay (resistance & capacitance)
- signal latency

Advantages of optical interconnections on chip-level

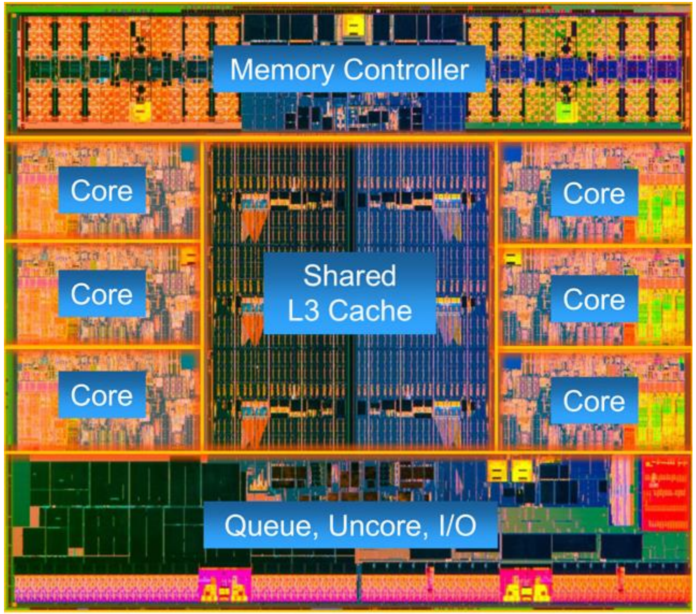
- no charge transport – less heat dissipation!
- no signal latency!
- high bandwidth

→ increasing data transmission speed!

MULTI-CORE PROCESSOR

- multi-core architecture to mitigate power dissipation
- parallel processing cores provides better performance per watts than single processor
- intra-chip communication networks becomes more and more important

Intel Core i7 4960x

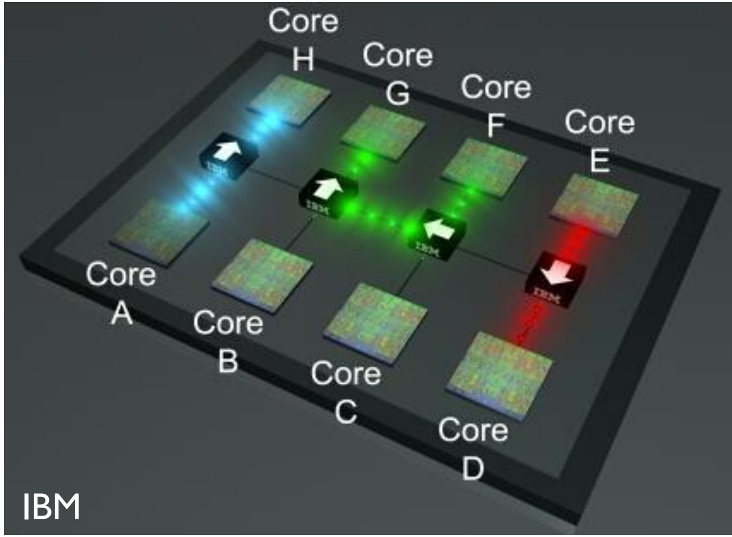


OPTICAL DATA TRANSMISSION BETWEEN CORES

- multi-core architecture to soften power dissipation
- parallel processing cores provides better performance per watts than single processor
- intra-chip communication networks becomes more and more important

→ **optical interconnections at specific data bottleneck is the next technology step: Between cores!**

Optoelectronic ICs



optical interconnections between cores

SILICON PHOTONIC

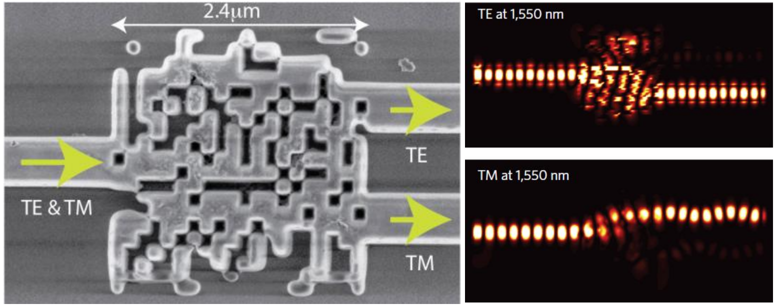
Increasing research field for new applications

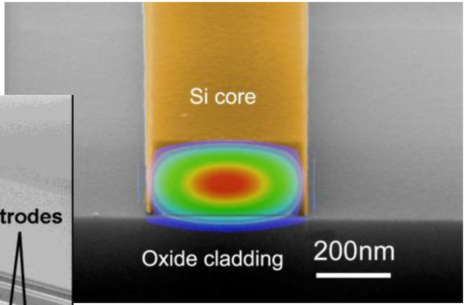
- Si-based components have already been demonstrated (waveguide, detectors, optical modulators, switches, ...)

→ **<u>Open question: Laser?</u>**

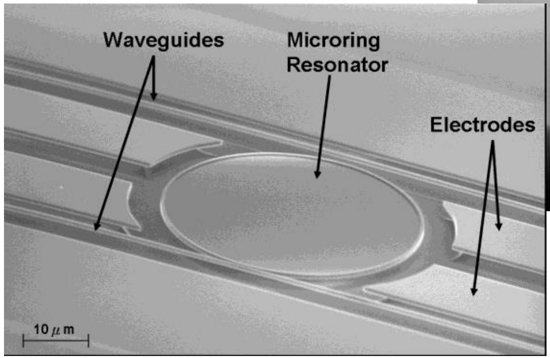
How to integrate a light source?

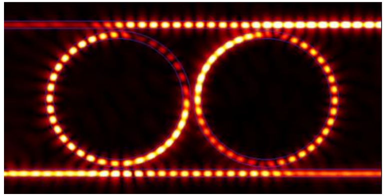
B. Shen, Nature Photonics 9 (2015) 378



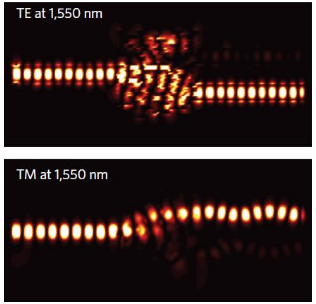


UC Berkeley



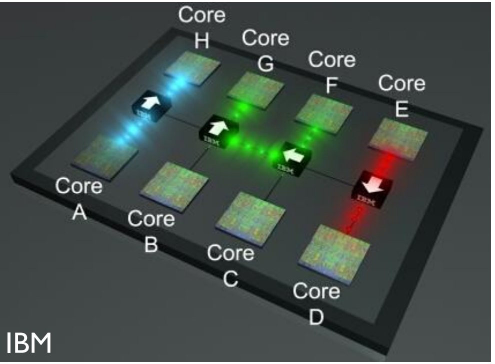


LASER INTEGRATION

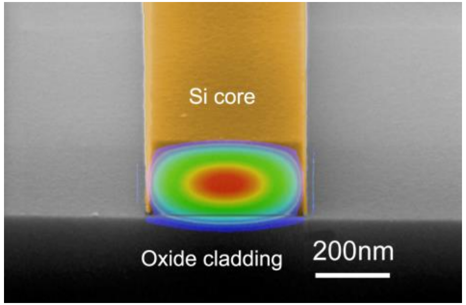


Device requirements

- sufficient power & **life time (CW)**
- compatible to the current CMOS process
- easy to process/fabricate in mass production
- cheap!!!



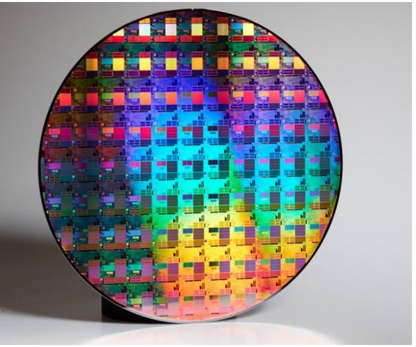
- ❖ **III/V Hybrid integration**
- ❖ **Monolithic Hetero Epitaxy**



CW: continuous wave

OUTLINE

+



Part I: Fundamentals

- Laser
- Hetero epitaxy & defect formation

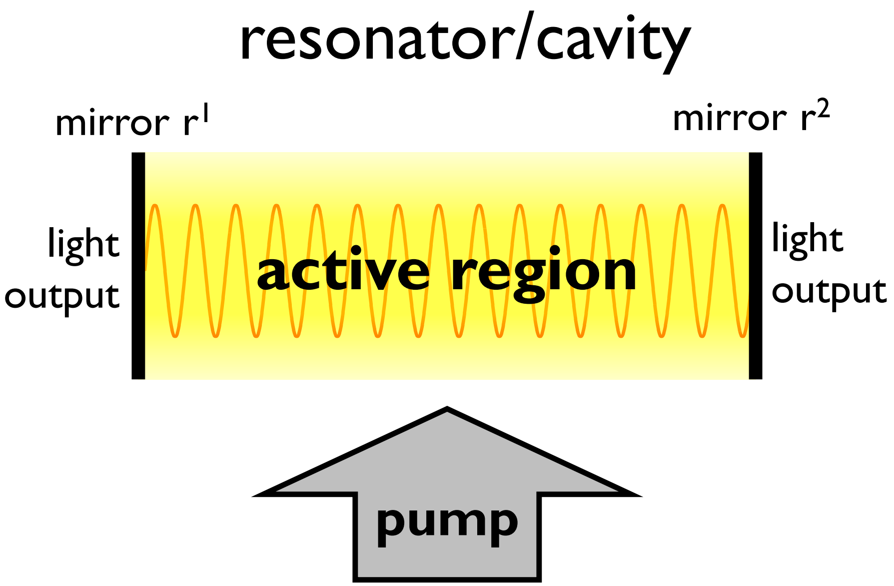
Part II: Laser integration

- Monolithic Hetero epitaxy

LASER: PRINCIPLE

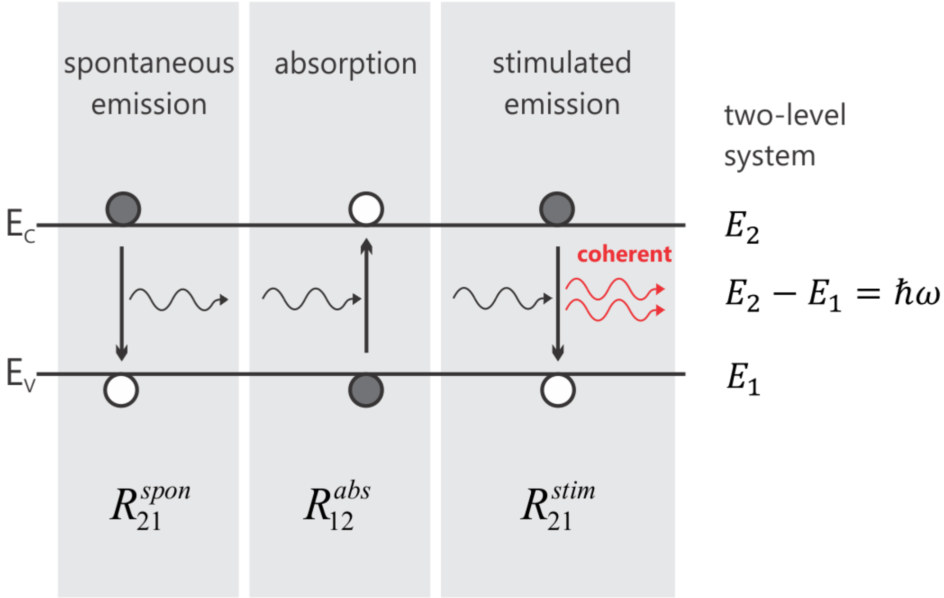
Light amplification by stimulated emission of radiation

1. Active region
   → material to provide optical gain $g(\hbar\omega)$
2. Pump (electrical or optical)
   → achieving carrier inversion
3. Resonator
   → light field back coupling



SEMICONDUCTOR LASER

Active region: Electron transition between conduction and valence band



e occupation probability

e vacancy probability

photon density

$$R_{21}^{spon} = A \cdot f_2(1 - f_1)$$

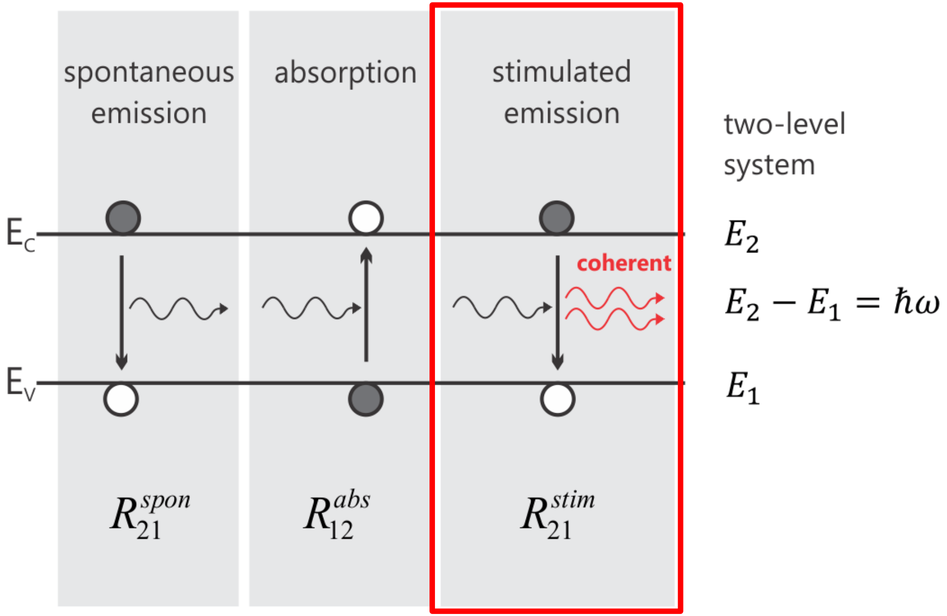
$$R_{12}^{abs} = B \cdot f_1(1 - f_2) \cdot P(\hbar\omega)$$

$$R_{21}^{stim} = B \cdot f_2(1 - f_1) \cdot P(\hbar\omega)$$

f Fermi-Dirac-distribution; *A*, *B* Einstein-coefficient

SEMICONDUCTOR LASER

Active region: Laser operation requires optical gain!



$$\frac{R_{21}^{stim}}{R_{21}^{spon}} = \frac{B}{A} \cdot P(\hbar\omega)$$

Resonator: sufficient photon density

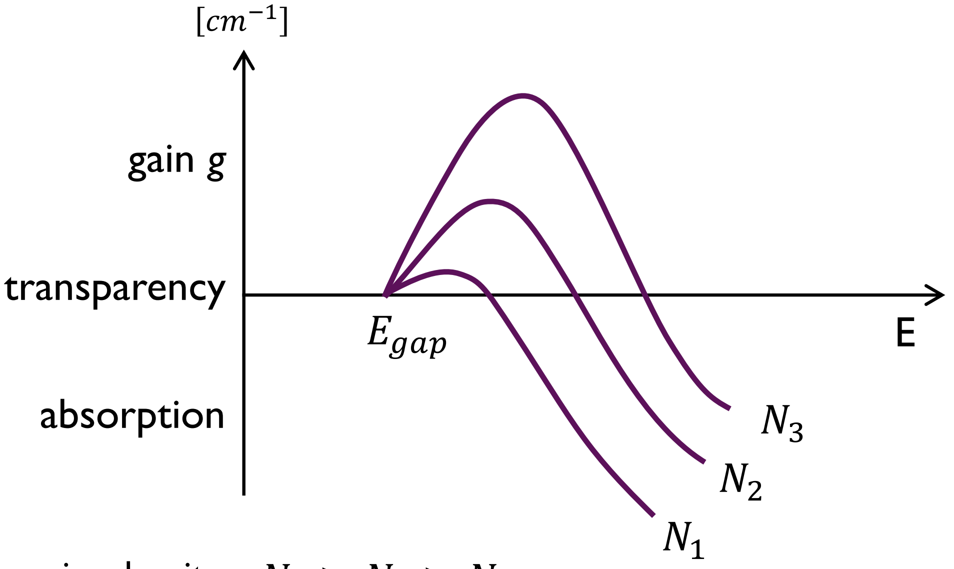
$$R_{21}^{stim} > R_{12}^{abs} \Rightarrow f_2 > f_1$$

Pump: inverted electron density
or population inversion

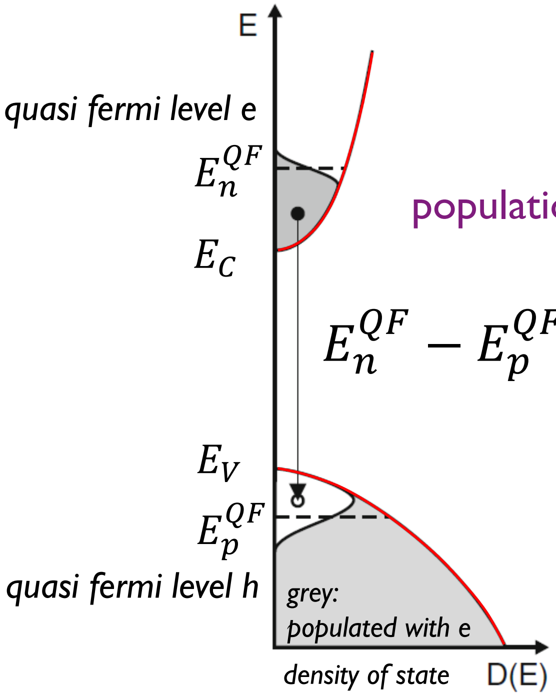
f Fermi-Dirac-distribution; A, B Einstein-coefficient

OPTICAL GAIN IN SEMICONDUCTOR

$$R^{stim} > R^{abs}$$



carrier density $N_3 > N_2 > N_1$



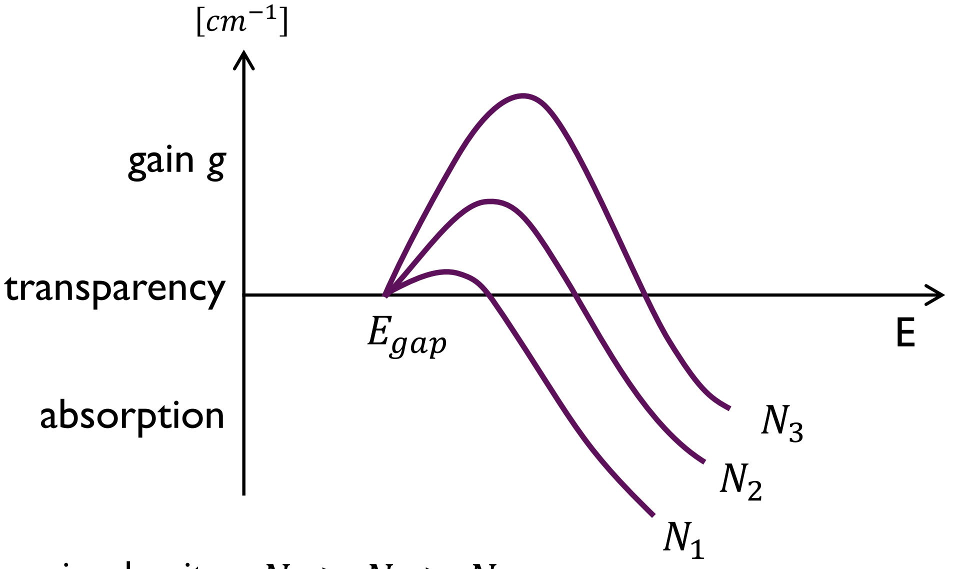
population inversion

$$E_n^{QF} - E_p^{QF} > E_C - E_L$$

[*The Physics of semiconductors*, Marius Grundmann, Springer 2010]

OPTICAL GAIN IN SEMICONDUCTOR

$$R^{stim} > R^{abs}$$



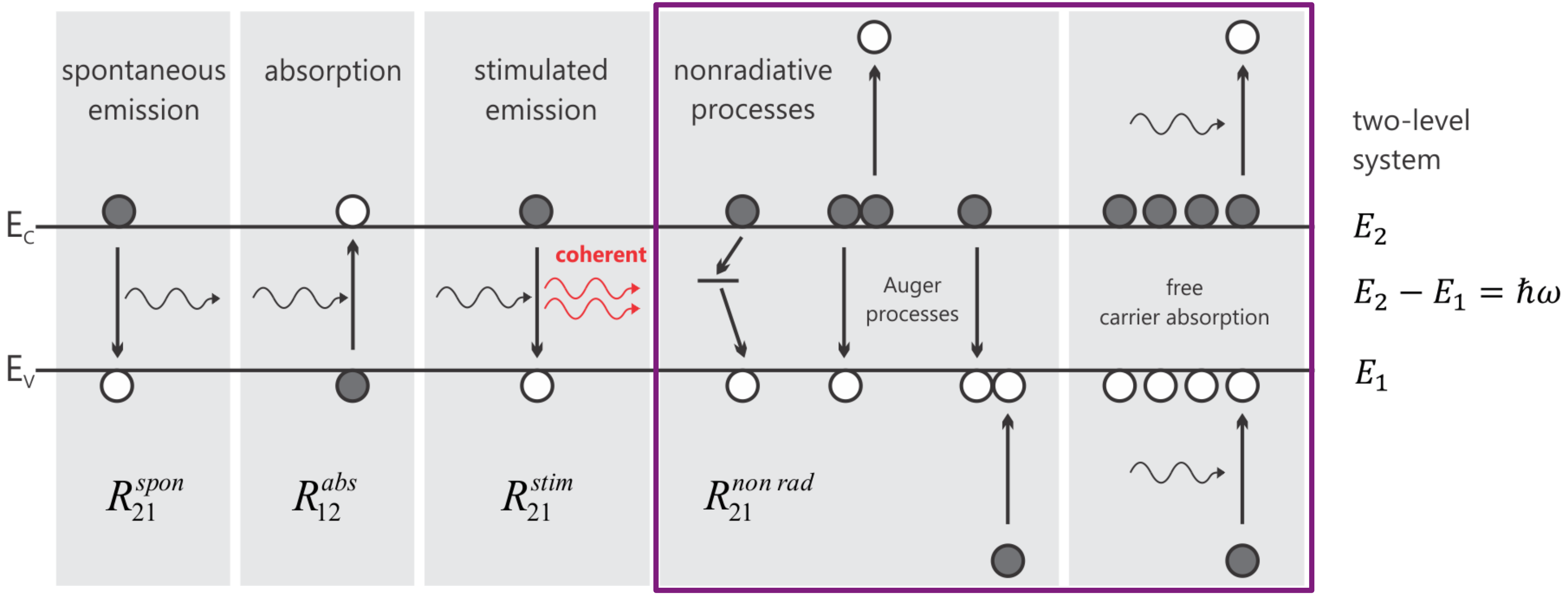
carrier density $N_3 > N_2 > N_1$

- stimulated emission dominated over absorption
- g depends on the dipole-matrix-element, density of state, quasi fermi distribution, …
- model: free carrier picture & microscopic many body gain model

f Fermi-Dirac-distribution for electrons and holes

SEMICONDUCTOR FOR LASER

Additional loss mechanisms



LASER THRESHOLD

Laser threshold condition:

Traversal round trip: gain satisfies all losses → no attenuation

gain — confinement factor

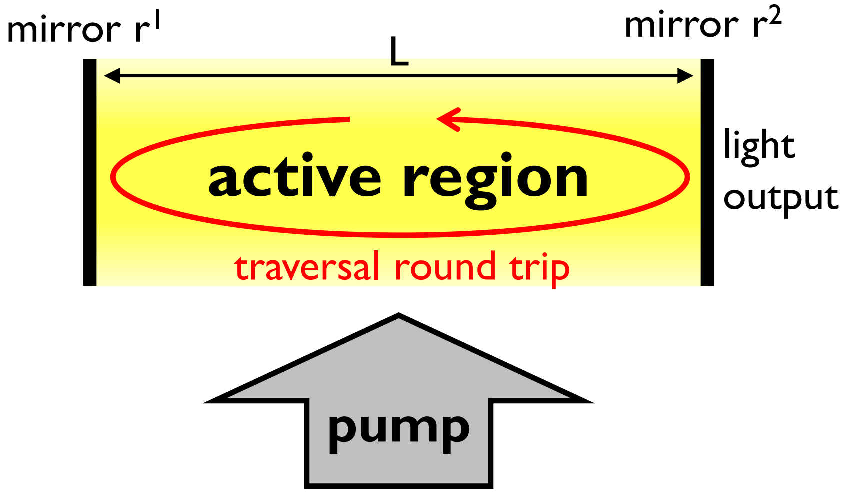
$$r^1 r^2 \exp[(g(\hbar\omega)\cdot\Gamma - \alpha_{loss})\cdot 2L] = 1$$

modal gain — additional losses

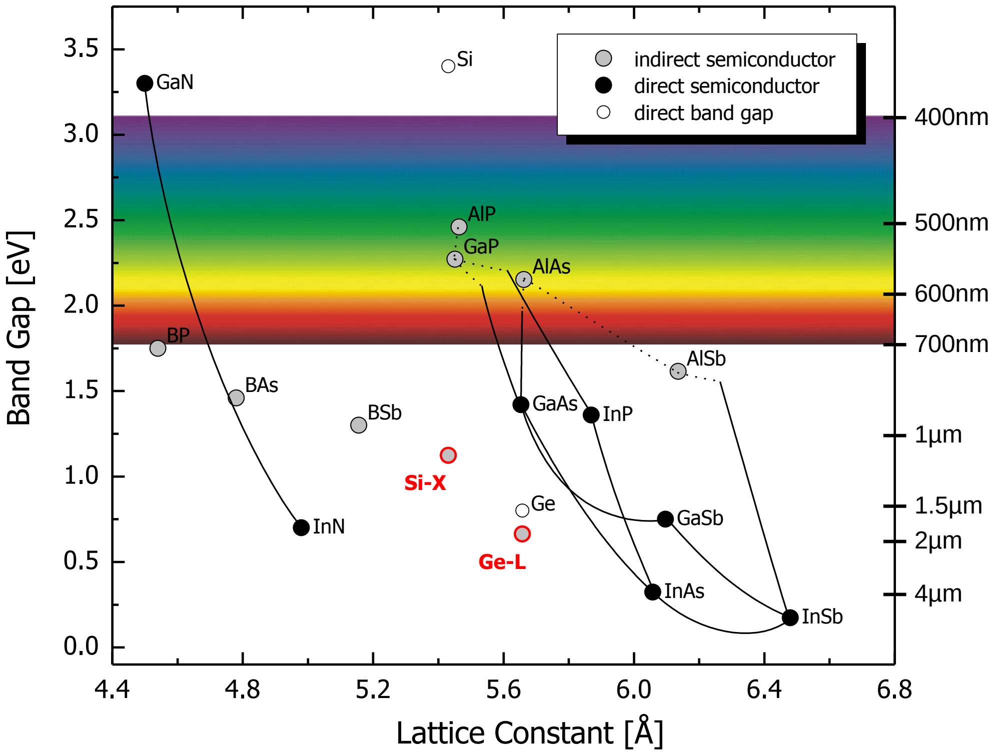
$$g(\hbar\omega)\cdot\Gamma = \alpha_{loss} + \frac{1}{L}\ln\left(\frac{1}{\sqrt{r^1 r^2}}\right)$$

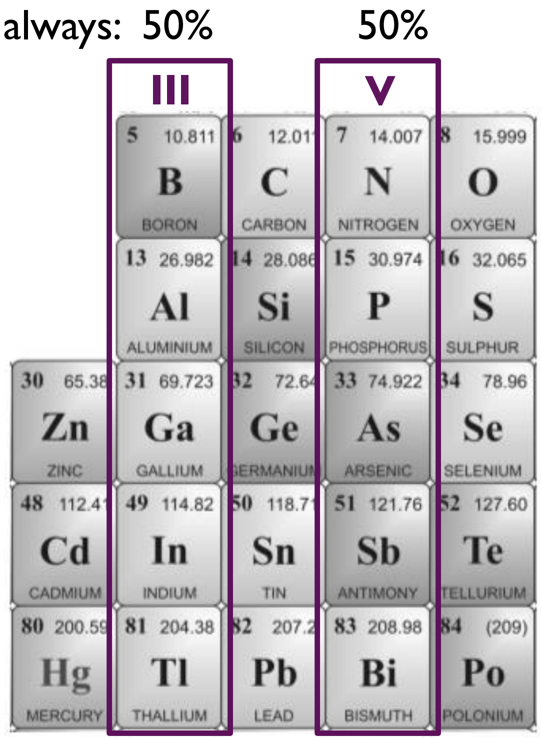
laser threshold

resonator/cavity

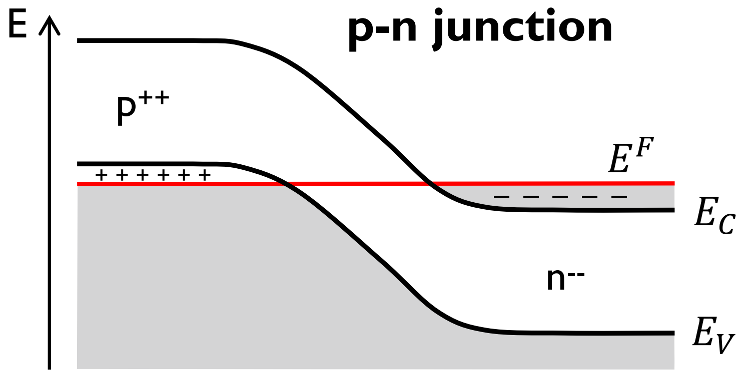


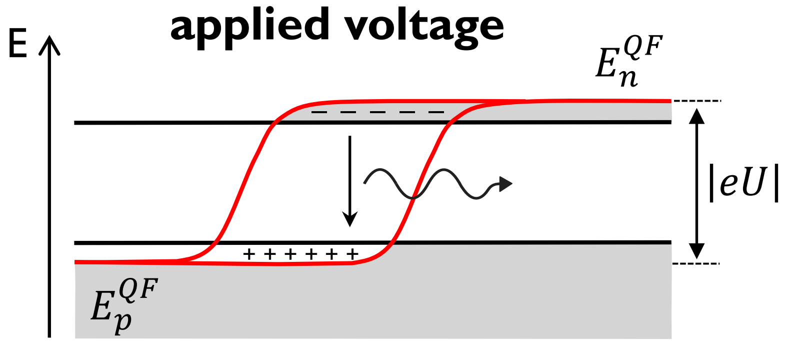
III/Vs AS ACTIVE MATERIAL

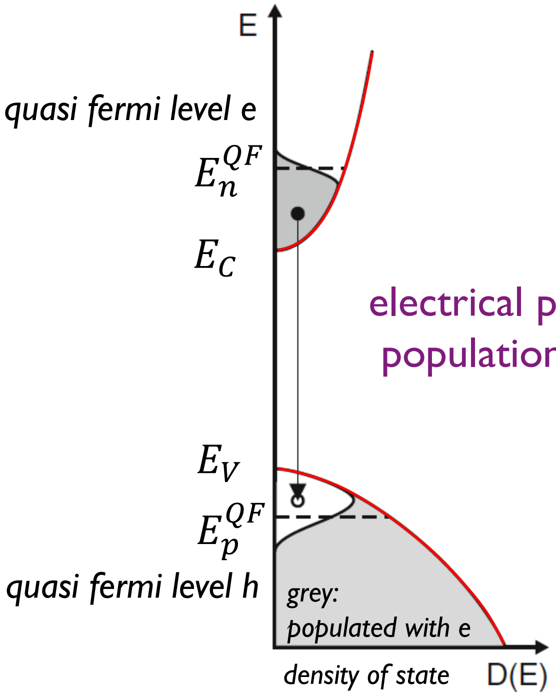




HETERO-STRUCTURE



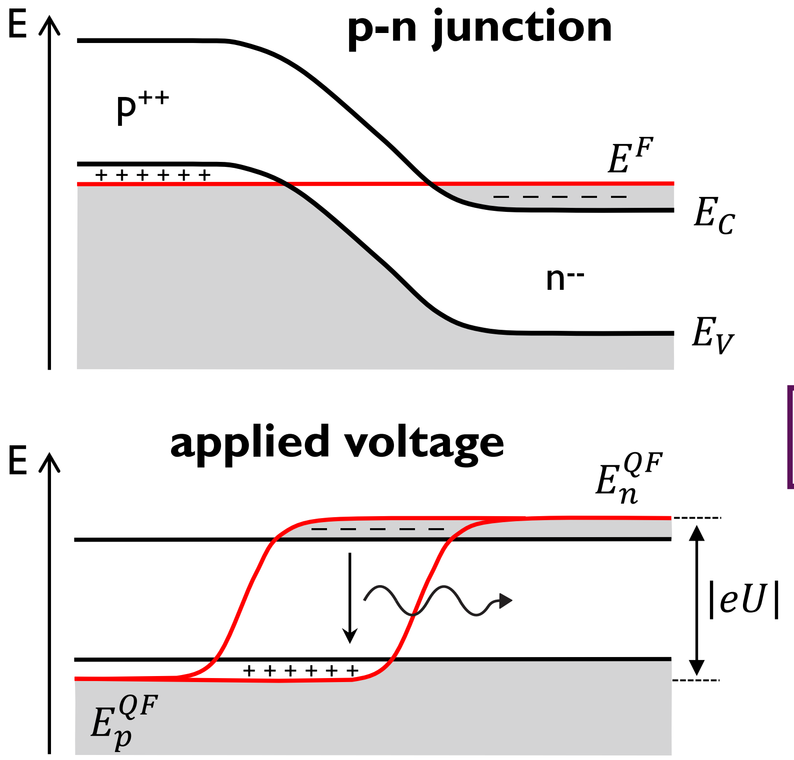


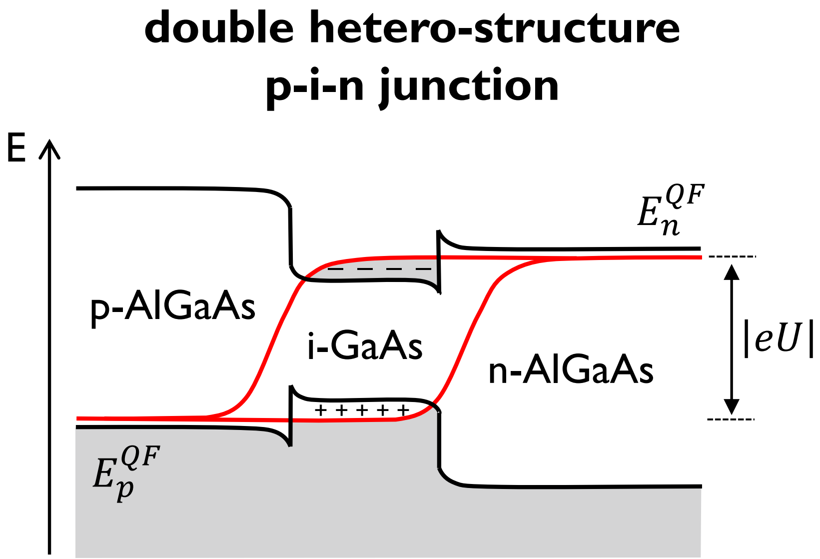


electrical pumping for population inversion

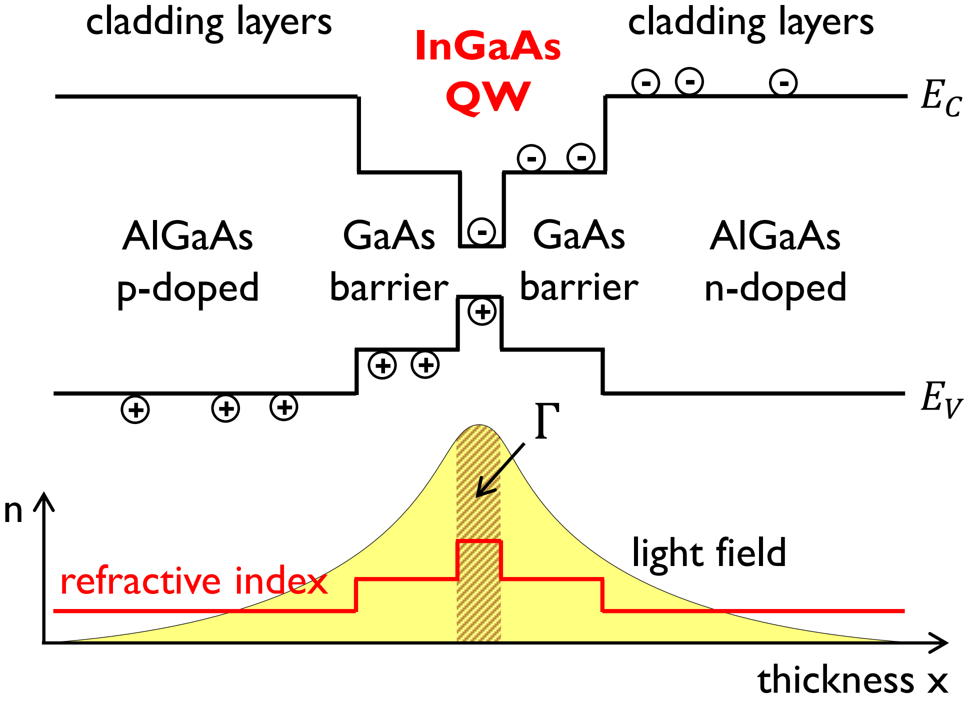
[*The Physics of semiconductors*, Marius Grundmann, Springer 2010]

HETERO-STRUCTURE

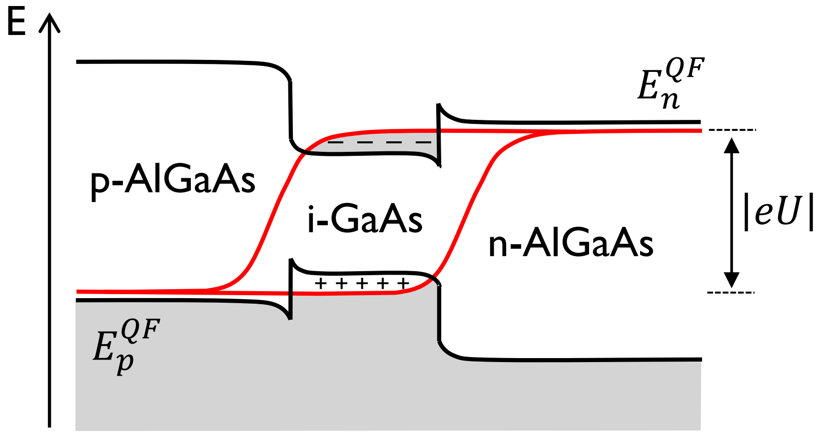




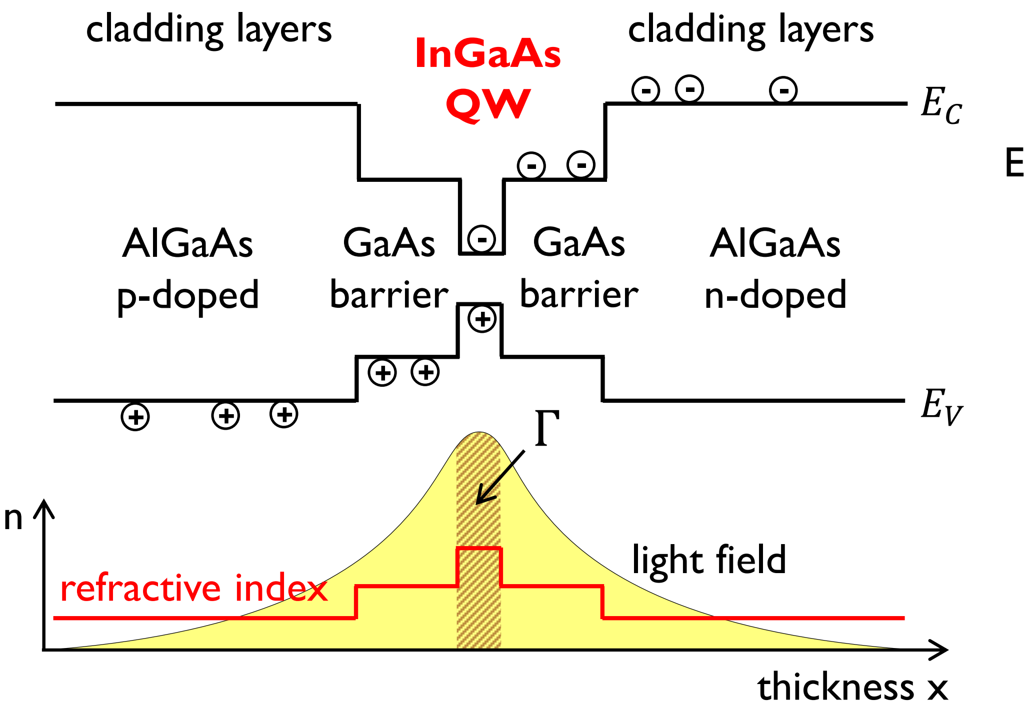
SEPARATE CONFINEMENT HETERO-STRUCTURE (SCH)



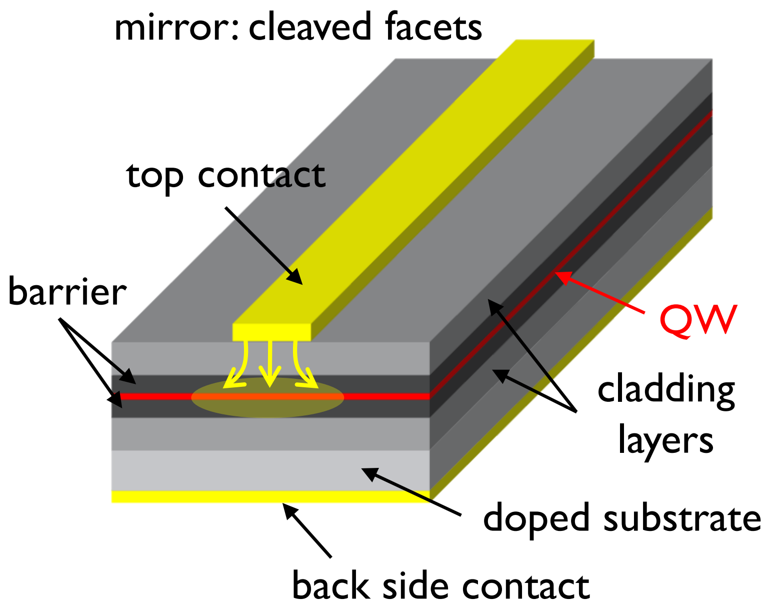
double hetero-structure p-i-n junction



EDGE EMITTER

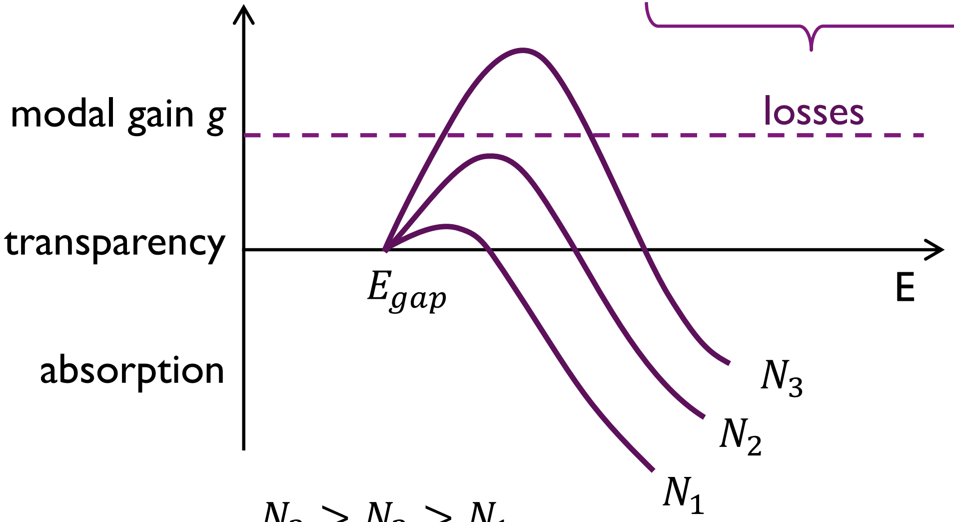


broad area laser



EDGE EMITTER: FABRY-PÉROT LASER

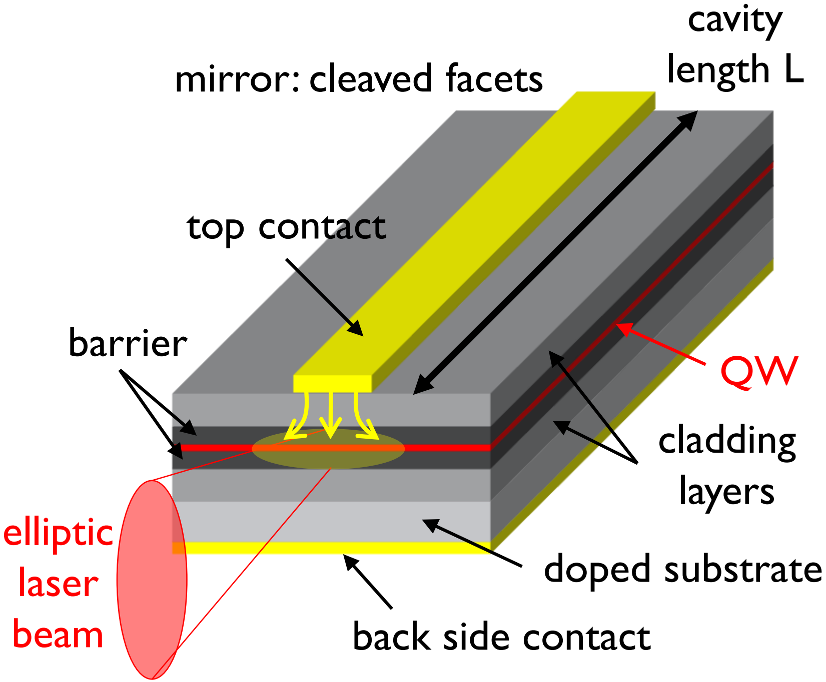
$$\underbrace{g(\hbar\omega)\cdot\Gamma}_{\text{modal gain}} > \underbrace{\alpha_{loss} + \frac{1}{L}\ln\left(\frac{1}{\sqrt{r^1 r^2}}\right)}$$



$N_3 > N_2 > N_1$

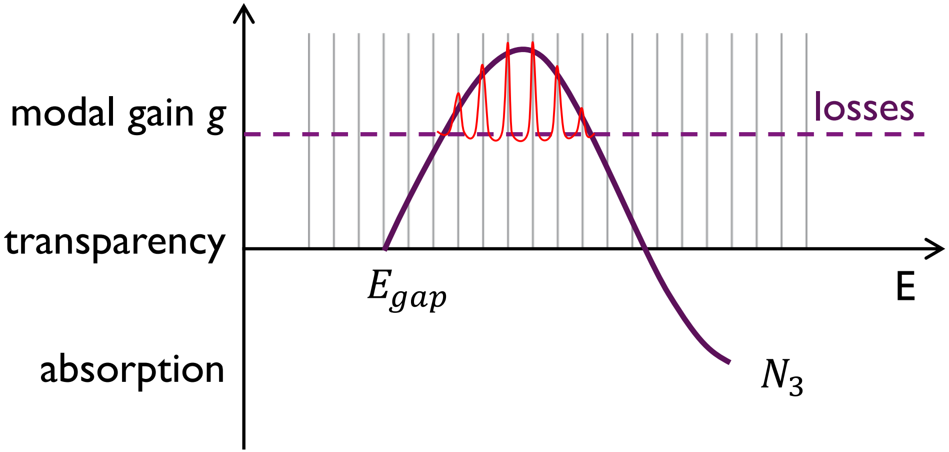
N_x carrier density, n refractive index

broad area laser

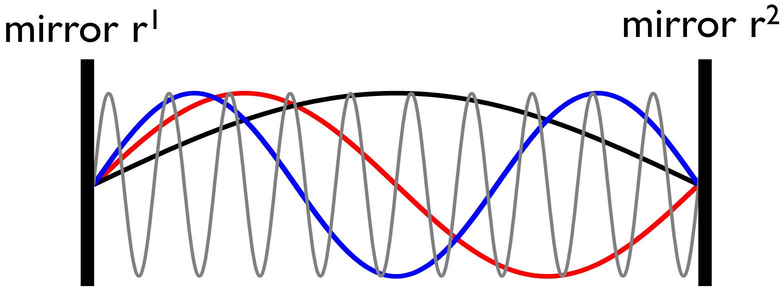


EDGE EMITTER: FABRY-PÉROT LASER

allowed modes in the Fabry-Pérot cavity



different cavity modes

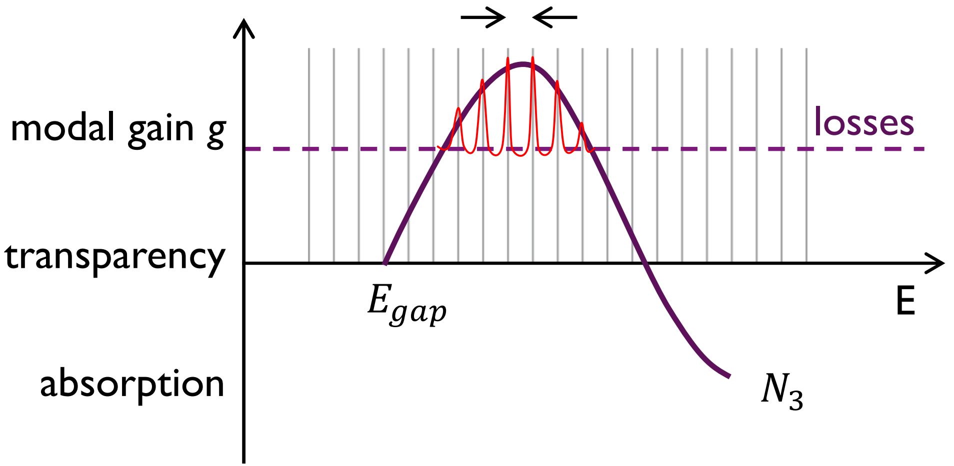


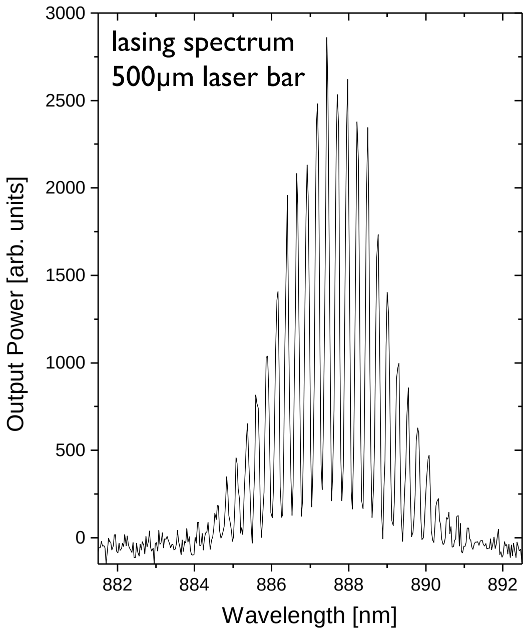
N_x carrier density, n refractive index

EDGE EMITTER: FABRY-PÉROT LASER

mode spacing: $\Delta\lambda = \frac{\lambda^2}{2n \cdot L}$ L: cavity length

$$g(\hbar\omega) \cdot \Gamma > \alpha_{loss} + \frac{1}{L}\ln\left(\frac{1}{\sqrt{r^1 r^2}}\right)$$

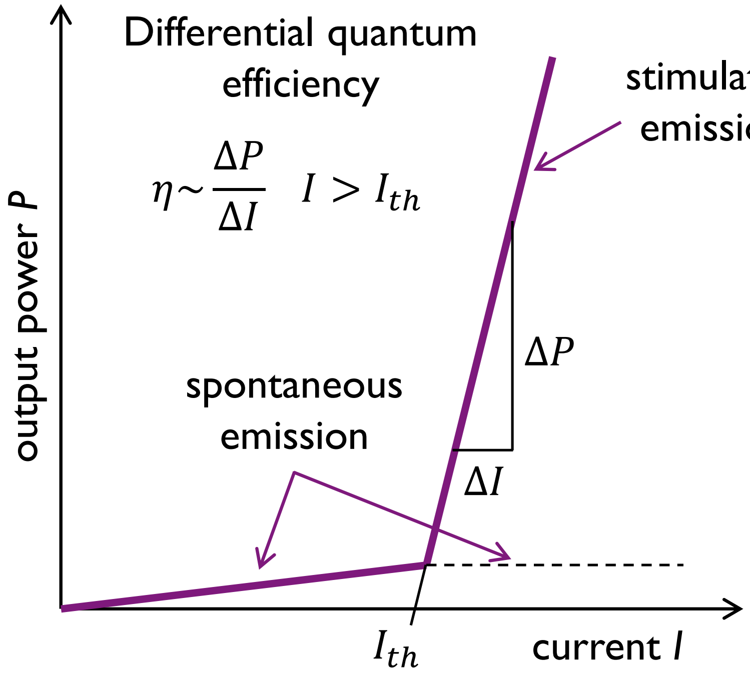




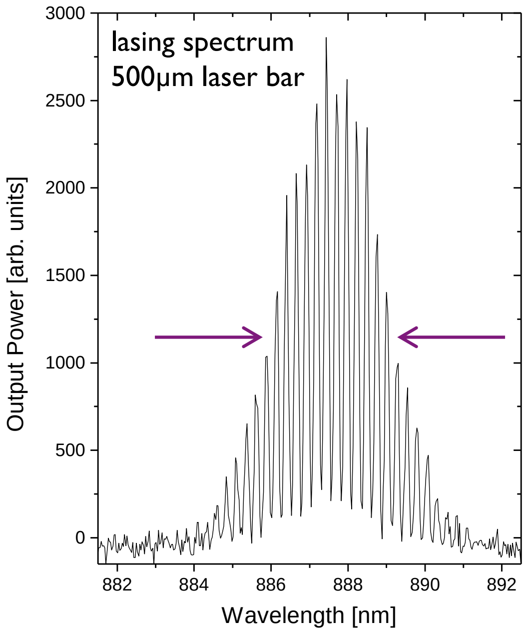
N_x carrier density, n refractive index

EDGE EMITTER: FABRY-PÉROT LASER

Characteristics of a laser!

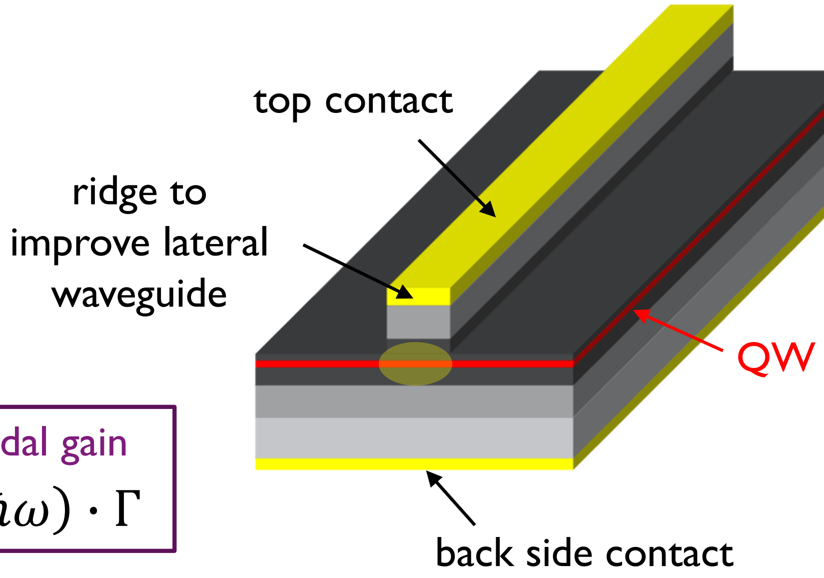


laser line width << PL line width

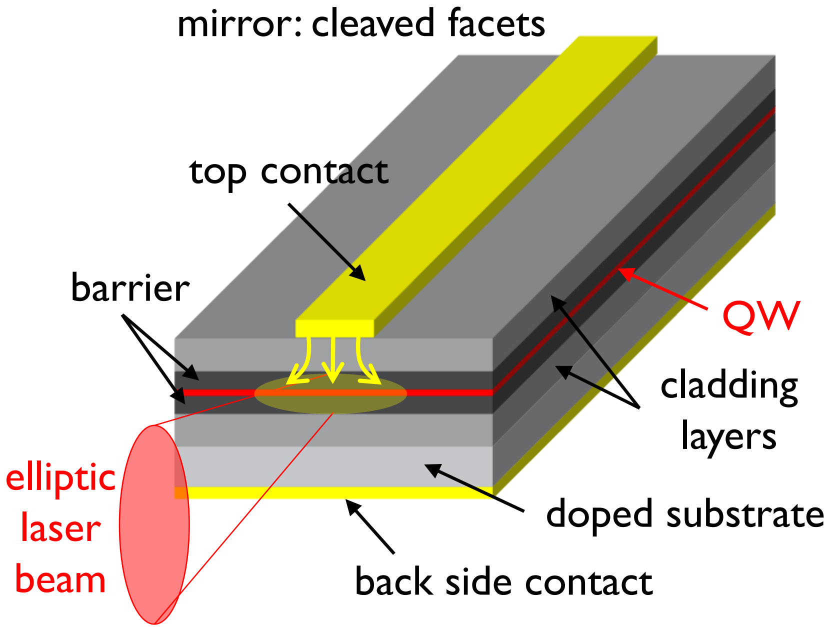


EDGE EMITTER

Fabry-Pérot Laser
ridge waveguide laser



broad area laser

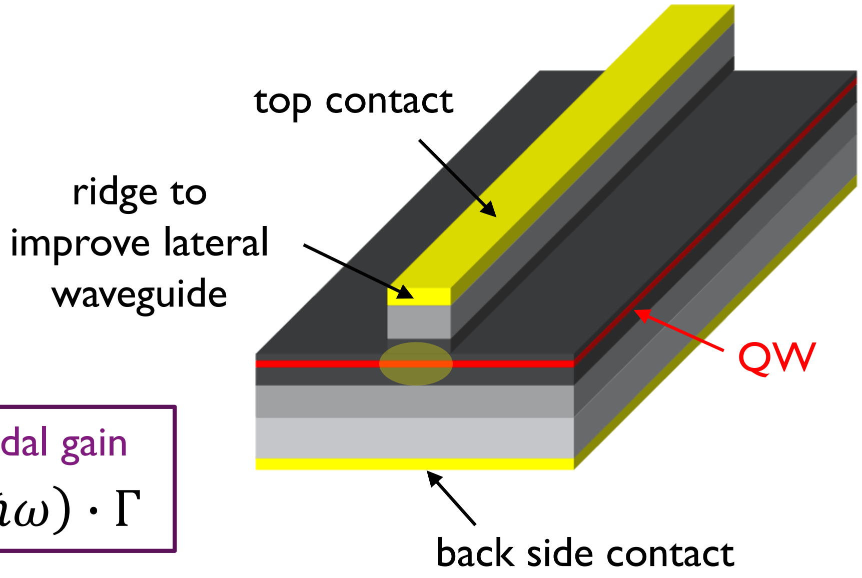


modal gain

$$g(\hbar\omega) \cdot \Gamma$$

EDGE EMITTER

Fabry-Pérot Laser
ridge waveguide laser

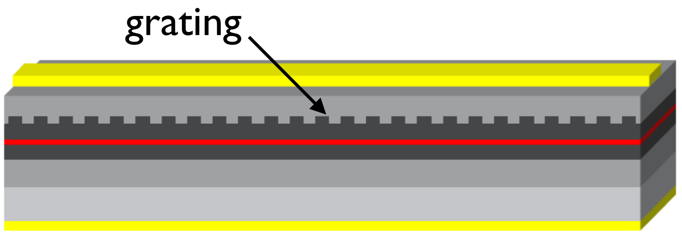


modal gain

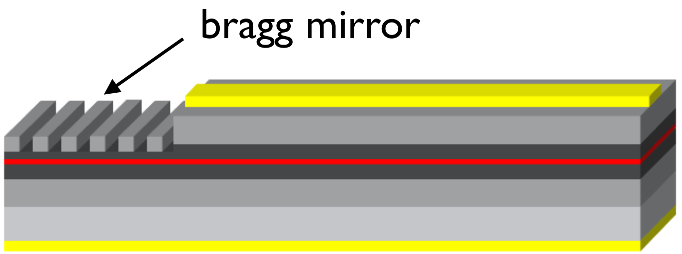
$$g(\hbar\omega) \cdot \Gamma$$

Single frequency laser

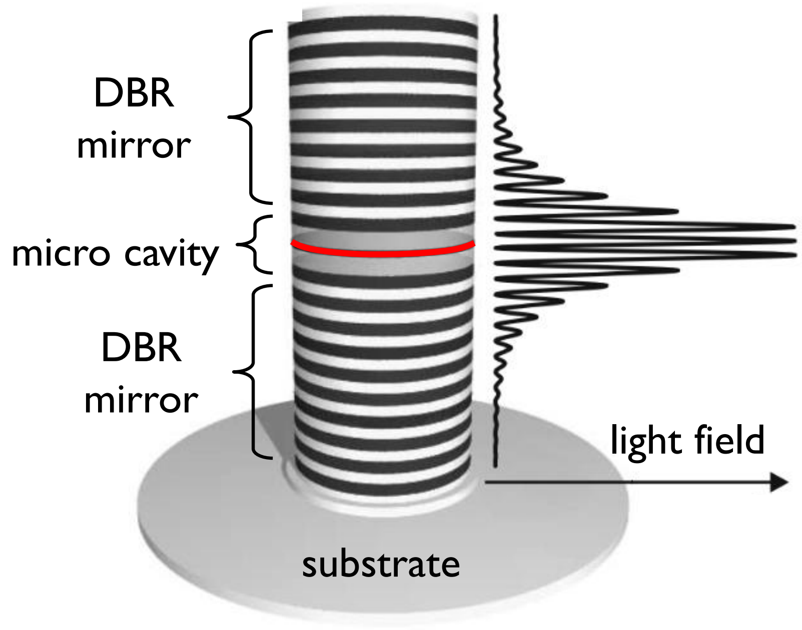
DFB Laser (Distributed Feedback Laser)

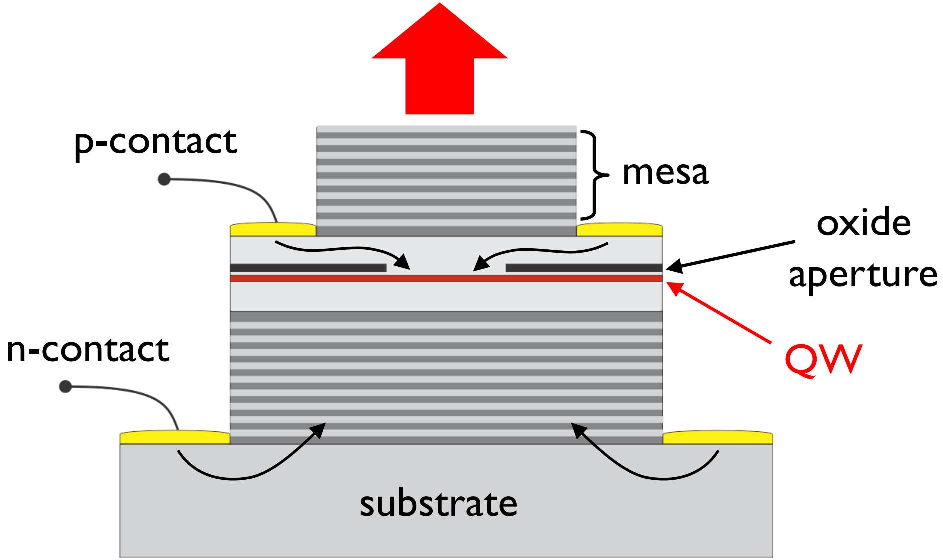


DBR Laser (Distributed Bragg Reflector Laser)



VCSEL:VERTICAL CAVITY SURFACE EMITTING LASER

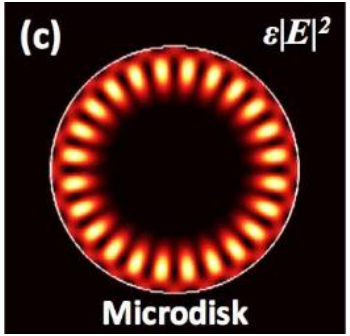




Philip Wolf, Seminar

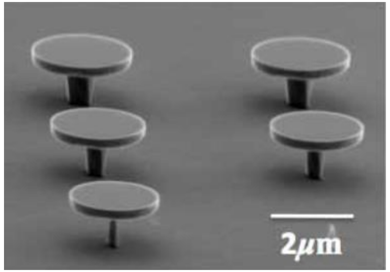
MICRO DISK LASER

Whispering Gallery-mode



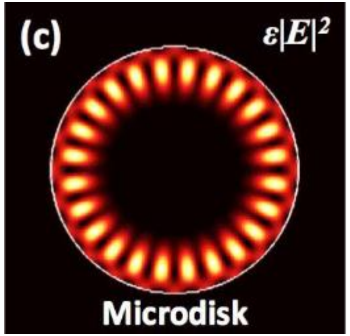
S.L. McCall, Appl. Phys. Lett. 60 (1992) 289
M. Fujita, Appl. Phys. Lett. 80 (2002) 2051
A.C. Tamboli, Nature Photonics 1 (2007) 61
M.V. Maximov, Nanosc. Research Letters, (2014) 9:657
...

micro disk resonator

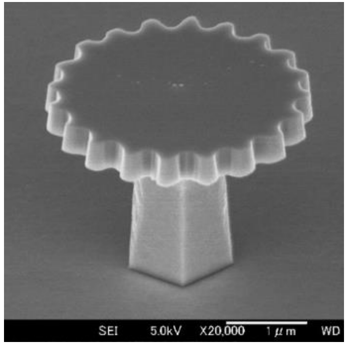


MICRO DISK LASER

Whispering Gallery-mode



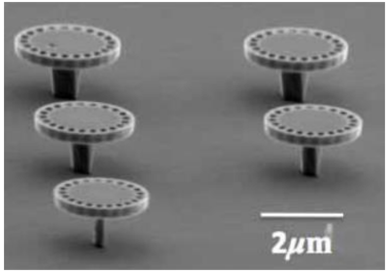
GaInAsP Microgear Disk



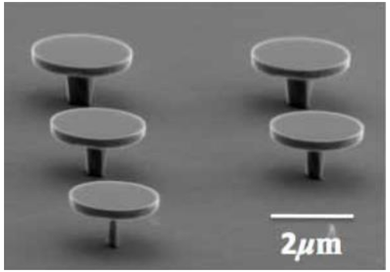
S.L. McCall, Appl. Phys. Lett. 60 (1992) 289
M. Fujita, Appl. Phys. Lett. 80 (2002) 2051
A.C. Tamboli, Nature Photonics 1 (2007) 61
M.V. Maximov, Nanosc. Research Letters, (2014) 9:657
...

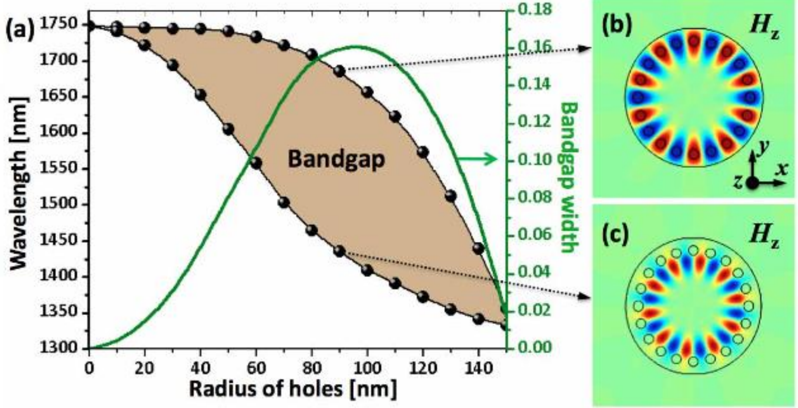
InGaAs/InAlGaAs-MQWs

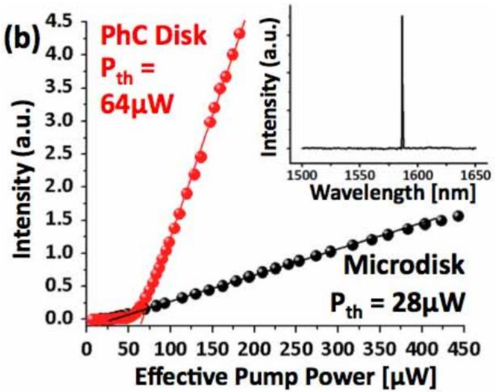
Photonic crystal resonator



micro disk resonator



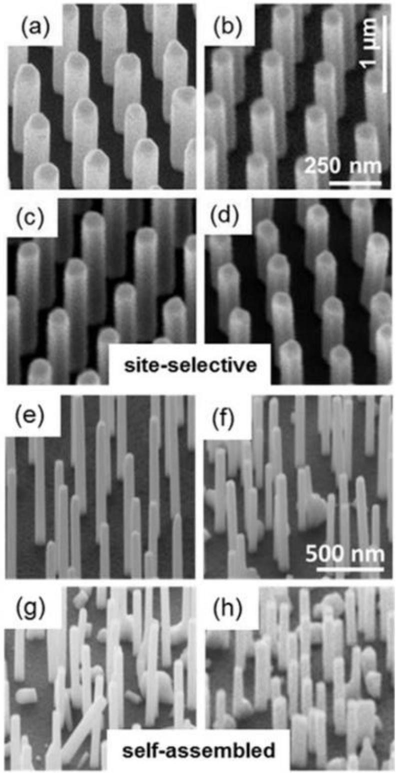




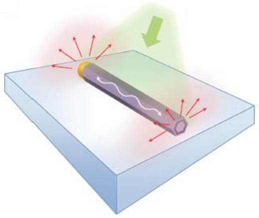
NANO WIRE LASER

InGaAs NWs

SiO_x-masked Si(111) ⇔ nano-imprinted SiO_2/Si(111) template

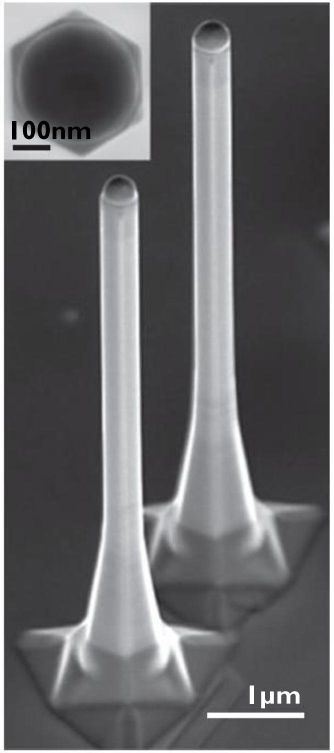


R. Yan, Nature Photonics, 3 (2009) 569
D. Saxena, Nature Photonics 7 (2013) 963
Y. Ma, Advances in Optics and Photonics 5 (2013) 216
G. Koblmüller, Phys. Status Solidi RRL 8, No. 1, (2014) 11
...



Australian National University

GaAs/AlGaAs/GaAs



Growth modes:

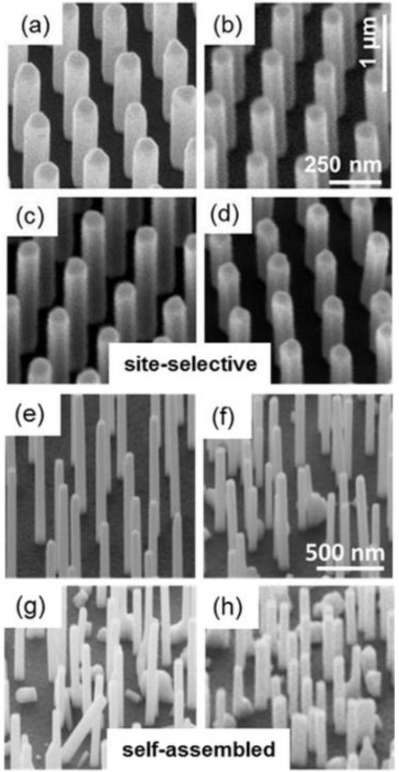
catalyst-assisted vapor-liquid-solid (VLS) growth
self-catalyzed VLS growth
catalyst-free vapor-solid (VS) growth

self-assembled or site selective

NANO WIRE LASER

SiO$_x$-masked Si(111) ⇔ nano-imprinted SiO$_2$/Si(111) template

InGaAs NWs



R. Yan, Nature Photonics, 3 (2009) 569
D. Saxena, Nature Photonics 7 (2013) 963
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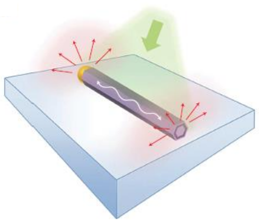
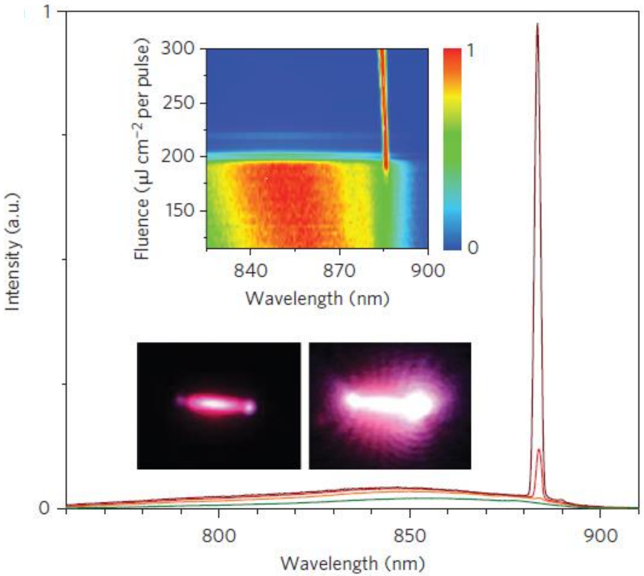
G. Koblmüller, Phys. Status Solidi RRL 8, No. 1, (2014) 11
...

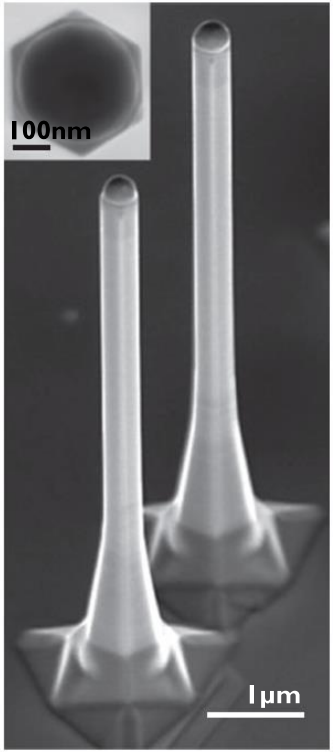


far-field optical image of
a lasing GaN nanowire



Australian National University

GaAs/AlGaAs/GaAs



LASER: SUMMARY

Light amplification by stimulated emission of radiation

1. Active region

   → material to provide gain $g(\hbar\omega)$

   Semiconductors: hetero-layers & microstructures

2. Pump (electrical or optical)

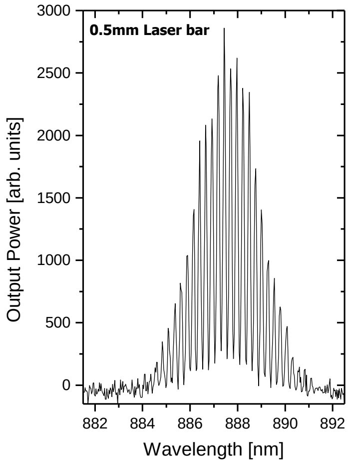
   → achieving carrier inversion: electrical carrier injection

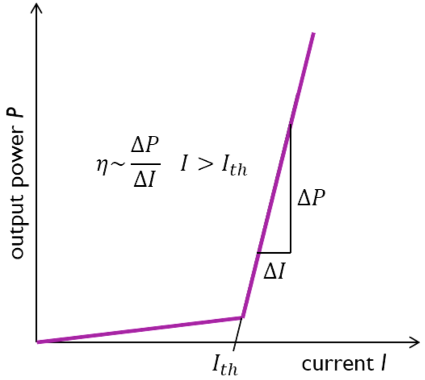
3. Resonator

   → light field back coupling

   → large overlap of the light field with the gain material: $\Gamma\uparrow$

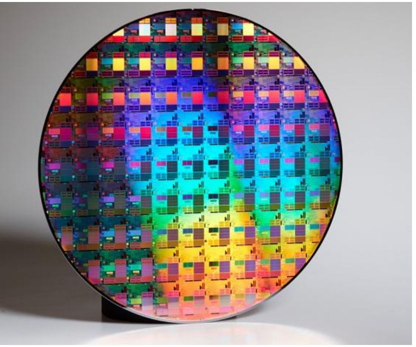
   → various types of laser design …





OUTLINE

+



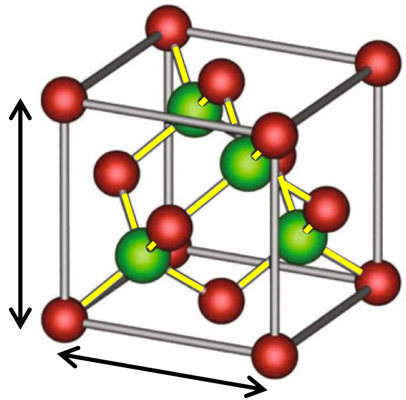
Part I: Fundamentals

- Laser
- Hetero epitaxy & defect formation

Part II: Laser integration

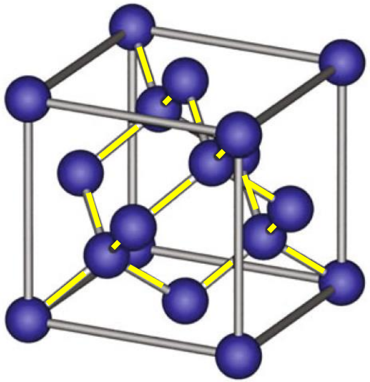
- Monolithic Hetero epitaxy

III/V SEMICONDUCTOR



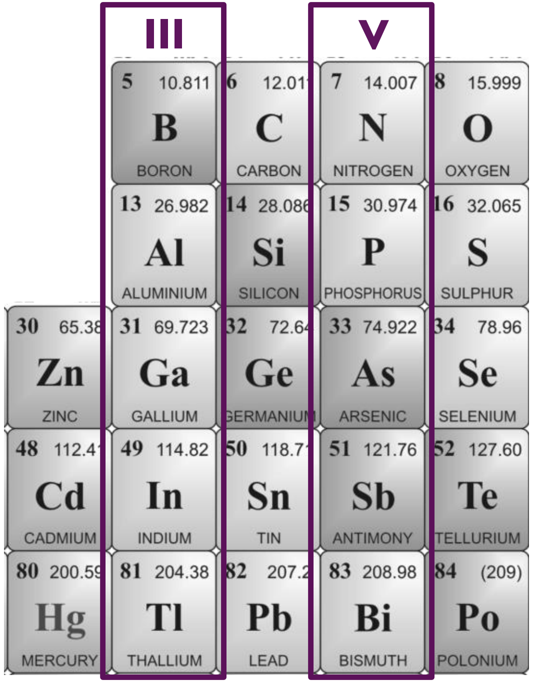
lattice constant *a*

zincblende structure
GaAs, InP, ...

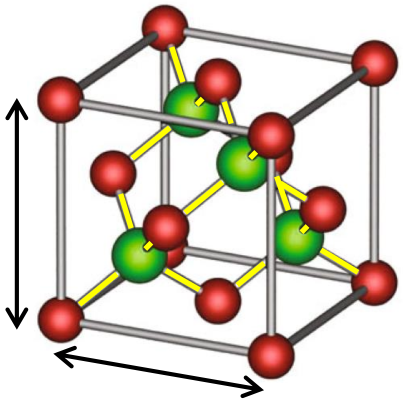


diamond structure
Si, Ge, C

always: 50% 50%

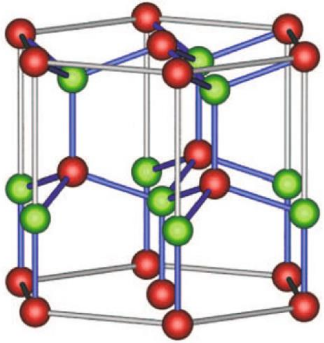


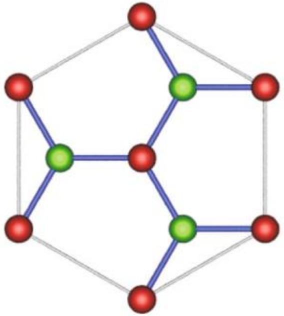
III/V SEMICONDUCTOR



lattice constant *a*

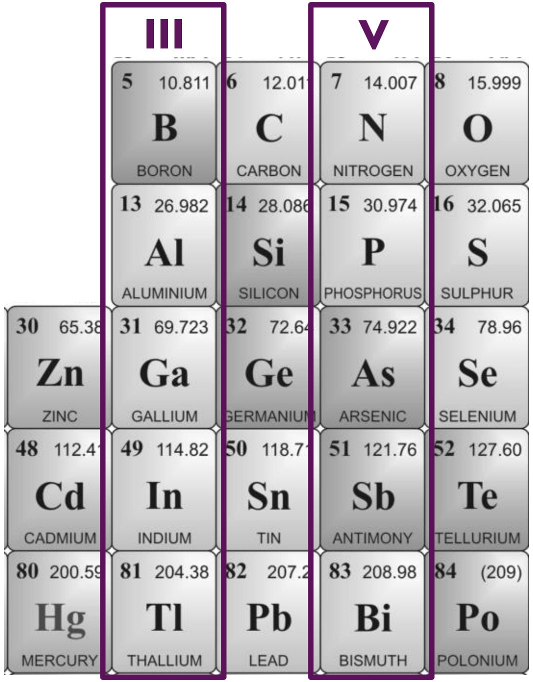
zincblende structure
GaAs, InP, ...



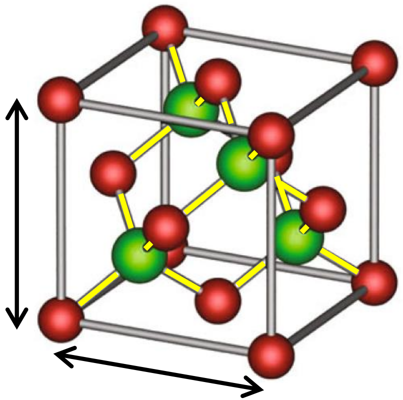


wurtzite structure
AlN, GaN, InN,
ZnS, ZnSe, ...

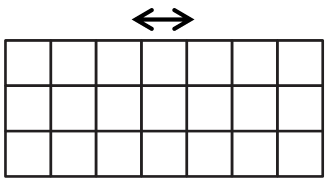
always: 50% 50%



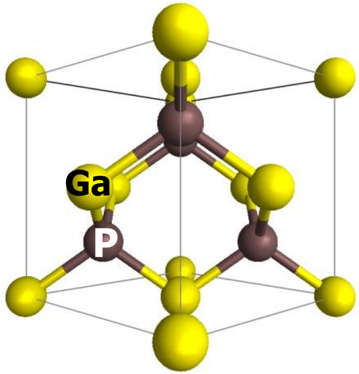
ZINCBLENDE STRUCTURE



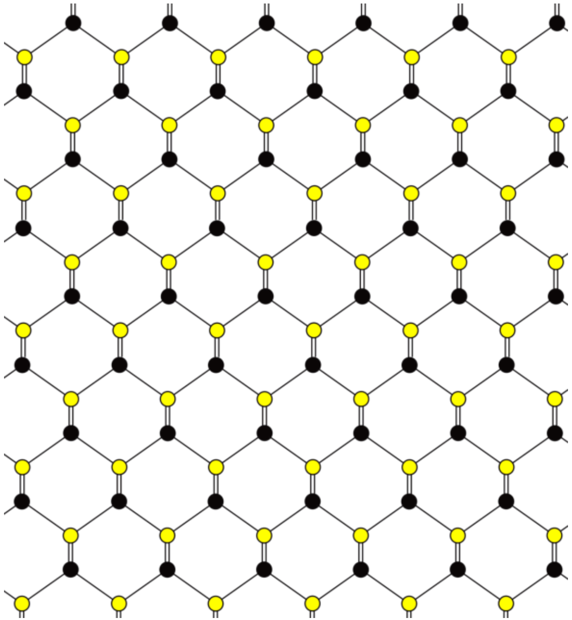
lattice constant *a*



Example: GaP

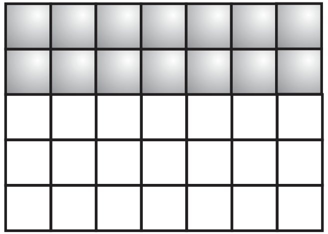


Ga-polar

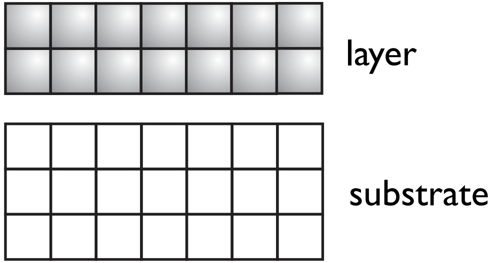


HOMO EPITAXY

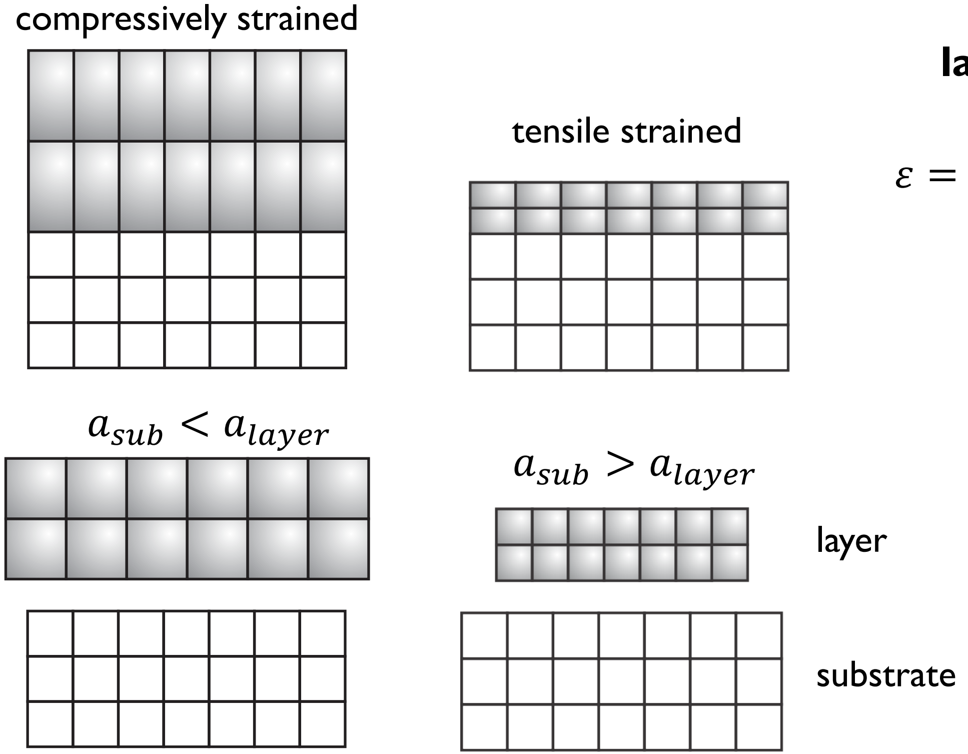
no strain



$a_{sub} = a_{layer}$



HETERO EPITAXY



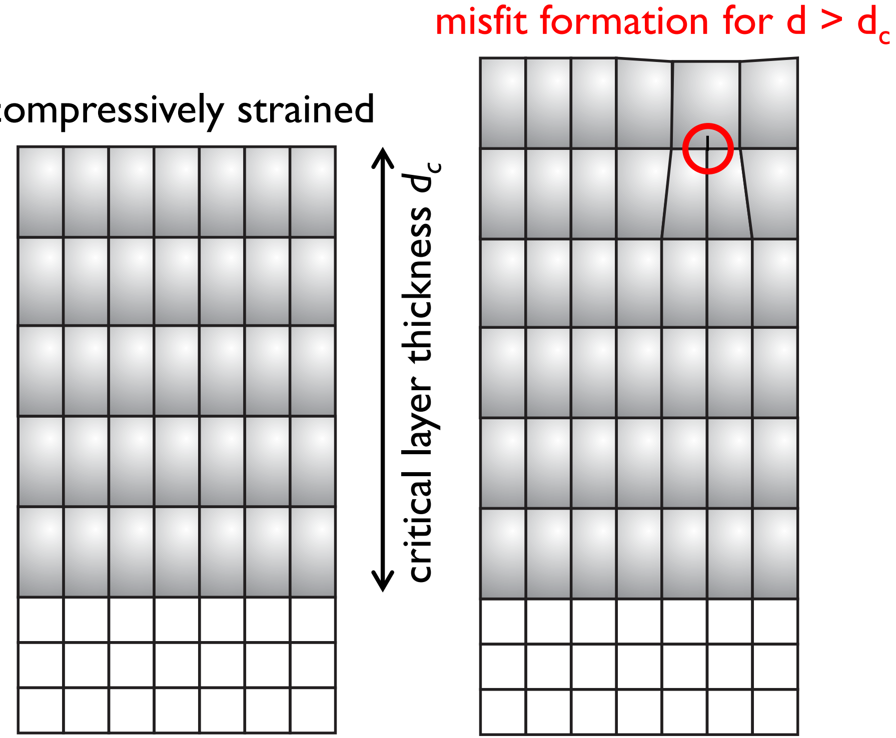
lattice strain

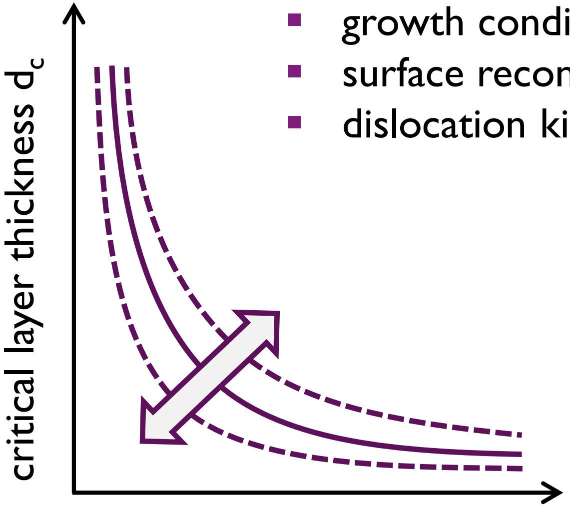
$$\varepsilon = \frac{a_{sub} - a_{layer}}{a_{layer}}$$

lattice mismatch

$$m = \frac{a_{layer} - a_{sub}}{a_{sub}}$$

MISFIT FORMATION



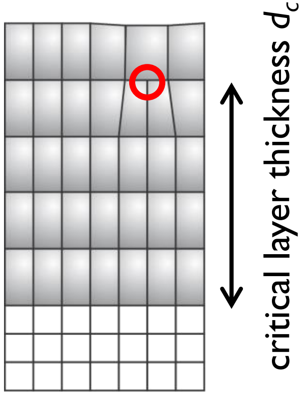


- growth conditions
- surface reconstruction
- dislocation kinetics

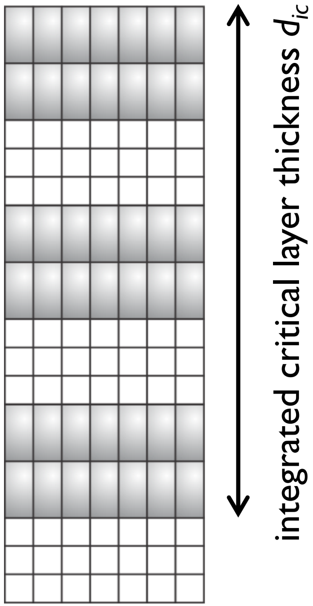
$$\varepsilon = \frac{a_{sub} - a_{layer}}{a_{layer}}$$

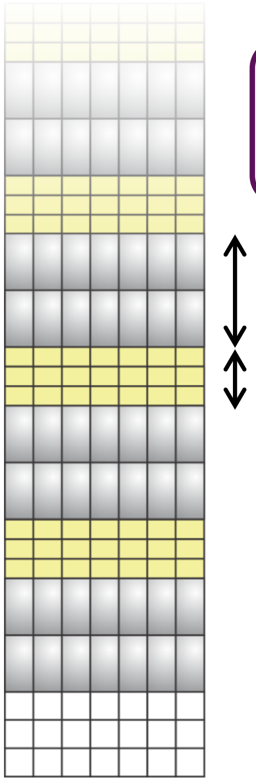
STRAIN MANAGEMENT

strained layers separated by non-strained material



strain compensation





strain balance

$$\varepsilon_{tensile} \cdot d_{tensile} + \varepsilon_{comp.} \cdot d_{comp.} = 0$$

$$d_{comp.} < d_c$$

$$d_{tensile} < d_c$$

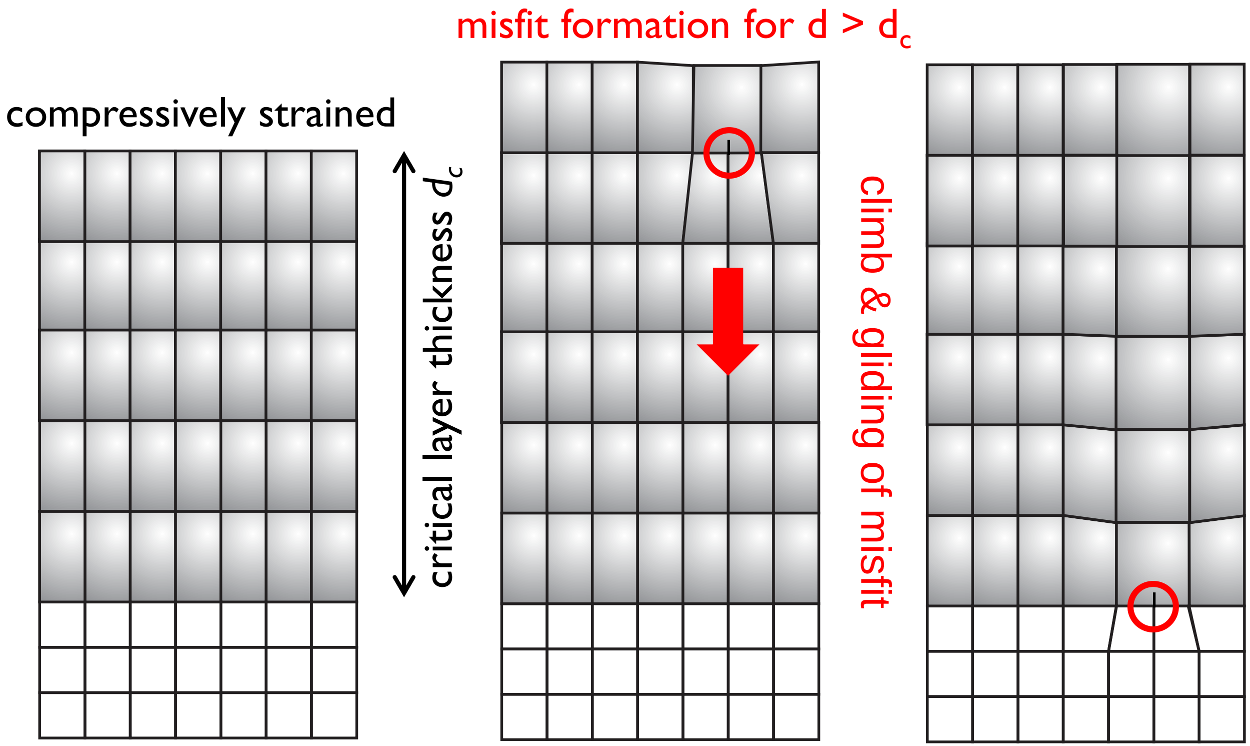
Integration of thin-strained layers:

→ multi-quantum wells in LED and lasers

→ etch-stop layers

…

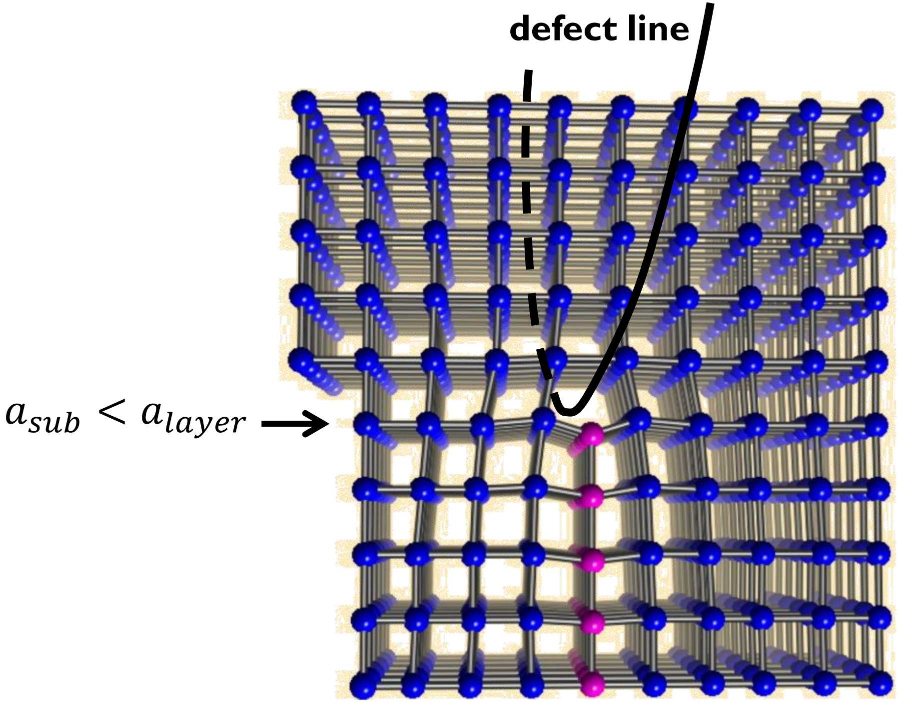
MISFIT FORMATION IN THICK LAYERS



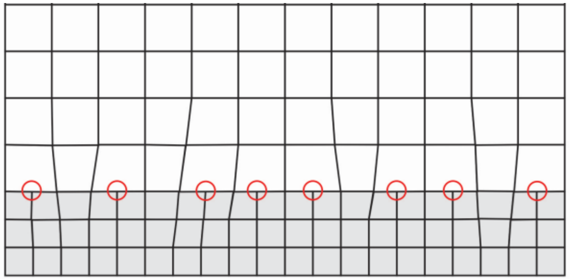
- misfit nucleation for d > d_c
- strain release most efficient at the interface: driving force for the misfit to glide/climb down towards the interface
- complex variety of misfit dislocation: 90°, 60°, partial dislocation, etc.

Misfit at the hetero interface!

THREADING & MISFIT DISLOCATIONS MD: LINE DEFECT



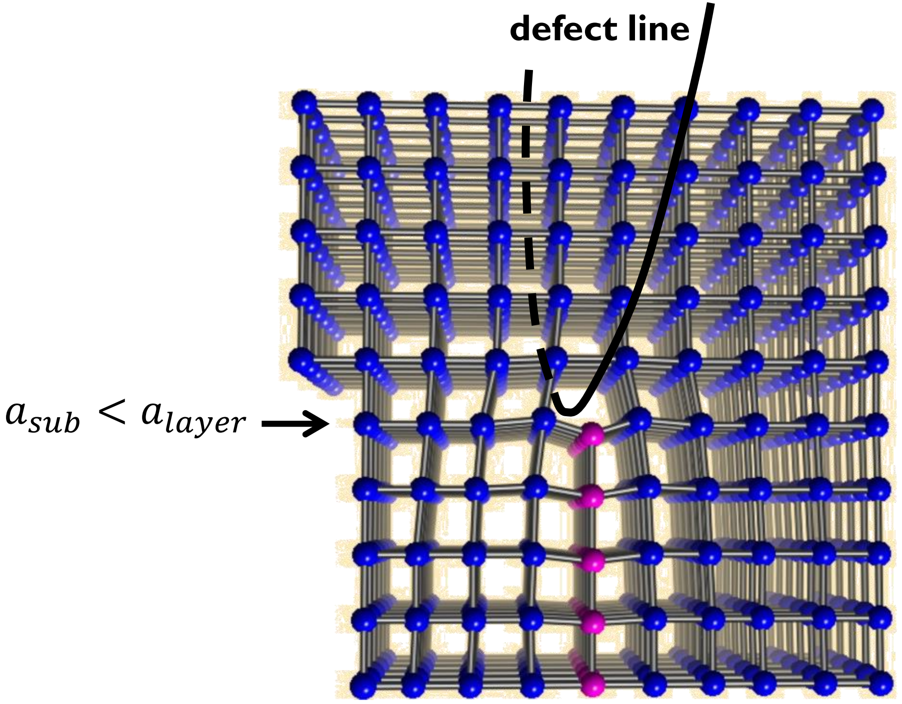
→ line defect: cannot end in the crystal!



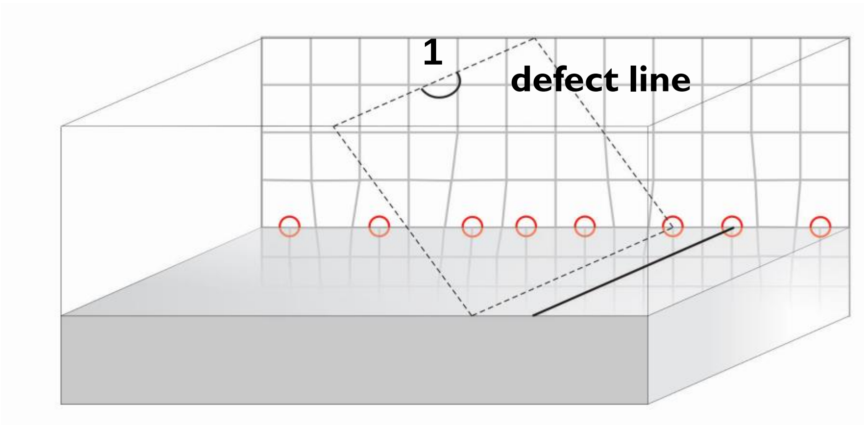
ideal case:
III/V on Si

TD: Threading dislocation, MD: Misfit dislocation

THREADING & MISFIT DISLOCATION MD: LINE DEFECT

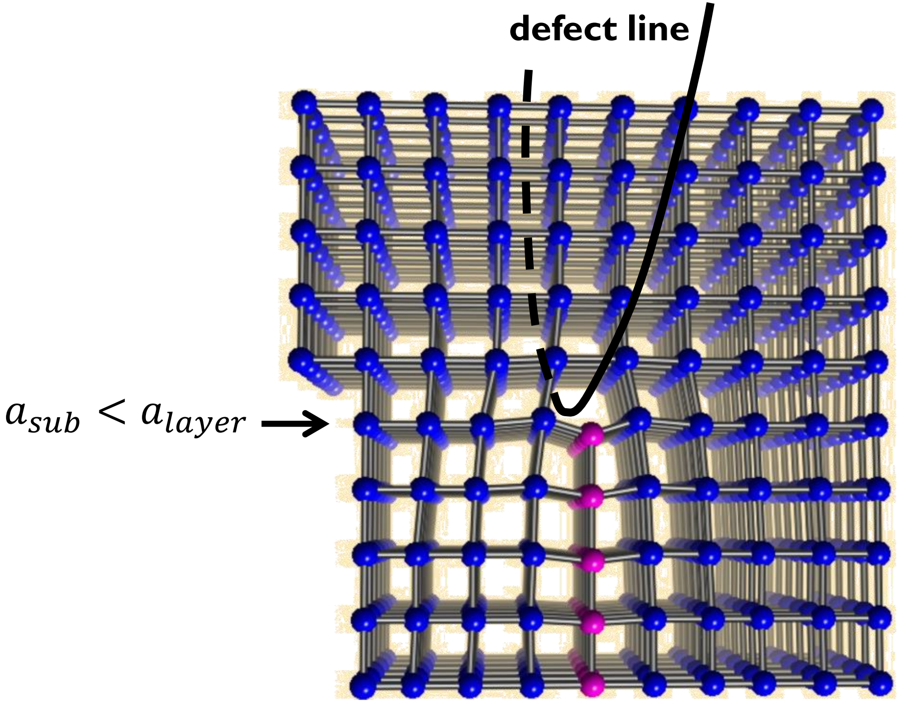


1. Defect Nucleation: Half-loop formation & motion

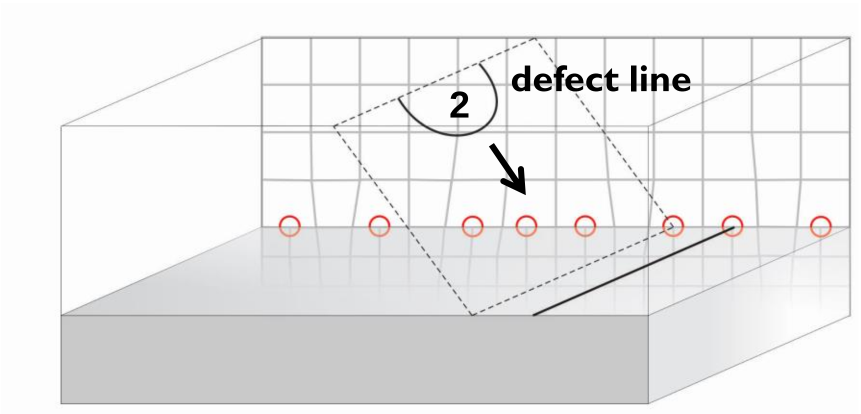


TD: Threading dislocation, MD: Misfit dislocation

THREADING & MISFIT DISLOCATION MD: LINE DEFECT

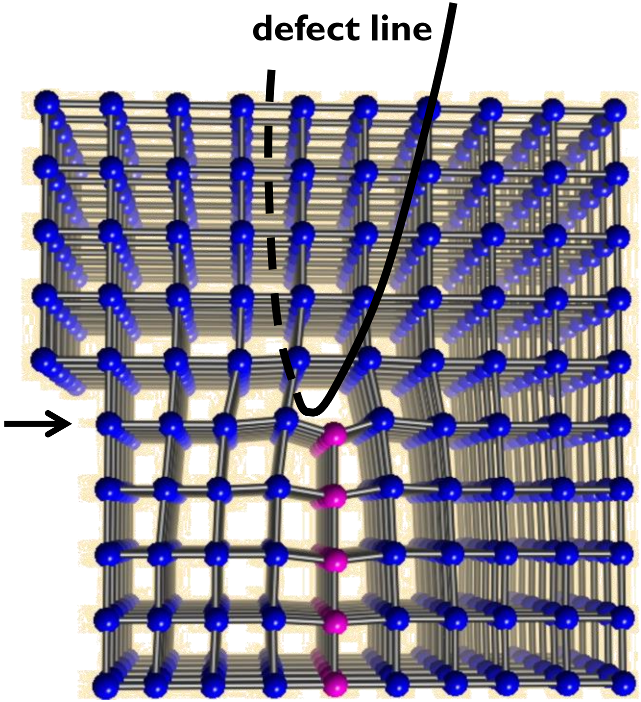


1. Defect Nucleation: Half-loop formation & motion
2. Gliding down on {111} plane towards the interface



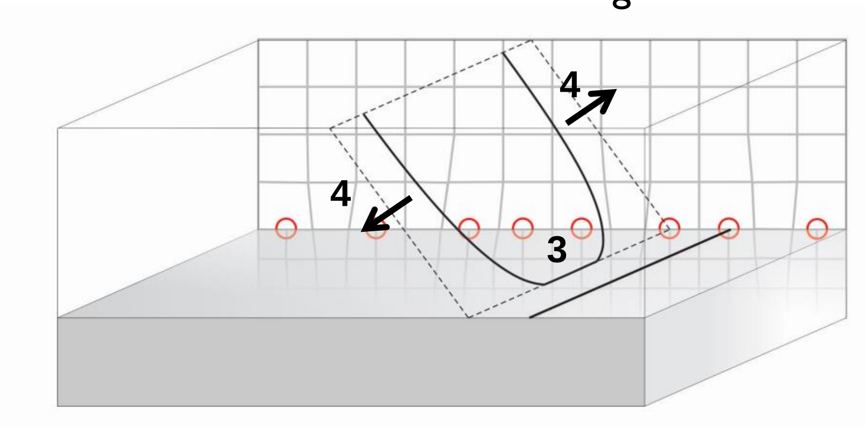
TD: Threading dislocation, MD: Misfit dislocation

THREADING & MISFIT DISLOCATION MD: LINE DEFECT



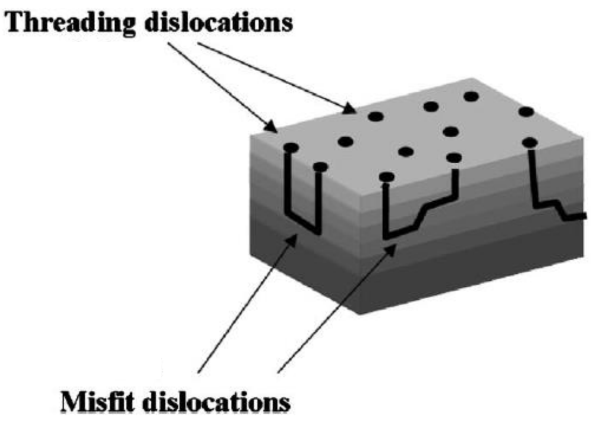
$a_{sub} < a_{layer}$ →

1. Defect Nucleation: Half-loop formation & motion
2. Gliding down on {111} plane towards the interface
3. Strain release at the hetero interface: MDs
4. Lateral movement of threading dislocations TDs



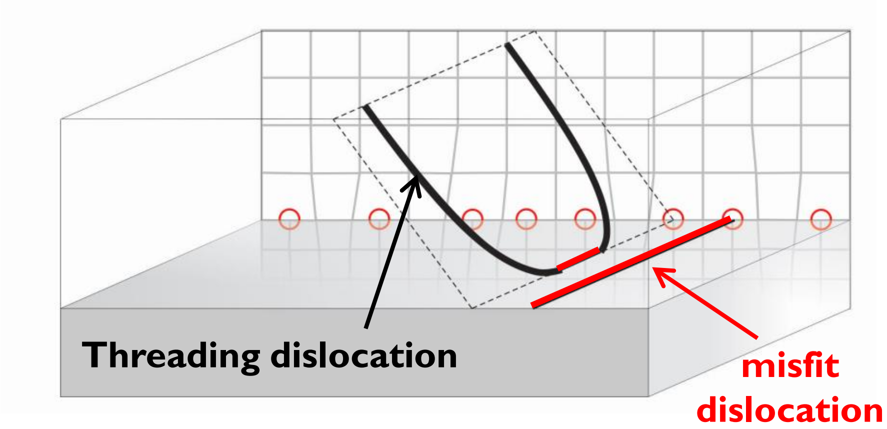
THREADING & MISFIT DISLOCATION MD: LINE DEFECT

- line defect: cannot end in the crystal!
- interaction possible: repulsing & self-annihilation



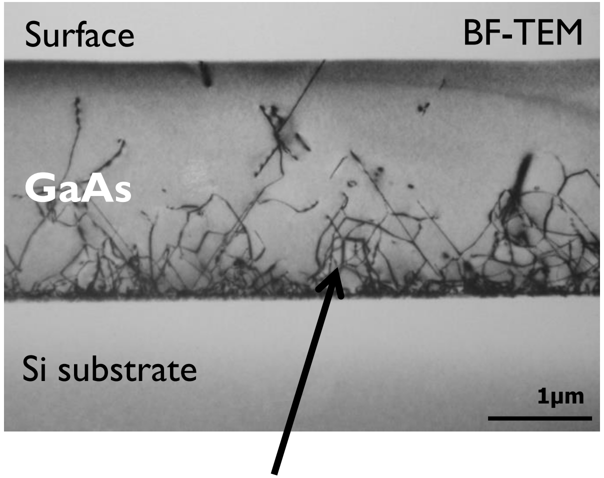
N.J. Quitoriano J. Appl. Phys. 102 (2007) 033511

1. Defect Nucleation: Half-loop formation & motion
2. Gliding down on {111} plane towards the interface
3. Strain release at the hetero interface: MDs
4. Lateral movement of threading dislocations TDs



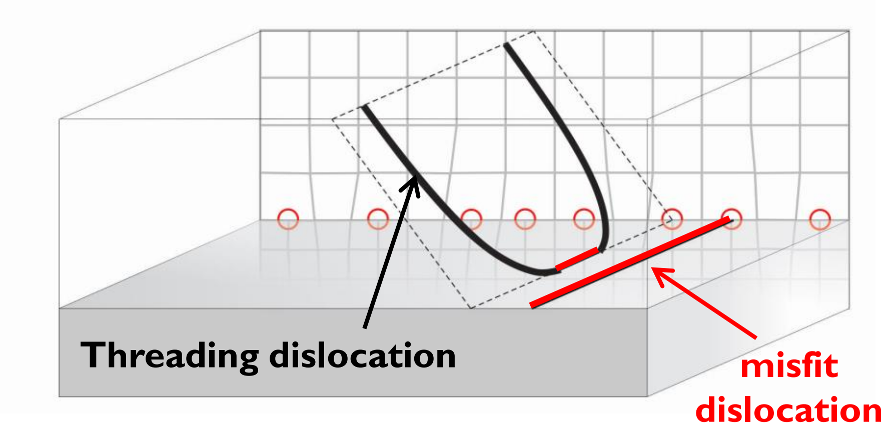
TD: Threading dislocation, MD: Misfit dislocation

THREADING & MISFIT DISLOCATION MD: LINE DEFECT



Threading dislocation network:
High defect density!

1. Defect Nucleation: Half-loop formation & motion
2. Gliding down on {111} plane towards the interface
3. Strain release at the hetero interface: MDs
4. Lateral movement of threading dislocations TDs

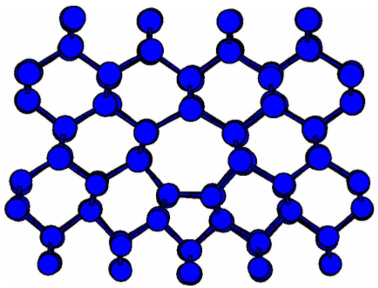


TD: Threading dislocation, MD: Misfit dislocation

MISFIT DISLOCATION

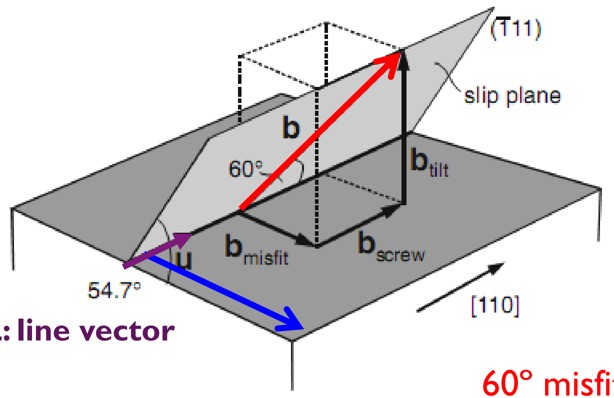
- open/faults bonds
- strong distortion – local strain
- line defect - defined by "burger vector"
- Dynamics of dislocations: low energy for gliding along the slip plane – high energy for climbing perpendicular to the slip plane

high mismatch



90° misfit dislocation

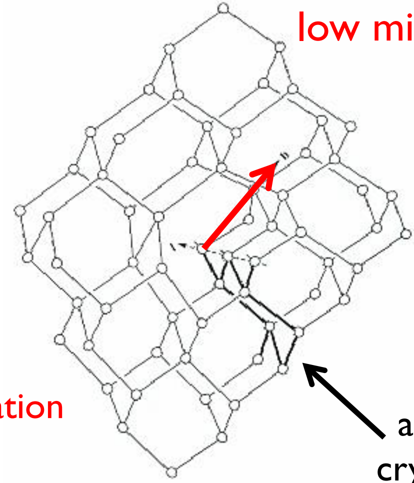
b ⊥ L



60° misfit dislocation

L ⊾ b = 60°

low mismatch

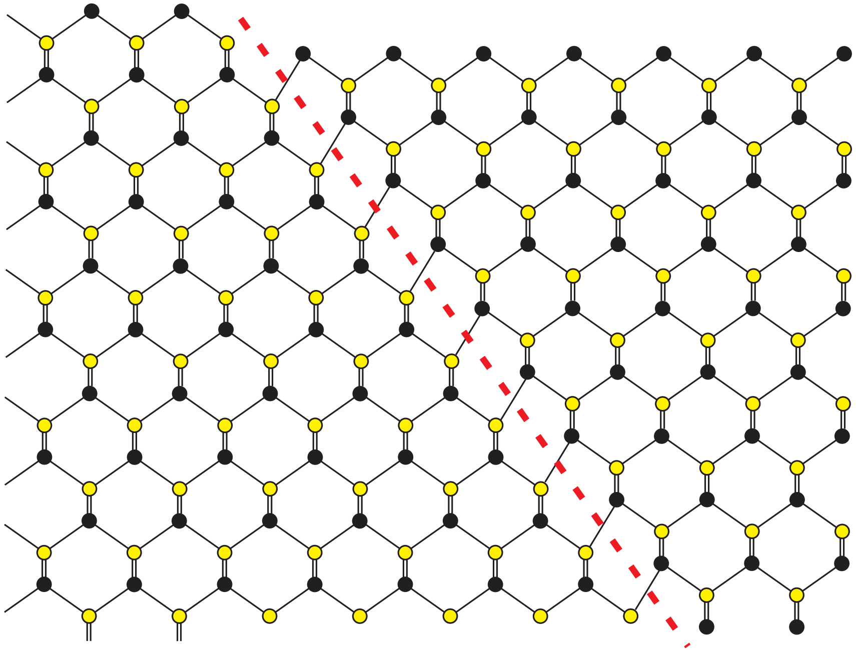


additional crystal plane

E. Spieker, J. Phys.: Condens. Matter 14 (2002) 12767–12776

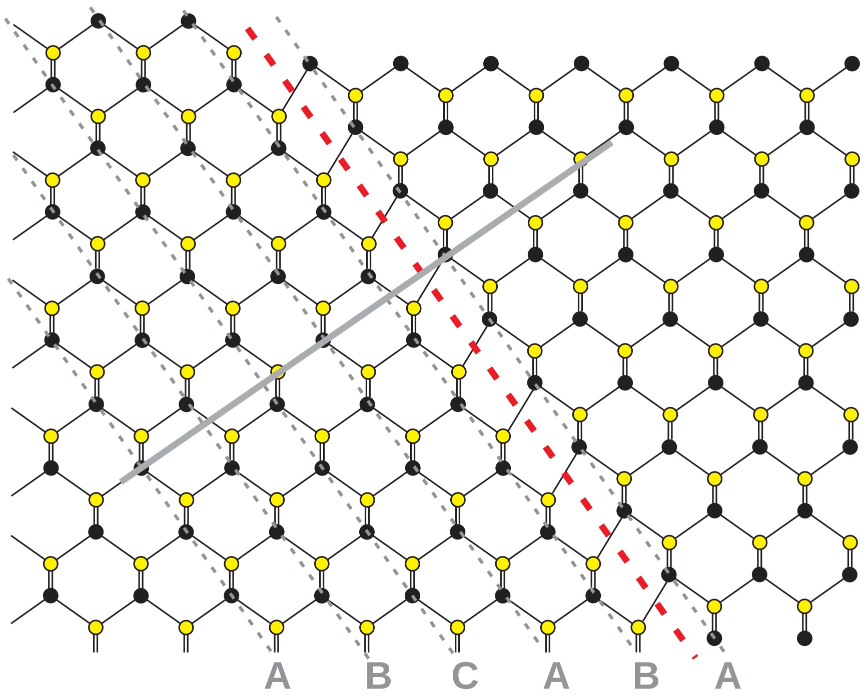
STACKING FAULT

- no open/wrong bonds
- slight distortion
- wrong stacking sequence along {111}
  - different version
- planar defect



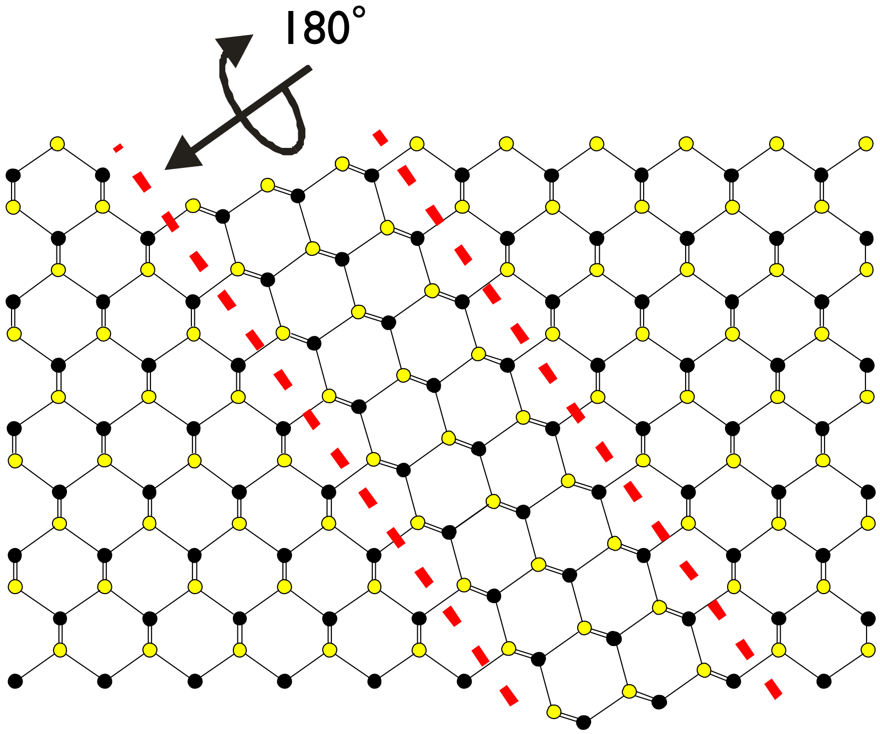
STACKING FAULT

- no open/wrong bonds
- slight distortion
- wrong stacking sequence along {111}
  - different version
- planar defect



TWINS

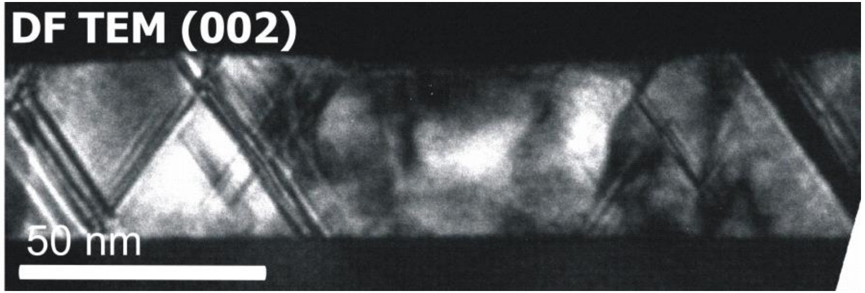
- no open/wrong bonds
- slight distortion
- rotated crystal area
- planar defect

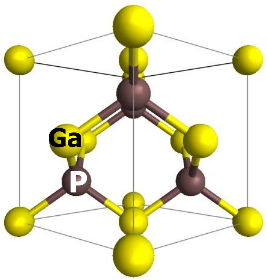


HIGH RESOLUTION TEM: TWINS

GaP

Si

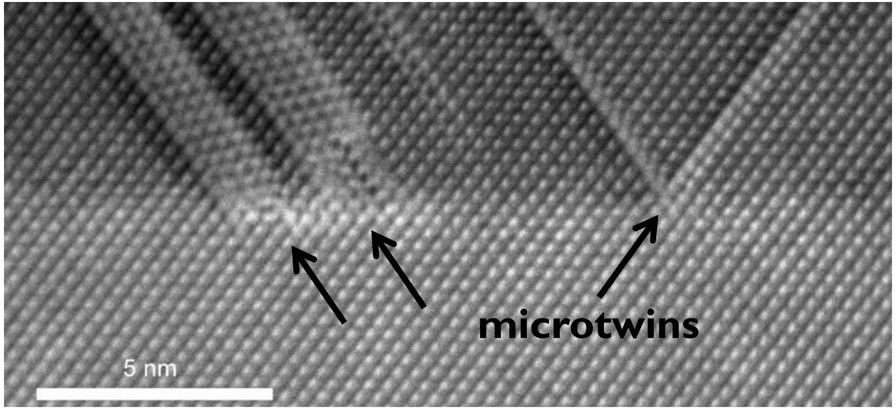


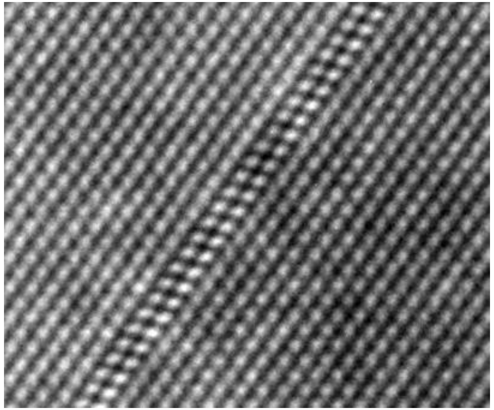


thin twin area:
microtwin

GaP

Si





[PhD Igor Nemeth, Philipps University Marburg 2008]

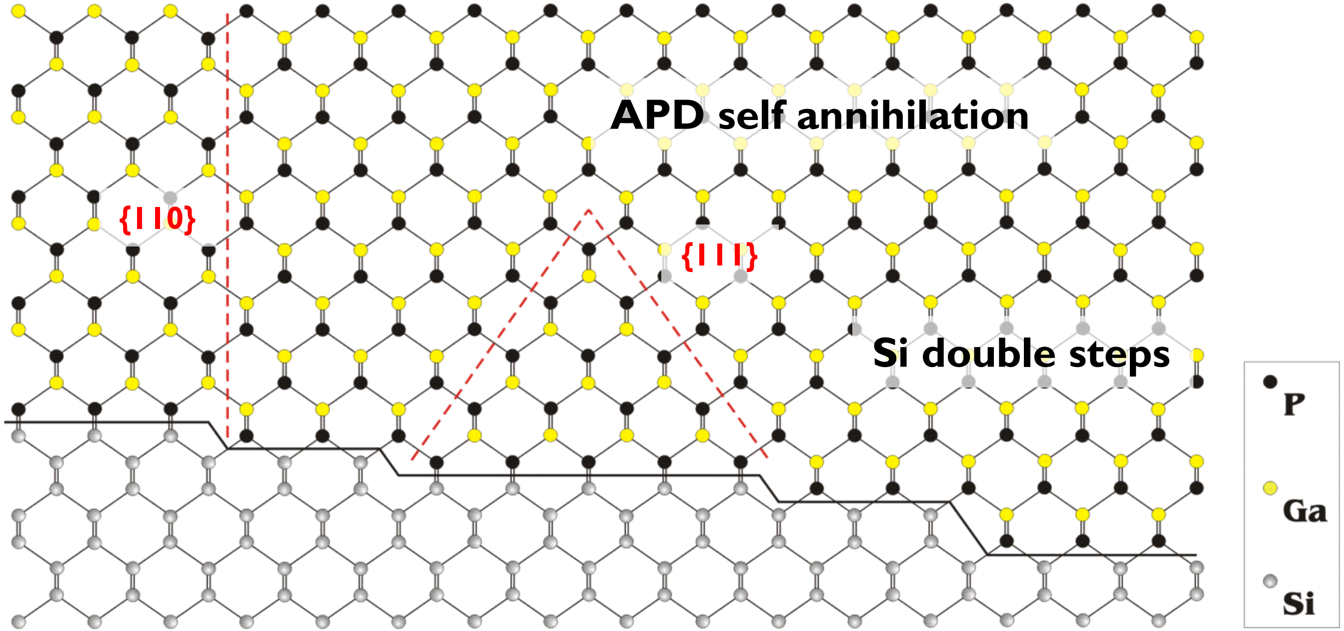
ANTI-PHASE DOMAINS: APD

substrate specs

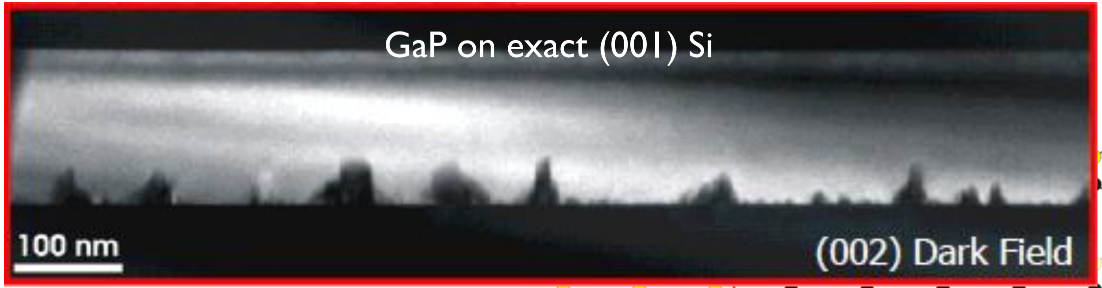
- exact (001): more difficult to achieve double steps
- easier on offcut: (001) 2° - 6°

→ mainly applied!

anti-phase boundary along {110}



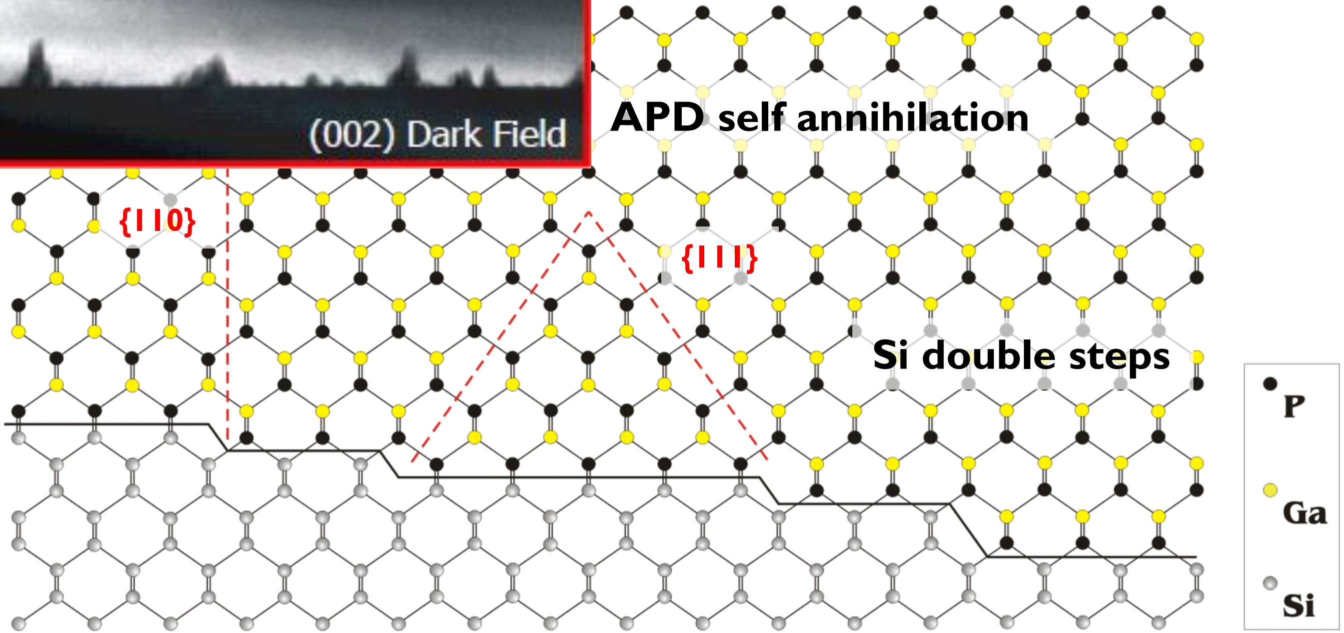
ANTI-PHASE DOMAINS: APD



B. Kunert, Thin Solid Films 517 (2008) 140
K. Volz, J. Crystal Growth 315 (2011) 37

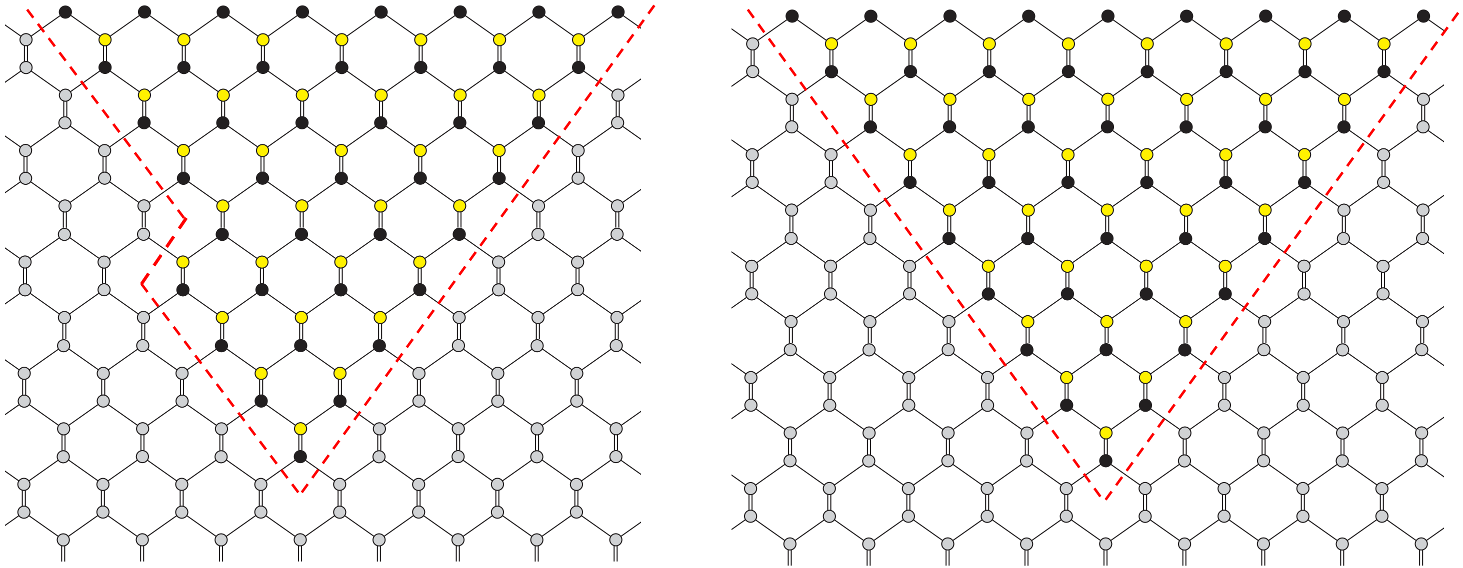
- easier on offcut: (001) 2° - 6°

→ mainly applied!



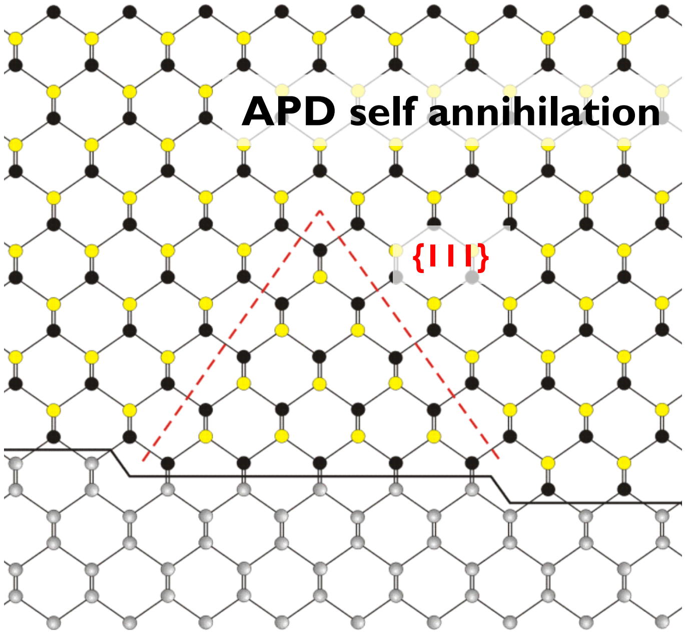
V-SHAPE APPROACH

- III/V growth in {111} trenches: less APD formation

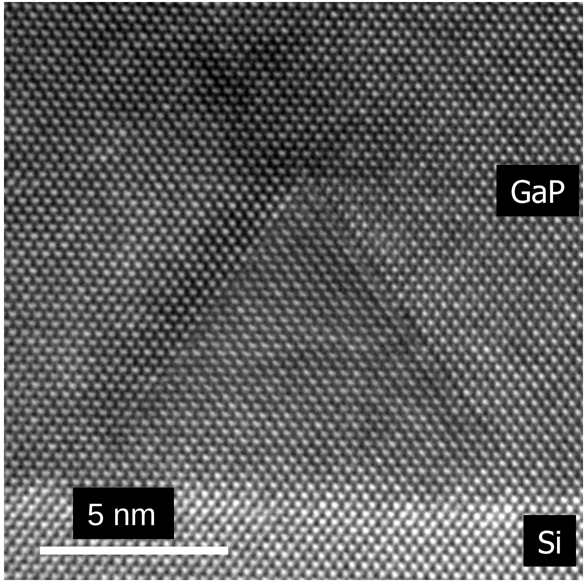


M. Paladugu et al., Cryst. Growth Des., (2012) 12 (10), pp 4696

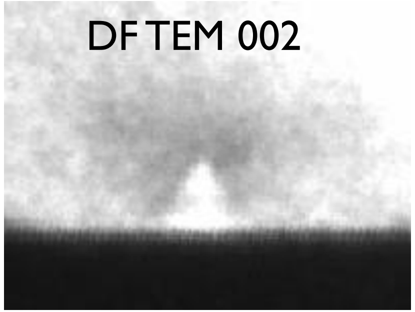
TEM INVESTIGATION: APD

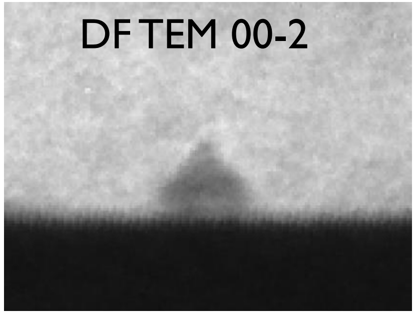


High resolution TEM



Dark field image:

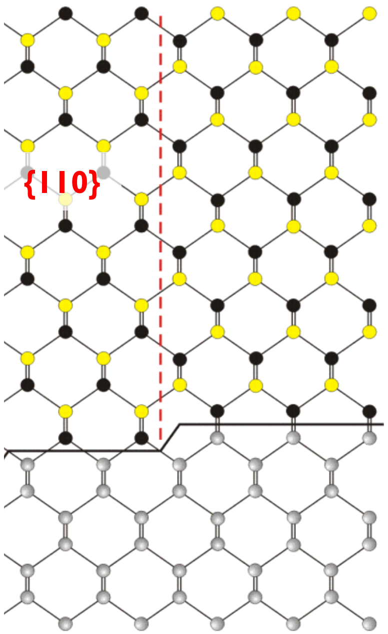


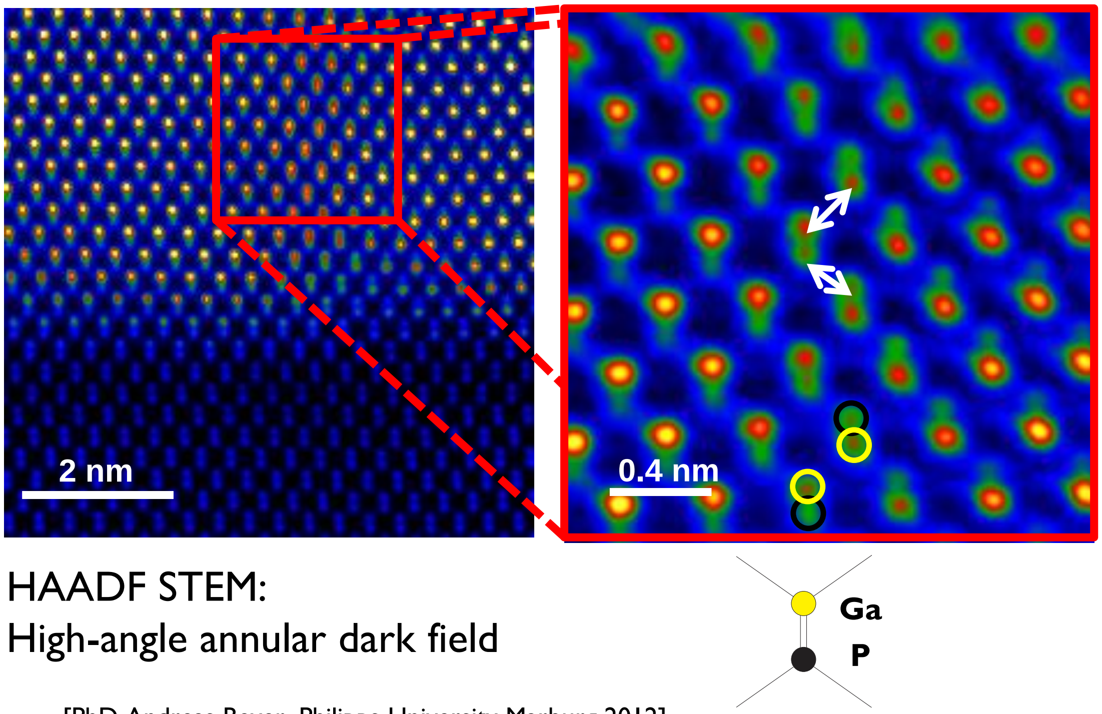


[PhD Igor Nemeth, Philipps University Marburg 2008]

ANTI-PHASE DOMAINS: APD

APB along {110}



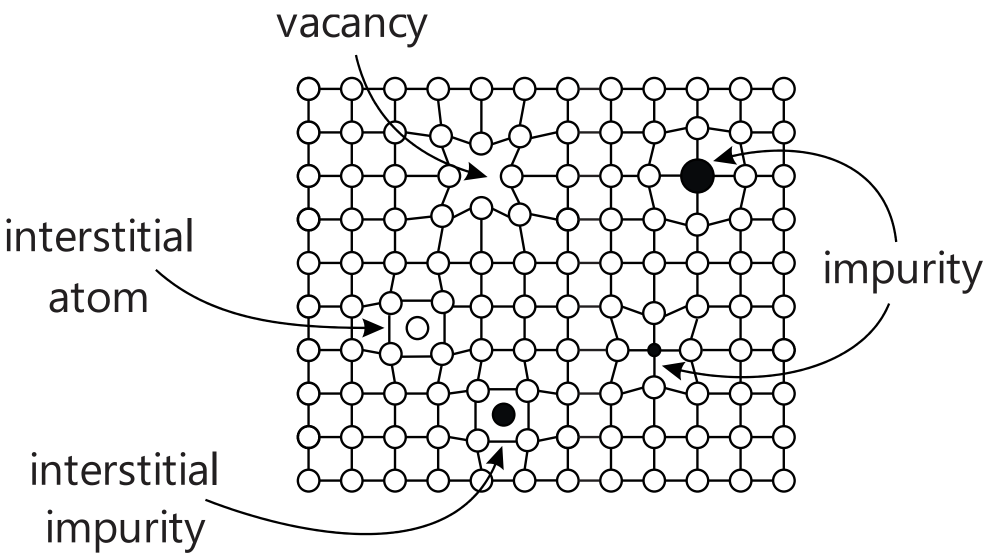


HAADF STEM:
High-angle annular dark field

[PhD Andreas Beyer, Philipps University Marburg 2012]

POINT DEFECTS

- very localized defects
- can act as dopant or carrier trap
- crucial for device performance
- MOVPE: high risk of C-incorporation at low growth temperature

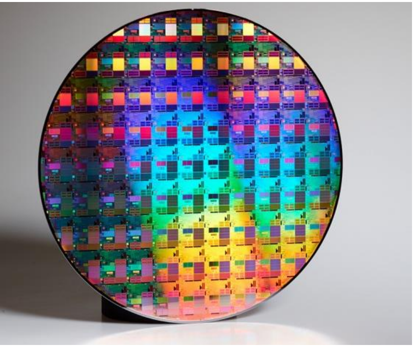


SUMMARY: DEFECT OVERVIEW

Type	Cause/origin	Characteristics
misfits & threading dislocations	**lattice mismatch/strain**	▪ **line defect!** ▪ **strong distortion – local strain** ▪ **open/faults bonds** → **causing dark line defects DLDs**
twins & stacking faults	strain, impurities and wrong growth conditions	▪ planar defect! ▪ slightly strained boundary ▪ no open/faults bonds
anti phase domains/boundary	due to different crystal base	▪ planar defect! ▪ strained boundary ▪ faults bonds – can be highly charged!
point defects & impurities	wrong growth conditions, contamination via tool & sources	▪ can act as doping and carrier trap

OUTLINE

+



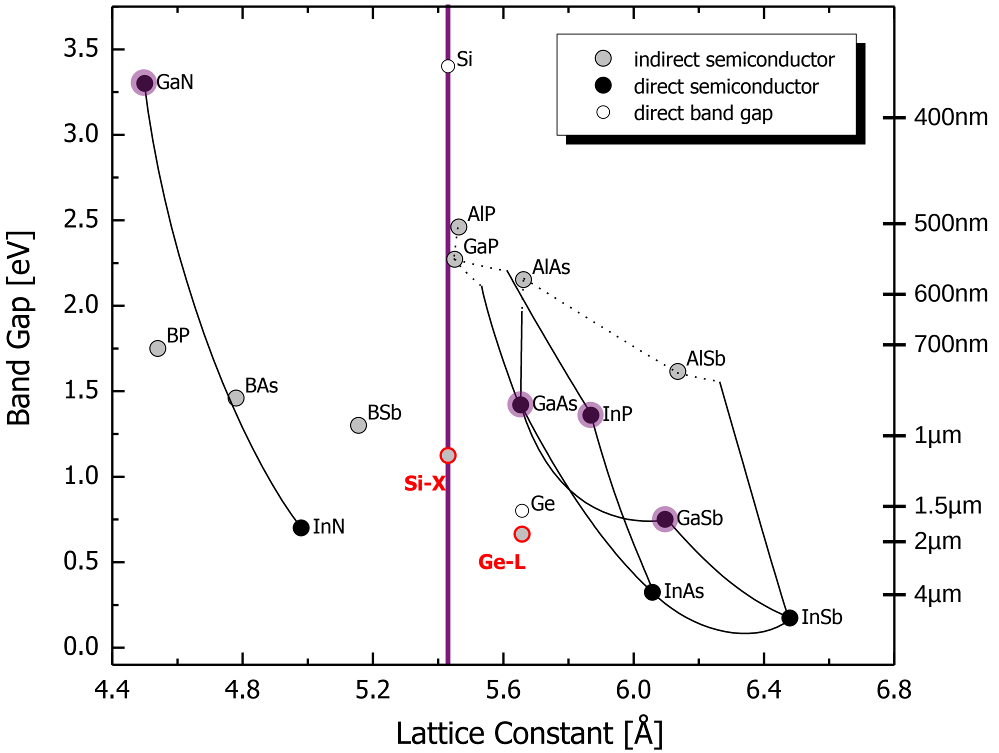
Part I: Fundamentals

- Laser
- Hetero epitaxy & defect formation

Part II: Laser integration

- Monolithic Hetero epitaxy

CHALLENGES FOR LASER ON SI



III/V laser materials on Si:

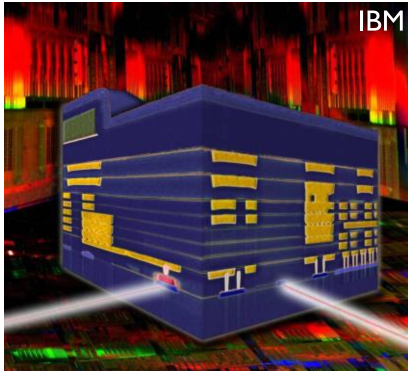
- Large lattice mismatch
  - → defect formation to release strain
- different lattice structure
  - → antiphase-disorder
- different expansion coefficient
  - → introducing strain during cooling down after growth
- risk of cross-doping between group IV and III/V

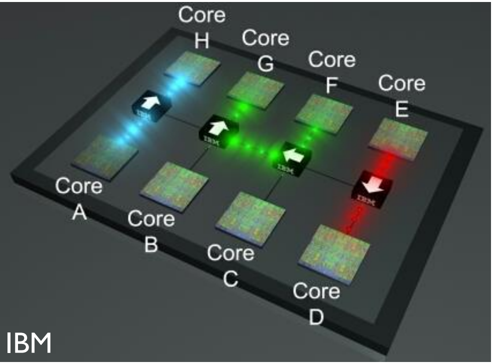
Group IV: Si and Ge are indirect!?

LASER INTEGRATION

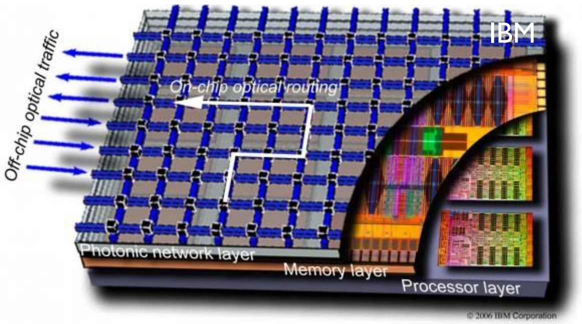
Device requirements

- sufficient power & **life time (CW)**
- compatible to the current CMOS process
- easy to process/fabricate in mass production
- cheap!!!





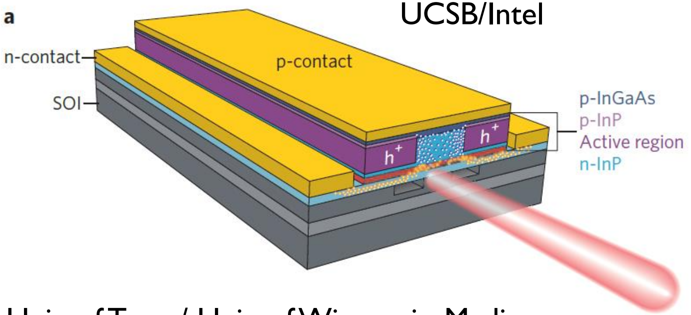
- ❖ **III/V Hybrid integration**
- ❖ **Monolithic Hetero Epitaxy**



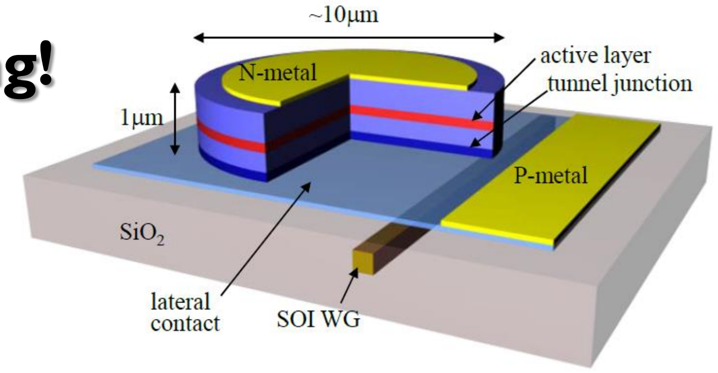
HYBRID INTEGRATION

Wafer – Chip – Device bonding!

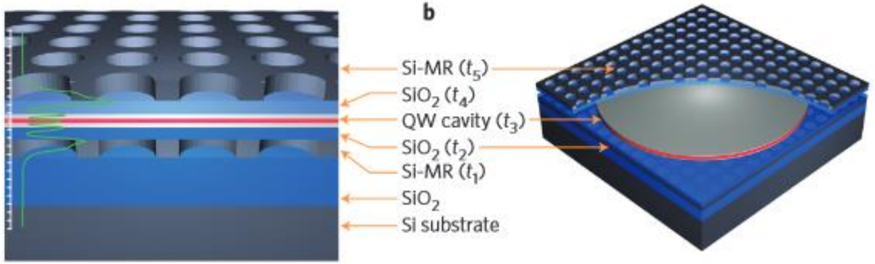
UCSB/Intel

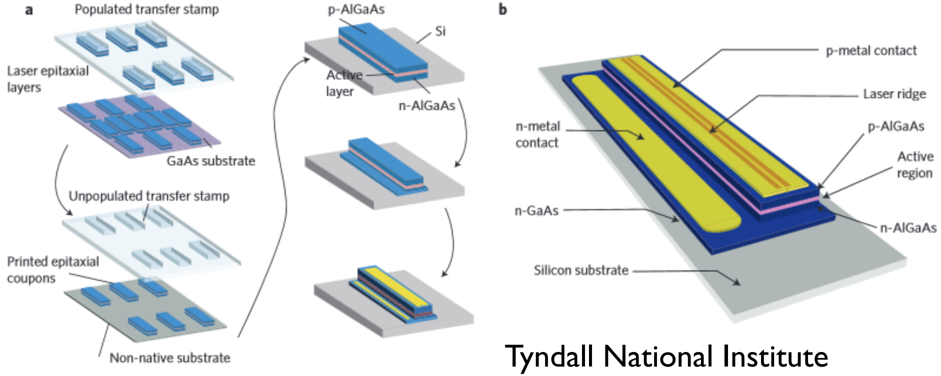


Gent Univ./Imec



Univ. of Texas/ Univ. of Wisconsin-Madison



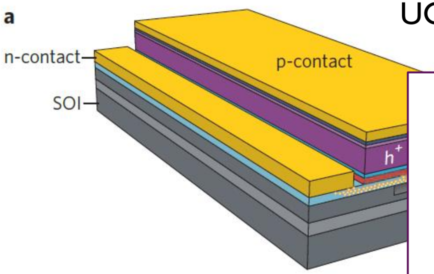


Tyndall National Institute

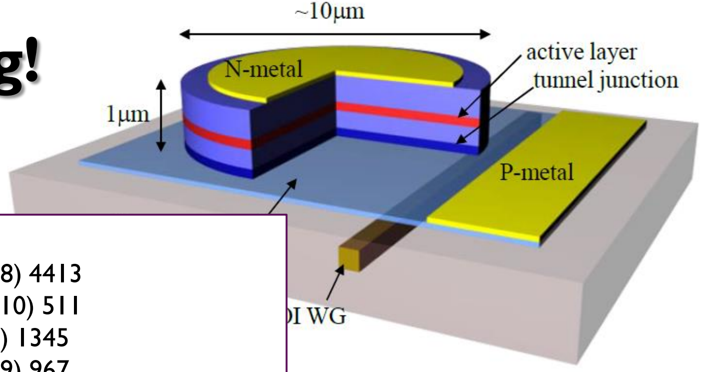
HYBRID INTEGRATION

Wafer – Chip – Device bonding!

UCSB/Intel

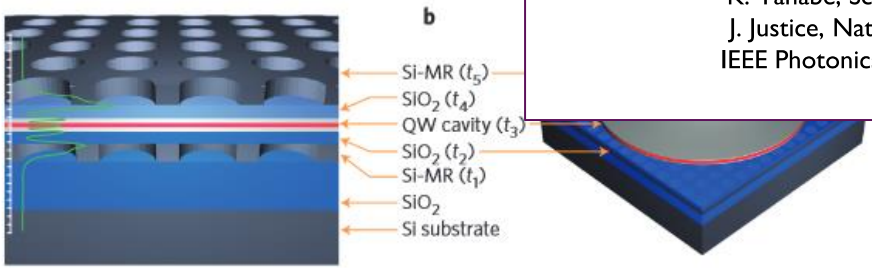


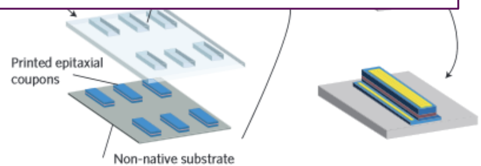
Gent Univ./Imec

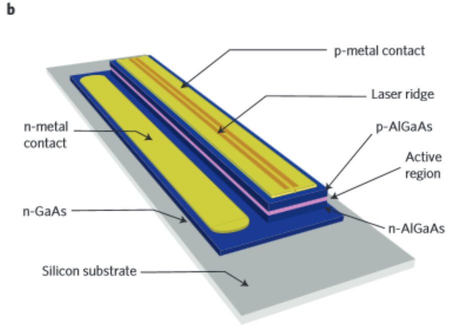


A.W. Fang, Opt. Express 16 (2008) 4413
D. Liang, Nature Photonics 4 (2010) 511
X. Sun, Optics Letters 34 (2009) 1345
M.-T. Xien Appl Phys A 95 (2009) 967
G.H. Duan, IEEE J. Select. Topic. Quant. Elect. 20 (2014) 6100213
J. Van Campenhout, IEEE J. Select. Topic. Quant. Elect. 21 (2015) 1500610
H. Yang, Nature Photonics 6 (2012) 615
K. Tanabe, Scientific Report 2:349 (2012)
J. Justice, Nature Photonics 6 (2012) 610
IEEE Photonics Tech. Lett. 25 (2013) 1111

Univ. of Texas/ Univ. of Wiscons







Tyndall National Institute

HYBRID INTEGRATION

Wafer – Chip – Device bonding!

- choice of optimal laser material and device!
- complex and expensive process flow!
- compatibility to the CMOS process?
- sufficient reliability, performance and uniformity to be demonstrated?

→ **Huge field of research – fast development progress!**

MONOLITHIC HETERO EPITAXY

Epitaxial growth of active material on Si

- collective integration process!
- cost efficient
- highly scalable
- lattice mismatch: defect formation to release strain!
- required device performance to be demonstrated!

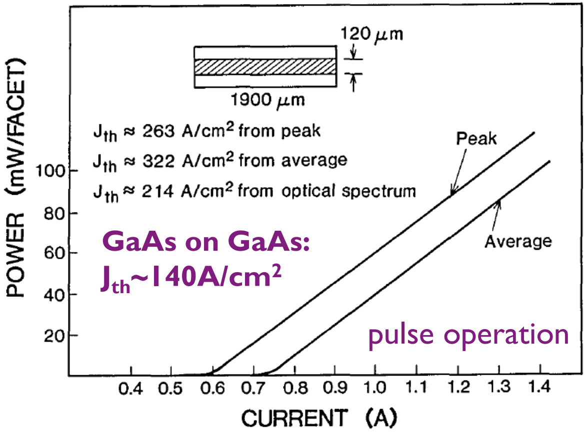
HOW DID IT START?

Continuous-wave operation of extremely low-threshold GaAs/AlGaAs broad-area injection lasers on (100) Si substrates at room temperature

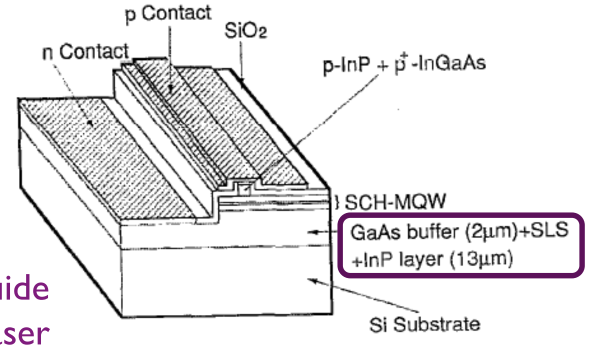
H. Z. Chen, A. Ghaffari, H. Wang, H. Morkoç,* and A. Yariv
California Institute of Technology, Pasadena, California 91125

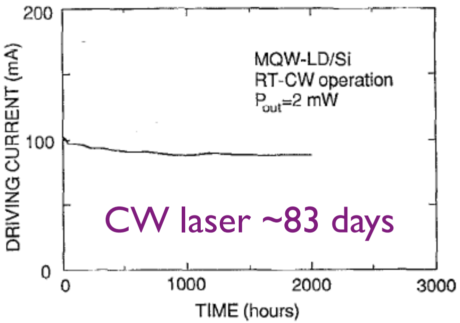
Optical letters: 1987

CW-laser operation: for 4min



Ridge waveguide laser





Stable cw operation at room temperature of a 1.5-μm wavelength multiple quantum well laser on a Si substrate

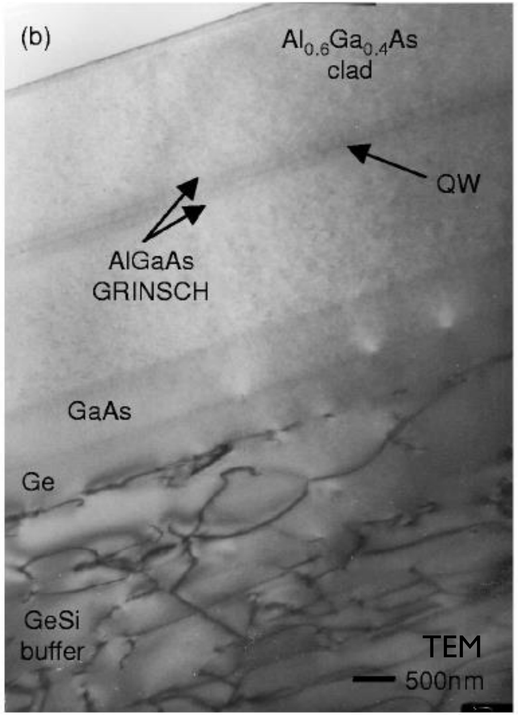
M. Sugo, H. Mori, Y. Sakai, and Y. Itoh
NTT Opto-electronics Laboratories, 3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-01, Japan

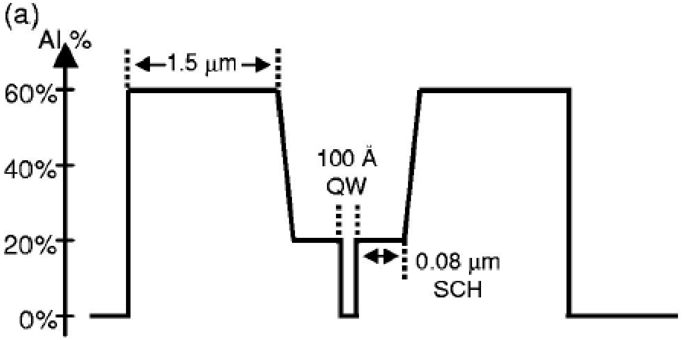
Appl. Phys. Lett.: 1991

Monolithic integration of room-temperature cw GaAs/AlGaAs lasers on Si substrates via relaxed graded GeSi buffer layers

Michael E. Groenert,[a)] Christopher W. Leitz, Arthur J. Pitera, and Vicky Yang
Department of Materials Science and Engineering, MIT, Cambridge, Massachusetts 02139

J. Appl. Phys.: 2003

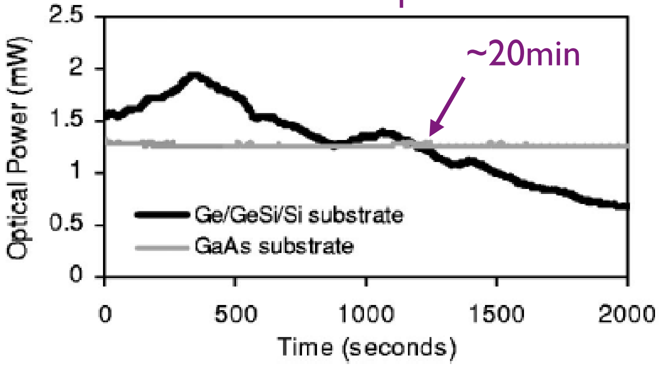




GaAs/AlGaAs Laser
on
Ge/SiGe/Si substrate

[~10µm thick & $1 \cdot 10^{6} cm^{-2}$ TDD]

CW laser operation



What limits the life time?

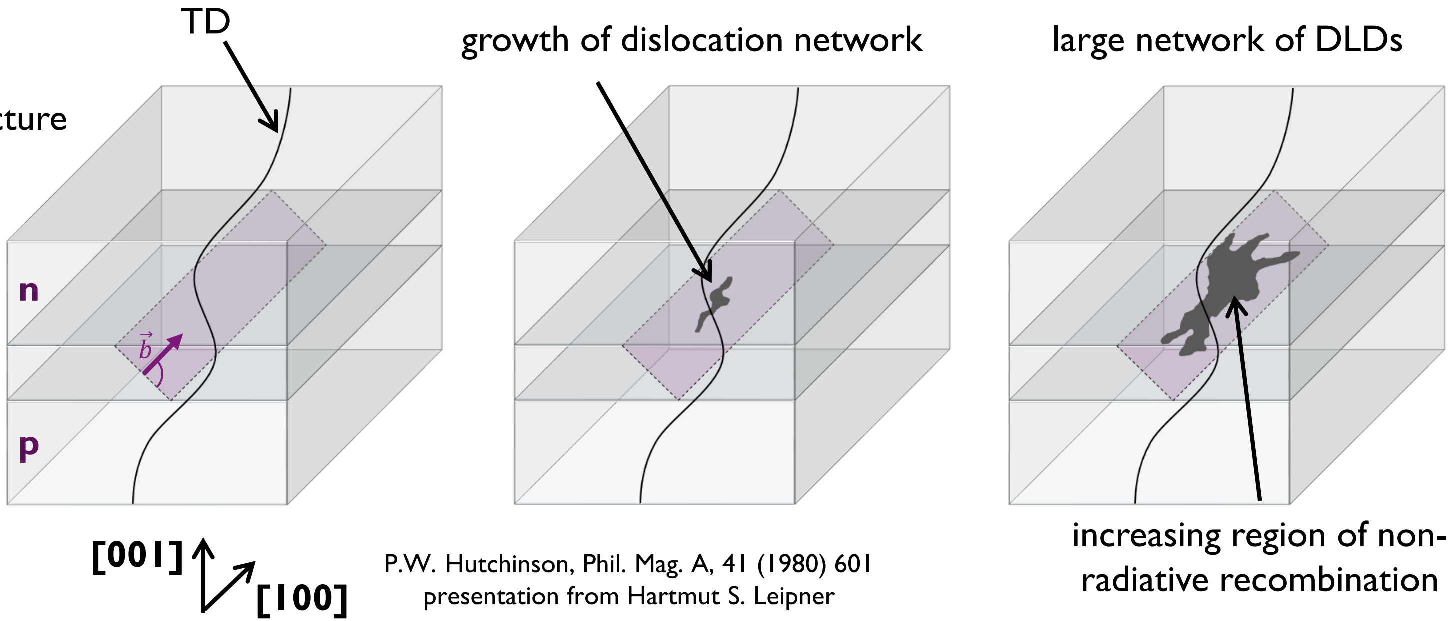
LASER OPERATION ⇔ DARK LINE DEFECTS

Dark Line Defects DLD: Growing network of defects during laser operation initiated at a TD!

double hetero structure
p-n junction

active region:
high carrier density
high recombination rate
high temperature

→TD: non-radiative recombination



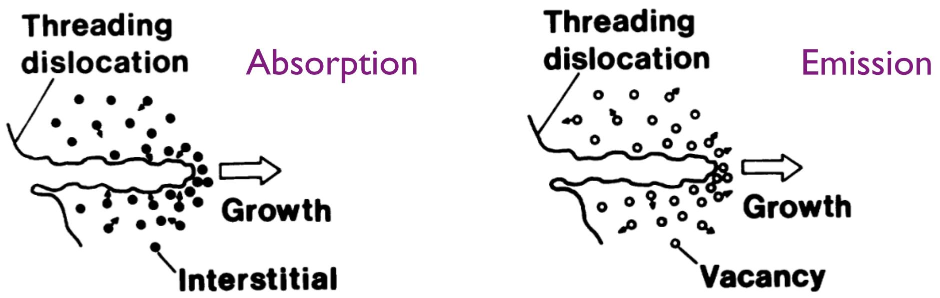
increasing region of non-radiative recombination

P.W. Hutchinson, Phil. Mag. A, 41 (1980) 601
presentation from Hartmut S. Leipner

LASER OPERATION ⇔ DARK LINE DEFECTS

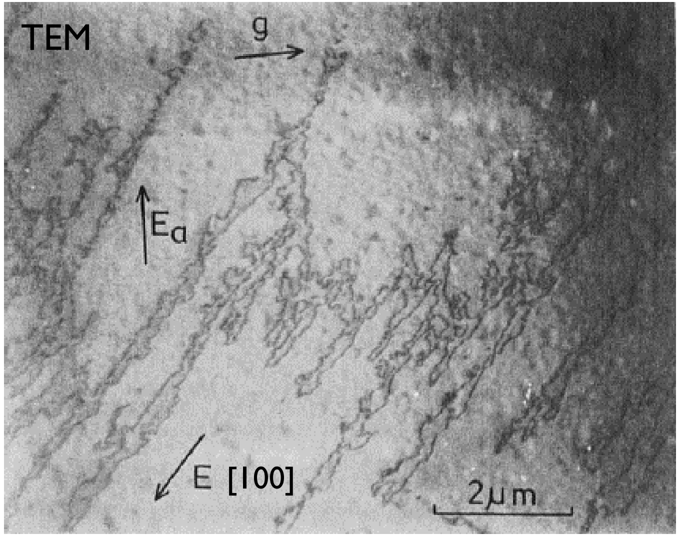
Recombination enhanced defect reaction:
generation, motion/gliding, transformation

Two models proposed for the elongation of DLD via dislocation climb



P.W. Hutchinson, Phil. Mag. A, 41 (1980) 601
presentation from Hartmut S. Leipner

grown dislocation network



GENERATION OF DLDS "KILLS" ANY DEVICE PERFORMANCE

- **Laser: high carrier density/temperature/recombination rate → driving force to initiate defects at present TDs!**
- **Dark Line Defects (DLDs)**
  - increasing dislocation network and point defects
  - recombination-enhanced dislocation climb
  - dislocation glide increase due to non-radiative recombination of carriers

→ Only a low defect density in the active region can guarantee sufficient life time!!!

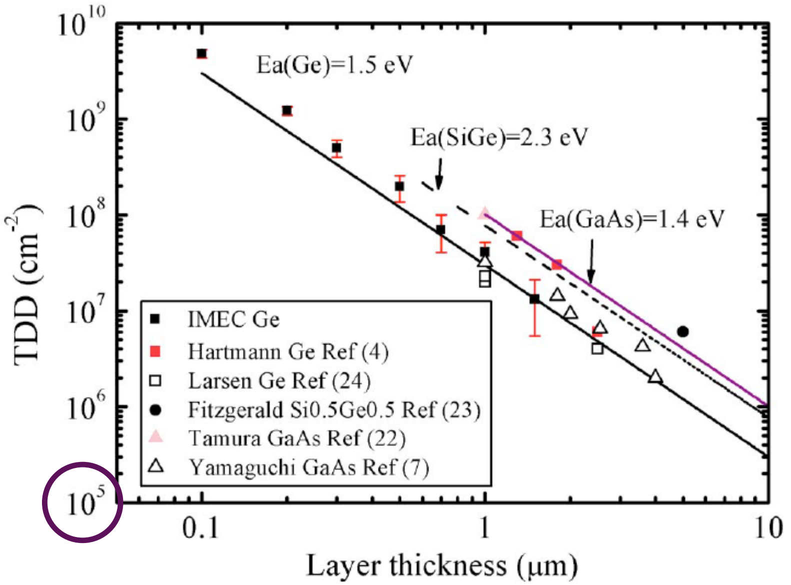
Laser requirement
$< 1 \cdot 10^4 cm^{-2}$

HOW TO REDUCE THE DEFECT DENSITY?

STRATEGIES TO REDUCE THE TDD

Laser requirement
$< 1 \cdot 10^4 cm^{-2}$

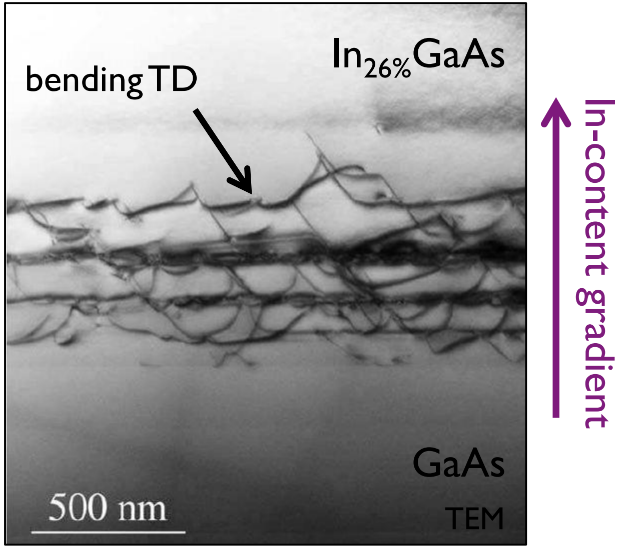
Correlation between TD density and layer thickness



G. Wang, Appl. Phys. Lett. 94 (2009) 94

- thick buffer growth
  - cycle annealing → enhanced TD gliding and annihilation
  - strain relaxed buffer SRB: bending TDs by strain/composition gradient

STRATEGIES TO REDUCE THE TDD



PhD Yves Mols, Katholieke Universiteit Leuven 2008

Laser requirement
$< 1 \cdot 10^4 cm^{-2}$

- thick buffer growth
  - cycle annealing → enhanced TD gliding and annihilation
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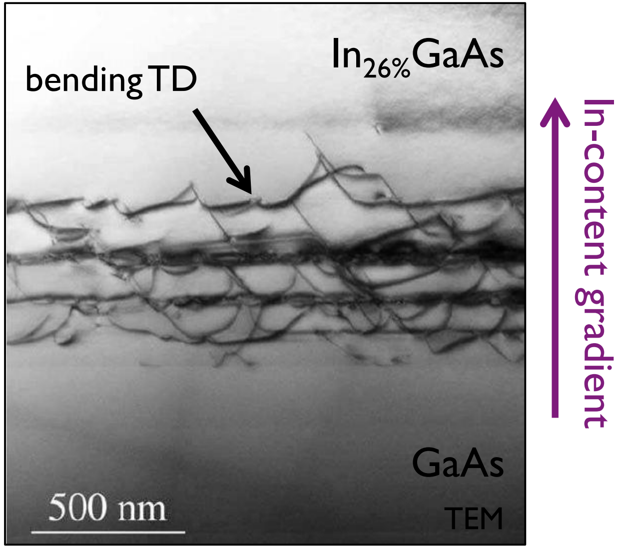
STRATEGIES TO REDUCE THE TDD



PhD Yves Mols, Katholieke Universiteit Leuven 2008

Laser requirement
$< 1 \cdot 10^4 cm^{-2}$

- thick buffer growth
  - cycle annealing → enhanced TD gliding and annihilation
  - strain relaxed buffer SRB: bending TDs by strain/composition gradient
- drawbacks:
  - production cost
  - difference in thermal expansion coefficient
  - co-integration with CMOS?

STRATEGIES TO REDUCE THE TDD

Many different approaches!

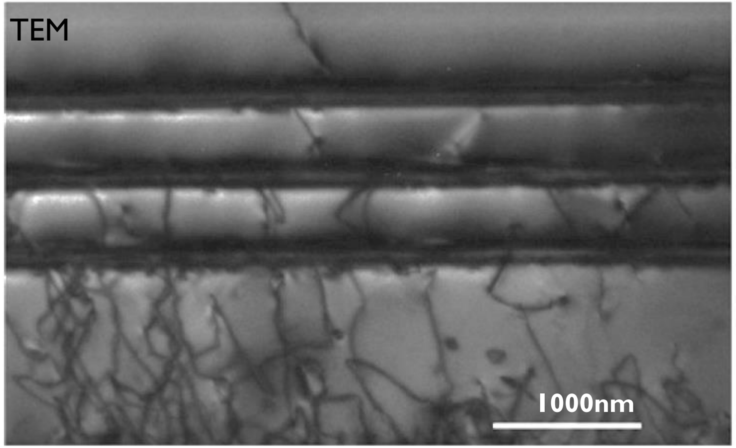
Selected topics of current activities:

- defect filter layer
- very large lattice mismatch
- defect trapping & epitaxial lateral overgrowth
- nano structures
- lattice matched GaNAsP
- Group IV based

DEFECT FILTER LAYER

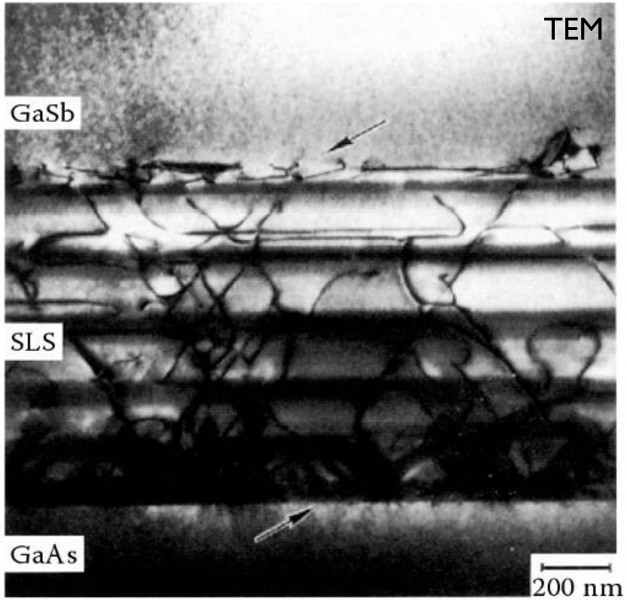
DEFECT FILTER LAYER: DFL
STRAINED LAYER SUPERLATTICE: SLS

InAlAs/GaAs-SLS on Si



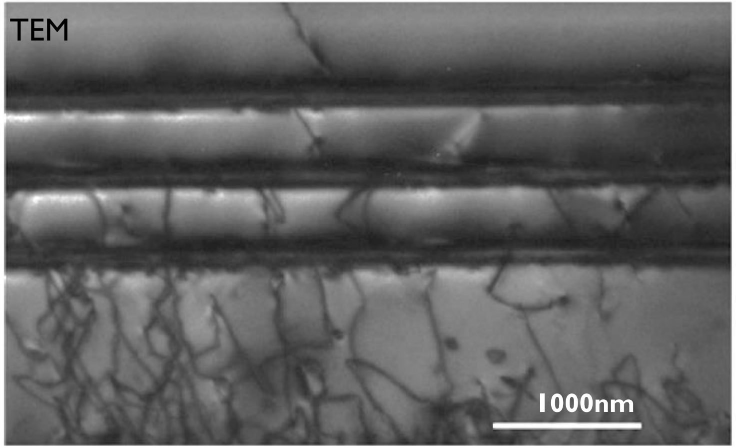
M. Tang, IET Optoelectron. 9 (2015) 61
W. Qian J. Electrochem. Soc. 144 (1997) 1430
M. Yamaguchi, Appl. Phys. Lett. 54 (1989) 2568
K. Nozawa, Jpn. J. Appl. Phys. 30 (1991) 668

AlSb/GaSb-SLS



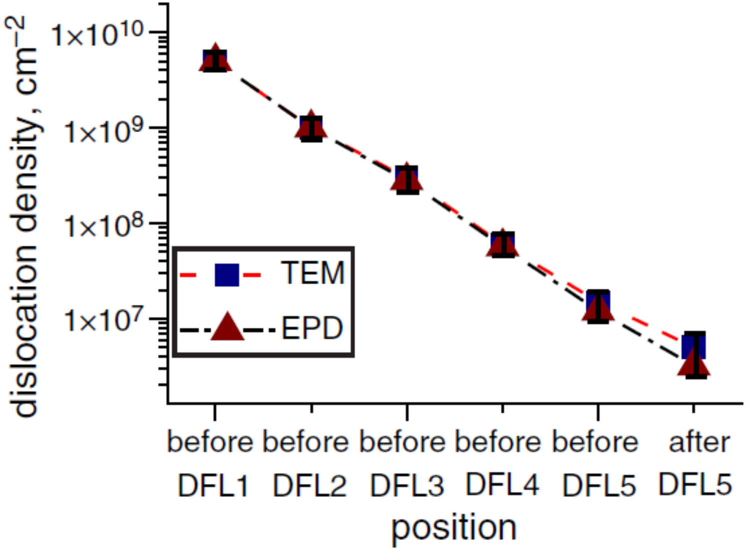
DEFECT FILTER LAYER: DFL
STRAINED LAYER SUPERLATTICE: SLS

InAlAs/GaAs-SLS on Si



M. Tang, IET Optoelectron. 9 (2015) 61
W. Qian J. Electrochem. Soc. 144 (1997) 1430
M. Yamaguchi, Appl. Phys. Lett. 54 (1989) 2568
K. Nozawa, Jpn. J. Appl. Phys. 30 (1991) 668

University College London



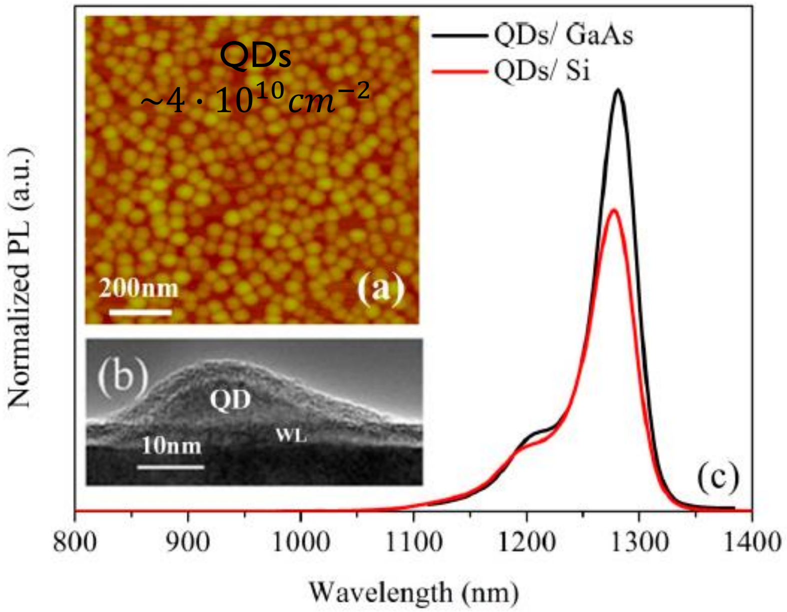
S.M. Tang, Elect. Lett. 50 (2014) 1467

QUANTUM DOTS AS GAIN MATERIAL

QDs in general:

- laser: low threshold current, low temperature dependence, …
- 3D-structure less sensitive to the present of TD

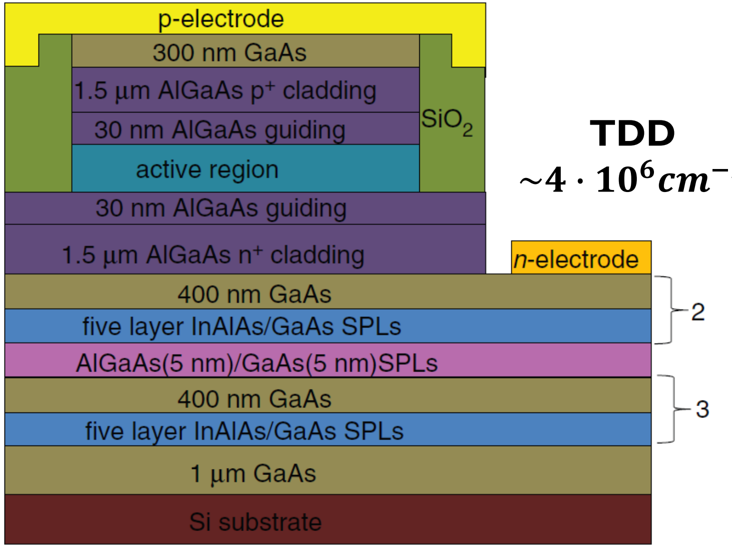
a) AFM, b) TEM, c) PL



S. Chen, Photonics 2 (2015) 646

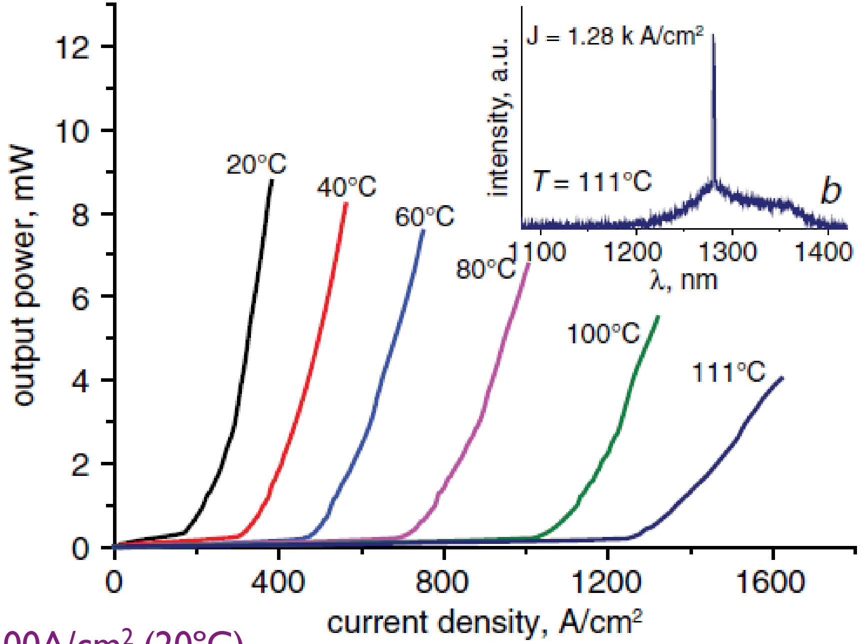
QD LASER ON SLS-ON-SI

University College London



TDD
$\sim 4 \cdot 10^6 cm^{-2}$

active region: 5x InAs-QD/GaAs multi layers
pulse operation



S.M. Tang, Elect. Lett. 50 (2014) 1467
M. Tang, IET Optoelectron. 9 (2015) 61

J_{th} = 200A/cm² (20°C)

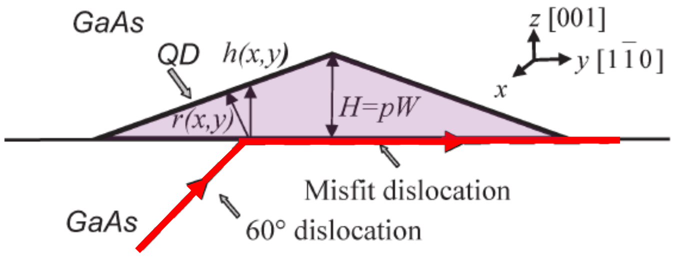
DEFECT FILTER LAYER: QUANTUM DOTS AS TD-FILTER

QDs in general:

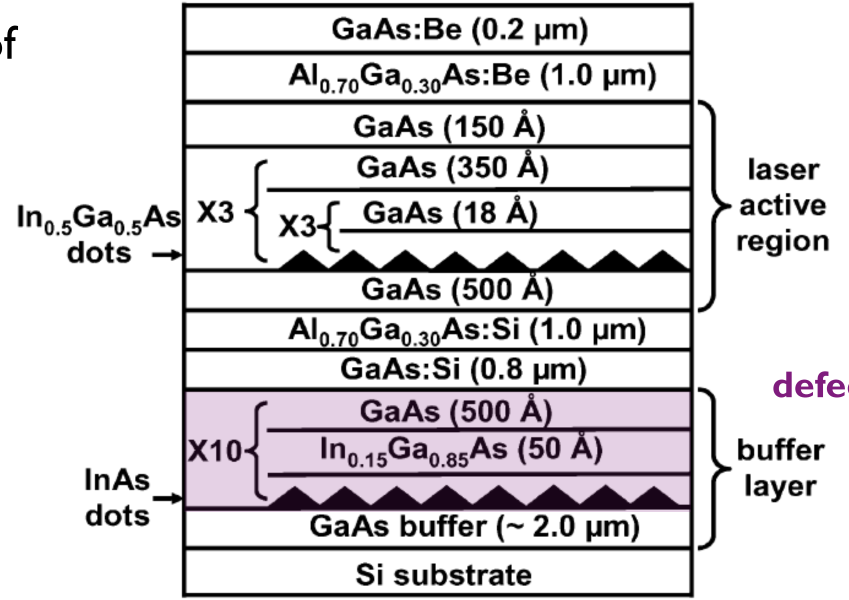
- surround strain-field leads to bending of threading dislocation

→ application of QDs filter layers

University of Michigan



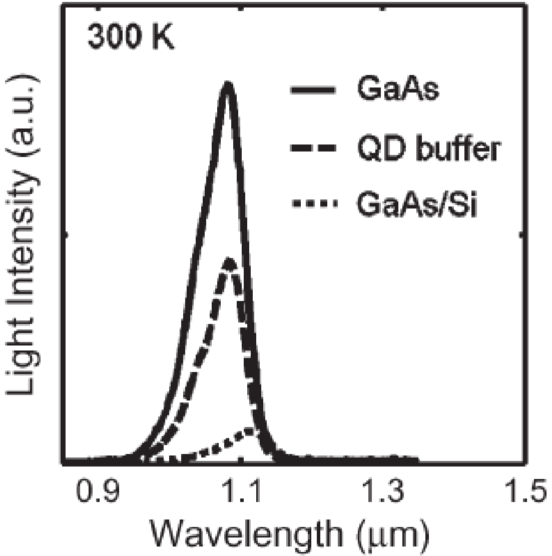
Z. Mi, Proc. IEEE 97 (2009) 1239
J. Yang, IEEE Trans. Elect. Dev. 54 (2007) 2849



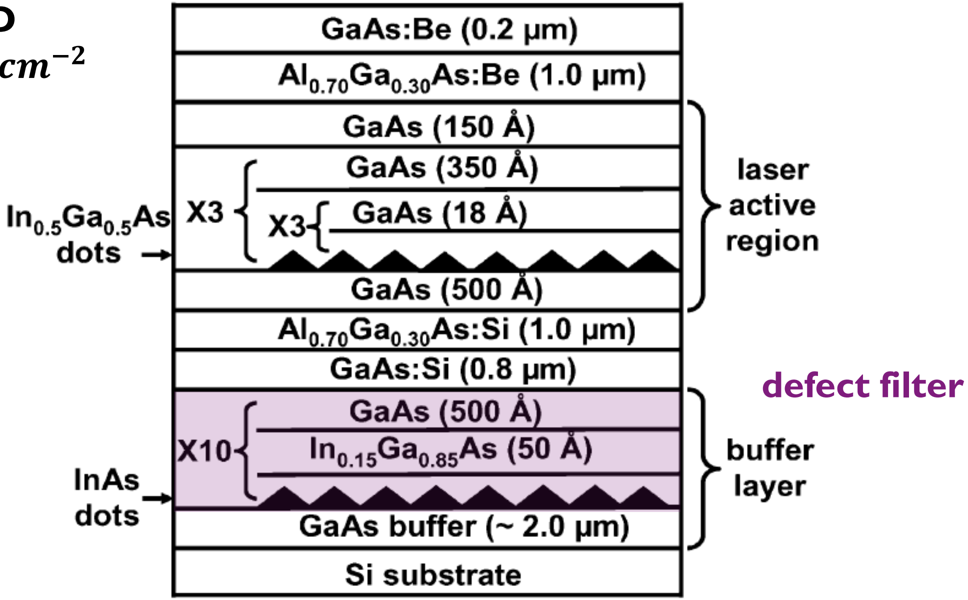
defect filter

DEFECT FILTER LAYER: QUANTUM DOTS AS TD-FILTER

University of Michigan



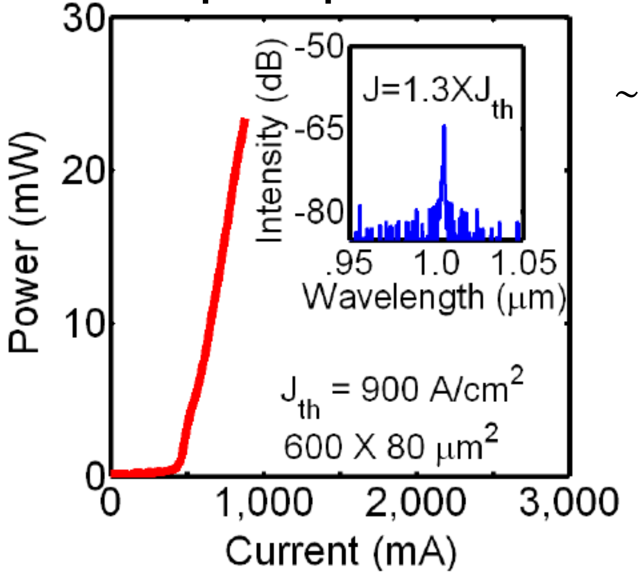
TDD
$\sim 5 \cdot 10^{7} cm^{-2}$



Z. Mi, Proc. IEEE 97 (2009) 1239
J. Yang, IEEE Trans. Elect. Dev. 54 (2007) 2849

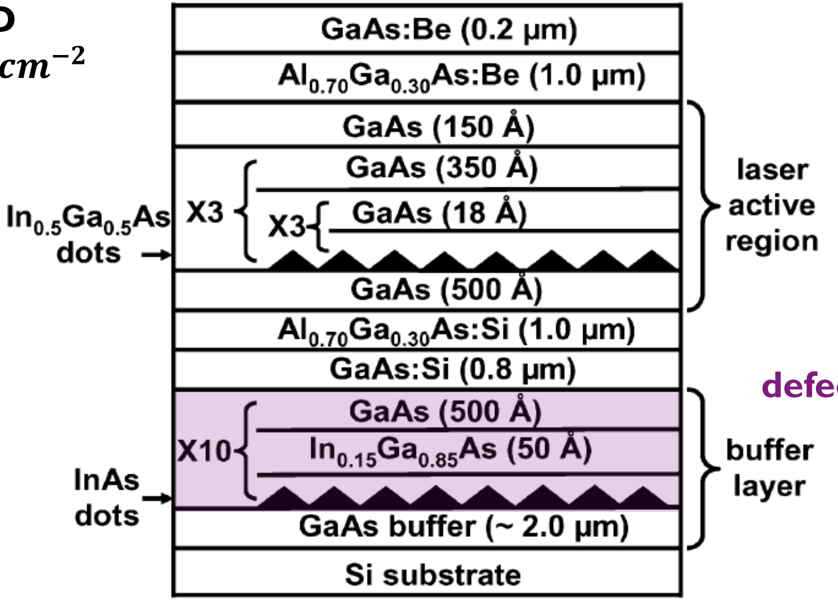
DEFECT FILTER LAYER: QUANTUM DOTS AS TD-FILTER

pulse operation



TDD
$\sim 5 \cdot 10^7 cm^{-2}$

University of Michigan

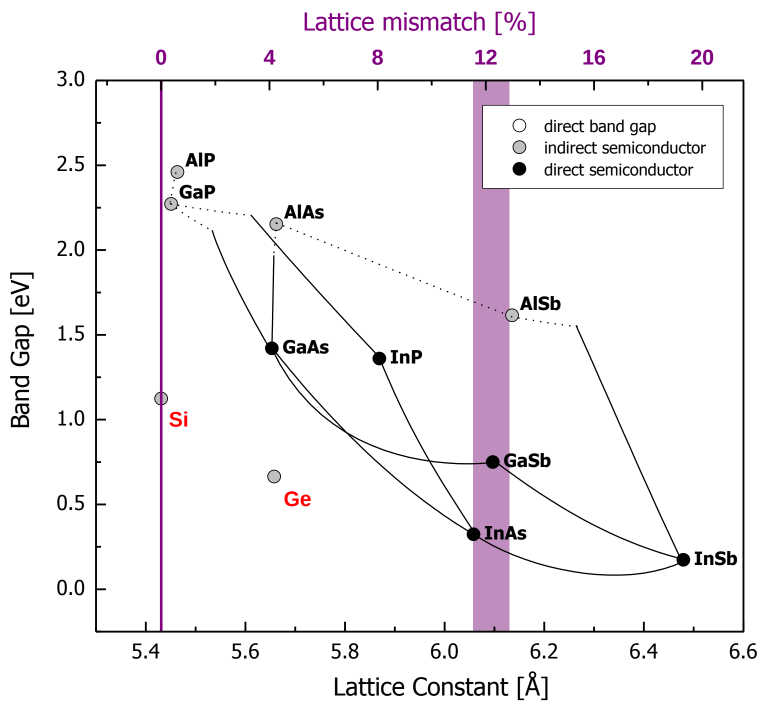


defect filter

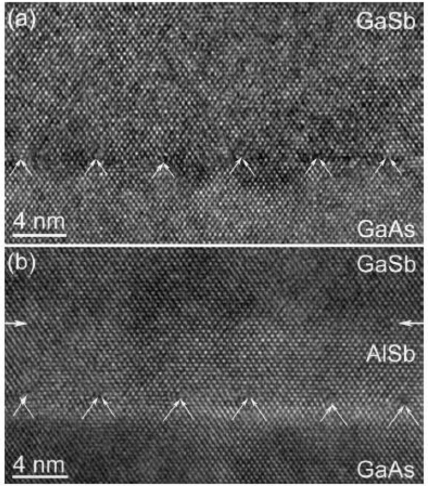
Z. Mi, Proc. IEEE 97 (2009) 1239
J. Yang, IEEE Trans. Elect. Dev. 54 (2007) 2849

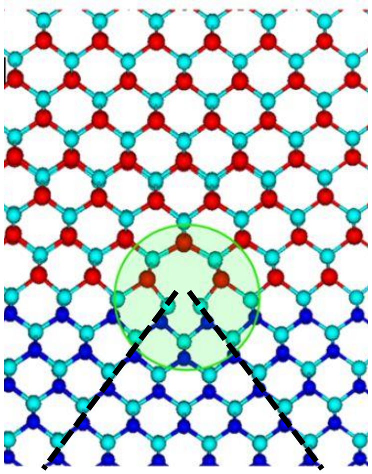
LARGE LATTICE MISMATCH

LARGE LATTICE MISMATCH



- e.g. GaSb based material system!
- formation of a periodic misfit pattern



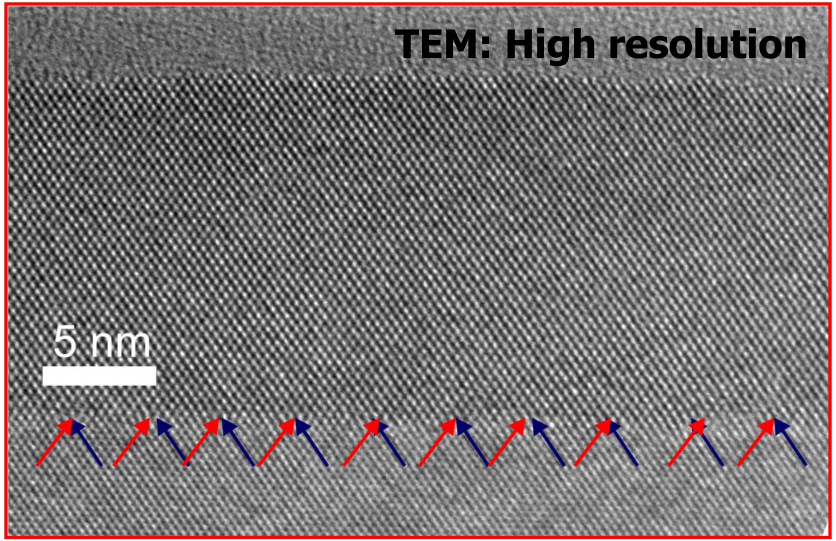


Y. Wang, J. Appl. Phys. 109 (2011) 023509
Y. Wang, J. Appl. Phys. 110 (2011) 043509
A. Jallipalli, Nano. Res. Lett. 4 (2009) 1458

90° misfit dislocation: two additional planes

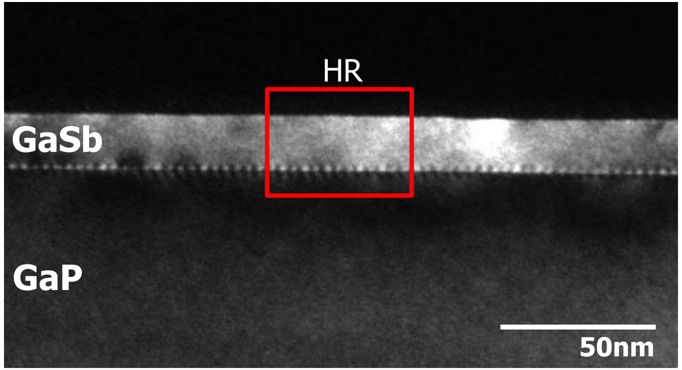
DEALING WITH THREADING DISLOCATIONS

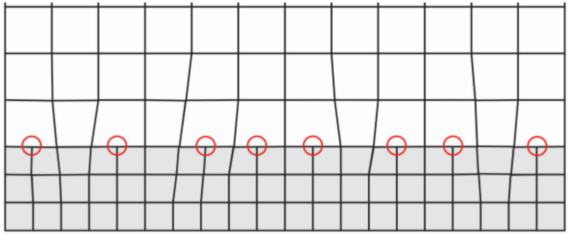
[US MOVPE 2011 conf. B. Kunert]



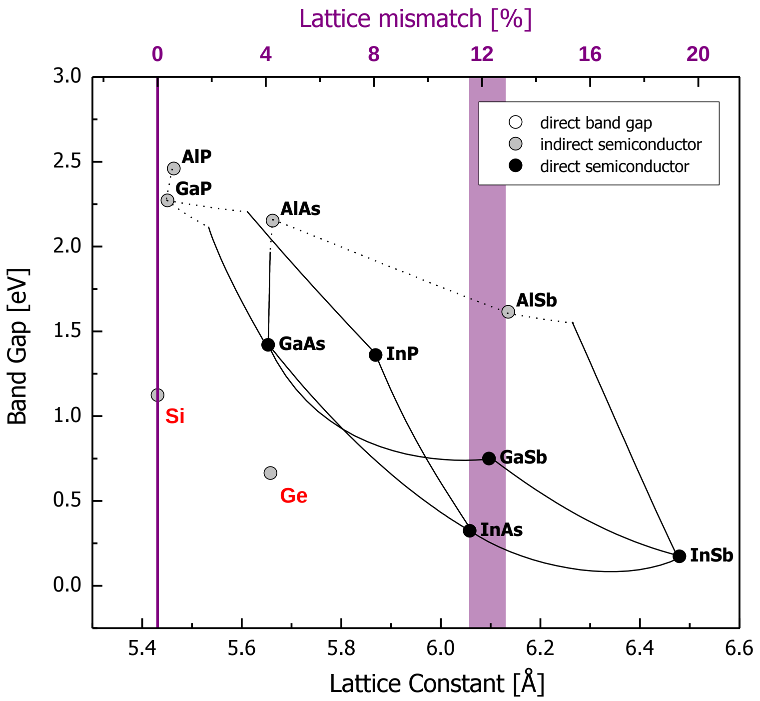
periodic arrangement of 90° misfits

TEM: [1-10] cross section DF (002)

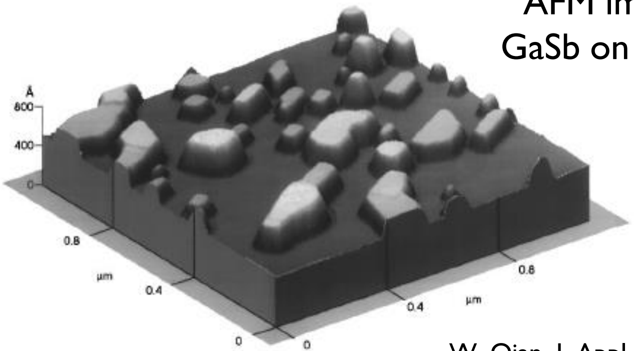




LARGE LATTICE MISMATCH



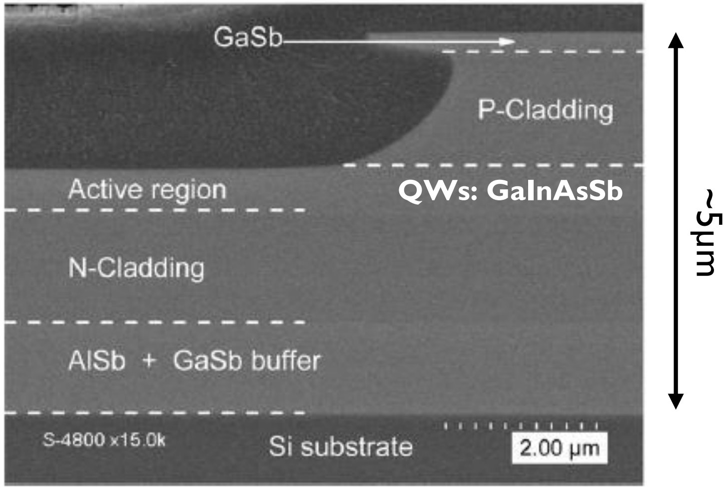
- e.g. GaSb based material system!
- formation of a periodic misfit pattern
- risk of 3-dimensional nucleation
  - non-uniform relaxation of the island
  - likely to forming planar defects after merging



AFM image:
GaSb on GaAs

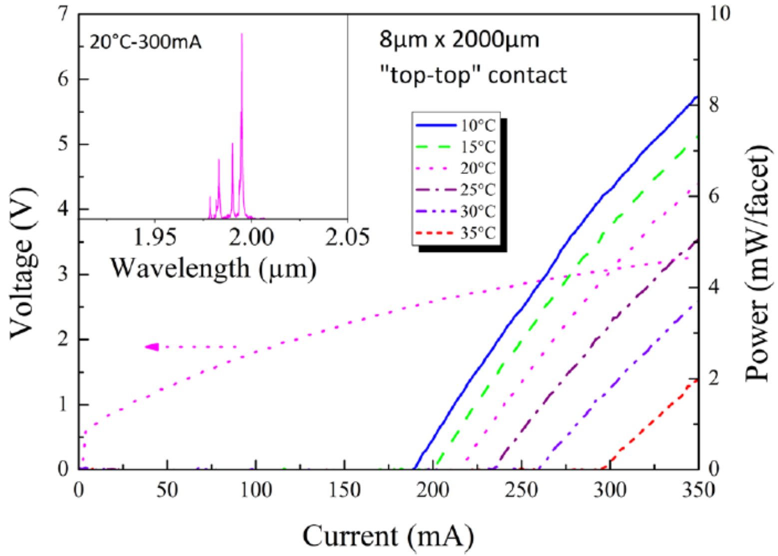
W. Qian, J. Appl. Phys. 81 (1997) 7268

GASB BASED LASER: ~2μm



Université Montpellier

Ridge waveguide laser
J_{th} = 900A/cm^2 - **pulse operation**



J.B. Rodriguez, Appl. Phys. Lett. 94 (2009) 061124
J.R. Reboul, Appl. Phys. Lett. 99 (2011) 121113
L. Cerutti, IEEE Phot. Tech. Lett. 22 (2010) 553

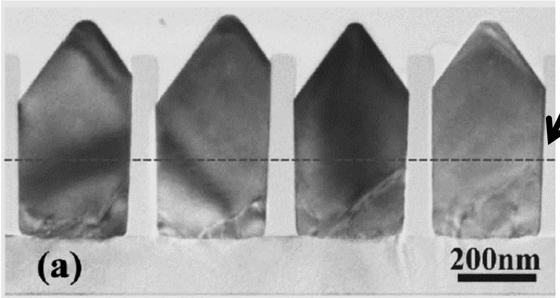
DEFECT FILTER LAYER & LARGE LATTICE MISMATCH

- room temperature operation
- reasonable threshold current
- TD density still to high!
- device life time?

DEFECT TRAPPING & EPITAXIAL LATERAL OVERGROWTH

SELECTIVE AREA GROWTH
ASPECT RATIO TRAPPING: ART

TEM cross section



Amber Wave

SiO$_2$

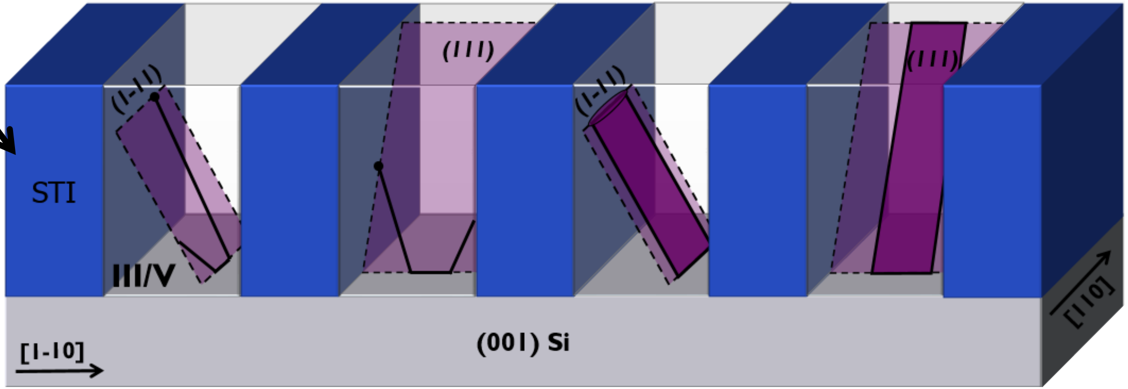
threading dislocations: TDs

planar defects: PD
stacking faults & twins

TDs trapped at the STI sidewall

PDs trapped!

PDs in (111) not trapped!

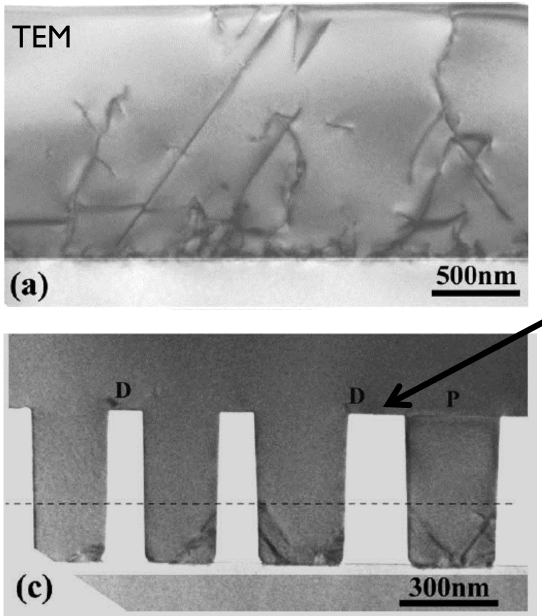


J.-S. Park, Appl. Phys. Lett. 90 (2007) 052113, J.Z. Li, Appl. Phys. Lett. 91 (2007) 021114

Shallow Trench Isolation

ART + ELOG
EPITAXIAL LATERAL OVERGROWTH

Amber Wave

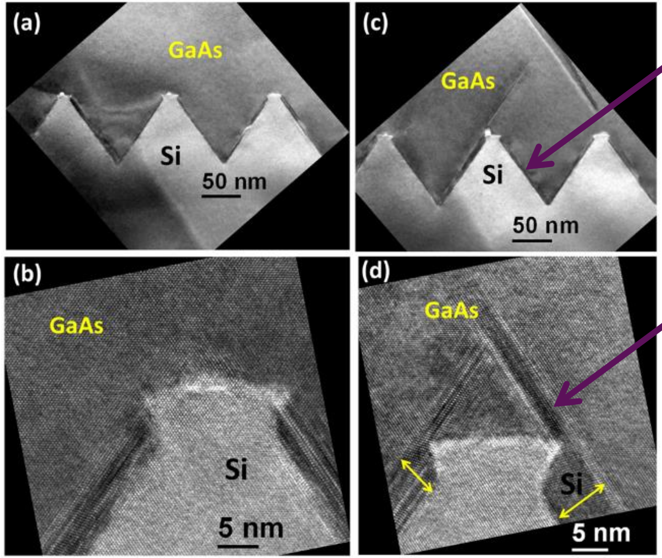


P: planar defect, D: dislocation

coalesced region is likely to form defects

quality of the merged region?

Hong Kong University

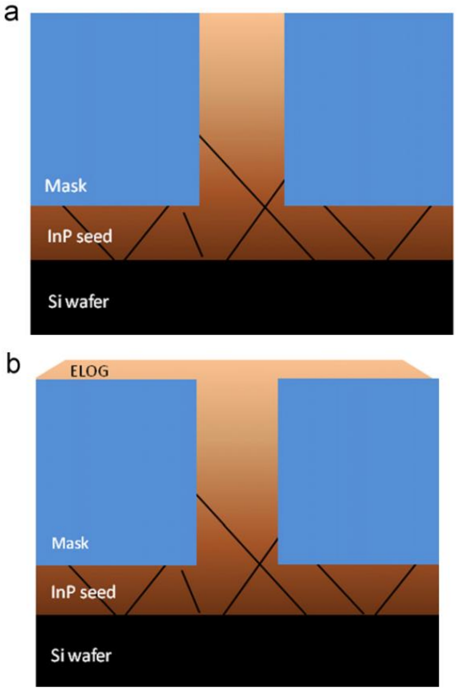


avoid antiphase disorder

not all planar defects are trapped yet

J.Z. Li, Appl. Phys. Lett. 91 (2007) 021114
Q. Li, Appl. Phys. Lett. 106 (2015) 072105
M. Paladugu et al., Cryst. Growth Des., (2012) 12 (10), pp 4696

ART + ELOG
EPITAXIAL LATERAL OVERGROWTH



KTH-Royal Institute of Technology

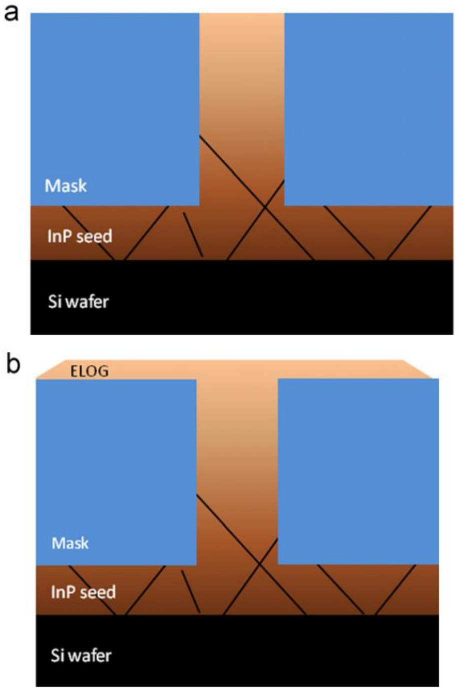
- InP buffer growth on Si
- CMP: chemical mechanical polishing
- SiO_2 deposition
- pattern/trench process

→ low trench width to trap defect

- ELOG & coalesced ELOG

F. Olsson, J. of Appl. Phys. 104 (2008) 093112
Z. Wang, Materials Science and Eng. B *177 (2012) 1551*
H. Kataria, Semicond. Sci. Technol. 28 (2013) 094008

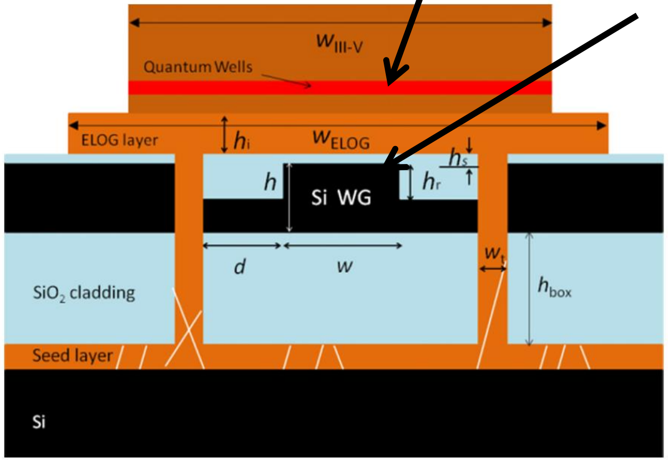
ART + ELOG
EPITAXIAL LATERAL OVERGROWTH

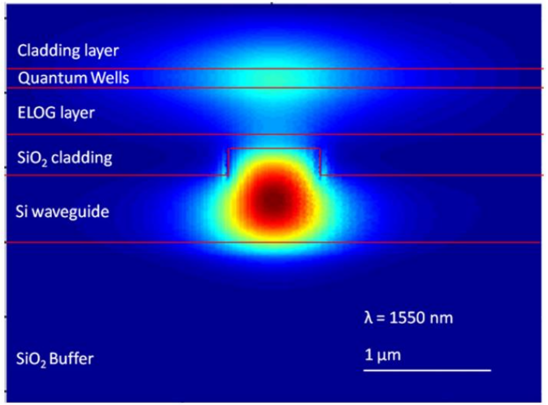


Monolithic Evanescently Coupled Silicon Laser (MECSL)

gain section: III/V mesa

Si waveguide cavity





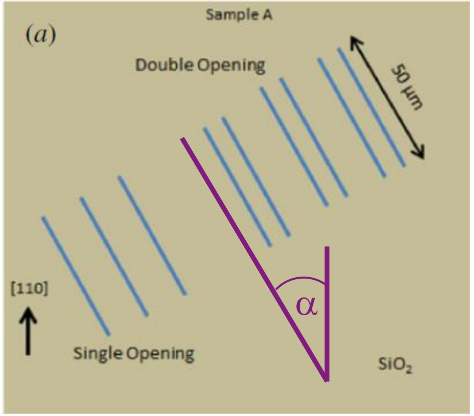
optical mode profile

Z. Wang, Materials Science and Eng. B *177 (2012) 1551*

DEFECT DENSITY

KTH-Royal Institute of Technology

mask top view with
open trenches for ELOG

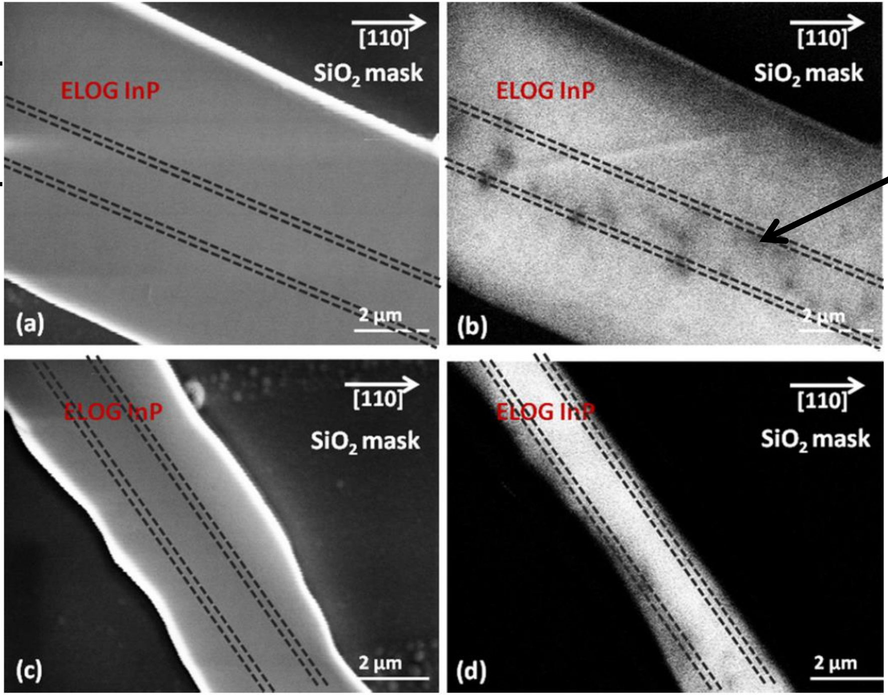


orientation
angle

double
opening

α: 30°

α: 60°



dark spots,
no CL
⇔
defect

no obvious
defects
in CL!

scanning electron microscopy (SEM) & cathodoluminescence (CL)

F. Olsson, J. of Appl. Phys. 104 (2008) 093112
Z. Wang, Materials Science and Eng. B *177 (2012) 1551*
H. Kataria, Semicond. Sci. Technol. 28 (2013) 094008

DEFECT TRAPPING & EPITAXIAL LATERAL OVERGROWTH

- interesting and promising approach to achieve a sufficient low defect density
- ELOG: still complex process flow...
- device demonstration?

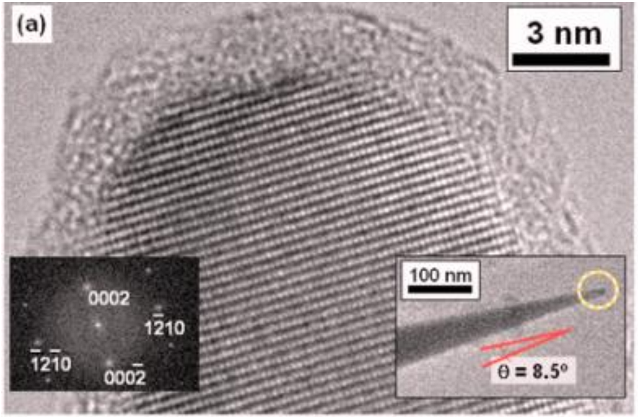
NANO STRUCTURES

NANO NEEDLES LASER: SELF-ASSEMBLED

UC Berkeley

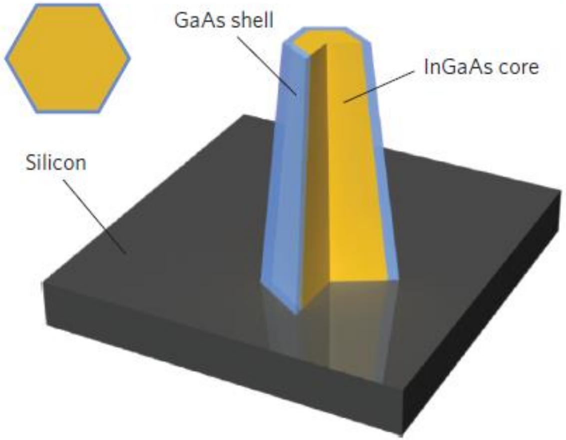
GaAs NN on (111) Si

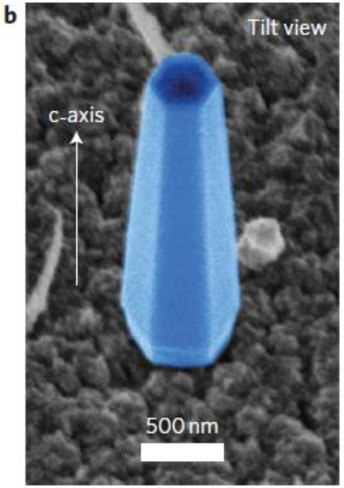
SEM



HRTEM: single wurtzite phase

InGaAs/GaAs hetero structure on (111)

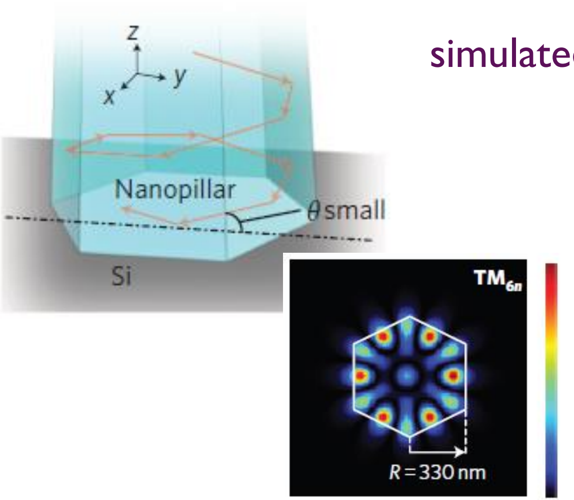




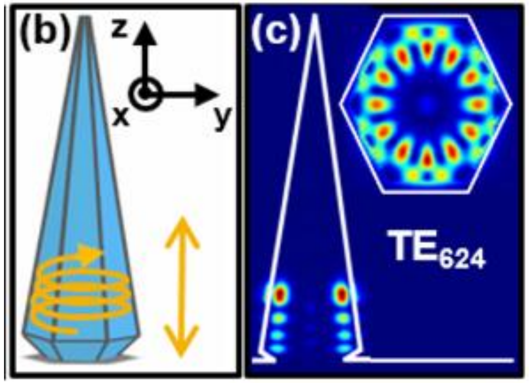
grown catalytic-free at low temperature, self-assembled: single wurtzite phase

NANO NEEDLES LASER: SELF-ASSEMBLED

UC Berkeley



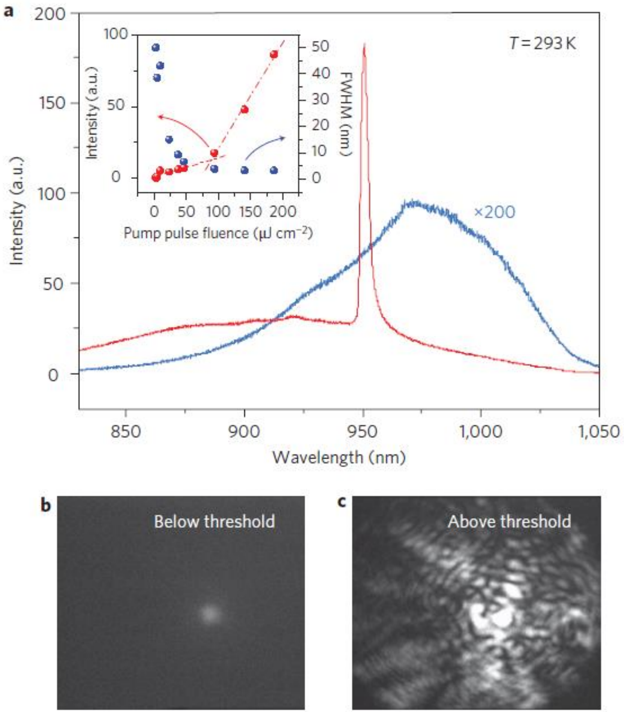
simulated field profile



hexagonal, whispering gallery-like mode pattern

R. Chen, Nature Photonics 6 (2011) 170
T.-T.D. Tran, Appl. Phys. Lett. 105 (2014) 111105
M. Moewe, Appl. Phys. Lett. 93 (2008) 023116
F. Ren, Appl. Phys. Lett. 102 (2013) 012115

InGaAs-DH NN: optical pumped, RT

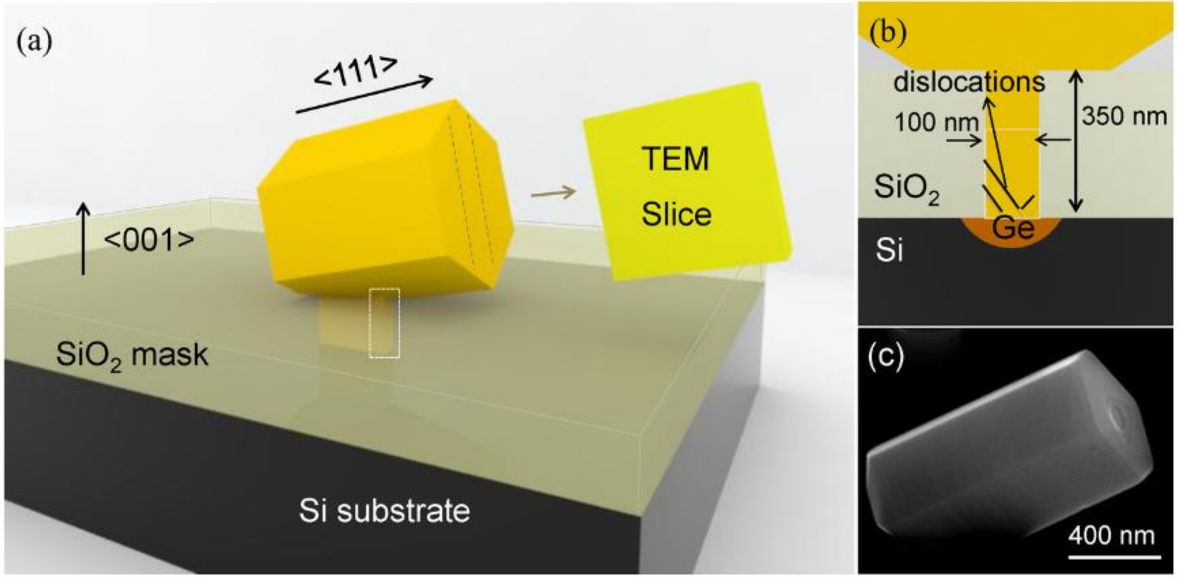


spontaneous emission speckle pattern

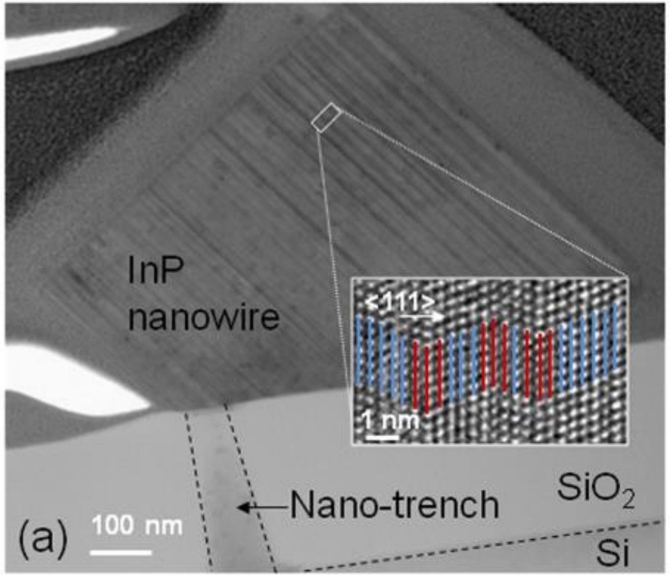
INP NANOWIRE LASER ON PATTERNED (001) WAFER

Gent Univ./Imec

ART



InP growth on patterned (001) Si

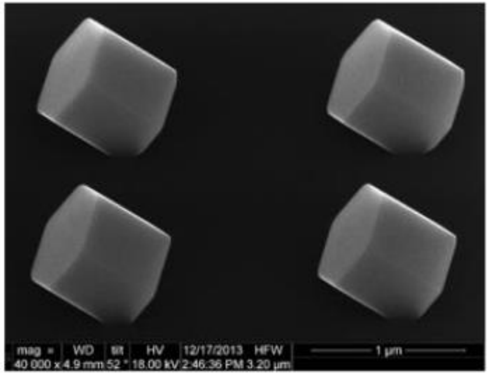


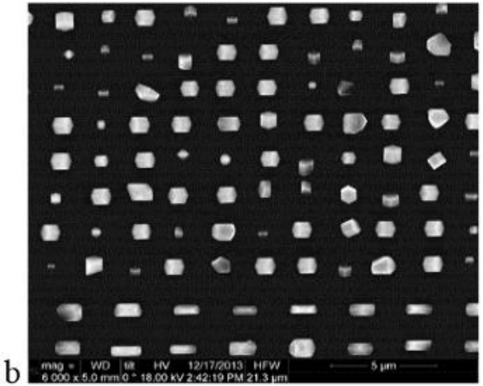
HRTEM: NW has a wurtzite/zinc-blende mixed structure

Z. Wang, Nano Lett. 13 (2013) 5063

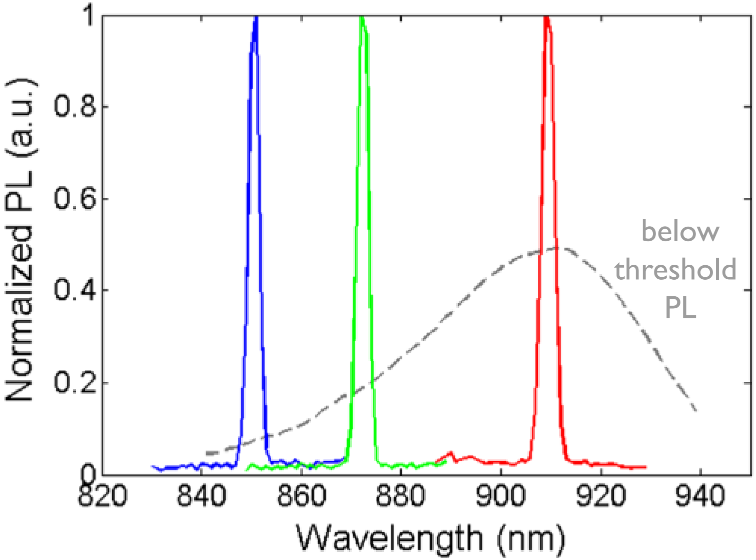
INP NANOWIRE LASER ON PATTERNED (001) WAFER

Gent Univ./Imec





Optical pumped, RT: different lasing modes

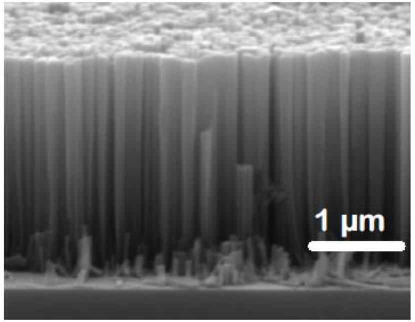


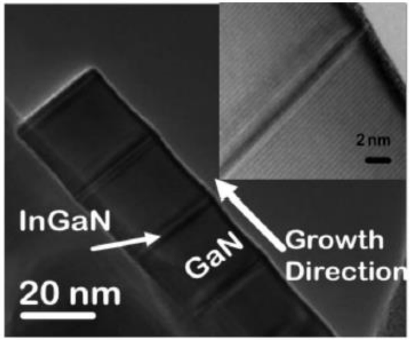
Broad optical gain due to wurtzite/zinc-blende mixed structure → lasing mode is define by nanowire dimension!

B. Tin, conf. presentation, IPRM 2014
Z. Wang, Nano Lett. 13 (2013) 5063

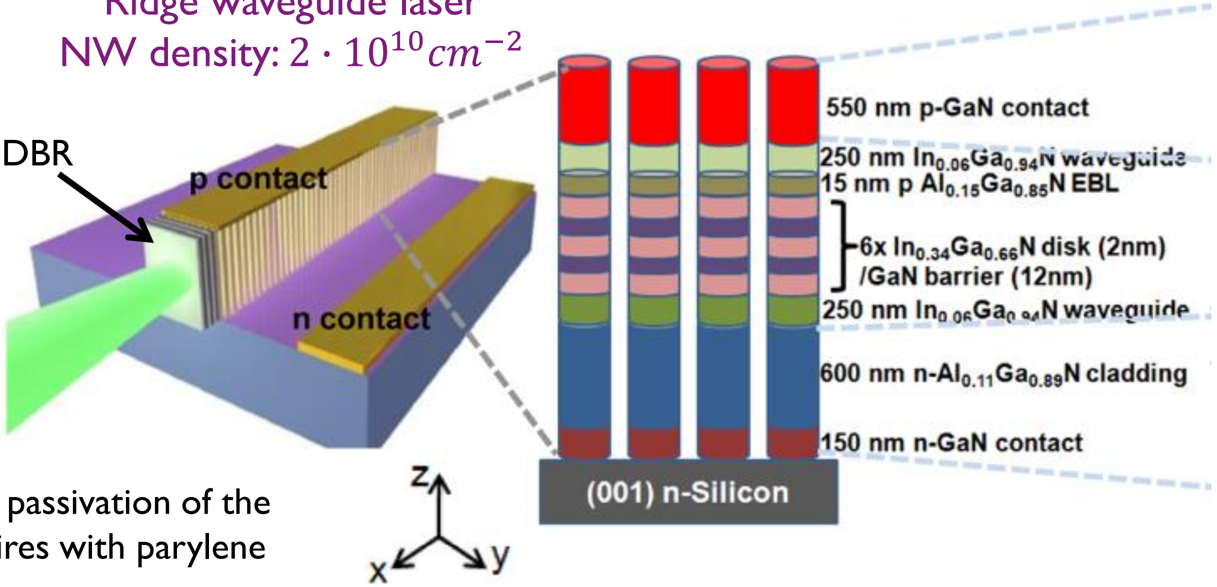
NANOWIRE ARRAY EDGE EMITTING LASER ON (001) SI

HRTEM: NW diameter 10-50nm





Ridge waveguide laser
NW density: $2 \cdot 10^{10} cm^{-2}$

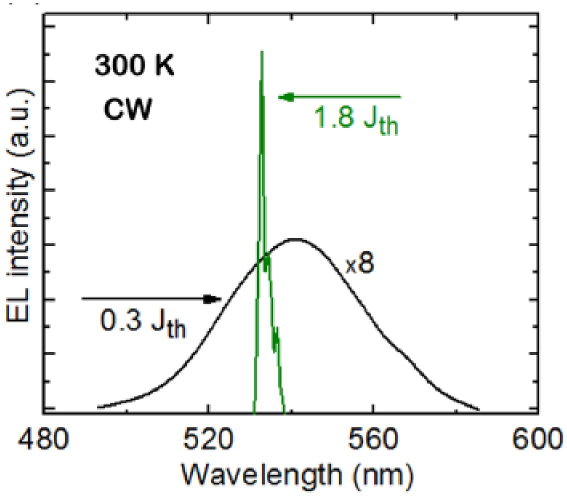


surface passivation of the nanowires with parylene

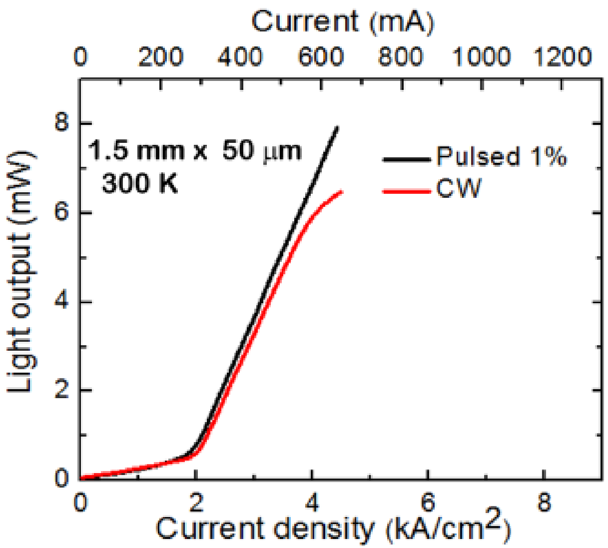
W. Guo, Appl. Phys. Lett. 98 (2011) 193102
T. Frost, Nano Lett. 14 (2014) 4535

University of Michigan

NANOWIRE ARRAY EDGE EMITTING LASER ON (001) SI

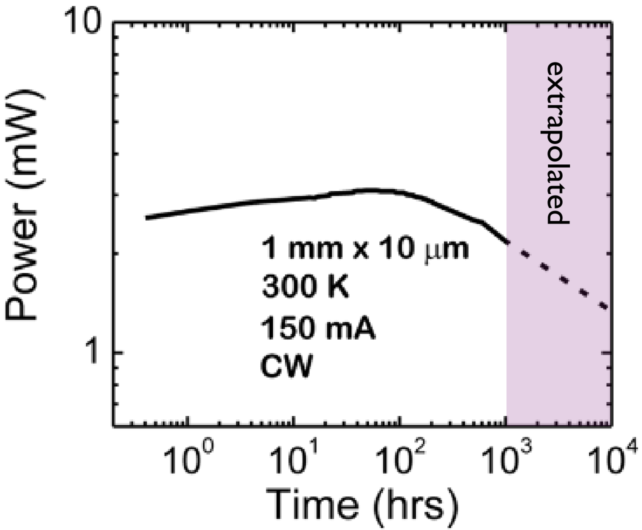


University of Michigan



W. Guo, Appl. Phys. Lett. 98 (2011) 193102
T. Frost, Nano Lett. 14 (2014) 4535

laser life time: CW



~7000h → 292d!

NANO STRUCTURES

- nano structures can more easily overcome lattice mismatch → low TDD!!!
- very small dimension & small foot print: high integration density
- surface passivation and waveguide/laser design important
- high tendency to switch between wurtzite and zinc-blend structure
- Au-catalyst-free growth required for CMOS integration
- nano structures prefer to grow along <111> direction – integration?
- efficient electrical current injection is still an issue
- scalable, low cost & high throughput assembly techniques are difficult!

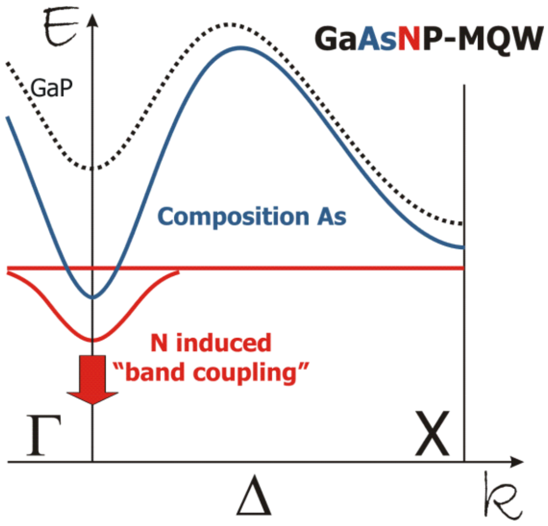
Interesting approach: NWs array!

F. Glas, Phys. Rev. B 74 (2006) 121302

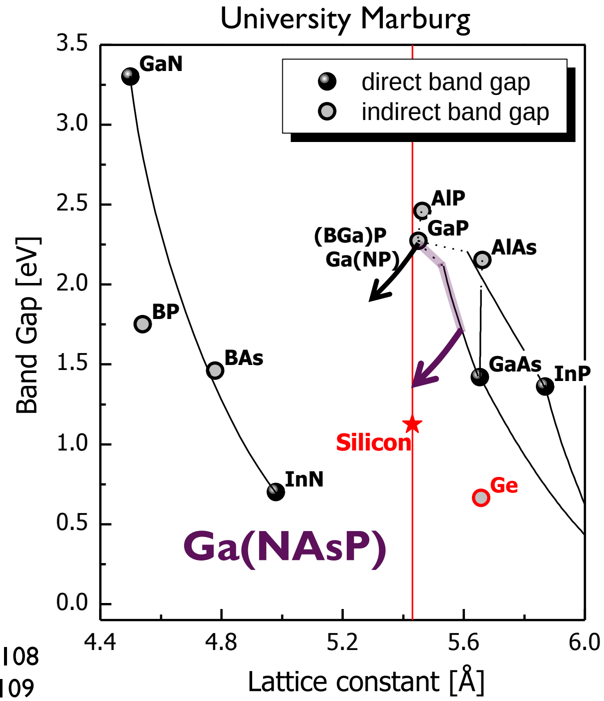
LATTICE MATCHED GANASP

LATTICE-MATCHED APPROACH: NOVEL DILUTE NITRIDE GA(NASP)

- developing of a new direct bang gap material
- pseudomorphic growth on Si: no misfit defect formation



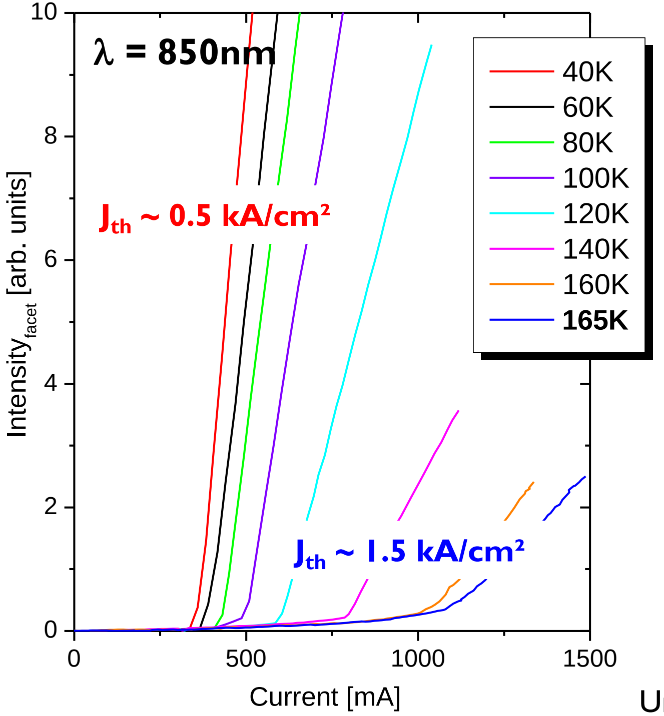
New dilute nitride: Direct band gap!



B. Kunert, Appl. Phys. Lett, 88 (2006) 182108
S. Liebich, Appl Phys. Lett, 99 (2011) 071109

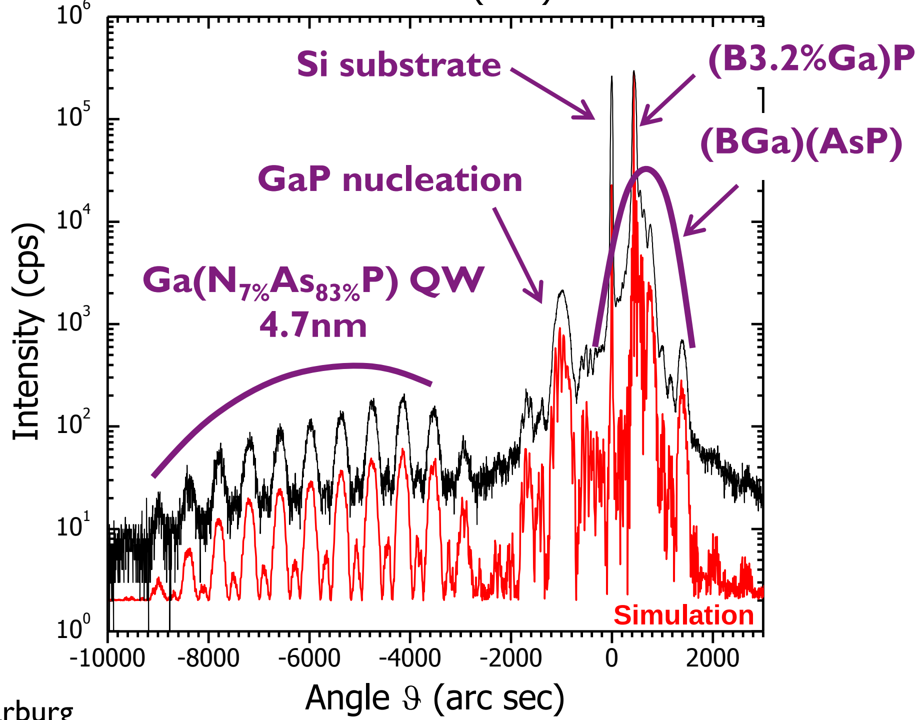
LASER OPERATION AT LOW TEMPERATURE

broad area laser: pulse operation



University Marburg

XRD-Measurement (400)-Reflection



imec

B. Kunert, J. of Crystal Growth 310 (2008) 4776, S. Liebich, Appl Phys. Lett, 99 (2011) 071109

LATTICE-MATCHED APPROACH

- unique lattice matched active material: no TD formation → potential for sufficient life time
- room temperature gain demonstrated
- many novel and metal stable materials involved: Diluted Nitrides and Diluted Boride → difficult to grow, unknown hetero-offsets, etc.
- CW device demonstration?

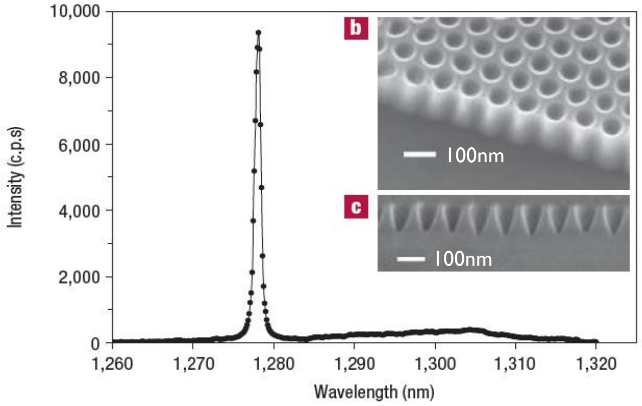
GROUP IV BASED

GROUP IV BASED

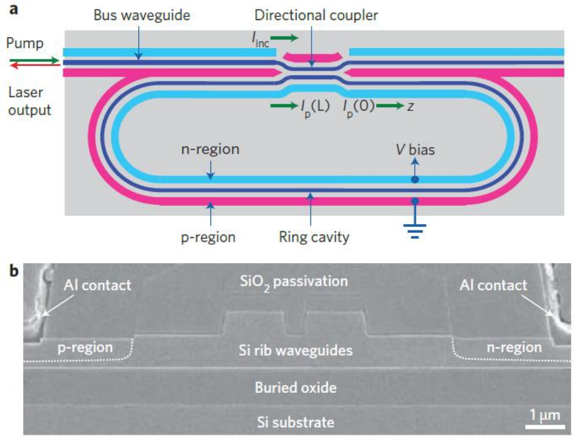
- Nanostructured Si
- Er-coupled Si-nanocrystals
- periodic nanopatterned crystalline silicon
- Si/SiGe quantum cascade structure
- Raman Si laser

- **Ge laser**
- **Laser of GeSn**

nanopatterned crystalline Si



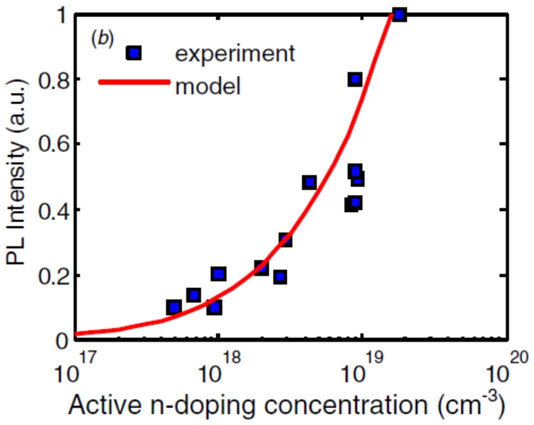
optical pumped
Si Raman laser



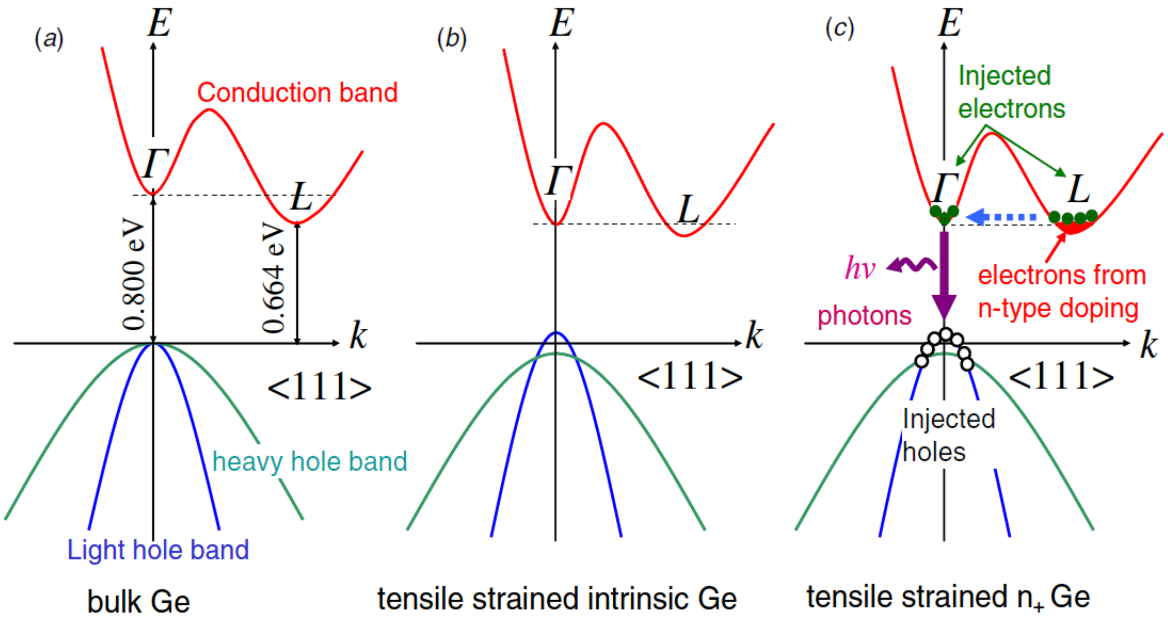
L. Pavesi, Nature 408 (2000) 440
S.G. Cloutier, Nature Materials 4, (2005) 887
I. Pelant, Phys. Status Solidi A 208, No. 3, 625–630 (2011)
J. Faist, Nature 433 (2005) 691
D. Liang, Nature Photonics, 4 (2010) 511
A. Polman, Appl. Phys. Lett. 84 (2004) 1037
...

GE-ON-SI LASER

- Ge completely relaxed on Si – during cooling / due to different expansion coefficient
- doping increased the PL



band structure of Ge



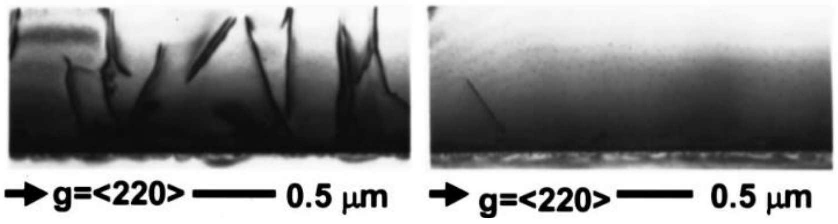
J. Liu, Semicond. Sci. Technol. 27 (2012) 094006 (13pp)

GE-ON-SI LASER

MIT

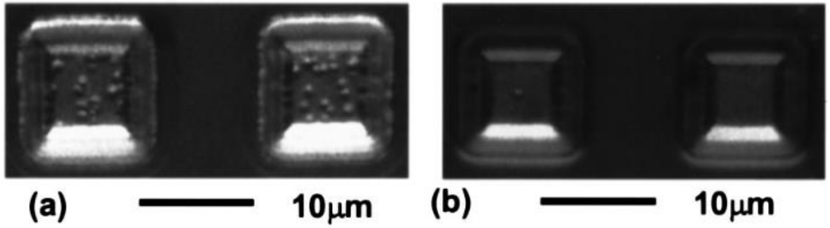
Impact of annealing on TD-density

no annealing | 10x cycle annealing



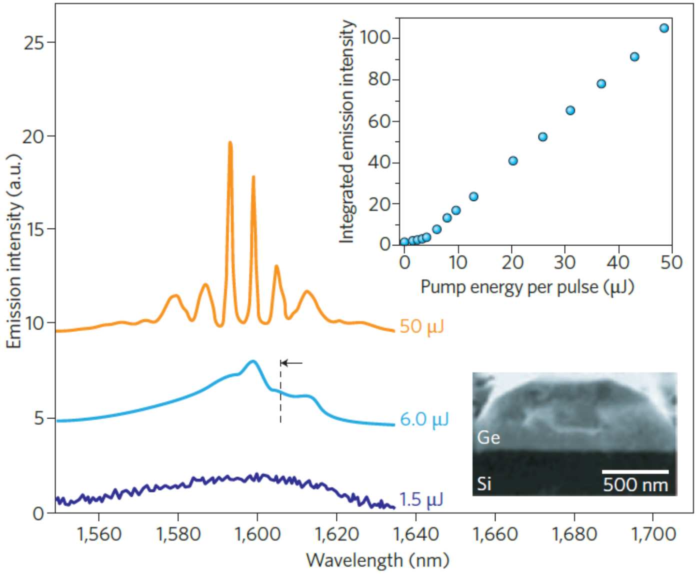
cross section TEM: Ge on Si

1x annealing | 10x cycle annealing



etch-pit-density (EPD) counting → TDs

Optical pumped edge emitter at RT
resonator length: 4.8mm

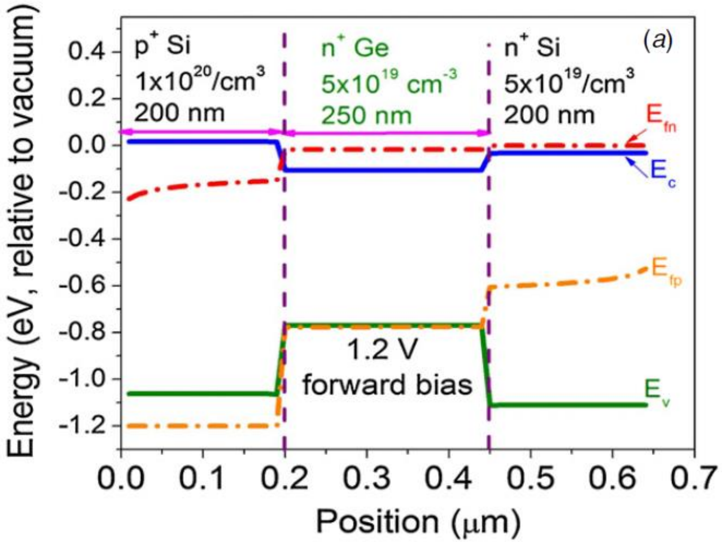


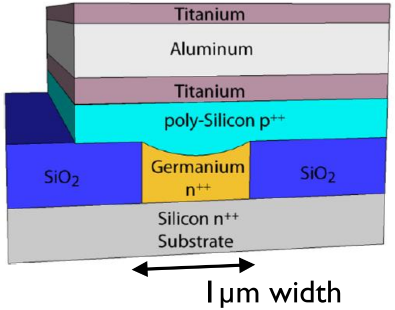
H. Luan, Appl. Phys. Lett. 75 (1999) 2909
D. Liang, Nature Photonics 4 (2010) 511

GE-ON-SI LASER

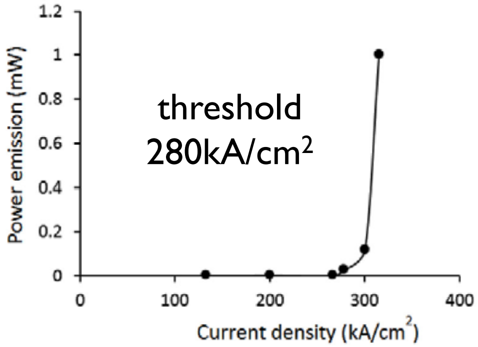
MIT

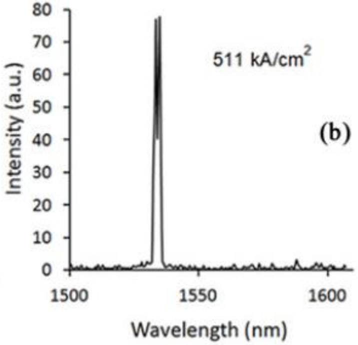
Electrical injection simulation of an n+ Si/n+Ge/p+ Si double heterojunction structure





electrically pumped, pulse operation at 15°C

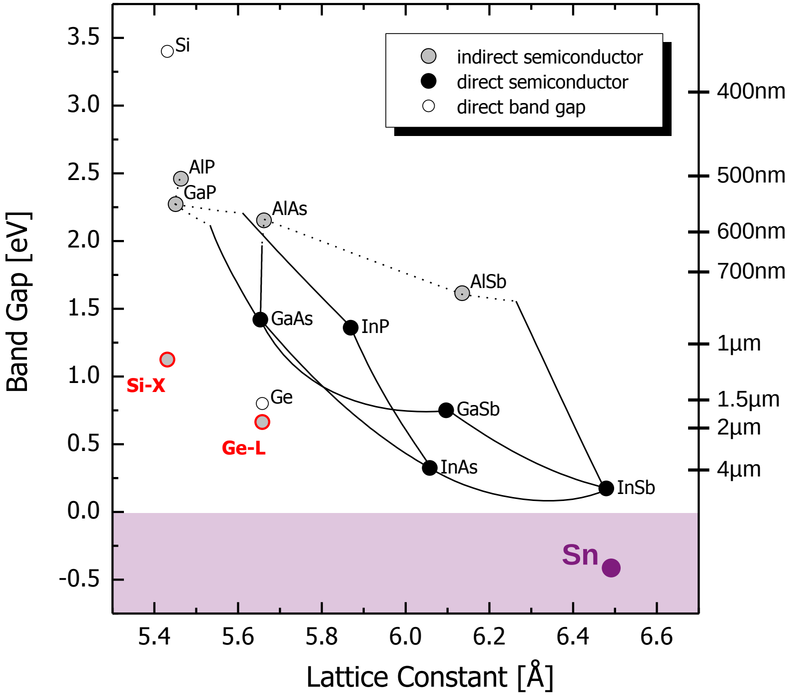




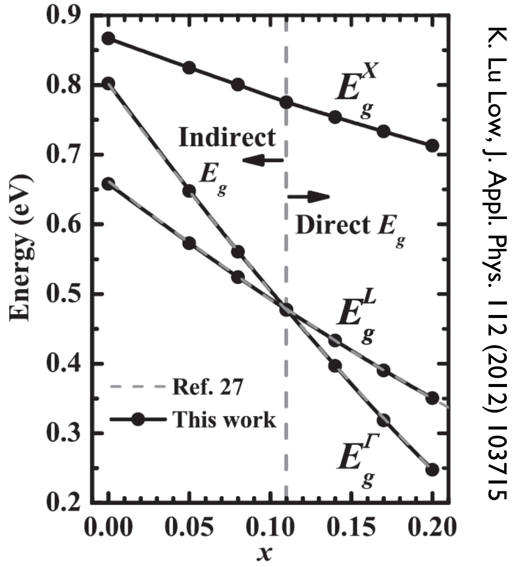
cavity length ~300µm, waveguide height 100nm

R.E. Camacho-Aguilera, Opt. Express 20 (2012) 11316
J. Liu, Semicond. Sci. Technol. 27 (2012) 094006 (13pp)
R. Koerner, Opt. Express 23 (2015) 14815

METAL TIN: SN



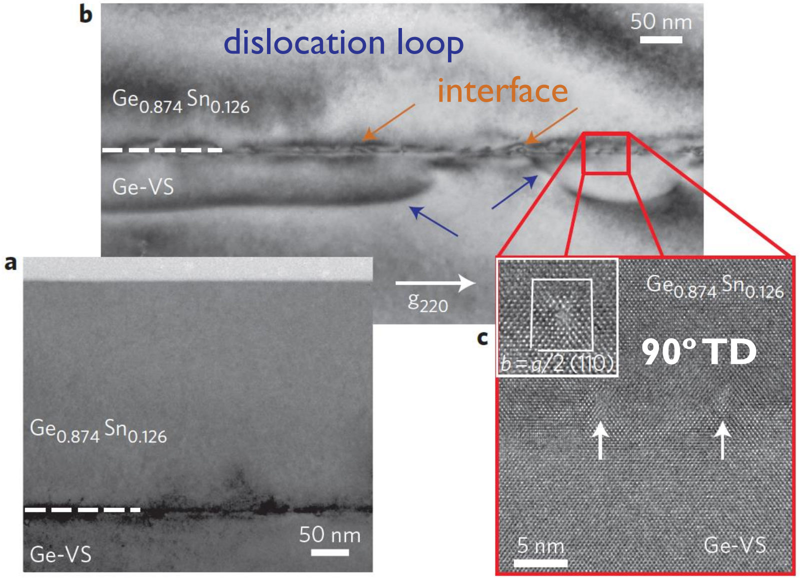
Calculated bang gap energy: $Ge_{(1-x)}Sn_x$



- low equilibrium solubility of Sn in Ge
- large lattice mismatch

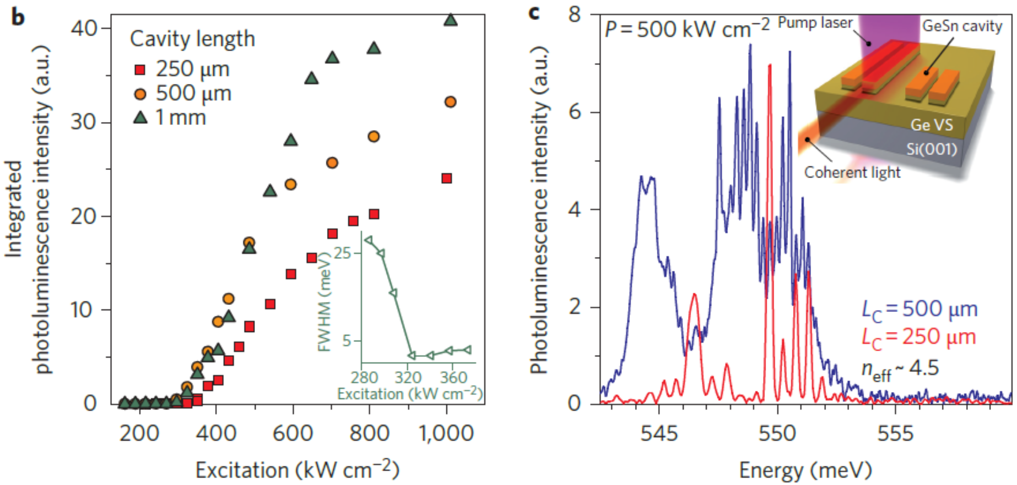
LASING: GESN ALLOY ON SI

$Ge_{(1-x)}Sn_x$ on Ge/Si virtual substrate



S. Wirths, Nature Photonics, 9 (2015) 88
R. Chen, Nano Lett. 14 (2014) 37

- **optical pumped lasing up to 90K!**
- experimental proof: direct band gap for Sn > 9%
- GeSiSn – more option for hetero structures and strain design



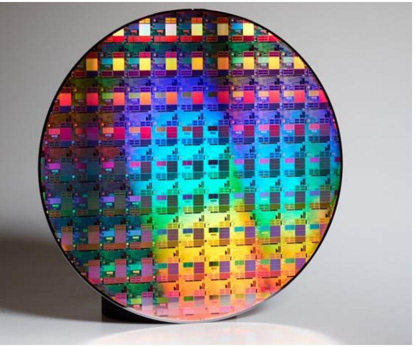
Forschungszentrum Jülich

GROUP IV BASED

- demonstration of Laser activity based on Ge!
- direct band gap material GeSn
- options of hetero structure design with SiGeSn alloys
- sufficient carrier injection and good confinement difficult (high threshold current)
- also low defect density required!
- Sn-based alloy hard to growth – meta stable
- RT device demonstration?

SUMMARY: III/V ON SI

+



- "Hot topic" due to the potential of Silicon Photonics
  - beyond laser application: III/V detectors, modulator, solar cells, etc.
- Very high crystal quality required for CW laser operation
  - Life time ⇔ defect density (DLD)
- Monolithic Hetero Epitaxy: Huge field of research!
  - Many – very different – very interesting – approaches!
- Tight competition but the final solution/direction is not clear yet!
  - different integration approaches might go into production depending on the application

THANK YOU FOR YOUR ATTENTION!