# Towards Low Power Electro-Optics Modulators

M. Berciano, G. Marcaud, P. Damas, X. Le Roux, C. Alonso-Ramos, D. Pérez-Galacho, V. Vakarin, P. Crozat, D. Benedikovic, D. Marris-Morini, E. Cassan, L. Vivien

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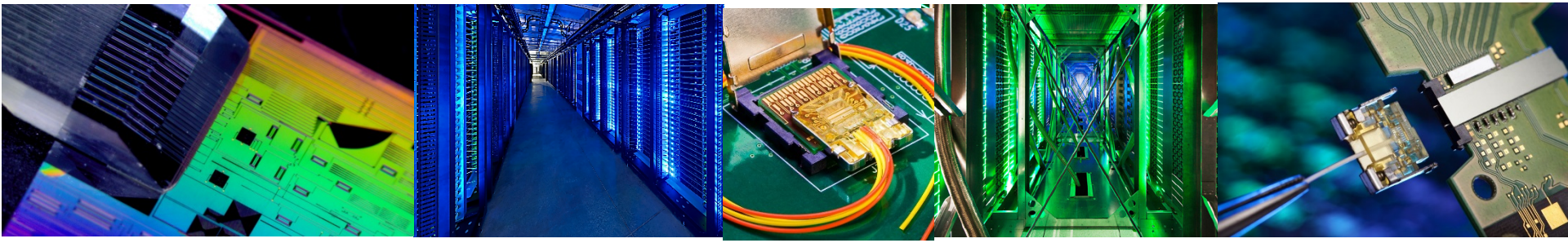
http://silicon-photonics.ief.u-psud.fr/



Source of images: Intel, Google

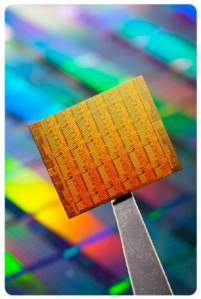
# Silicon photonics, what for?

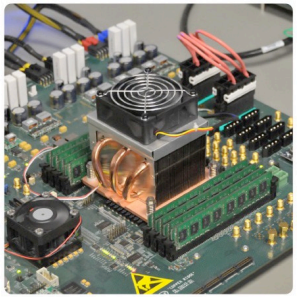
## Optical telecommunications

Long haul, Local network, FTTH, …

## Datacom

Rack-to-rack, chip-to-chip, on-chip interconnect, …





Use photonics at the chip scale to:

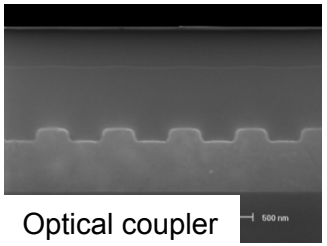
- Increase the data transmission
- Reduce the power consumption

Convergence between electronics and photonics

- Increase the data processing

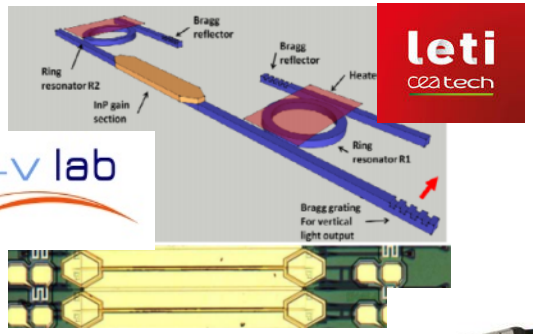
# Silicon photonic building blocks

Off-chip III-V laser

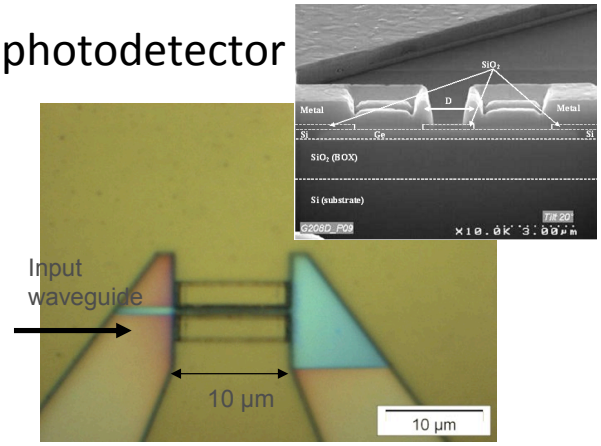



Optical coupler

On-chip III-V laser on Si




Ge photodetector




Germanium-based laser

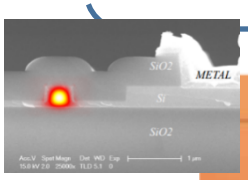
Hybrid laser with X materials

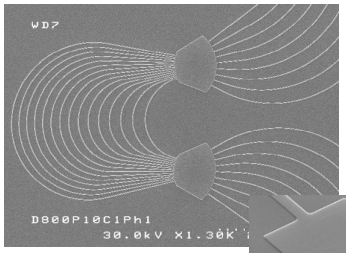
Emitter

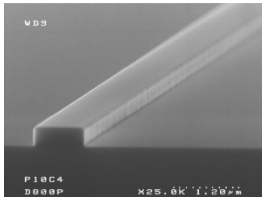
Laser — Modulator

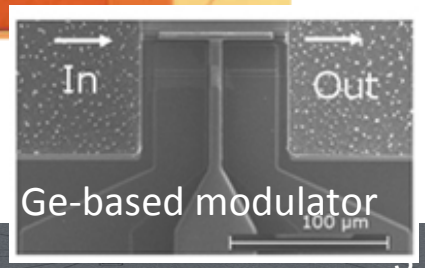
Receiver

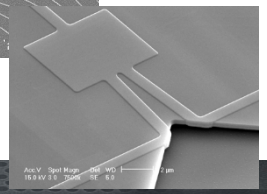
Detector





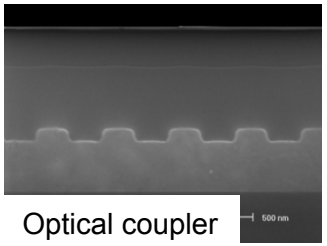




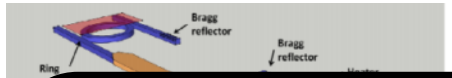
# Silicon photonic building blocks

Off-chip III-V laser

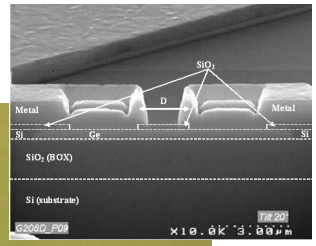


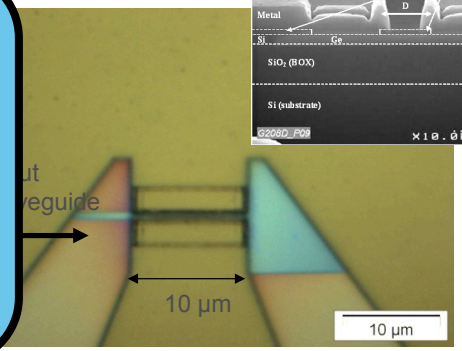

Optical coupler

On-chip III-V laser on Si




photodetector




Germanium-based laser

Hybrid laser

**Ideal characteristics:**

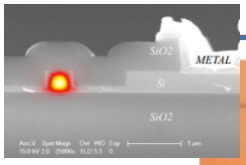
1. Fast
2. Low Power consumption
3. Chirp-free
4. High optical bandwidth
5. Si-Platform compatibility

Emitter

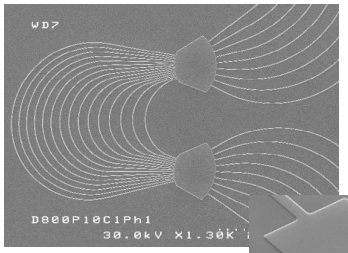
Laser — Modulator

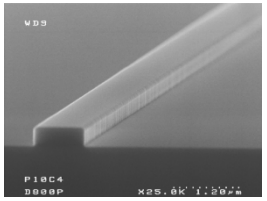
Receiver

Detector

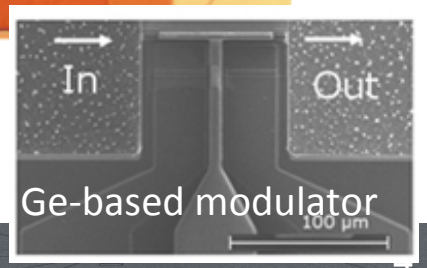


Si modulator

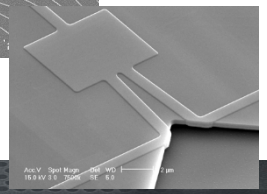




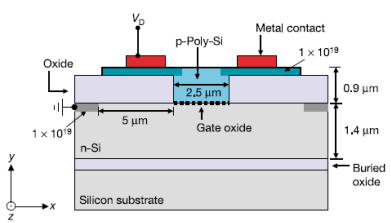
Bonded III-V EAM on Si

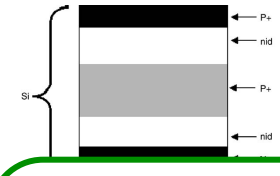



Ge-based modulator



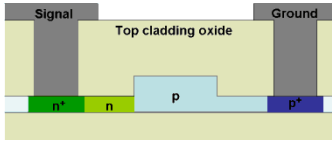
# Si optical modulators based on Plasma-dispersion effect

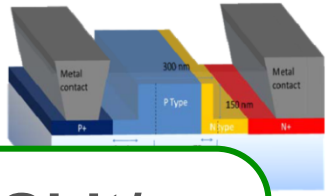


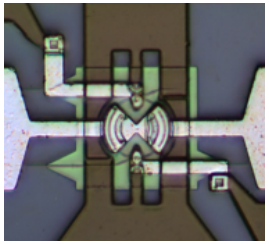



*PIPIN diode*

Metal Metal



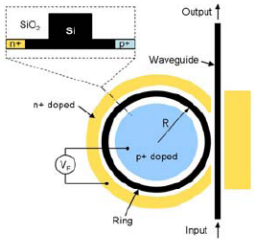


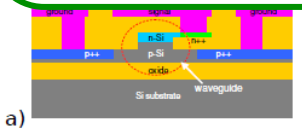
2004 2005 2006 2014 2015 2016

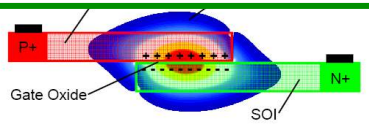
**Data transmission: >40Gbit/s**

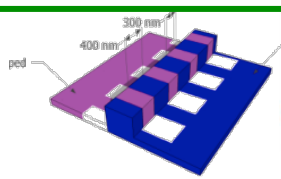
**Insertion loss: <6dB**

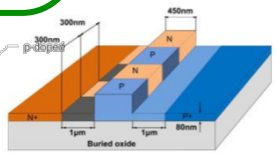
**Extinction ratio: ~8dB**



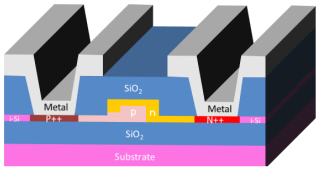




**Europe:** C2N – CNRS-Univ. Paris Sud, CEA Leti, IMEC/Gent Univ., Univ. of Southampton, UPV, RWTH, ST, …

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

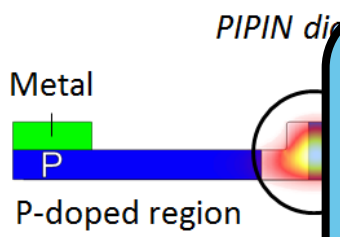
**North America:** Intel, IBM, Cornell/columbia, Luxtera, Ligthwire, Kotura, Oracle, MIT …



# Silicon Optical Modulation

## Plasma Dispersion-effect

- Refractive index is modified by free-carrier concentration variations




- Power consumption ~1000fJ/bit
  - Capacitance
  - Voltage swing
- Doped regions
  - ➢ Insertion loss
- Chirp

## Nonlinear-Phenomena

- Refractive index is modified by electric field effects

$E^3(t) + \cdots$

ect:

electro-optic effect

$$\Delta n = \frac{\chi^{(2)} E}{2n}$$

Silicon

o-symmetric crystal!

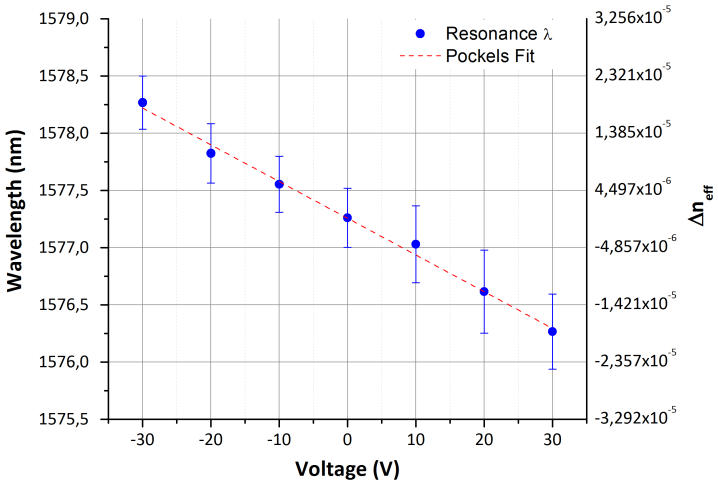
- Intrinsically high speed
- Low power consumption
- No doped regions

**Solution:**
Break the crystal symmetry
by **straining** the silicon lattice

# Pockels effect: State of the art

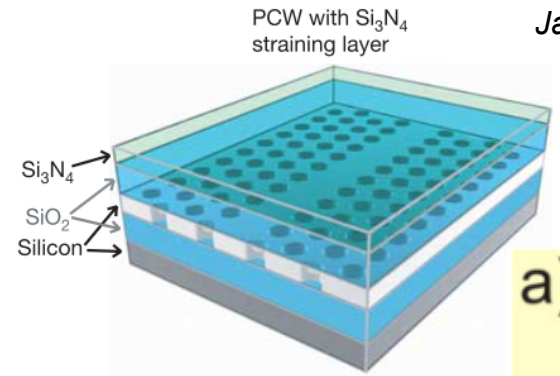
## Before 2015

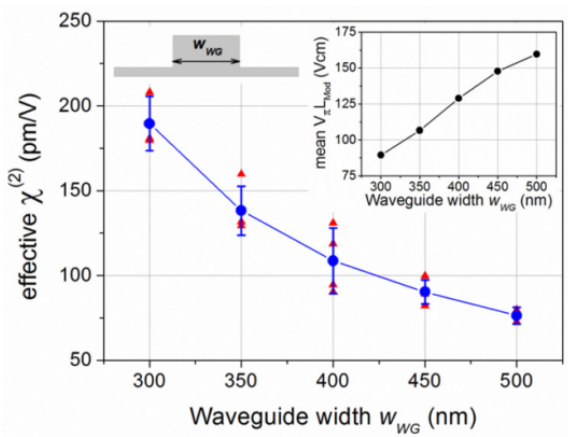
- Linear electro-optic effect:
  - √ Pockels effect!!!



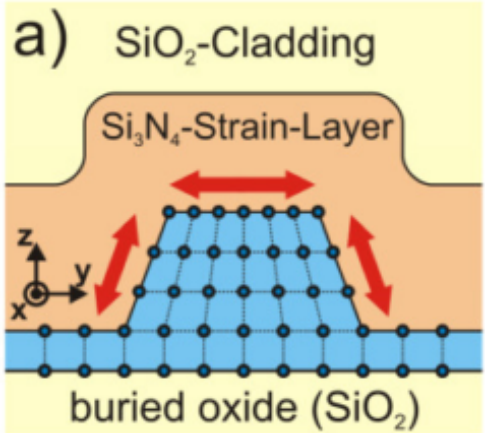

- Estimations of $\chi^{(2)}$ :
  - √ Highest value: 336 pm/V

*Jacobsen et al, Nature 2006*

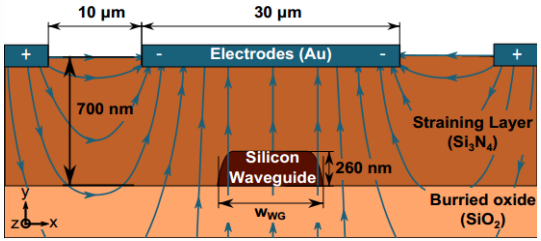



B. Chmielak et al., OE 2013




B. Chmielak et al., OE 2011




Damas et al. Opt. Express, 2014

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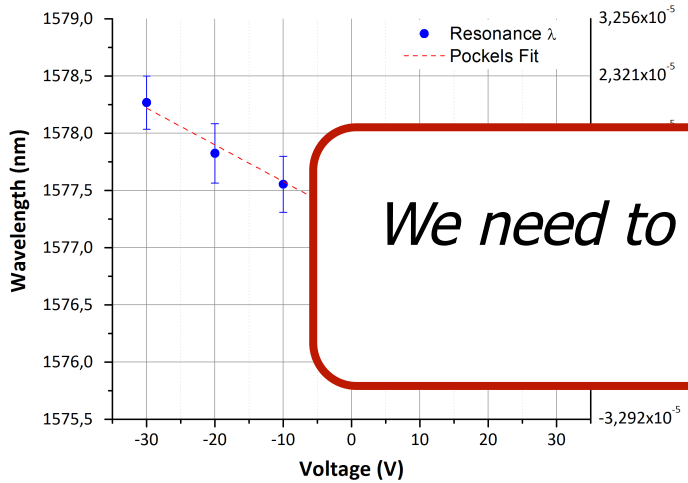



- Estimations of $\chi^{(2)}$ :
  - √ Highest value: 3~~.6~~ pm/V

- Silicon is a semiconductor
- Carriers play a BIG role
- $\Delta n_{neff}$ is mainly due to carriers

*We need to look closer to the silicon atomic arrangement…*

**Final electro optic effect:**

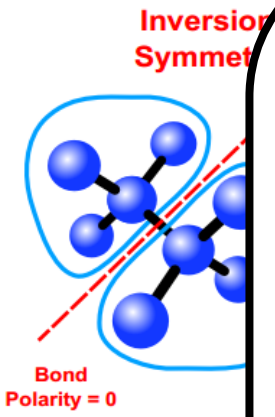
Pockels effect + Carriers effects

*Difficult to separate both effects*

Azadeh et al. Opt. Letters, 2015

# Model: strain vs $\chi^{(2)}$

energy in the




ics

del

**Macroscopic polarization versus strain**

$$\mathbf{P} = \mathbf{P}^{(0)} + \mathbf{P}^{(1)} + \mathbf{P}^{(2)} + \cdots$$

**Order 1 - Photo-elastic effect**

Very good agreement with the value of the photo-elastic coefficients

| | Experimental $p_{11} - p_{12}$ | Calculated $p_{11} - p_{12}$ |
|---|---|---|
| C | -0.292 [59, 60] | -0.251 |
| Si | -0.111 [32, 34, 60] | -0.108 |
| Ge | -0.030 [61] | -0.070 |

**Strain**

**w bond**
**efunction**

**moment of the bond**

**Sum over all bonds**

**Macroscopic polarization**

Damas et al. Phys. Rev. B **93**, 165208 (2016)

# Summary of the results

- General form of $\chi^{(2)}$ :

$$\chi^{(2)}_{ijk}(\mathbf{r};\overline{\overline{\eta}}) = \sum_{lmn} \Gamma_{ijk,mn}\,\eta_{lmn}$$

- Depend on the crystal nature
- Depends only on two unknown parameters
  - ✓ To be experimentally determined

- Depend only on the strain distribution
  - ✓ To be computationally simulated

$$\Delta n_{eff} = \Delta n_{eff_P} + \Delta n_{eff_c}$$

$\Delta n_{eff_P}$ → $\chi^{(2)}$

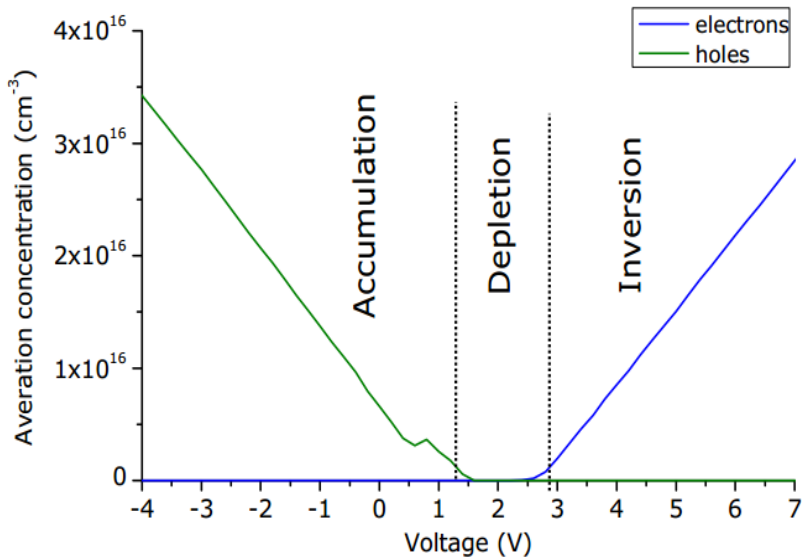
$\Delta n_{eff_c}$ → Carriers

Damas et al. Phys. Rev. B **93**, 165208 (2016)

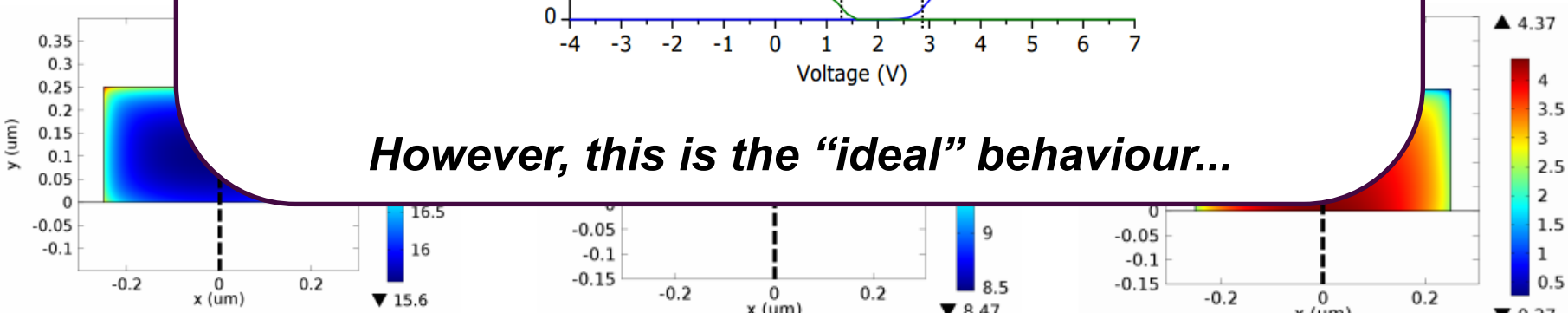
# Carrier effects

- Consider the waveguide capacitor structure
  - √ T
  - MI
- Co

**Average density of carriers in the waveguide**




***However, this is the "ideal" behaviour...***

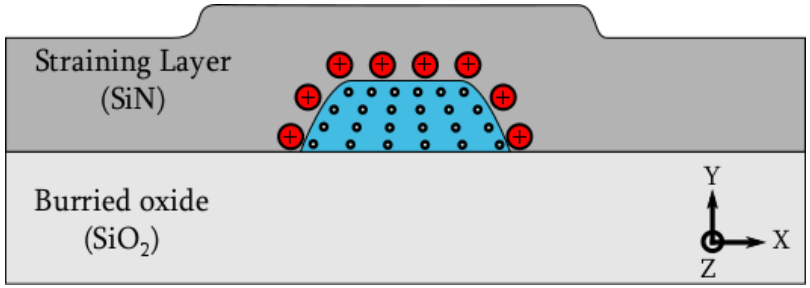



**Accumulation** **Depletion** **Inversion**

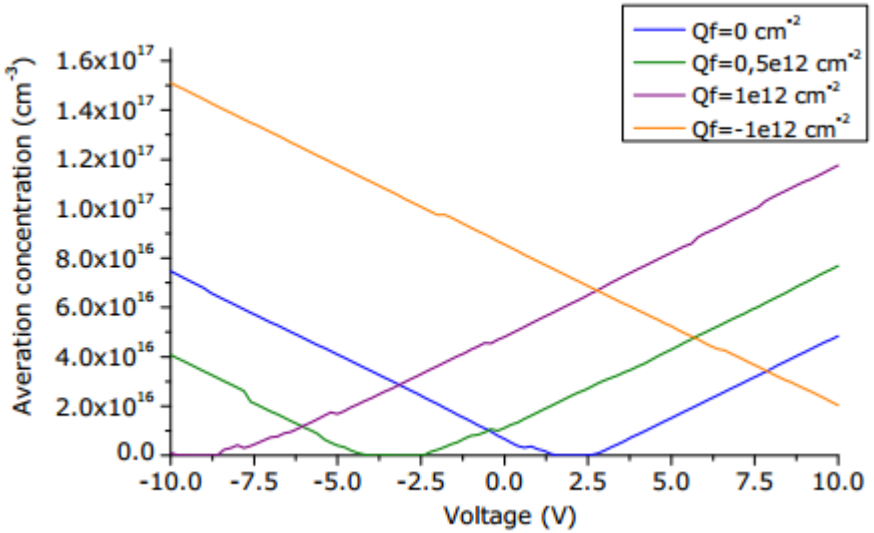
Damas et al. J. Appl. Physics **122**, 153105 (2017)

# Carrier effects

- Real SiN film possesses defects:
  - √ Charges in the layer
  - √ Traps at the interface




- Effect of the fixed charges (Qf)
  - √ Introduce a constant voltage shift
  - √ The shift depend on the Qf density

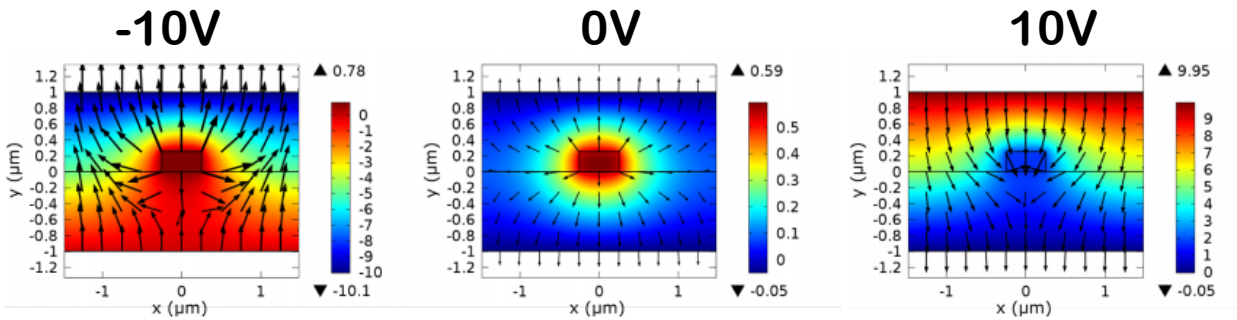


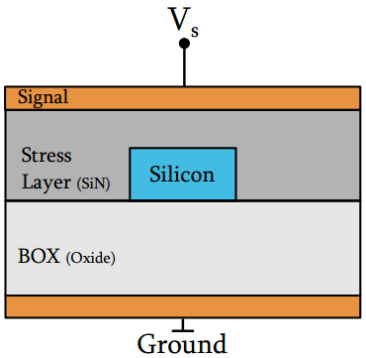

**Silicon Nitride**
Qf~ 3e12 $cm^{-2}$

Damas et al. J. Appl. Physics **122**, 153105 (2017)

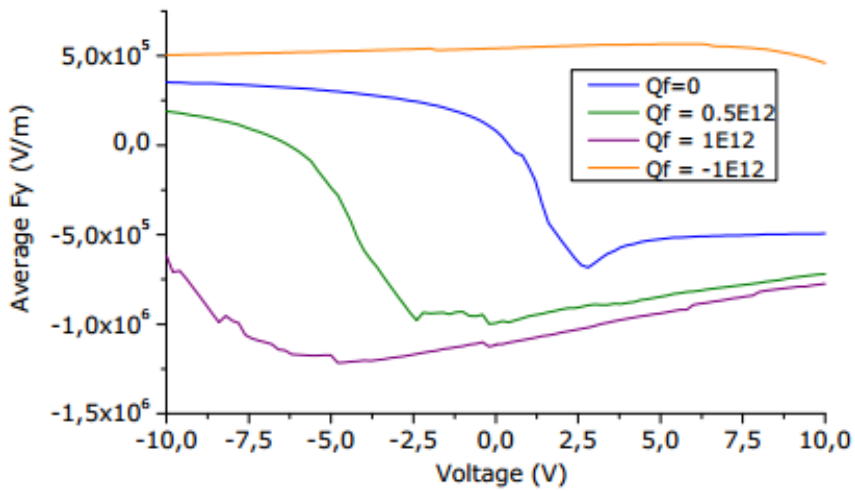
# The electrostatic field

- Carriers affect the electrostatic field




- Average electric field (y component):




**Nonlinear effect:**
The relation between Vs and the electrostatic field is nonlinear

Pockels effect is nonlinear with Vs

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# Pockels electro-optic effect

- Effective strain gradients:

$$\Delta n_{eff} = \sum_{ijk,mnl} \Gamma_{ijk,mnl} \widehat{\eta_{mnl}^{ijk}}$$

$$\widehat{\eta^{ijk}} \quad 2 \int \quad E_i E_j F_k \, dS$$

"Effective stra
Includes:
- Strain ef
- Optical r
- Electrost

**Final Pockels effect**

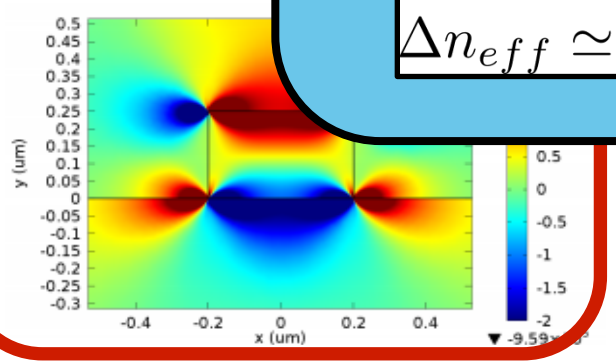
Sum of effective strain gradients

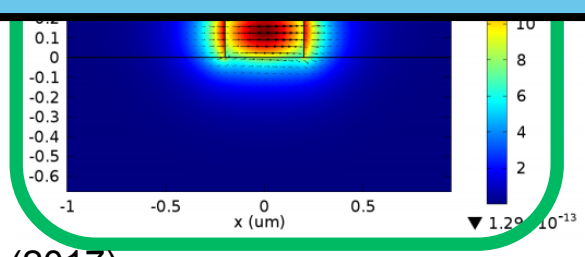
**TE Mode + Vertical electric field**

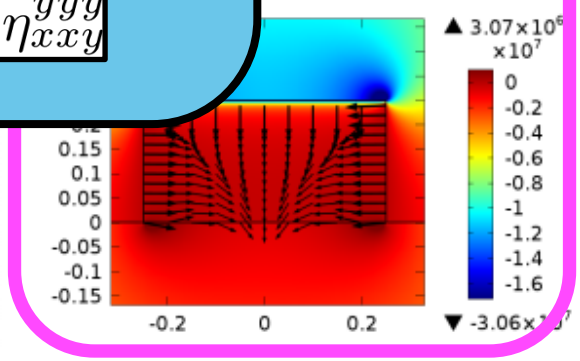
$$\Delta n_{eff} \simeq \Gamma_{xxy,xxy} \widehat{\eta_{xxy}^{xxy}} + \Gamma_{xxy,yyy} \widehat{\eta_{xxy}^{yyy}}$$

Strain gra

static field



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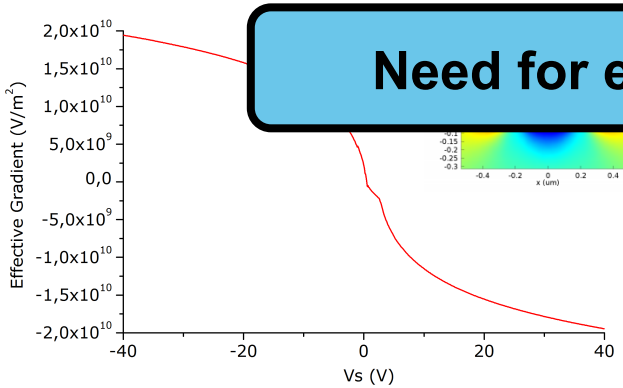
# E-O Simulations: Pockels effect

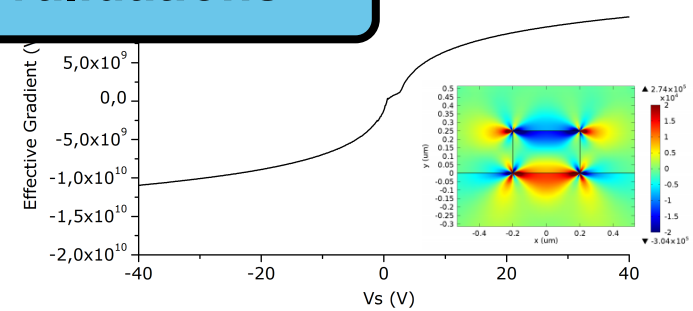
- The contribution from two effective gradients

$$\Delta n_{eff} \simeq \Gamma_{xxy,xxy}\,\widehat{\eta_{xxy}^{xxy}} + \Gamma_{xxy,yyy}\,\widehat{\eta_{xxy}^{yyy}}$$

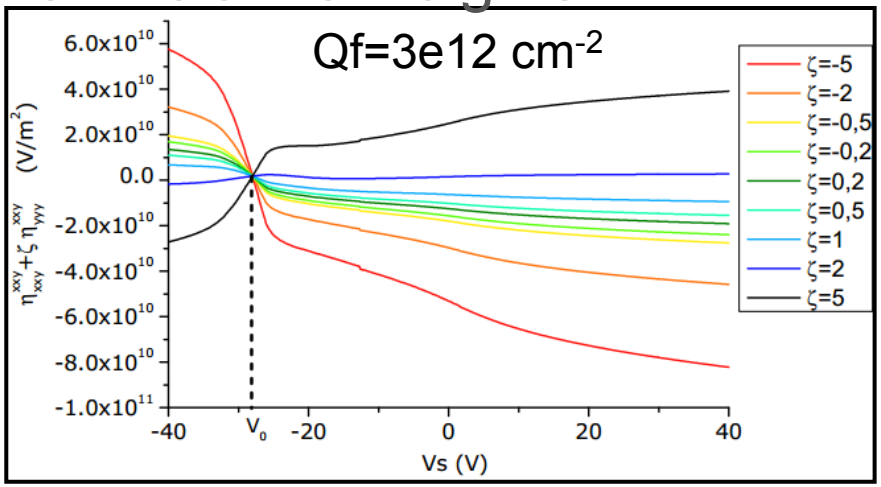
**Need for experimental validations**




+




- Effect of different relative weigths:

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# Electro-optic effects

- Two electro-optic effects:

$$\Delta n_{eff} = \Delta n_{eff_P} + \Delta n_{eff_c}$$

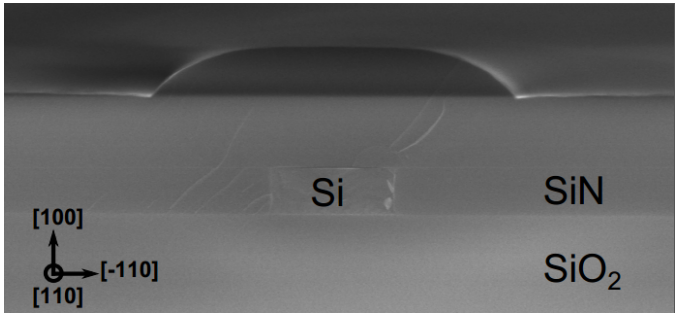
- Comparison

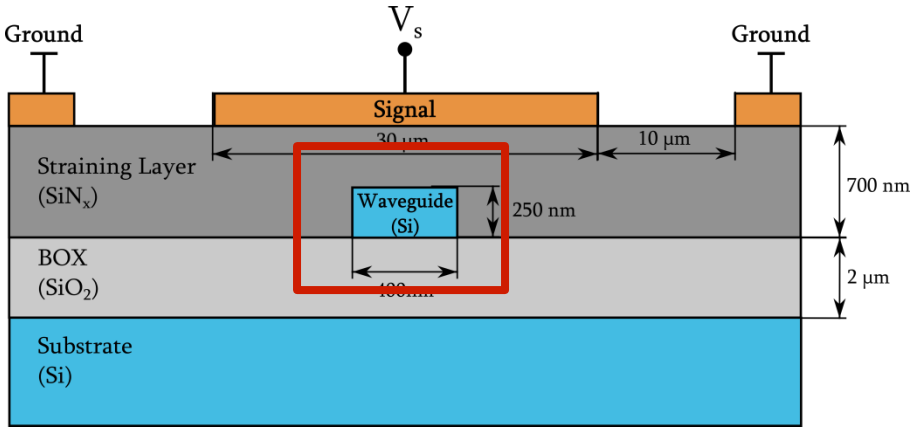
| | Pockels | Free carriers |
|---|---|---|
| **Origin** | Stress | Plasma dispersion effect |
| **$\Delta n_{eff}$ dependence** | Strain gradients | Distribution of carriers<br>Soref equation |
| **Speed** | **Fast** | "Slow":<br>limited by carrier mobility and lifetime |
| **Crystal orientation dependence** | **Yes** | May not be relevant |

# Strained silicon device

- Typical structure:
  - √ Stress layer: SiN
    - ➢ Deposited by PECVD
  - √ Internal stress: -1.2GPa

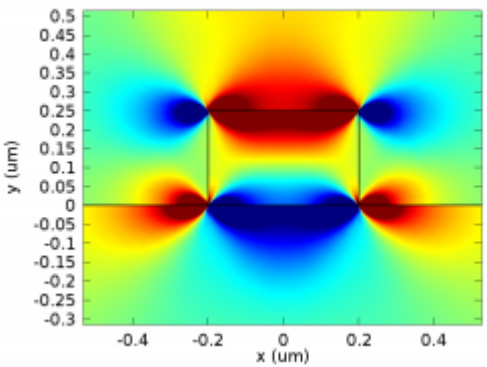
Stress distributed homogeneously inside the SiN film



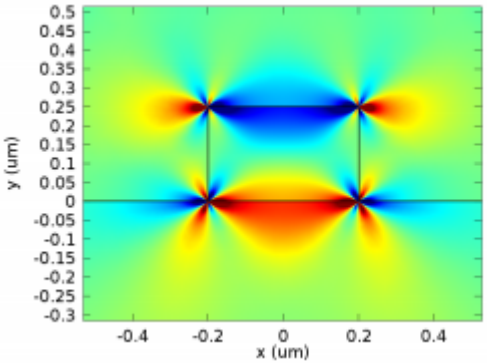




- Device layout:
  - √ TE single mode Waveguide
  - √ Electrodes:
    - ➢ Vertical electric field

Strain gradient distribution



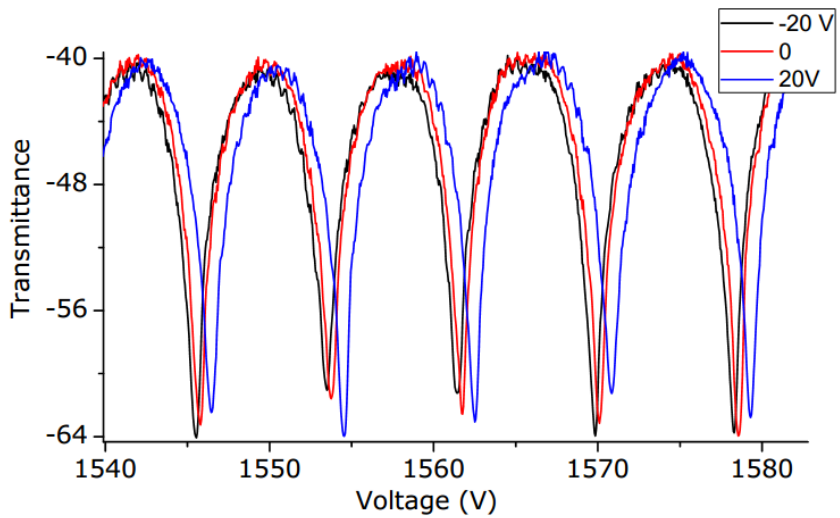

$\eta_{xxy}$

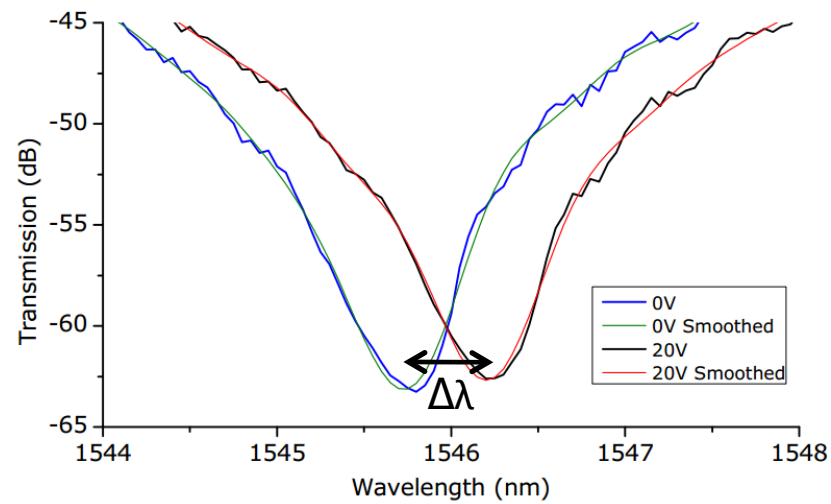



$\eta_{yyy}$

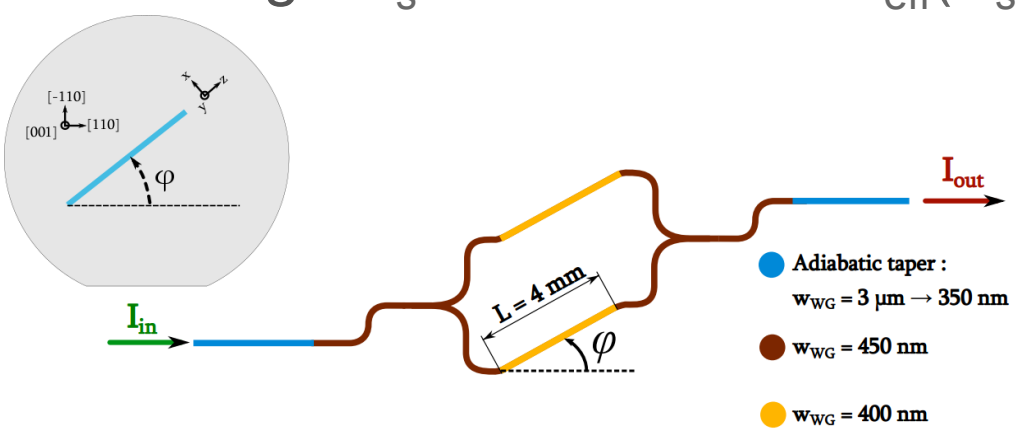
# DC characterization

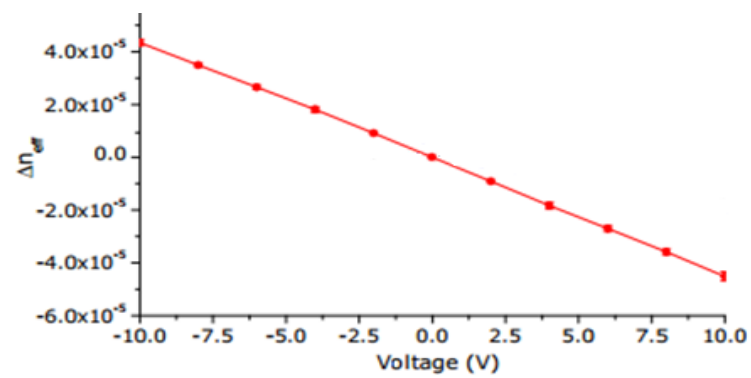
- Applying a voltage:



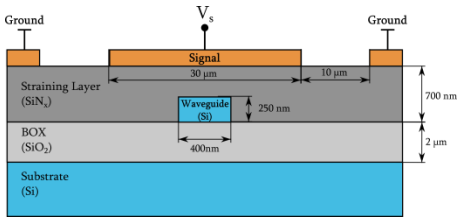

- Change $V_s$ to determine $\Delta n_{eff}(V_s)$: $\Delta n_{eff} = \Delta n_{eff_P} + \Delta n_{eff_c}$

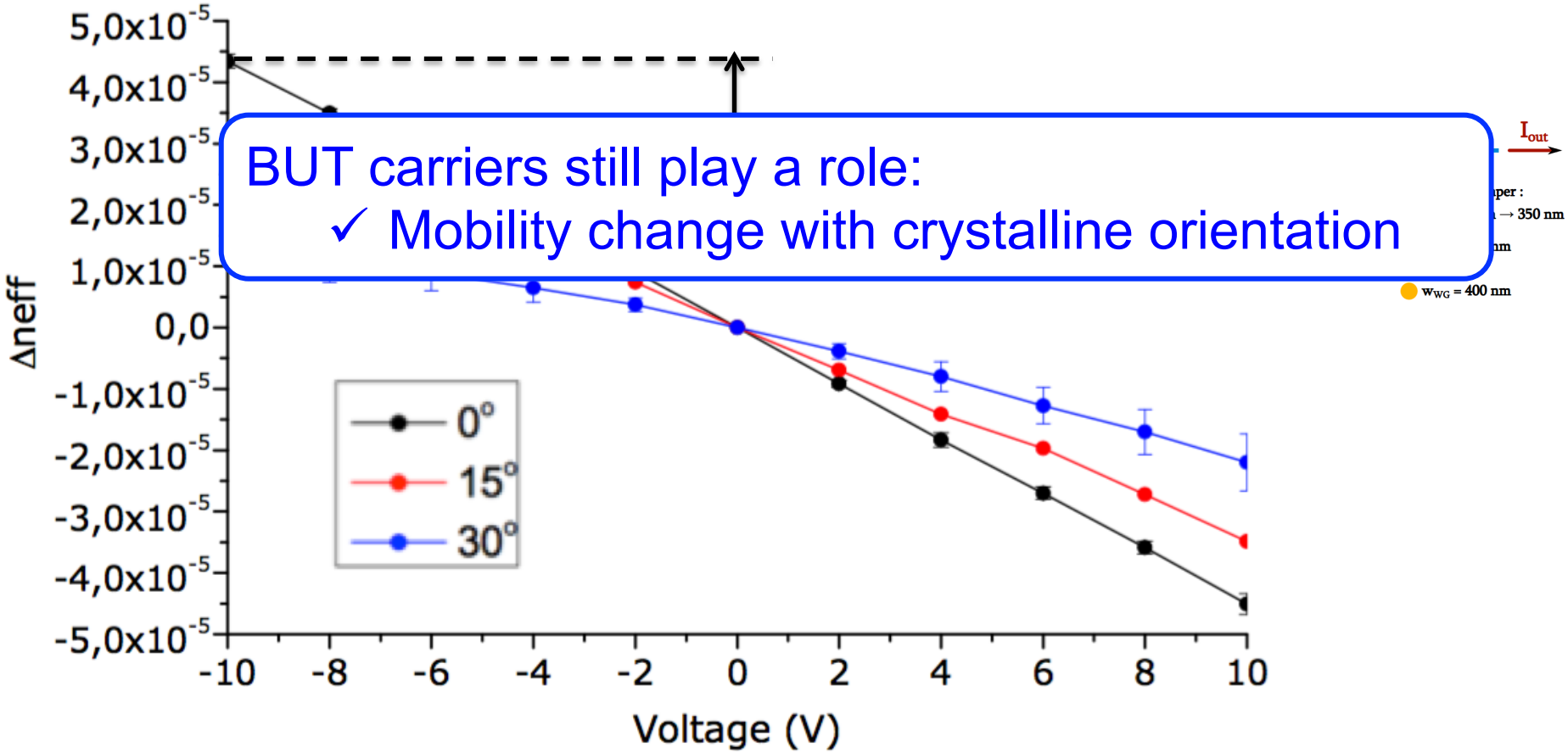


# Experimental results

- Effective index change vs angle



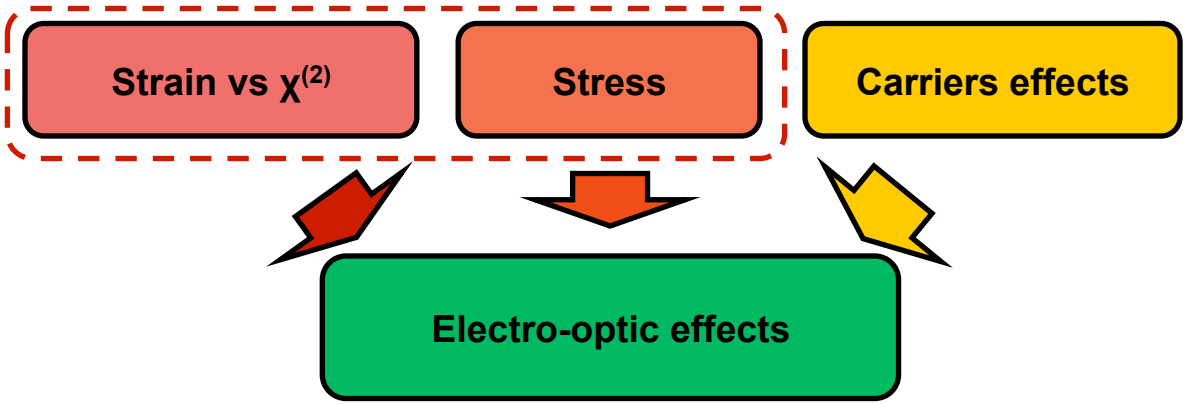




BUT carriers still play a role:

✓ Mobility change with crystalline orientation

# Conclusion

- Development of a model for strain-induced Pockels effect




- Design and fabrication of Devices

to validate the model

- Detection E-O angle dependence
  - √ Pockels effect!
- Detection of high speed modulation
  - √ Pockels effect!
- Final estimative of $\chi^{(2)}$ distribution
  - √ Effective $\chi^{(2)}$ few pm/V

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