POLITECNICO DI MILANO

Laboratory for Nanotechnology Epitaxy and Spintronics on Silicon

SiGe heterostructures for optoelectronics applications

Fabio Isa, Jacopo Frigerio, Daniel Chrastina, Stefano Cecchi, and Giovanni Isella

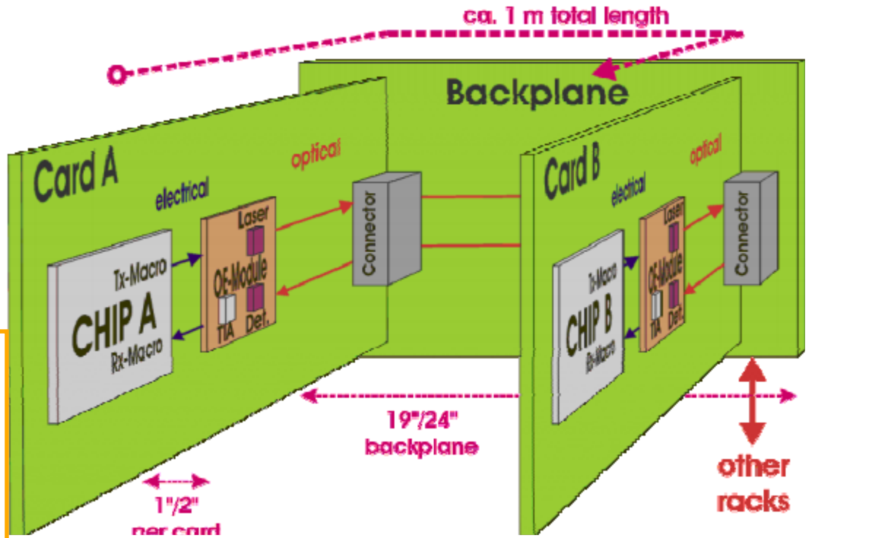
Outline

- Importance of optoelectronics interconnections
- Low Energy Plasma Enhanced CVD
- SiGe heterostructures for optoelectronics applications
  - Ge photodiodes and infrared cameras
  - MQWs as modulators, light sources
  - Ge virtual substrate for III-V integration on Si
- Conclusions

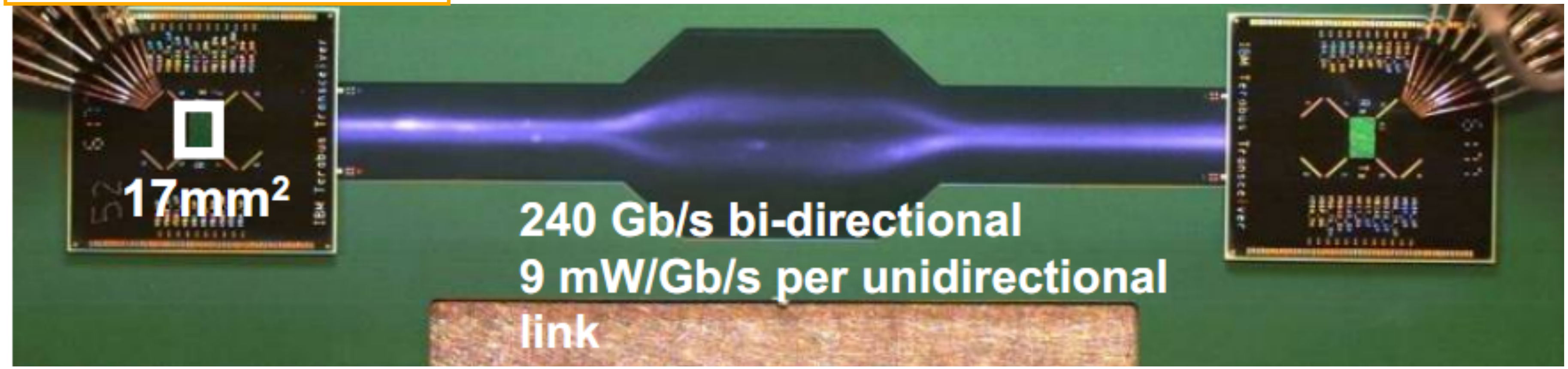
Optical interconnections – different scales

Rack to Rack
L ≈ 100m

Card to Card
L ≈ 1m



Chip to Chip L ≈ 1cm

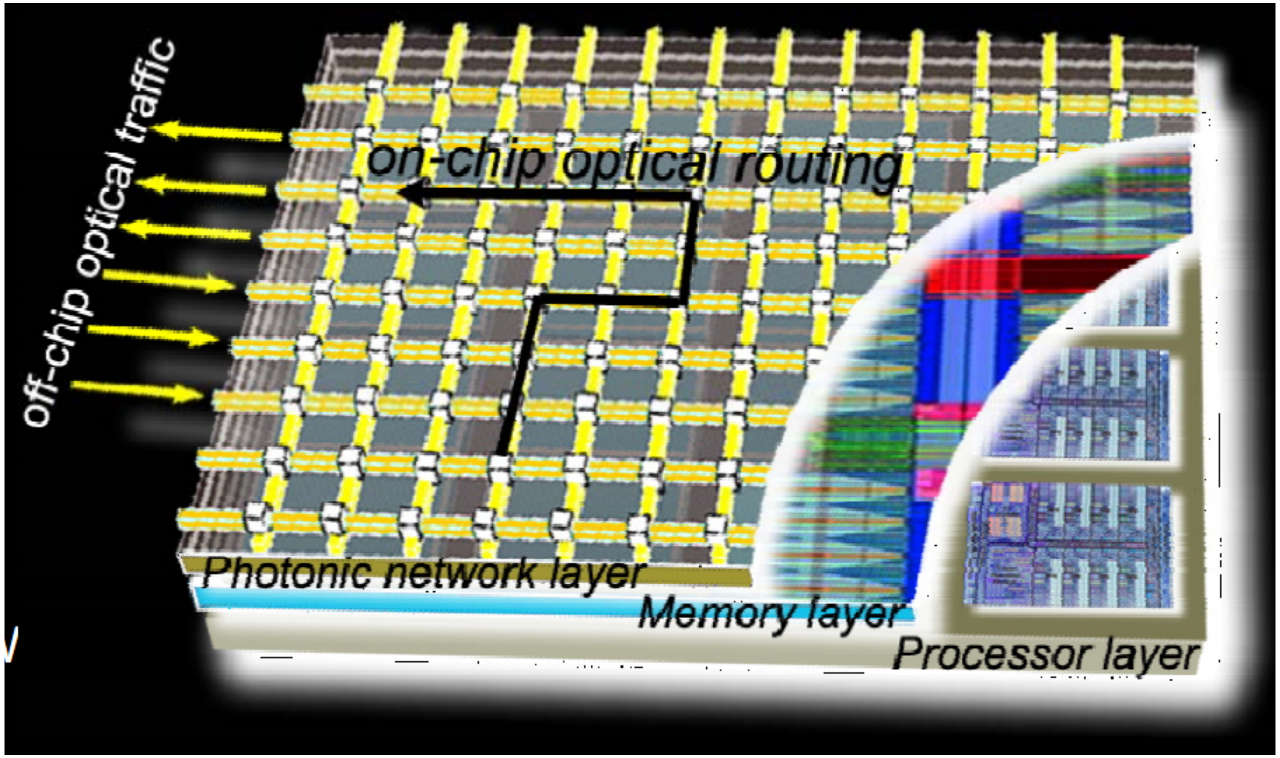


Courtesy of IBM

Optical interconnections – on chip

Metallic interconnections dissipate energy by Joule effect

Optical interconnections can save the dissipated energy by heat

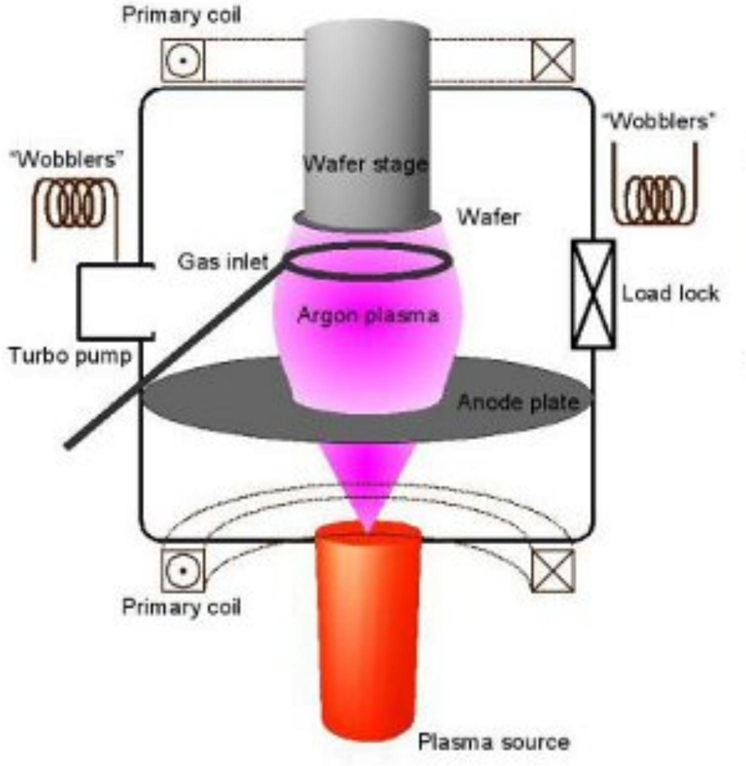


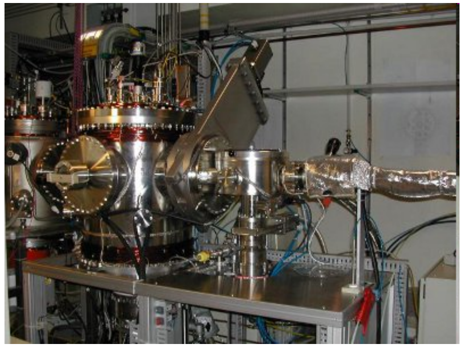
Optical interconnections – building blocks

- Light source
- Wave guide
- Revelators
- Elettro-optical modulator

fabio.isa@mail.polimi.it

LEPECVD reactor schematics





- ❑ High density - low energy plasma

  No ion induced damage → epitaxy

- ❑ Deposition rate independent on substrate temperatures

  Control of surface diffusion lenght

- ❑ Wide range of deposition rates

  From 0.1 to 10 nm/s

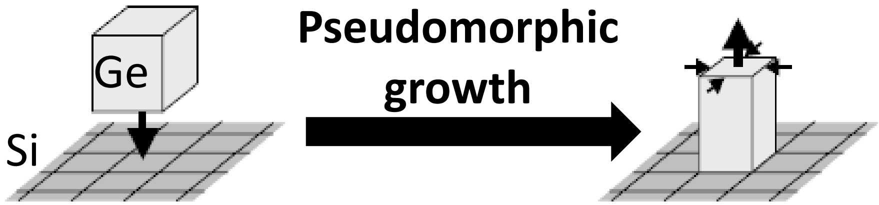
- ❑ Good control of film composition

  Sharp interfaces between different layers

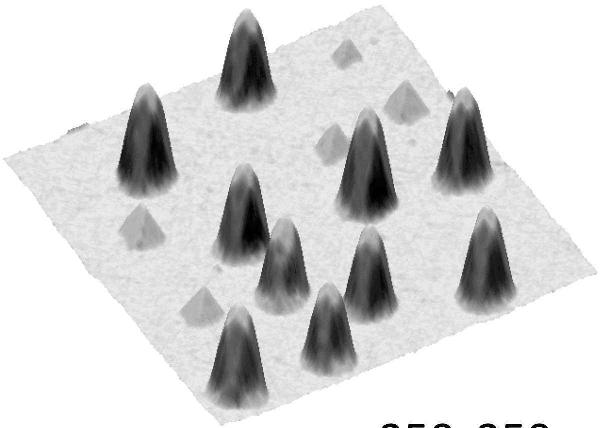
Strain and film morphology in SiGe epitaxy

Ge has a lattice parameter 4.2% larger than Si

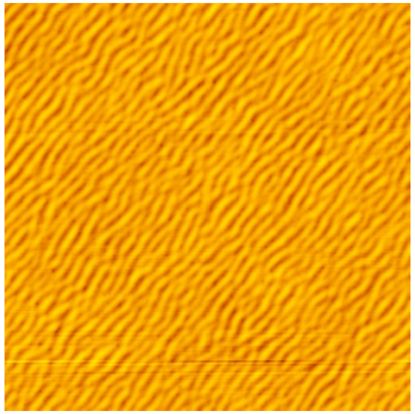
Mismatch strain can lead to the formation of
- 3D island
- Surface roughening
- Poorly defined interfaces



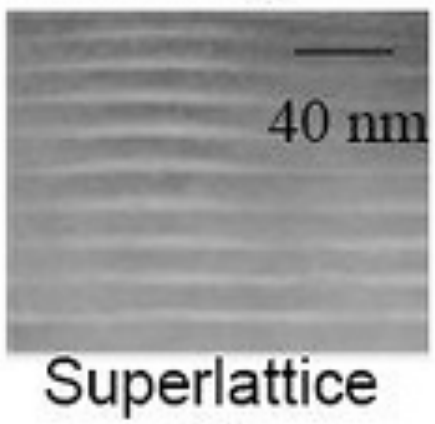
All these phenomena can be partially suppressed reducing surface atoms diffusion



250x250nm



20x20µm

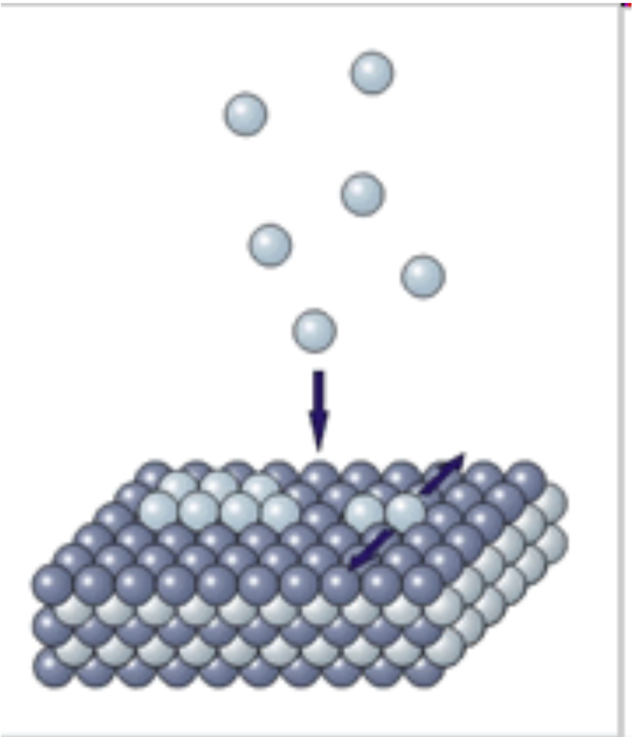


fabio.isa@mail.polimi.it

Superficial diffusion

The morphology of epitaxial film is strongly influenced by

- Rate of arrival of reactive species: deposition rate
- Diffusivity of the adsorbed species on the surface: substrate temperature



$$L = 2\sqrt{D\tau}$$

L

Diffusion lenght

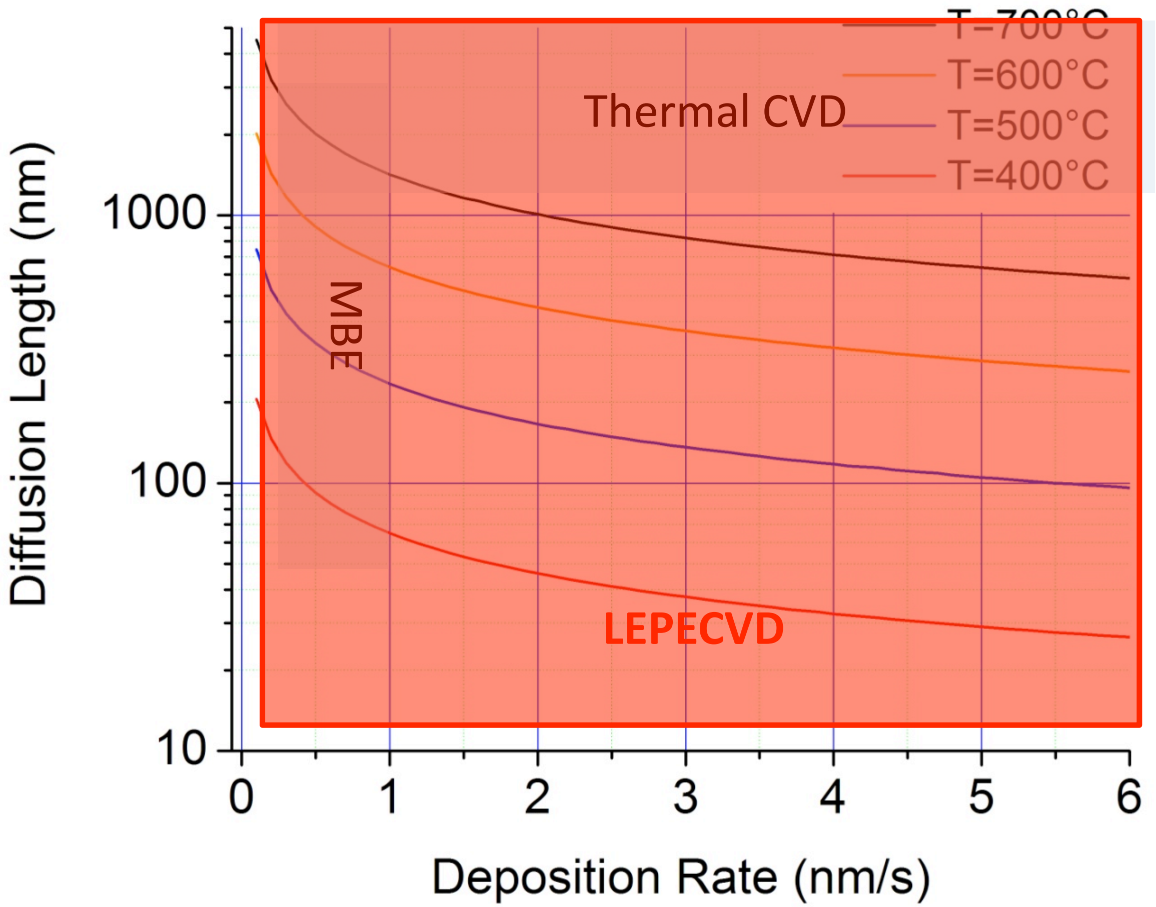
$$D = D_0 e^{-\frac{E_A}{kT}}$$

Diffusion coefficient

τ

Time for the deposition of a 1 atomic layer

Germanium epitaxy: diffusion lenght



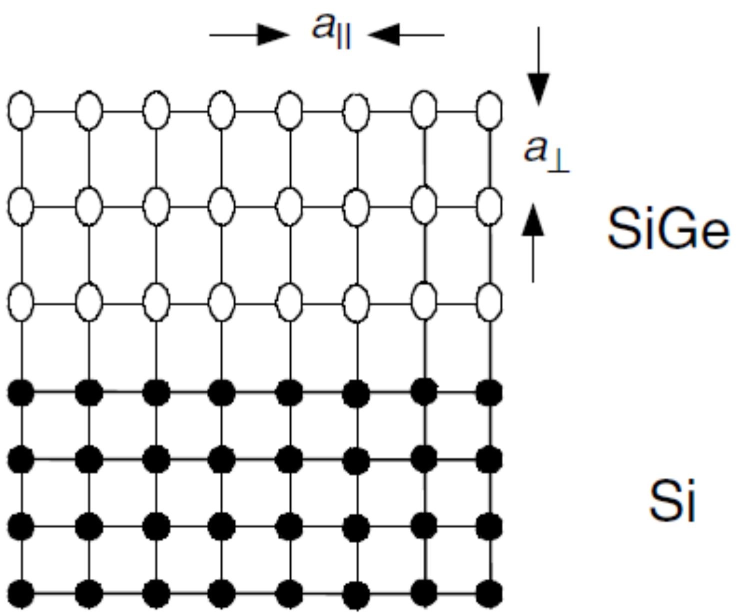
$$L = 2\sqrt{D\tau}$$

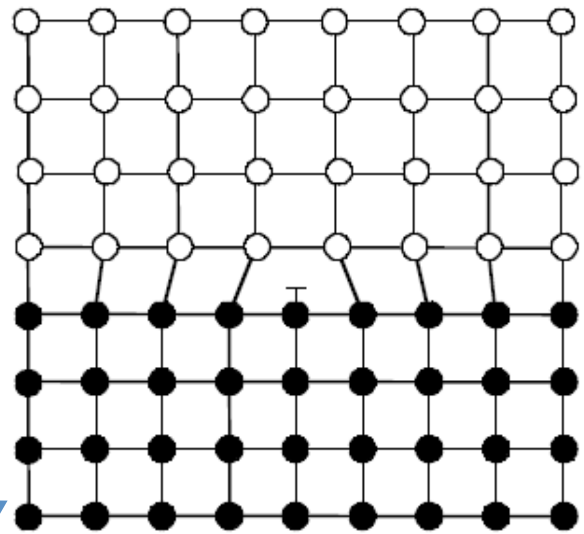
$$D = 6.08\times10^{-2} e^{-\frac{-1.24eV}{kT}} \, cm^2/s$$

τ = Time required for the deposition of 1monolayer

G.M. Vanacore et. al.
Phys. Rev B **82**, 125456 (2010)

Plastic relaxation in SiGe system

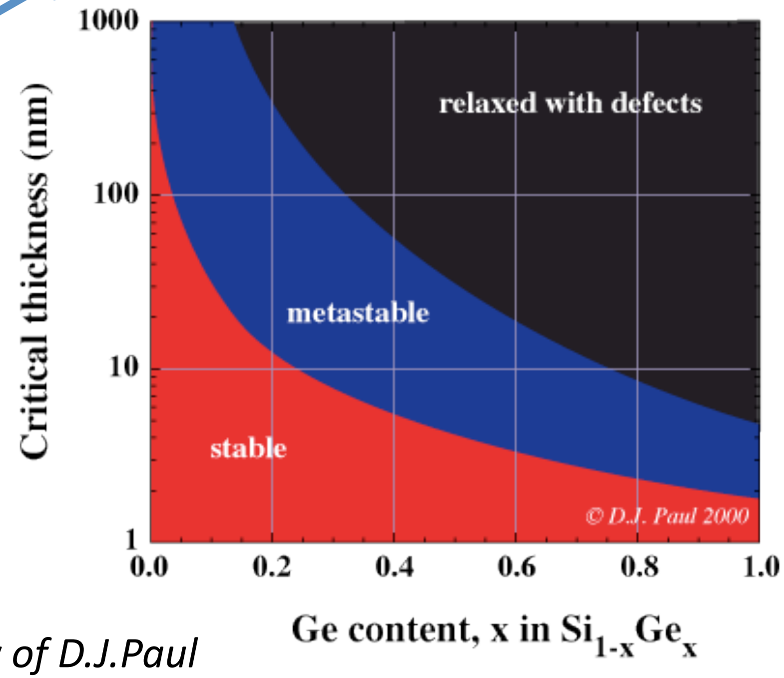


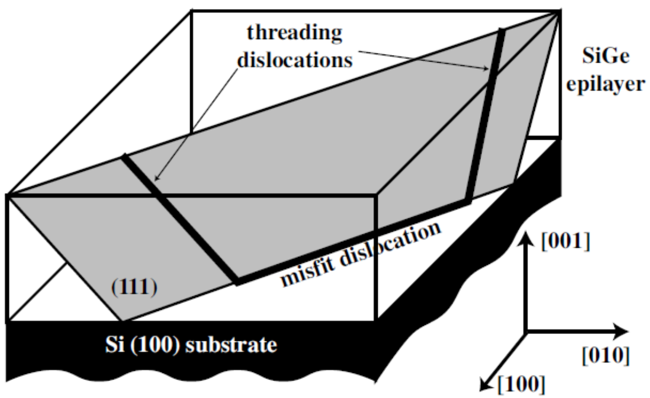


strain energy per unit area stored in the heteroepitaxial layer is :

$E_{\varepsilon} = h\, Y\, \varepsilon^2$ h = film thickness

Y = biaxial modulus

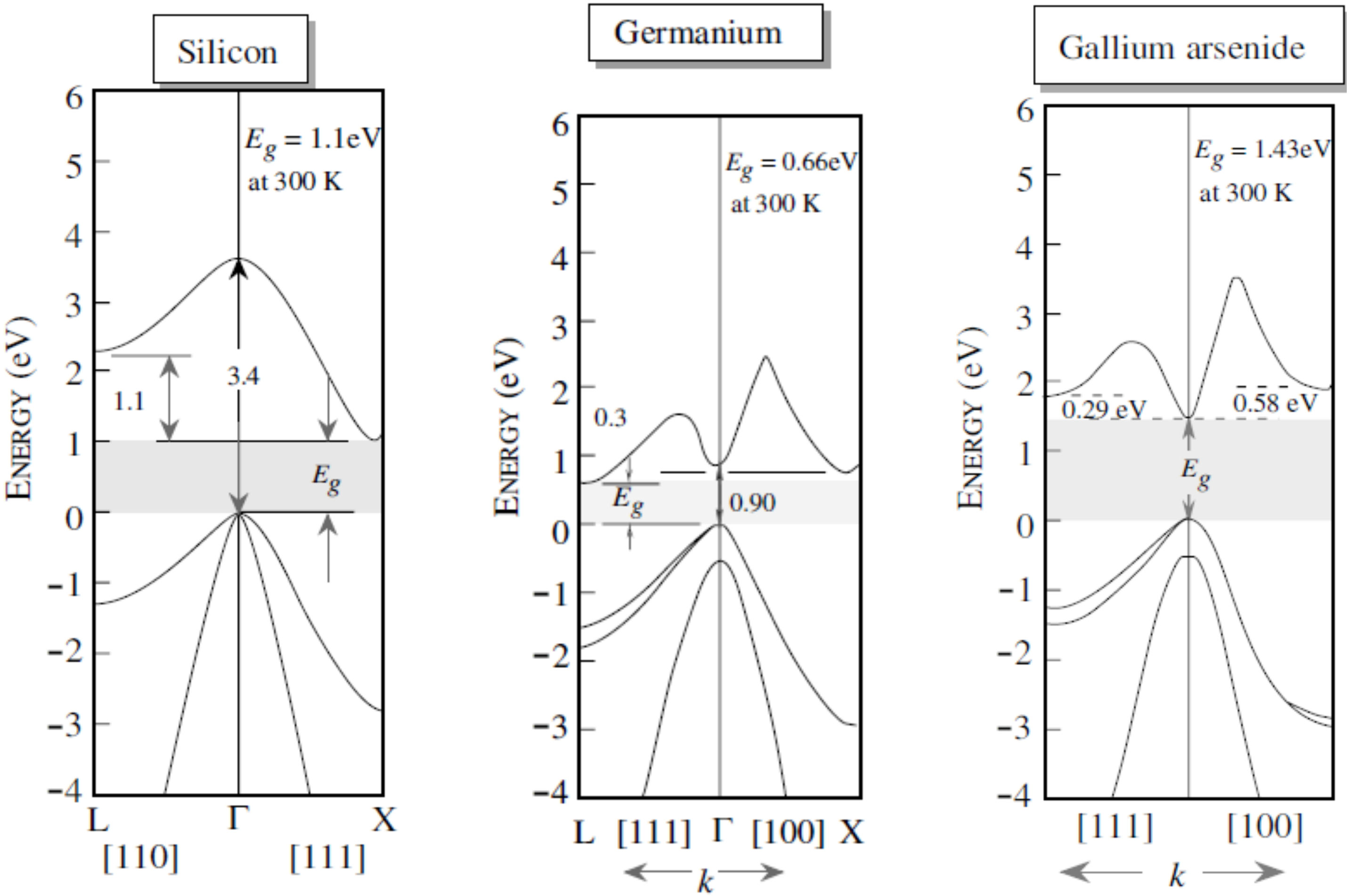




Courtesy of D.J.Paul

Bulk bandstructures

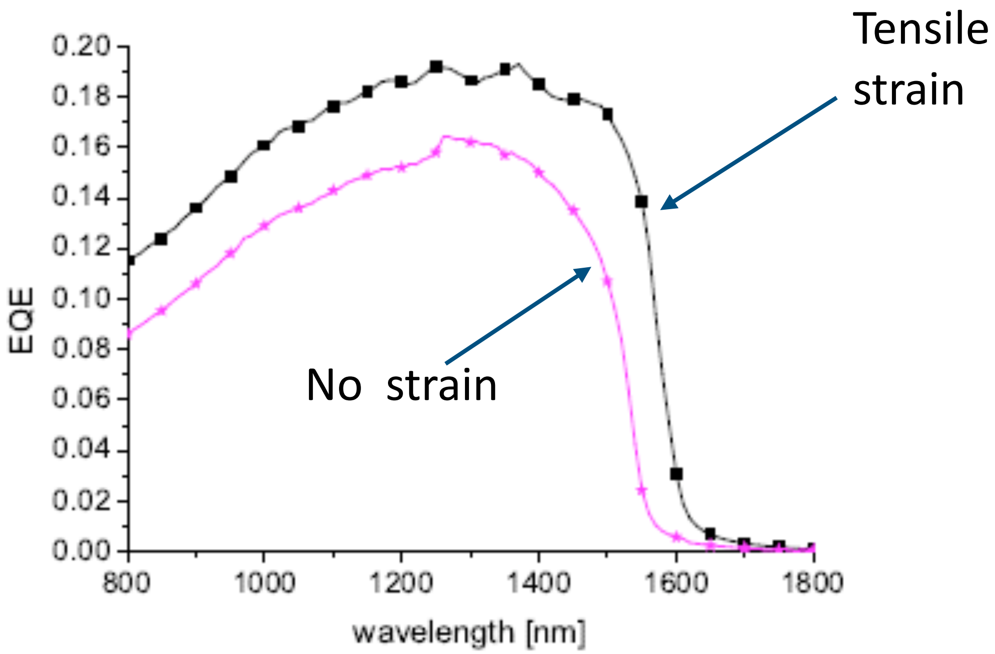
13 Al	14 Si	15 P
31 Ga	32 Ge	33 As

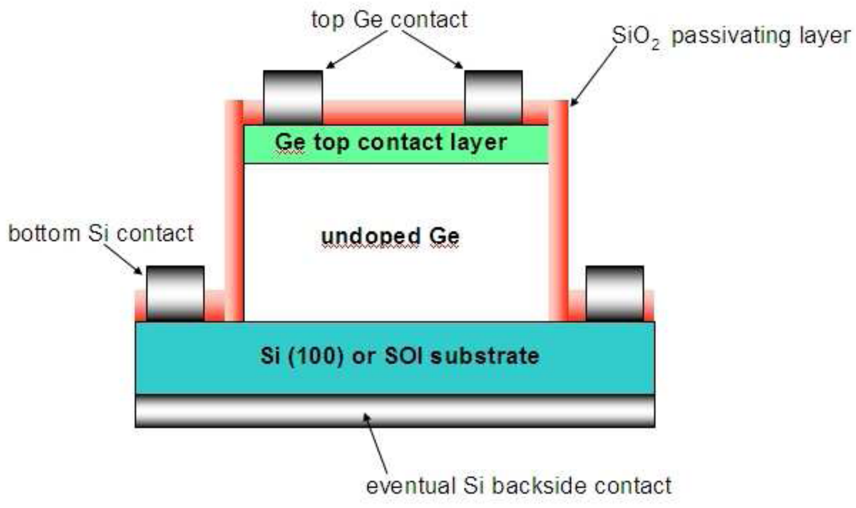


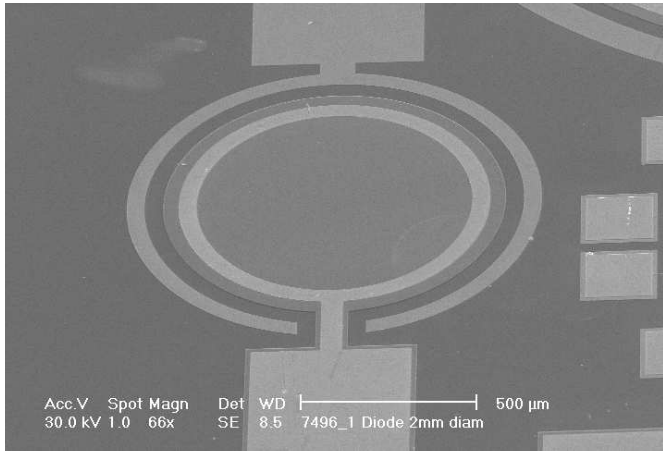
fabio.isa@mail.polimi.it

Ge-on-Si photodiodes

Ge features a good responsivity at 1550nm which can be further enhaced by means of a small tensile strain (0.1%) reducing the direct gap



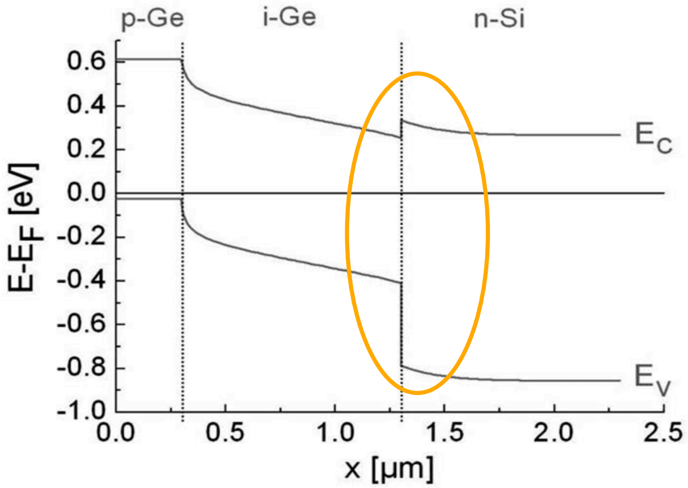


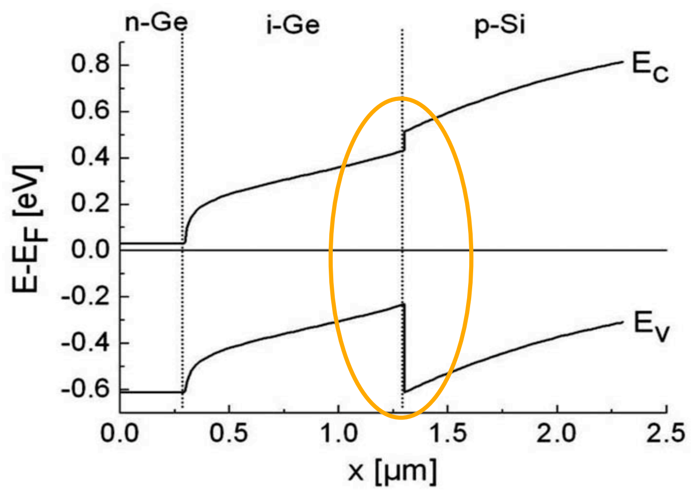


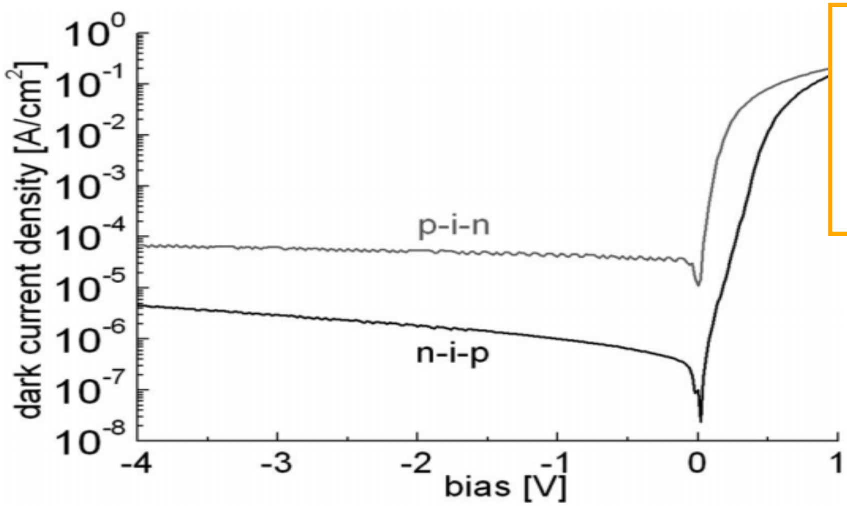
J. Osmond et. al. *Thin Solid Films* **517**, 380 (2008).
G. Isella et. al. *Semicond. Sci. Technol.* **22**, S26 (2007).

Ge-on-Si photodiodes p i n versus n i p structure

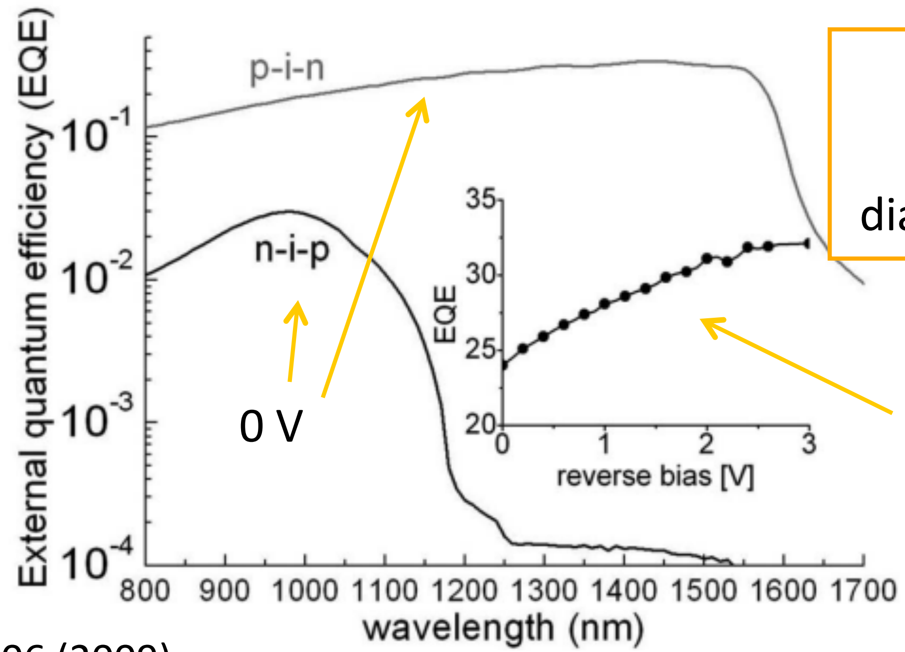
Band alignment







Dark current for 3mm diameter diode

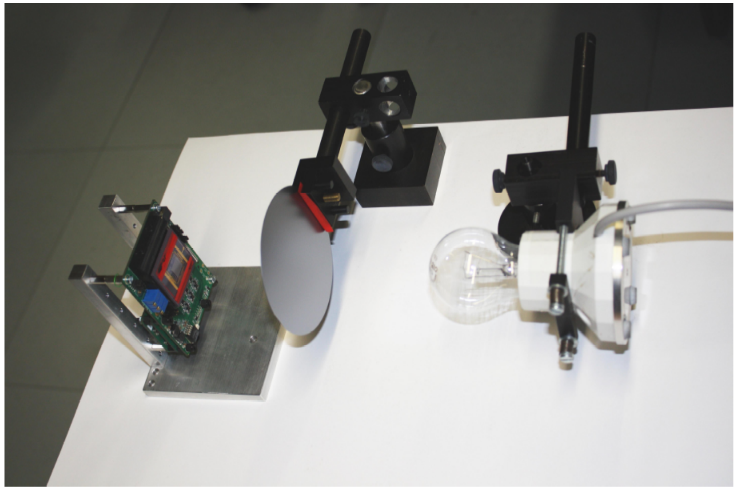


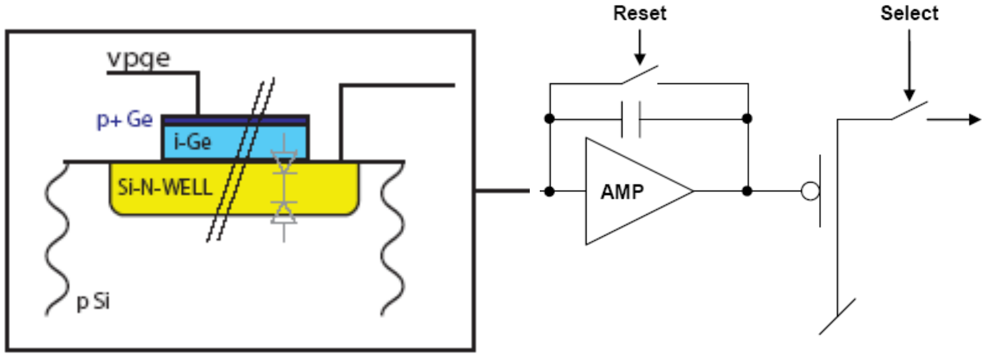
EQE for 3mm diameter diode

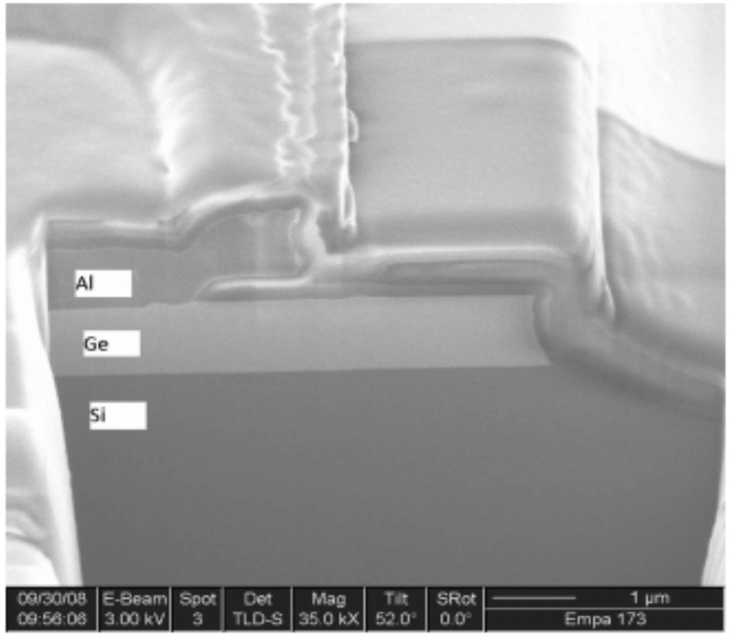
J. Osmond et. al. *Appl. Phys. Lett.* **94**, 201106 (2009).

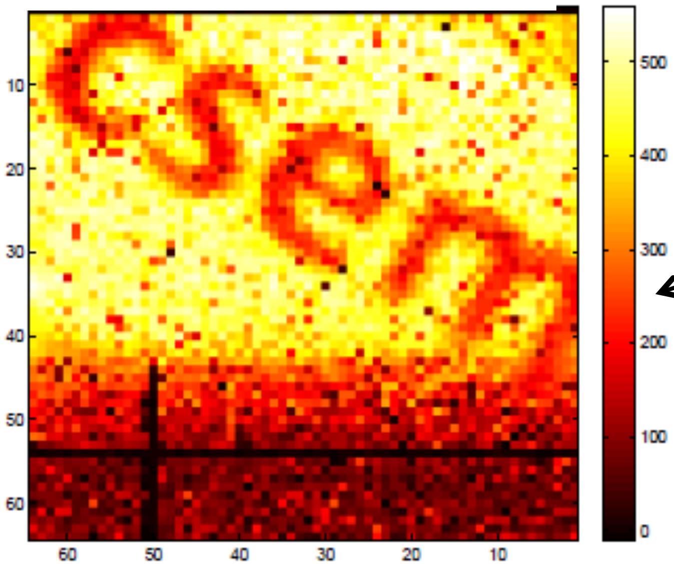
Ge-on-Si infrared camera

The low temperature and the low thermal budget annealing employed in the deposition are compatible with front end CMOS processing









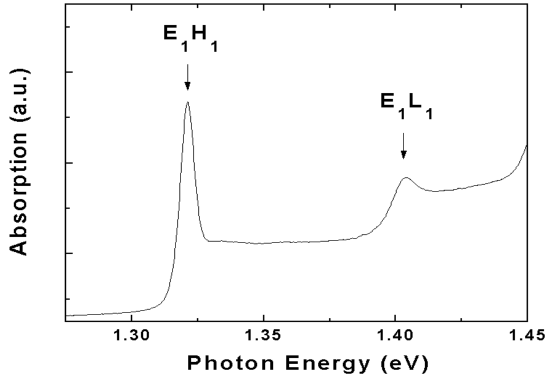
64x64 pixels of 150µm, operating voltage is 5V, operating current is 50mA

R. Kaufmann et al, J. Appl. Phys. **110** (2) 023107 (2011)

SiGe MQWs for optoelectronic applications

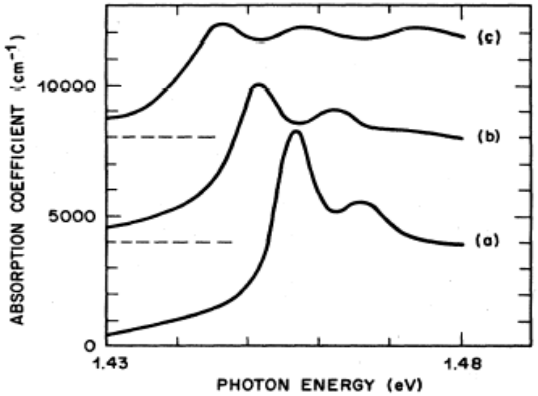
'80s and '90s III-V QWs

Excitonic peaks at RT



$In_{0.2}Ga_{0.8}As/GaAs$ (8nm/15nm)×15
G.S. Solomon and J.S. Harris (Stanford EE)

Quantum confined Stark effect



GaAs/AlGaAs
D. A. B. Miller, D. S. Chemla *et al.* Phys. Rev. *B 32, 1035 (1985)*

nature Vol 437|27 October 2005|**doi:10.1038/nature04204**

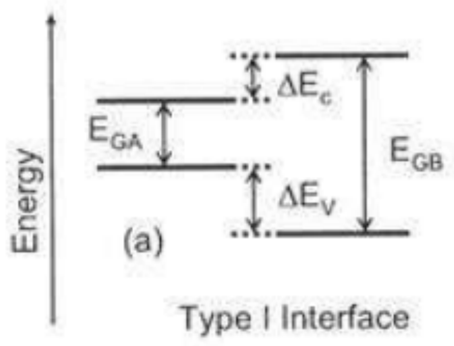
LETTERS

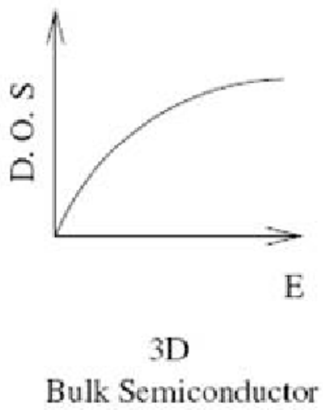
2005

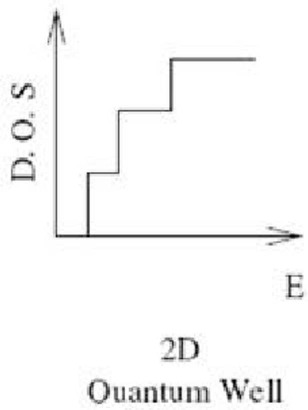
Strong quantum-confined Stark effect in germanium quantum-well structures on silicon

Yu-Hsuan Kuo[1], Yong Kyu Lee[1], Yangsi Ge[1], Shen Ren[1], Jonathan E. Roth[1], Theodore I. Kamins[1,2], David A. B. Miller[1] & James S. Harris[1]

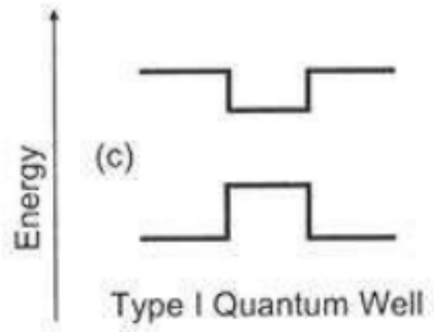
SiGe MQWs – electronic properties

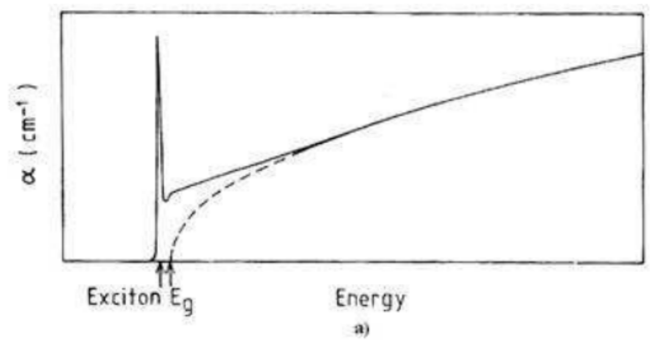


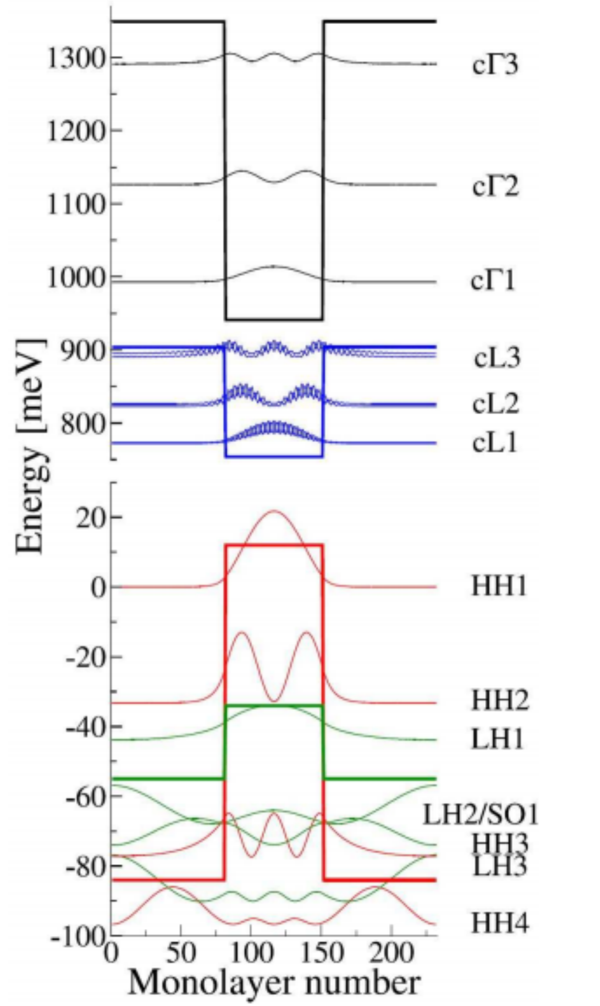




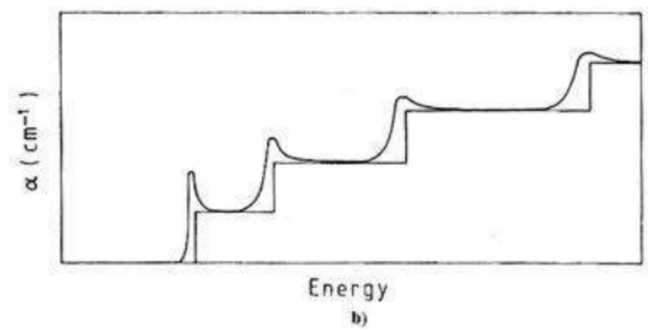
LEPECVD Ge QWs band structure





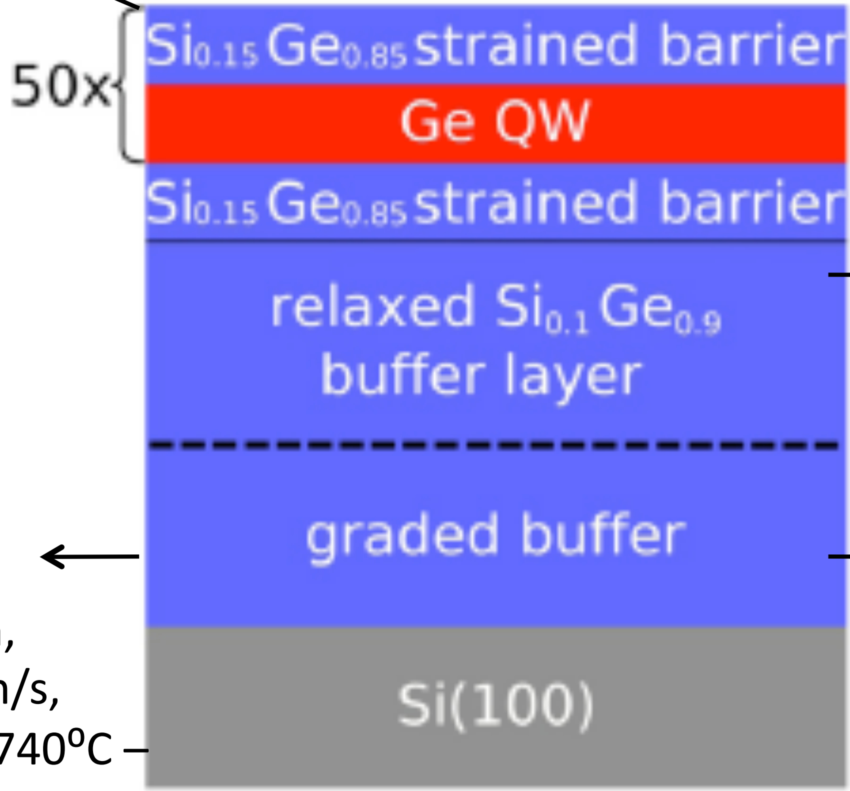


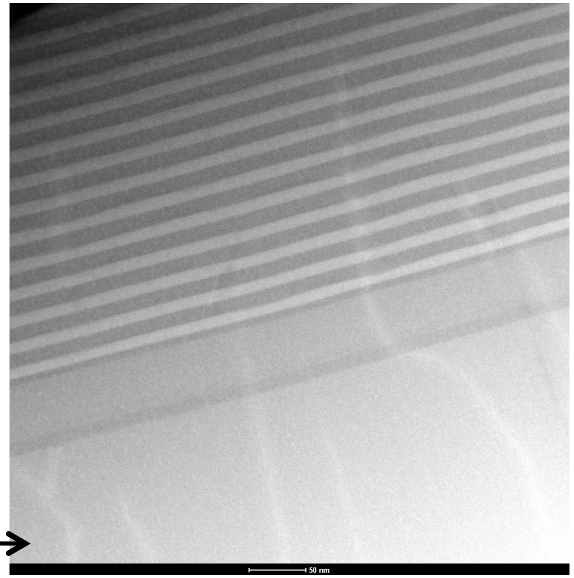
Carriers are free to propagate along the x-y directions. Both electrons and holes are confined in the z direction, due to band alignment.

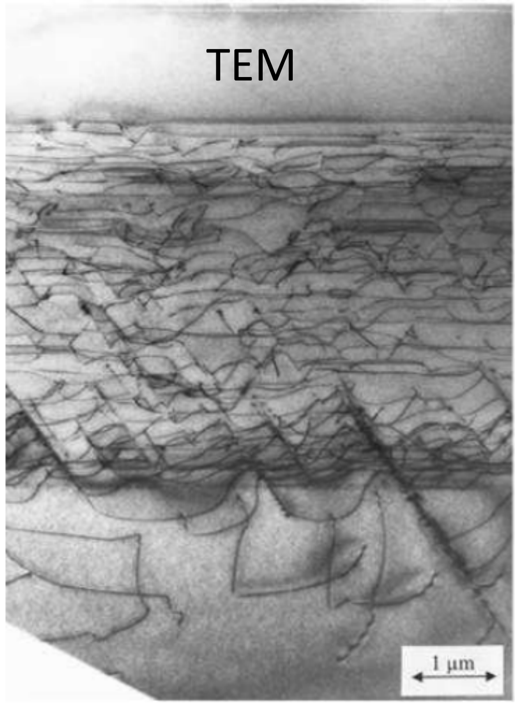


SiGe MQWs – growth procedure

Nominally 14.2nm Ge well,
19.8nm $Si_{0.15}Ge_{0.85}$ barrier Growth rate 0.1nm/s,
Growth temperature 500°C



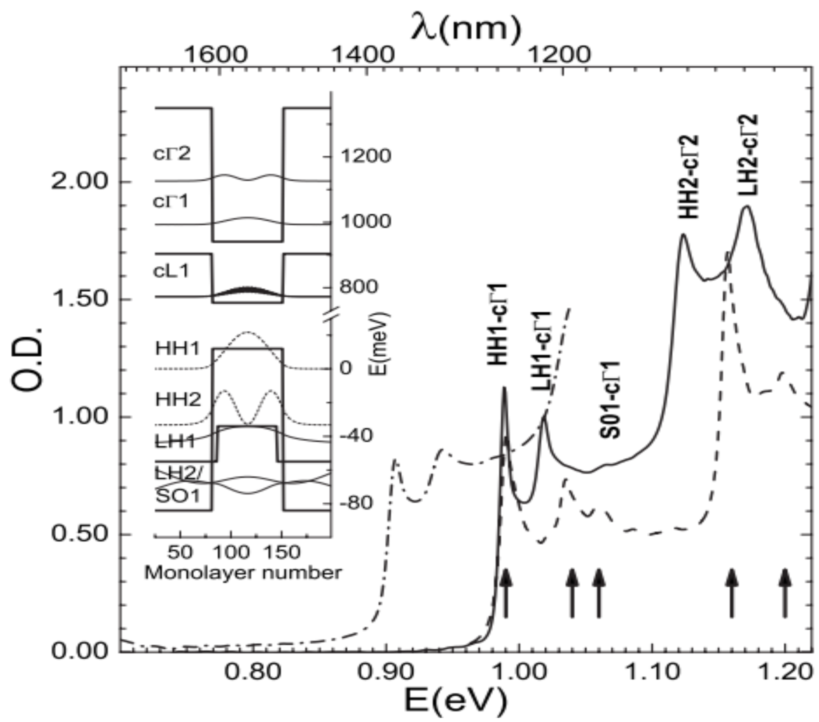


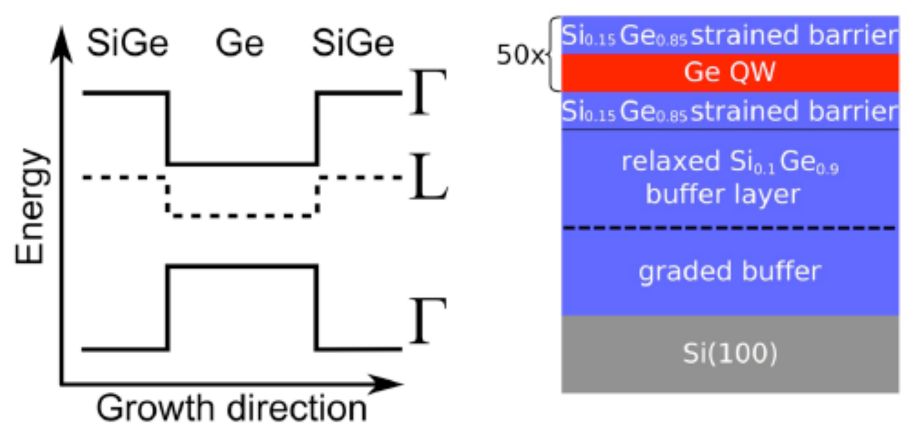


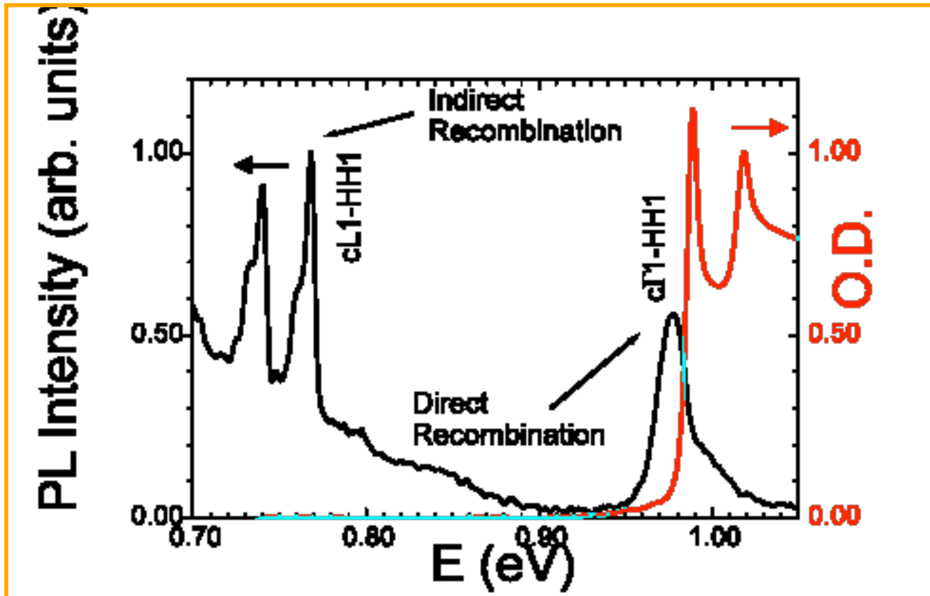
From Si to $Si_{0.1}Ge_{0.9}$
Grading rate 7%/µm,
growth rate 4-10nm/s,
Temperature range 740°C – 520°C

Ge MQWs - optical properties

Absorption properties are dominated by the direct gap confined states. Indirect gap states can be probed by PL





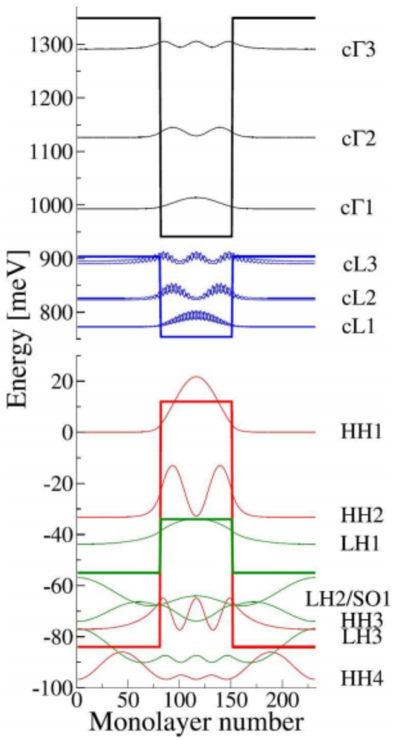


PL and transmission measurements M. Guzzi,Unimib

M. Bonfanti *et. al. Phys. Rev. B* **78**, 041407(R) (2008

M. Bonfanti et. al. Physica E **41**, 972 (2009). M. Virgilio et. al. *Phys. Rev. B* **79**, 075323 (2009)

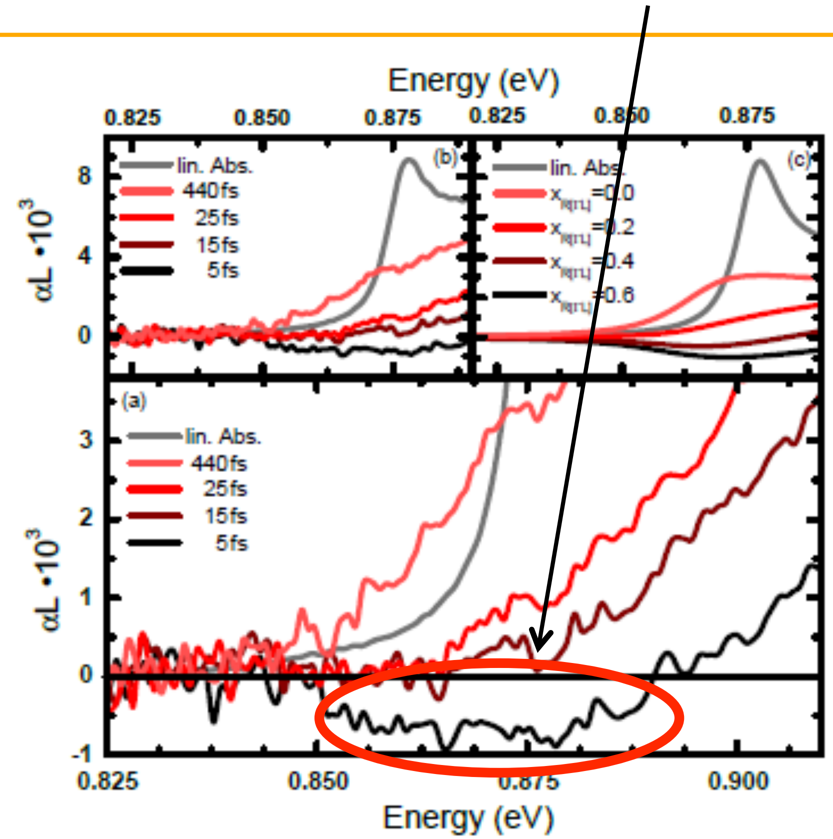
Ge MQWs – transient gain



Ge MQWS

band structure

Pump-probe experiments show transient population inversion at the direct band gap

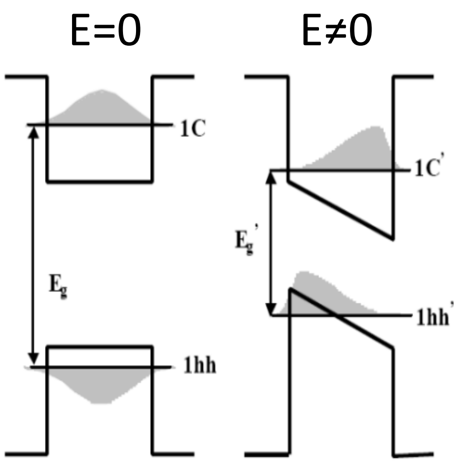


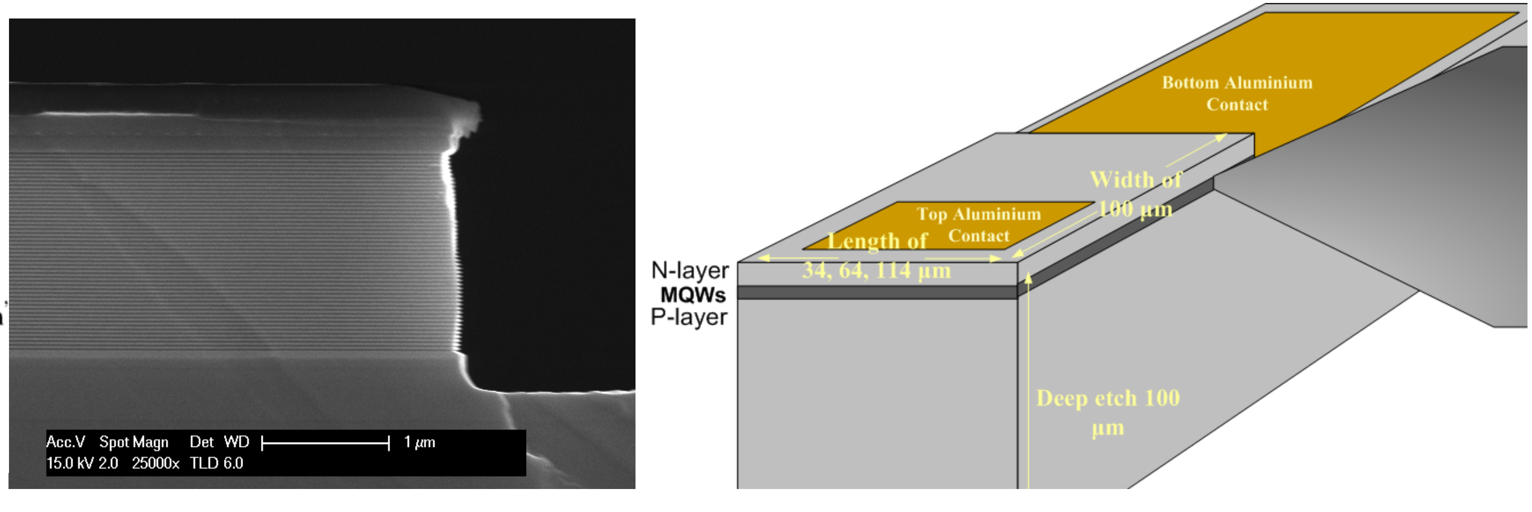
Pumping at the HH1-CΓ1 transition , pumping time is 80fs, photon density is 2.5* 10^{19} cm $^{-2}$!!
The absorption is probed by white light.

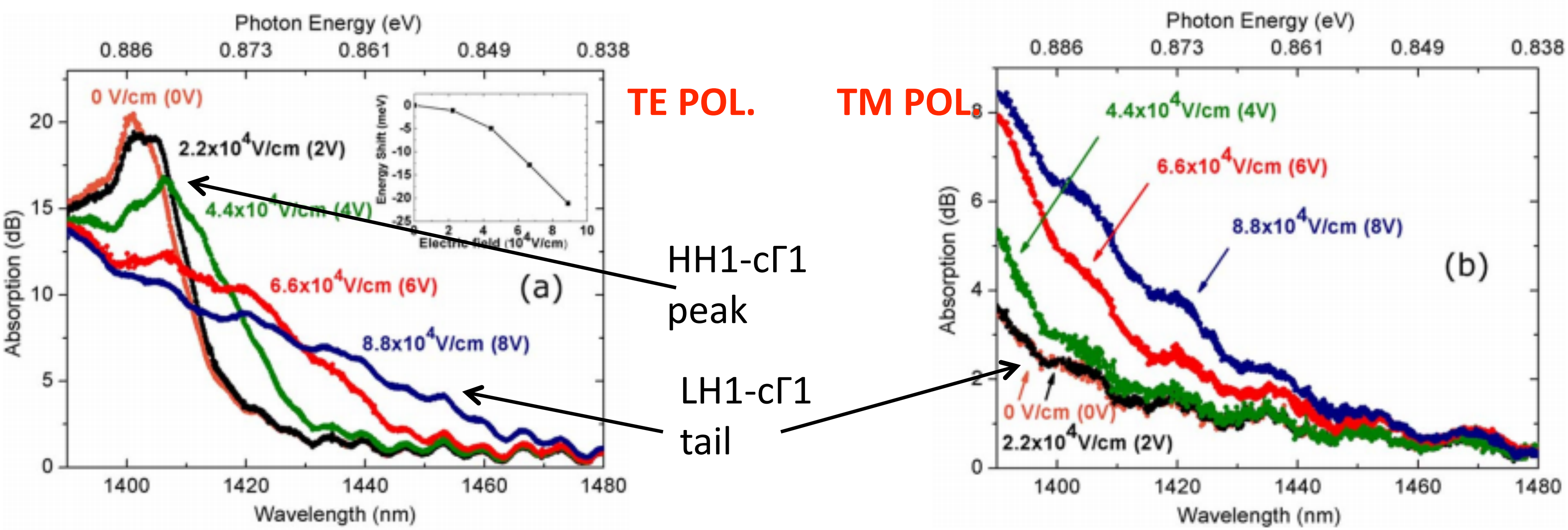
P. Chaisakul et al , Phys. Rev. B **79**, 201306(R) (2009).
P. Chaisakul et al ,Phys. Rev. B **81**, 045320 (2010).

P-p by S. Chatterjee – Marburg Uni

Quantum confined Stark effect modulators

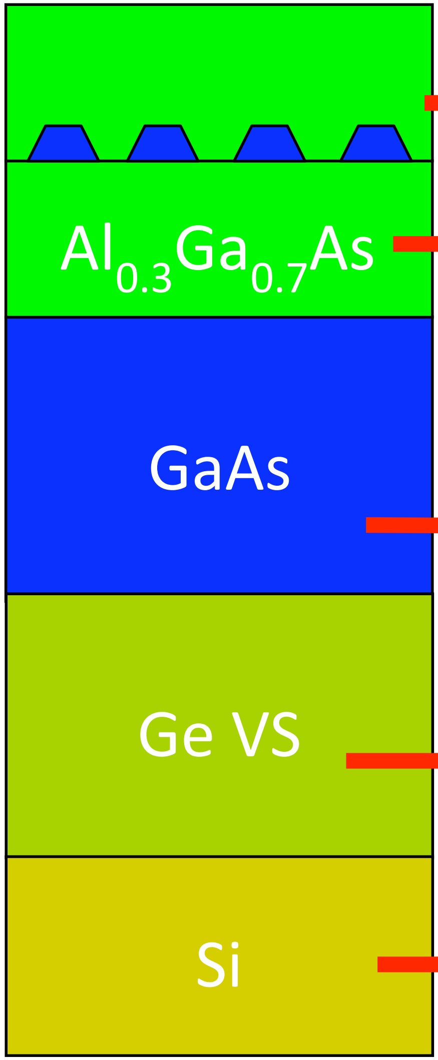






Optics Lett. **35**, 2913 (2010).   Device fabrication and measurements D. Marris-Morini – UPS Paris

Ge for III-V integration on Si



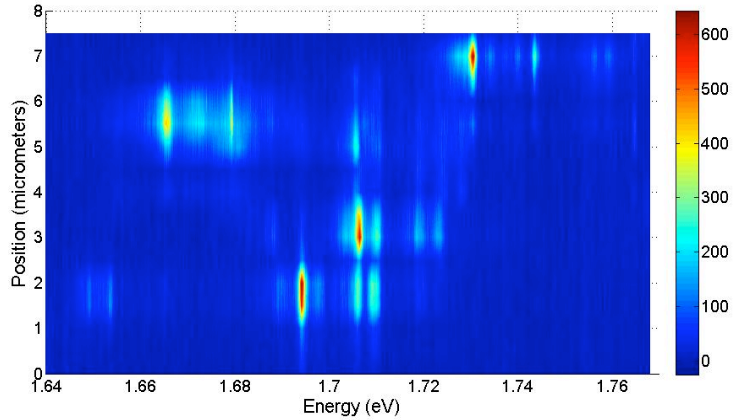
GaAs Nanostructures grown by Droplet Epitaxy

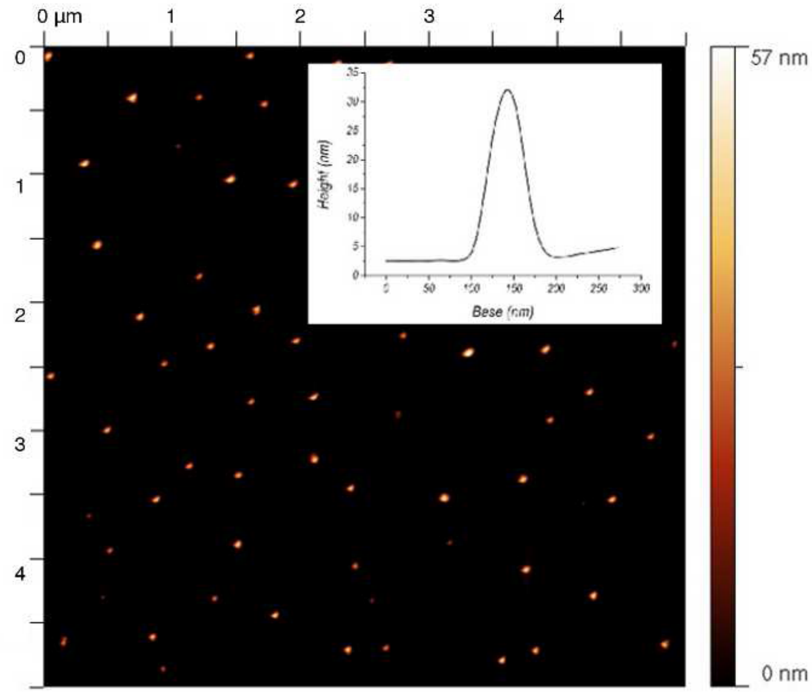
$Al_{0.30}Ga_{0.70}As$ barrier layer grown by MBE at 350 °C

1 µm GaAs growth at 580°C Anti-Phase Domain free

2 µm Ge growth at 500 °C by LEPECVD - thermal cycles 600-780 °C to reduce TDD

Si(001) substrate miscut 6° toward [110]





fabio.isa@mail.polimi.it

Conclusions

- The LEPECVD growth technique allows to obtain SiGe heterostructures with high optical performances
- Tunable pin and nip Ge photodiodes with ultralow dark current
- Ge infrared cameras
- Optical gain at the direct gap
- QCSE elettro-optical modulators
- High quality Ge for the III-V integration on Si

fabio.isa@mail.polimi.it