Stress relaxation and dopant activation in nsec laser annealed SiGe

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Université de Toulouse

Outline

1. Background
   - *Interest for nsec Laser Thermal Annealing*
   - *Basic LTA properties*
   - *Early studies*
2. nsec laser annealing of SiGe
   - *Melt regimes*
   - *Surface melt*
   - *Defect formation and stress relaxation*
   - *Impact of B doping on stress relaxation*
3. Conclusion

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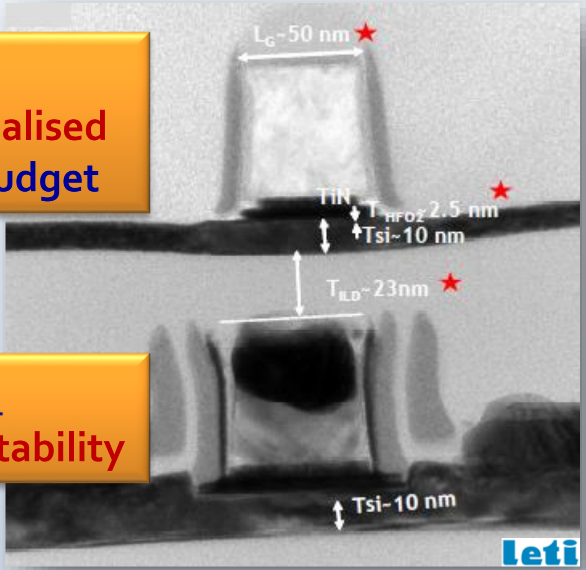
Today: Laser annealing for advanced nanoelectronic devices

3D integration (CoolCube™)

Top FET:
- **Low or localised thermal budget**

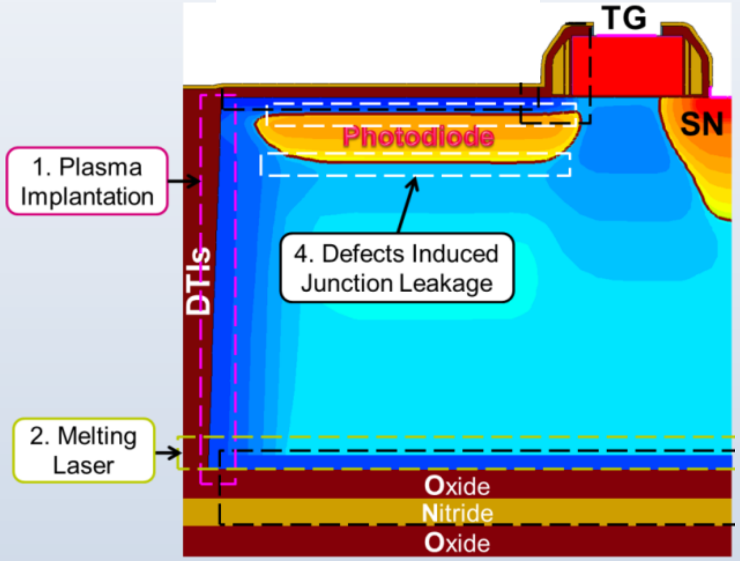
Bottom FET:
- **Thermal stability**



P. Batude et al., IEDM 2011

- High dopant activation
- Surface confined heating

CMOS imagers



F. Roy et al., Phys. Stat. Sol. C, 2014

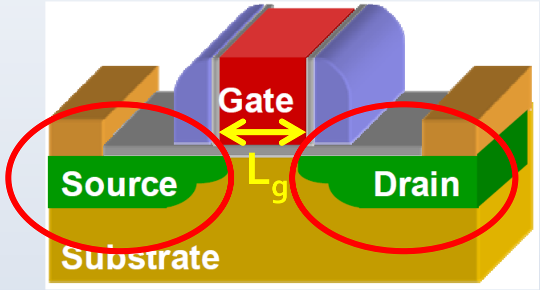
- Backside Si/SiO_2 interface Passivation

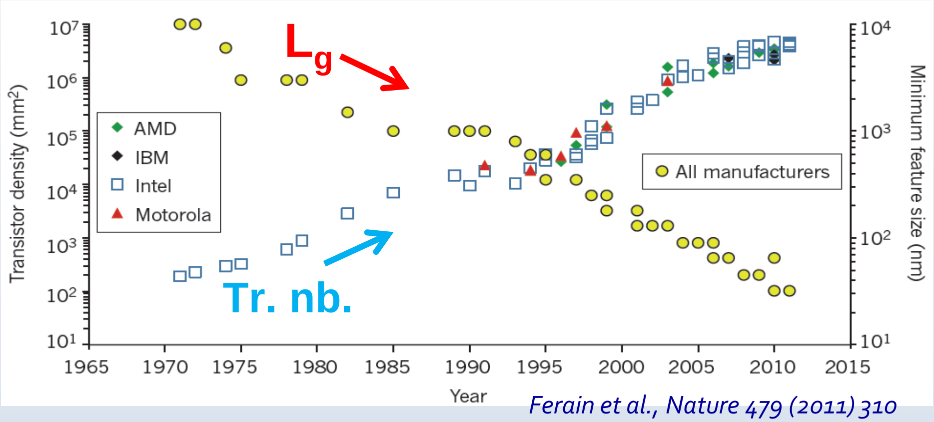
- Solar cells: optimised different annealing of p^+ and n^+ emitters

X. Yang et al., En. Procedia, 2014

History: I² for ultra-shallow S/D junctions

MOSFET scaling





Ferain et al., Nature 479 (2011) 310

The S/D USJs roadmap

- Reduce junction depth
- Reduce resistance

$$R_S = \frac{1}{q.\mu.N_A.x_j}$$

Technology solutions

- Improved implant methods
  - Ultra Low Energy implants
  - Plasma doping
  - pre-amorphisation
- Improved annealing methods
  - high temp (up to *melt*)
  - fast anneals (down to *nsec*)
  - Low temp. SPER
- Strain engineering
  - high μ materials (*SiGe, s-Si…*)
  - process induced strain

Laser Thermal Annealing (LTA)

Technology solutions

- Improved implant methods
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  - Plasma doping
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91125

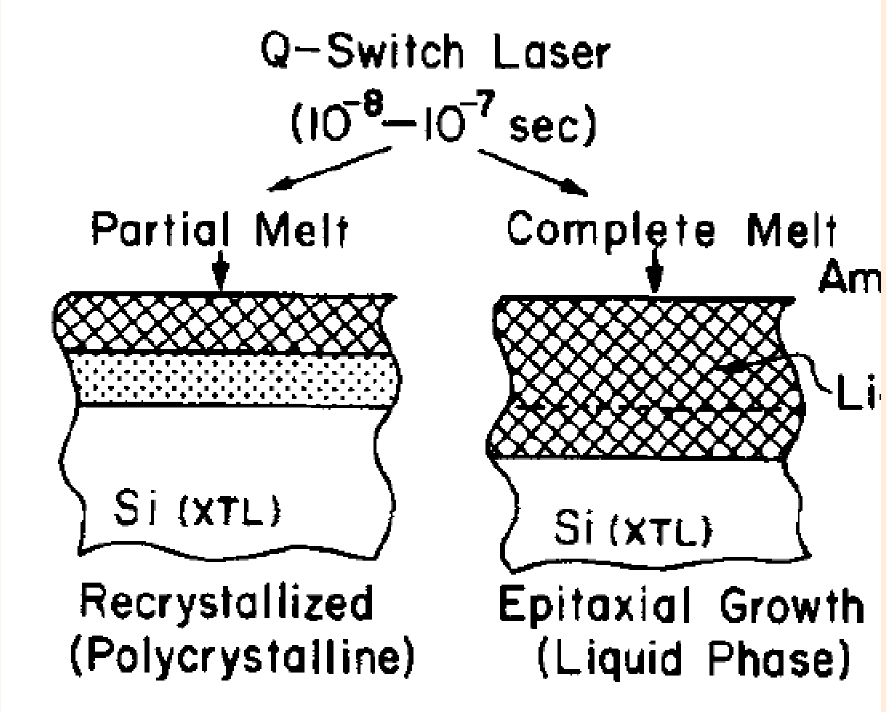


Fig. 6 Schematic representation of the general features of laser annealing for recrystallization of implanted-amorphous silicon.

There has ... pulsed electro... and vacuum deposit... apers published in t... ish- ed in the Cata... emi- conductors" an... rials Research Society. Interest in laser annealing was enhanced by the

Solid Phase Epitaxial Regrowth

IEEE Transactions on Nuclear Science, Vol. NS-30, No. 2, April 1983

EFFECTS OF LOW TEMPERATURE ANNEALING OF $B^+ + Si^+$

Introduction

Technology solutions

- Improved implant methods

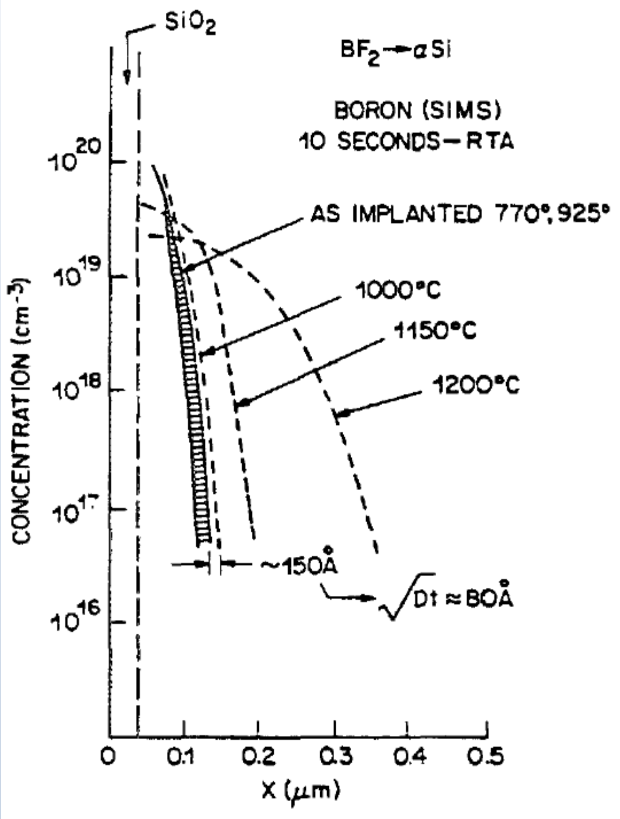
So who won the war, LTA or SPER ?

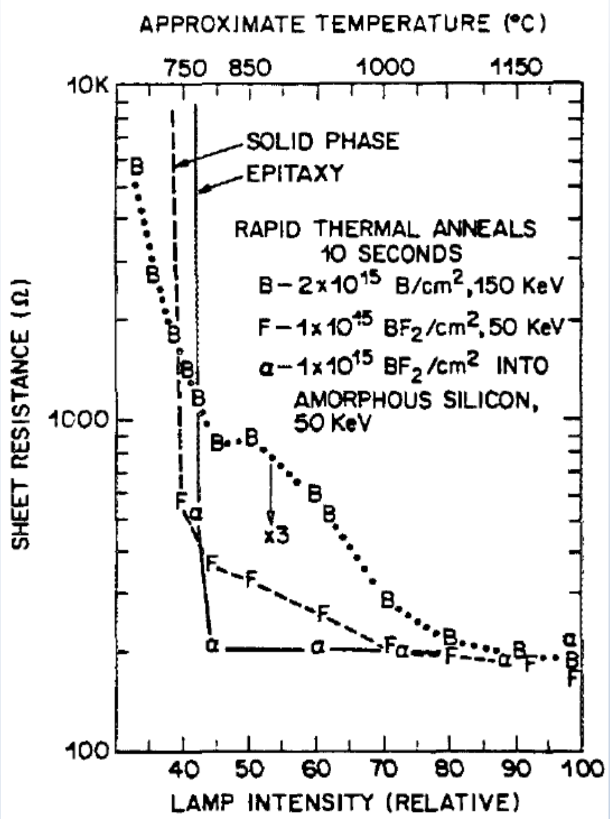
Advantages

- Ability to localise the defects far from the dopants
- Activation above solid solubility

Ref 3: Lau et al, proc. of the « Laser-Solid Interactions and Laser Processing » conf. 1978, published in AIP Conf Proc.1979

Low T SPER or LTA ? None of them…RTA !





- RTA helped to reduce TED wrt to furnace anneals
- Combined with PAI, it provides the best activation levels

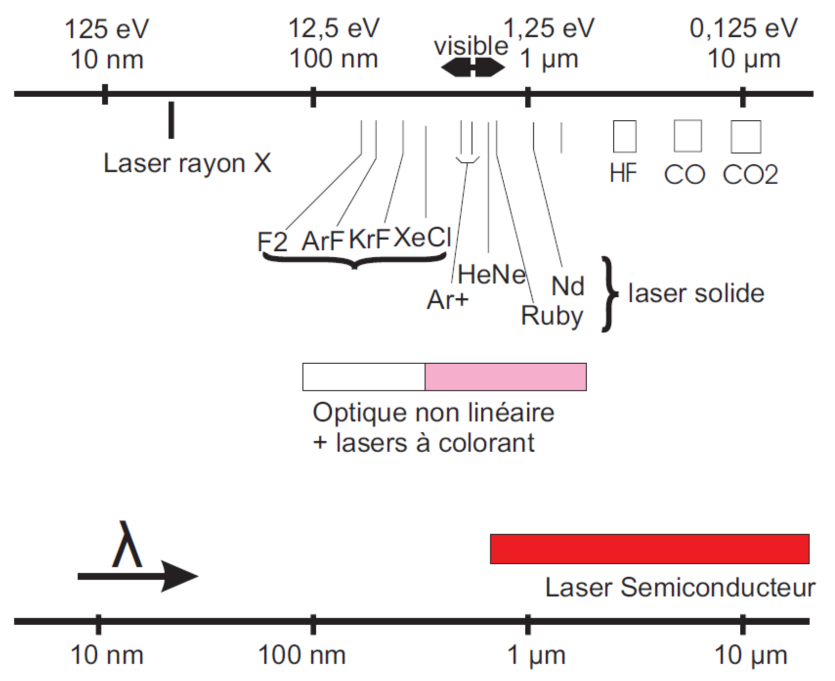
Seidel et al., IEEE-EDL 1983, JAP 1985

Laser Thermal Annealing (LTA)

Table 1: Energy pulse methods for short time annealing

Energy source	Temperature pulse duration	Power
fs-laser	1 ps	1 TW
ps-laser	50 ps	1 GW
ns-laser	50 ns	50 MW
Free running pulse laser	100 µs	10 KW
CW-laser	1...10 ms	10 W
Flash lamp	1…10 ms	100 KW
Arc lamp	5 s	100 KW
Halogen lamp	1....30 s	
Ion pulse	140 ns	200 keV
CW-Electron beam	10 ms	10 KW
Electron pulse	50 ns	10 MW

Materials Science Forum Vols. 573-574 (2008) pp 237-256
Online available since 2008/Mar/24 at www.scientific.net
© (2008) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/MSF.573-574.237



M. Hernandez, PhD, Univ. Paris, 2005

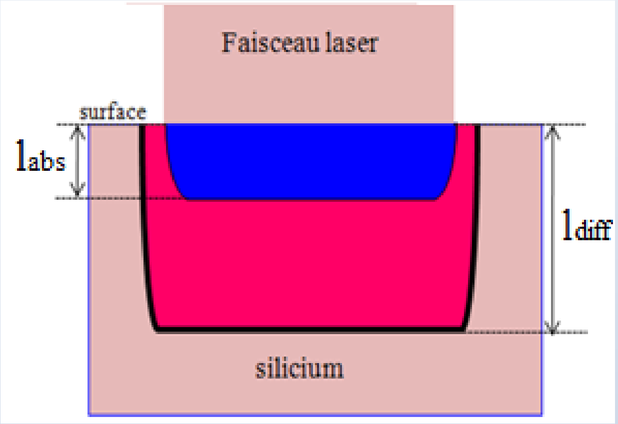
Pulse duration → Power → Heat Flow density

→ Temperature increase

Wavelength → Absorption

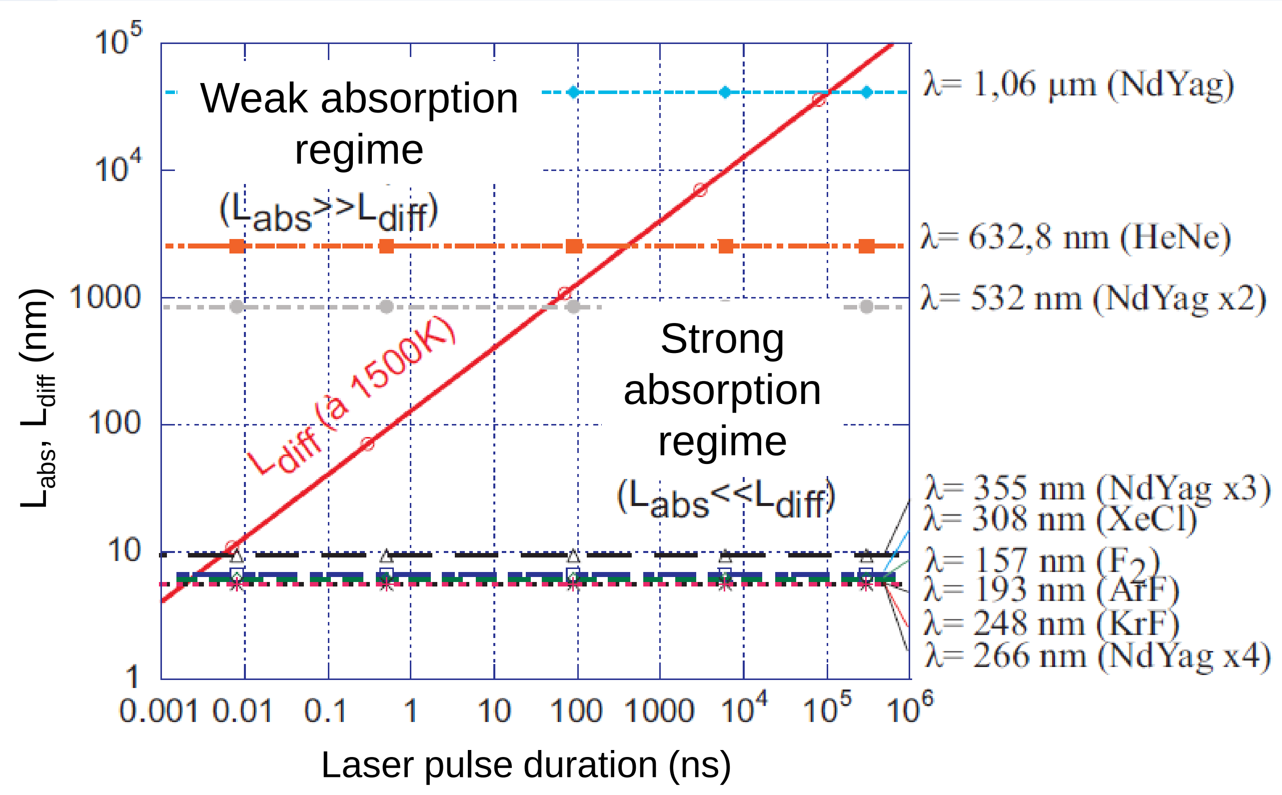
→ Penetration depth

Laser Thermal Annealing (LTA)



$$l_{abs} = \frac{1}{\alpha\ (\lambda)}$$

$$l_{diff} = \sqrt{2D\tau}$$



Strong absorption regime corresponds to optimum conditions for effective doping

Dopant activation in Melt LTA of Si

ELECTRICAL PROPERTIES OF LASER ANNEALED SILICON

J. L. Benton, L. C. Kimerling, G. L. Miller, D. A. H. Robinson
Bell Laboratories, Murray Hill, New Jersey 07974

G. K. Celler
Western Electric Engineering Research Center
Princeton, New Jersey 08540

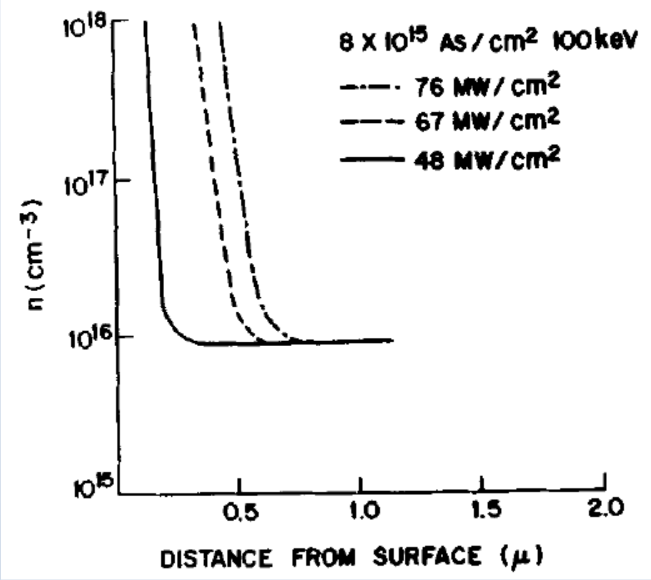


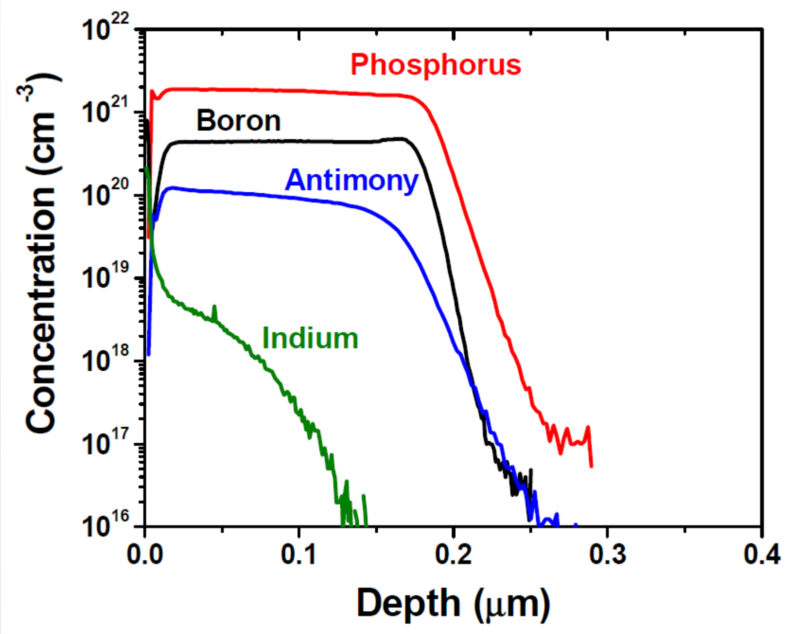
Fig. 1. Spreading resistance profiles of angle lapped samples which were ion implanted and annealed at increasing laser powers.

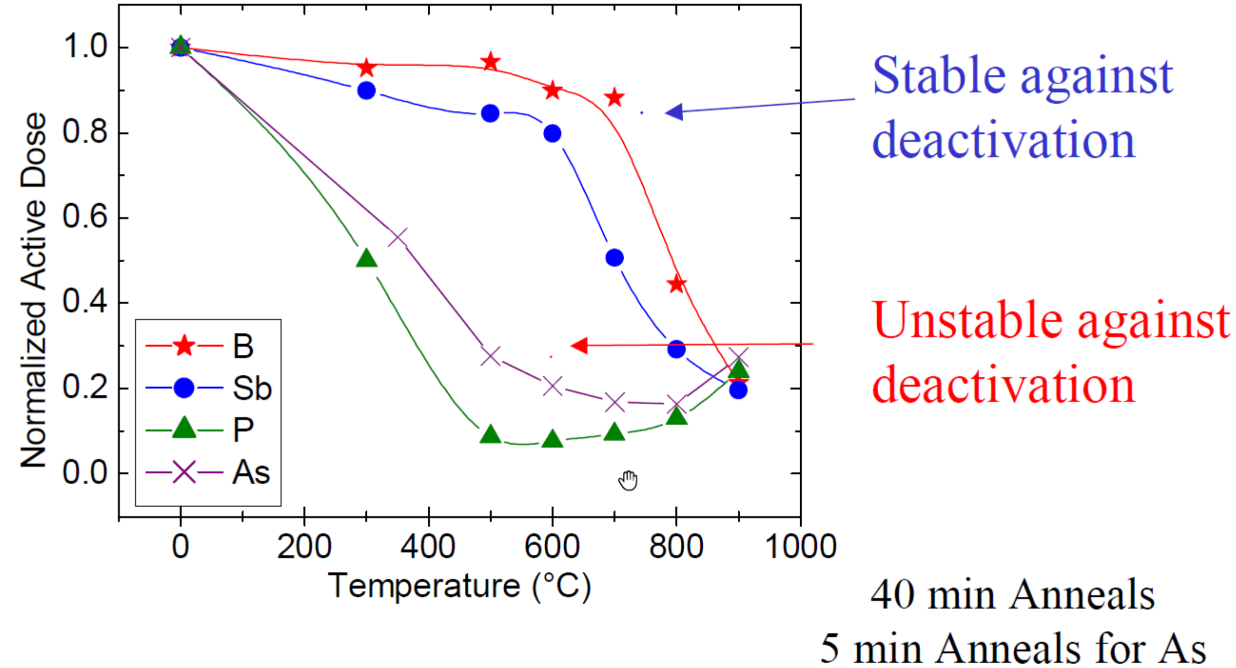
Junction depth increases with laser energy, in agreement with the increased melt depth

Metastable activation by Melt LTA

Thermal stability of dopants in laser annealed silicon

Y. Takamura,[a] S. H. Jain, P. B. Griffin, and J. D. Plummer
Center for Integrated Systems, Stanford University, Stanford, California 94305



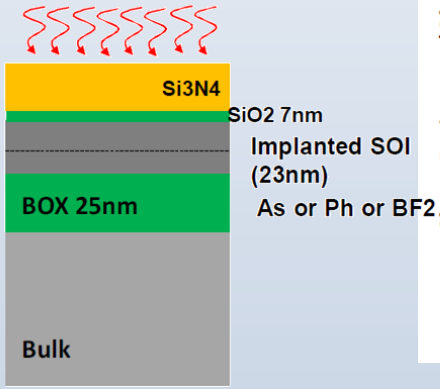


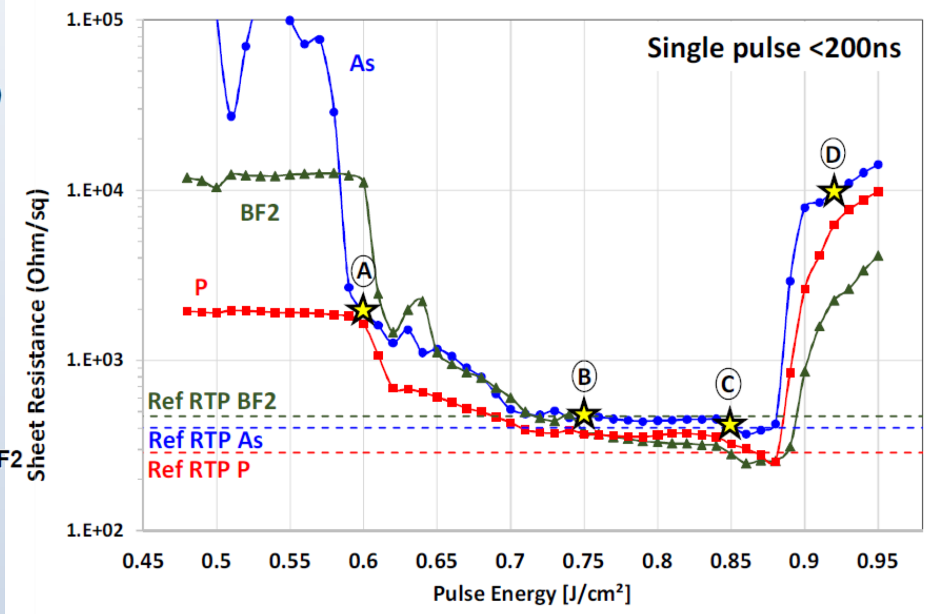
- P activation as high as 1x10^{21} cm^{-3} is achieved
- Vacancy-mediated mechanism is prposed to explain the fast P and As deactivation

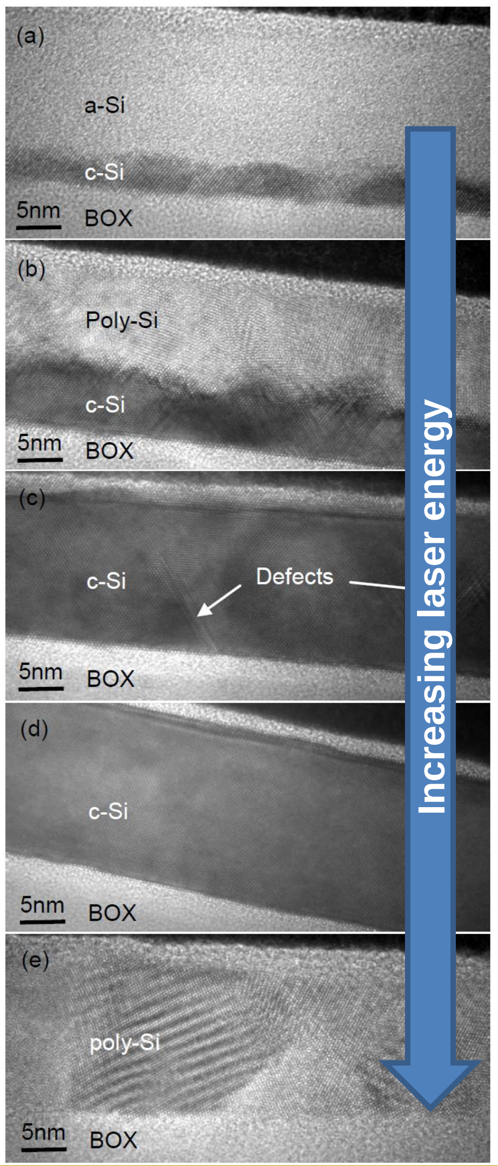
J. Appl. Phys., Vol. 92, No. 1, 1 July 2002

Dopant activation in Melt LTA of Si

- Si 12nm/ BOX 25 nm
- Si epitaxy → 23nm
- Implantation (As 1E15cm-2 9keV)
- SiO_2 capping (7nm, SACVD)
- Si_3N_4 capping (30nm, PECVD)
- ns LASER ANNEAL





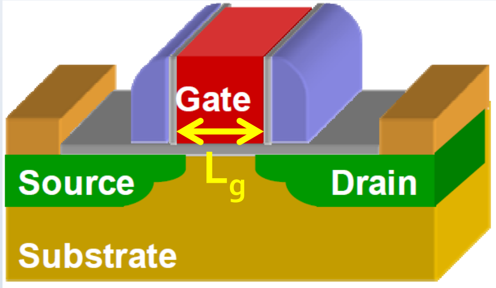


- LTA can crystallize and activate dopants in junctions as good as or better than RTP

[S. Kerdilès et al. IWJT 2016]

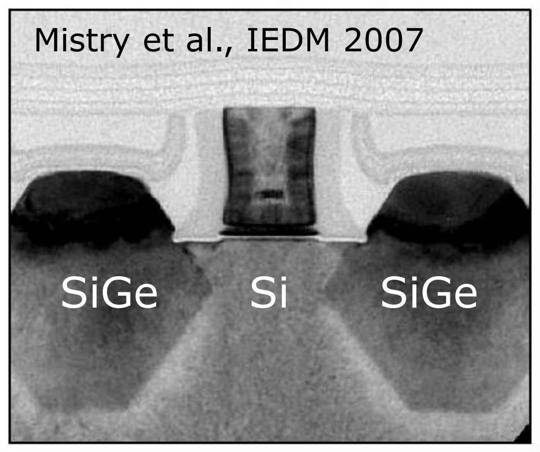
Integration of SiGe

Today: Increased complexity → (i) from planar to 3D – (ii) new materials



Planar

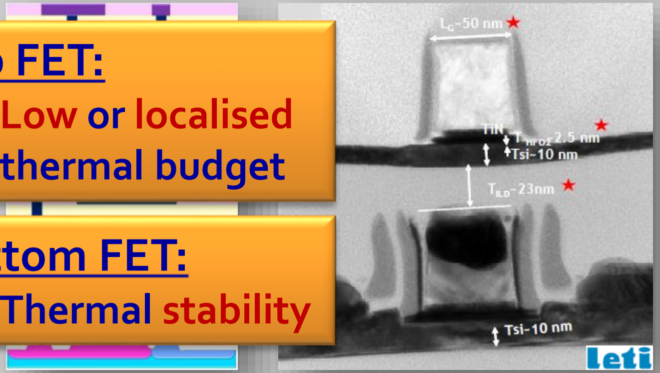
- **SiGe source/drain**



Alternative to scaling

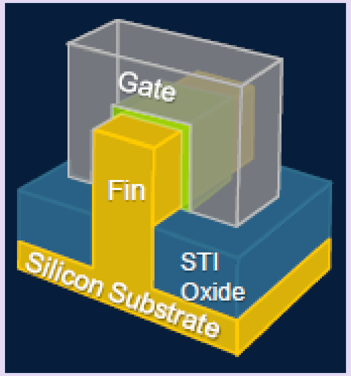
Top FET:
- Low or localised thermal budget

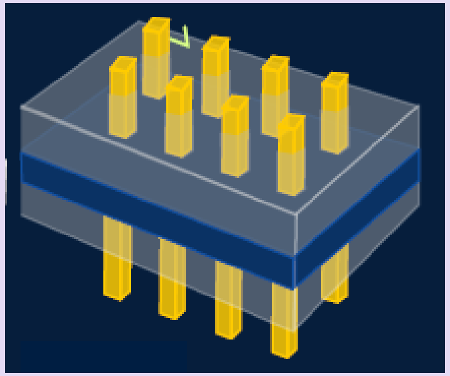
Bottom FET:
- Thermal stability



- **3D integration (Coolcube™)**

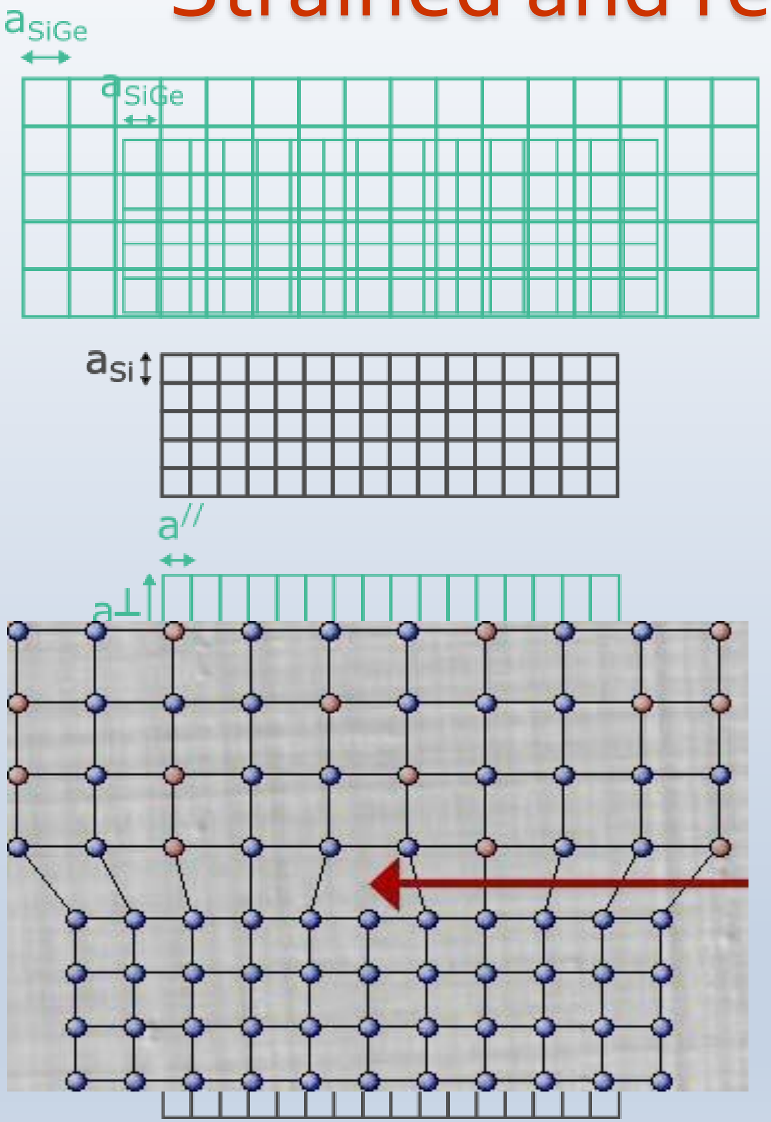
Non-planar





- **FinFETs, NWs (vertical or horiz.)...**

Strained and relaxed SiGe



SiGe alloys

- Diamond cristalline structure
- Lattice parameter

$a_{Si} < a_{SiGe} < a_{Ge}$

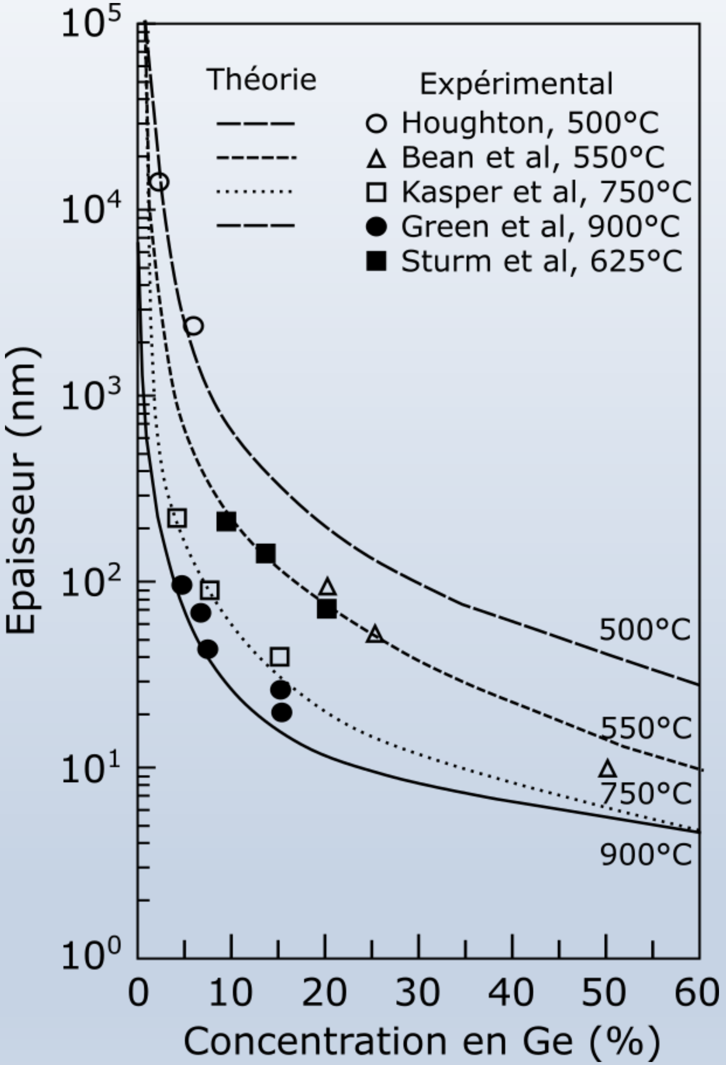
Grown by epitaxy (CVD, MBE…)

- Pseudomorphic growth
- Strained SiGe

$a_{//} = a_{Si}$

Elastic energy accumulation

- **Depends on thickness and Ge content**
- Relaxation occurs beyond a critical thickness



Houghton, Journal of Applied Physics 1991

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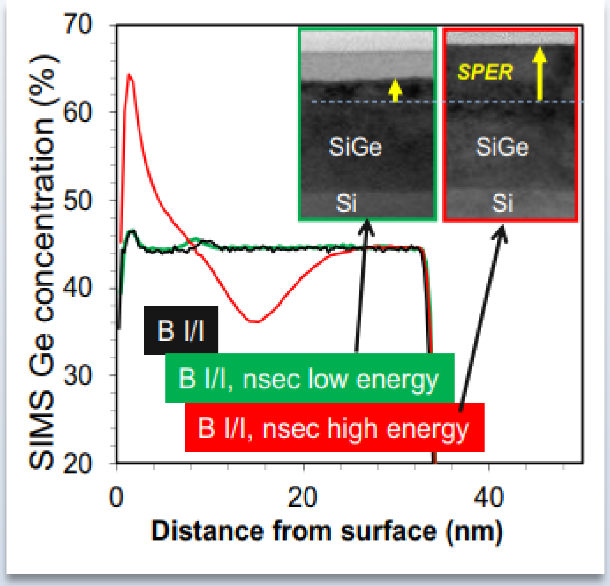
LTA of SiGe

The impact of UV-NLA on SiGe is not as well known as on Si

- NLA on SiGe ➔ beneficial for contact formation (1,2,3)
- Germanium segregation towards surface
  - Observed by several teams (3,4,5)
- Strain relaxation
  - Unclear



Chang et al., *IWJT* 2017

(1) Chang et al., IWJT 2017
(2) Gluschenkov and Jagannathan, *ECS Trans.* 2018
(3) Ni et al., *VLSI-TSA* 2016
(4) Ong et al., *Appl. Phys. Lett.* 2008
(5) Lombardo et al., *Mater. Sci. Semicond. Process.*, 2017

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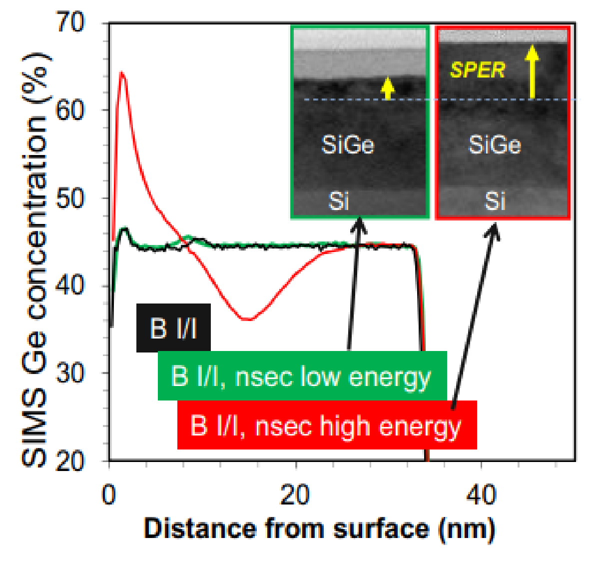

Chang et al., *IWJT* 2017

LASSE-SCREEN LT-3100 platform for UV-NLA

- **Present study**
  - Un-doped SiGe layers with varying content
  - Impact of UV-LTA on strain, available process windows
- **Laser : SCREEN LT3100 system**
  - Excimer laser (XeCl) with 308 nm wavelength
  - Pulse duration at 160 ns

SCREEN

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(1) Chang et al., IWJT 2017
(2) Gluschenkov and Jagannathan, *ECS Trans.* 2018
(3) Ni et al., *VLSI-TSA* 2016
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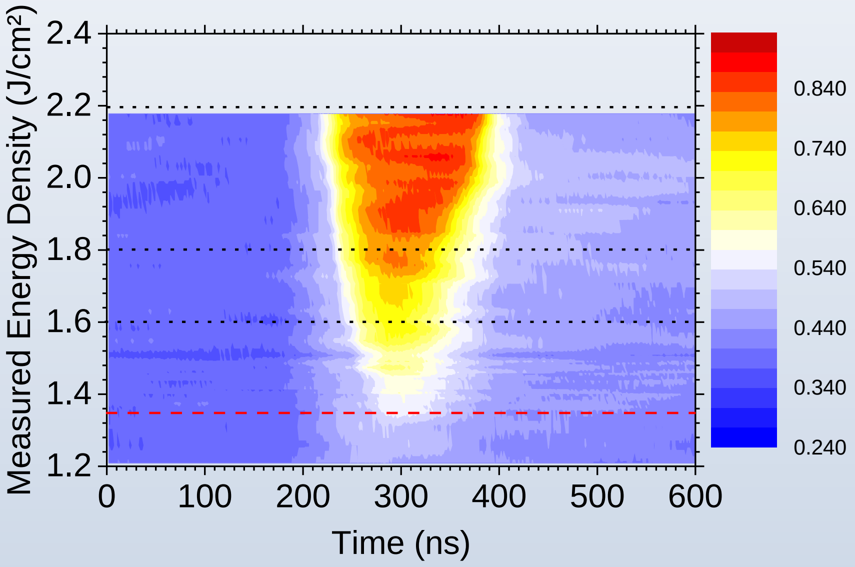
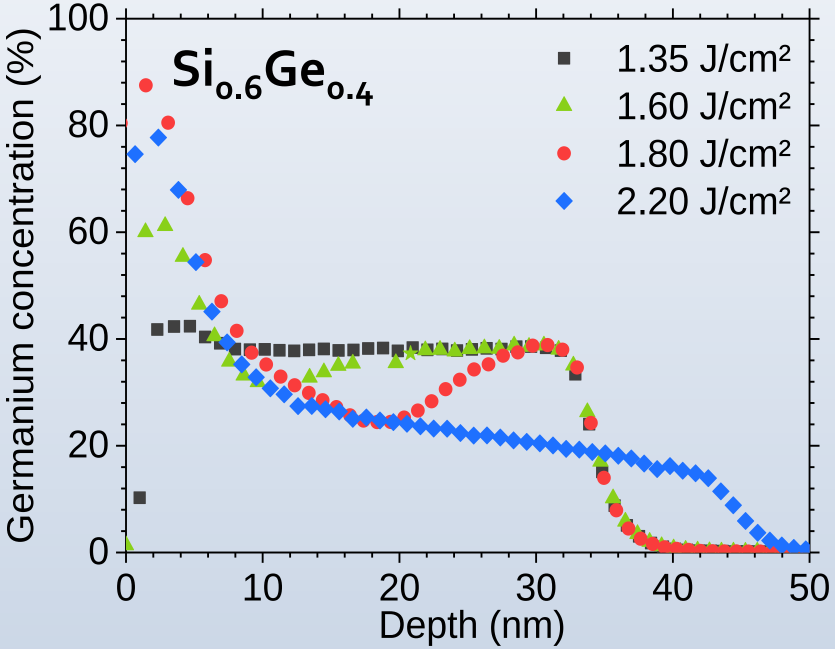
Regimes identification

In-Situ Time-Resolved Reflectometry & SIMS





- E < 1.35 J/cm^2 : Sub-melt → No detectable Ge redistribution
- 1.35 < E < 1.8 J/cm^2 : Partial Melt → partial Ge redistribution
- E > 2.2 J/cm^2 : Full Melt → Ge redistribution beyond initial SiGe thickness

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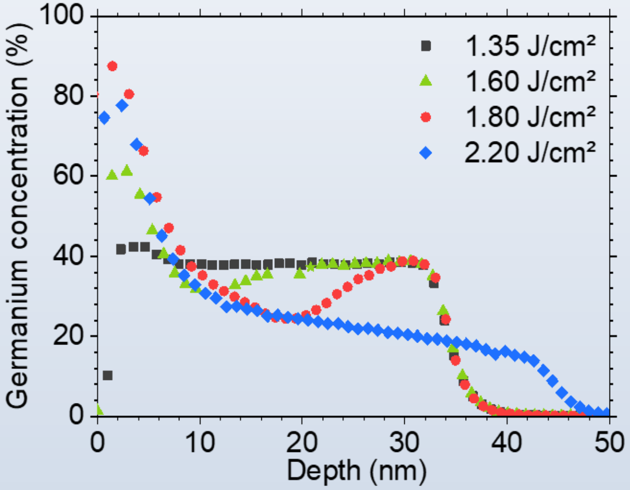
Dagault et al., ECS-JSS 2019
Dagault et al., SSDM 2019
Dagault et al., App. Surf. Sci. 2020

Regimes identification

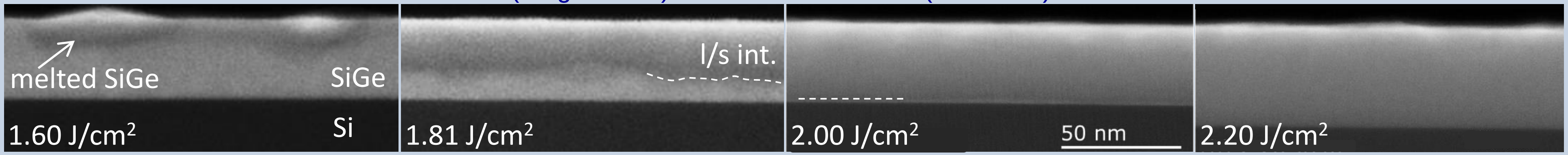


- <u>Surface melt regime</u>: ~15 nm-thick liquid islands before a continuous liquid layer is formed
- <u>Surface and partial melt regimes</u>: Rough l/s interface favors the formation of strain relieving defects
- Rough l/s interface favors the
- Melt beyond the initial SiGe thickness

<u>Annealing regimes</u> ($Si_{0.6}Ge_{0.4}$)

Surface melt	Partial melt (rough l/s int.)	Partial melt (flat l/s int.)	Full melt

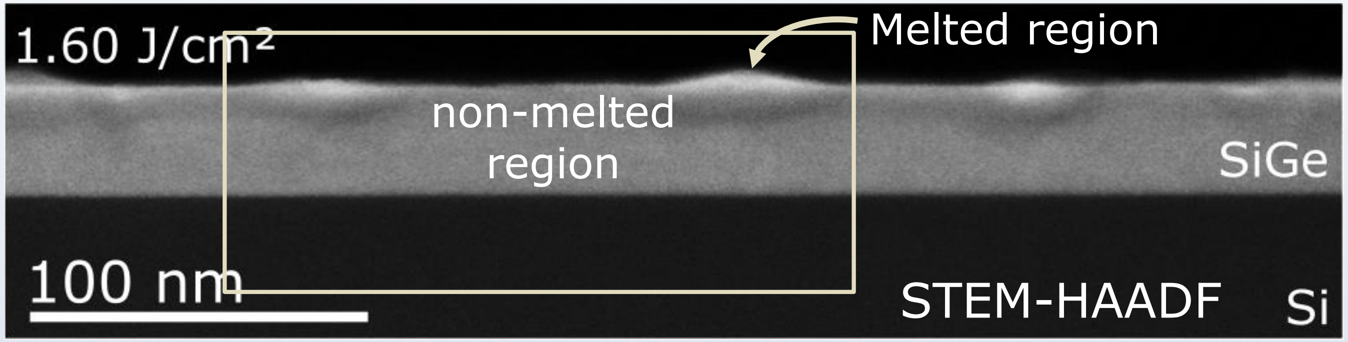
TEM

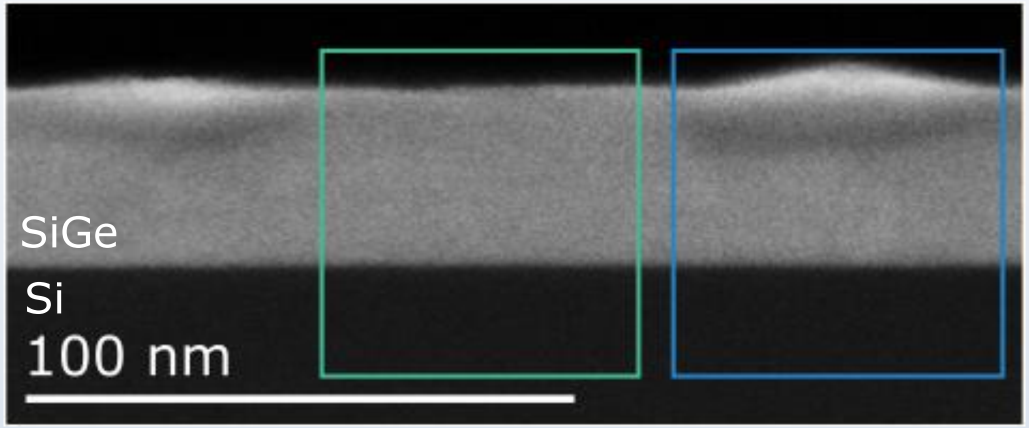


Dagault et al., ECS-JSS 2019
Dagault et al., SSDM 2019
Dagault et al., App. Surf. Sci. 2020

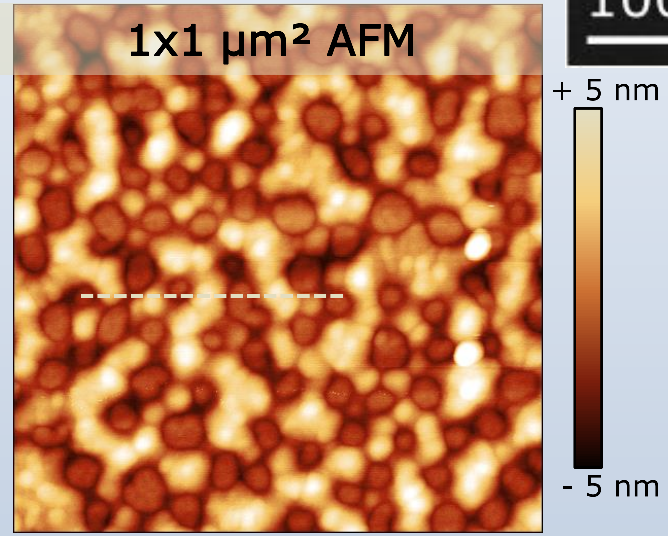
Surface melt regime: isolated melted islands

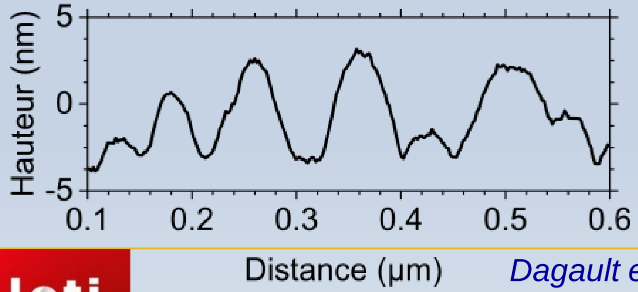
TEM & AFM

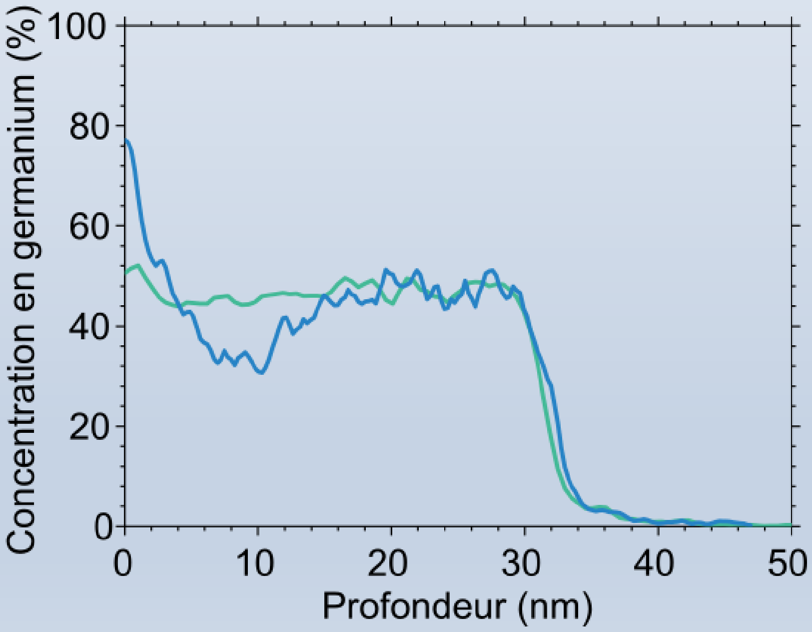




- Surface hillocks
- Same sizes by TEM & AFM
- STEM-EDX Ge profiles
  - **Flat surface** ➔ no Ge ségrégation
  - **Hillocks** ➔ Ge segregation





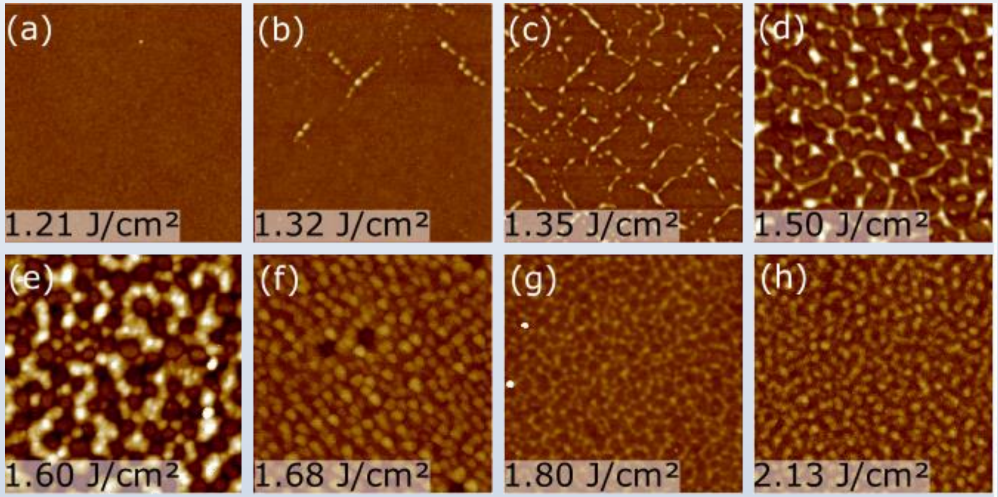


Observed hillocks correspond to melted areas

Dagault et al., ECS-JSS 2019
Dagault et al., SSDM 2019
Dagault et al., App. Surf. Sci. 2020

Surface melt regime: isolated melted islands

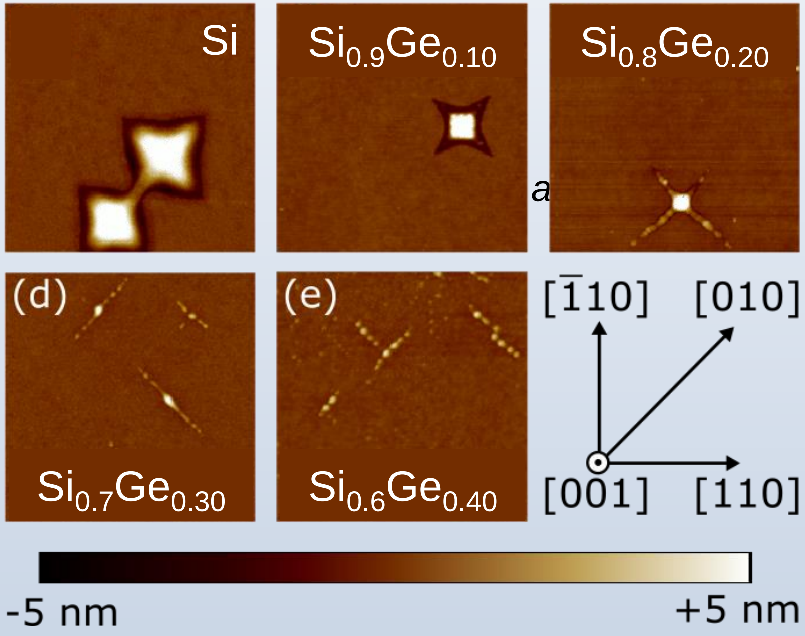
Laser energy effect
(surface coverage - $Si_{0.6}Ge_{0.4}$)



- Progressive surface coverage with increasing energy density
- Observed in all investigated SiGe samples (including bulk Si)

➔ Transition from locally melted surface to a continuous liquid layer

Ge content effect (hillocks geometry)



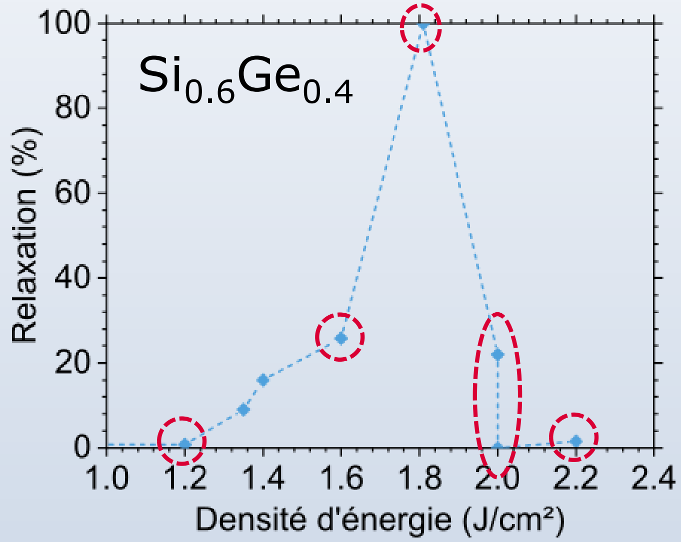
- Hillocks shape modification with increasing Ge content

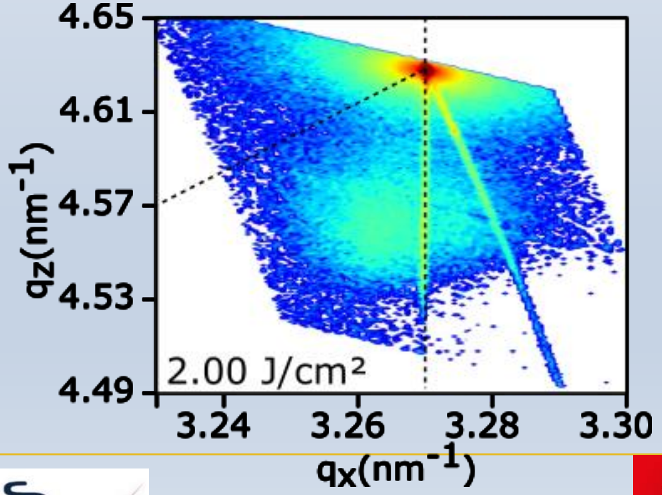
➔ Possibly induced by the strain associated to the unmelted SiGe regions

Dagault et al., ECS-JSS 2019
Dagault et al., SSDM 2019
Dagault et al., App. Surf. Sci. 2020

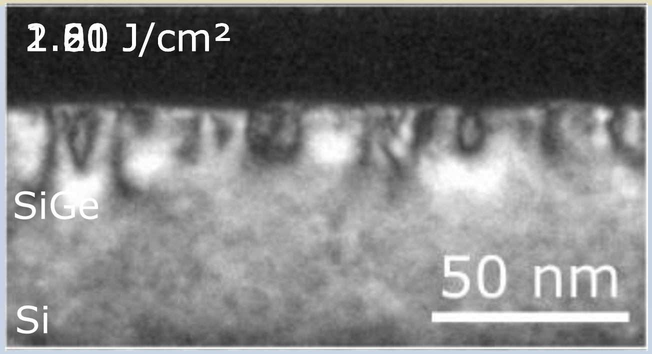
Strain relaxation

RSM (Reciprocal Space Mapping)





- **Sub-melt ➔** Strained layer
- **Surface melt**
  - Partial strain relaxation (<30%)
  - Strain relieving defects in the whole layer
- **Partial melt**
  - Fully relaxed layer
  - Additional misfit dislocations (parallel to surface)
- **Partial and full melt regime**
  - Bi-layer formed: relaxed upper layer and strained lower layer
  - Defects formed only in the relaxed layer



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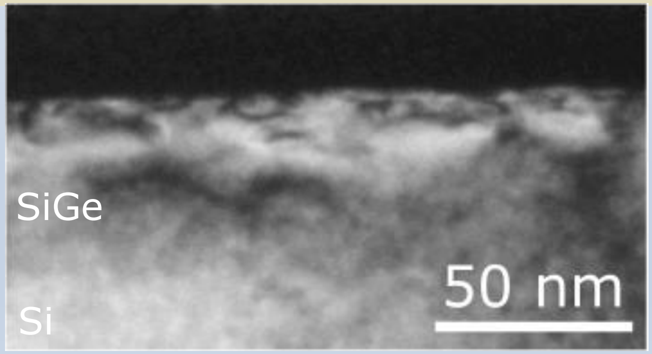


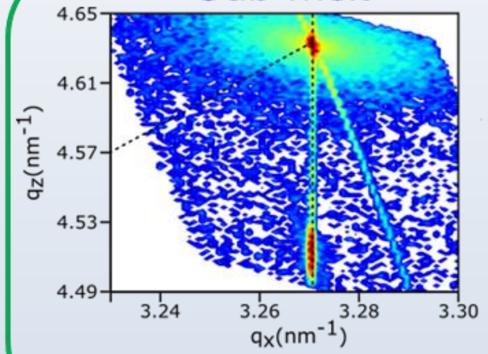
g = [220]

Dagault et al., ECS-JSS 2019
Dagault et al., SSDM 2019
Dagault et al., App. Surf. Sci. 2020

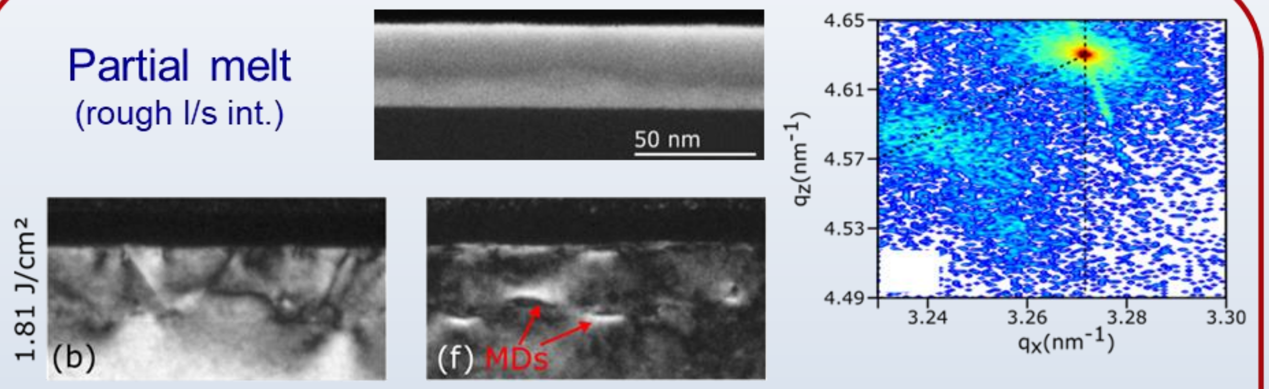
Strain relaxation: summary

$Si_{0.6}Ge_{0.4}$

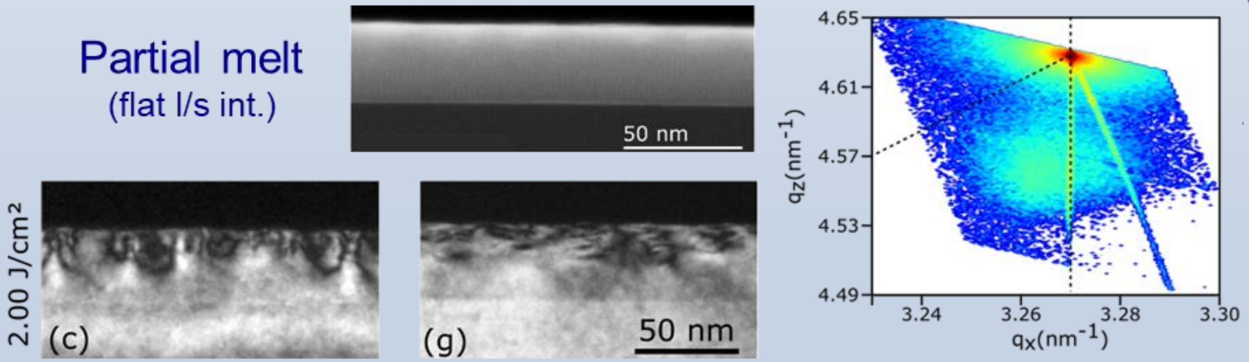
Sub-melt



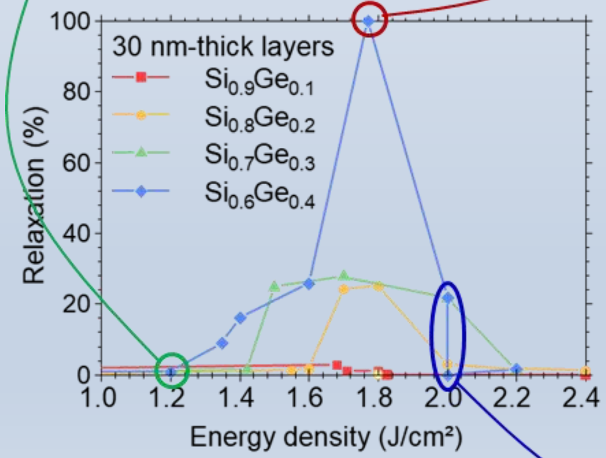
- Fully strained



- Rough l/s int. → strain relieving defects in whole layer



- Defects and relaxation determined by elastic energy



Dagault et al., ECS-JSS 2019
Dagault et al., SSDM 2019
Dagault et al., App. Surf. Sci. 2020

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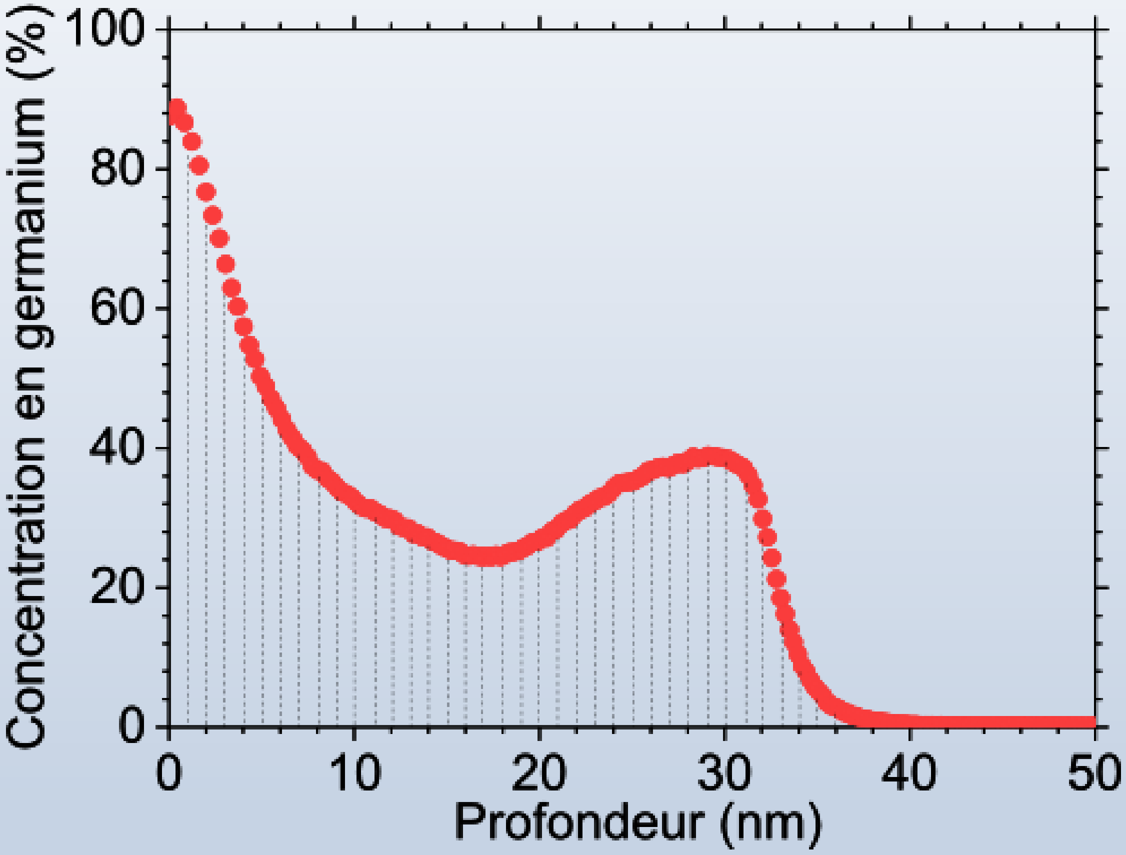
Elastic energy calculation



- Elastic energy depends on
  - Ge **concentration**, x
  - Layer **thickness**, h

$$E_{EL} = 2\mu \cdot \frac{1+\nu}{1-\nu} \cdot \varepsilon_x^2 \cdot h$$

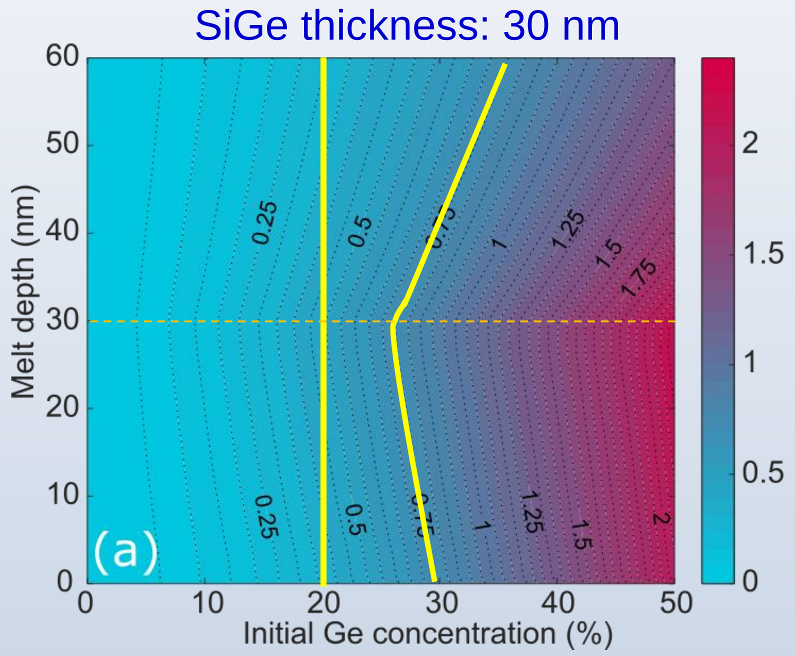
with $\varepsilon_x = \frac{a_{Si_{1-x}Ge_x} - a_{Si}}{a_{Si}}$

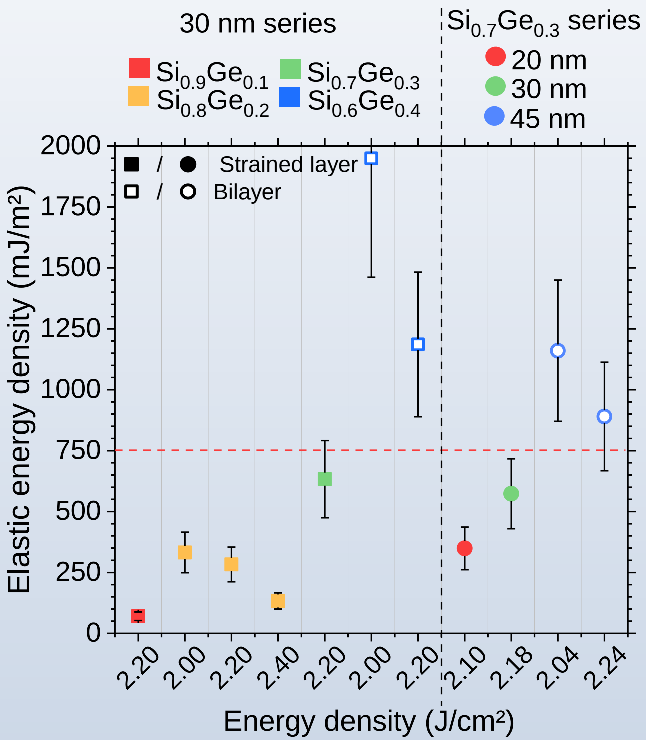
- In the presence of a Ge gradient
  - Layer divided in several slices (0.5 nm)
  - **Total elastic energy density, E_{EL}**

$$E_{EL} = \int_{z=0}^{z=z_{max}} 2\mu(z) \cdot \frac{1+\nu(z)}{1-\nu(z)} \cdot \varepsilon_x(z)^2 \cdot dz$$

Dagault et al., ECS-JSS 2019
Dagault et al., SSDM 2019
Dagault et al., App. Surf. Sci. 2020

Elastic energy calculation: comparison with experiments





Elastic energy

- determined by Ge depth profile
- calculated accounting for initial Ge concentration, melt depth and Ge redistribution during regrowth

Flat l/s interface

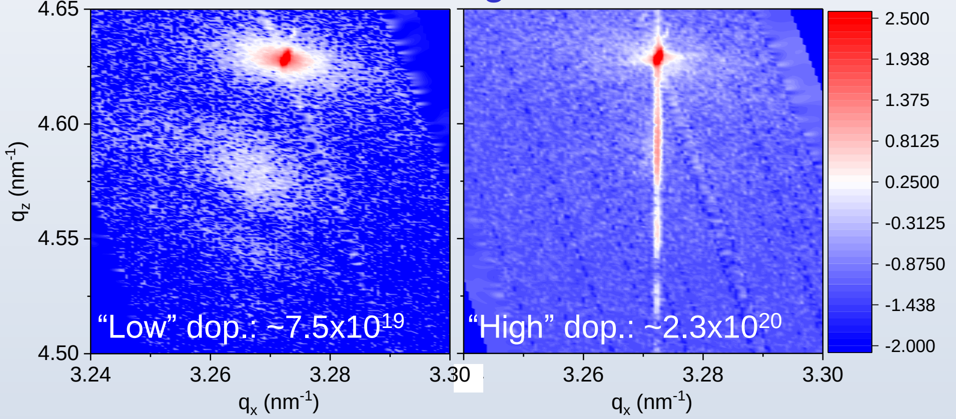
- Critical elastic energy for relaxation: ~750 mJ/cm^2
- Can be increased if l/s roughness is eliminated (possibly by a decrease of the laser pulse duration)

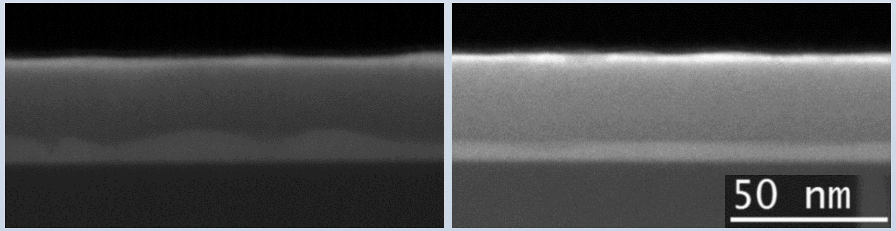
Dagault et al., ECS-JSS 2019
Dagault et al., SSDM 2019
Dagault et al., App. Surf. Sci. 2020

In-situ Boron doping: impact on strain relaxation

$Si_{0.7}Ge_{0.3}$

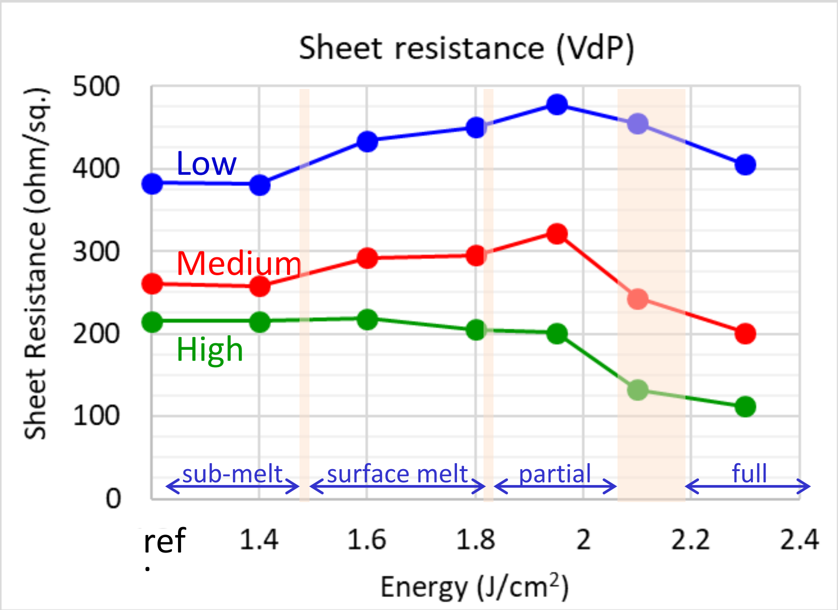
Laser annealing: 1.95 J/cm^2





<u>Strain compensation by B incorporation</u>

- Flat l/s interface
- Defect free, fully strained layers



<u>Rs evolution determined by several phenomena</u>:

- Relaxation and defects formation
- Dissolution of Boron-related clusters
- Ge and B redistribution

→ Combination with SIMS measurements for Hall effect data interpretation (in progress)

Dagault et al., ECS-JSS 2019
Dagault et al., SSDM 2019
Dagault et al., App. Surf. Sci. 2020

Outline

1. Background
    - *Interest for nsec Laser Thermal Annealing*
    - *Basic LTA properties*
    - *Early studies*
2. nsec laser annealing of SiGe
    - *Melt regimes*
    - *Surface melt*
    - *Defect formation and stress relaxation*
    - *Impact of B doping on stress relaxation*
3. Conclusion

Conclusions

- Evolution of annealing methods for microelectronics
  - Laser annealing is a **crucial enabling technology** to achieve localised annealing needed for future microelectronics devices
- SiGe Laser anneal: impact on segregation/relaxation
  - Evidence of a **partial surface melt regime** at low annealing energies
  - **High Ge content at surface** by segregation during LTA → S/D contact engineering
  - Role of the **l/s interface roughness** on the strain relaxation mechanism
  - Identification of a **critical elastic energy threshold** for strain relaxation of SiGe under LTA
  - Impact of ***in-situ* Boron doping** investigated:
    - Reduction of the l/s interface roughness
    - Conservation of strain in partially melted SiGe structures

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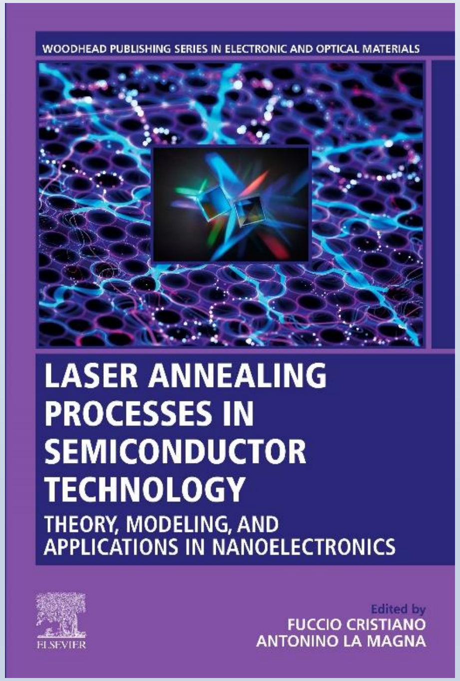
Thank you for your attention



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https://www.elsevier.com/books/laser-annealing-processes-in-semiconductor-technology/cristiano/978-0-12-820255-5