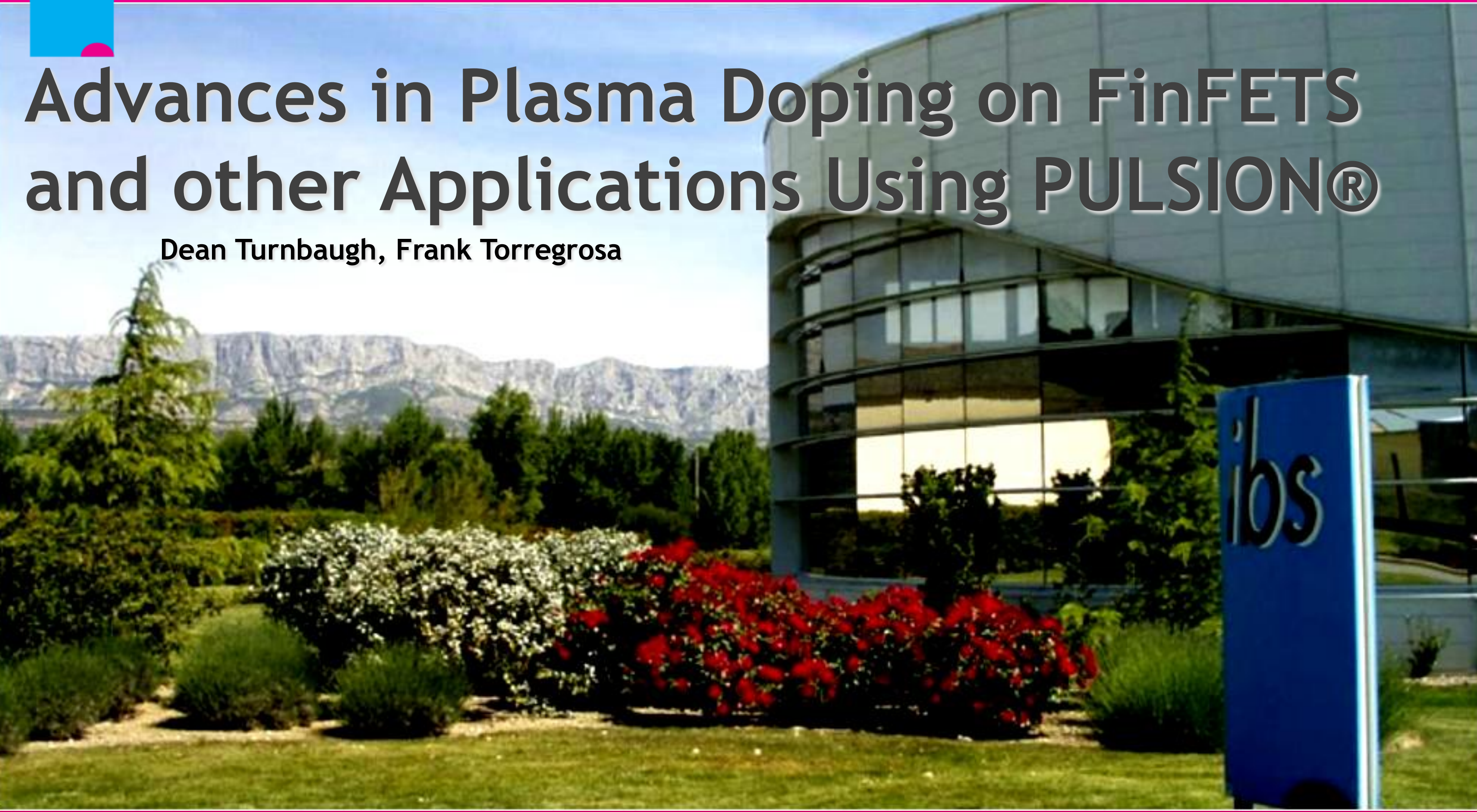
ion beam services
the total ion implantation solution

Advances in Plasma Doping on FinFETS and other Applications Using PULSION®

Dean Turnbaugh, Frank Torregrosa



Semicon West 2014 – San Francisco

Outline

- Introduction
- PULSION® PIII implanter
- FinFET Doping
- Hot Implantation using PULSION
- CMOS imager
- 450 mm
- Modeling
- Conclusions

Ion Beam Services -Implant Specialists for 24 Years

- Based in Peynier, France
- Implant Services, Implant Outsourcing, Second Source Parts
- Key Implant Technology for many French and EU Research Projects
- Created Plasma Implant tool with Remote Plasma Source in 2001
  - "PULSION™"
  - First PULSION installed at LETI in Grenoble, France in July 2007
  - Second installed 2011

IBS Cost Savings Products and Services

- **Implant Services**
  - R&D Partnering and Services
    - Simulations, Consulting
  - Foundry services for overload or unique processes
  - Over 60 Species including many exotics
  - Conformal Doping
  - 0 to 200KeV up to 6” including off size and shape substrates
  - 0- 250KeV up to 8”
  - Up to 5 MeV
- **System Products**
  - IMC-200 Custom Beamline Implanter
  - SiC Implant System
  - PULSION Nano (Plasma Implant for Labs)
  - PULSION HP (Plasma Implant for Production)
- **Upgraded IHC ion source**
  - Varian Viision
- **ESC Refurbishing and Repair (8 different models)**
- **Safety and Productivity Gasbox Retrofits**
  - Varian VIISta and AMAT XR

PULSION® Configurations

PULSION nano	PULSION nano Auto-loading	PULSION HP
		
Manual loading 1 chamber	Auto loading 1-2 chambers	Auto loading 1-4 chambers
Labs	Device qualification	Production

+ Substrate heating (up to 500° C)

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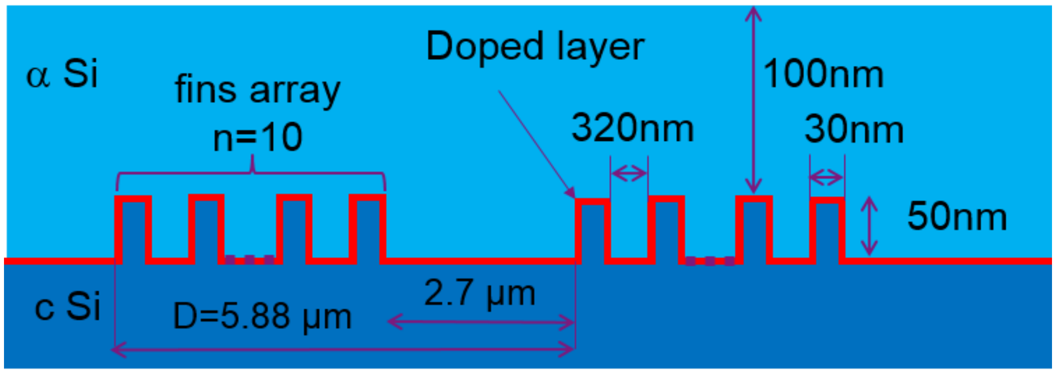
FinFET AsH_3 Doping using PULSION®

FinFET doping requirements for < 10 nm nodes

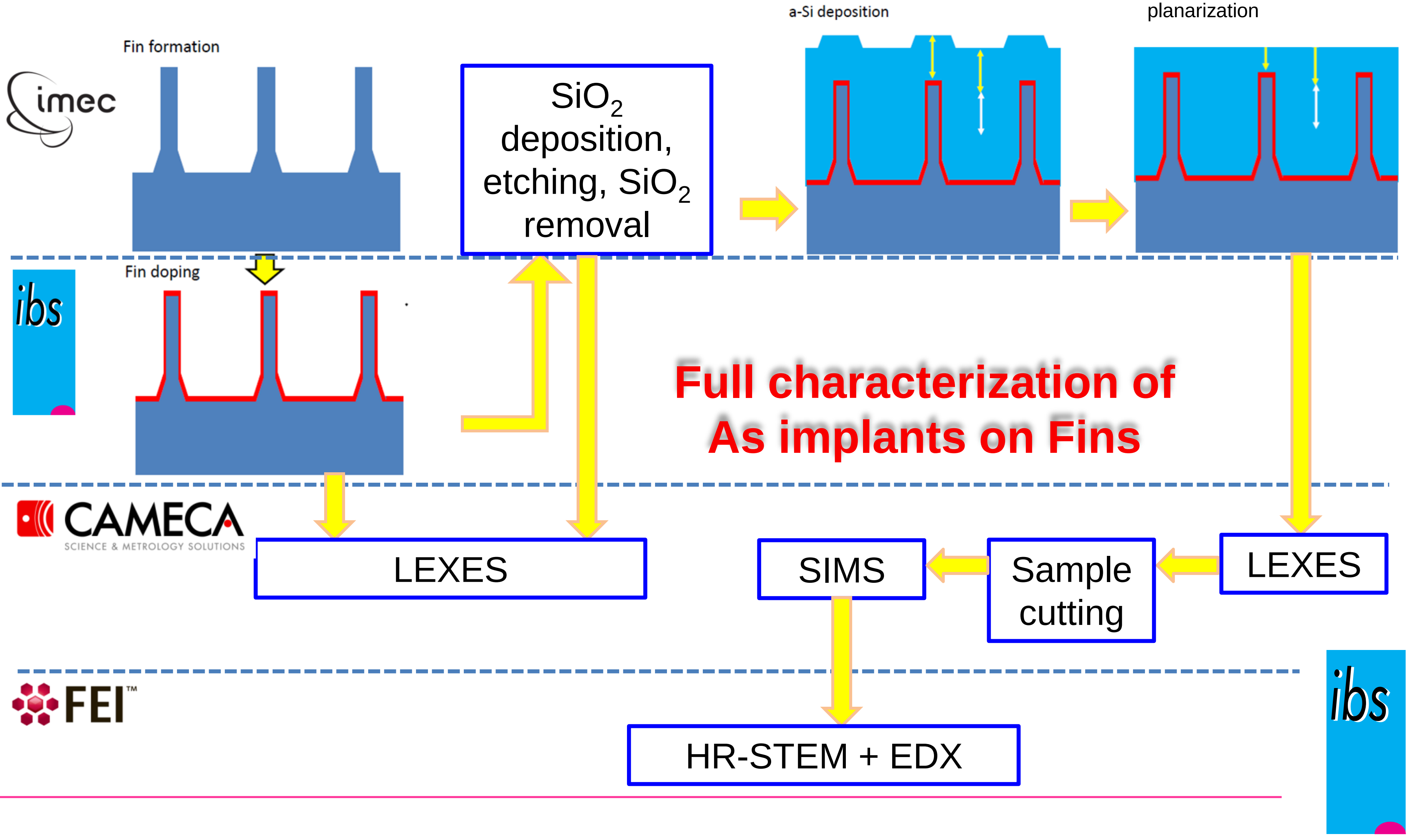
- Ultra shallow junction (< 5 nm)
- Conformal doping
- No Fin erosion
- High retained dose
- Perfect crystal recovery after activation annealing

Tested on the following structure :



FinFET AsH_3 Doping using PULSION®

Experiment design

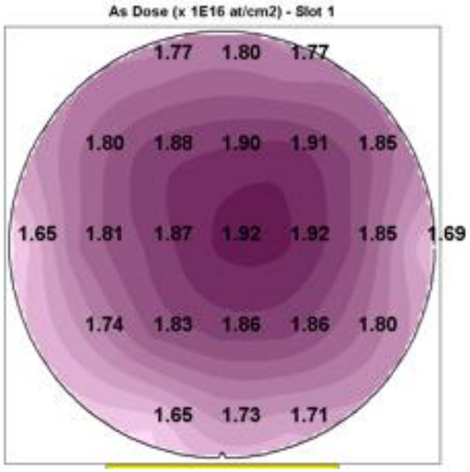


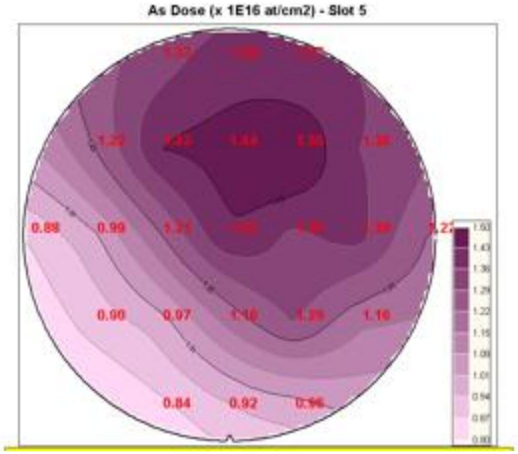
FinFET AsH_3 Doping using PULSION®

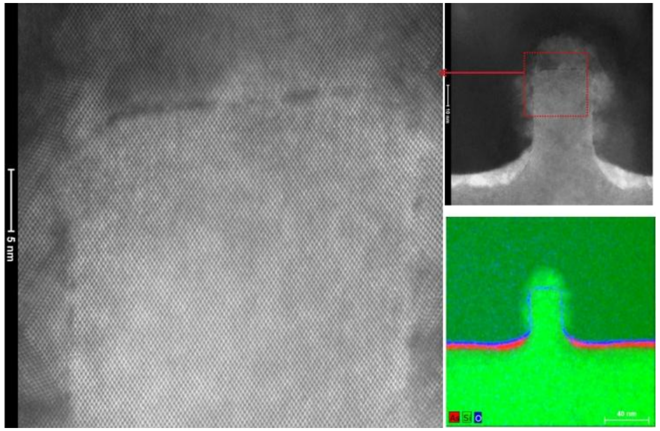
Main results :

As implanted

After SiO2 cap dep. / annealing / SiO2 cap etching







Good non uniformity of PULSION implantation on Fin structured wafers (Non unif < 3%)

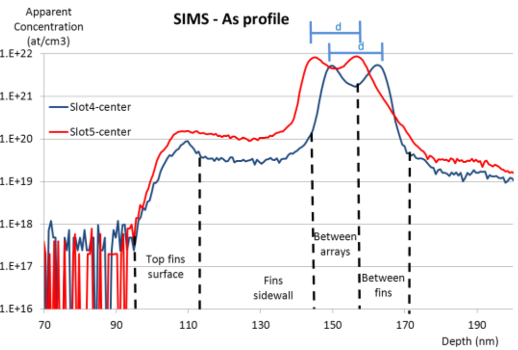
Dose loss and non uniformity if SiO_2 cap layer deposition & etch and annealing processes are not well controlled (Non unif = 15%)

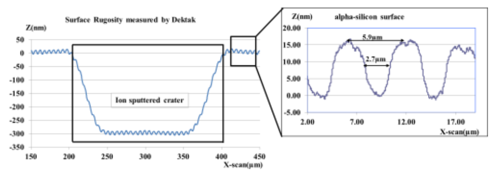
No Fin etching
Perfect cristal regrowth

FinFET AsH_3 Doping using PULSION®

Main results :

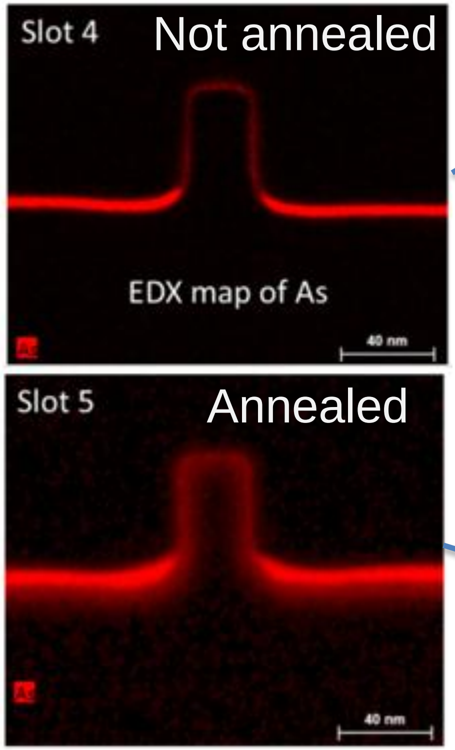
SIMS

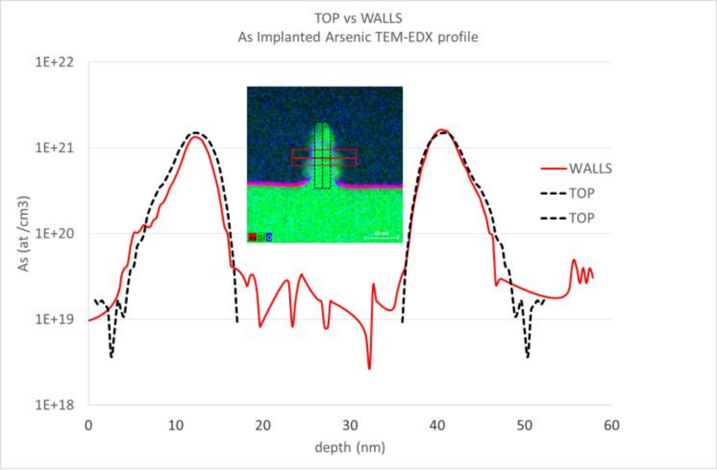


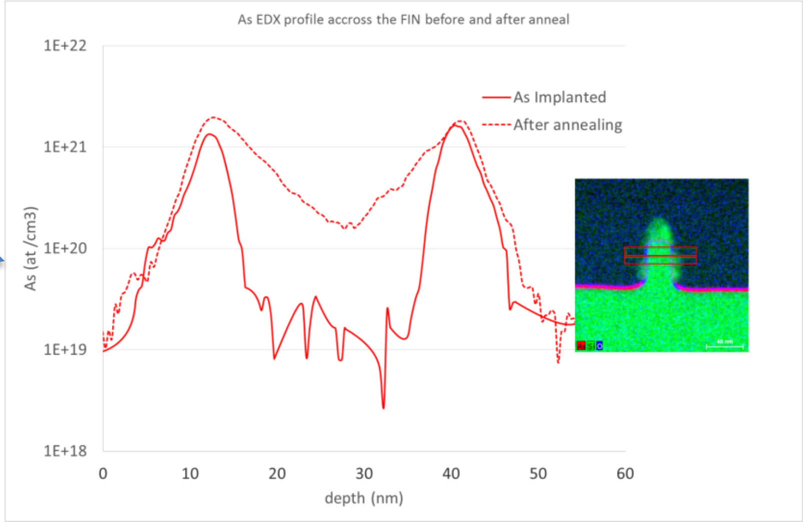


Double pic at the FIN foot due to surface roughness after CMP

TEM-EDX





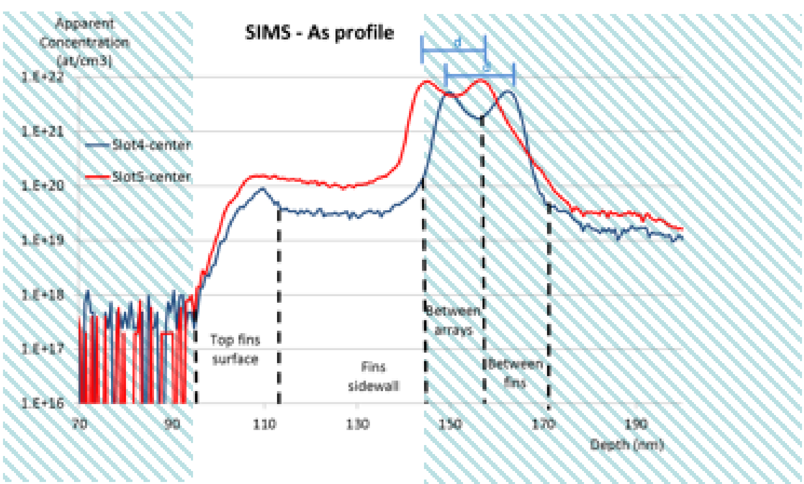


Very good conformality,
Efficiency of SiO2 cap layer to avoid dose loss

FinFET AsH_3 Doping using PULSION®

Main results :

Sample	SIMS (center)		EDX (center)	
	Dose Top / Sidewall (at/cm²)	Conformality	Dose Top / Sidewall (at/cm²)	Conformality
Slot 4 (as implanted)	8.9E14 / 8.0E14	90 %	7.8E14 / 7.0E14	90 %
Slot 5 (annealed)	2.1E15 / 2.1E15	100 %	1.5E15 / 1.5E15	100 %



SIMS uses integral deconvolution to calculate As dose at fin top and fin sidewall.

EDX dose is calculated by the integral of the EDX profiles

Very good and coherent conformality were found.

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FinFET AsH_3 Doping Using PULSION®

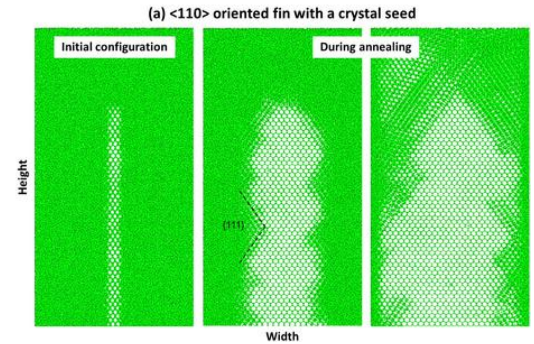
Summary :

- AsH_3 PULSION® implantation shows a very good conformality on FIN structures
- No Fin erosion nor crystal defect after annealing was observed
- SiO_2 cap layer is effective to avoid dose loss during annealing and allow high dose retention in silicon.
- SiO_2 cap layer deposition and etching as well as RTA processes must be well controlled not to degrade the good non-uniformity obtained after implantation

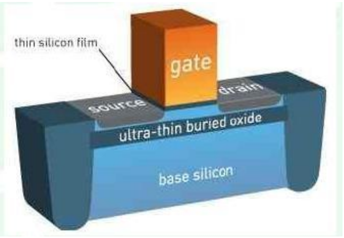
Hot Implantation

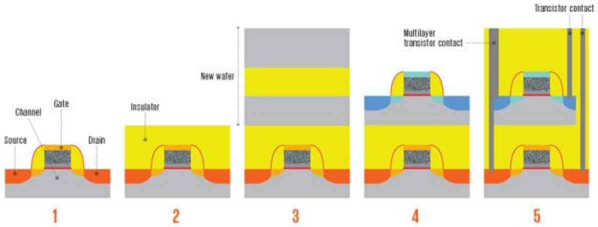
Advanced device requirements for Ion Implantation :

- FinFET : 3D conformal shallow doping + no amorphization of the FIN for good crystal regrowth
- FD-SOI : shallow doping + no amorphization of the Si-Top film to allow crystal Epi regrowth and Epi layer deposition (elevated S/D)
- III-V, SiGe, SiC, Diamond, or other exotic and thermally unstable semiconductor : need to reduce defects during implant to limit thermal budget of post implant annealing
- 3D integration : Need to reduce thermal budget for activation and crystal recovery after implantation



L. A. Marqués et al., J. Appl. Phys. 111, 034302 (2012)

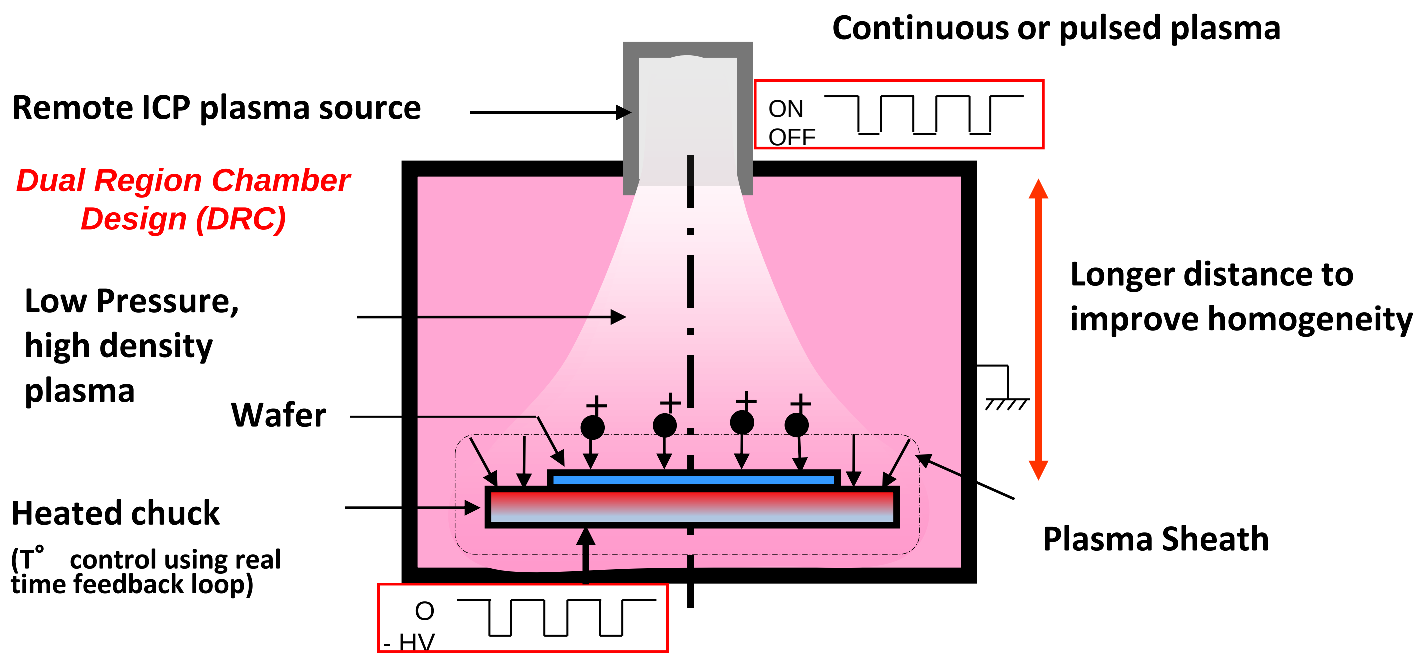




➡ PIII + hot implantation

= PULSION® with high temp. option

PULSION® PIII Implanter

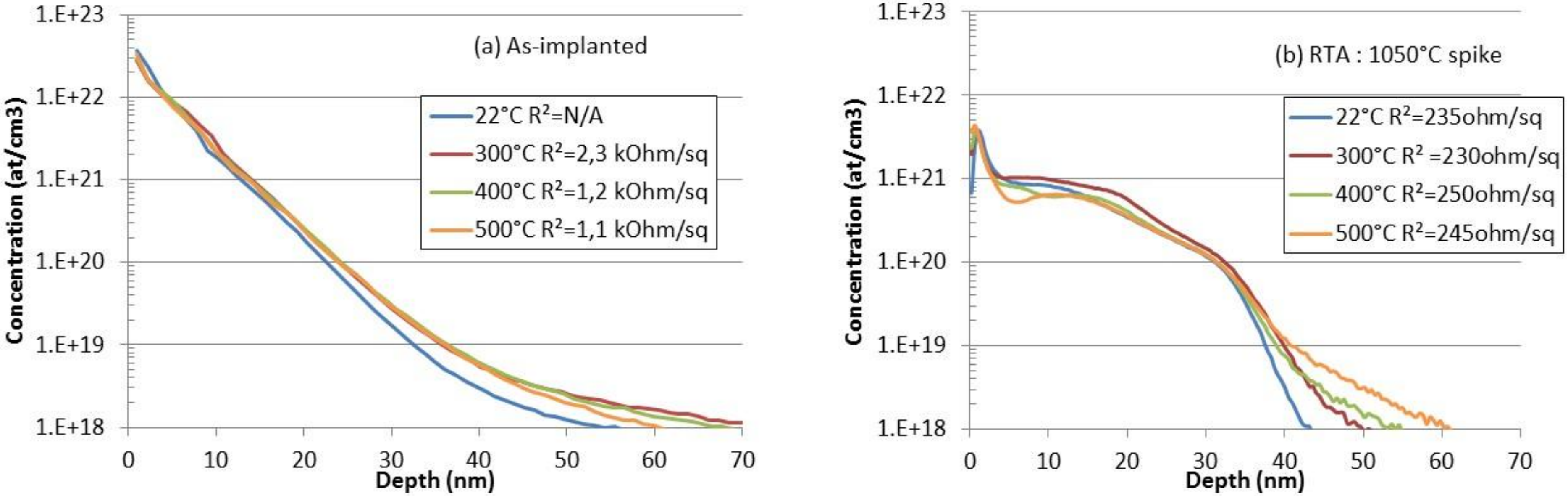


Schematic of PULSION® with high temp chuck option

- Heated chuck with realtime feedback loop to compensate heating by plasma and implant.
- Up to 500° C

Experiment 1 : AsH_3 10 kV high dose

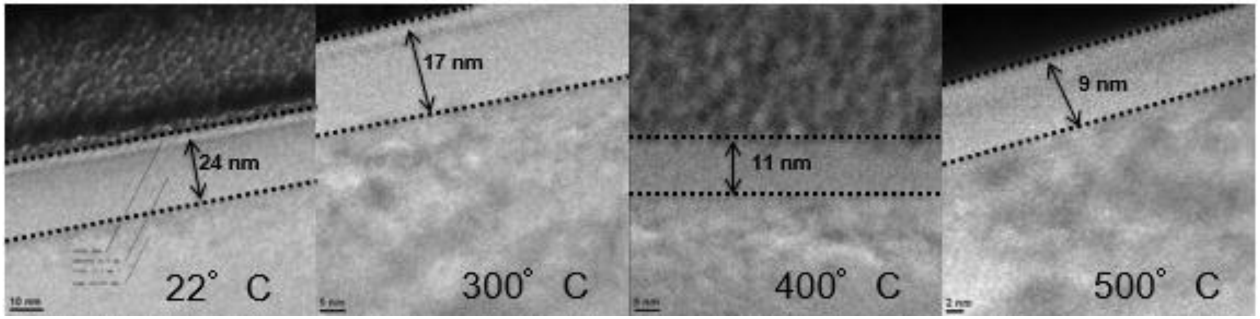
For the same as-implanted retained dose (~ 1.2 E16 /cm²)

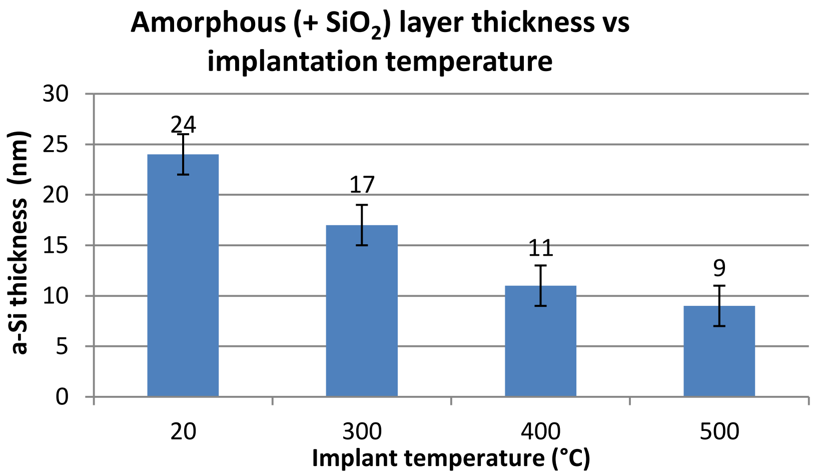


- After implant :
  - High temp implant are ~ 10% deeper
  - Same "channeling" tail for samples implanted at high temp.
- After annealing :
  - no big difference in profile above 1E19/cm³
  - below 1E19/cm³ the tail increases with implant temperature

Experiment 1 : AsH_3 10 kV high dose

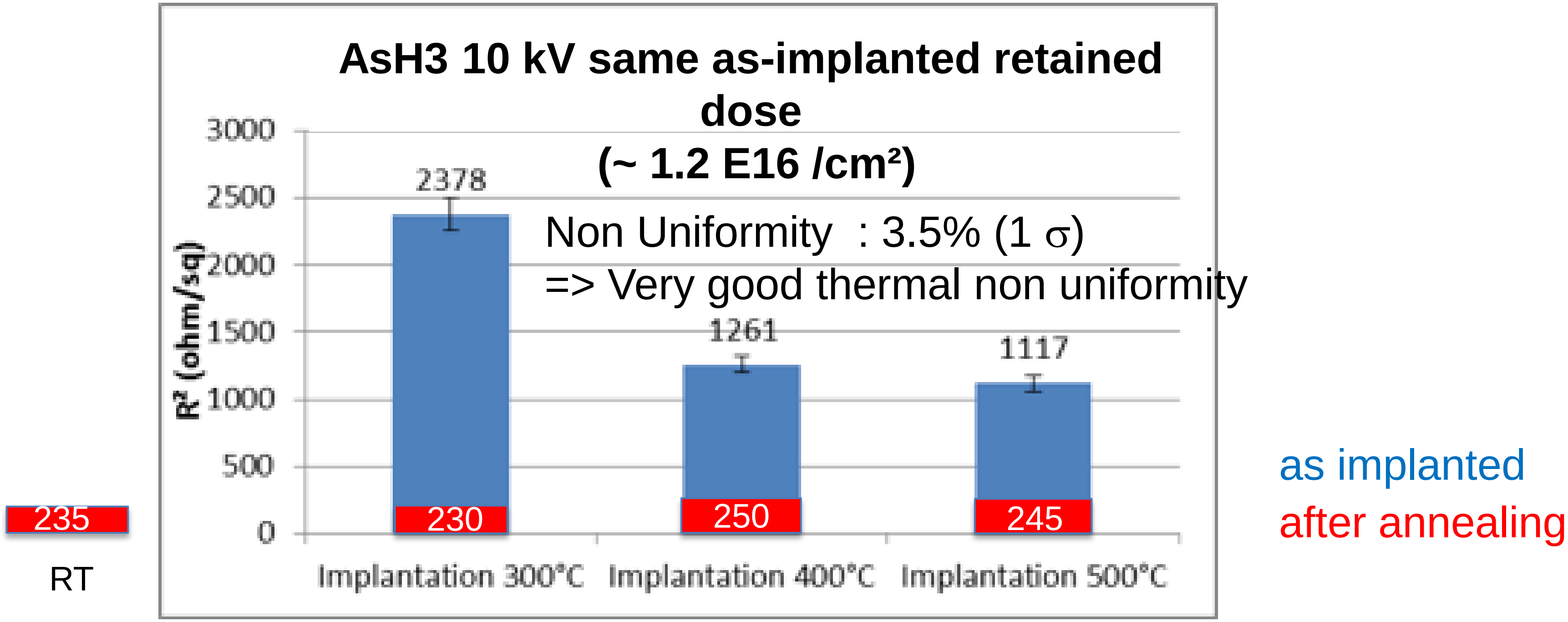
TEM images and thickness measurement of the amorphous layer on as implanted samples as a function of implant temperature





- Important reduction of the amorphous layer thickness is observed when implanting above 400° C

Experiment 1 : AsH_3 10 kV high dose



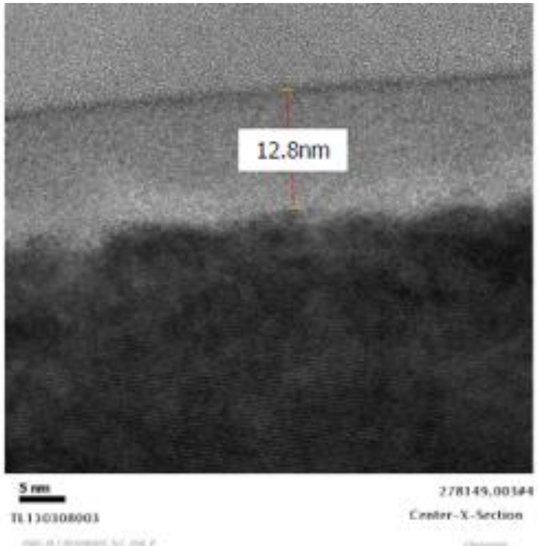
- Partial activation is observed just after implantation when implanting at high temperature + very good the
- No significant change of the sheet resistance after annealing ~ (240 +/-10) Ω/sq regardless of implantation temperature

➢ Possible to make high dose As implantation (~ 1.2 E16 /cm²) on 30 nm with only 9 nm amorphous layer (without affecting final sheet resistance)

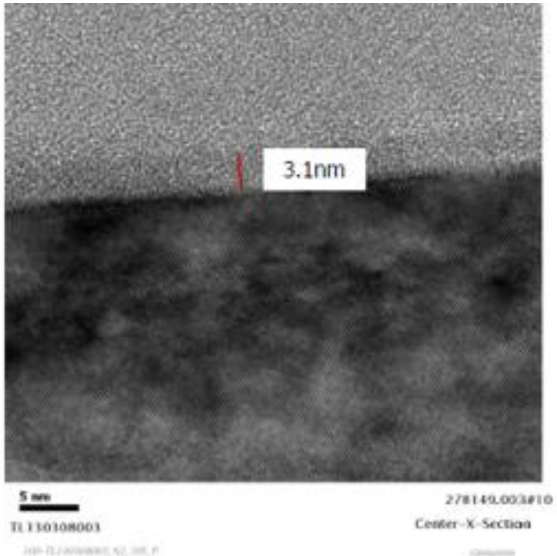
Experiment 2 : AsH_3 10 kV lower dose ($2^E15/cm^2$)

TEM on as implanted wafers (20 nm implant depth)

RT



500° C



	Room T°	500°C
Amorphous layer thickness (as implanted)	12.8 nm	3.1 nm

- Drastic reduction of the amorphous layer thickness

Micron

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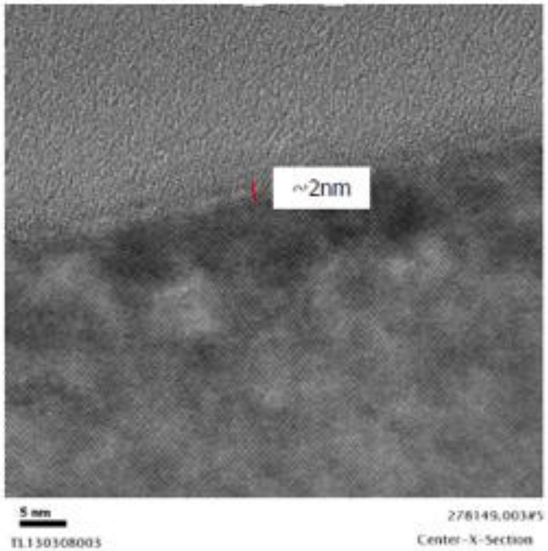
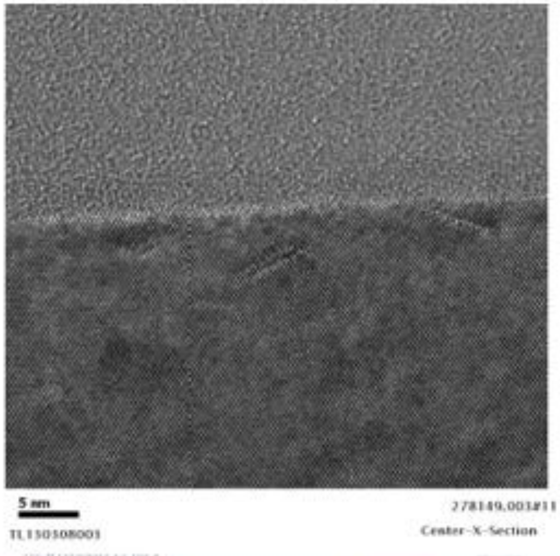
Experiment 3 : AsH_3 1 kV $2^{E}15/cm^2$

TEM on as implanted wafers (7 nm implant depth)

RT



500° C



	Room T°	500°C
Amorphous layer thickness (as implanted)	2 nm	0 nm

- Suppression of the amorphous layer
- Some remaining defects are visible

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High Temp Implant Summary

- Up to 500° C Plasma Immersion Ion Implantation is now available on PULSION® and has been qualified using AsH_3 plasma
- High temperature PIII implant allows drastic reduction of the thickness of amorphous layer after Arsenic implantation, even at high dose.
- Hot implantation induces 10% deeper profile (also observed on beam line) due to enhanced diffusion of interstitials and vacancies during implant and channeling.
- Partial activation is observed after high temperature implantation even at 300° C, but after annealing sheet resistance does not depend on implant temperature if the as-implanted retained dose is the same.
- No big differences are observed between 400° C and 500° C implantations.

→ Application for FINFET doping and FD-SOI is under study (Places2Be European project)

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CMOS Imager Doping Summary

- PULSION can do uniform and conformal trench doping for DTI application (20:1 form factor)

- PULSION is an efficient solution for Boron USJ doping before laser anneal for BSI Application

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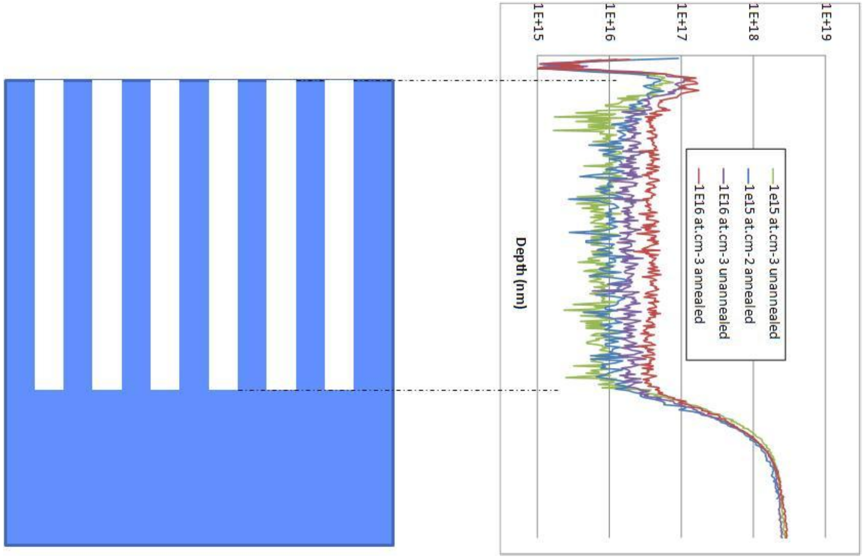
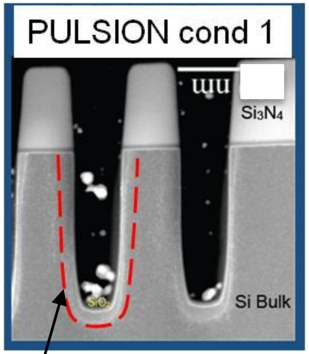
CMOS Imager Application : STI/DTI

- **Application to CMOS imager (STI) :** IBS / STM





Implant along DTI

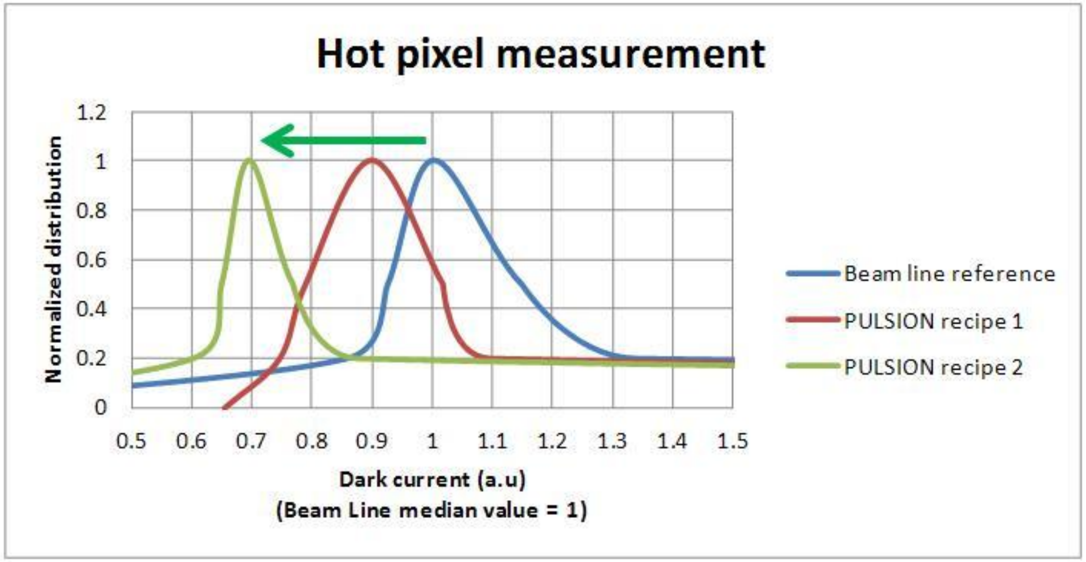
Test structures: 20/1 form factor
Uniform doping on the trench walls demonstrated

Real Devices
Conformal doping along DTi

Atemox European R&D project

CMOS Imager Application : STI/DTI

- **Application to CMOS imager (BSI) :** IBS / Customer A
  - PULSION Boron implantation
  - Laser anneal



Normalized results from customer feedback

Dark current reduction : 30%
This is due to the fact that the implant depth is ultra shallow and that PIII creates less defects than beam line
=> All the Implant defects are suppressed by the laser annealing

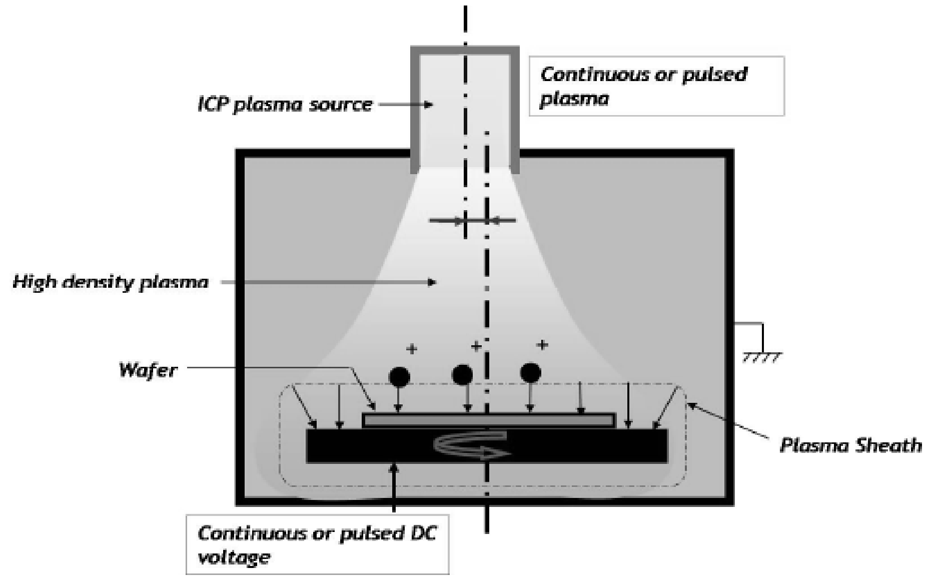
450 mm PULSION® scalability

PULSION® advantages for 450 mm :

- Implant time is independant from the surface
- Doping efficiency proven on the technology which will be installed on 450 mm (FinFET doping, material modification, memories)

300mm PULSION® tool

450mm prototype : same design



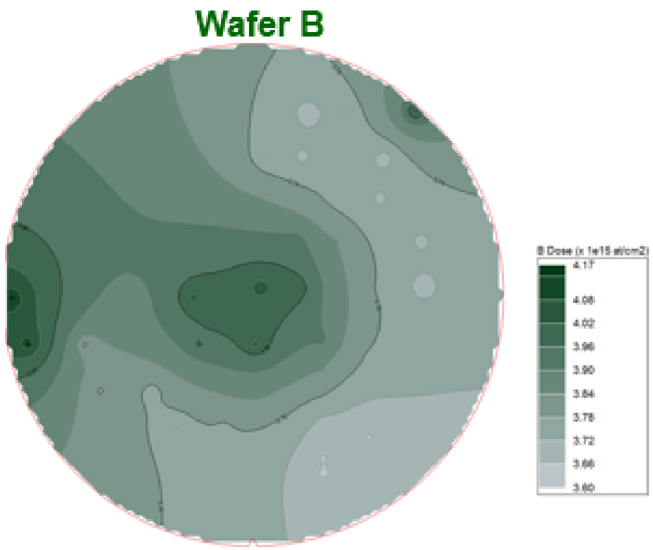
Roadmap for 450 mm :

- Phase 1 : demonstrate scalability : target < 4% non homogeneity
- Phase 2 : final design : < 1% non homogeneity

450 mm PULSION® scalability

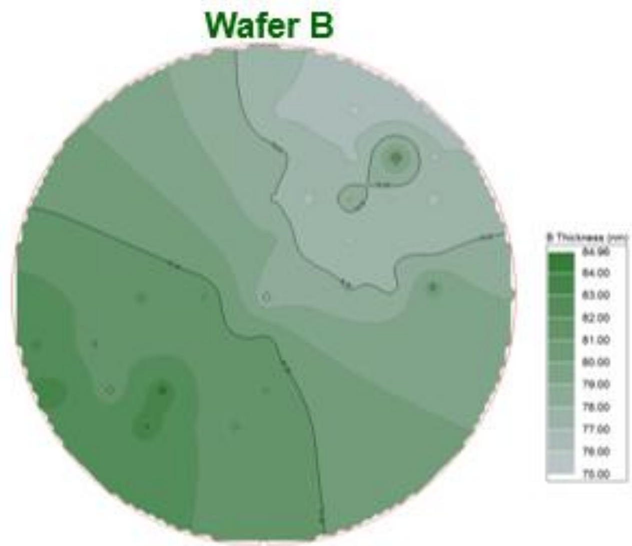
BF3 6kV implant on n-type 450 mm wafers
Dose and implant depth uniformity meseared by CAMECA LEXES
=> Less than 4% non uniformity demonstrated

450 mm wafer dose non-uniformity
47 points mapping



B average dose: 3.80e15 at/cm2
Non-uniformity : 3.91%

450 mm wafer thickness non-uniformity
32 points mapping

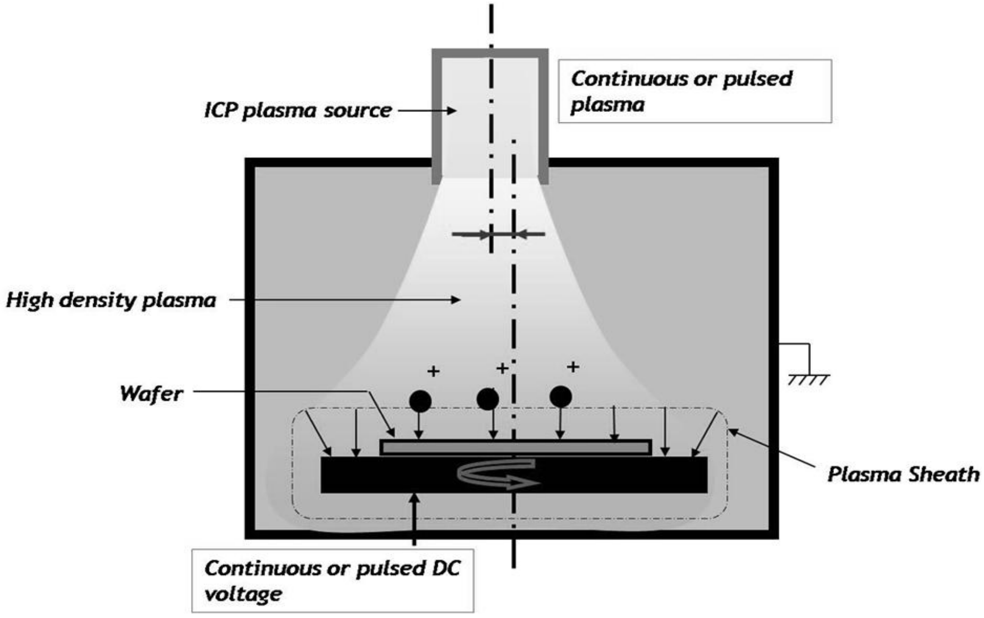


B average thickness: 79.59 nm
Non-uniformity : 3.59%

PULSION® implantation modeling

Efficiency of PULSION® is experimentally proven for advanced devices doping (FinFET, FD-SOI, Cmos Imager, Flash and DRAM memories…)

But TCAD model is now needed by designers



Multi ions implant.
Multi energetic implant.
Multi angles implant. (if collisional conditions)

→ challenge for simulation

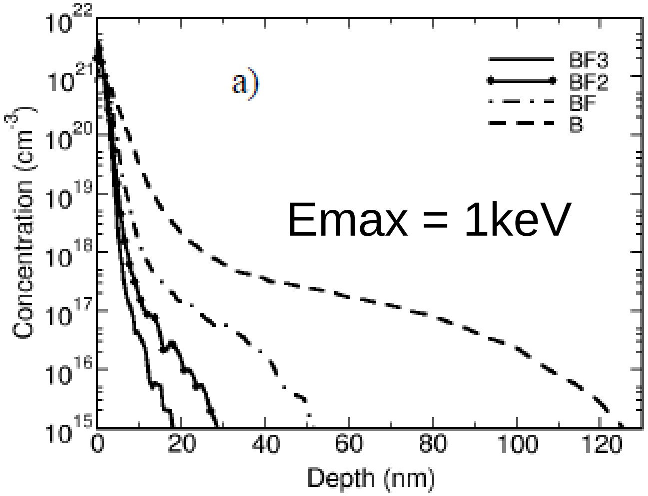
PULSION® implantation modeling

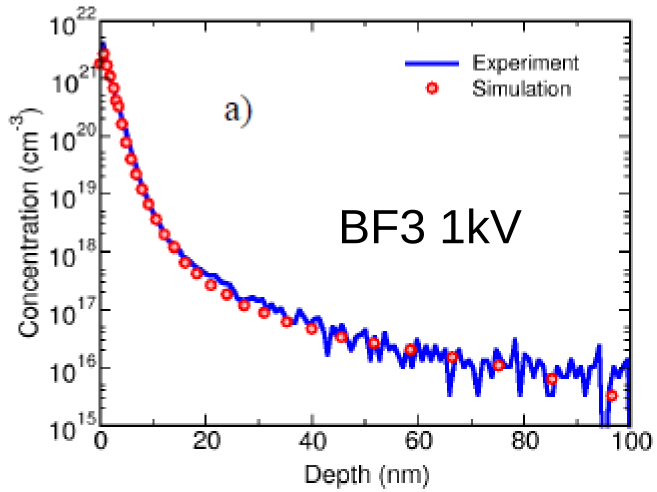
BF_3 implant modeling

$$f(E) = \frac{5}{6E_{max}} \left(\frac{E}{E_{max}}\right)^{-1/6}.$$

TABLE 1. Relative abundance of different ions extracted from BF3 plasma.

Ion	Abundance(%)
BF_3^+	0
BF_2^+	50
BF^+	40
B^+	10





IIT2012 : Simulation of BF3 Plasma Immersion Ion Implantation into Silicon

A. Burenkov*, A. Hahn*, Y. Spiegel, H. Etienne, and F. Torregrosa

PULSION® implantation modeling

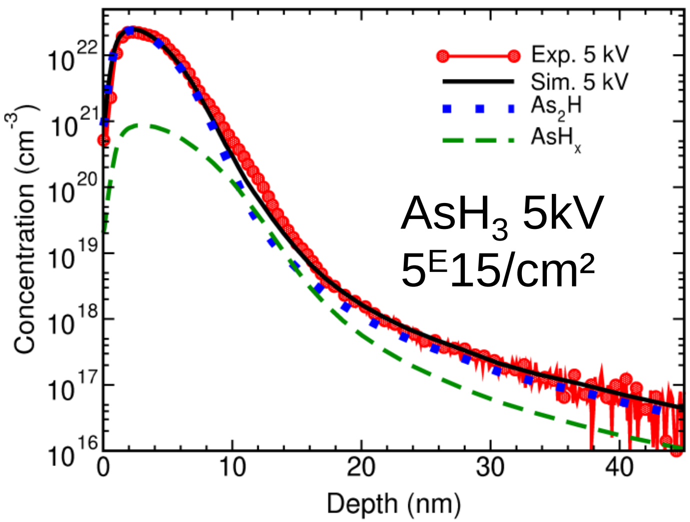
Fraunhofer IISB

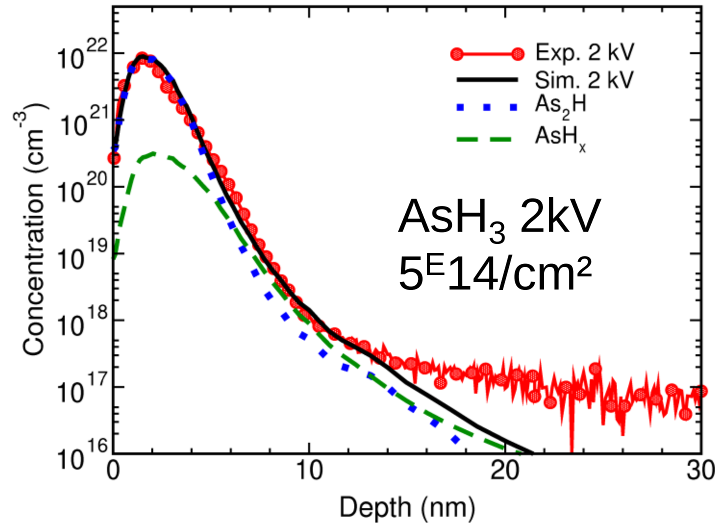
AsH_3 implant modeling

$$f(E) = \frac{5}{6(E_{max}^{5/6} - E_{min}^{5/6})} E^{-1/6}, \ E_{min} < E < E_{max}$$

Relative abondance of different ions extracted for BF3 plasma :
AsH_x^+ : 9.4 %
$As_2H_x^+$: 90.6%

+ Model for angular distribution of bombarding ions (Gaussian spread, σ=10°)





IIT2014 : Simulation of AsH3 Plasma Immersion Ion Implantation into Silicon
Alex Burenkov, Jürgen Lorenz, Yohann Spiegel, Frank Torregrosa,

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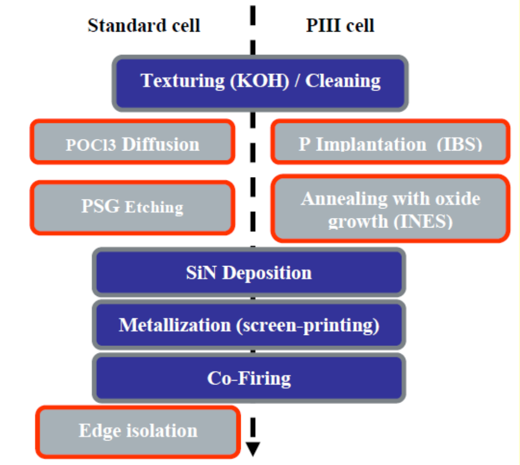
Solar cell fabrication on p-type c-Si

INES INSTITUT NATIONAL DE L'ENERGIE SOLAIRE

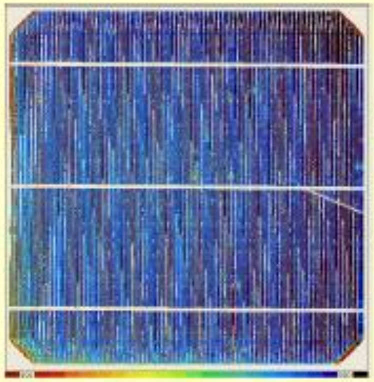
Cell performances

=> Standard and PIII processes applied on identical 239 cm² c-Si Cz wafers

(mean values)	Standard (PoCl3)	PIII (High dose)	PIII (Low dose)
Jsc [mA/cm²]	36.6	36.4	38.0
Voc [mV]	629	634	643
FF [%]	80.3	80.9	78.6
Eff [%] +/- 0.1%	18.5	18.7	**19.2**



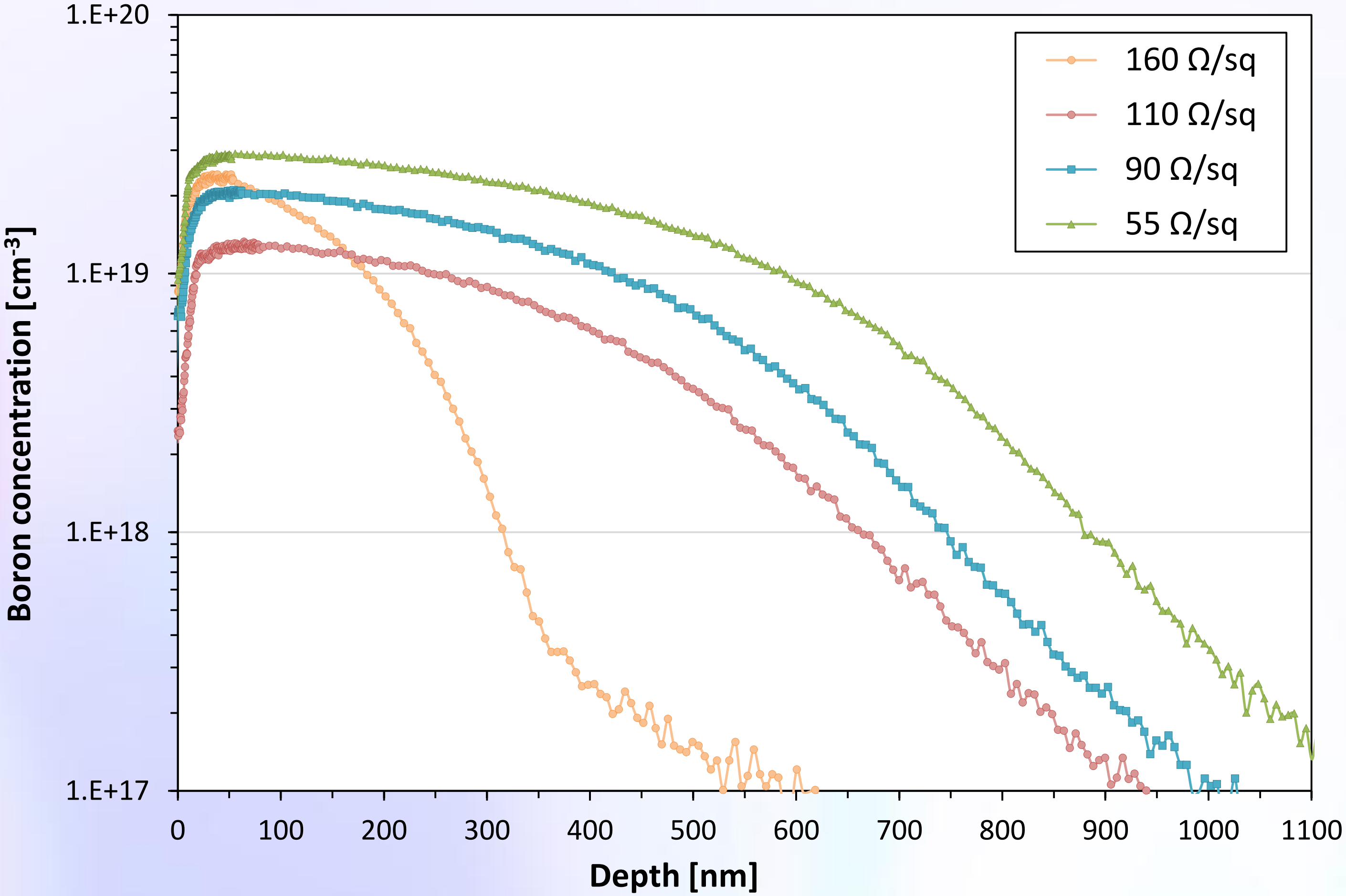
- *Best cell: **19.3%** (239cm²)*
- *Efficiency gain PIII / Diffusion: up to **+0.7%** (with same metallizations)*
- *High Dose: excellent Fill Factor / Low Dose: High Voc*
- *Weak dispersion of Eff. < +/- 0.15%*
- *Basic process repeatable and robust*



Map of Ligh Beam Induced Current of a 19.3% cell. Mean Diffusion Length ~700µm

⇨ 19.4% efficiencies demonstrated with advanced ARC layer on homogeneous emitter.

PULSION® – p-type doping



⇨ Oxidizing annealing to enable the growth of a thin oxide.

PULSION® Solar — 3 configurations

Solar cell research lab

- PULSION® Nano: up to 4 cells
  - Manual load lock
  - Other applications (semi, nanosciences)

Solar cell pilot line

- Large chamber: > 18 cells
- Manual loadloack

Solar cell production

- With loadlock
  - Medium throughput (600 cells/hr)
  - High productivity (2400 cells/hr)

Tool just installed in Taiwan

Conclusions

- Very good conformality with no fin erosion and good cristal recovery has been demonstrated with AsH_3 PULSION® doping
- Hot implantation is now available on PULSION® allowing drastic reduction of defects even using AsH_3 plasma doping with high dose
- PULSION® allows shallow doping and conformal doping for BSI and DTI Cmos imager application
- Possibility to easily extend to 450 mm has been demonstrated
- TCAD models are now availables for BF_3 and AsH_3 PULSION ® Implantations (planar doping conditions only for the time being)

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