25 imec Years of Making Technology Fly

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FINFET doping :
fabrication and metrology challenges

W.Vandervorst

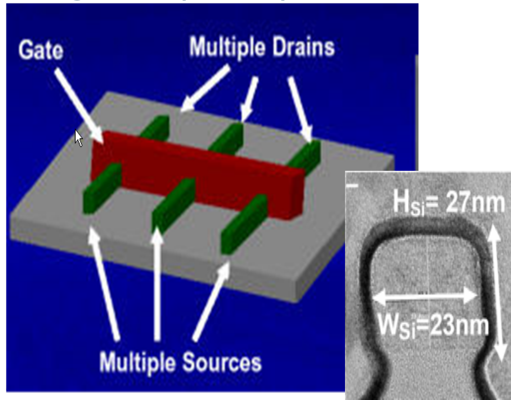
Imec, Belgium

Also : Inst. Kern- en stralingsfysika, KULeuven

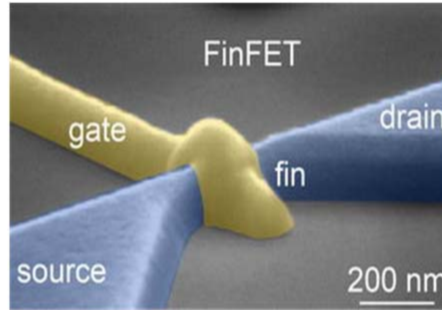
intel Micron Panasonic ideas for life qimonda SAMSUNG tsmc ELPIDA hynix Semiconductor PSC NXP infineon SONY QUALCOMM ST

Why FINFET?

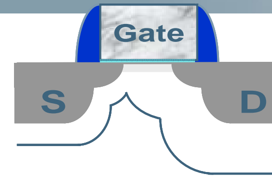
Trigate (Intel)

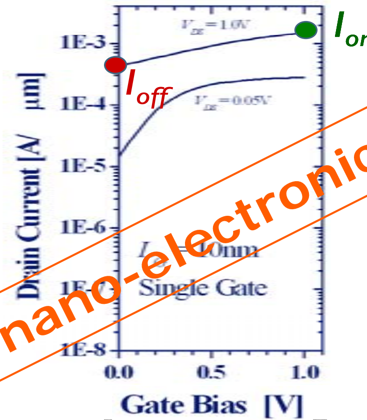


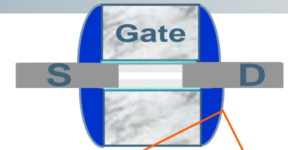
J. Kavalieros *et al*., *Symp. VLSI Tech. Dig.* 2006.

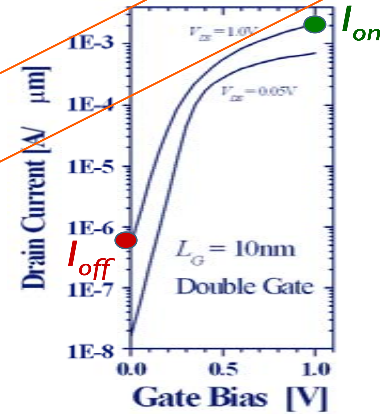


FinFET (IBM, AMD, Freescale, NXP)









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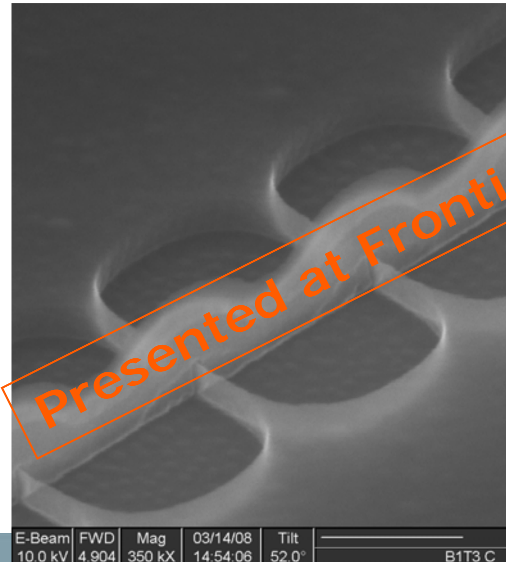
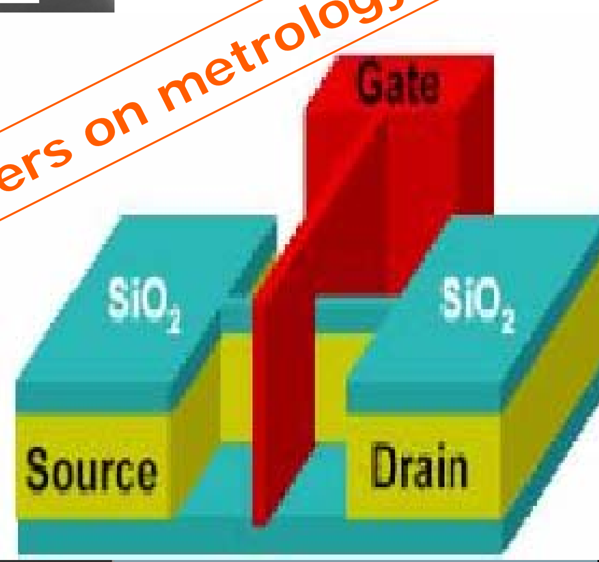
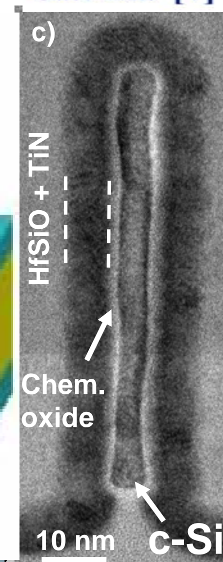
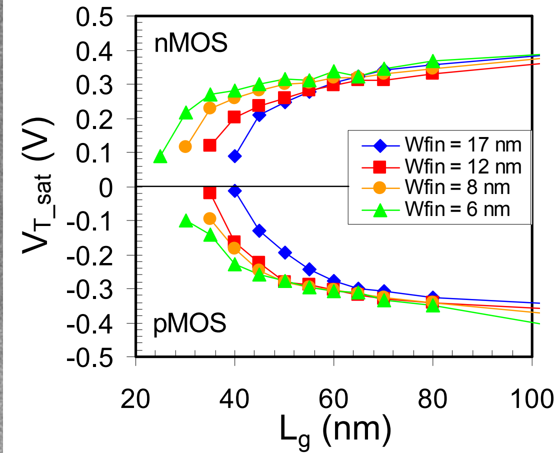
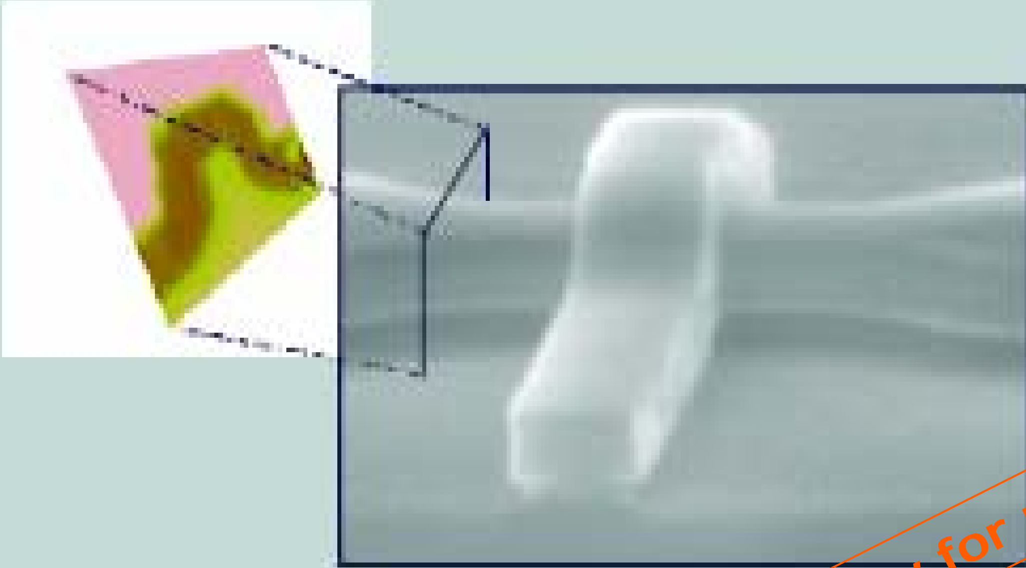


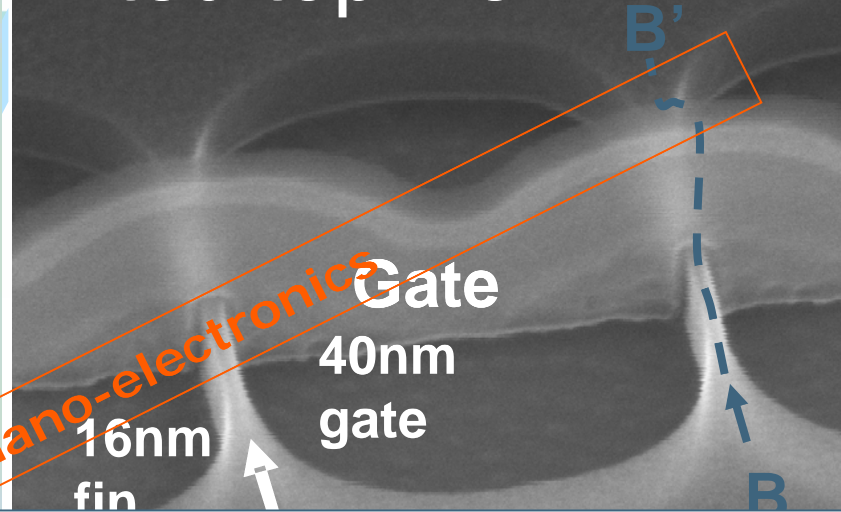


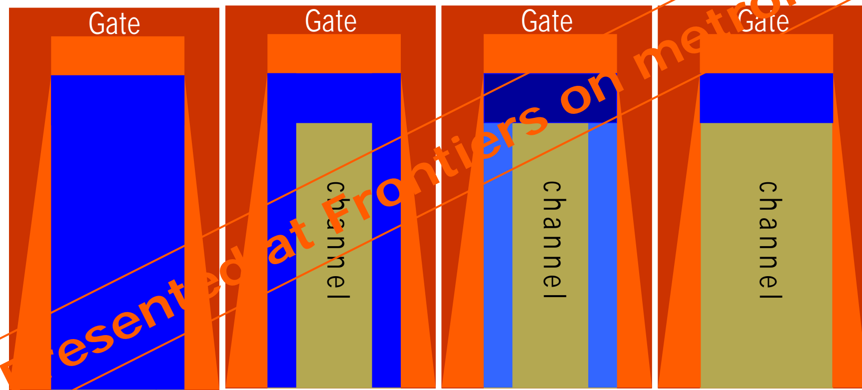


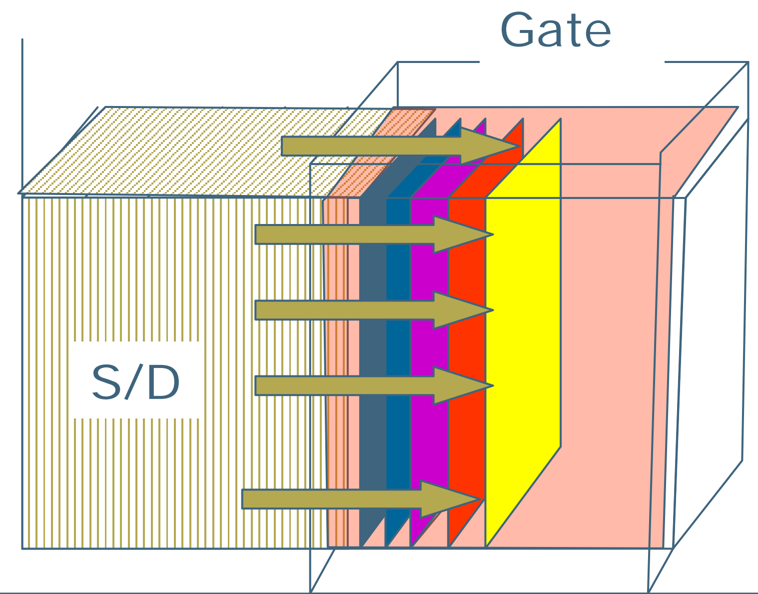


Conformal junctions in FINFET's : 3D-profiling









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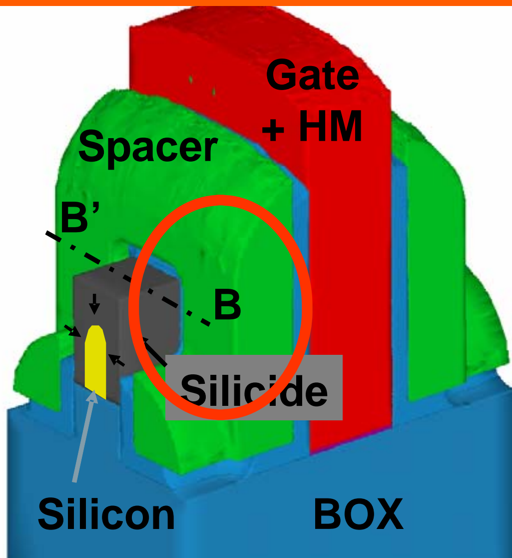
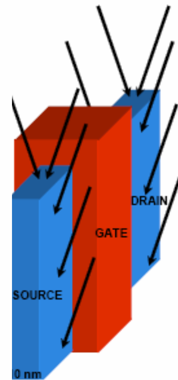
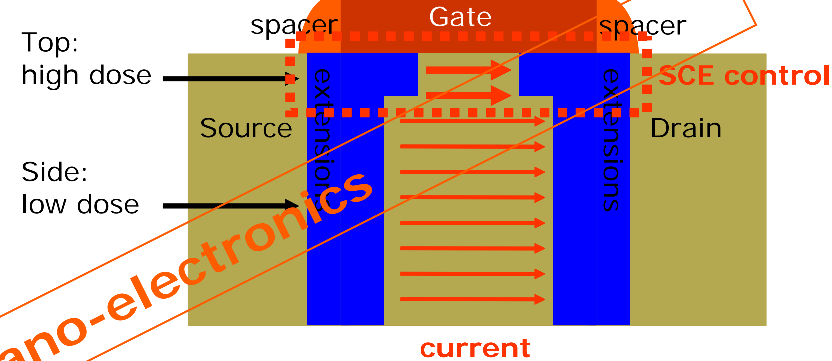
S/D Junction formation requirements

FIN resistance : high doping, overlap

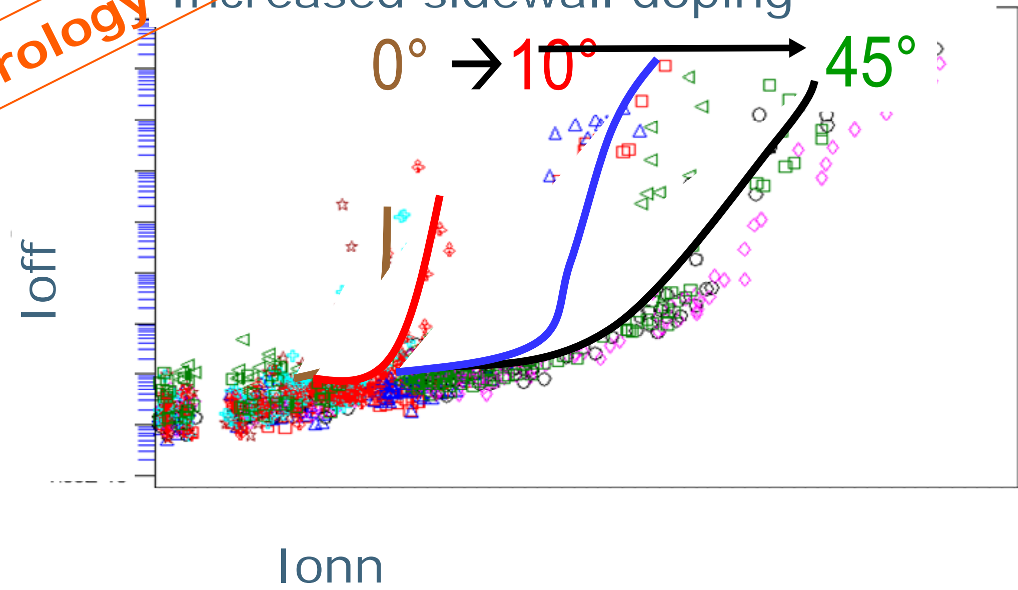
Junction conformality/uniformity

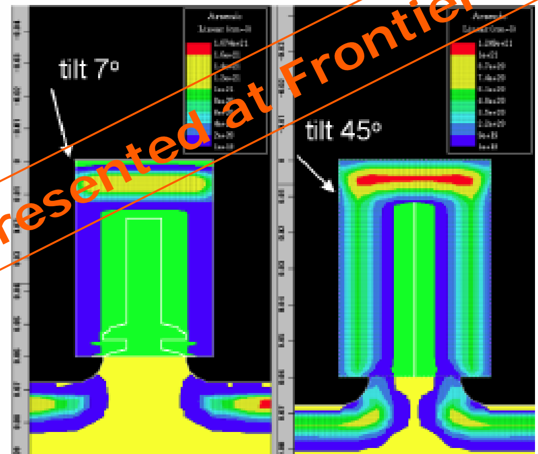






Increased sidewall doping





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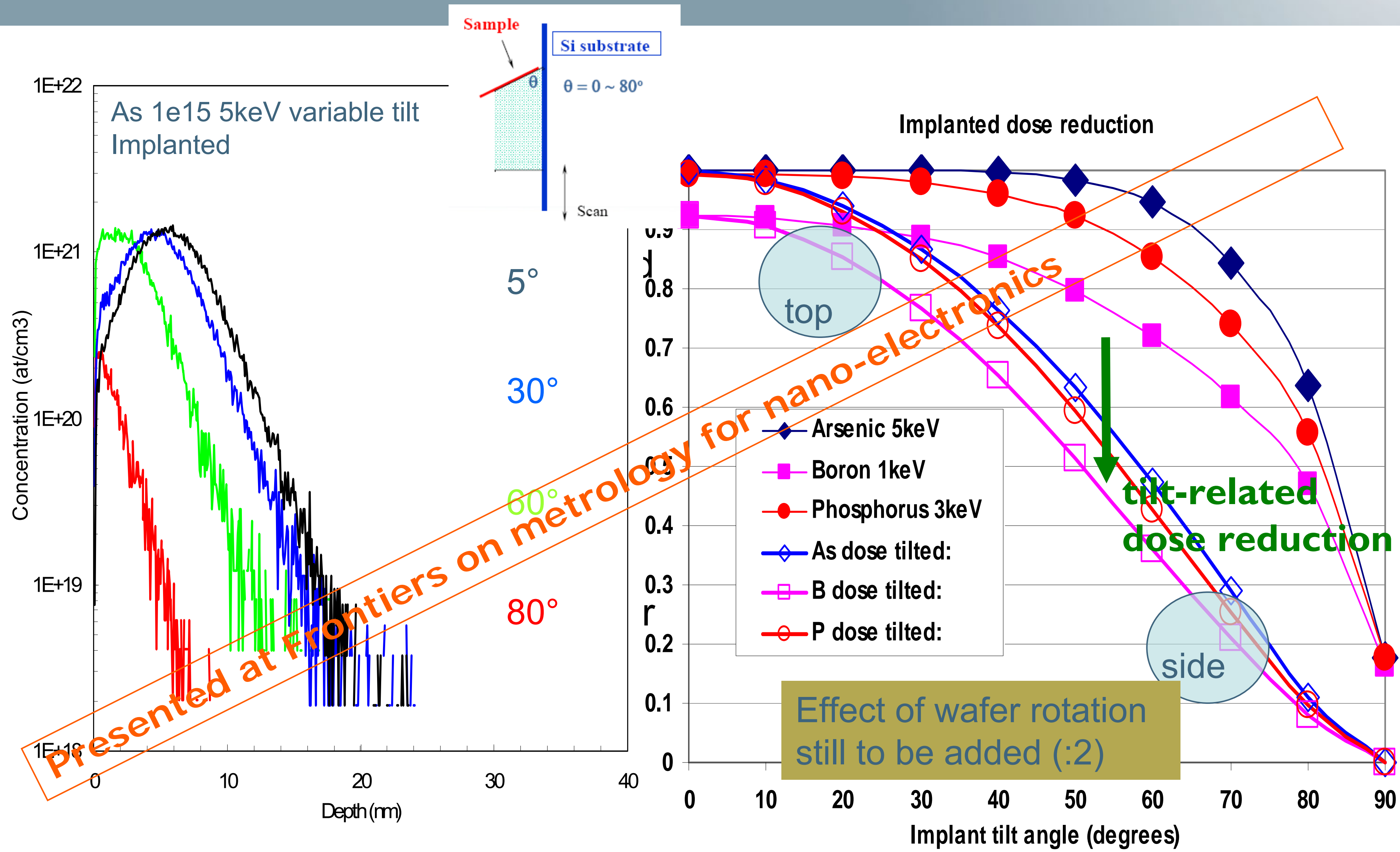
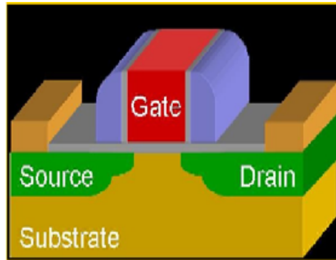
(non-conformal) Doping by I/I : Tilt angle effects



i.c.w. R.Duffy, B.J.Pawlak, NXP

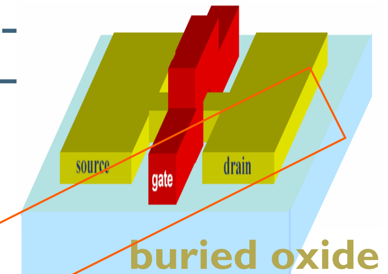
Junction parameters : Planar vs FINFET

PLANAR



- Rs
- Xj
  - Vertical
  - Lateral
- Steepness
  - Lateral
- Metrology
  - 1D (Rs, SIMS)
  - 2D (SSRM)

FINFET



- Rs
- Xj
  - ~~(Vertical)~~
  - Lateral
- Steepness
  - Lateral
- Conformality
- Metrology
  - 2D
  - 3D

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FINFET's conformal doping and its metrology

Conformal doping

- **Implantation**
  - *Tilt angle and incorporation efficiency*
  - *Shadowing in dense structures (< 10-20° tilt)*
  - *Amorphization and recrystallization*
- **Plasma immersion**
  - *Conformality ??*
  - *Incorporation versus erosion*
- **VPD**
  - *Integration*
  - *Outdiffusion*

Properties

Rs vs Xj has no meaning!

Lateral profiles, sidewall dose, conformality

Metrology

- ***SIMS through FINs***
- ***Resistors***
- ***S/D area's : X-SSRM***
- ***3D-SSRM***
- ***3D-Atomprobe***

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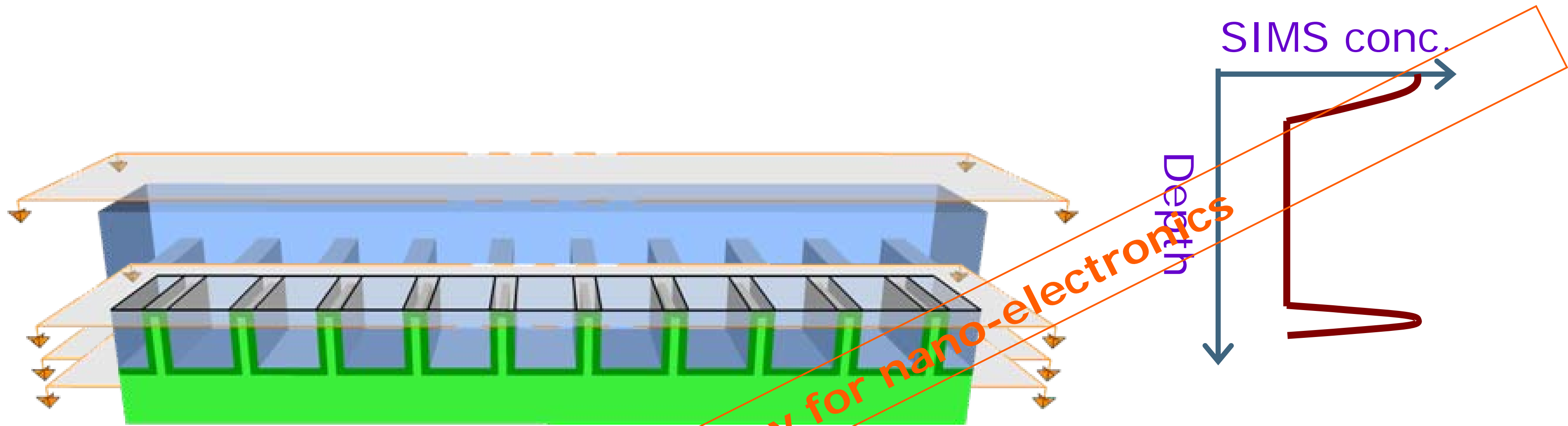
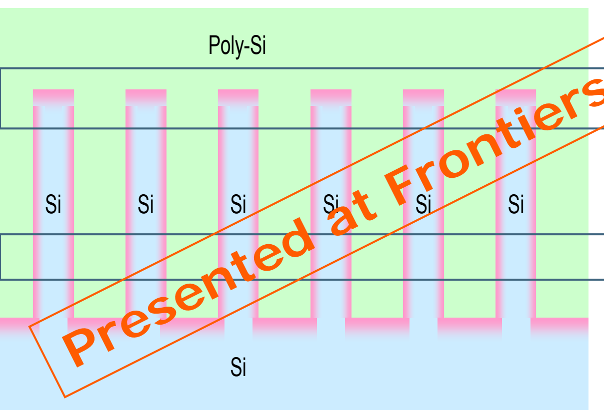
SIMS through FINs





$$N_{total} = Concentration \times \Delta H_{SIMS-crater} \times B_{SIMS-crater} \times W_{SIMS-crater}$$

$$N_{total} = No.\ of\ fins\ in\ SIMS\ crater \times D_{fin} \times \Delta H_{SIMS-crater} \times B_{SIMS-crater}$$

$$D_{fin} = Concentration \times P_{fin}$$

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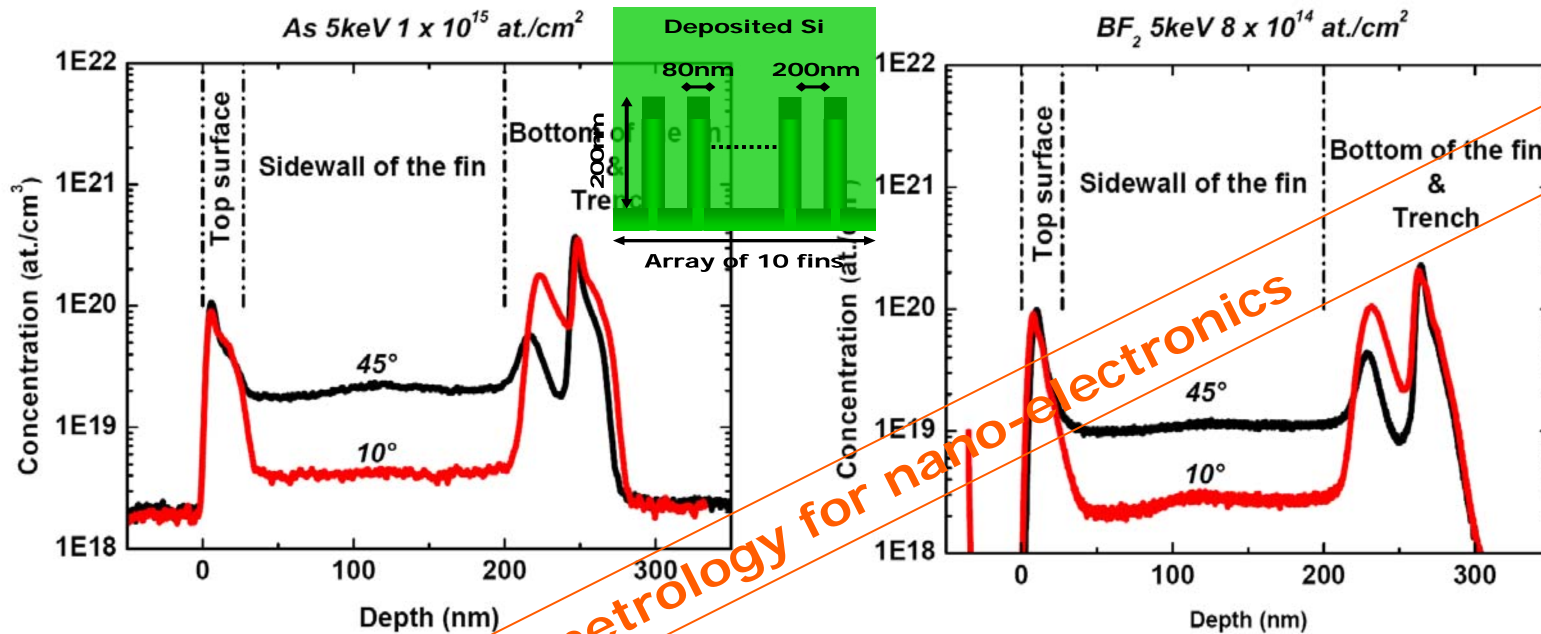
SIMS results

- BF_2 5keV 8e14 at 45° and 10°
- As 5keV 1e15 at 45° and 10°
- RTA annealed at 1050°C



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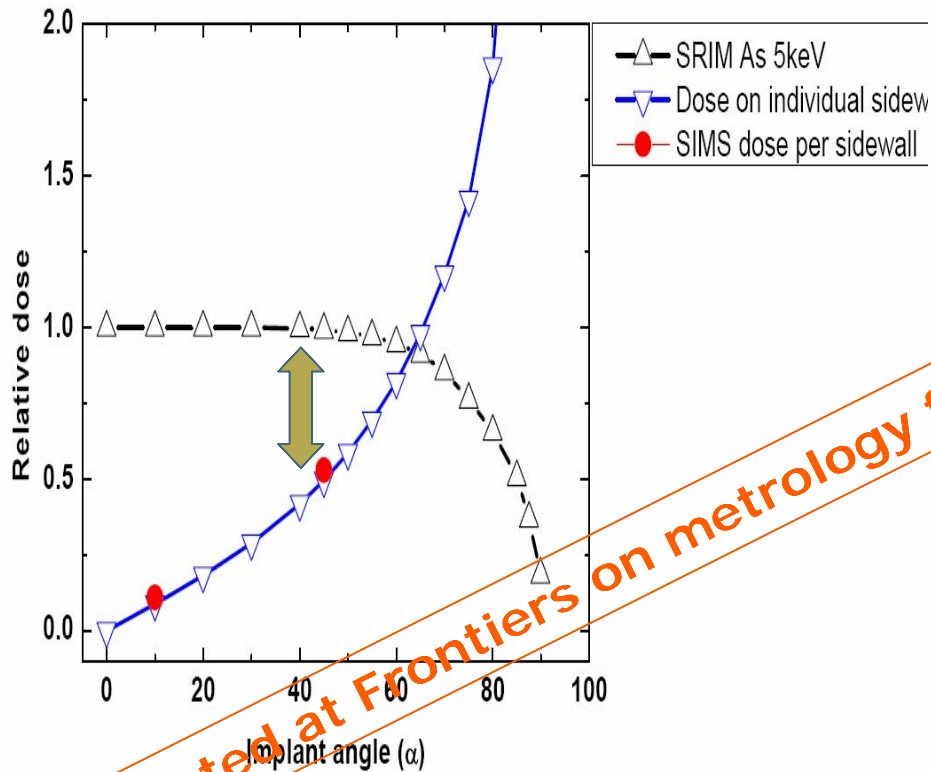
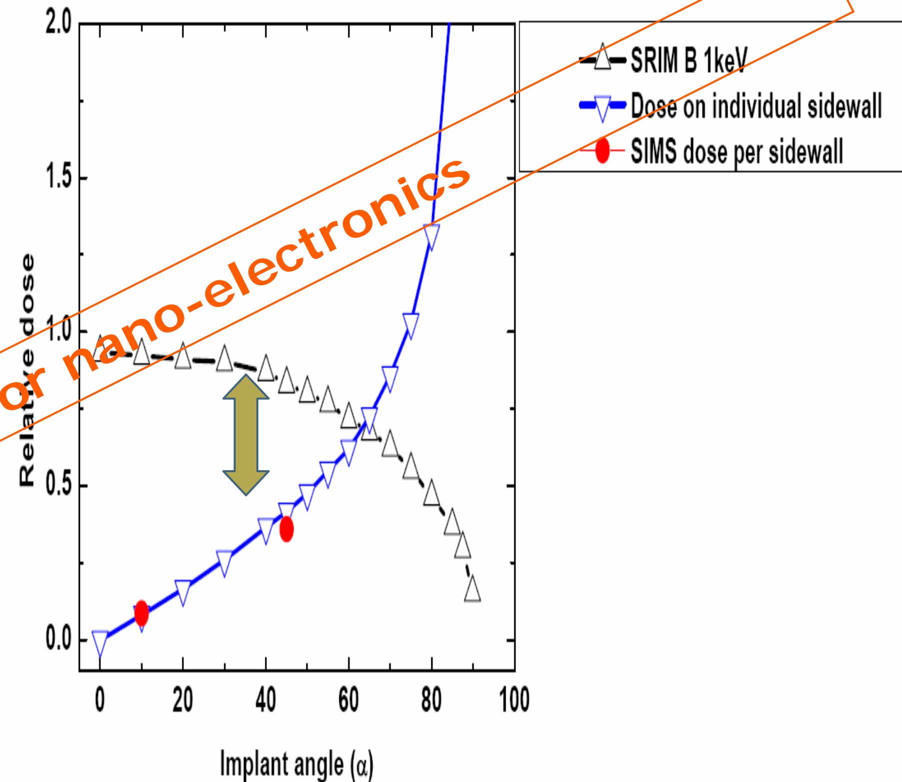
Implants at 5keV	Sidewall Dose retention		
	45° tilt	10° tilt	Sidewall dose retention Ratio (45° vs. 10 °)
Arsenic 1 x 10^{15} /cm^2	1.06 x 10^{15} /cm^2	2.20 x 10^{14} /cm^2	4.83
BF_2 8 x 10^{14} /cm^2	5.74 x 10^{14} /cm^2	1.38 x 10^{15} /cm^2	4.18

Sidewall doping by I/I :SIMS vs theory

Includes effect of 2 quad. implant





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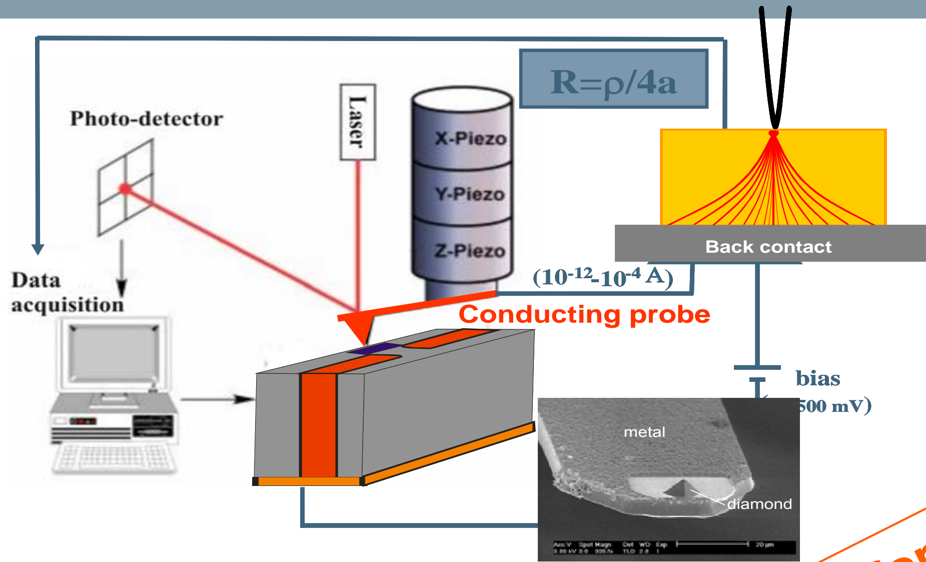
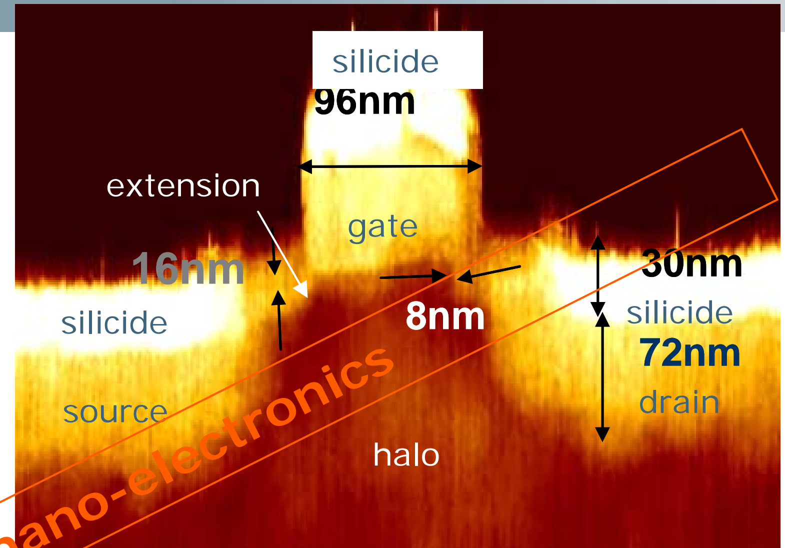
W.Vandervorst et al. , J. Vac. Sci. Technol. B 26 (1), Jan/Feb 2008, 396-401

Scanning Spreading Resistance Microscopy :

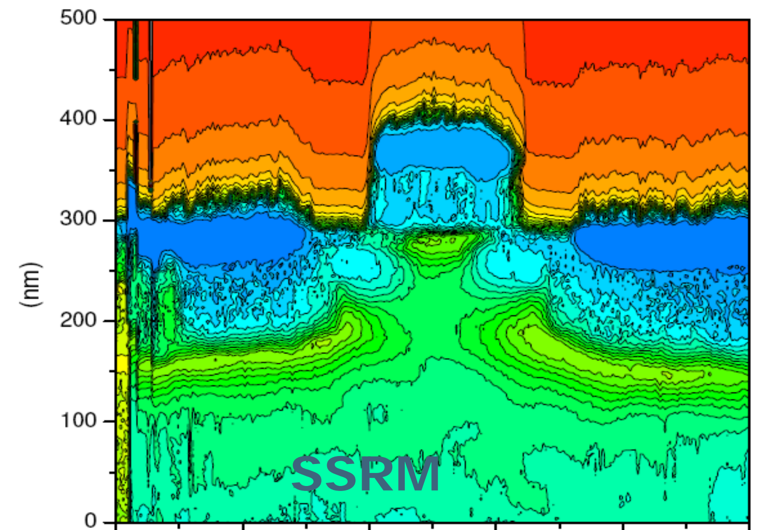
2D-profiling with sub-nm resolution





We can see it, can you make it?

	ITRS 2005	ITRS 2010	SSRM	ITRS 2016
Lateral/vertical steepness (nm/dec)	4.25	2.7	1 - 1.5	1.6
Lateral/depth resolution (nm)	2	2	0.5 - 1	1
Concentration precision (%)	2%	2%	3-5%	2%
Dynamic range (at/cm3)	10^{14} - 10^{21}	10^{14} - 10^{21}	10^{15} - 10^{21}	10^{14} - 10^{21}



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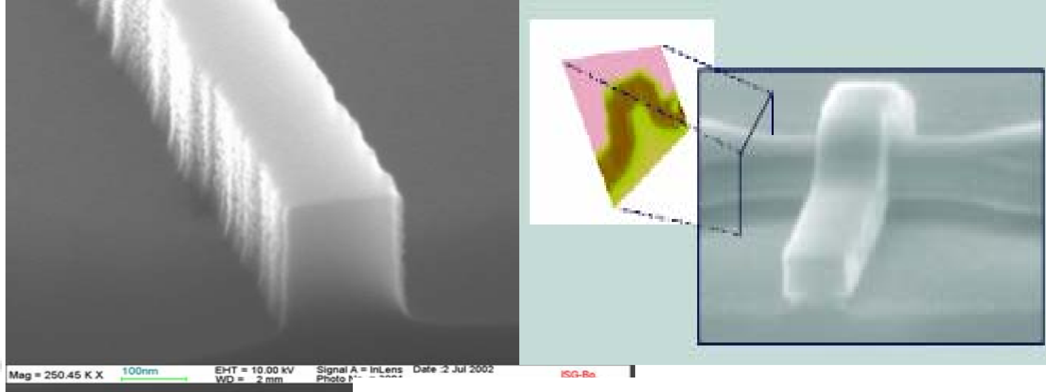
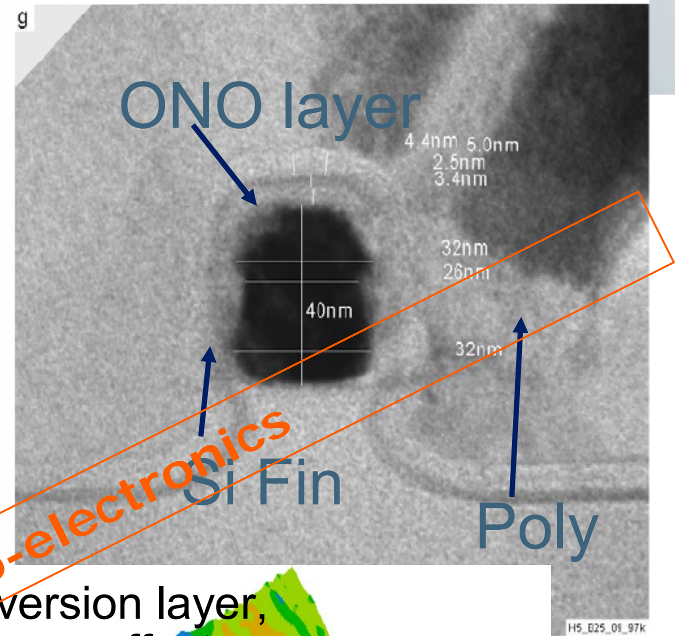
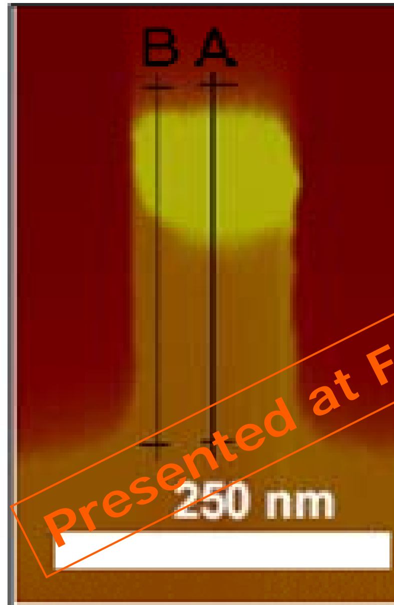
P.Eyben, W.Vandervorst, D.Alvarez,, M.Xu. and M.Fouchier, in “Scanning Probe Microscopy, Electrical and Electromechanical Phenomena at the Nanoscale”, edited by S. Kalinin and A. Gruverman (Springer, New York, 2007), Vol. 1, Chapter 2, p. 31

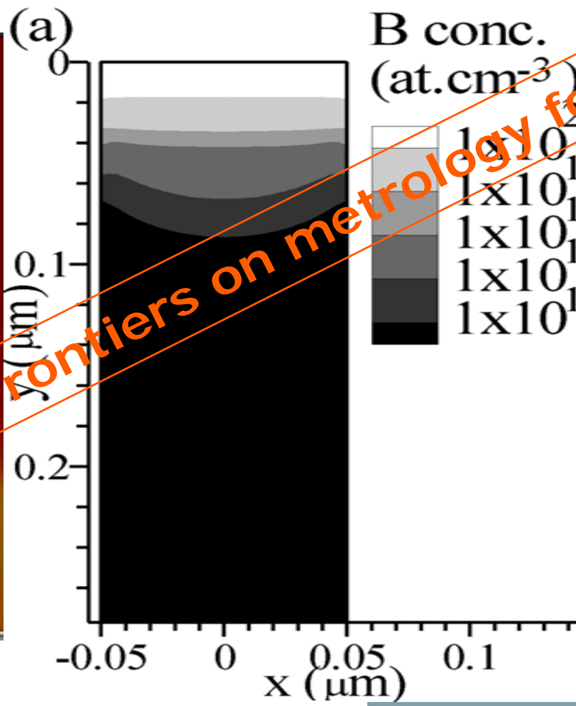
SSRM (FIN-like) applications

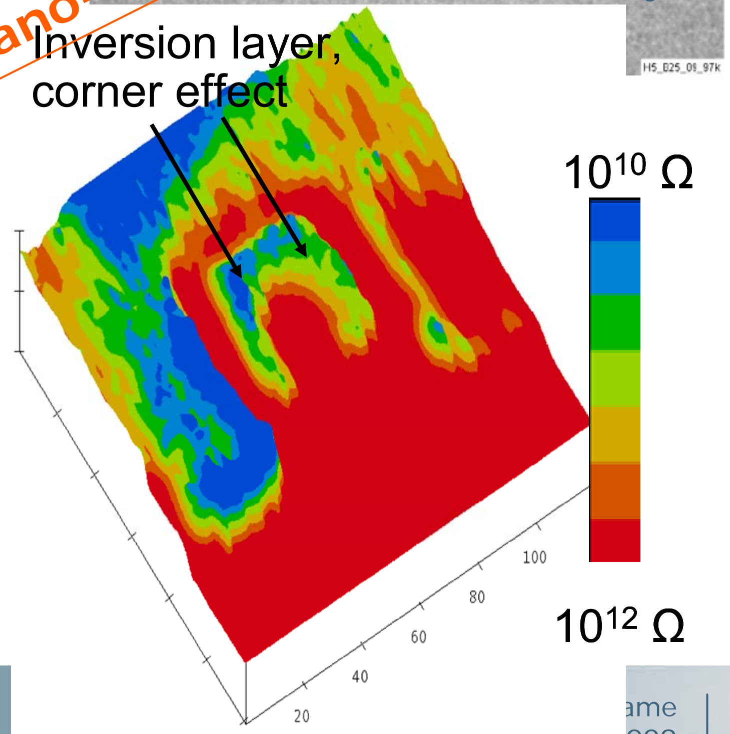
M.Specht, D.Alvarez











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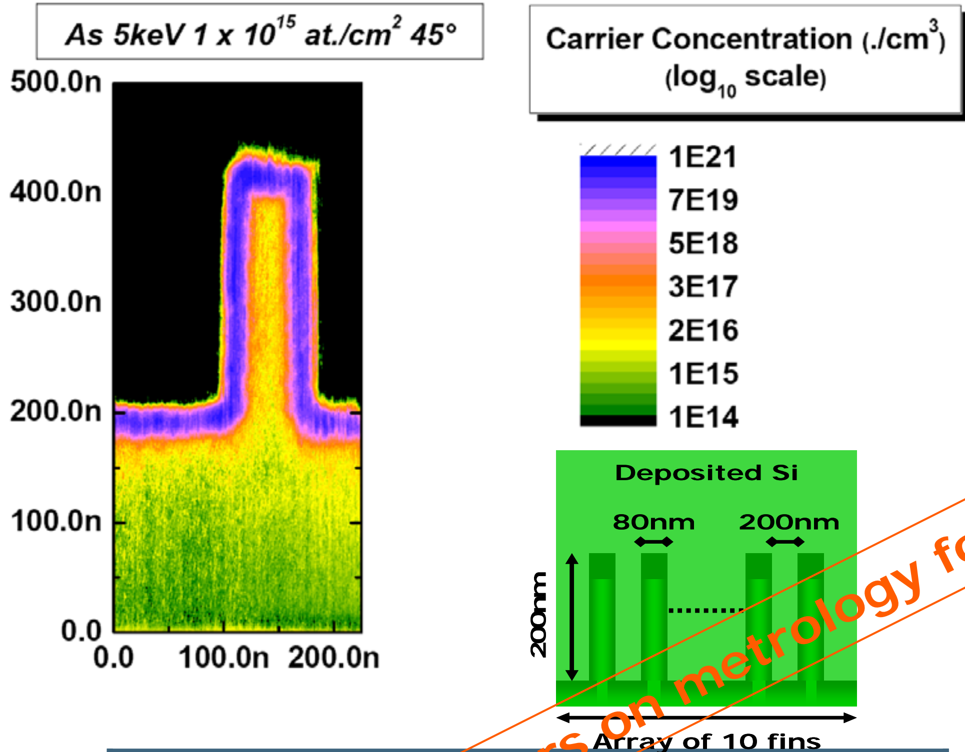
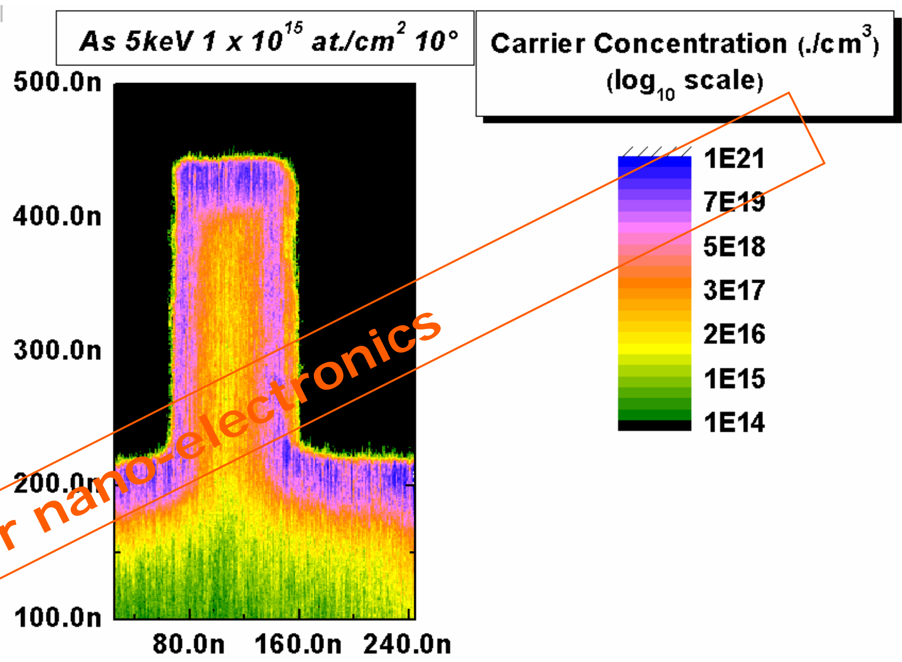
S.Kluth et al.

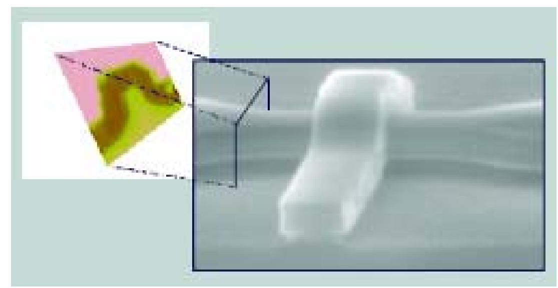
SSRM on FIN : As I/I





$$Depth_{sidewall} = tan(\alpha) \times Depth_{top-surface}$$

Arsenic Implant			
Implant angle	Top	Sidewall	Theoretical
45°	28nm	24nm	28nm
10°	35nm	18nm	6nm



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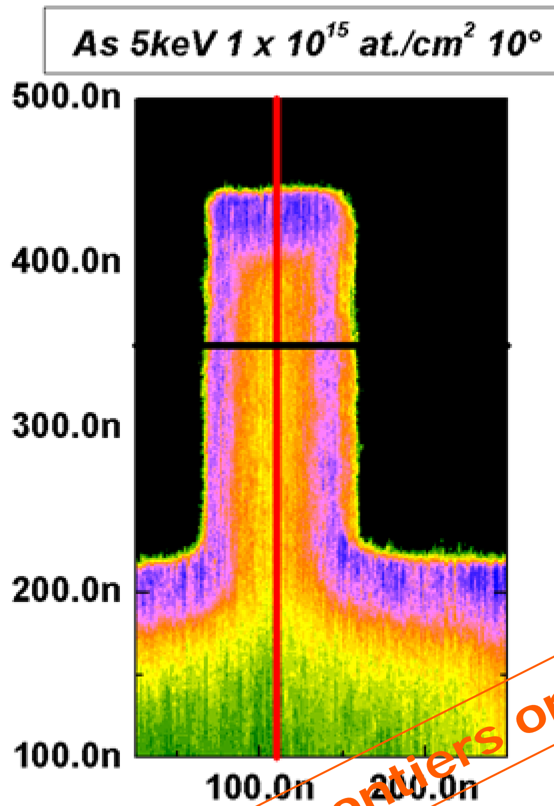
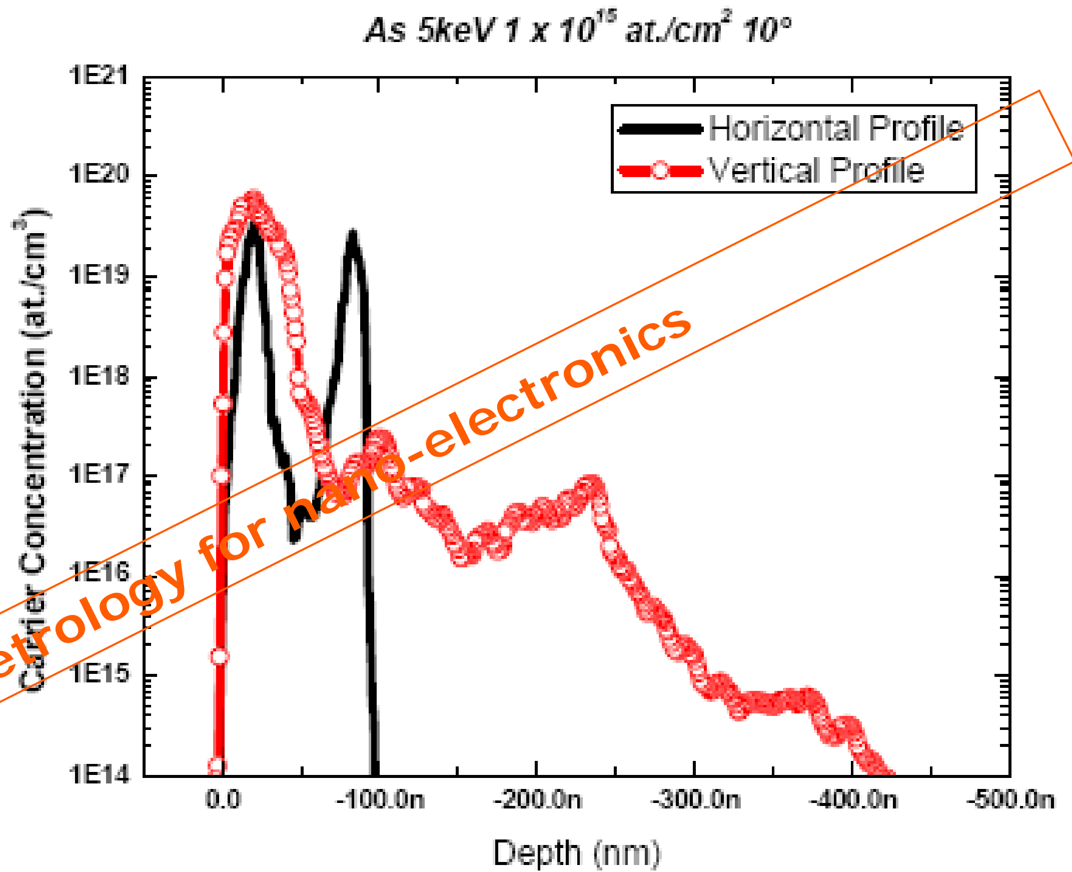
J.Mody et al, Insight-2009

Additional information using SSRM





- Ability to obtain 1D carrier profile with sub-nm resolution.
- Resolve the center of the fin which cannot be resolved using SIMS.

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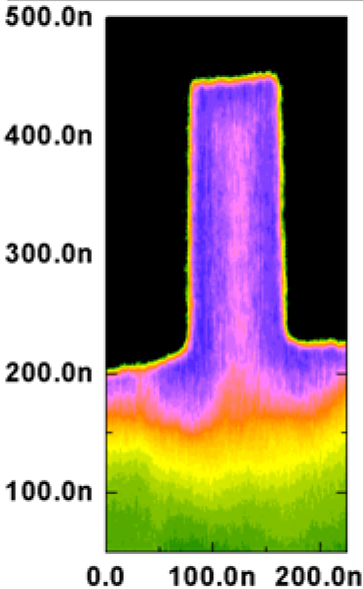
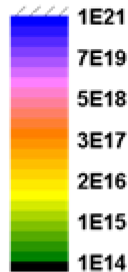
SSRM on FIN : BF2 I/I

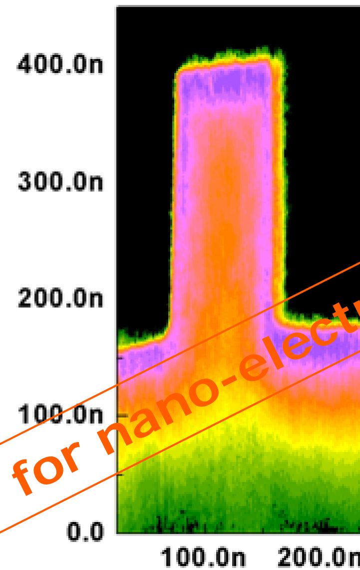
BF_2 5keV 8 x 10^{14} at./cm^2 45°



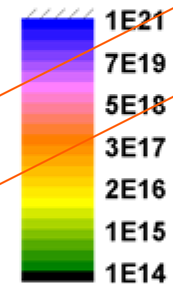
Carrier Concentration (./cm^3) ($\log_{10}$ scale)



BF_2 5keV 8 x 10^{14} at./cm^2 10°



Carrier Concentration (./cm^3) ($\log_{10}$ scale)



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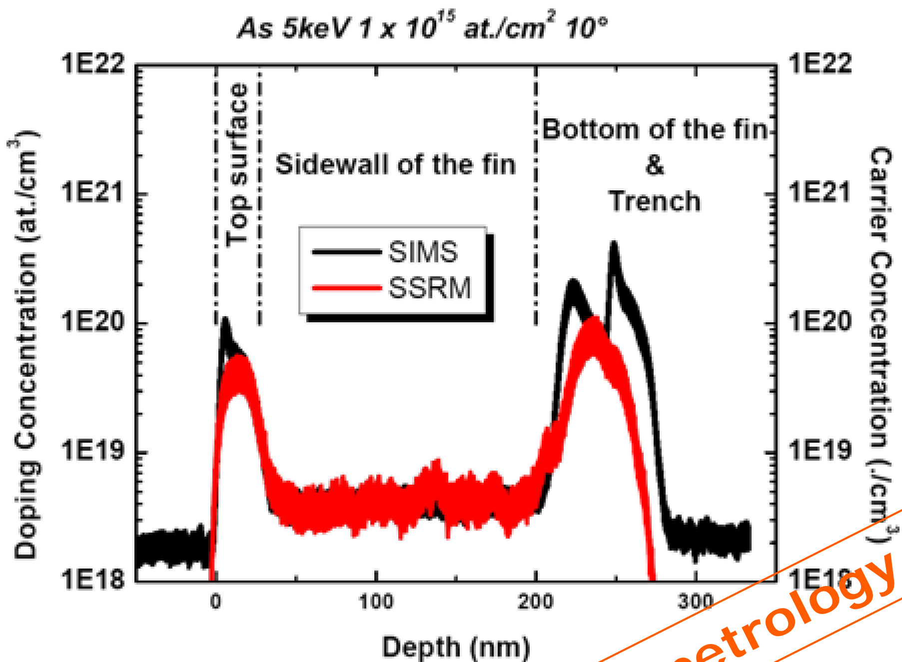
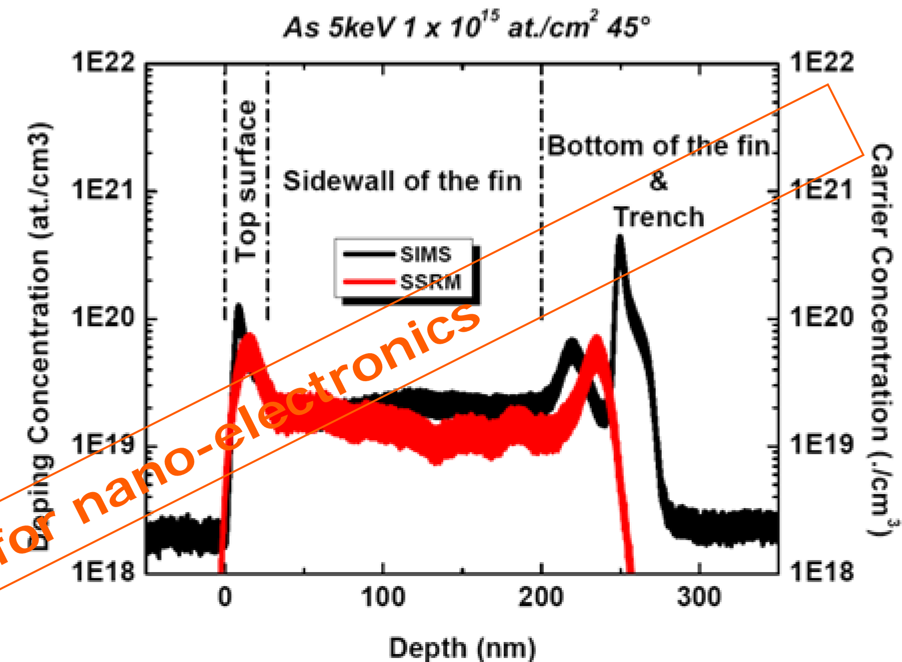
BF_2 Implant			
Implant angle	Top	Sidewall	Theoretical
45°	35nm	31nm	35nm
10°	36nm	15nm	7nm

$$Depth_{sidewall} = \tan(\alpha) \times Depth_{top-surface}$$

Comparison SIMS-SSRM





Implant	SIMS Sidewall Ratio (45° vs. 10°)	SSRM Sidewall Ratio (45° vs. 10°)
Arsenic	4.83	3.42

Implant	SIMS/SSRM Sidewall Ratio 10°	SIMS/SSRM Sidewall Ratio 45°
Arsenic	0.95	1.33

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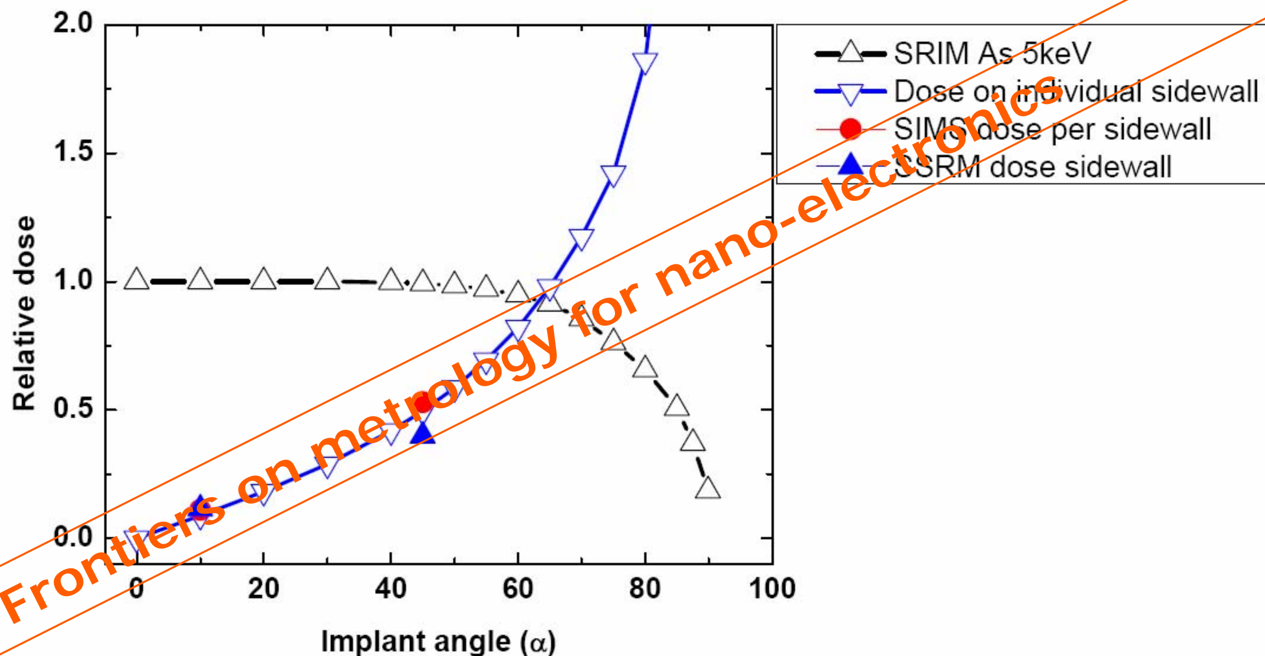
Summary of sidewall doping : As

$$Single\ sidewall\ dose = Implant\ Dose \times \sin(\alpha)/\cos(\alpha) \times incorporation\ efficiency\ (\alpha)$$

$$D_{fin} = (Concentration \times P_{fin})/2$$



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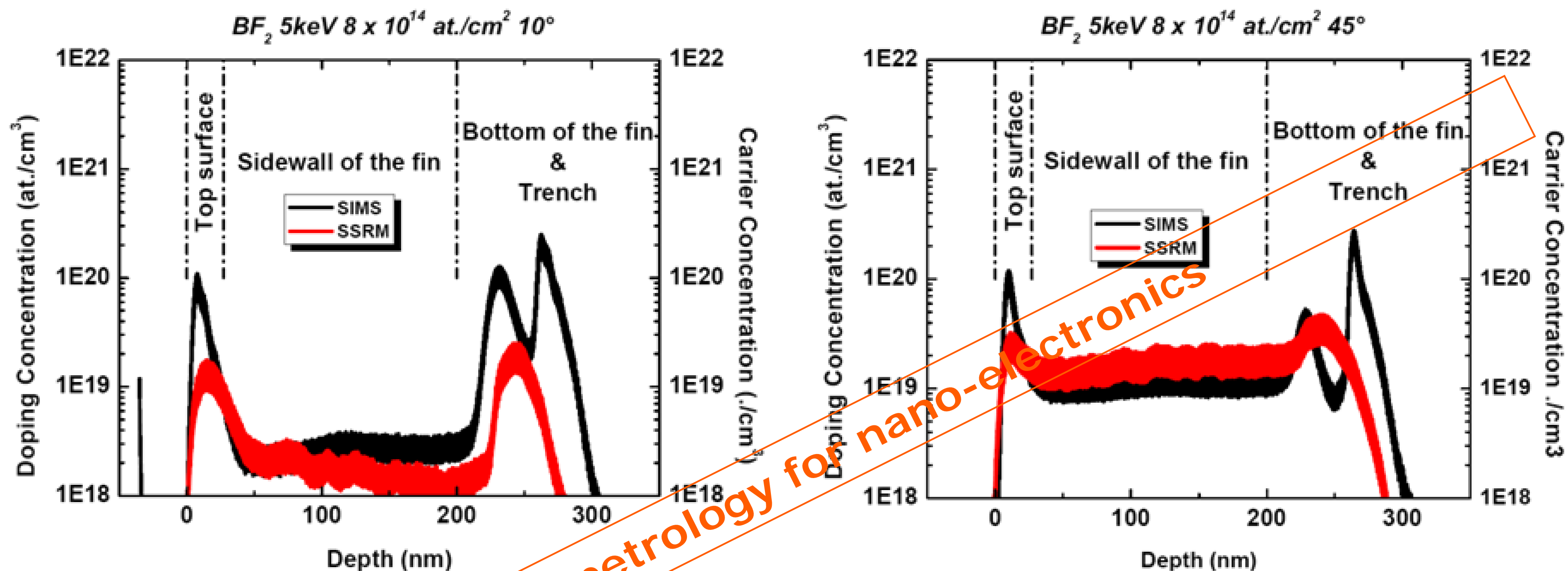
Comparison SIMS-SSRM



Implant	SIMS Sidewall Ratio (45° vs. 10°)	SSRM Sidewall Ratio (45° vs. 10°)
BF_2	4.18	9.79

Implant	SIMS/SSRM Sidewall Ratio 10°	SIMS/SSRM Sidewall Ratio 45°
BF_2	1.52	0.63

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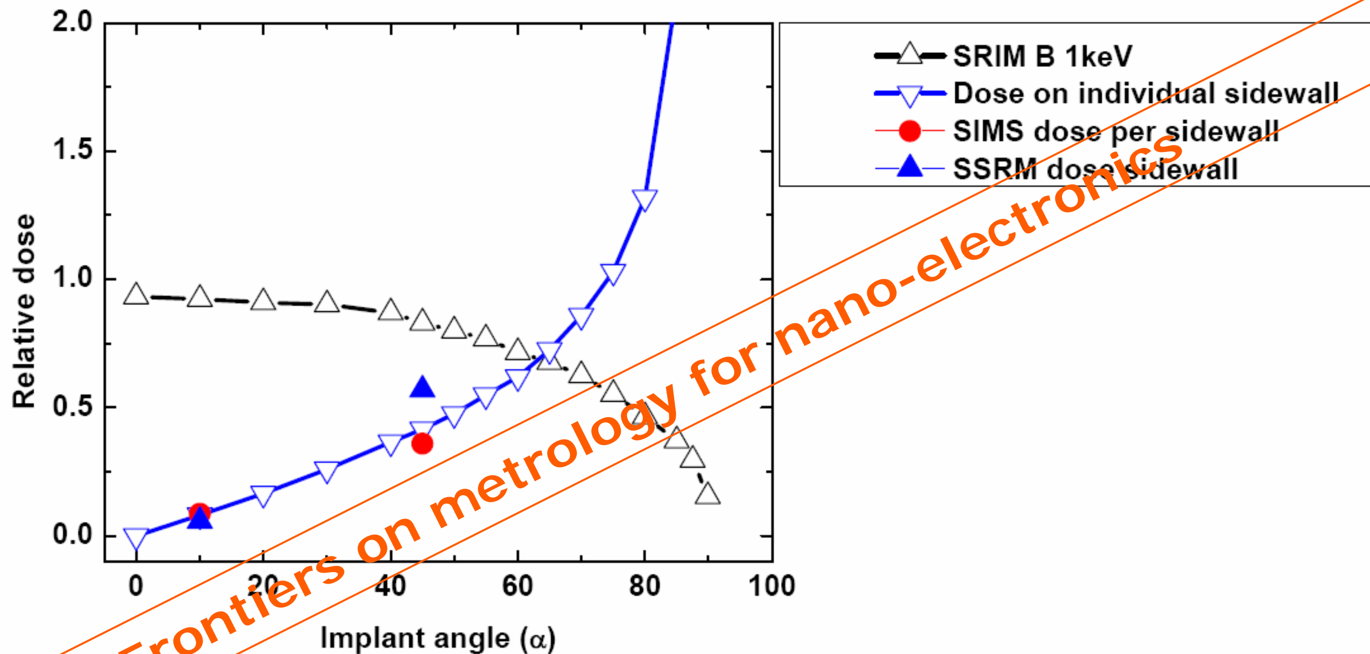
Summary of sidewall doping : BF2

$$\textit{Single sidewall dose} = \textit{Implant Dose} \times \sin(\alpha)/\cos(\alpha) \times \textit{incorporation efficiency}(\alpha)$$

$$D_{fin} = (\textit{Concentration} \times P_{fin})/2$$



- Good correlation between theoretical model, SIMS and SSRM

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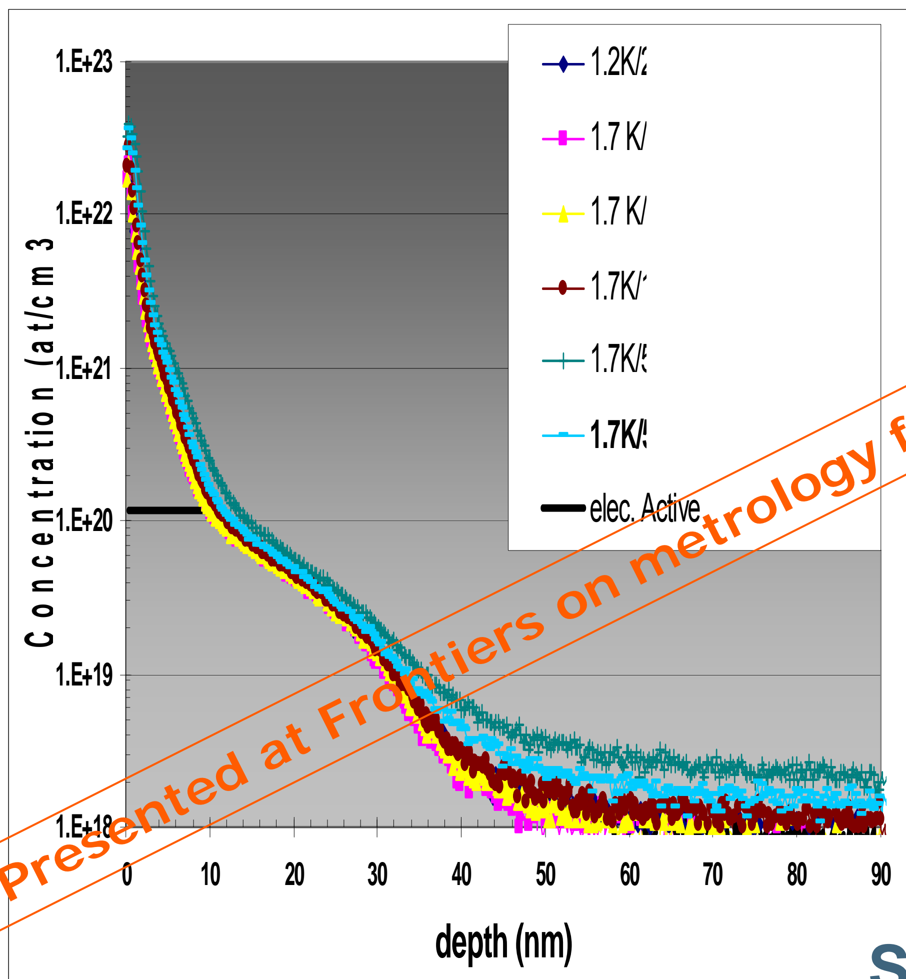
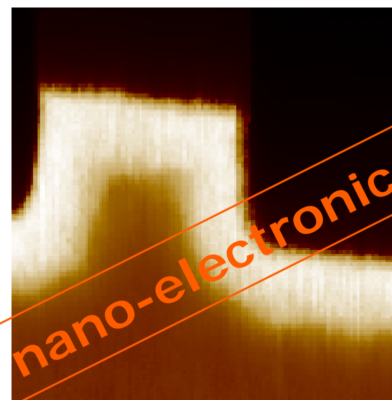
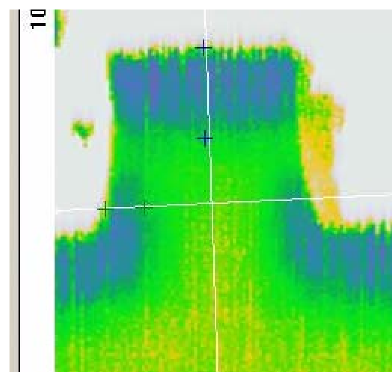
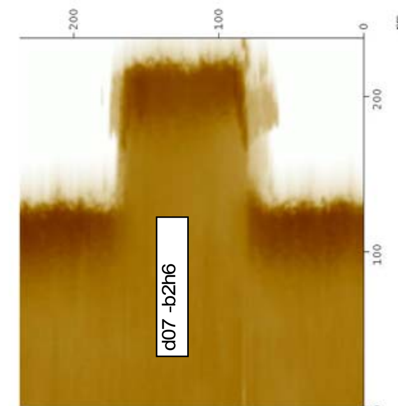
1D-profiles (and 1D-tuning) are **meaningless**





Dose (atm/cm2)	Rs (Ω/cm2)
2.47E15	457
2.52E15	457
2.51E15	-
4.98E15	446





Similar 1D-profiles give very different conformality!!!

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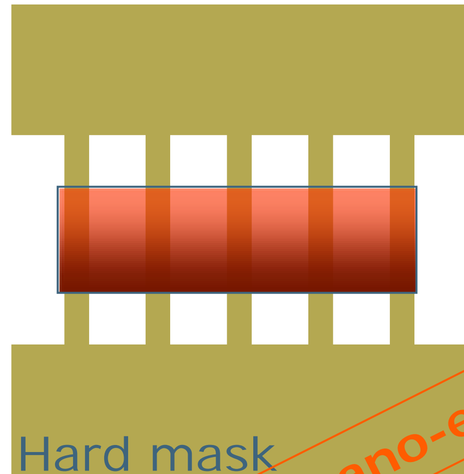
Resistor methodology

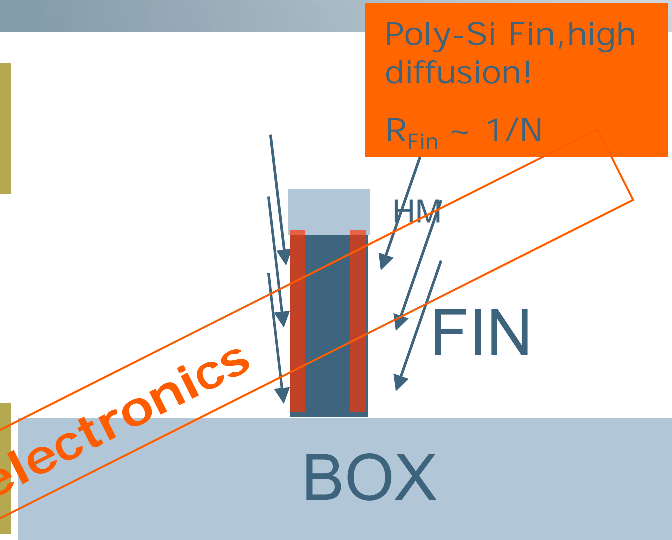


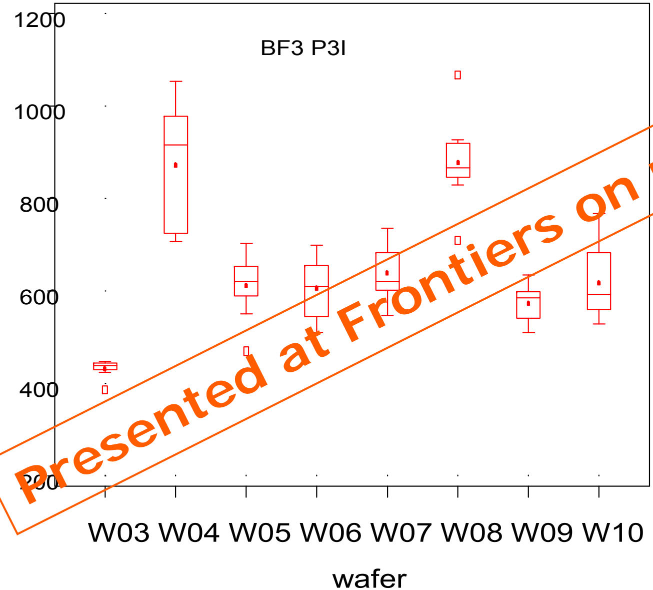
Hard mask protecting top of FIN

Implant or Plasma

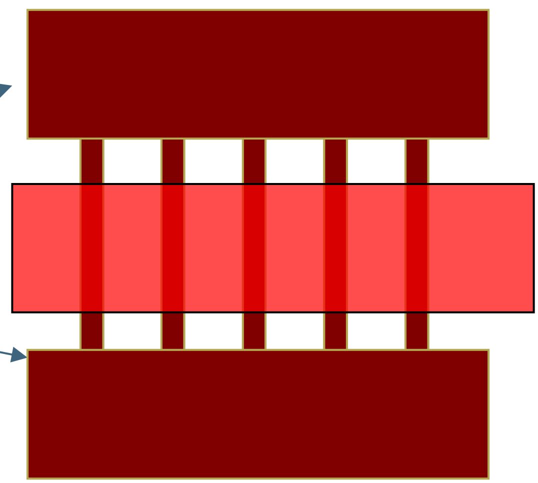
Poly-Si Fin,high diffusion!

$R_{Fin} \sim 1/N$





Full silicidation of unprotected area.



Pseudo VDP- or 2PP measurement

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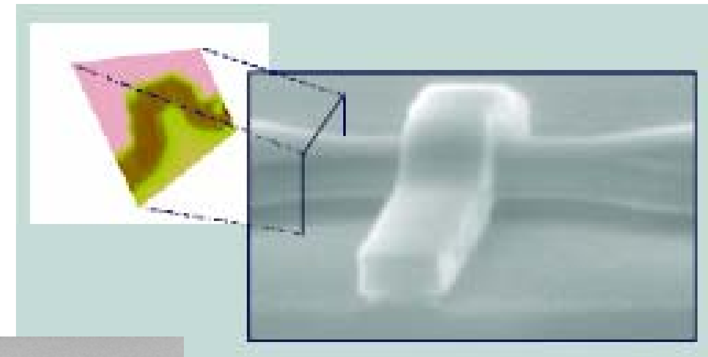
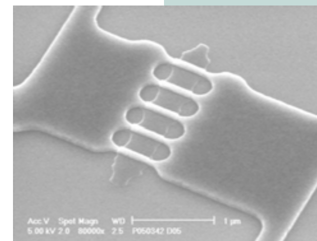
Metrology for conformality

- **SIMS through FIN's** :
  - Dopants,not active carriers
  - No details on lateral junctions depths
  - No wafer mapping
- **Scanning Spreading Resistance Microcopy (SSRM) on cross sections of S/D fin's**
  - Active carriers, real X_{lat} numbers
  - No wafer mapping
- **Resistors** (R ~ 1/Sidewall dose)
  - Relative
  - Wafer mapping

R.Duffy et al., MRS -2008, J.Mody, Insight-2009

P.Eyben, Vandervorst W. et al. . "Scanning Probe Microscopy" : *Electrical and Electromechanical Phenomena at the Nanoscale*. Chapter II:SSRM, pp.31-87 (2007) (Springer).





W.Vandervorst et al., Proc. INSIGHT-2007, JVST B (2008)

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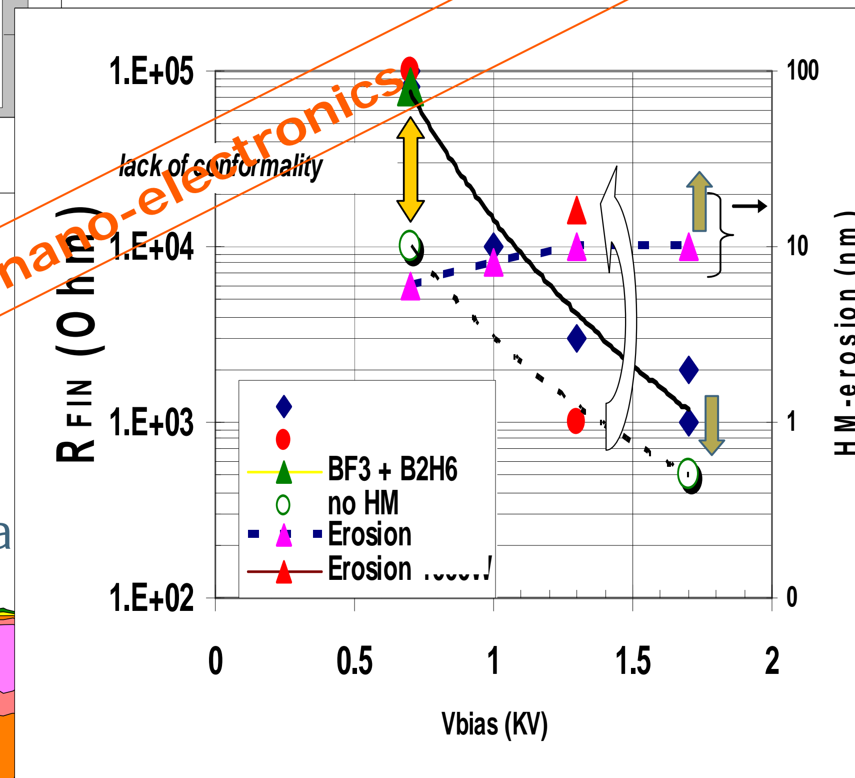
plasma doping : Concurrent doping and erosion.

1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
R FIN
0
50
100
150
norm. BF3-dose

Spreading Resistance (ohms)
1.00E+07
1.00E+06
1.00E+05
1.00E+04
1.00E+03
0
50
100
150
Depth (nm)
D06 vert in
D06 vert out
D06 lat in

SSRM : Conforma



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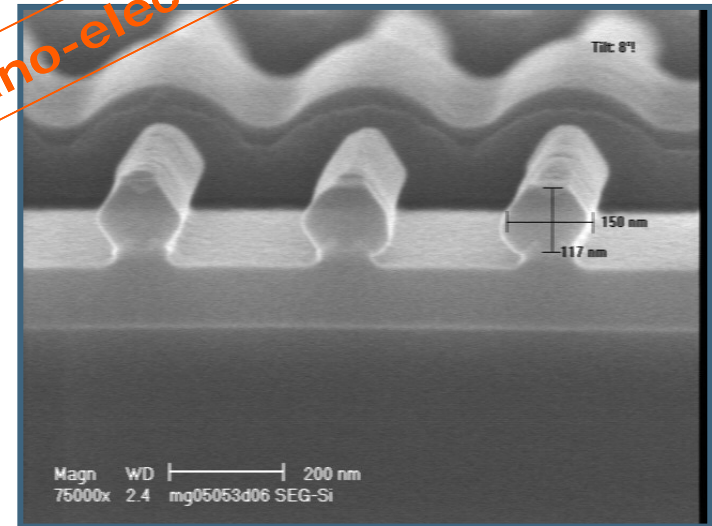
W.Vandervorst, IIT-2008

3D-metrology

- Carriers :
  3D-SSRM : Slice and view

- Dopants
  Tomographic atomprobe



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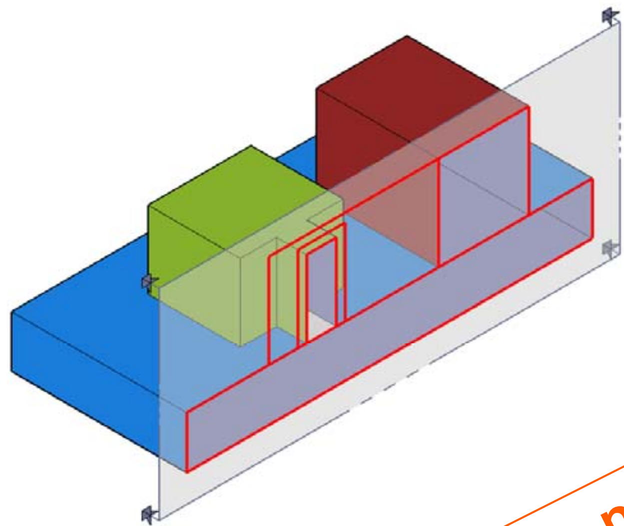
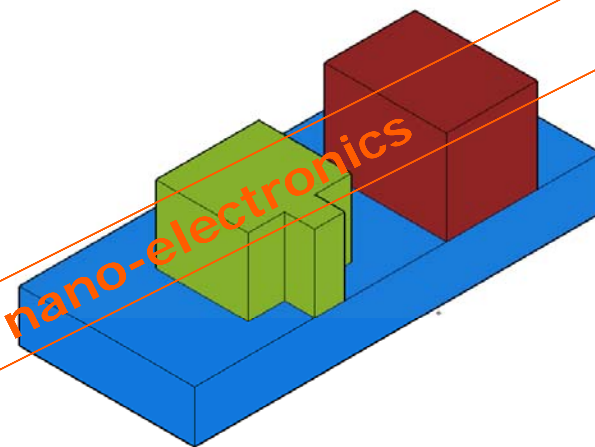
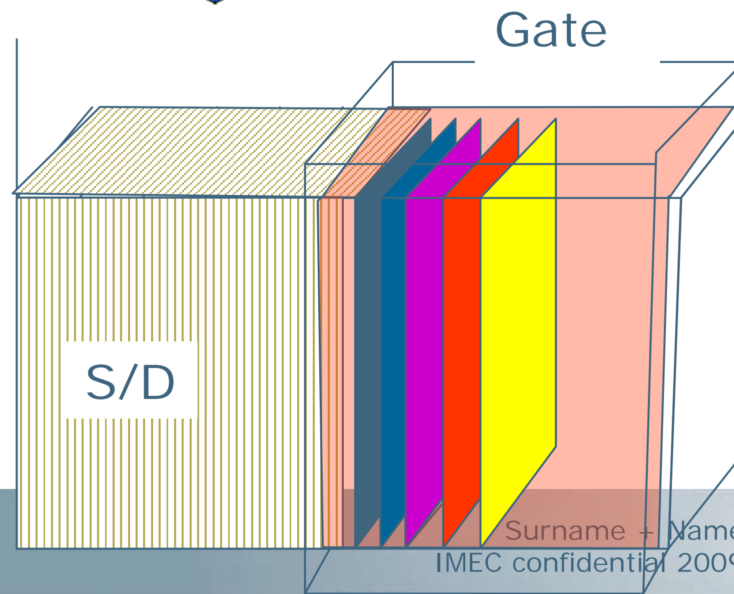
3D-profile in FinFET : SSRM slice and view







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j.mody, mrs 2008

Practical Problems

- To obtain 3D-profile we must obtain successive 2D-spreading resistance maps in one of the planes with 1nm step.
    - Polishing ???
    - Cleaving ???
- Cleaving and polishing with nanometer step in the planes ???
- Successive cleaving with 1nm step on the same transistor ???
- Successive polishing with 1nm step on the same transistor ???

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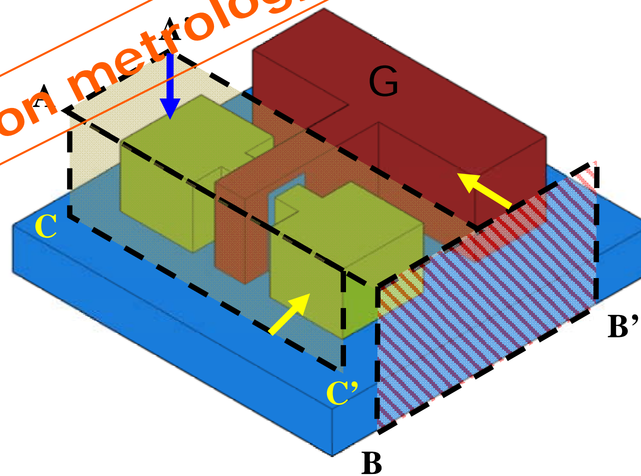
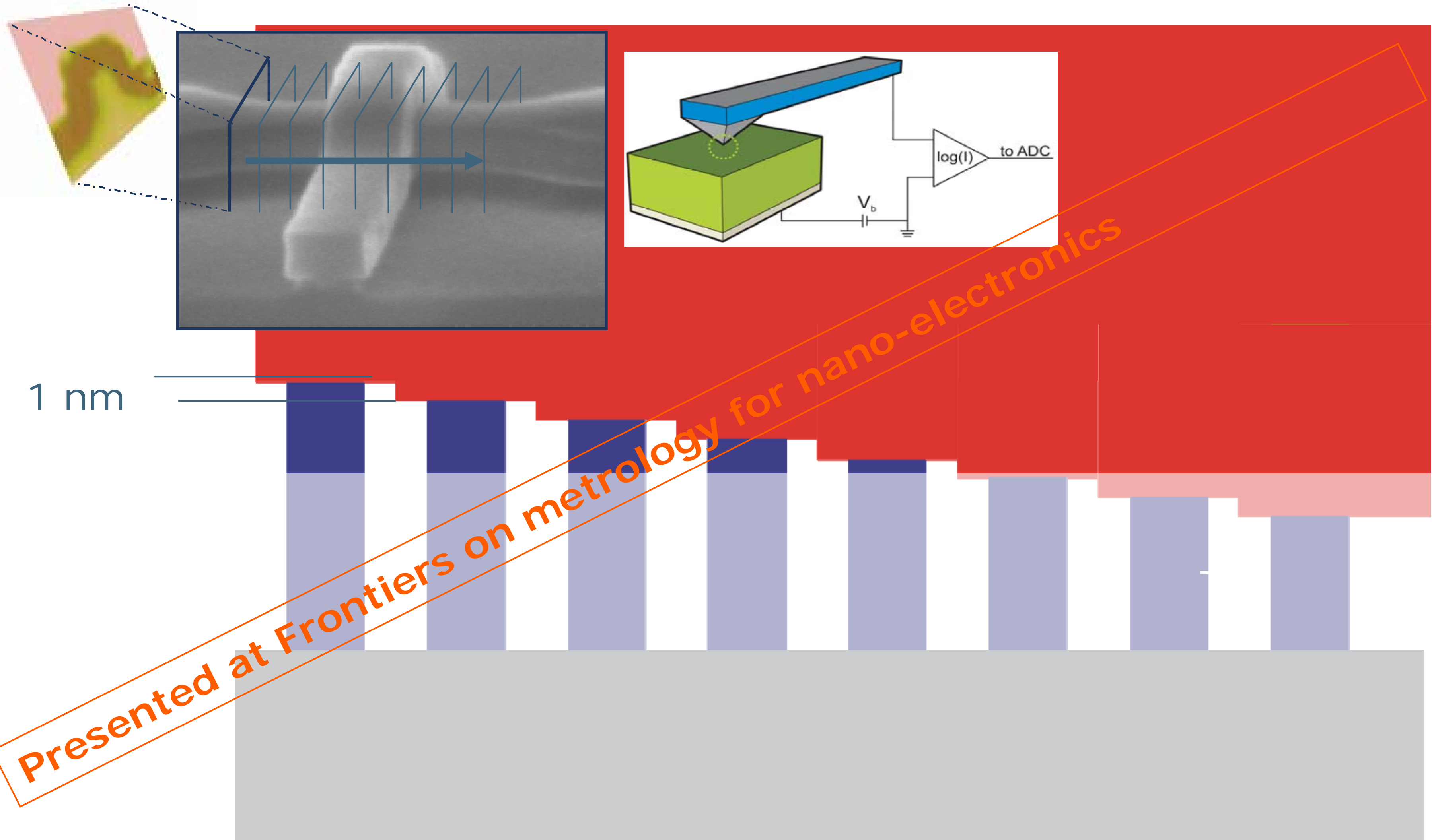


3D SSRM : slice and view



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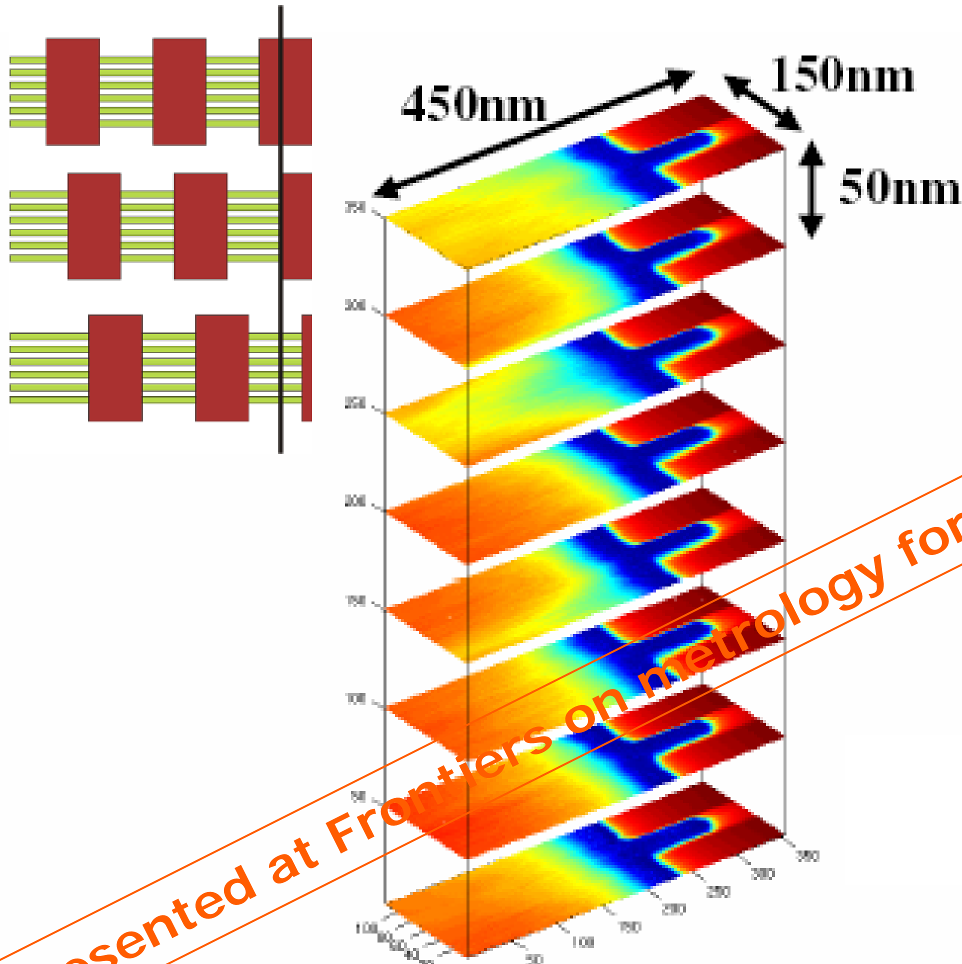
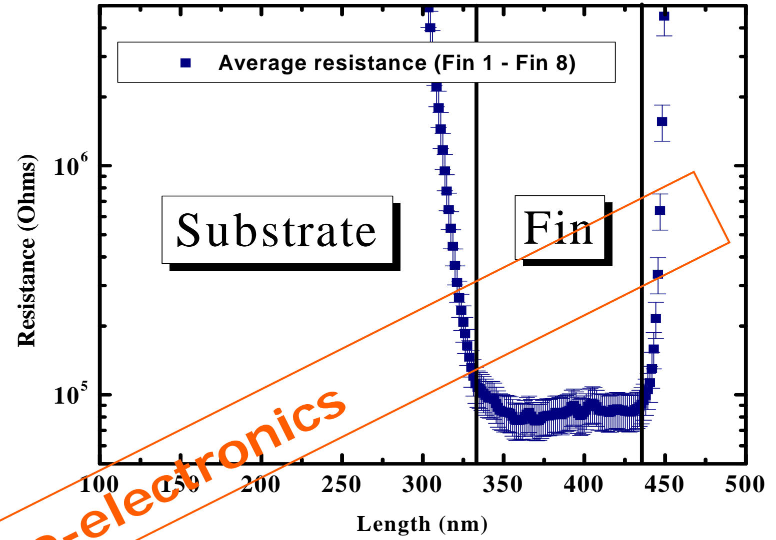
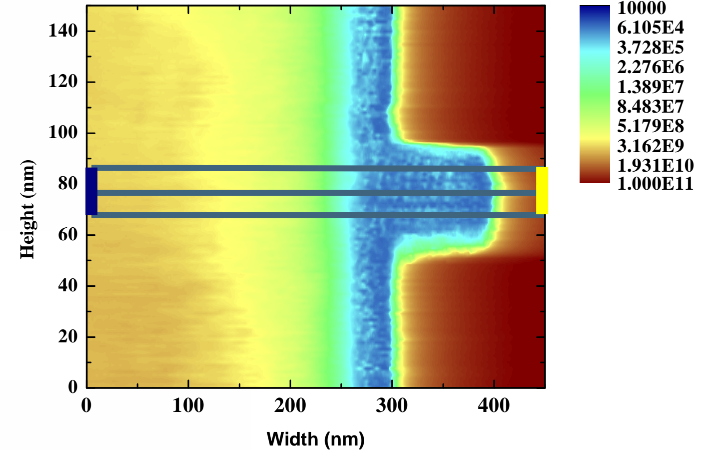
3D-SSRM : proof of concept



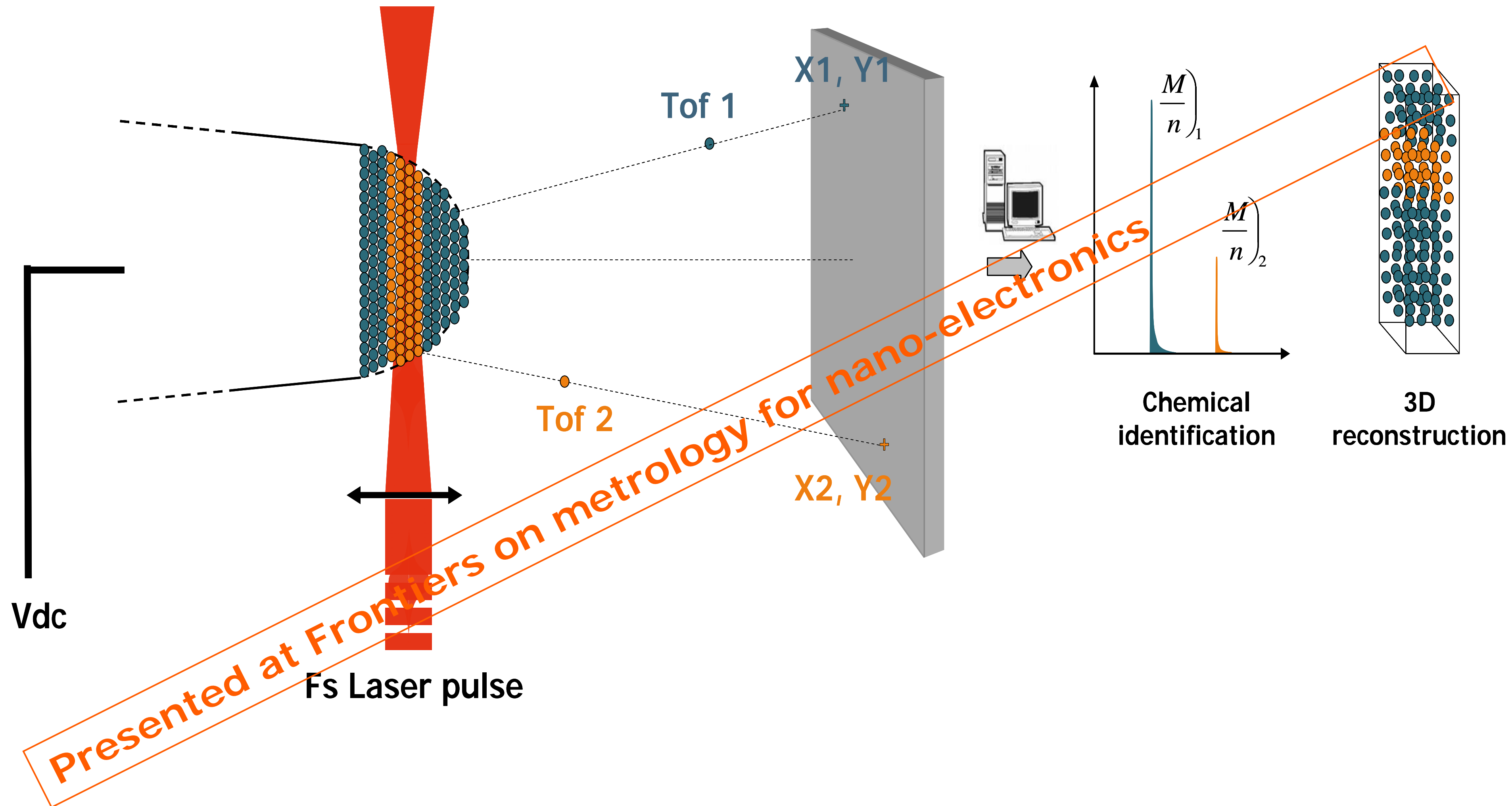




Presented at Frontiers on metrology for nano-electronics

J.Mody et al., MRS-Spring 2008

Tomographic Atomprobe



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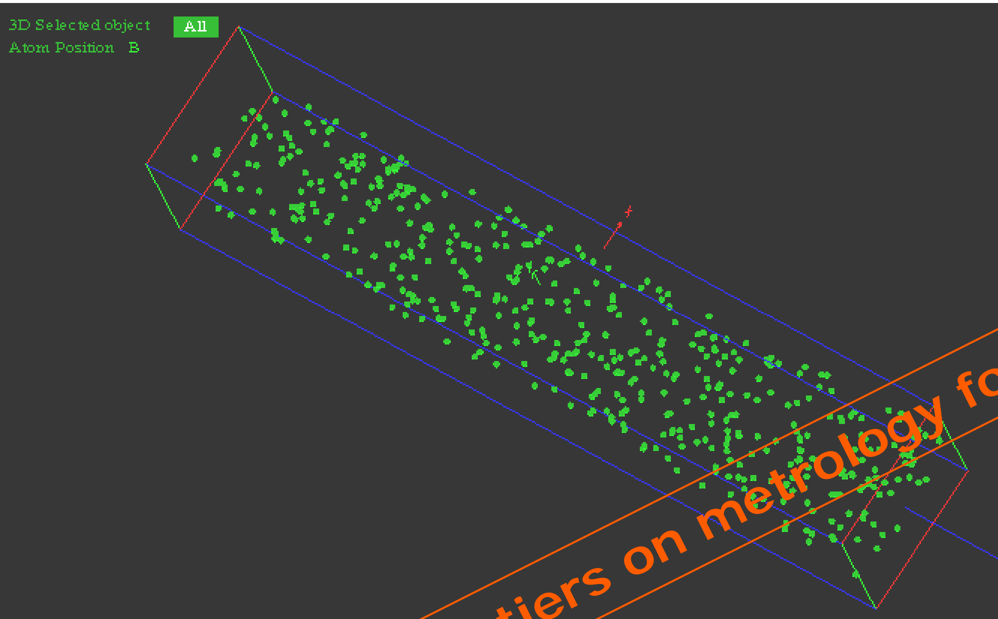
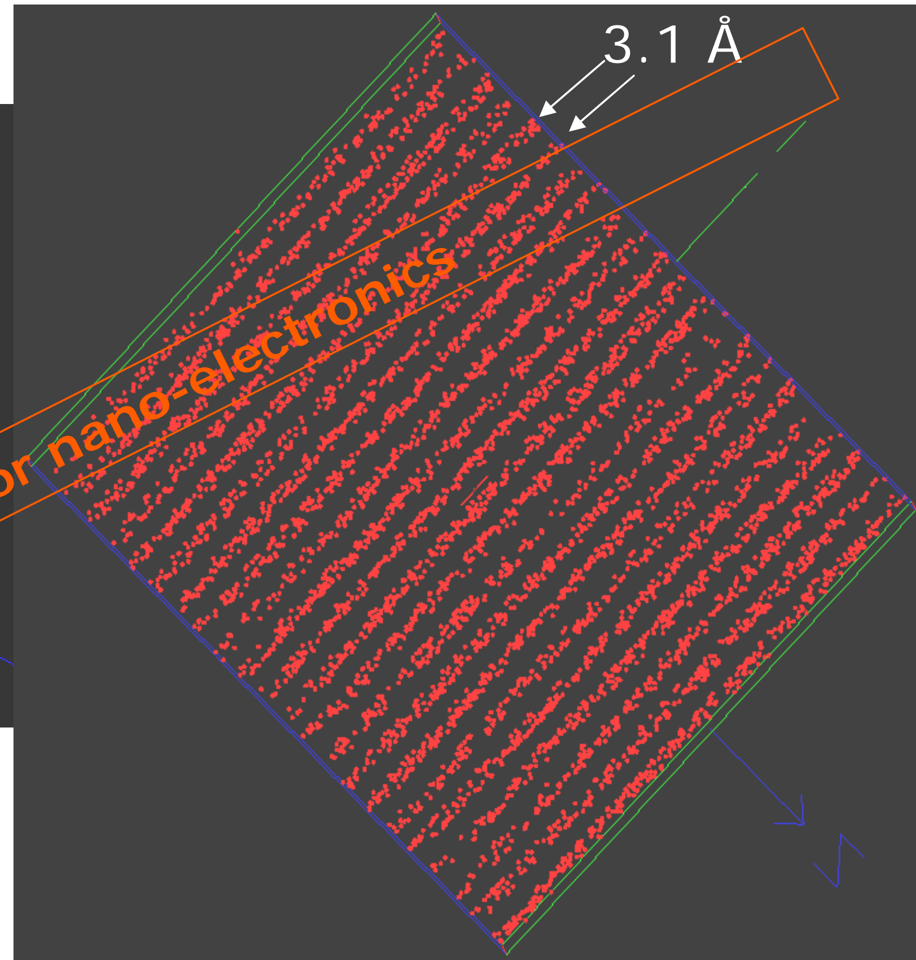
Atomic resolution with the Atomprobe: analysis of doped Si





"homogeneously" B-doped Si

Estimated depth resolution <0.2 nm

Si-atoms/ lattice planes in Si<111>

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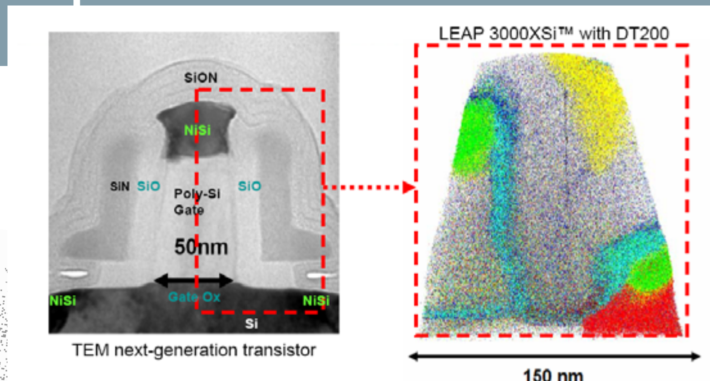
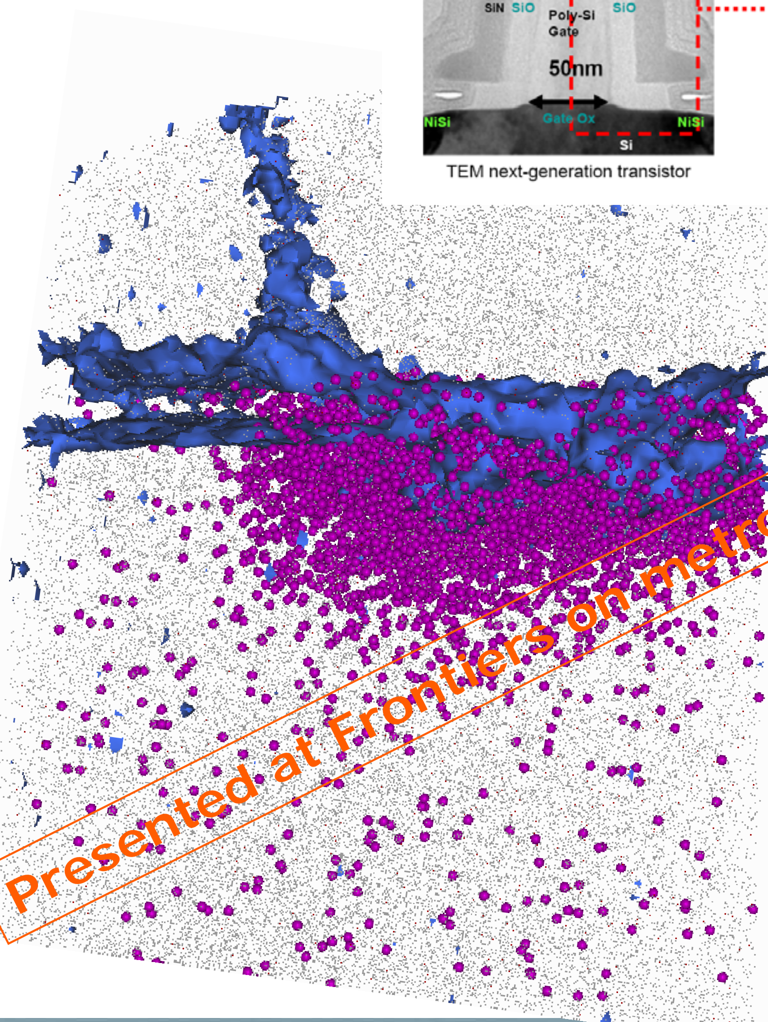
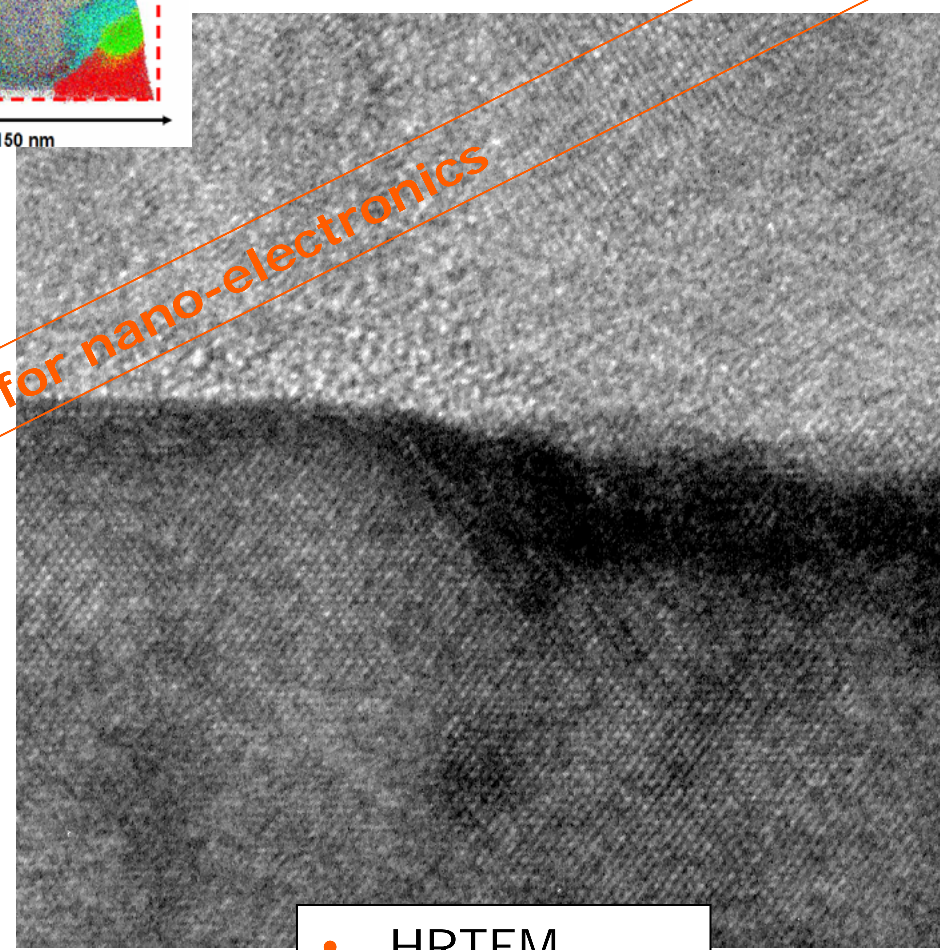
W.Vandervorst et al, AIP 2007

Lateral As-profile







- HRTEM

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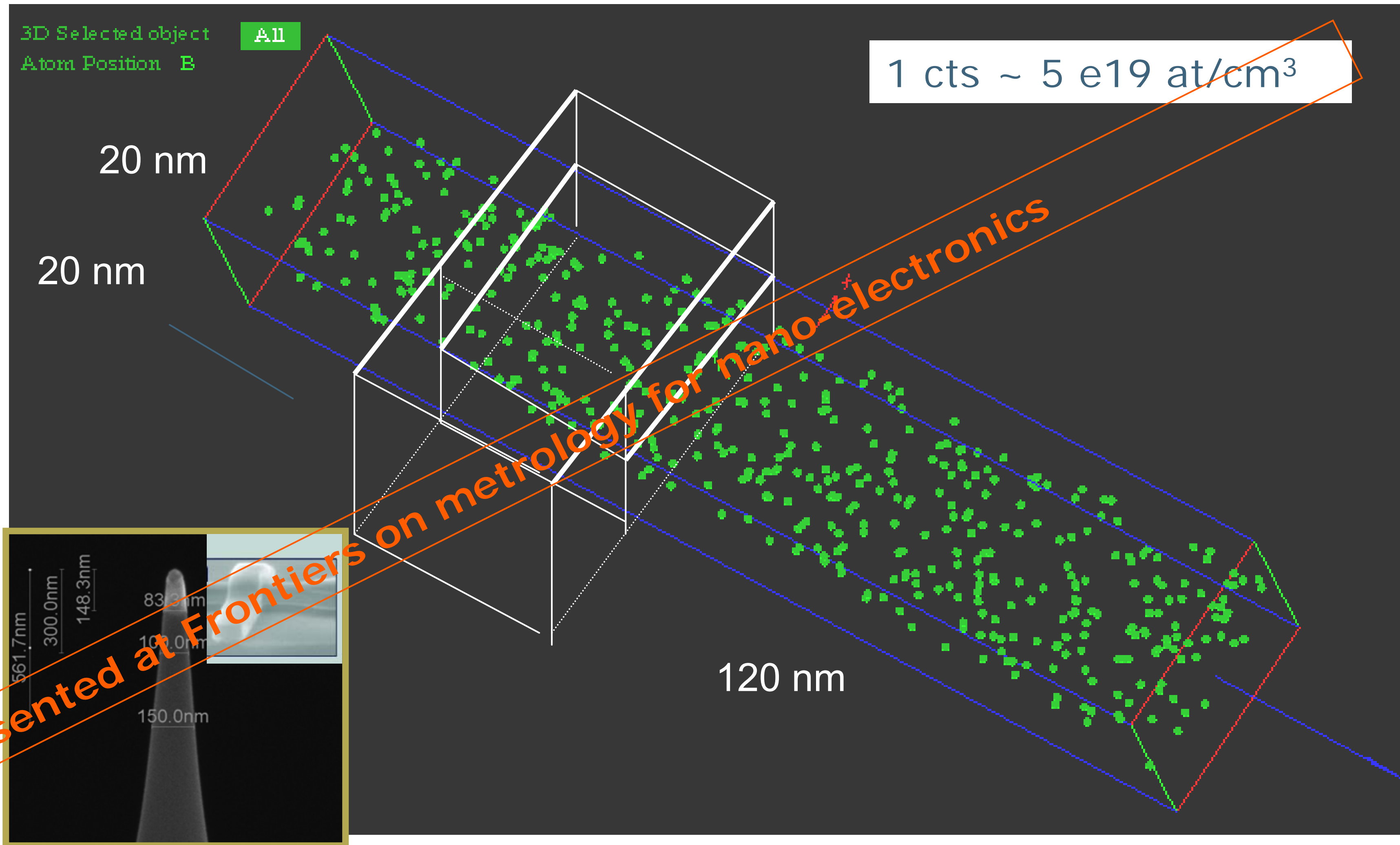
K.Jones, IIT-2006, Univ. Florida

3D-dopant profiling counting atoms



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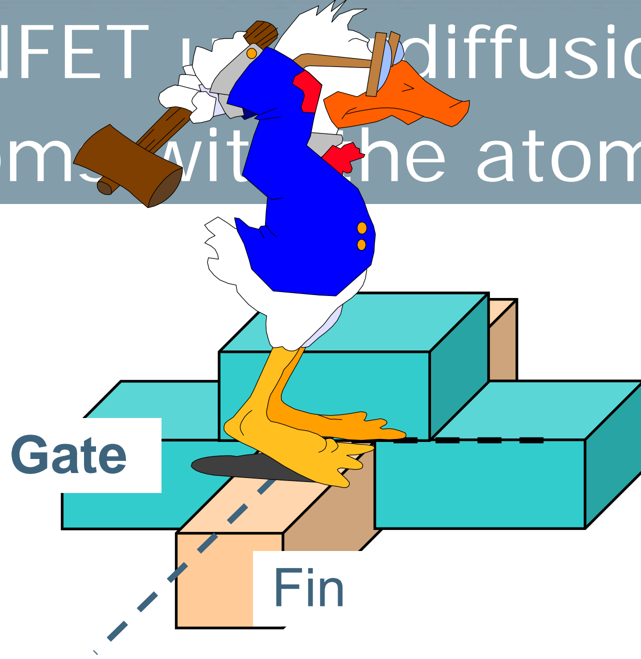
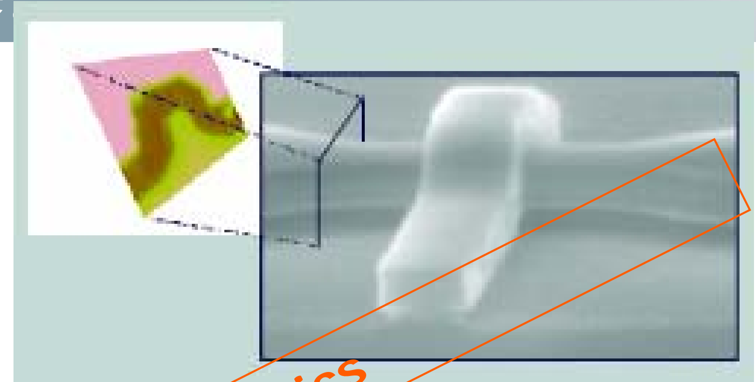
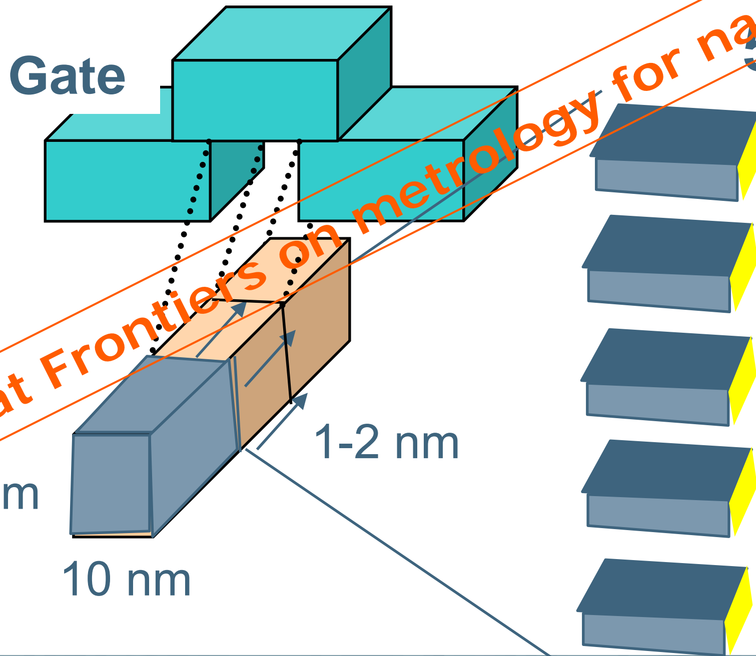
FINFET […]diffusion : Counting single atom[…] wit[…]he atomprobe





10 x 1 x1 = 500 Si atoms

5e19 ~ 0.5 cts/pixel



- Gradients : 1nm/dec

5e20 ~ 5 cts/pixel

5e19 ~ 0.5 cts/pixel

- **Registration to gate (LER)**

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Conclusions

- FINdoping fabrication and metrology is a major challenge
  - I/I (☹) , plasma doping (😐☹), VPD (☺)
- Metrology
  - **conformality ☺:**
    - ***SIMS through FINs***
    - ***Resistors***
    - ***S/D area's : X-SSRM***
  - *3D-profiles 😐☹*
    - ***Pseudo 3D-SSRM : dedicated test structures***
    - ***3D-Atomprobe : statistics!!!***

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Acknowledgements

Device fabrication
Highly automated volume

nm-scale characterization
Skillfull experts

- The art of many student-experts :

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- Collaboration Cameca (LAWATAP)

25 imec

Years of Making Technology Fly