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Silicon photonics: Integrated modulators and detectors

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Integrated modulators and detectors

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http://silicon-photonics.ief.u-psud.fr/

Silicon photonics:
Waveguide modulators and detectors

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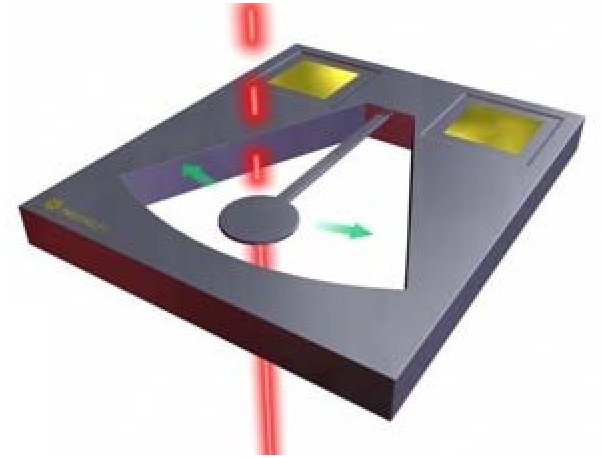
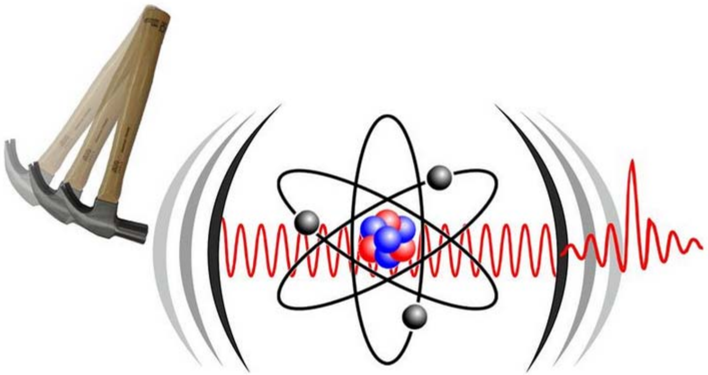
Outline

- Motivation
  - √ Silicon photonics in two words!
- Photodetectors on silicon
  - √ Main characteristics
  - √ Main results
- Optical modulators
  - √ Figures of Merit
  - √ Modulation in silicon
  - √ Main results
- Electronic-Photonic convergence
- Conclusion

How can we modulate optical light to code information?





Optical modulation

Direct modulation of the laser beam

- Simple ☺
- Cost-effective ☺
- Compact ☺
- Chirp: output frequency shifts with drive signal 😐
  - √ Carrier induced (Transient chirp)
  - √ Temperature variation due to carrier modulation (slow chirp)
- Limited extinction ratio 😐
  - √ Laser is not turn off at 0-bits
- Impact on "distance . bit-rate" product 😐

External modulation

- Additional component 😐
- Additional loss 😐
- Higher speed ☺
- Large extinction ratio ☺
- Low chirp ☺
  - Push pull configuration
- Low modulation distortion ☺

High performance optical transmission systems are based on external modulation

External optical modulator

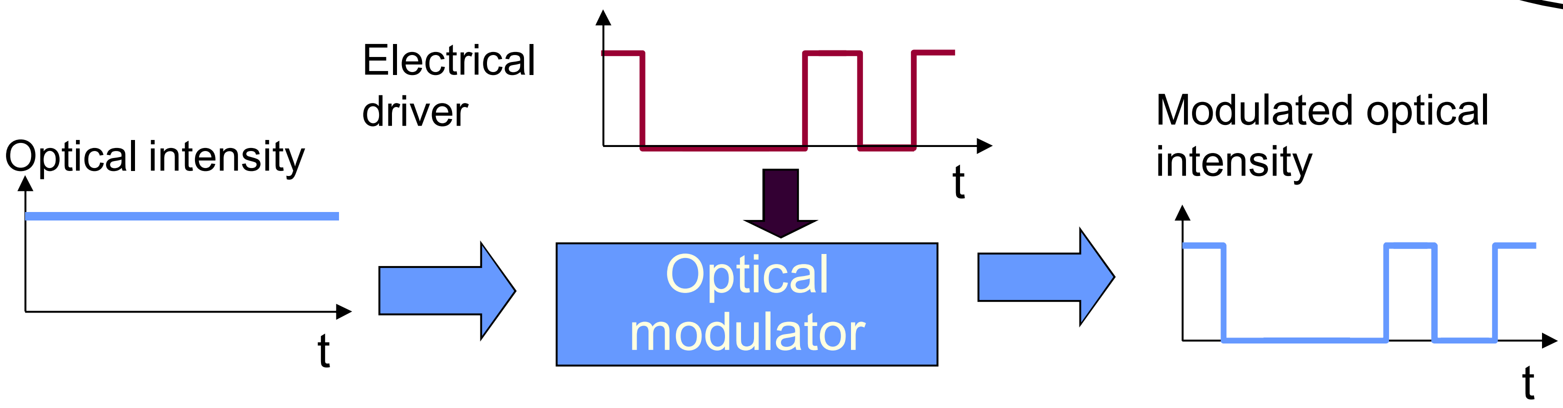
III-V modulator on Si

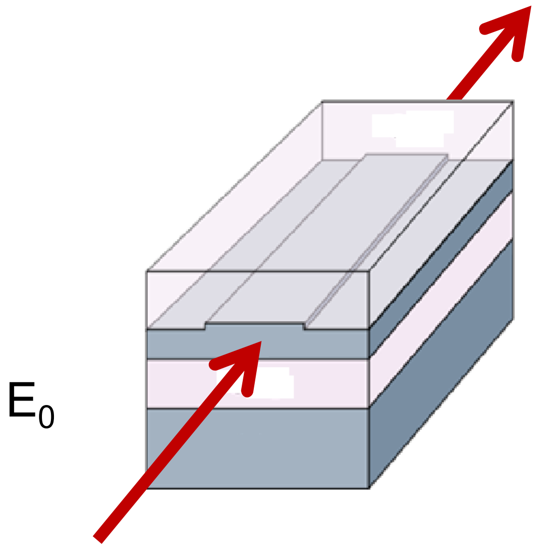
- Bonding technology 😐
- Limitation of the number of modulator on the silicon chip 😐
- Cost 😐
- Well known ☺
- Good performances ☺
- Mature device ☺

Silicon-based modulator

- Less mature device 😐
  - But more and more mature ☺
- Physical effect for optical modulation: 😐
  - more limited in silicon than in III-V material
  - Less flexibility on material alloys
- Integration ☺
- Compatible with CMOS technology ☺
- Low cost ☺
  - for high production volume

Optical modulation

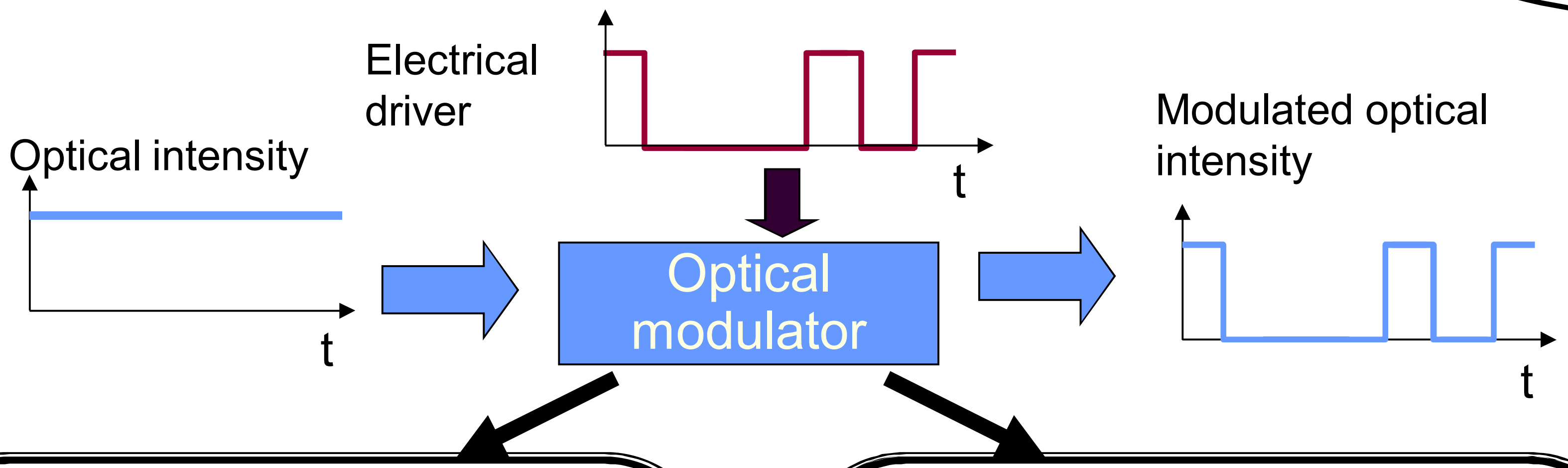




$$E_0\, e^{-\alpha L/2}\, e^{j2\pi n L/\lambda}$$

Electro-absorption

Electro-refraction



Electroabsorption

Absorption coefficient variation under an electric field

⇩

Intensity modulation

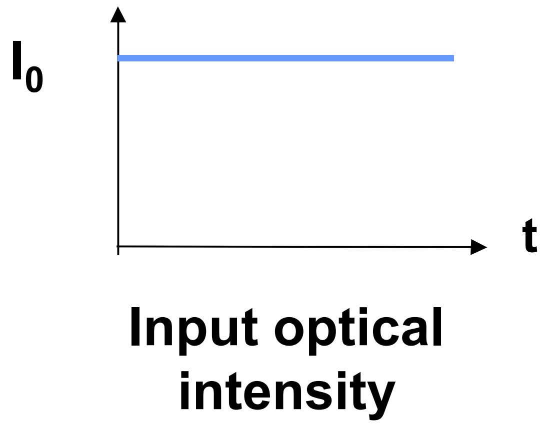
Electrorefraction

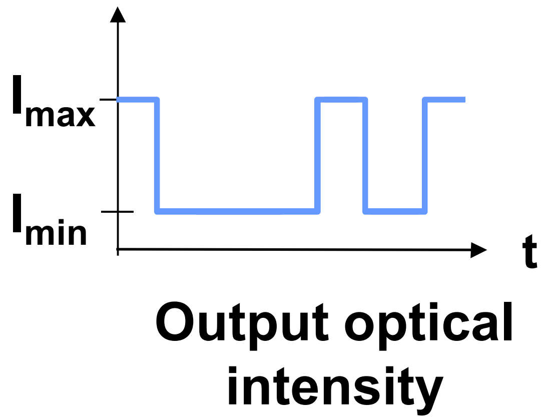
Refractive index variation under an electric field

Phase modulation

⇩ *interferometer*

Intensity modulation





- Distinction between I_{min} et I_{max}
  - MD : Modulation Depth - %

$$MD = \frac{I_{max} - I_{min}}{I_{max}}$$

  - Extinction ratio (ER) - dB

$$ER = 10 \log \left(I_{max} / I_{min} \right)$$

  - Insertion loss - dB

$$P = 10 \log \left(I_0 / I_{max} \right)$$

What are the limitations of the modulator speed?

- ❑ Intrinsic speed
  - ✓ Physical phenomenon limitation
- ❑ RC time constant
  - ✓ Electrical circuit limitation
- ❑ RF signal propagation
  - ✓ impedance adaptation
  - ✓ Matching of electrical and optical velocities

Modulator speed

- ***Intrinsic speed:*** Time constant of the physical phenomenon responsible of the interaction between the semiconductor and the EM wave. The intrinsic speed depends on the physical effect used:

  √ ***Electro-absorption :***
  - The cut-off wavelength (at the absorption edge) is shifted by applying an external voltage to the semiconductor: Intrinsically high speed (f >>GHz).

  √ ***Electro-refraction:*** depends on the index variation origin
  - Thermal variation of the refractive index : very slow
  - Linear (Pockels) and nonlinear (Kerr) electro-optic effects
  - Free carrier concentration variation : time constant from ps (carrier depletion) to ms (carrier recombination)

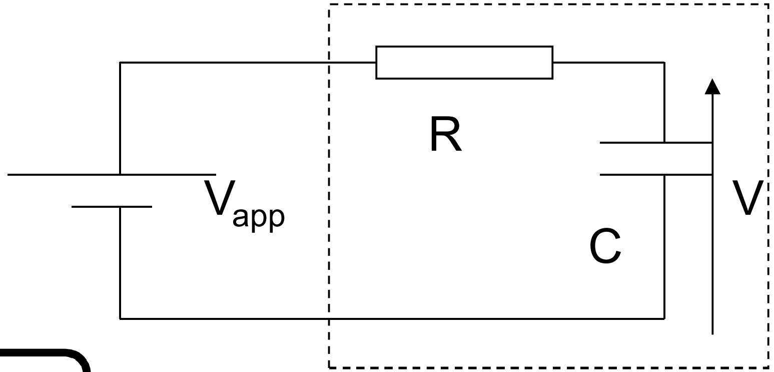
Modulator speed

Bandwidth of the electrical circuit

The equivalent electrical scheme for MOS capacitor and pin diode under reverse bias voltage is a capacitor

$$f_c = \frac{1}{2\pi.RC} \nearrow \quad \text{when R and/or C} \searrow$$

Modulator electrical scheme



$$V = \frac{V_{appl}}{1 + j2\pi RCf} = \frac{V_{appl}}{1 + j\frac{f}{f_C}}$$

- ❑ RC time constant should be minimized
  - ✓ Resistance R
    - ➢ Increase of the doped regions of contacts
    - ➢ Decrease of the distance between contacts and active region
  - ✓ Capacitance C
    - ➢ Directly given by the geometry and the modulator optimization process

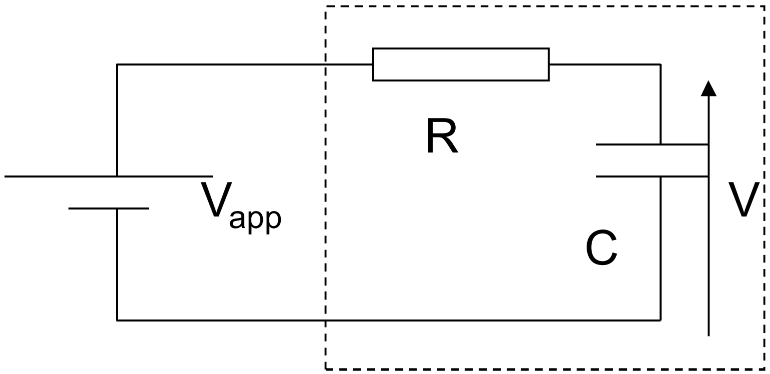
Modulator speed

RF electrical signal propagation

- √ RF signal at f> GHz is a wave propagating on an electrical waveguide.
  - ➢ Coplanar electrodes are mainly used. They have to be defined according to the optical modulator geometry and the required cut-off frequency
- √ Copropagating electrical and optical waves:
  - ➢ Matching of electrical and optical wave velocities
- √ Impedance adaptation is required to avoid electrical signal reflection
  - ➢ 50 ohms is the impedance of the most RF equipments

Energy consumption

Modulator electrical scheme



Energy to charge the device

Energy/bit = 1/4 $(CV_{pp})^2$

Energy dissipation of photocurrent

Energy/bit = 1/B $(I_{ph}V_{bias})$

How can we reduce the energy consumption?

Specifications

Silicon based modulator: key element to develop high speed optical links in the telecom wavelength range

- Compatibility with silicon technology
- Low bias voltage
- High bandwidth
  - Frequency operation > 10 GHz
  - High data operation from 10 Gbit/s to 40 Gbit/s
- Integration in submicron SOI waveguide
  - Low insertion loss
  - Large extinction ratio

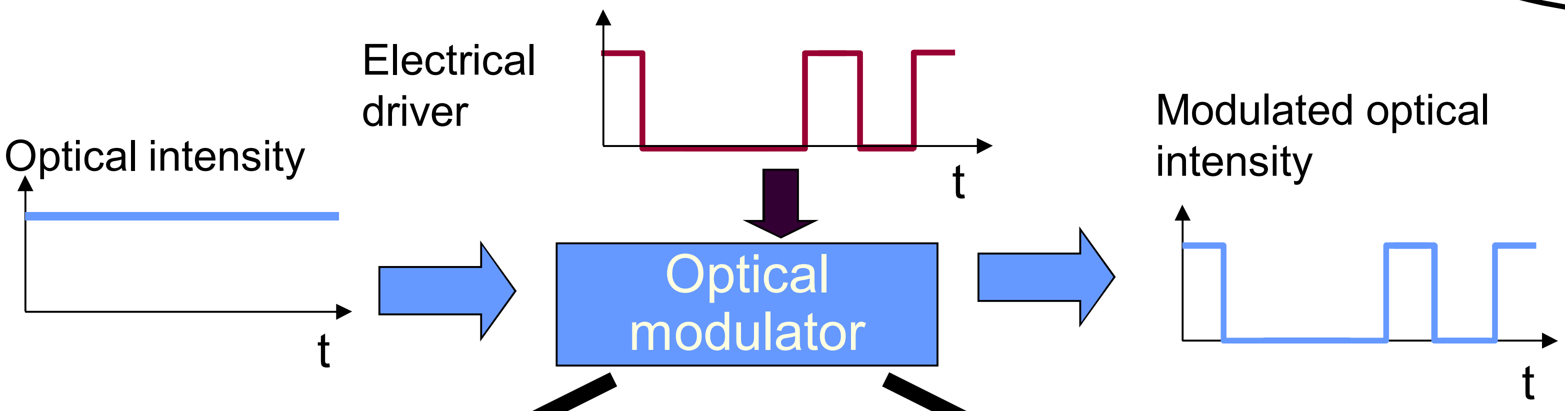
Silicon based modulator: key element to develop high speed optical links in the telecom wavelength range

Figures of merit

- $V_{\pi}L_{\pi}$ Modulation efficiency
- IL Insertion loss
- f_c -3dB bandwidth
- ER Extinction ratio

- Voltage swing
- Power consumption

Optical modulation



Electroabsorption

Absorption coefficient variation under an electric field

⇓

Intensity modulation

Electrorefraction

Refractive index variation under an electric field

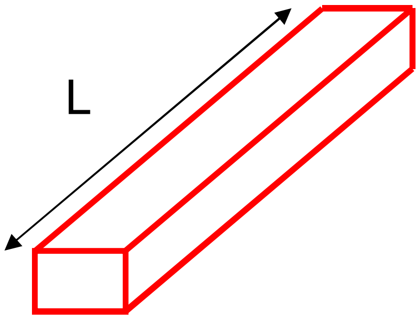
Phase modulation

⇓ *interferometer*

Intensity modulation

Phase modulation:

Refractive index variation in the waveguide



(E_1,φ_1)

Amplitude and phase after propagation in the waveguide

(E_0,φ_0)

Amplitude and phase at the waveguide input

$$\varphi_1 = \varphi_0 + \frac{2\pi}{\lambda}(n_{eff} + \Delta n_{eff})L$$

$$E_1 = E_0 e^{\left(-\alpha/_2 L\right)}$$

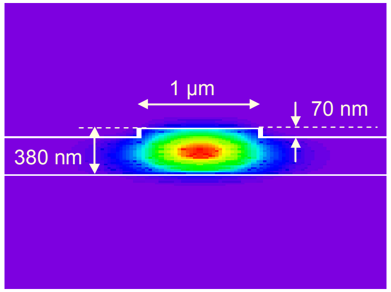
Δneff depends on:

- Physical effect
- The overlap between the optical mode and the refractive index variation region

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n_{eff} L$$

$$\Delta\varphi = \pi \Longleftrightarrow L = L_\pi = \frac{\lambda}{2\Delta n_{eff}}$$

Electro-refraction effect

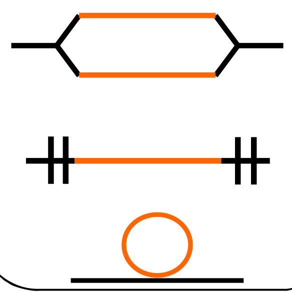


Refractive index variation

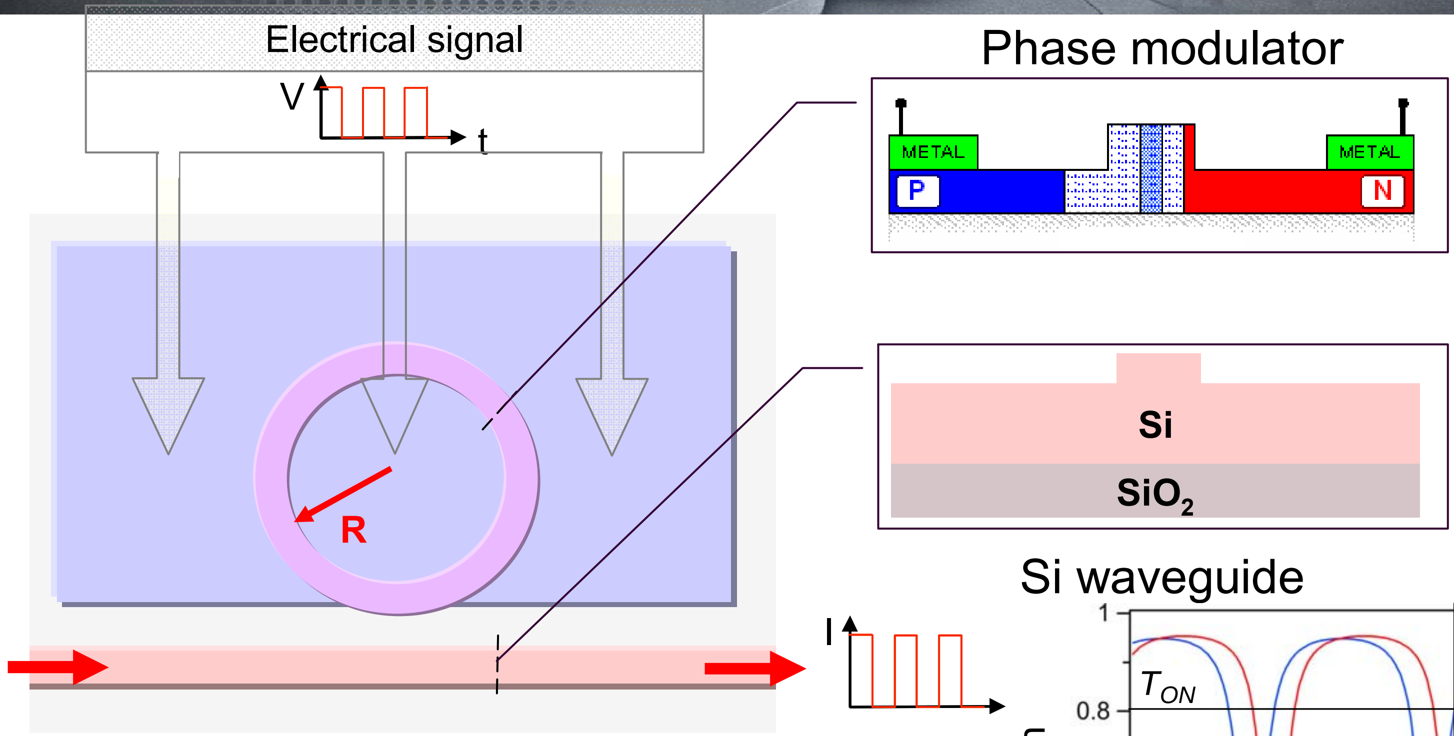
Effective index variation of the guided optical mode

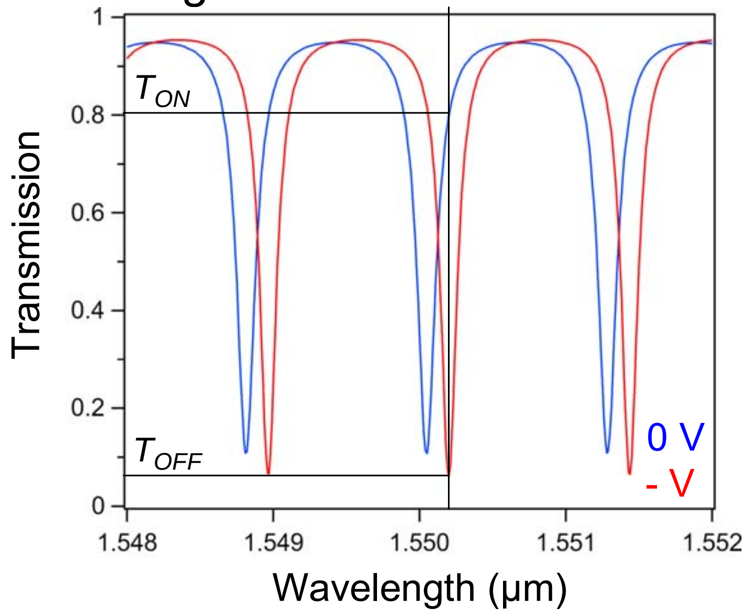
Phase variation

Interferometers

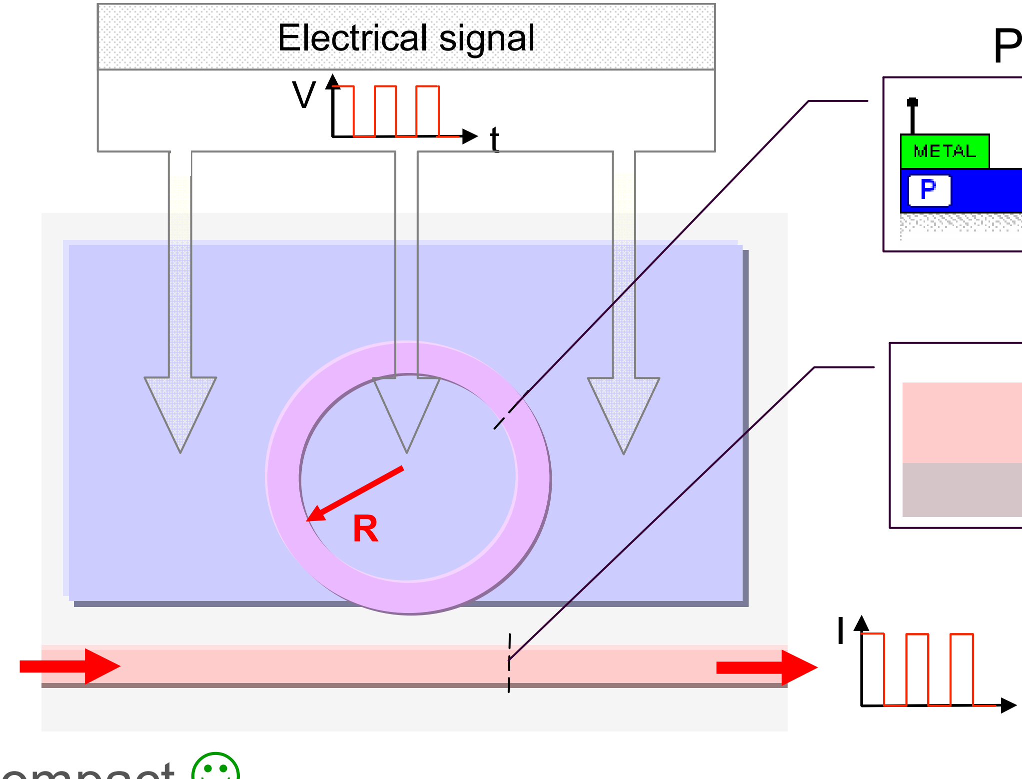


Optical intensity variation

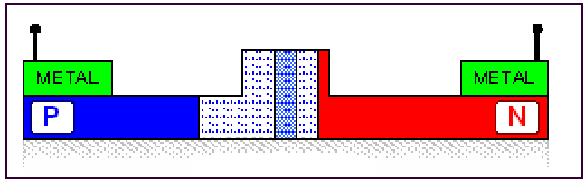


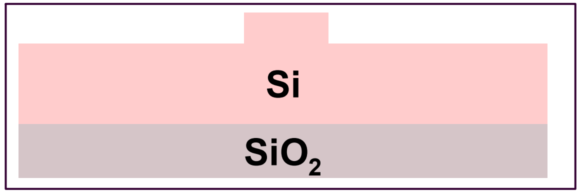


Advantages/desadvantages ?

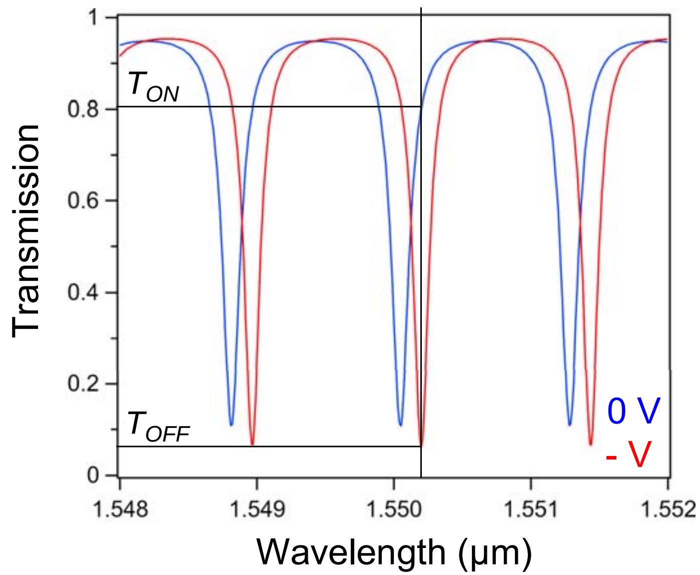


Phase modulator



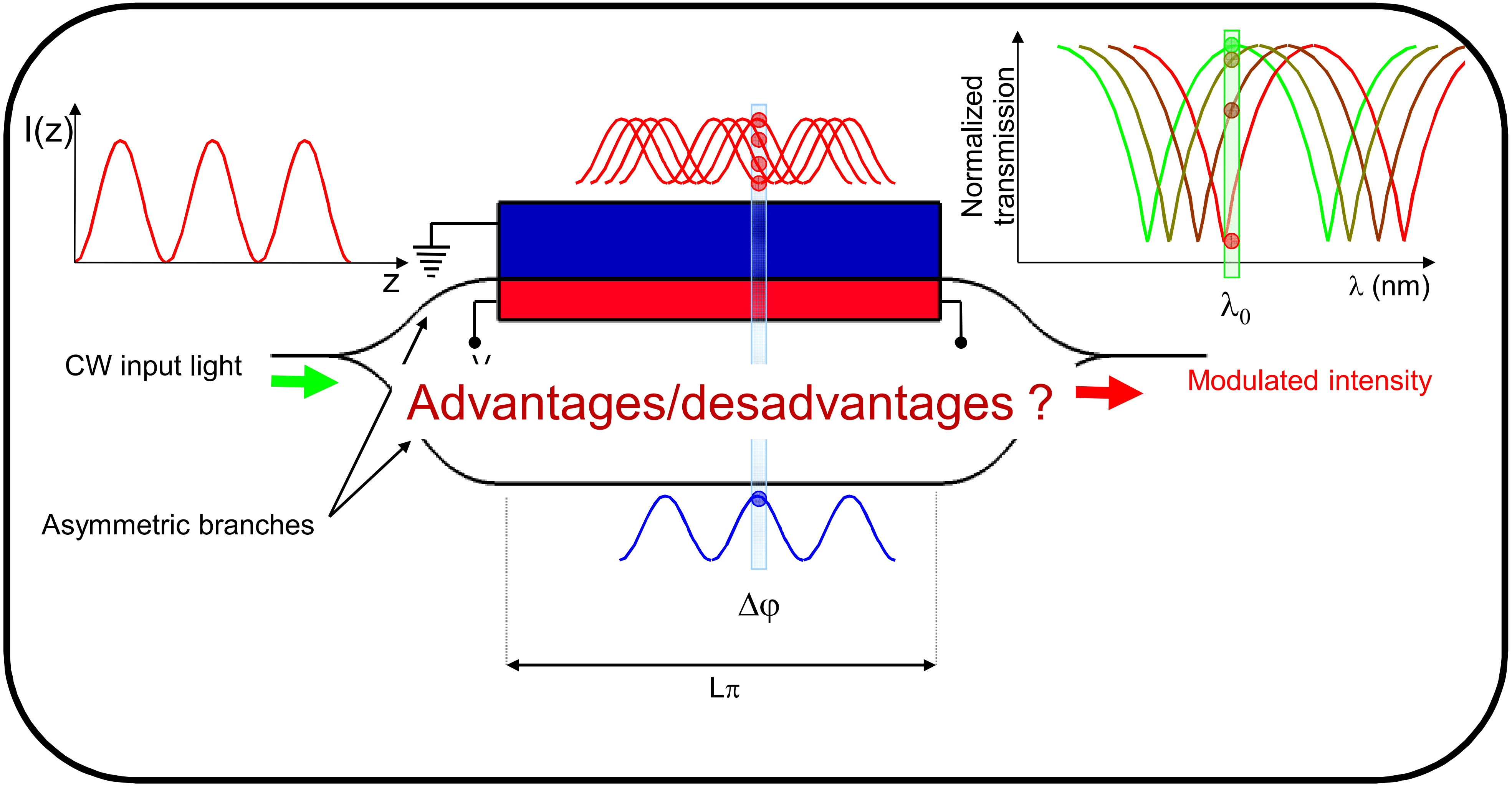


Si waveguide

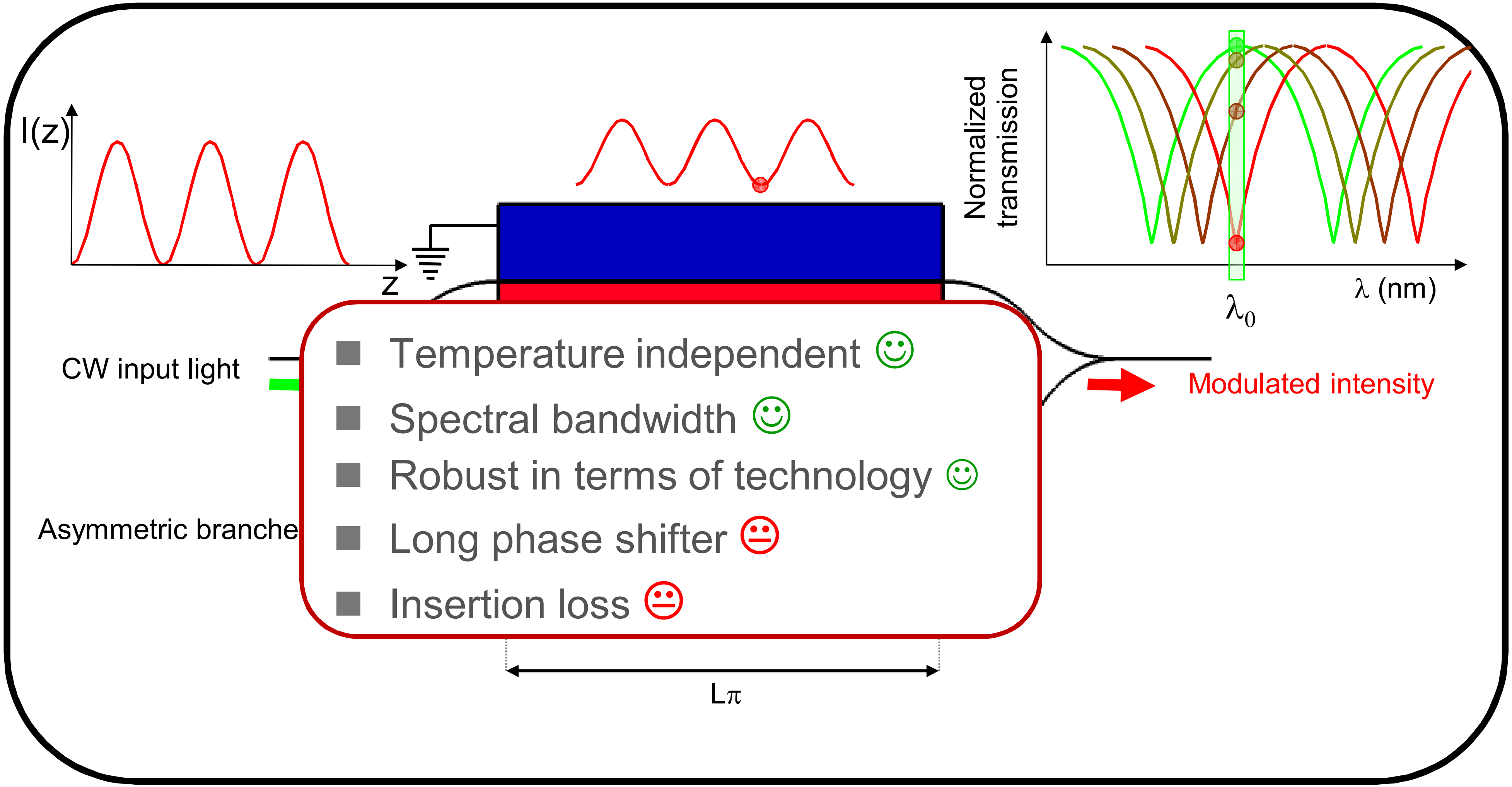


- Compact ☺
- Low insertion loss ☺
- Low power consumption ☺
- Temperature dependent 😐
- Limited spectral wavelength bandwidth 😐

- Asymmetric MZI



- Asymmetric MZI



- Temperature independent ☺
- Spectral bandwidth ☺
- Robust in terms of technology ☺
- Long phase shifter 😐
- Insertion loss 😐

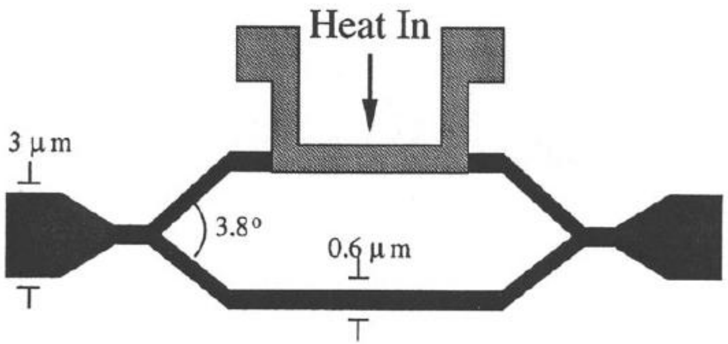
How can we perform EO effect?

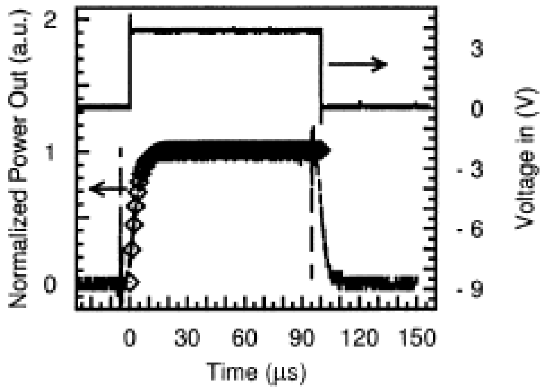
- ✓ Thermal effect
- ✓ Nonlinear effects:
  - ➢ Pockels effect
  - ➢ Kerr effect
- ✓ Plasma effect

- Thermo-optic coefficient
  - √ In silicon
    - ➢ 2.10^{-4} K^{-1} at 1.55μm

$$\Delta n = \frac{dn}{dT}\Delta T$$

- Demonstration of silicon optical modulator:
  - ➢ Bandwidth limited to few 100 kHz





Thermal effect can be a parasistic effect for high speed optical modulators.

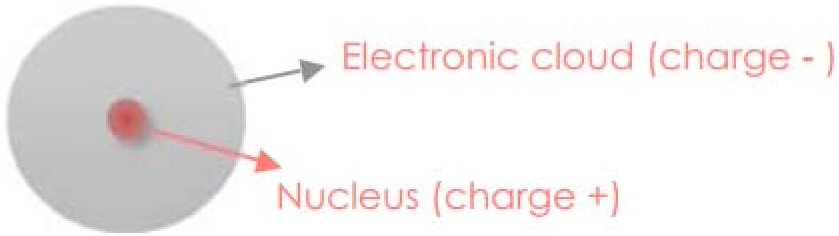
Espinola et al IEEE PTL, 15, 1366 (2003).

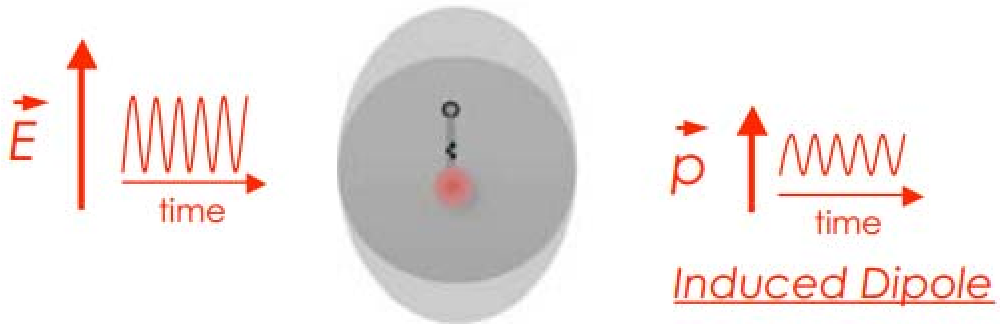
Electro-optic effect

Linear and Nonlinear Polarization:

$$\tilde{P}(t) = \chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \cdots$$

Simplistic model for an atom =





Linear and Nonlinear Polarization:

In silicon

$$\tilde{P}(t) = \chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \cdots$$

√ **Pockels effect**:
- Linear electro-optic effect

√ Wavelength conversion
- Second Harmonic Generation (SHG)

Silicon is a centro-symetric material !

√ **Kerr effect**:
- Nonlinear electro-optic effect

√ Wavelength conversion
- Four wave mixing (FWM)

Weak effect to be efficient for modulation

$$n = n_0 + I * n_2$$

$$n_2^{Si} \sim 10^{-14}\,\text{cm}^2/\text{W} \quad >> \quad n_2^{glass} \sim 10^{-16}\,\text{cm}^2/\text{W}$$

is it possible to obtain a linear electro-optic effect in silicon ?

Nonlinear Polarization:

$$\tilde{P}(t) = \chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \cdots$$

Without straining layer

With straining layer

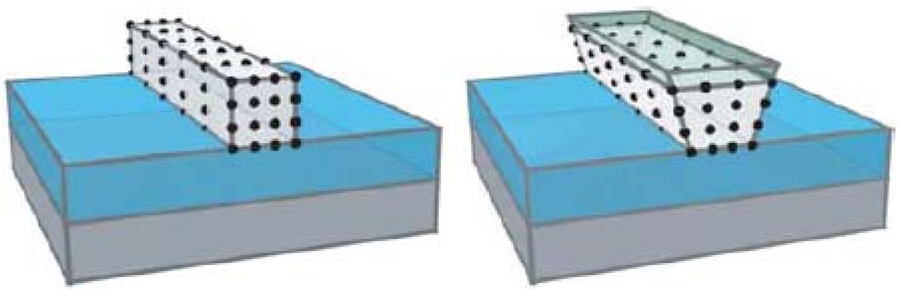
Silicon is a centro-symetric material !

- √ Pockels effect:
  - ➢ Linear electro-optic effect
- √ Wavelength conversion
  - ➢ Second Harmonic Generation (SHG)

Break the symmetry of silicon crystal

⇩

Strained silicon photonics

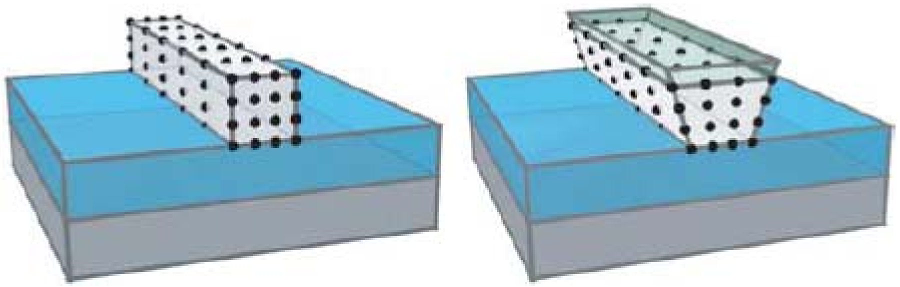


Electro-optic effect in silicon

❑ Strained silicon

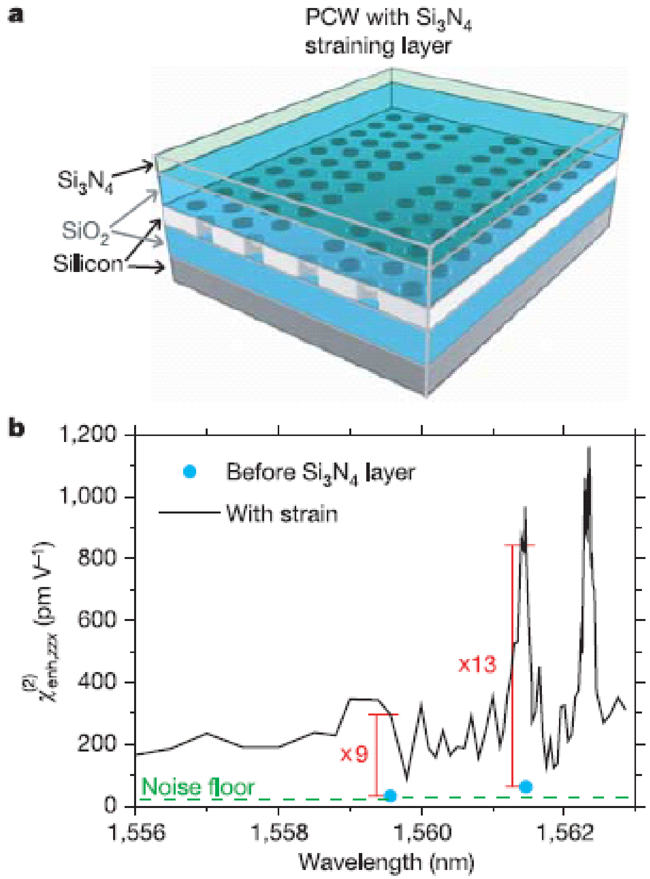
- Breaking the crystal symmetry by depositing a straining layer (Si_3N_4) on top of a silicon waveguide. The amorphous Si_3N_4 layer is compressively strained,

Without straining layer — *With straining layer*



$$\chi^{(2)} \approx 15\,pm/V \qquad \Delta n = \frac{\chi^{(2)}E}{2n_0}$$

At E = 5.10^5 V/cm, $\Delta n = 10^{-6}$



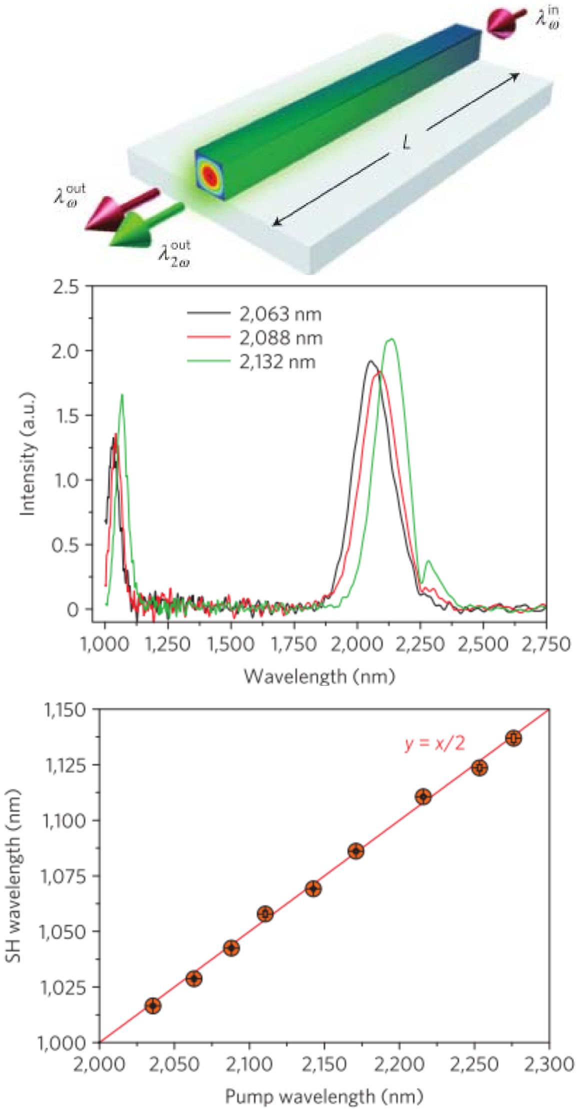
Jacobsen et al, Nature 441, 199 (2006)

M. Cazzanelli et al., Nature Materials, 2011

- Second Harmonic Generation
- Pumping pulsed Lasers:
  - √ 4 ns
  - √ 100 fs
- Efficiency:

$$\eta = \frac{P_{2\omega}}{P_\omega} = 5 \times 10^{-8}$$

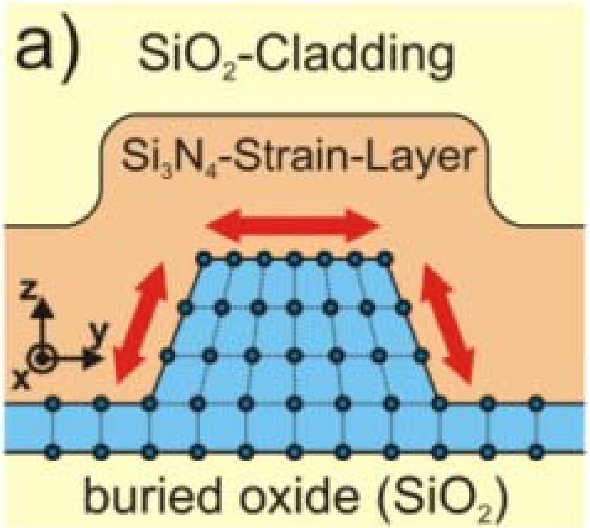
- Nonlinearity depends on:
  - √ Intensity of strain
  - √ Inhomogeneity of strain
  - √ Distribution of strain vs optical mode



- Pockel's effect:
  - √ $V = 30\text{V} \rightarrow \Delta n = 2.4 \times 10^{-5}$
  - √ $\chi^{(2)} = 122\text{pm/V}$

- Waveguide width effects:

Waveguide width (nm)	χ^2 (pm/V)
450	71.5
400	122

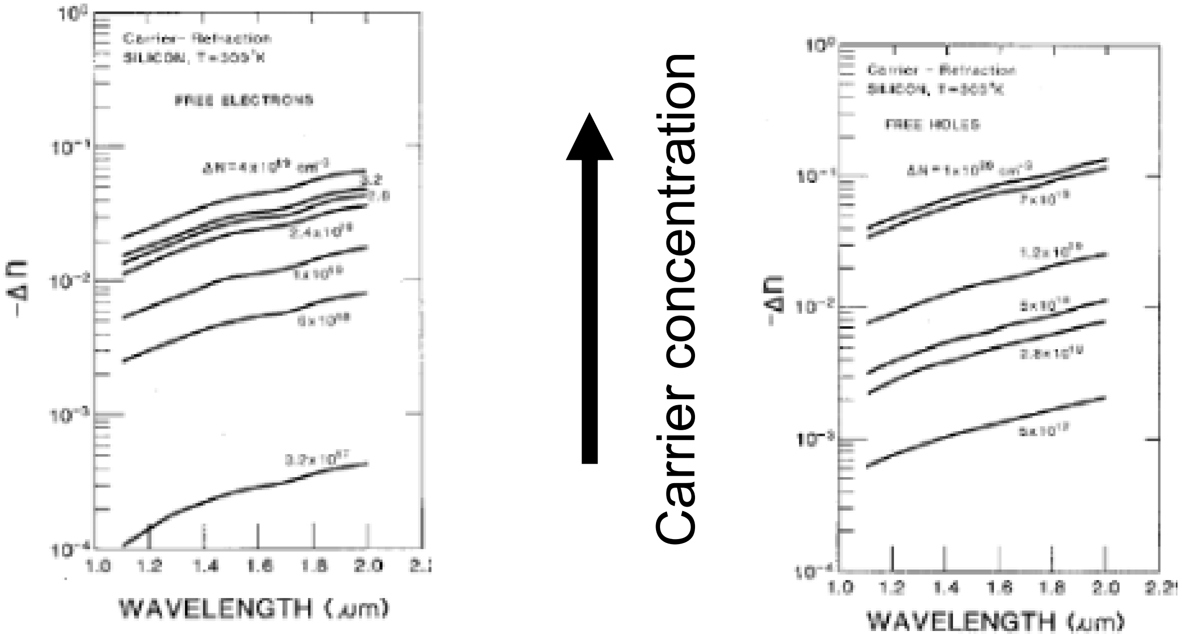


- Conditions to achieve strain:
  - √ Bottom of waveguide fixed and top is strained
  - √ SiN induces strain all around the waveguide
  - √ Thermal annealing

Bartos Chmielak et al. (2011) Opt. Express

❑ Free carrier density variation in silicon

- Refractive index are modified by free-carrier concentration variations:
  - Plasma dispersion effect



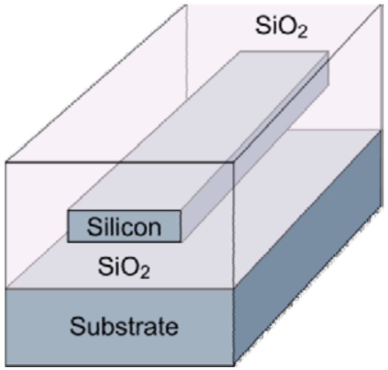
Free electrons Free holes

Soref et al IEEE JQE QE-23 (1), (1987).

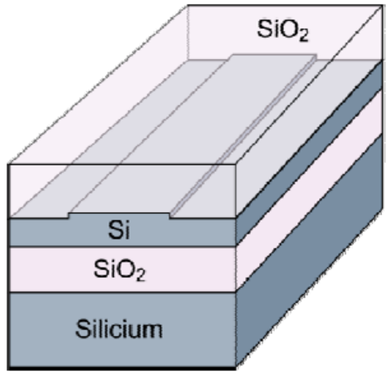
What are the possibilities to obtain a free carrier concentration variation in silicon-based materials ?

- Carrier injection in pin diode under forward bias voltage
- Carrier accumulation in metal-oxide-semiconductor (MOS) capacitors
- Carrier depletion in a pin diode under reverse bias voltage

- Free carrier concentration variation in a silicon waveguide:
  - √ The electronic structure has to be integrated in an optical waveguide



Strip



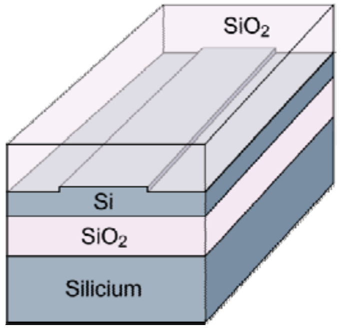
Rib

Which kind of silicon waveguide has to be used?

Integrated optical modulator

- Free carrier concentration variation in a silicon waveguide:
  - √ The electronic structure has to be integrated in an optical waveguide

Rib waveguides are required (in strip waveguide it is not possible to have the electrical contacts)

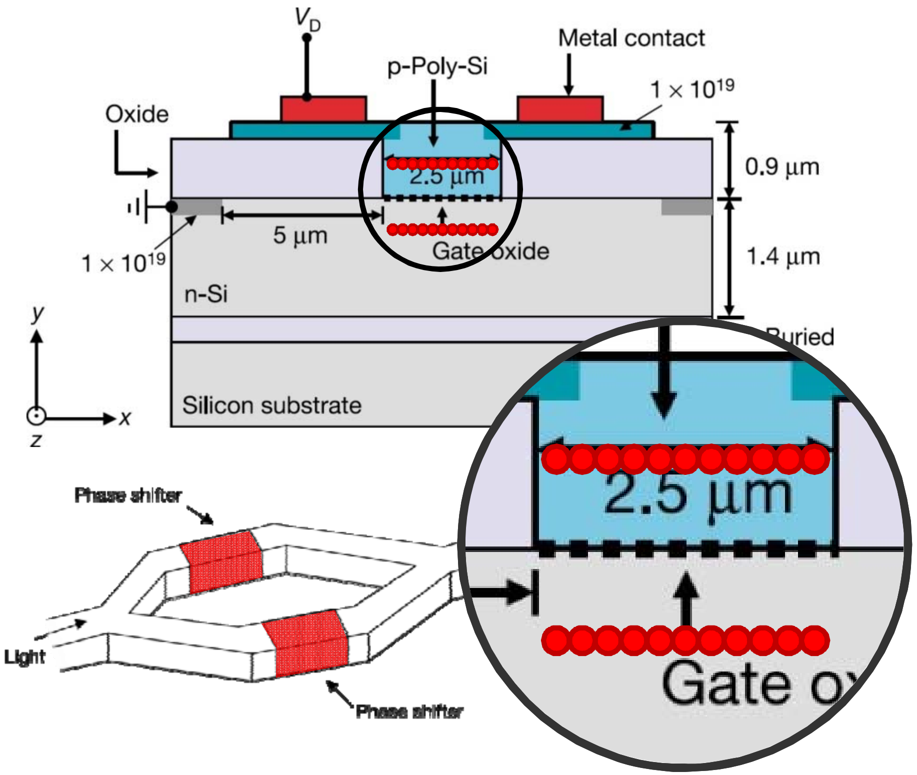


- Doped silicon and metal are responsible for large optical loss

Careful design of the electronic structure is required, to achieve simultaneously:
• large refractive index variation,
• large overlap of the active region with the guided mode,
• low optical loss

Modulator based on carrier accumulation

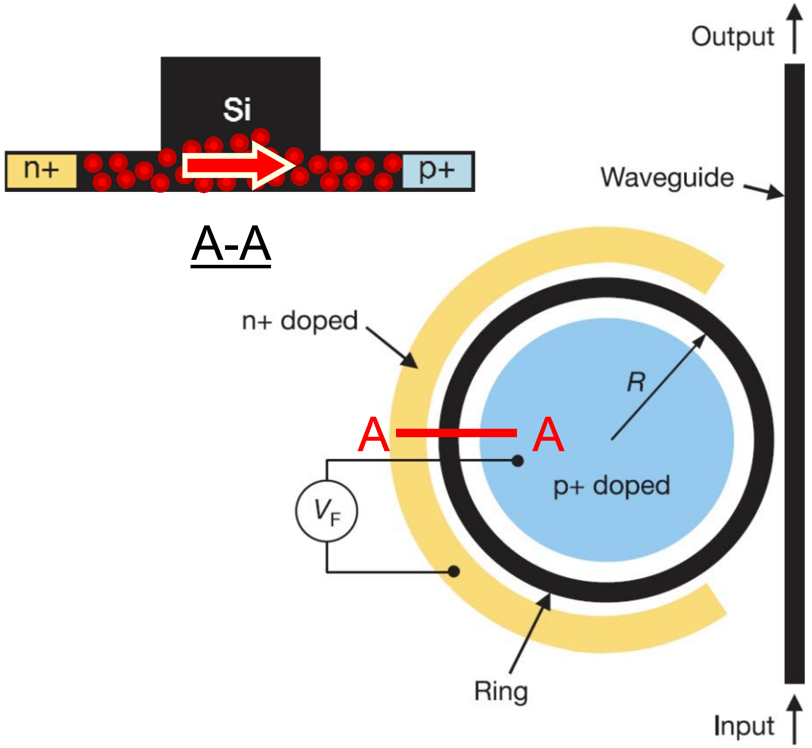
- Intel (2004) : 1st optical modulator working at 1 GHz.



Research lab now involved

- [1] A. Liu et al, « A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor », Nature, vol. 427, pp. 615-618 (2004).
- [2] L. Liao et al, « High speed silicon Mach-Zehnder modulator », Optics Express, vol. 13, pp. 3129-3135 (2005).

- Cornell Univ : modulator based on carrier injection in a ring resonator



Research lab now involved :

Cornell University

UNIVERSITY OF CAMBRIDGE

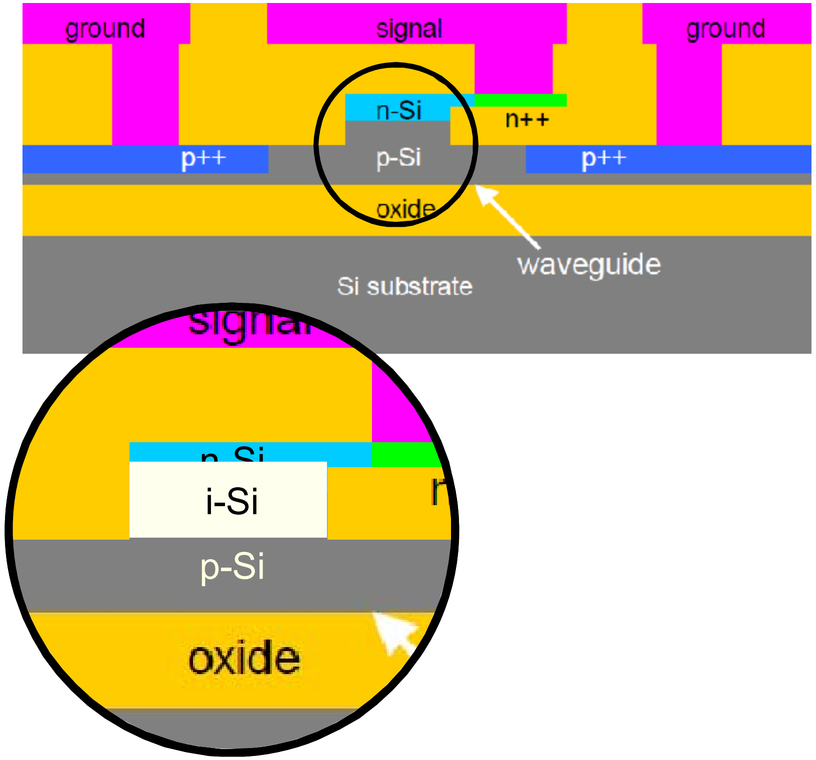
Agency for Science, Technology and Research SINGAPORE

IBM

- [1] Q. Xu et al, « Micrometer-scale silicon electro-optic modulator », Nature, vol. 435, pp-325-327 (2005).
- [2] L. Chen et al, « Integrated GHz silicon photonic interconnect with micrometer-scale modulators and detectors », Optics Express, vol. 17, pp.15248-15256 (2009).

Modulator based on carrier depletion

- Intel : 1st modulator working up to 40 Gbit/s



Research lab now involved :

Université Paris-Sud 11

University of Surrey

Intel

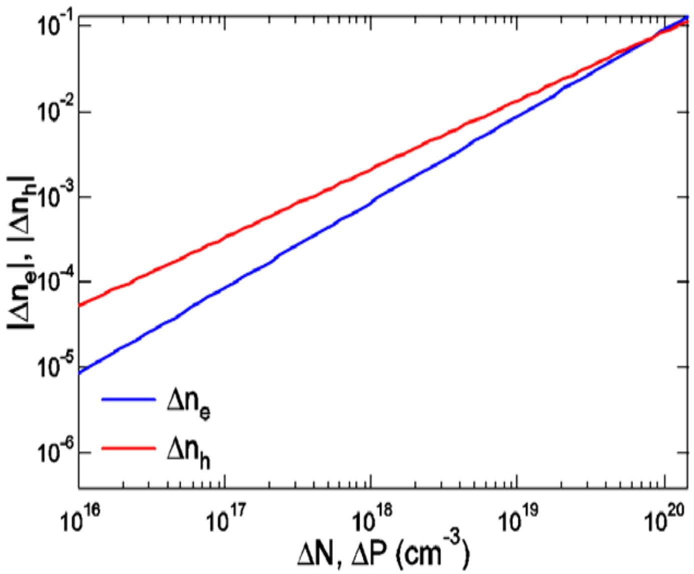
Agency for Science, Technology and Research SINGAPORE

Massachusetts Institute of Technology

- [1] A. Liu et al, « High-speed optical modulation based on carrier depletion in a silicon waveguide », Optics Express, vol. 15, pp. 660-668 (2007).

Carrier depletion in reverse biased diode:

- When a diode is reverse biased, the electrical field increase in the intrinsic region.
- If carriers are located in the intrinsic region at equilibrium, they will be depleted with reverse bias.



Which carriers should we use?

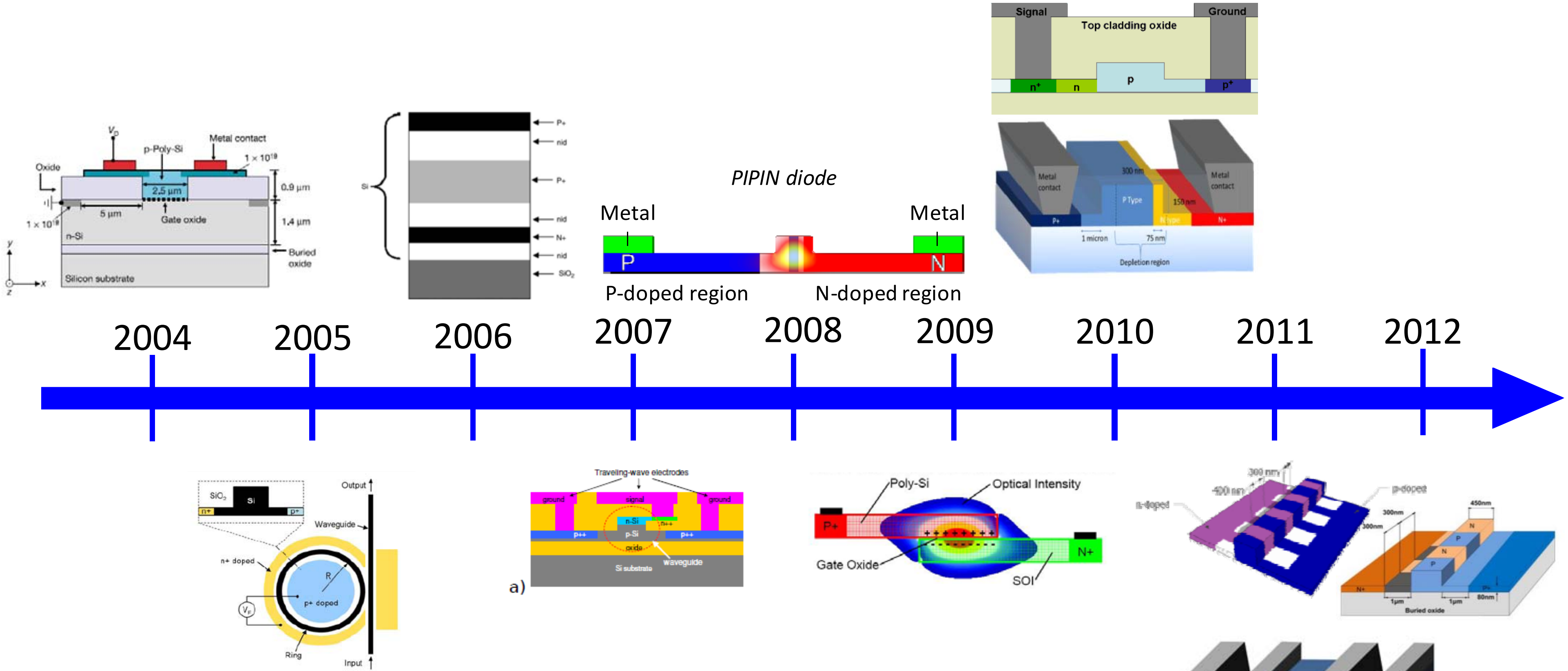
λ=1.55 µm

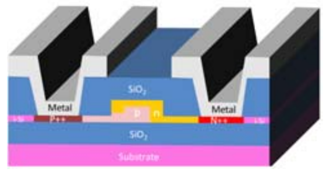
$$\Delta n = -8.8 \times 10^{-22} \Delta N - 8.5 \times 10^{-18} \Delta P^{0,8}$$

Free holes are more efficient than free electrons for refractive index variation for $\Delta N, \Delta P < 10^{20}$ cm^{-3}

Soref et al IEEE JQE QE-23 (1), (1987).

Carrier depletion Si optical modulator





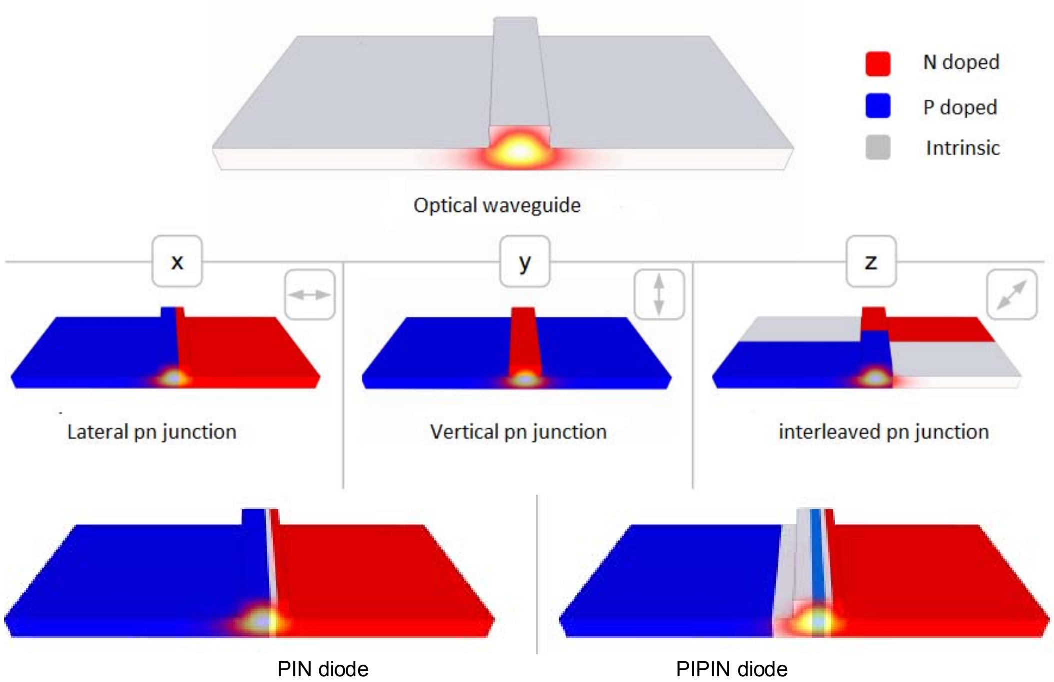
Europe: Univ. Paris Sud, CEA Leti, IMEC, Univ. of Southampton…

Asia: A*Star, Petra, AIST, Chinese Academy of Sciences, Samsung Electronics, Tokyo Institute of Technology …

North America: Intel, IBM, Cornell, Luxtera, Ligthwire, Kotura, Oracle …

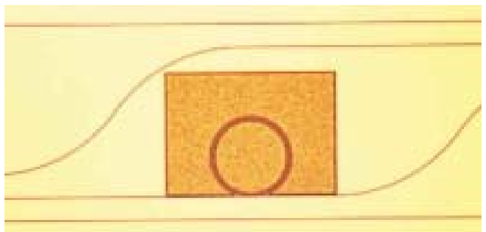
❑ Phase shifters:

- PN diode
- Interleaved PN diode
- PIN diode
- PIPIN diode

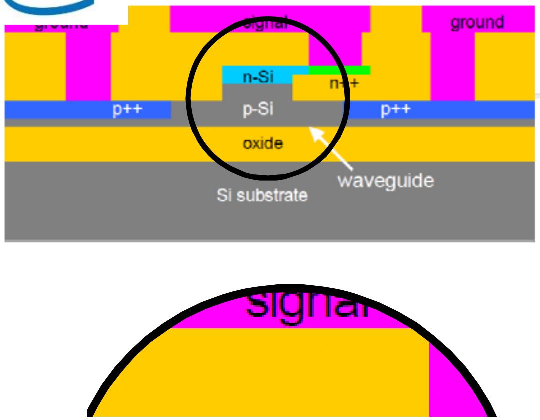


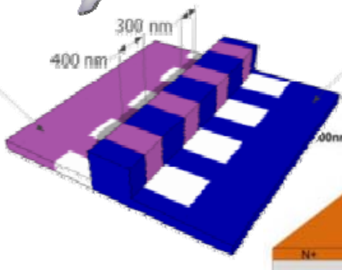
❑ Interferometers

- Ring resonator
- Mach-Zehnder
- Photonic cristals

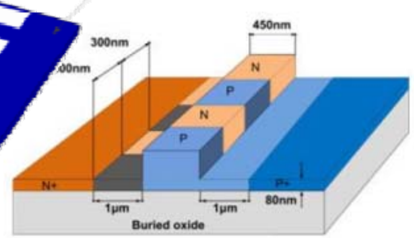


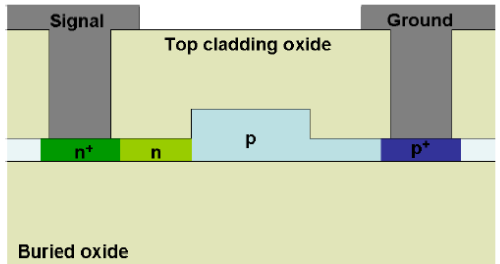
Carrier depletion pn modulators :

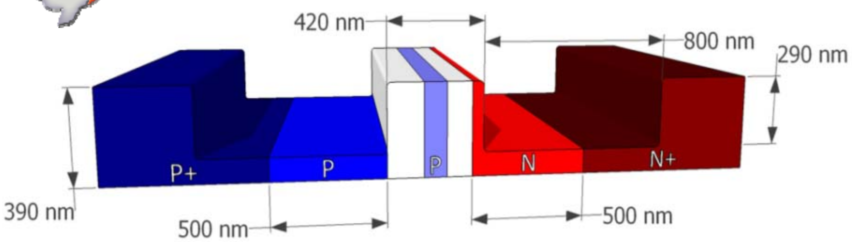




Chinese Academy of Sciences



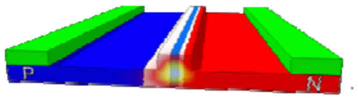




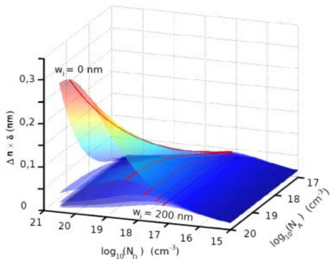
PIPIN diode

- ✓ Space charge extension due to carrier depletion is limited ~100 nm typically.
- ✓ The optimization of “classical” modulators relies on the optimization of the overlap between the optical mode and the depleted region.

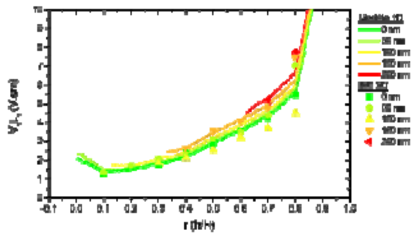
From the idea to the final device



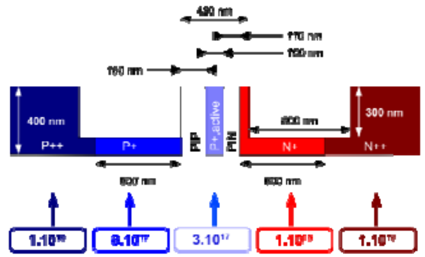
Simulation of the diode



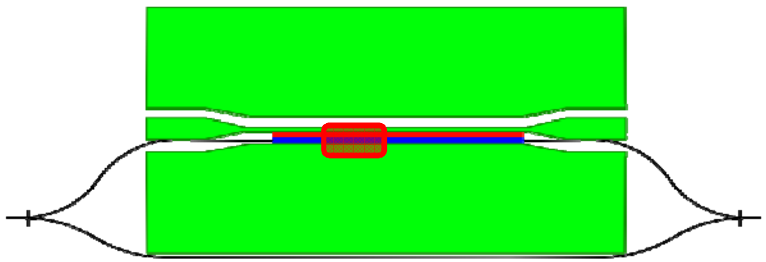
Optimization



Figures of merite

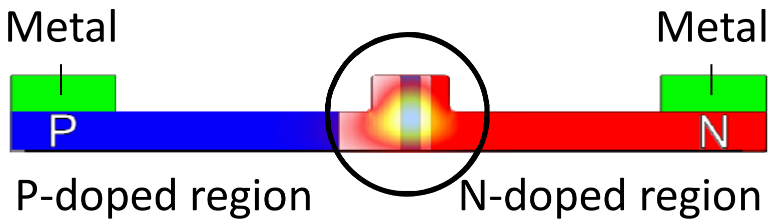


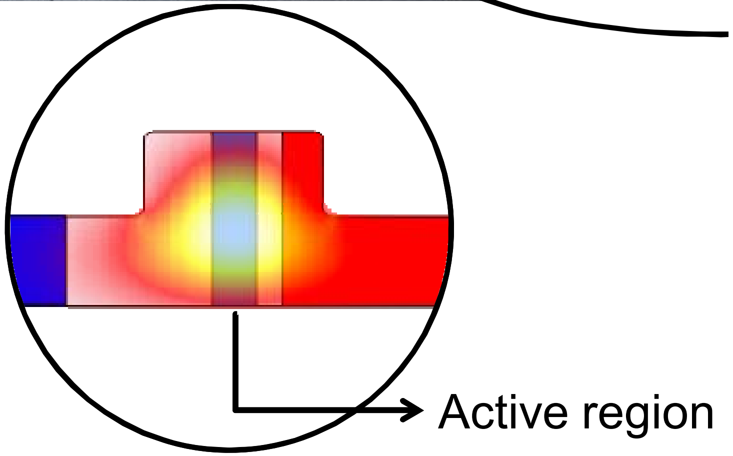
Optimized structure



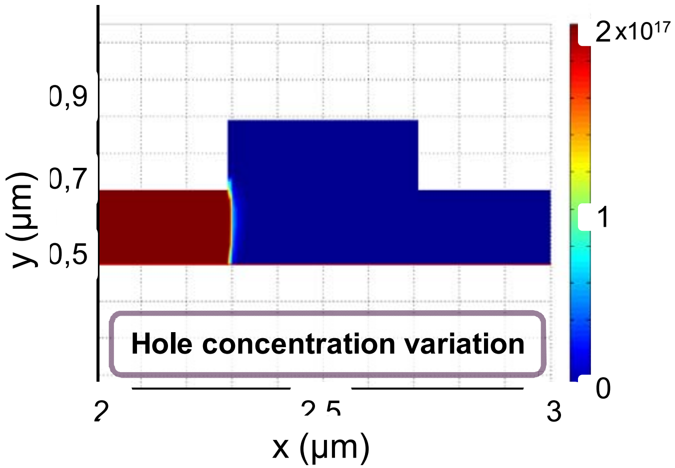
PIPIN diode principle

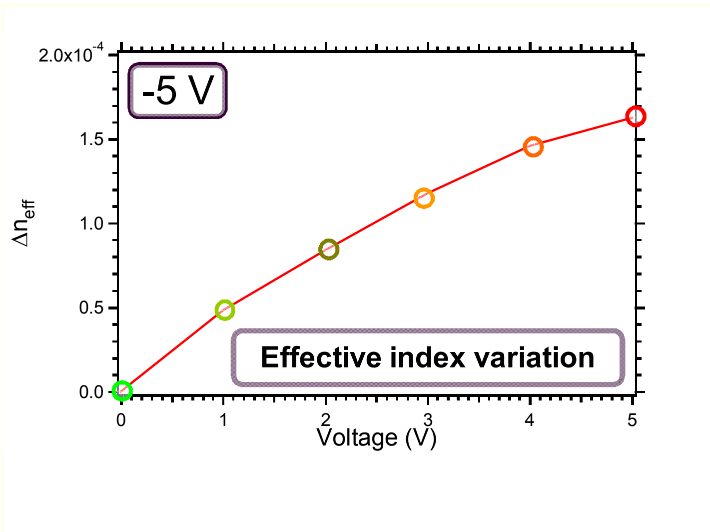
PIPIN diode



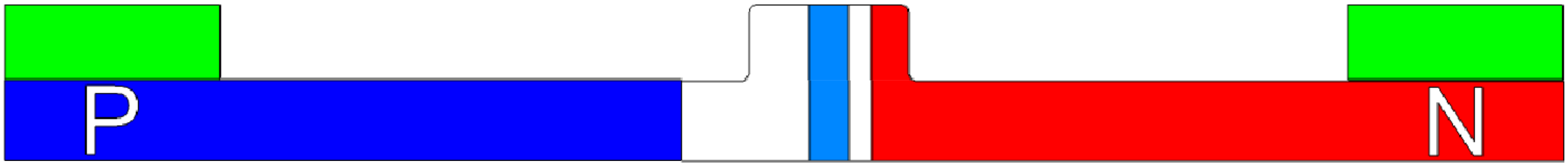


- ✓ Optimization of the overlap between the optical mode and the depleted region.
- ✓ Low insertion loss

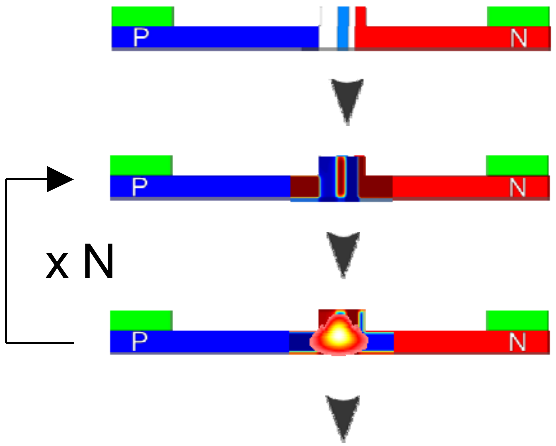




Optimization of the active region



2D EO simulations:



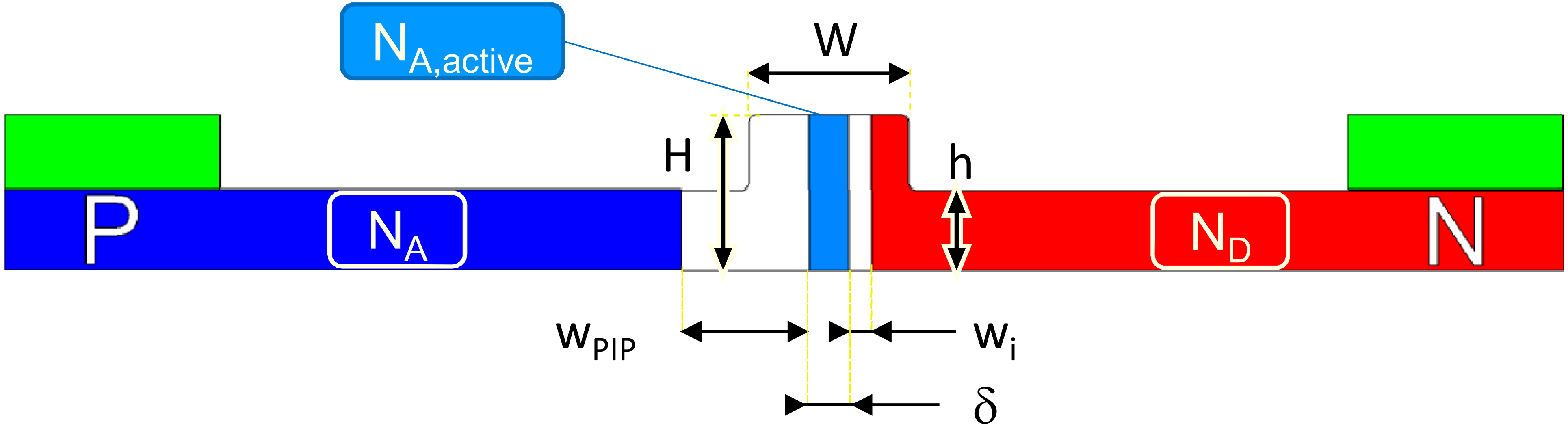
$V_\pi L_\pi$, IL, f_c, ER, …

slow simulations *(+2h/structure)*

Iterative process

Very long process to optimize the structure

Optimization of the active region



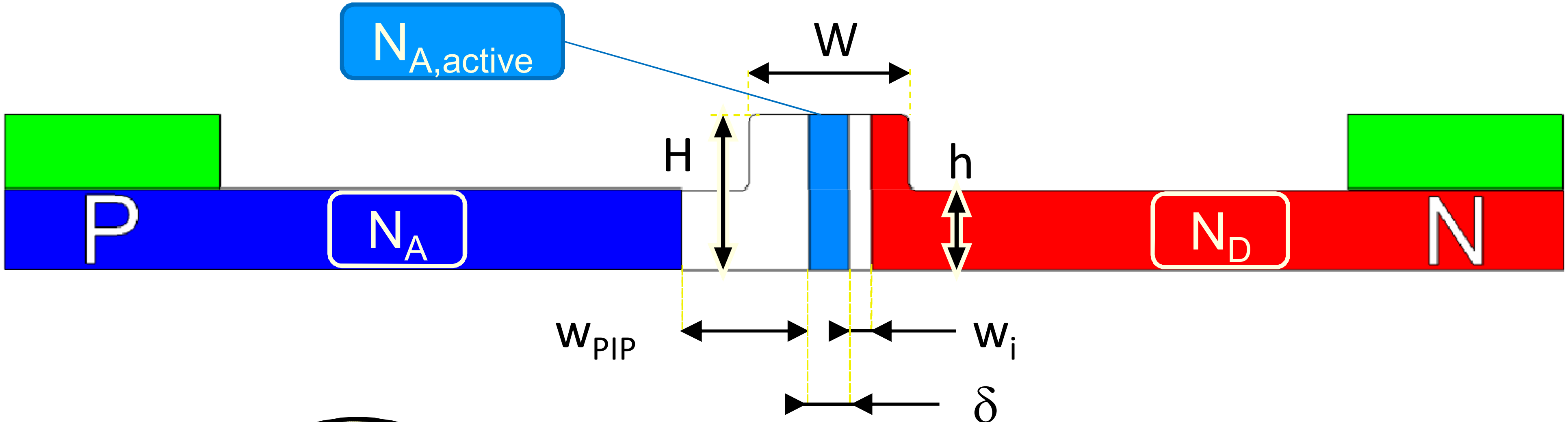
10 Parameters to be determined:

W: Waveguide width
H: Waveguide height
h: Slab height
δ: Width of the active region

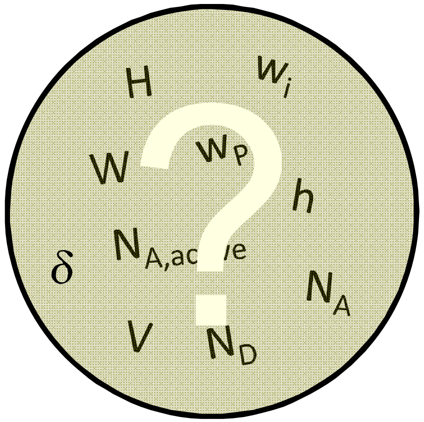
V: Bias voltage

w_{PIP}: PIP region width
w_i: PIN region width
$N_{A,active}$: Active doped region concentration
N_A: P doped concentration
N_D: N-doped concentration

Optimization of the active region



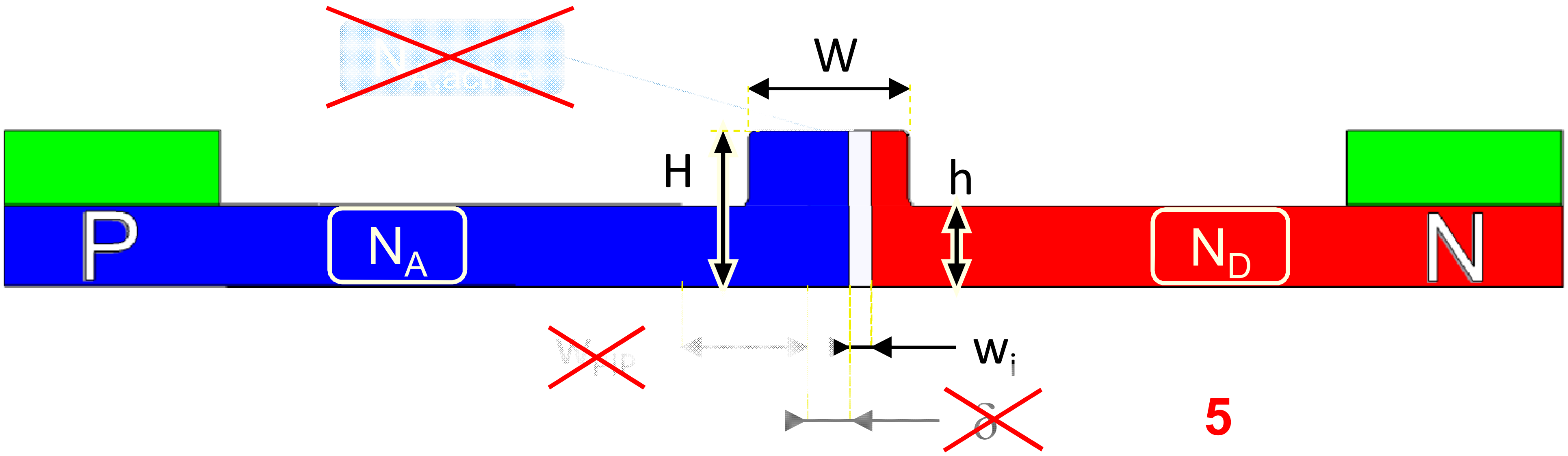
Figures of merit



10 parameters need for optimization

$V_\pi L_\pi$	Modulation efficiency
IL	Insertion loss
f_c	-3dB bandwidth
ER	Extinction ratio

How can we easily obtain an optimized diode?



PIPIN: 10 parameters ➤ PIN: ~~7~~ 5 parameters

Fixed values

H = 400 nm
V_π = 5 V
λ = 1.55 µm

W: Waveguide width
h: Slab height

Waveguide geometry

w_i: PIN region width
N_A: P doped concentration
N_D: N-doped concentration

Diode geometry

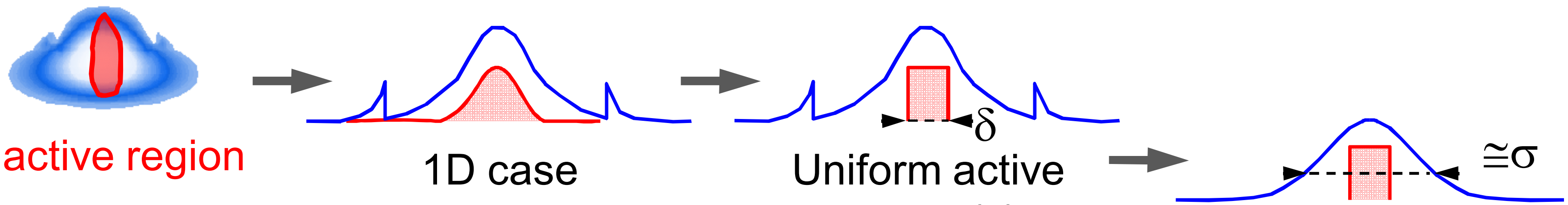
Effective index variation

- General approximation of the effective index variation :

$$\Delta n_{eff,i}(z) = \iint_{\Re} \left|\Psi_i(x,y)\right|^2 \Delta n(x,y,z)\,dxdy$$

$$\Delta n = -8.8\times10^{-22}\,\Delta N - 8.5\times10^{-18}\,\Delta P^{0.8}$$

$|\Psi_0(x,y)|^2$

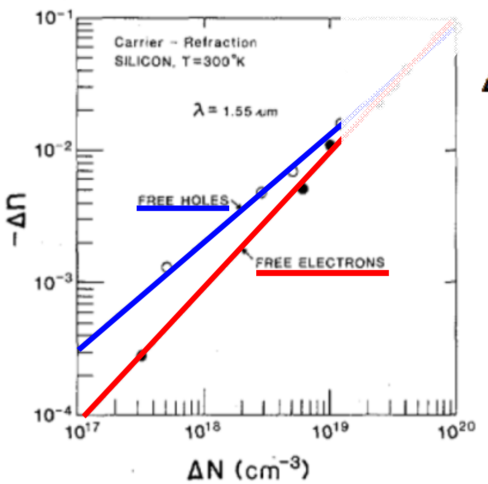


active region

1D case

Uniform active region (δ)

Gaussian distribution (σ)



$$\Delta n_{eff,0}(z) = \int_{\Re} \left|\Psi_0(x)\right|^2 \Delta n(x,z)\,dx$$

$$\Delta n_{eff,0}(z) = \int_{\Re} \left|\Psi_0(x)\right|^2 \Delta n(x,z)\,dx$$

$$\Delta n_{eff,0}(z) = \frac{\Delta n}{\sigma\sqrt{2\pi}} \int_{-\delta/2}^{+\delta/2} e^{-\frac{x^2}{2\sigma^2}}\,dx$$

$\delta << \sigma$

N_A, N_D, w_i

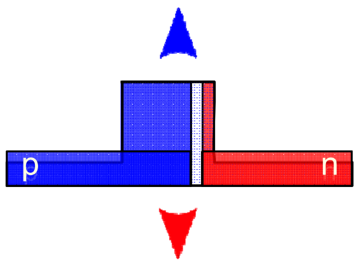
Optimization of the index variation

Fixed values

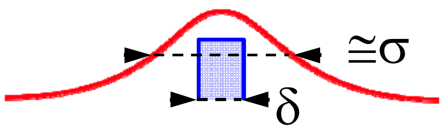
H = 400 nm
V_π = 5 V
λ = 1.55 µm

$$\Delta n_{eff} \approx \frac{\Delta n \times \delta}{2\sqrt{2}\sigma}$$

Optical mode confinement



W, h



$|\Psi_0(x,y)|^2$ $\Delta n(x,y)$

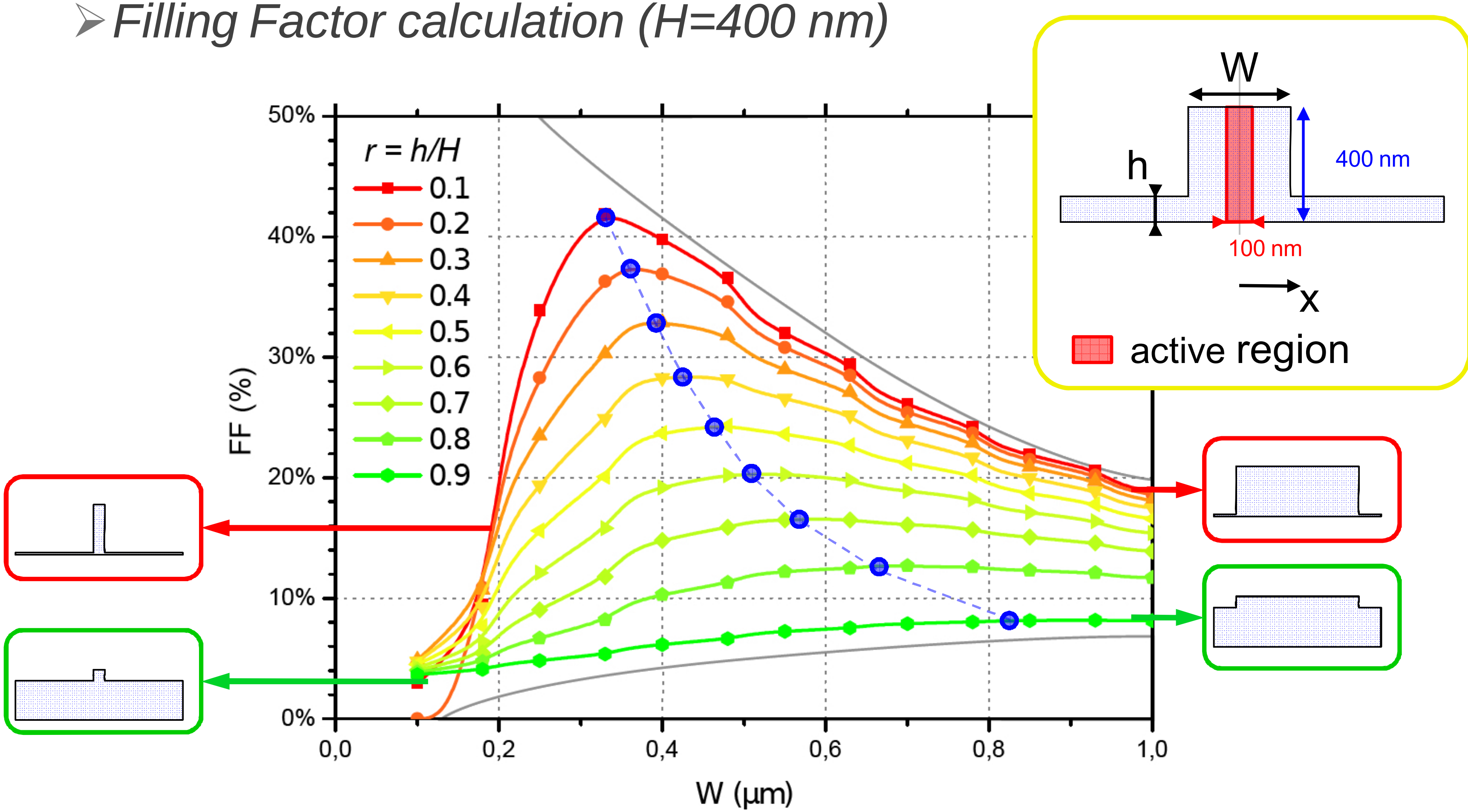
Modulation efficiency optimization

$$\Delta n_{eff} \approx \frac{\Delta n \times \delta}{2\sqrt{2}\sigma}$$

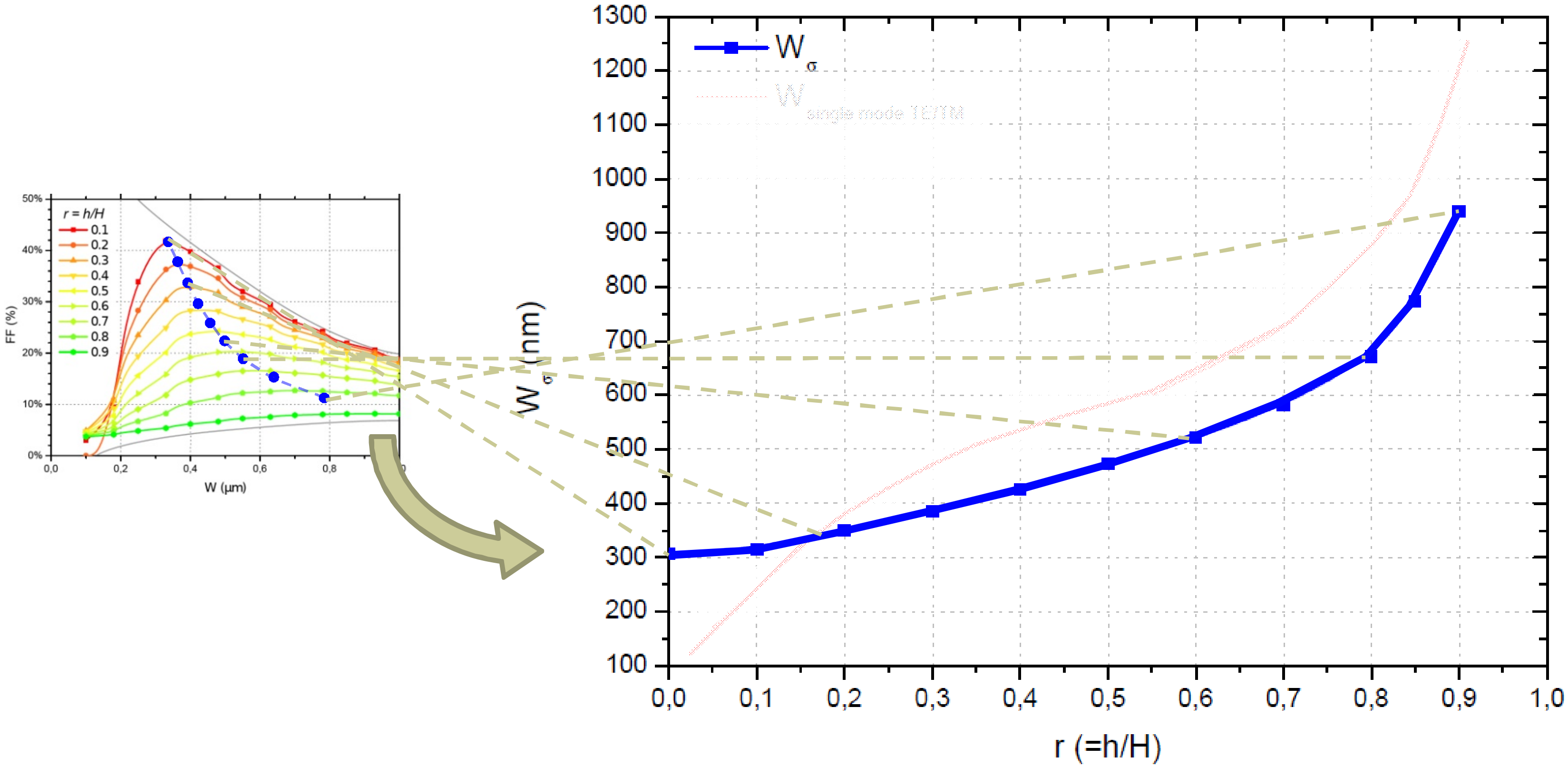
Optical mode confinement

- Waveguide geometry

➢ *Filling Factor calculation (H=400 nm)*

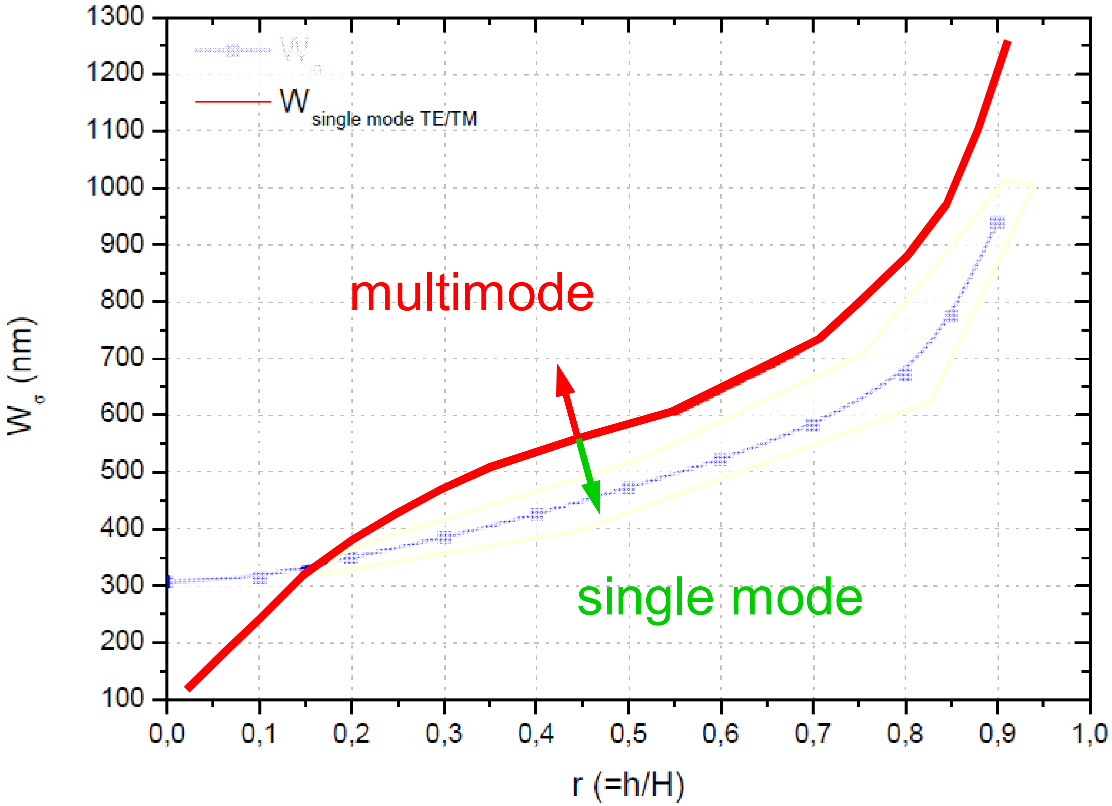


- Waveguide geometry : Maximal Confinement Condition (MCC)

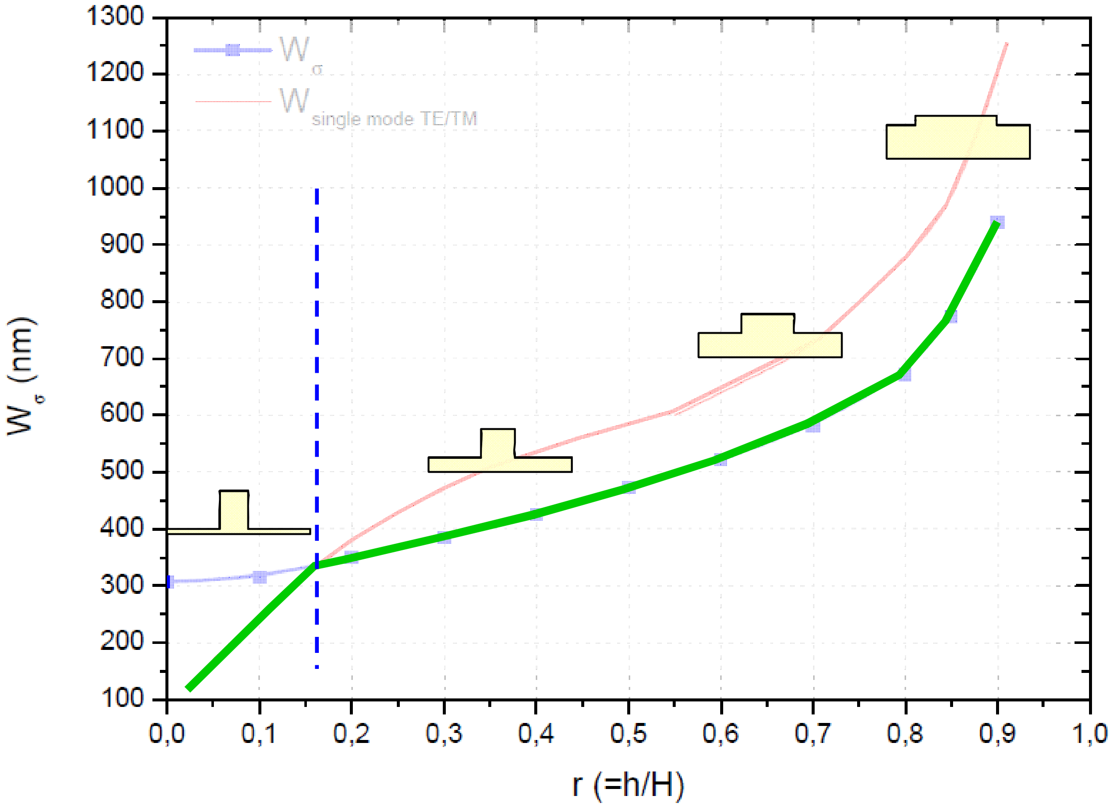


Modulation efficiency optimization

- Waveguide geometry : Single Mode TE/TM Condition (SMC)

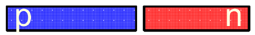


- Waveguide geometry : optimization results

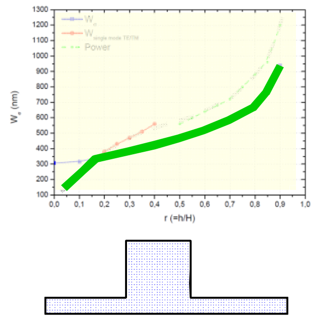


N_A, N_D, w_i

Junction optimization



$$\Delta n_{eff} \approx \frac{\Delta n \times \delta}{2\sqrt{2}\sigma}$$



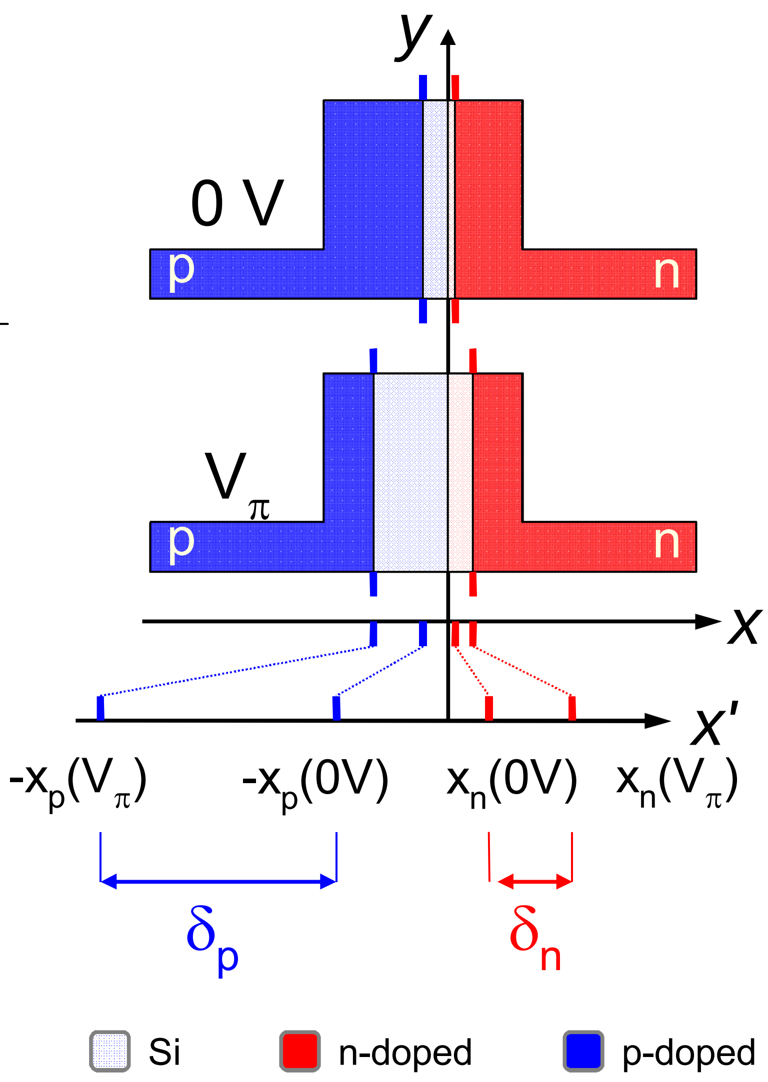
√ Electrical model for the p-i-n junction

- Evolution of the space charge region :

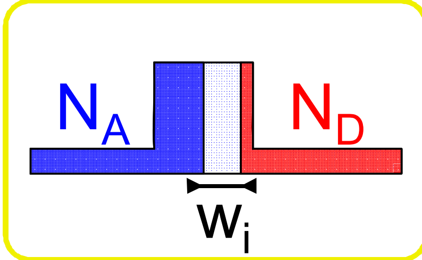
$$w_{ZCE}(V_\pi) = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_b - V_\pi) + w_i^2}$$

- Active region width: δ_n and δ_p

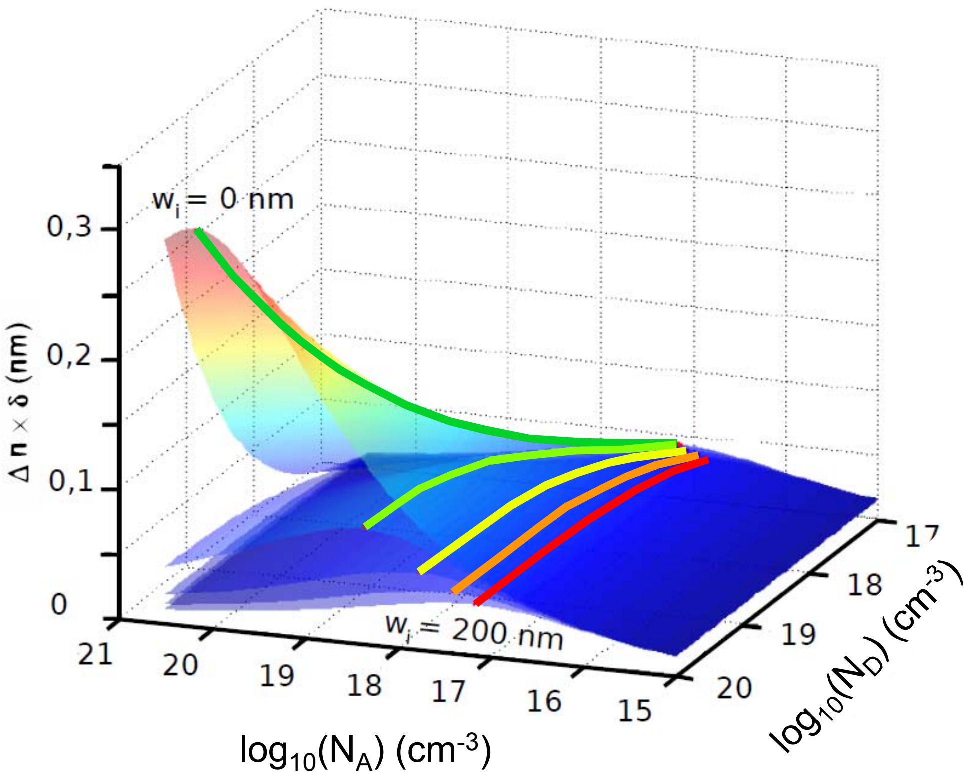
$$\delta_{n,p} = x_{n,p}(V_\pi) - x_{n,p}(0V)$$



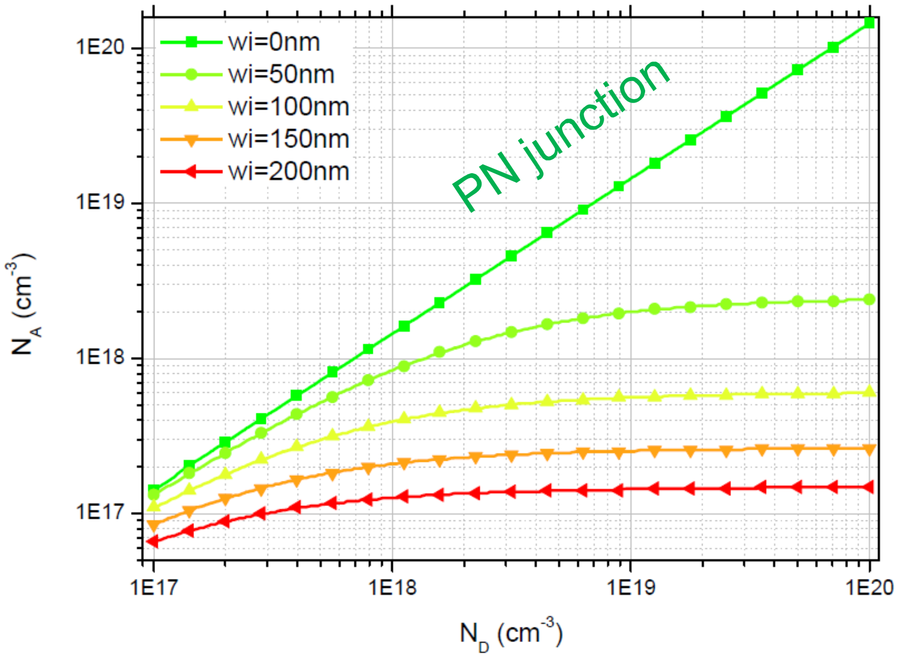
- The product $\Delta n \times \delta$ depends on the junction parameters N_A, N_D and w_i.



$$\Delta n = -8.8 \times 10^{-22} \Delta N - 8.5 \times 10^{-18} \Delta P^{0.8}$$

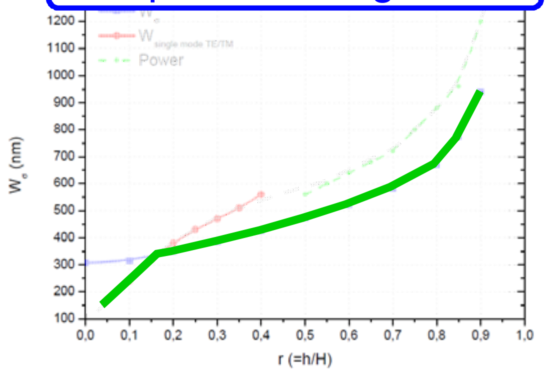


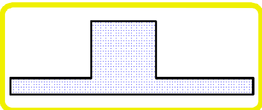
N_A vs N_D that give the maximum on $\Delta n\delta$



Optimal modulator designs

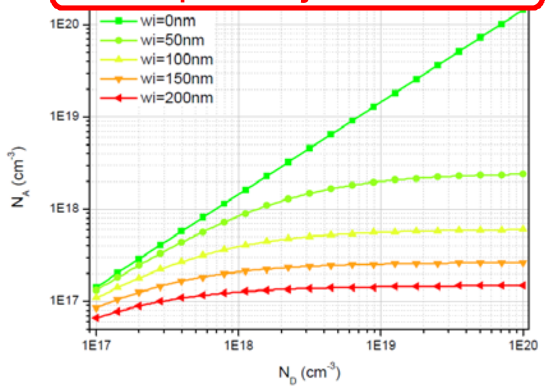
Optimal waveguide

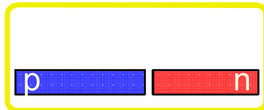




$$\Delta n_{eff} \approx \frac{\Delta n \times \delta}{2\sqrt{2}\sigma}$$

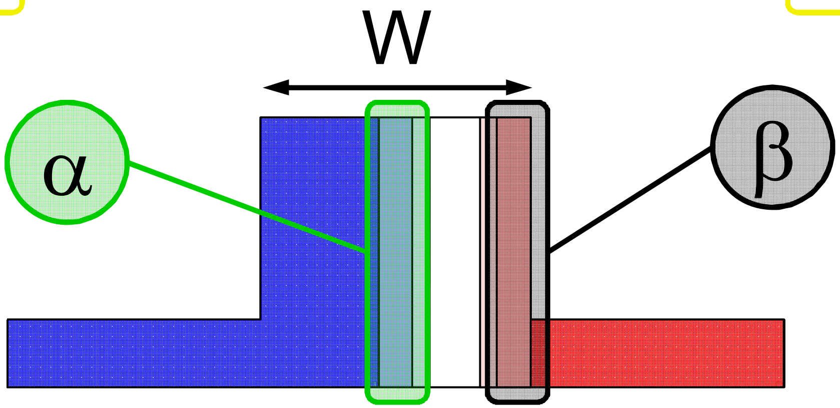
Optimal junction





α

Active p-doped region must be centered under the rib

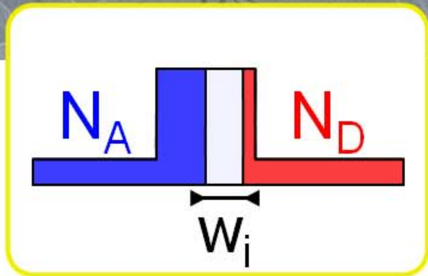


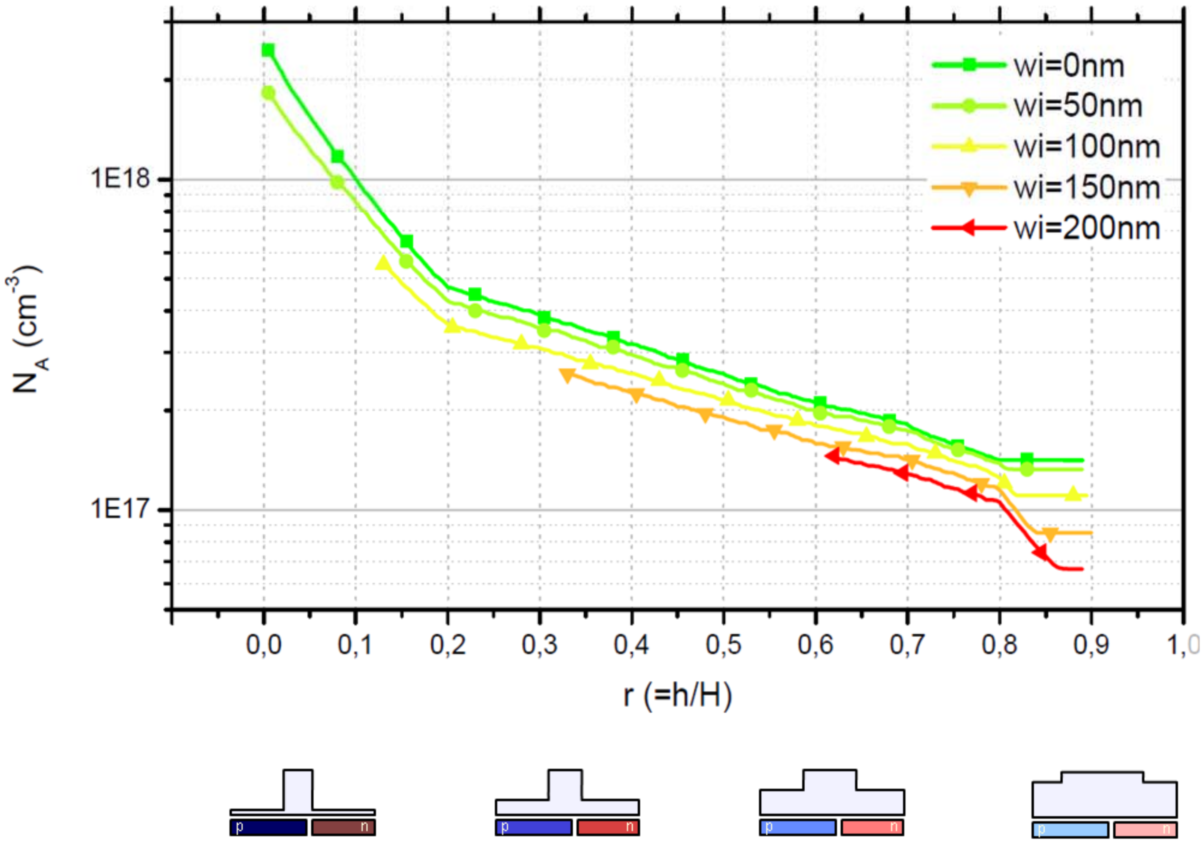
β

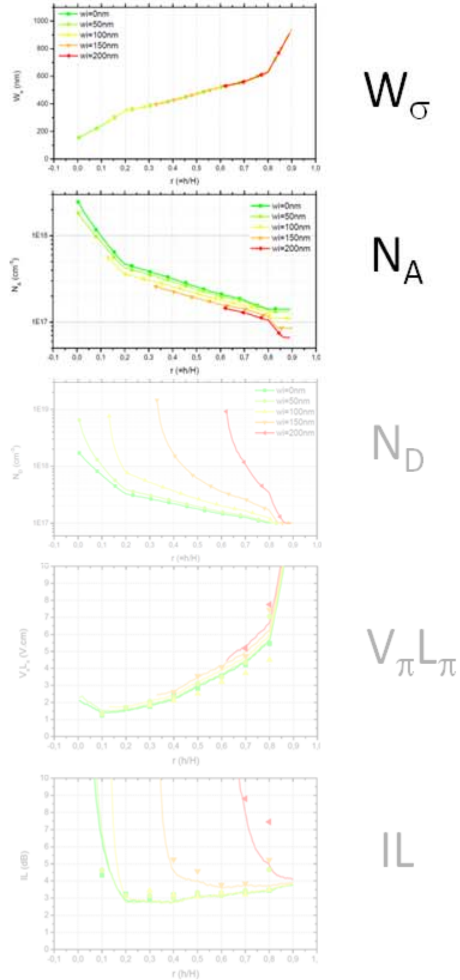
n-doped active region must be positionned on the border of the rib

Optimal modulator

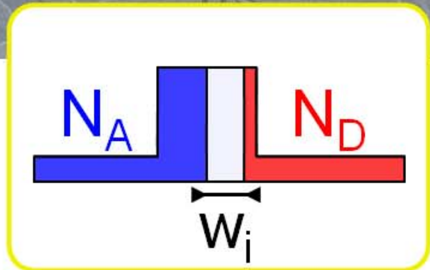
Optimization results

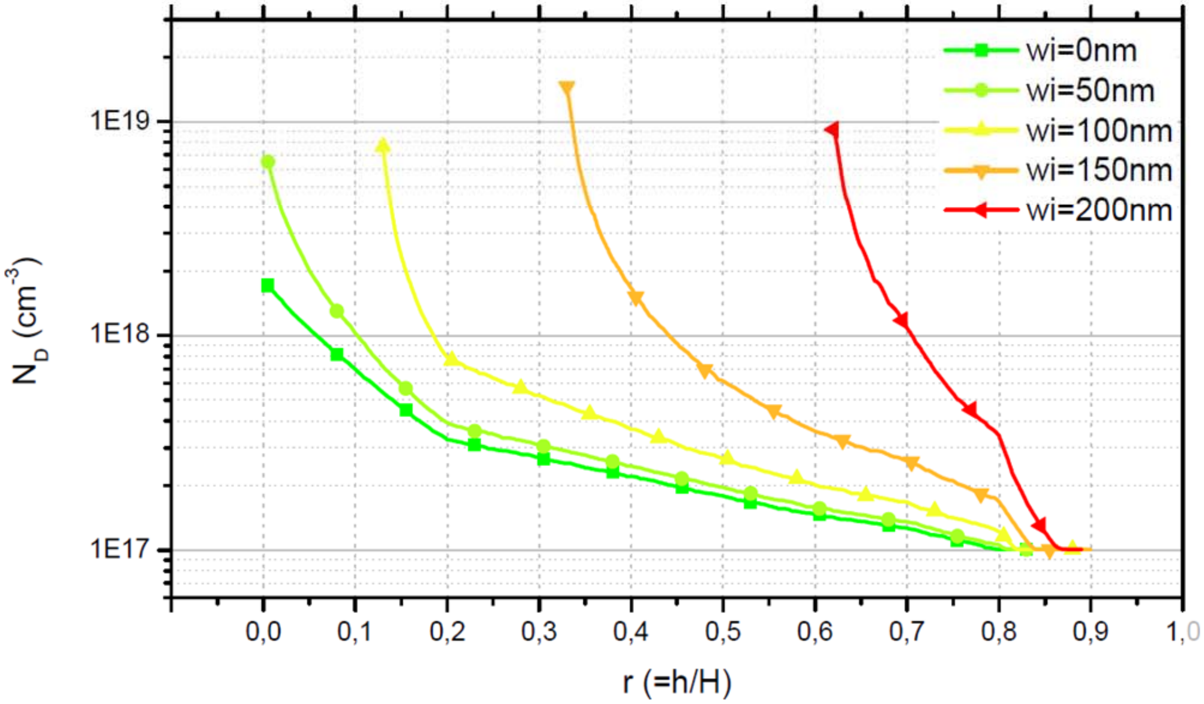


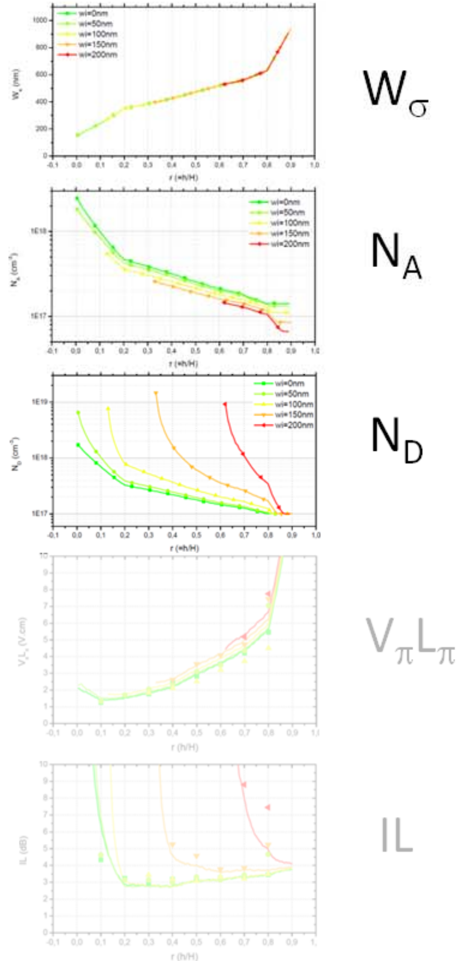




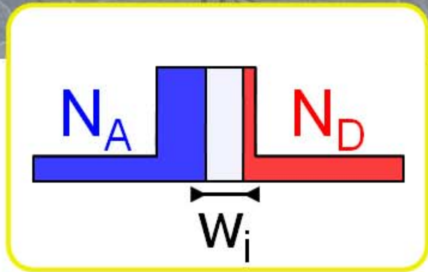
Optimization results

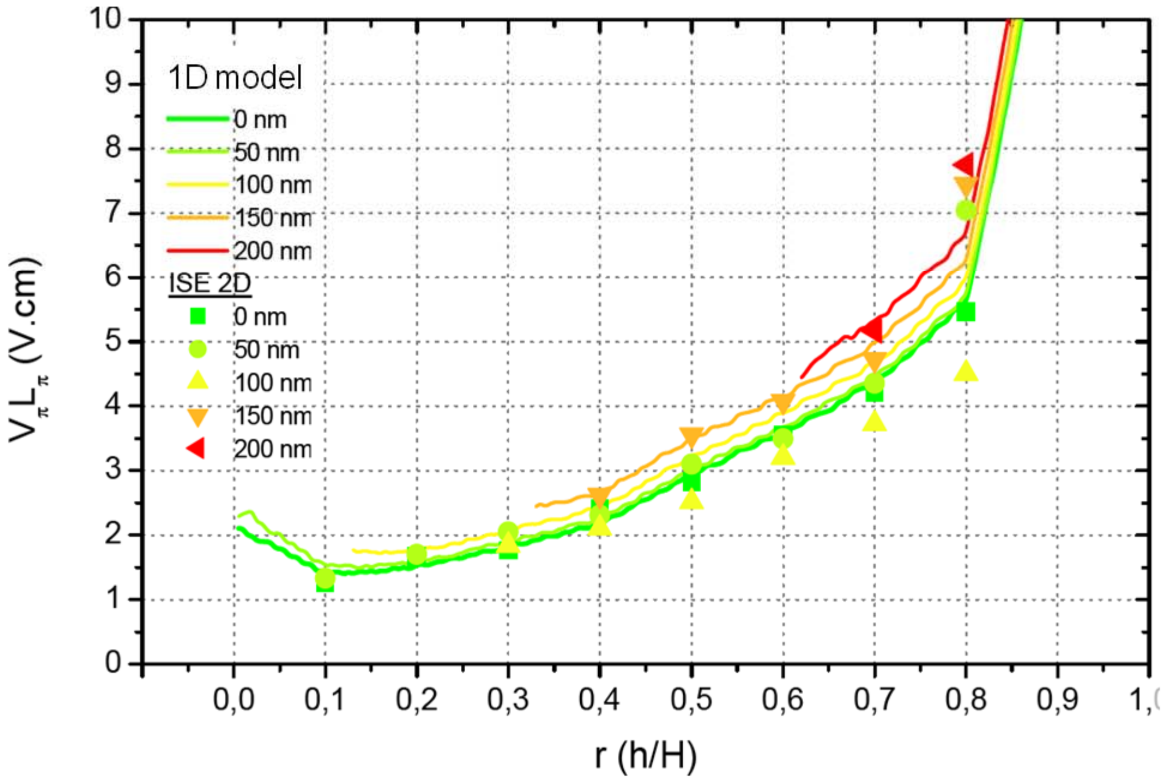


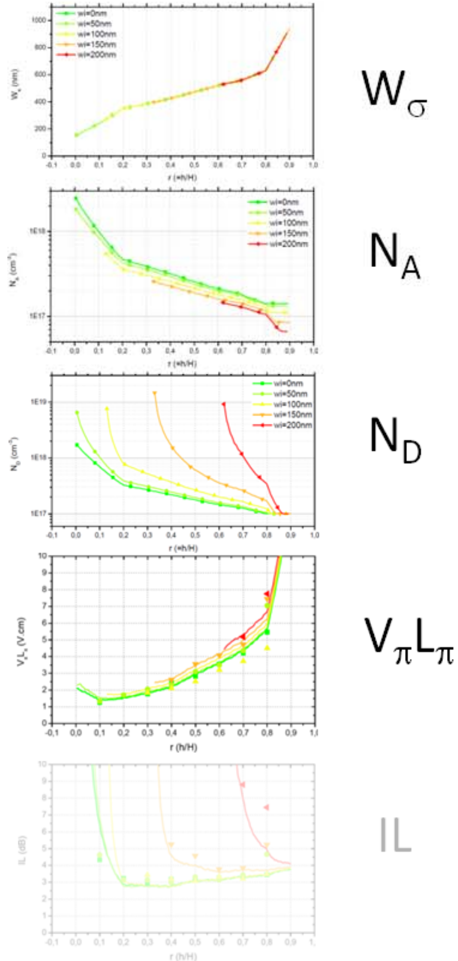




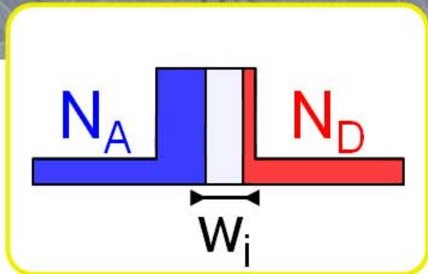
Optimization results

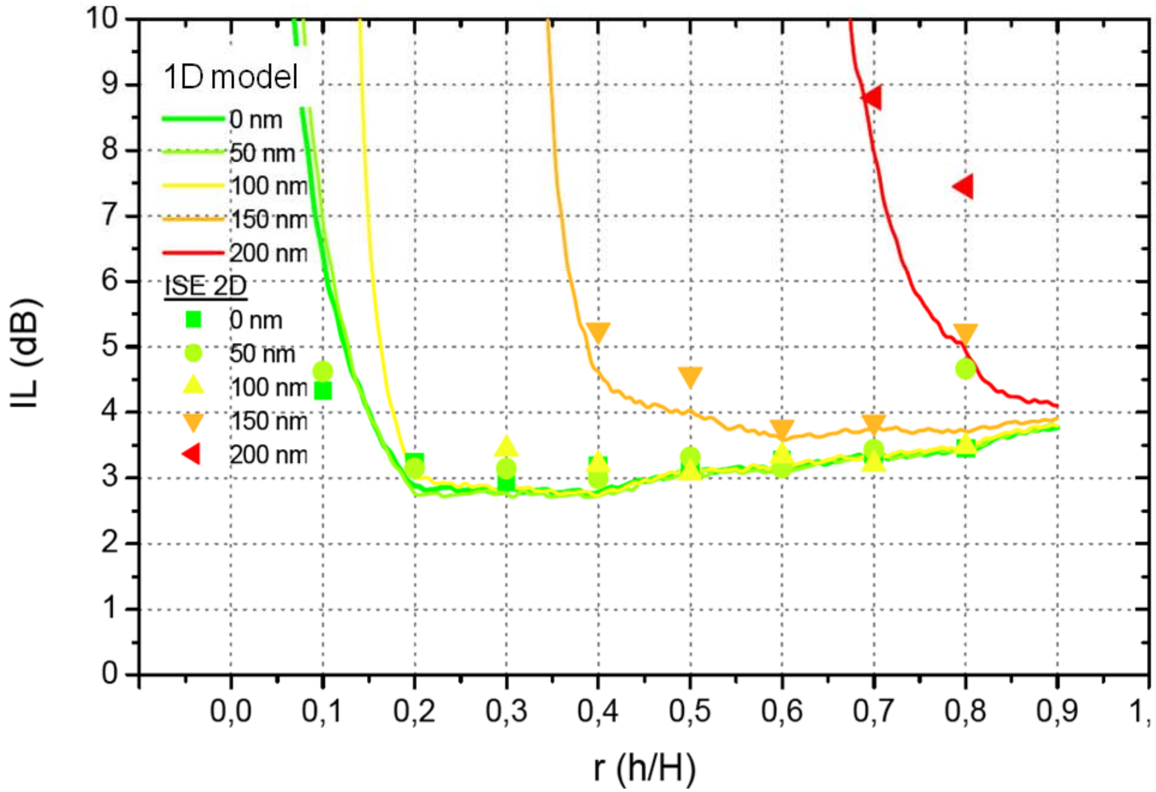


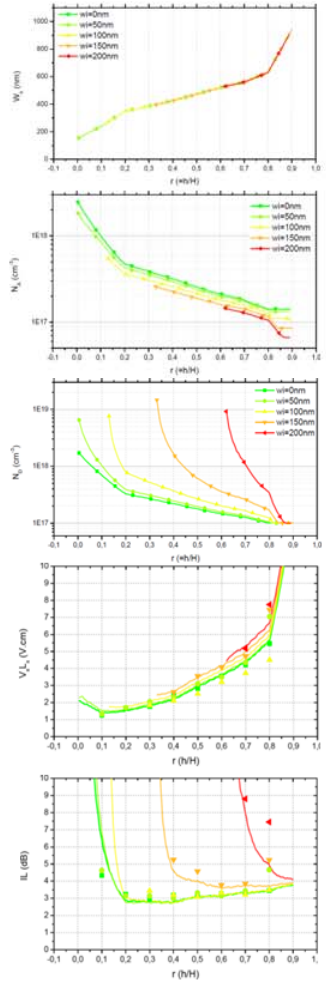




Optimization results







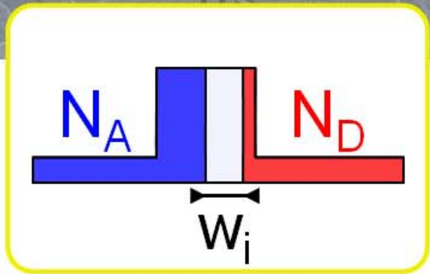
W_σ

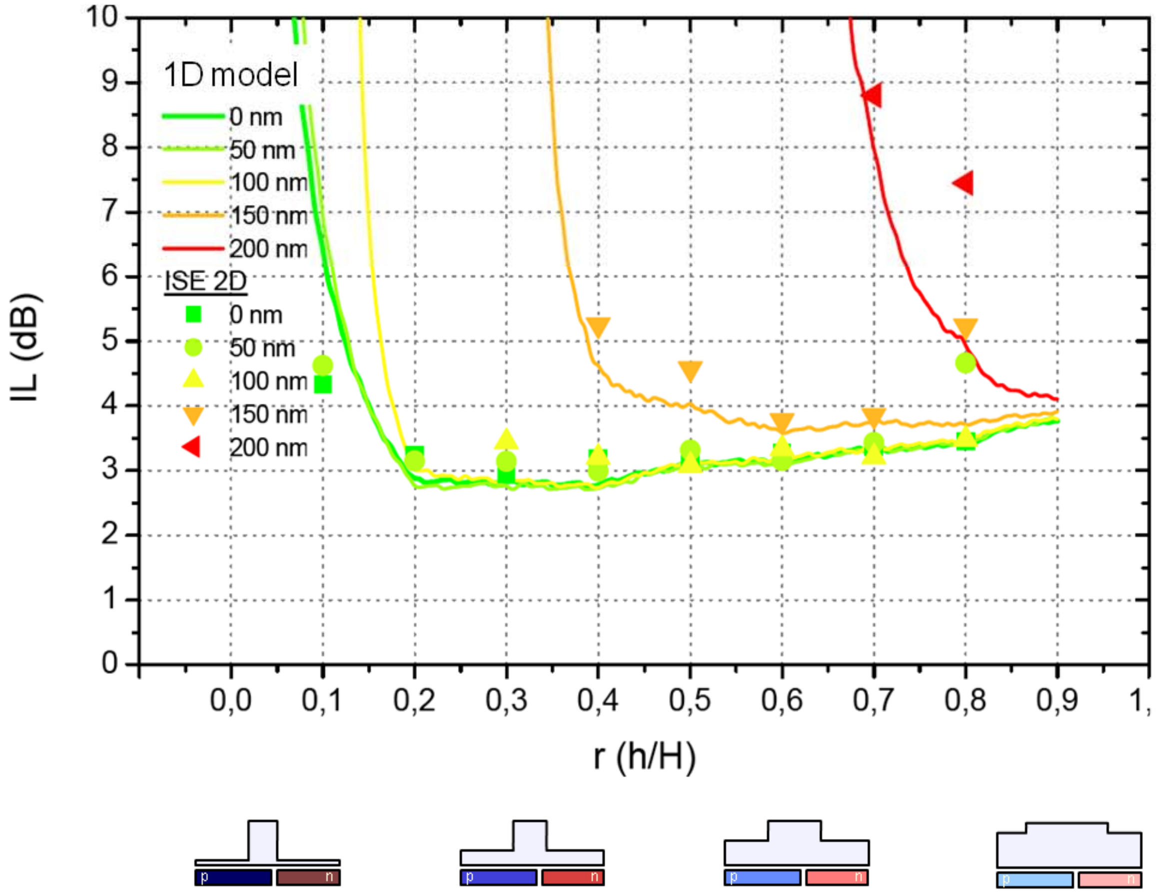
N_A

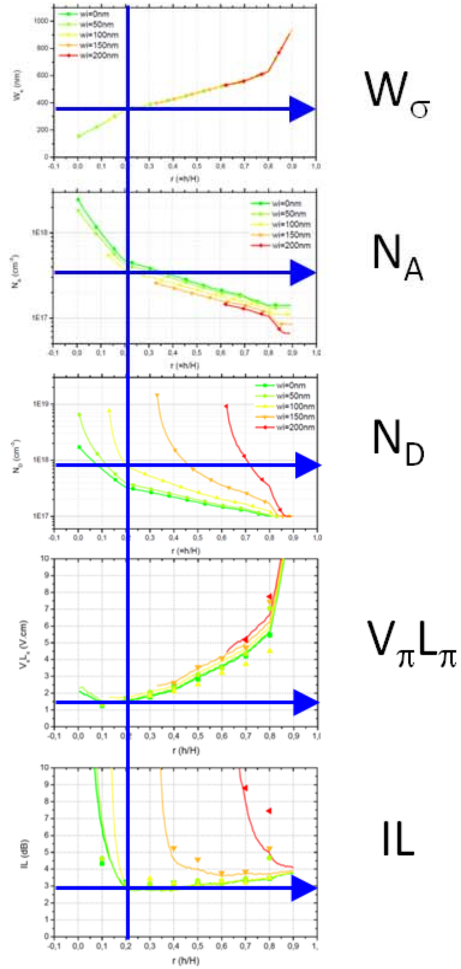
N_D

$V_\pi L_\pi$

IL


N_A
N_D
W_i


1D model
0 nm
50 nm
100 nm
150 nm
200 nm
ISE 2D
0 nm
50 nm
100 nm
150 nm
200 nm
IL (dB)
r (h/H)
p
n

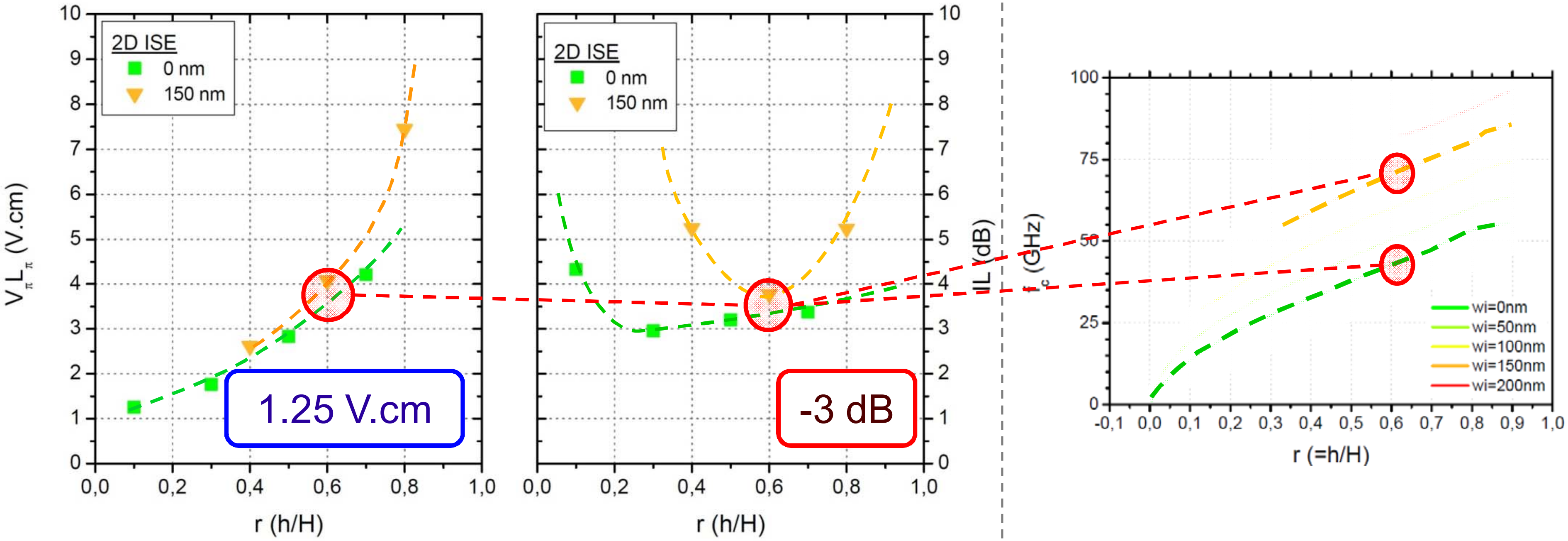

Wσ
N_A
N_D
VπLπ
IL

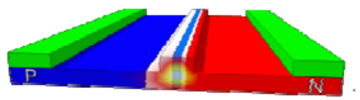
- Electro-optical simulations

Optical Figures of Merit (FoM) : $V_\pi L_\pi$ (V.cm) and IL (dB)

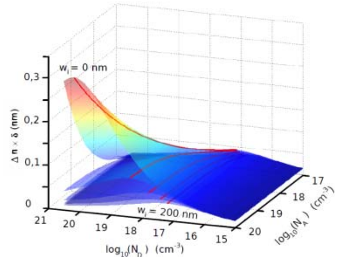
Electrical bandwidth f_c (GHz)

RC time constant calculation

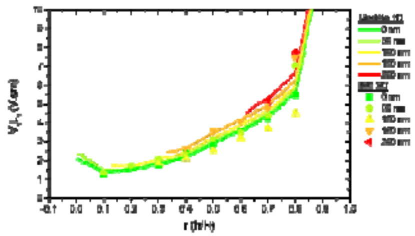




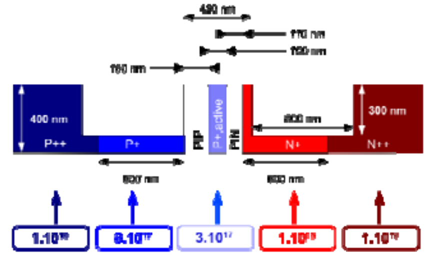
Simulation of the diode



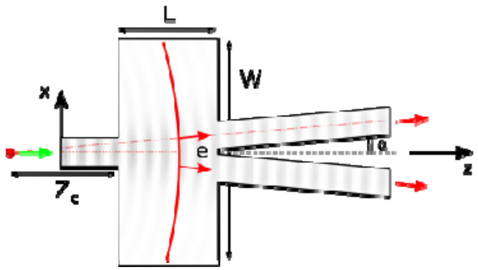
Optimization



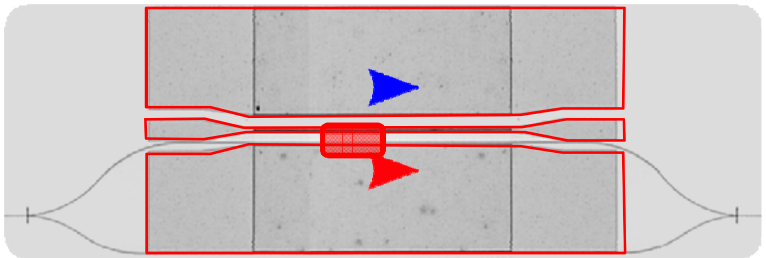
Figures of merite

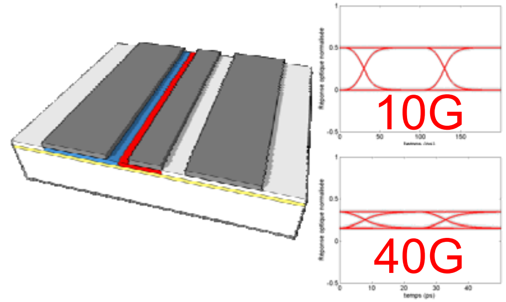


Optimized structure

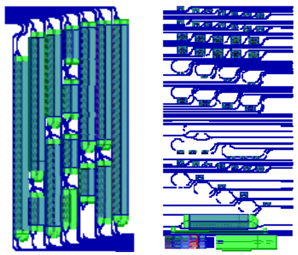


Couplers

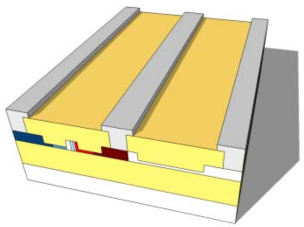




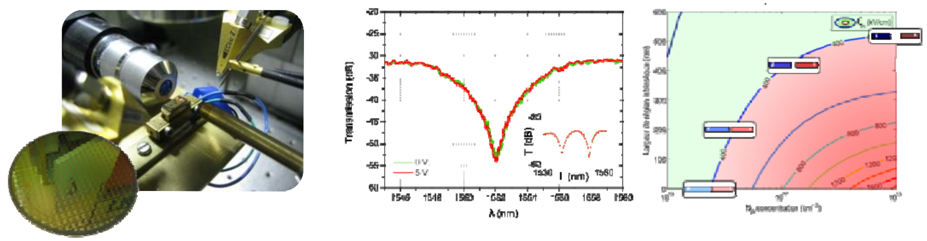
Frequency and data transmission



Layout

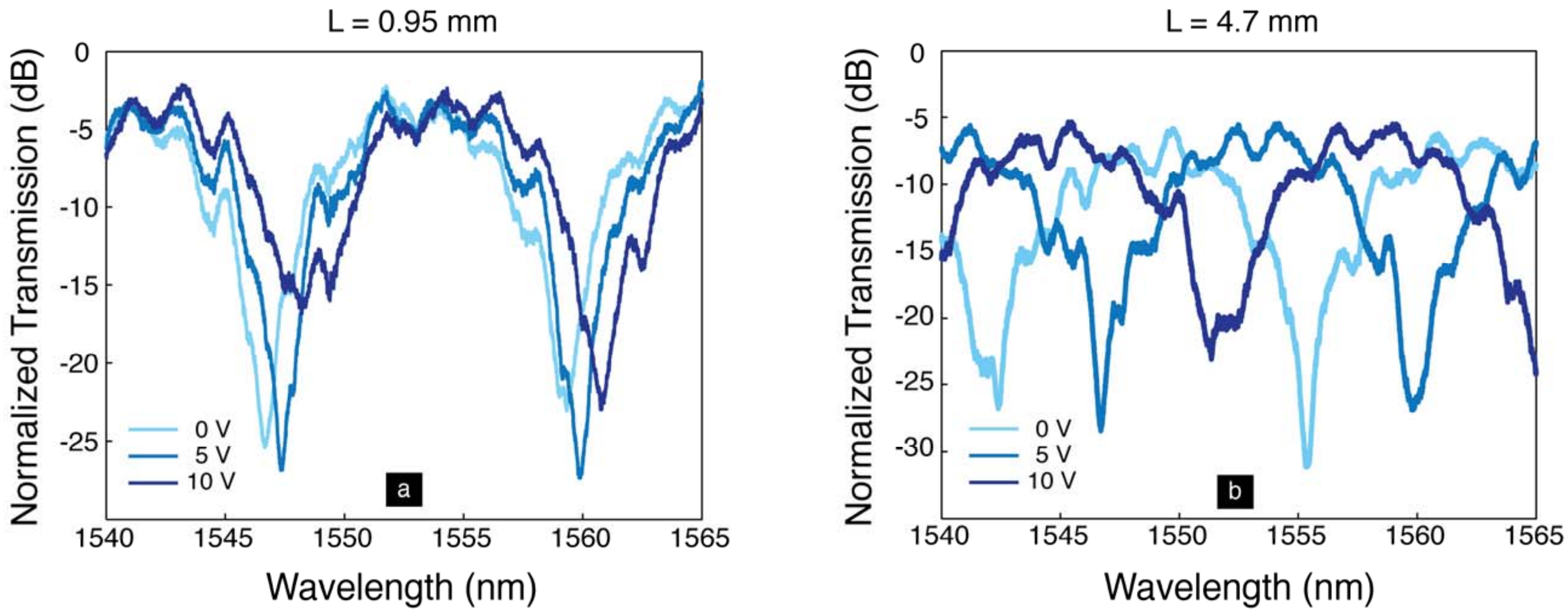


Technology



Characterization

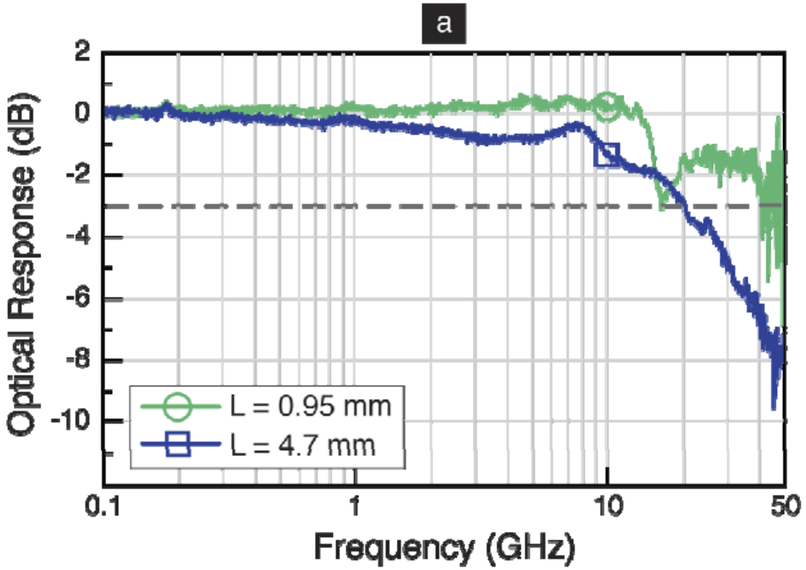
Reverse current: <μA

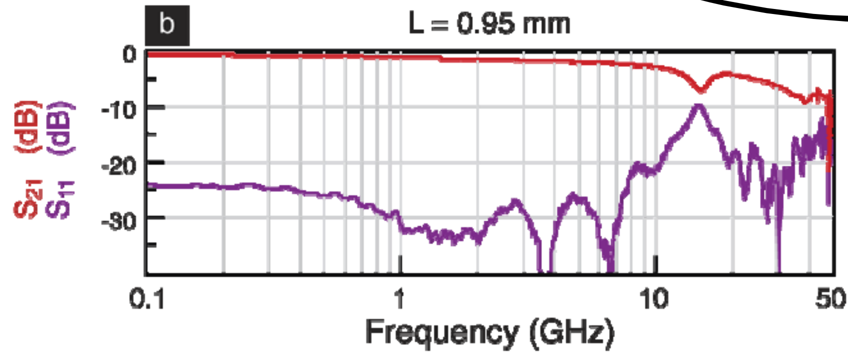


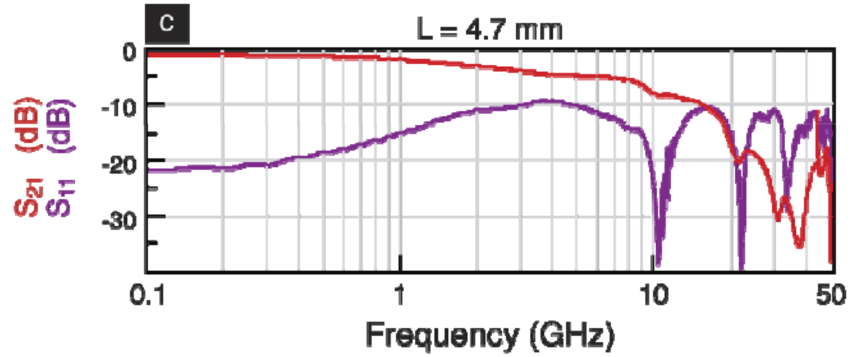
Insertion loss: 4.5 dB

Insertion loss: 6 dB

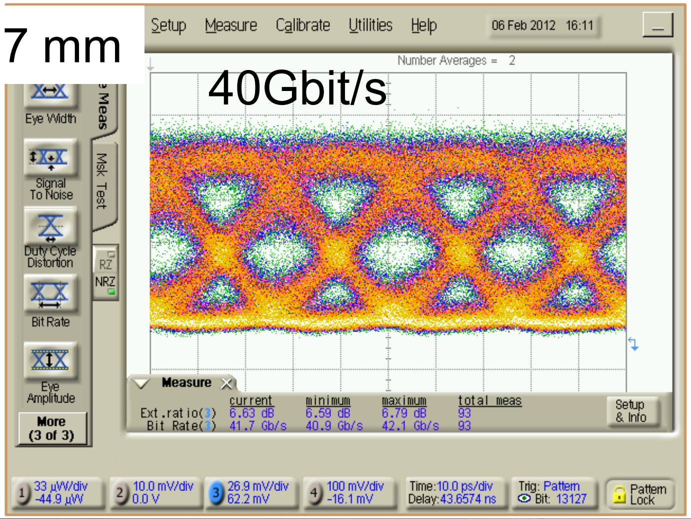
$V_{\pi}L_{\pi}$ = 3.5 V·cm







L = 4.7 mm



Extinction ratio: 6.6 dB

Insertion loss: 6 dB

Short distance and high volume applications (electrical bottleneck)

Optical interconnects

Data-center

Main challenges:

- ✓ Driving voltage of modulator
- ✓ Power consumption

ITRS Roadmap: Optical interconnect

- (…) A large variety of CMOS compatible modulators have been proposed in the literature (…)
- "The primary challenges for optical interconnects at the present time are producing <u>cost effective, low power components.</u>"

Power consumption

Energy to charge the device

$$\text{Energy/bit} = 1/4\,(CV_{pp})^2$$

Energy dissipation of photocurrent

$$\text{Energy/bit} = 1/B\,(I_{ph}V_{bias})$$

- Reduction of capacitance of depletion device
  - √ Slow-wave device for reducing the length
  - √ Ring Modulators

How do we still reduce the power consumption ?

Targets : **~100 fJ/bit** for longer off-chip distances, **10's of fJ/bit** for dense off-chip connections and **a few fJ/bit** for global on-chip connections.

*D. A. B. Miller, Proc. IEEE **97**(7), 1166–1185 (2009).*

Power consumption

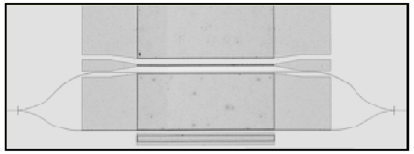
For emitters and short optical links:

~100 fJ/bit down to fJ/bit

(D.A.B. Miller, Opt Exp. , 2012)

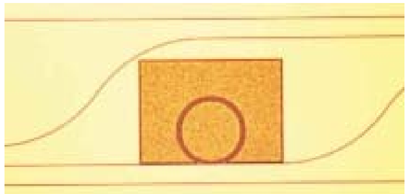
Mach Zehnder modulators

~ 3 pJ/bit



Ring resonator modulators

~ 0.5 to 1 pJ/bit



Power consumption

Energy to charge the device

$$\textbf{Energy/bit} = 1/4\,(CV_{pp})^2$$

Energy dissipation of photocurrent

$$\textbf{Energy/bit} = 1/B\,(I_{ph}V_{bias})$$

- Reduction of capacitance of depletion device
  - √ Slow-wave device for reducing the length
  - √ Ring Modulators
- Improvement of the modulation efficiency
  - √ Improve efficiency of Si modulator
  - √ MZM or EAM Hybrid modulator
  - √ Ge EAM modulators (QCSE or FK)

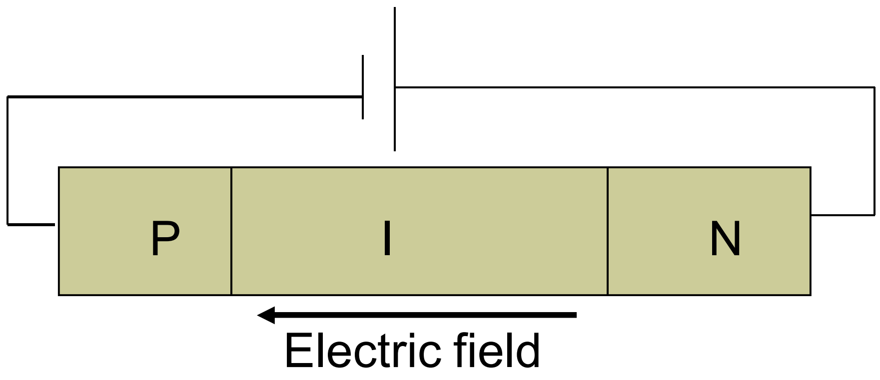
Targets : **~100 fJ/bit** for longer off-chip distances, **10's of fJ/bit** for dense off-chip connections and **a few fJ/bit** for global on-chip connections.

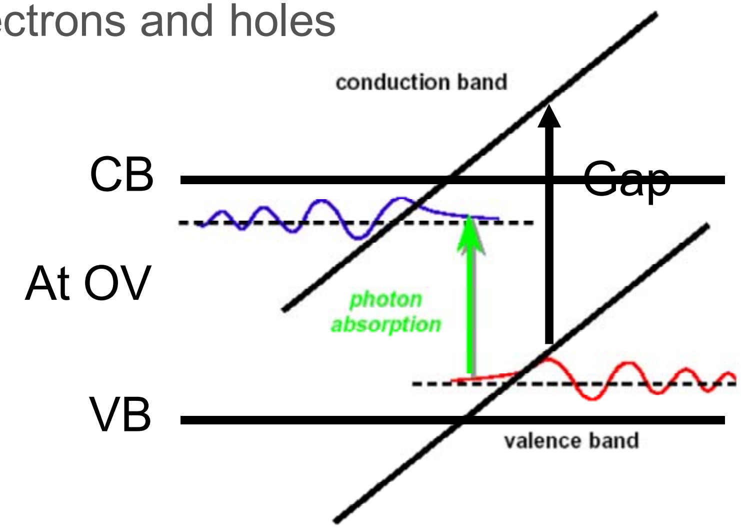
*D. A. B. Miller, Proc. IEEE **97**(7), 1166–1185 (2009).*

Under electric field: Homogeneous material

- Example: pin diode under reverse bias voltage

  - The absorption phenomenon is described by solving Shrödinger equations
    - √ Determination of wavefunction of electrons and holes



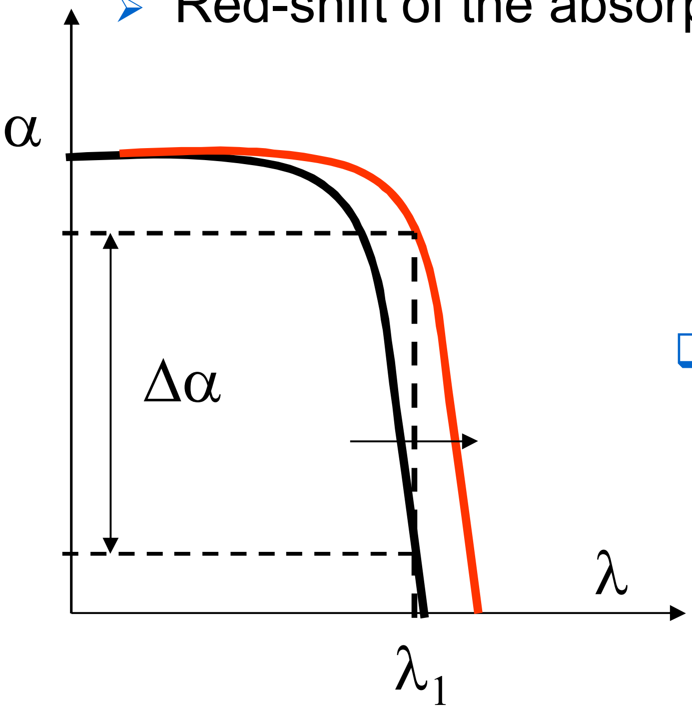


- At a given energy, there is a greater probability of finding the electron (or hole) inside the energy gap
  - ➢ Tunnelling allows overlap of electron and hole wavefunctions for photon energy less than bandgap

Franz-Keldysh effect: Photon-assisted tunnelling absorption effect

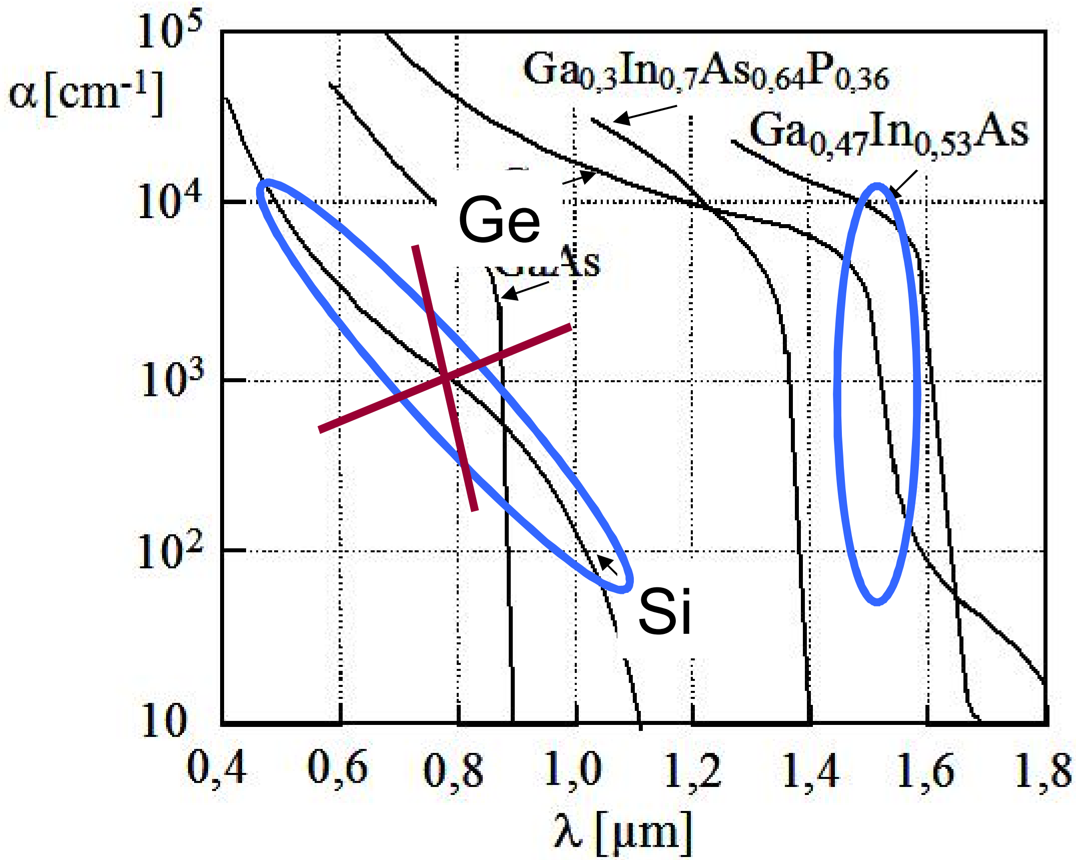
Under electric field: Homogeneous material

- Optical modulator based on Franz-Keldysh effect:
  - Red-shift of the absorption band-edge



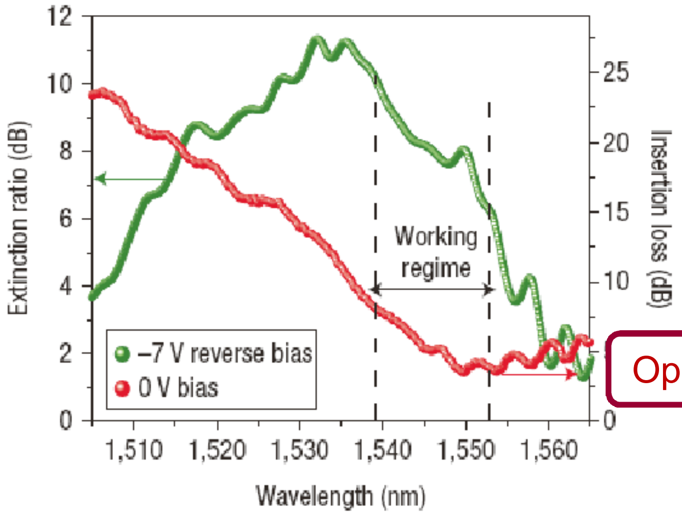
- Direct band-gap SC
  - Absorption coefficient variation
    - Abrupt absorption band edge

Does we use Franz-Keldysh effect with indirect bandgap materials?

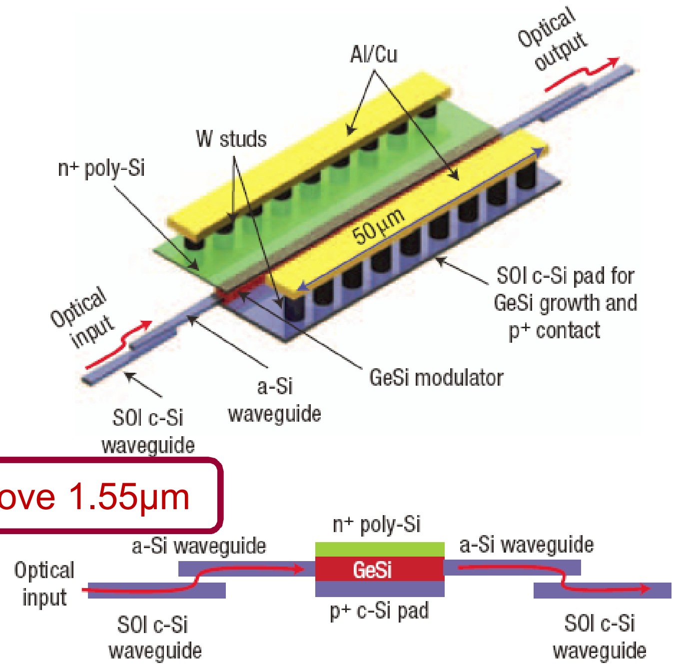


10^5
$\alpha\,[cm^{-1}]$
10^4
10^3
10^2
10
0,4
0,6
0,8
1,0
1,2
1,4
1,6
1,8
λ [µm]
$Ga_{0,3}In_{0,7}As_{0,64}P_{0,36}$
$Ga_{0,47}In_{0,53}As$
Ge
GaAs
Si

- GeSi material at 1.55µm

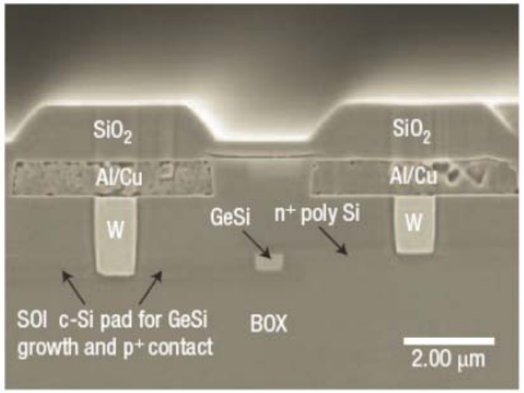


Operating wavelength above 1.55µm



- Integrated GeSi optical modulator

small active device area of 30 µm^2

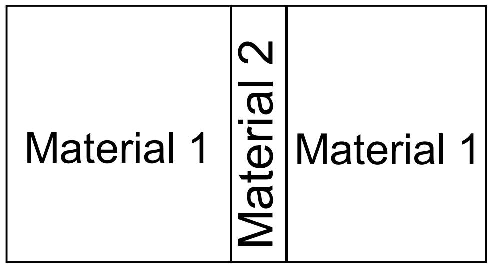


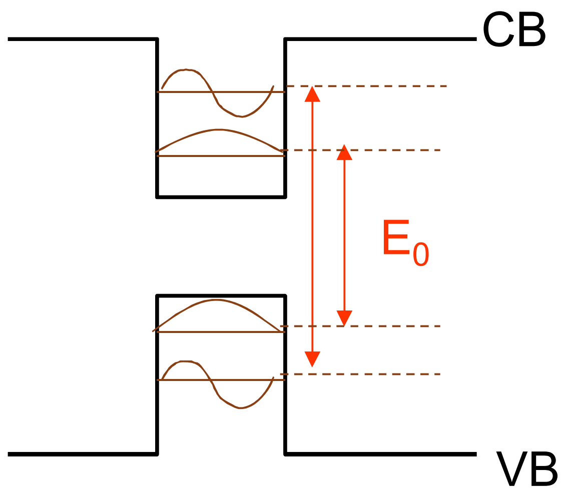
Liu et al., Opt. Express 15, 623 (2007)
Liu et al., Nature Photonics 2, 433 - 437 (2008)

Ex : GaAlAs / GaAs/GaAlAs

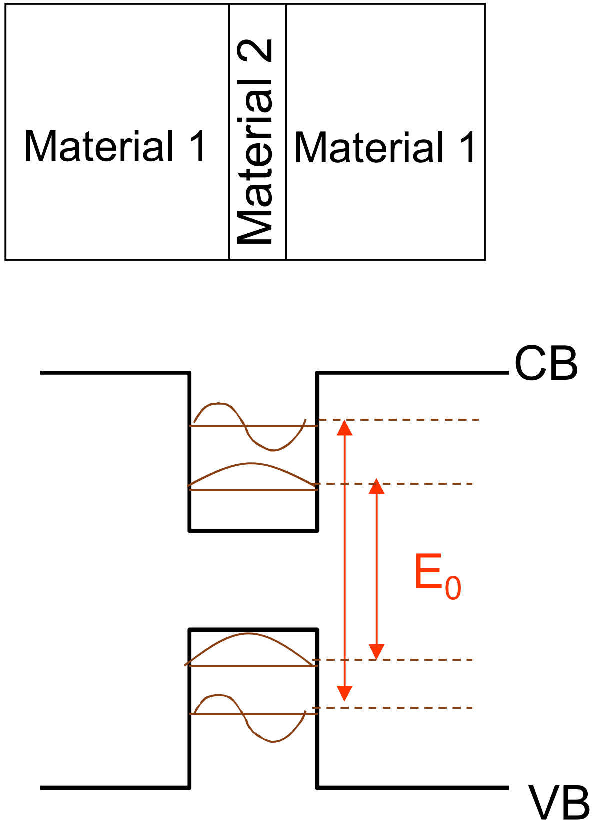
Quantum well structures:

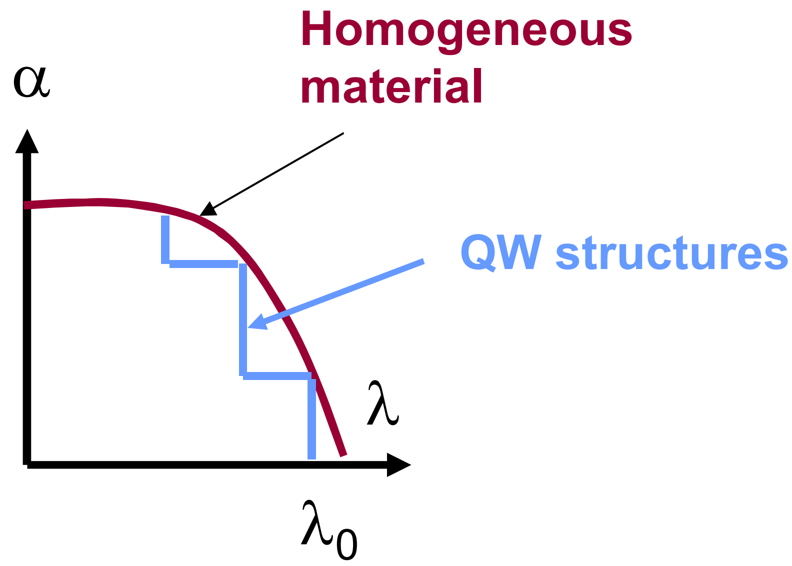
- Heterostructures formed by a thin layer of a narrower-gap semiconductor between thicker layers of a wider-gap material lead to the formation of a potential well for both electrons and holes.
  - Possible transition between discrete energy level for electrons





Absorption effect in Quantum Well strucutres

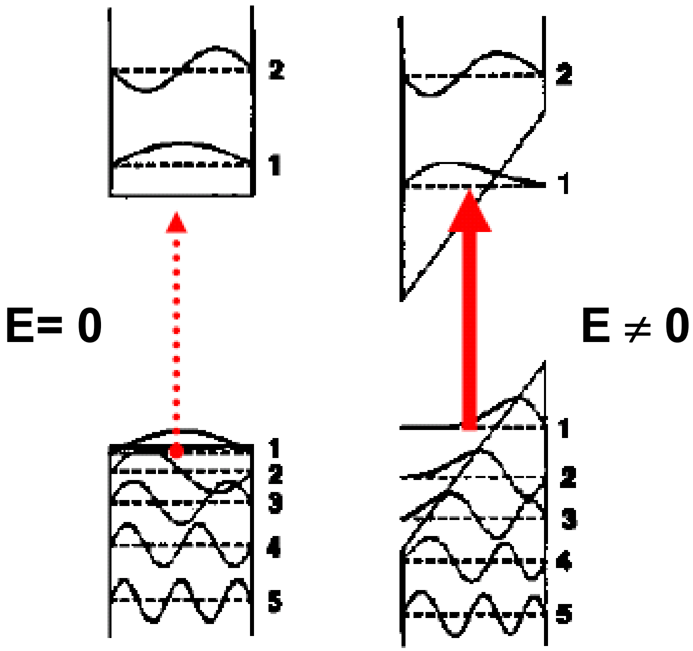


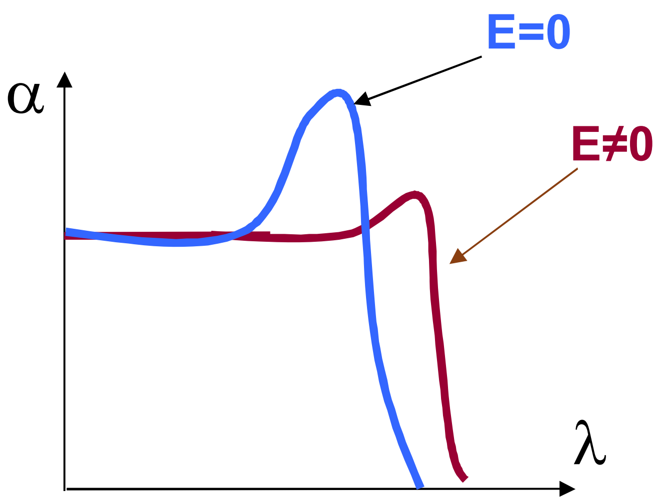


$$E_0 = hc/\lambda_0$$

- Absorption edge more abrupt
- E_0 depends on the quantum well thickness
  - Adjustment of the wavelength is possible

Absorption effect in Quantum Well structures

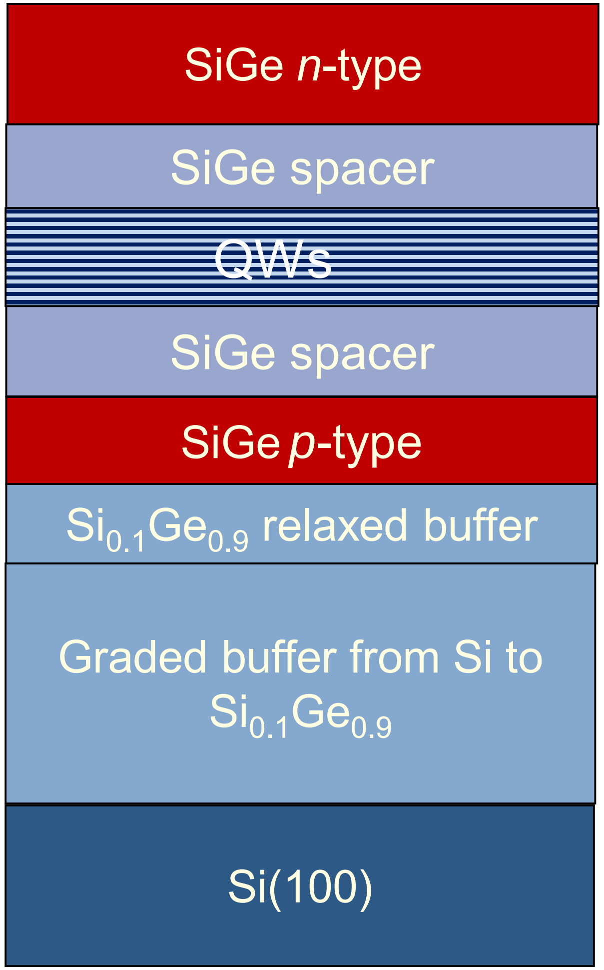




- Quantum Well, E = 0 (Usual case seen before)
- Quantum Well, E ≠ 0
  - √ Bands tilt and energy of quantum states decreases ⇨ red-shift of the absorption edge
  - √ Wavefunction overlap decreases ⇨ reduction of the excitonic peaks

Quantum Confined Stark Effect (QCSE)

Active region design and growth

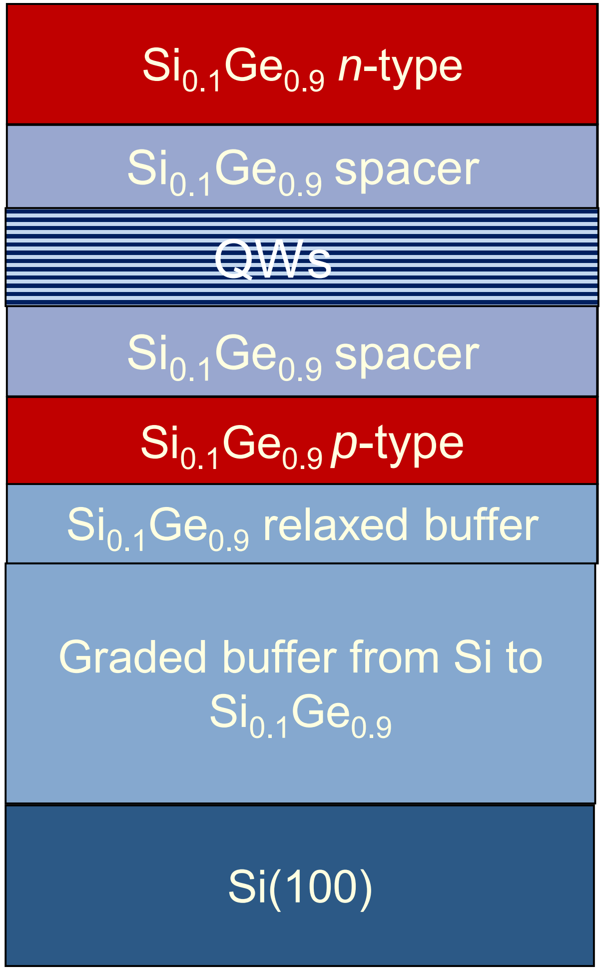


QW structure:
10 nm Ge well/ 15 nm $Si_{0.15}Ge_{0.85}$ barrier

Strain-compensated structure

Average Ge in MQWs = 90%
=> $Si_{0.1}Ge_{0.9}$ buffer

4.2% lattice mismatch between Si and Ge



- ✓ Low-rate growth (~0.3 nm/s) for optimum layer and interface control
- ✓ Around 1 hr

- ✓ High-rate growth (5-10 nm/s)
- ✓ 40 minutes for 13 μm buffer

LEPECVD Graded buffer : TDD (Threading dislocation denstity) ~ 10^6 cm^{-2}

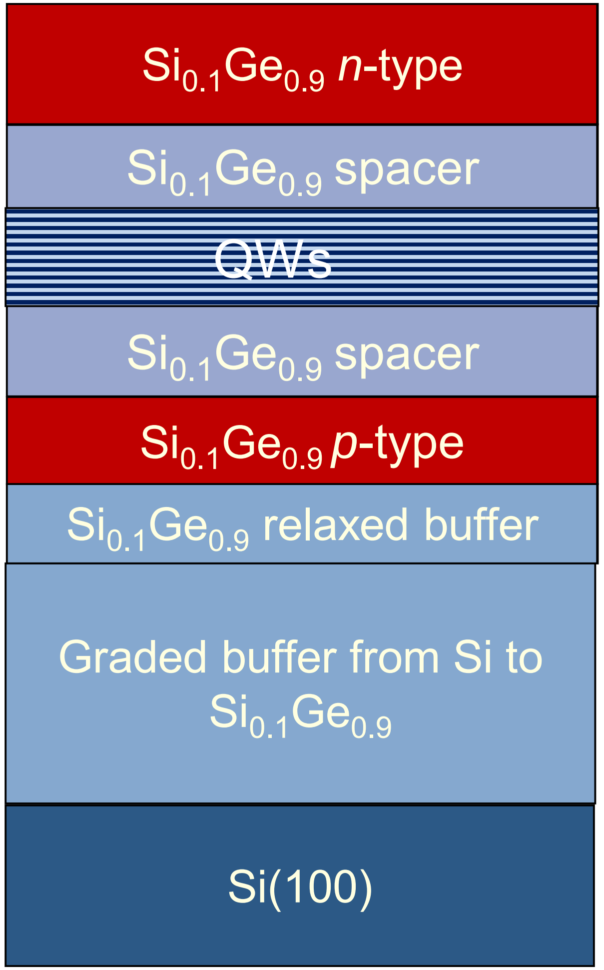
Low Energy Plasma Enhanced Chemical Vapour Deposition (LEPECVD)

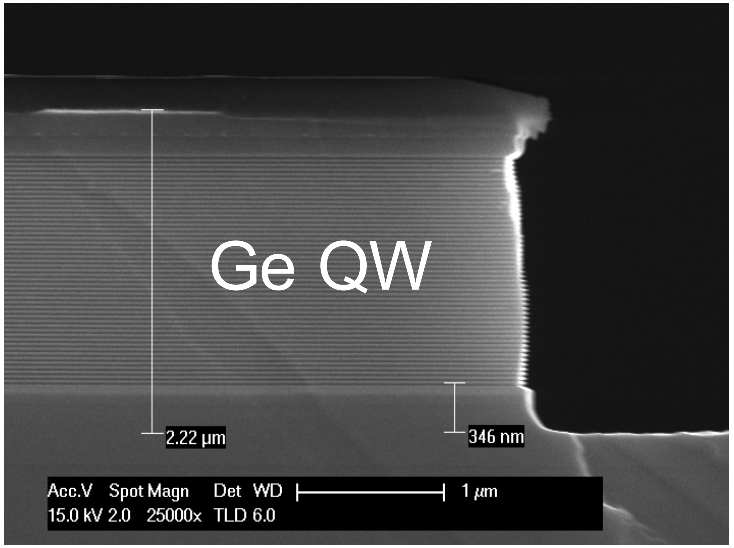
POLITECNICO DI MILANO

L-NESS

G. Isella, D. Chrastina, J. Frigerio

Active region design and growth





- ✓ High-rate growth (5-10 nm/s)
- ✓ 40 minutes for 13 µm buffer

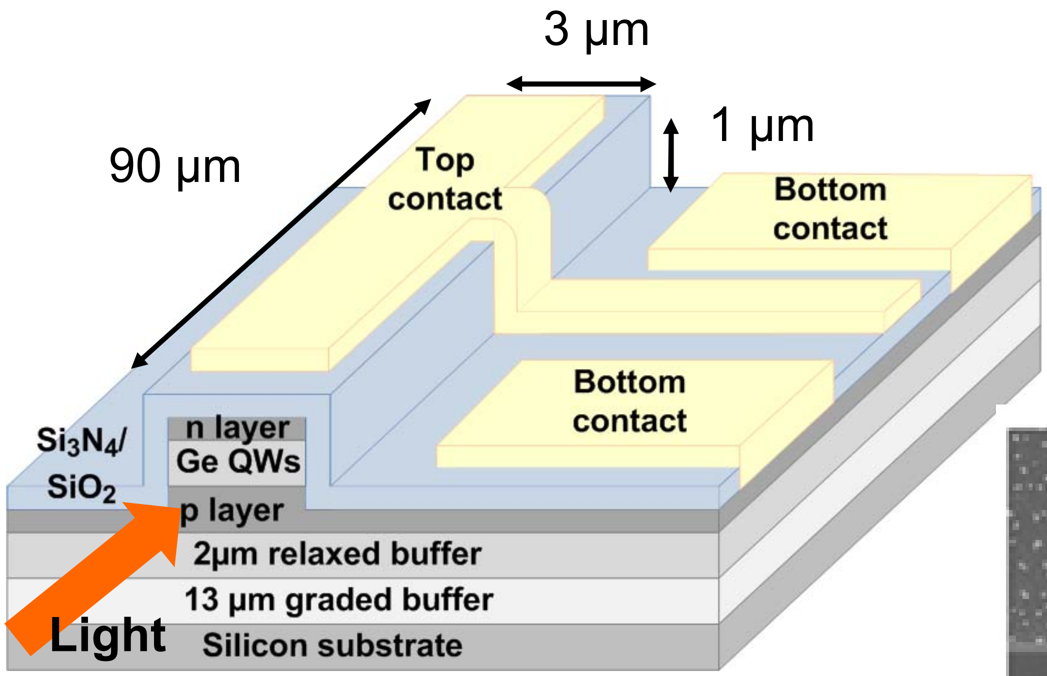
Low Energy Plasma Enhanced Chemical Vapour Deposition (LEPECVD)

POLITECNICO DI MILANO

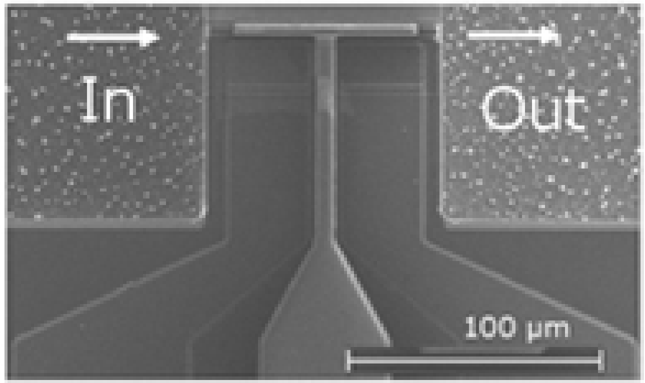
L-NESS

LEPECVD Graded buffer : TDD (Threading dislocation denstity) ~ 10^6 cm^{-2}

G. Isella, D. Chrastina, J. Frigerio

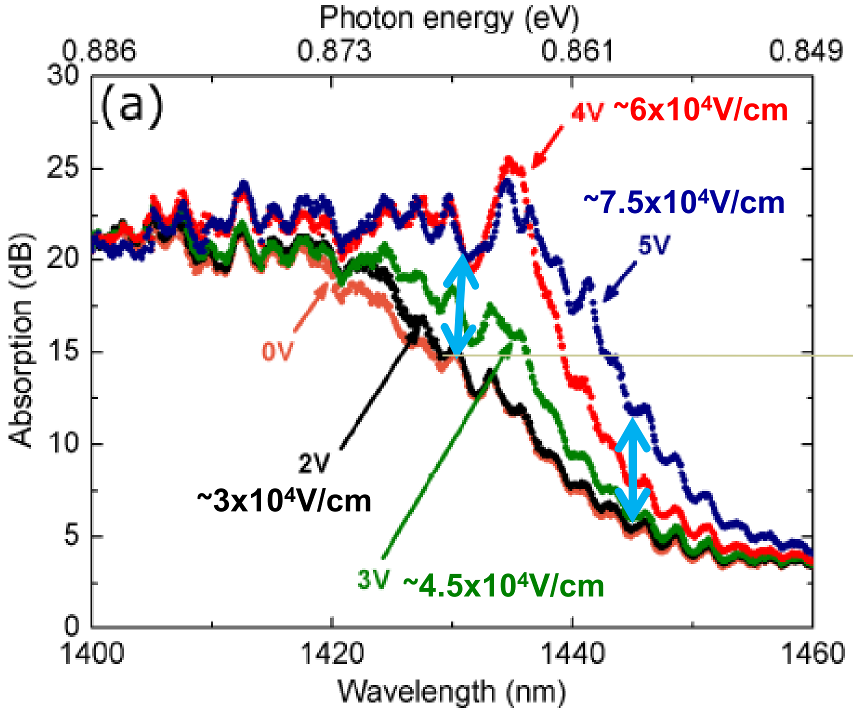


20 Ge/SiGe QW

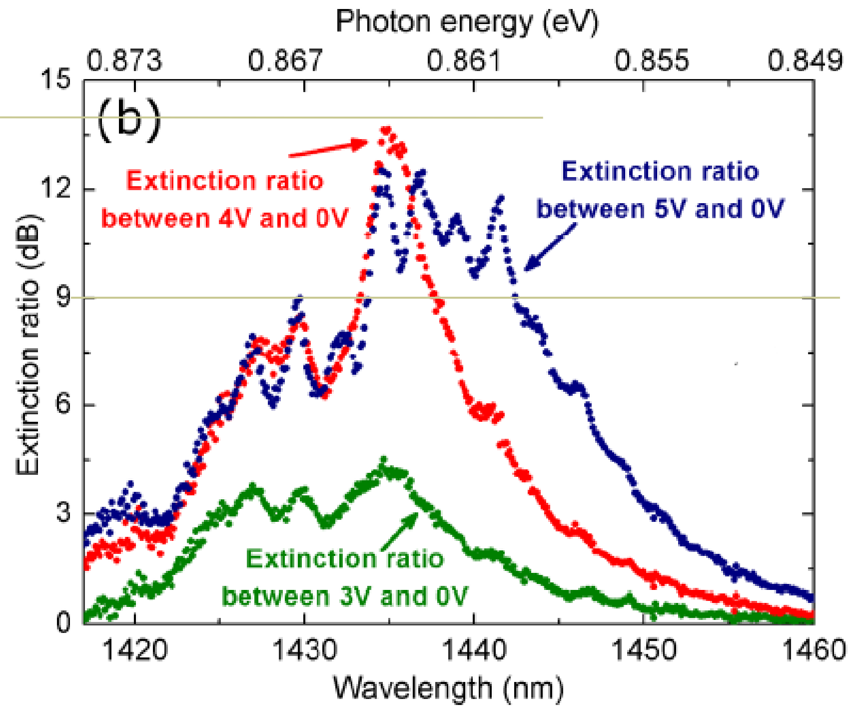


P. Chaisakul et al., Optics Express (2012).

Static performance: optical transmission

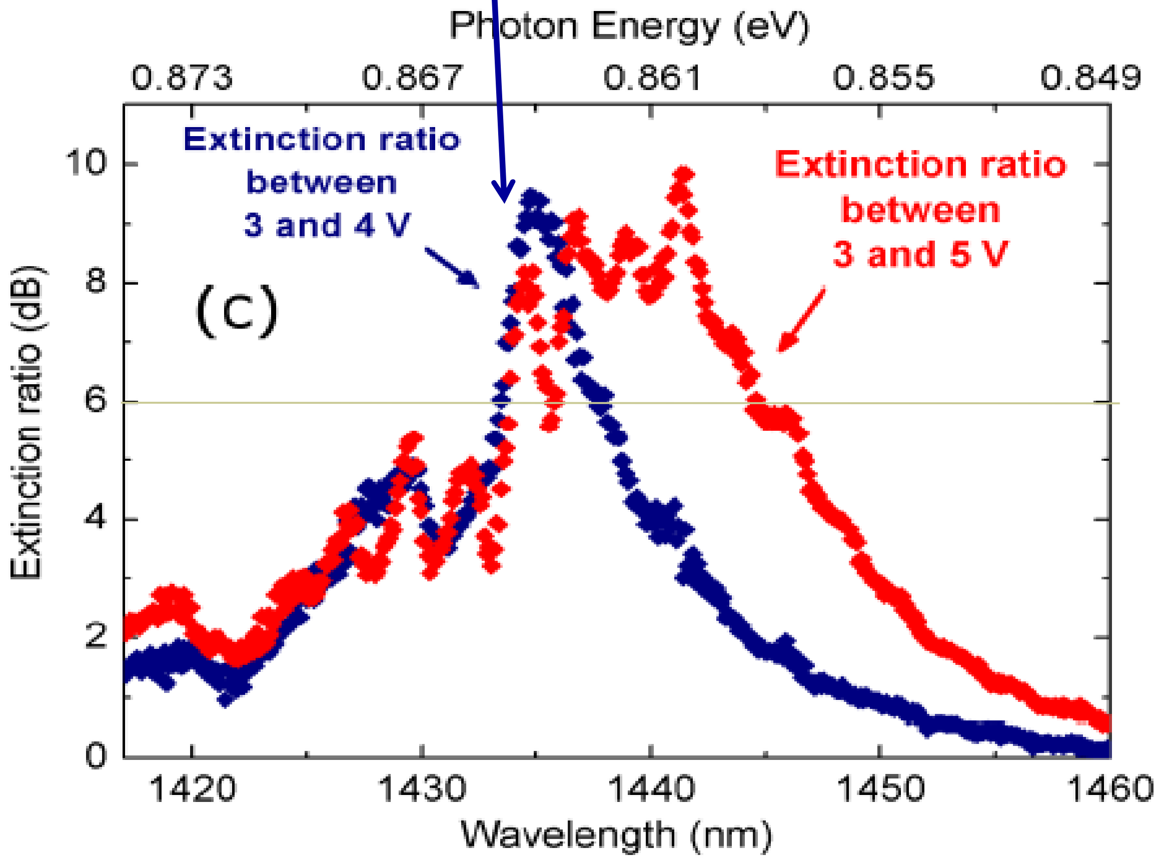


Bias from 0 to 5V :
Extinction Ratio (ER) > 6 dB for 20 nm range
Insertion Loss (IL) : 5 to 15 dB

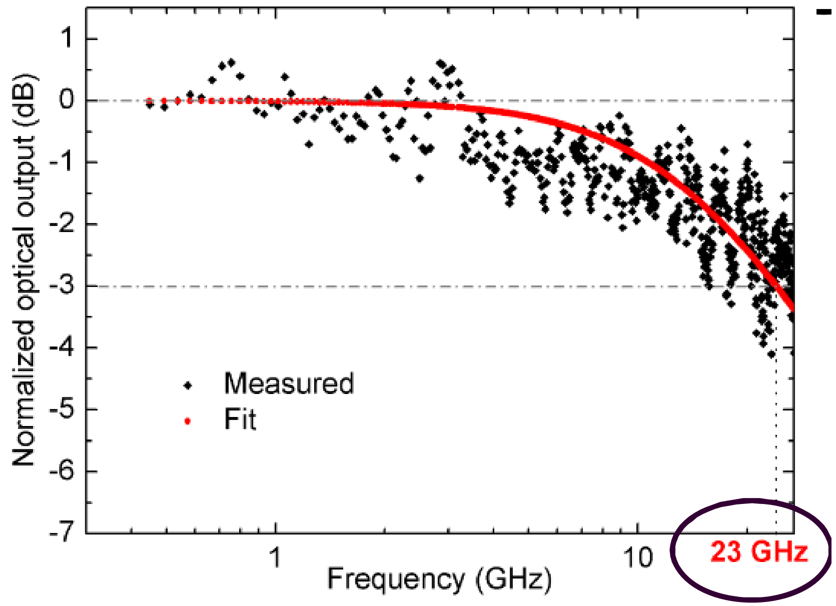


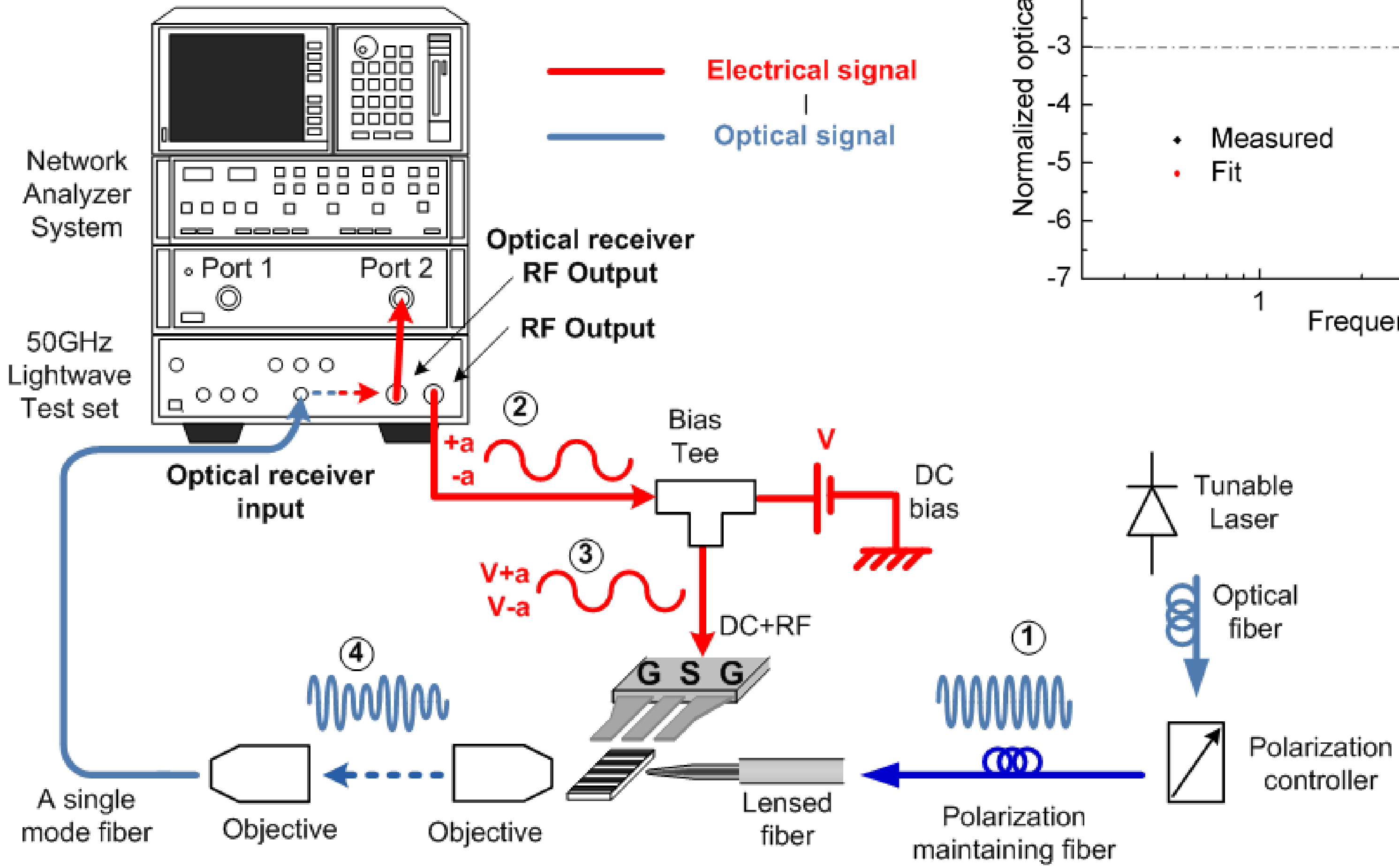
Static performance: optical transmission

1V swing 2V swing

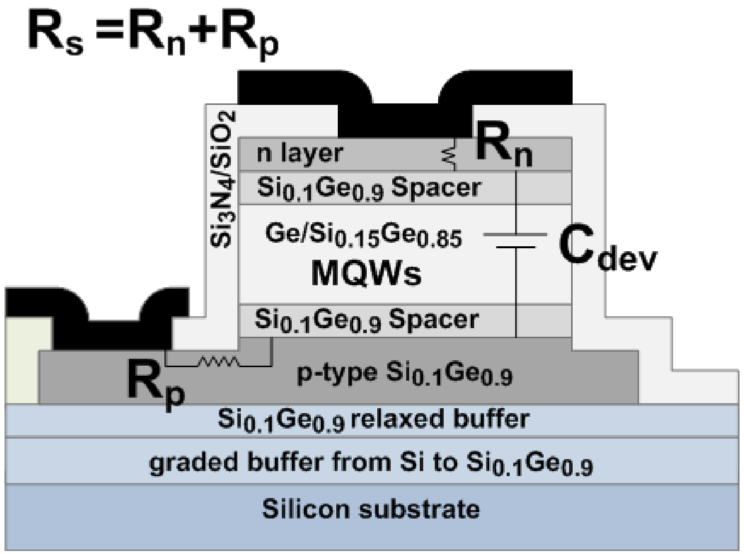


Frequency response





Energy consumption



Energy to charge the device

Energy/bit = $1/4\,(CV_{pp})^2$

Energy dissipation of photocurrent

Energy/bit = $1/B\,(I_{ph}V_{bias})$

C ~ 62 fF ➡ Energy/bit = **70 fJ/bit**

(for a voltage swing of 1 V , 20 Gbps, 0.5 mW input power)

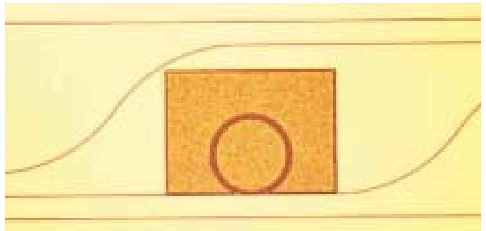
Power consumption evolution

Carrier depletion modulator MZi

Energy/bit ~ 3 pJ/bit

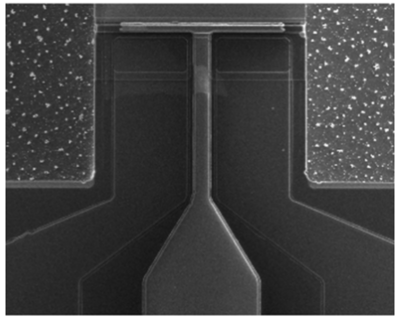
Ring resonator modulator

Energy/bit ~ 0.7 pJ/bit



EA Ge/SiGe modulator

energy/bit ~ 0.07 pJ/bit



Ultra low power consumption modulator

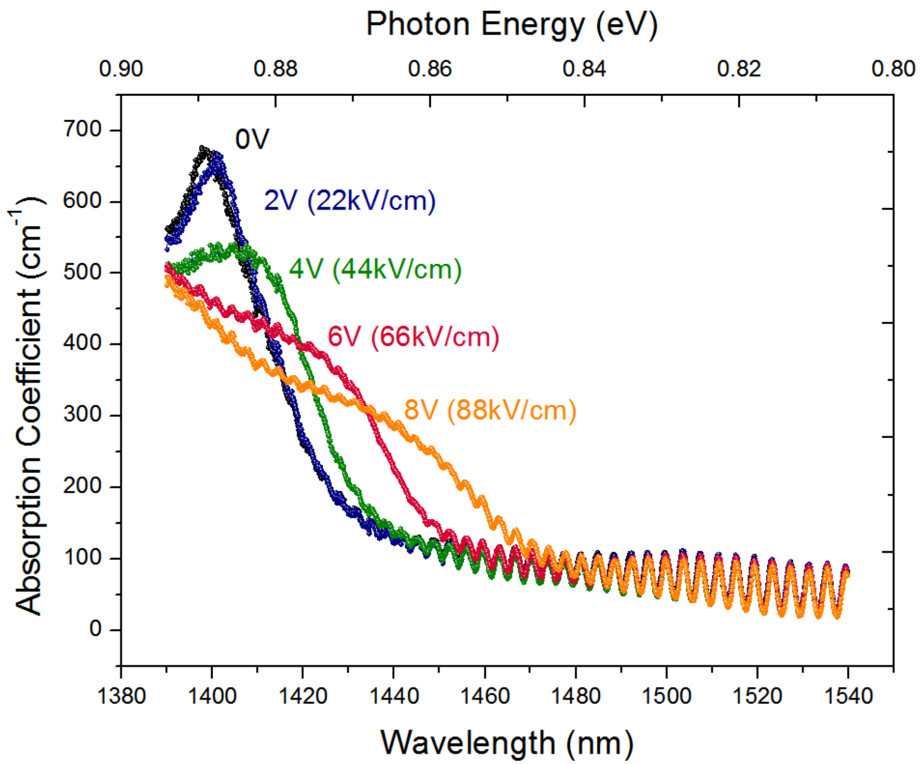
energy/bit ~ few fJ/bit

What do absorption variation also induce ?

….

Interesting for optical modulation

Electro-refraction

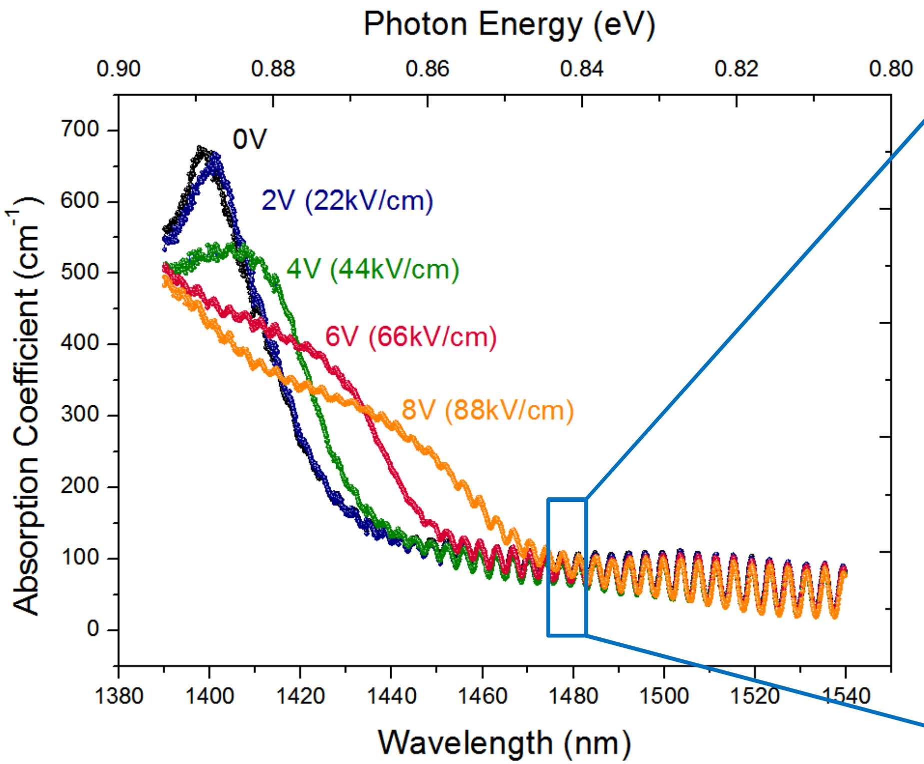


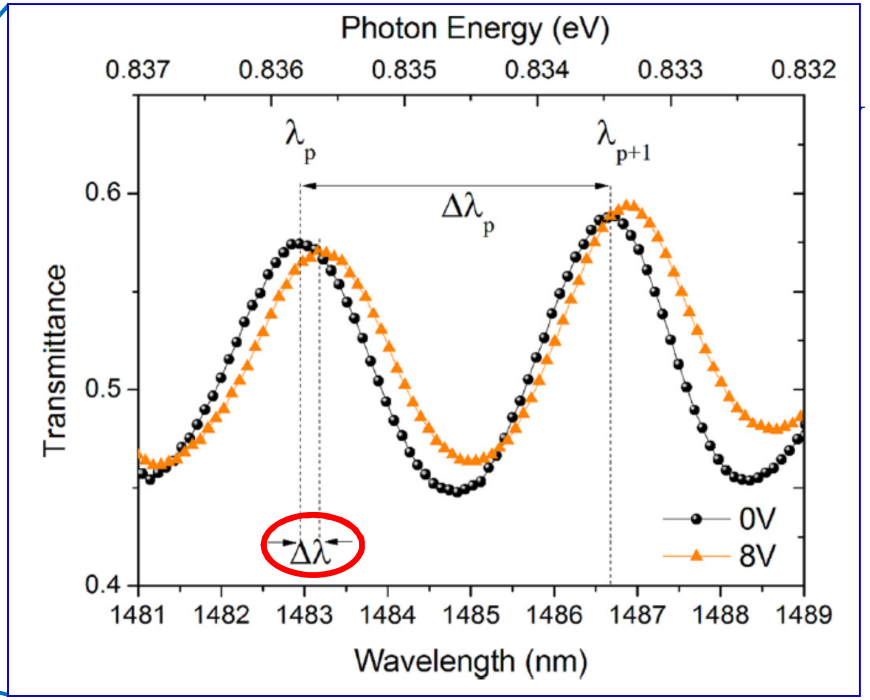
- The absorption edge shifted to 0.8 eV (quantum confinement + strain)
- QCSE observed
- Fabry-Perot (FP) fringes observed at energy lower than the absorption edge

The shift of the Fabry-Perot fringes Δλ with the electric field is connected to the variation of the effective refractive index by:

$$\Delta n_{eff}(\lambda) = \frac{\Delta\lambda}{\lambda} n(\lambda)$$

Electro-refraction in Ge QW





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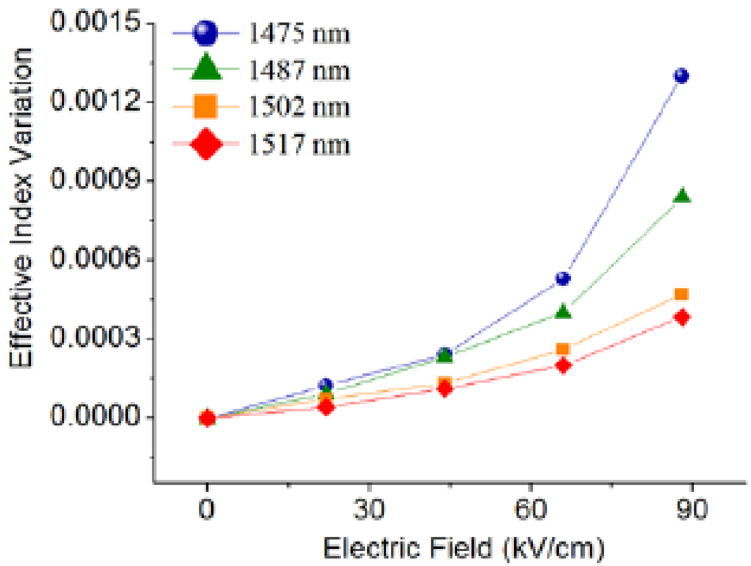
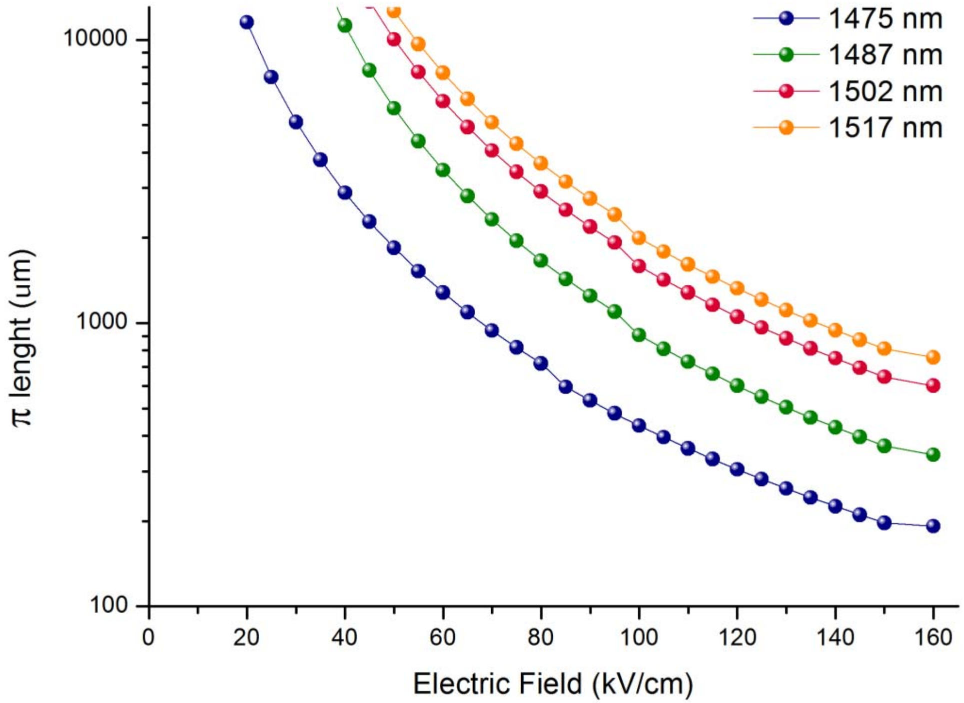
Electro(refraction in Ge QW



One order of magnitude higher than
the variation obtained with carrier depletion modulator

Ge/SiGe MQW phase-shifter

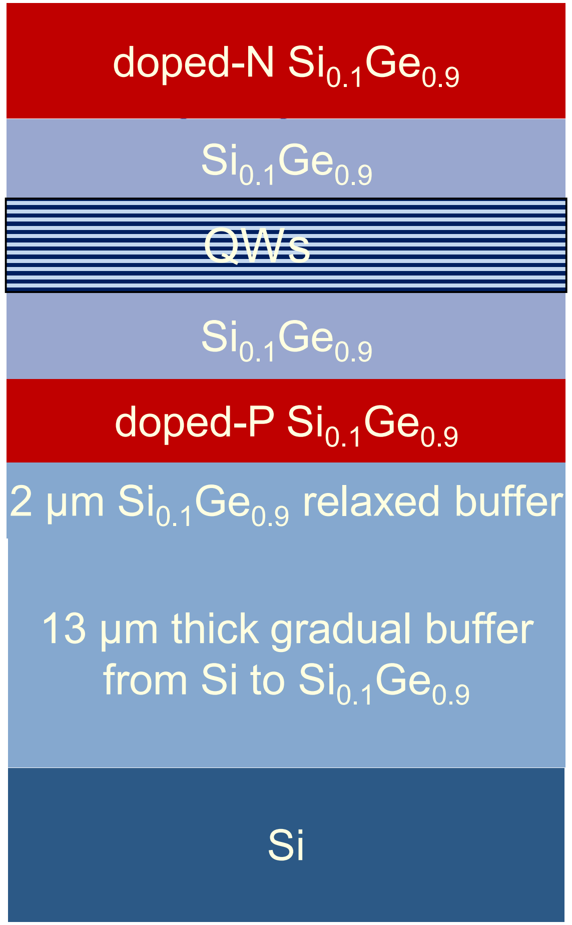


$$L_\pi = \lambda/(2\Delta n_{eff})$$

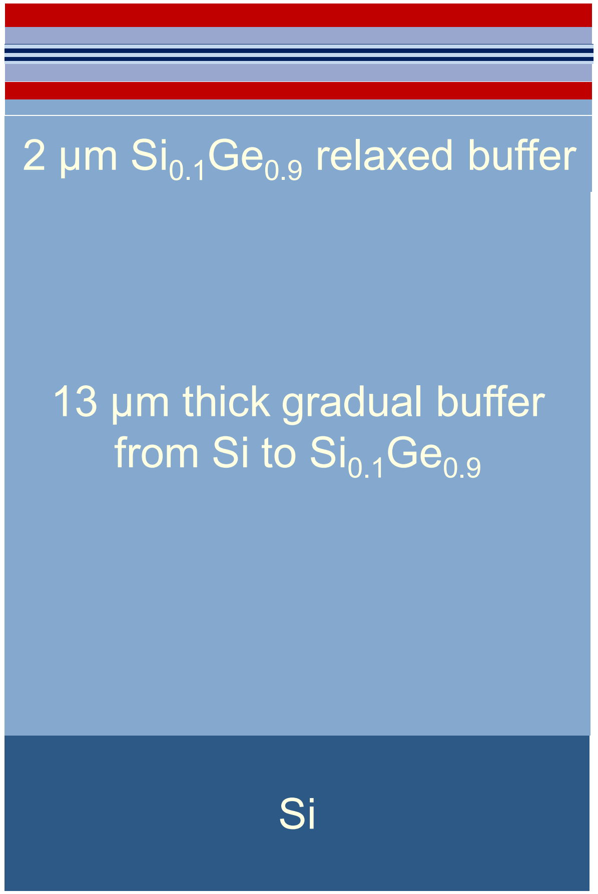
figure of merit $V_\pi L_\pi$ of 0.46 Vcm (88kV/cm, 1475 nm)

- GaAs/AlGaAs MQW → 0.55 Vcm — J.S. Sites et al. J. Lightwave Technol. 12, 1167 (1992)
- InAlGaAs MQW on Si system → 0.4 Vcm — H.-W. Chen et al., IEEE 20, 1920 (2008)

Integrated circuits based on Ge/SiGe QW ?



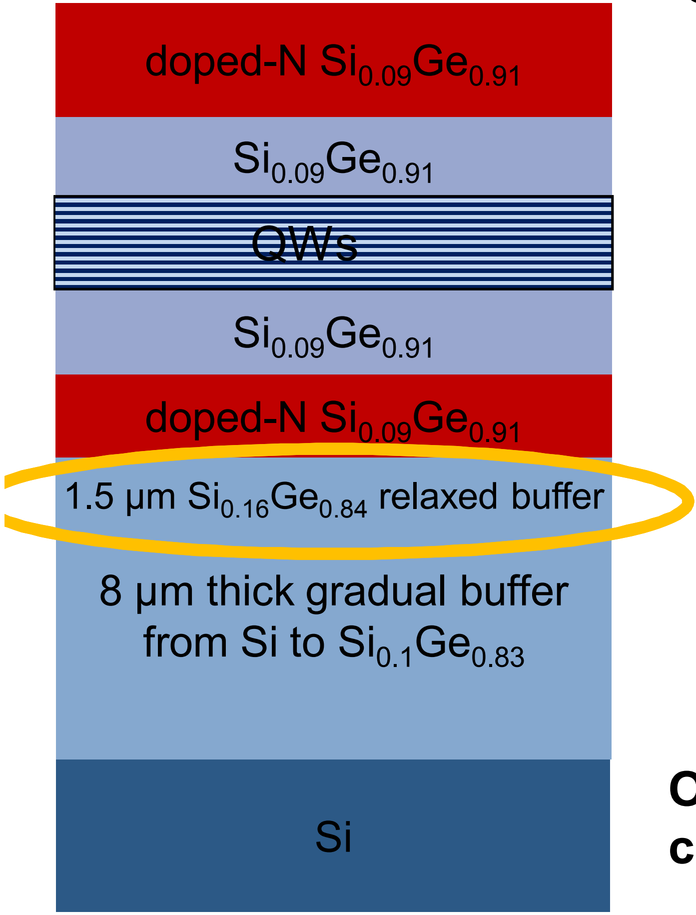
Schematic description



The real scale

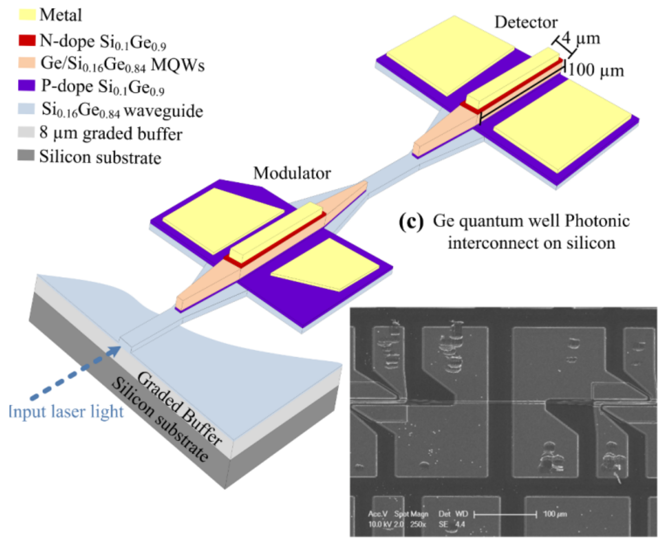
Challenge: coupling the light from silicon to Ge/SiGe QW

1st option: waveguide in the relaxed SiGe layer (thanks to the graded buffer)



Ge concentration in the waveguide: trade-off between

- Strain compensation
- Optical loss



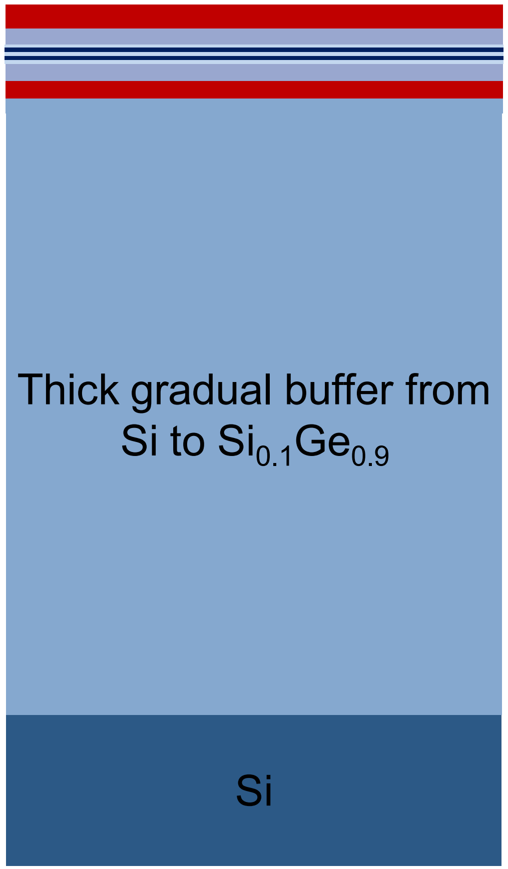
Optical loss of each device, including input/output coupling with $Si_{0.16}Ge_{0.84}$waveguide < 5dB

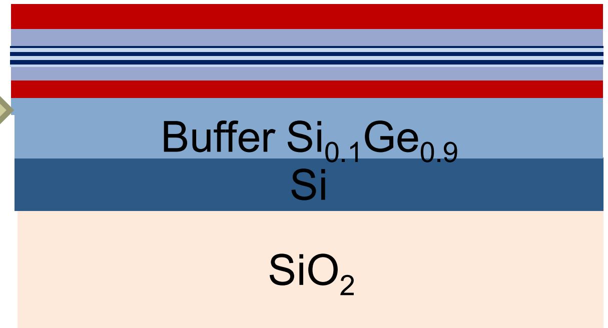
P. Chaisakul et al, accepted to Nature Photonics

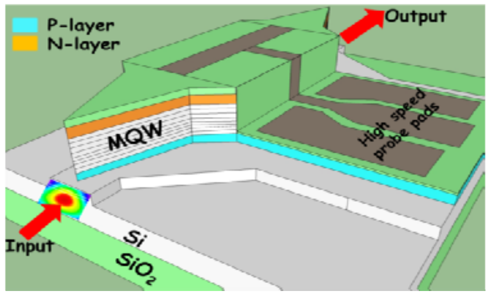
Integration on SOI

<u>2nd option: decrease the thickness of the buffer layer</u>

Challenge: keeping homogeneous and high quality layers

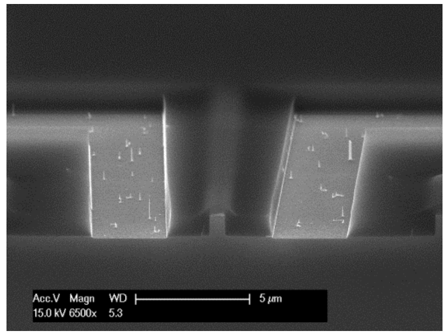






Ge/SiGe modulator integrated with SOI : estimated performance : Extinction ratio = 7.7 dB, loss = 4 dB

M-S. Rouifed et al, soumis



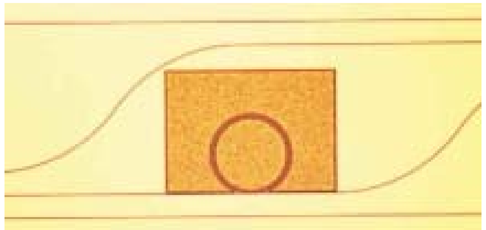
Under fabrication

Carrier depletion modulator MZi

Energy/bit ~ 5 pJ/bit

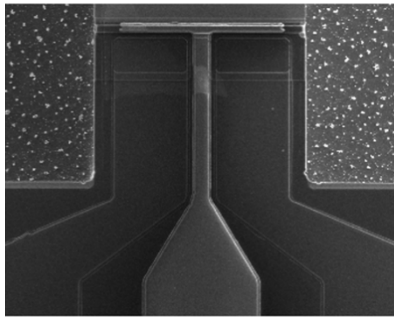
Ring resonator modulator

Energy/bit ~ 0.7 pJ/bit

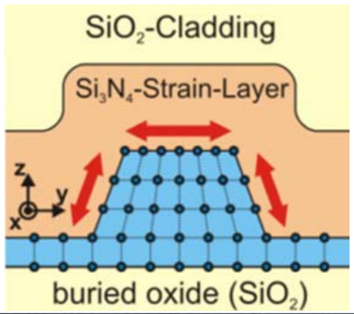


EA Ge/SiGe modulator

energy/bit ~ 0.07 pJ/bit



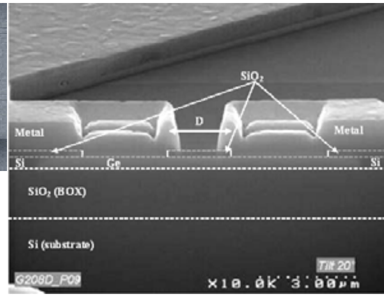
Strained modulator



Ultra low power consumption modulator

energy/bit ~ few fJ/bit

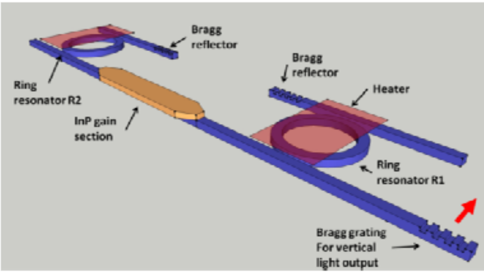
The silicon photonic link!



Ge-on-Si integrated photodetector

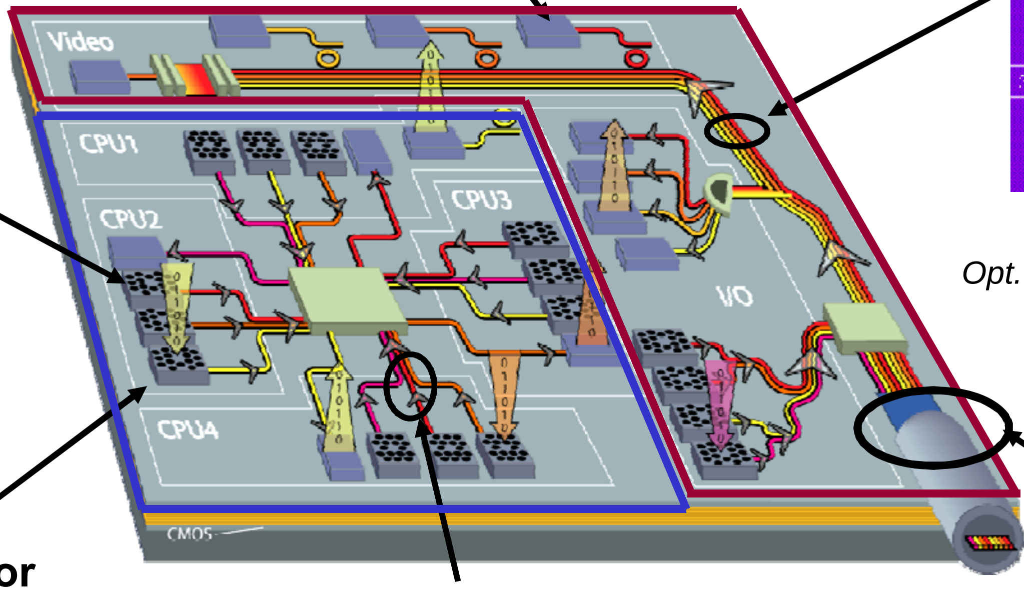
Bandwidth ~130 GHz
Responsivity ~0.8 A/W
Opt. Exp 20, 1096 (2012)

III-V tunable laser on silicon

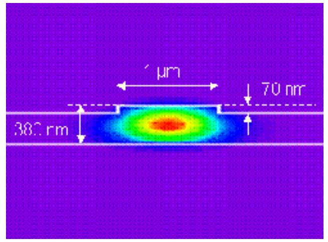


Tunable range > 45nm
Threshold = 20 mA
Output power ~ 10dBm

III-V lab G.H. Duan

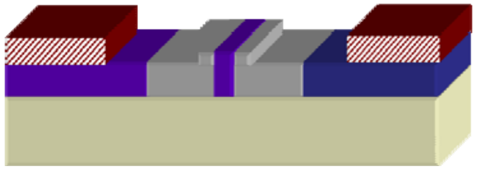


SiSi waveguide



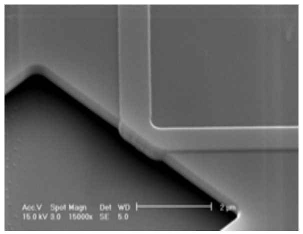
Loss = 0.1dB/cm
Opt. Lett. 28, 1150 (2003)

Silicon optical modulator

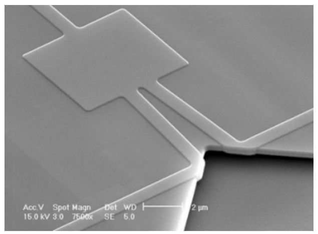


Bandwidth = 40GBit/s
Insertion loss = 6 dB
Contrast = 6 dB
Opt. Exp 19, 5827 (2011)

Appl. Phys. Lett. 87, 211102 (2005)

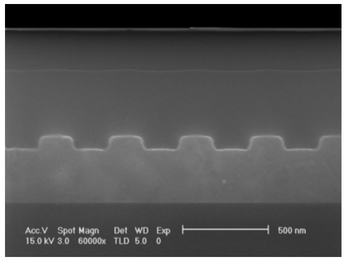


90° mirror
Loss = 0.5 dB



Beam splitter
loss = 0.5 dB

Grating coupler
Efficiency > 60%



J. Light. Techn. 24, 3810 (2006)