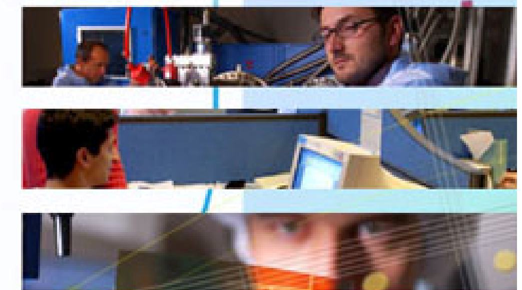
micro and nanoelectronics
microsystems
ambient intelligence
image chain
biology and health

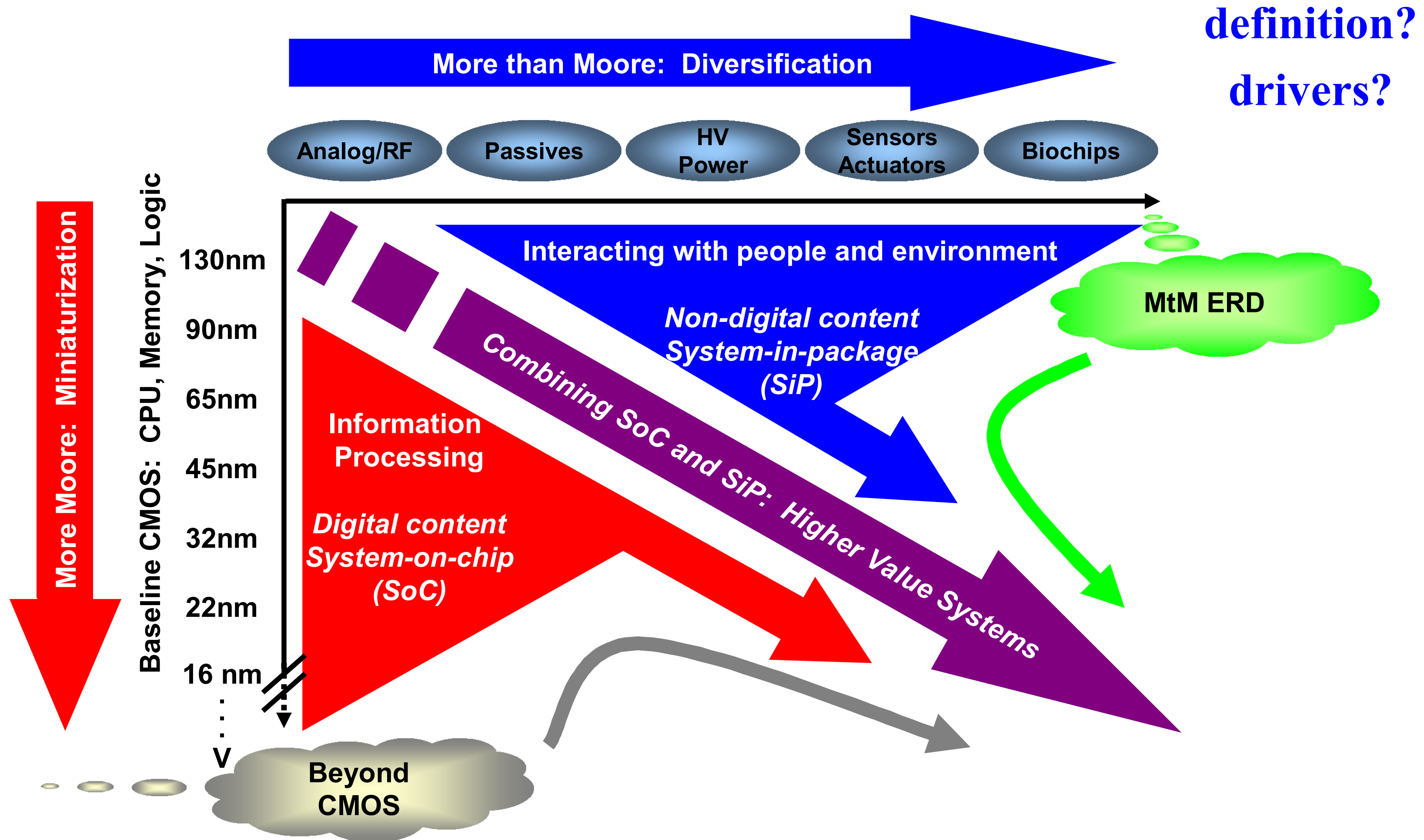
Nanocharacterization Challenges in a Changing Microelectronics Landscape

M. Brillouët



leti

The microelectronic landscape



Technology driven & long term view

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Outline

- Scaling
  - geometrical scaling
  - equivalent scaling
  - an evolving industry landscape
- "*More-than-Moore*"
  - what is it?
  - analog
  - healthcare devices
- Nanocharacterization challenges

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Scaling

A never-ending quest

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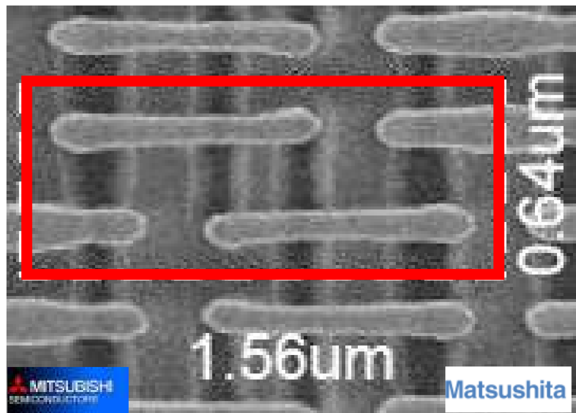
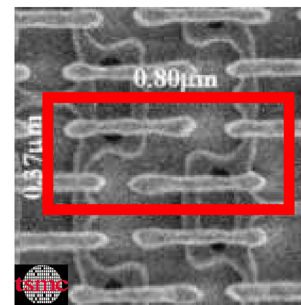
Scaling is a reality



K. Tomita et al.
VLSI 2002 #2.2
0.998µm²



F.L. Yang et al.
VLSI 2004 #2.1
0.296 µm²

B.S.Haram et al.
IEDM 2008, #27.1
0.100µm²

90nm 45nm 22nm

3x **3x**

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Geometrical scaling

"The good old days"…

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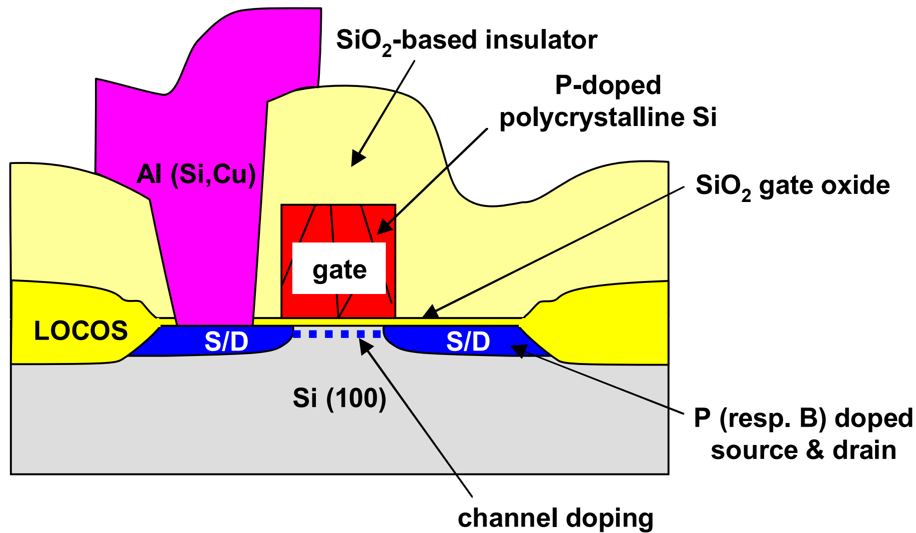
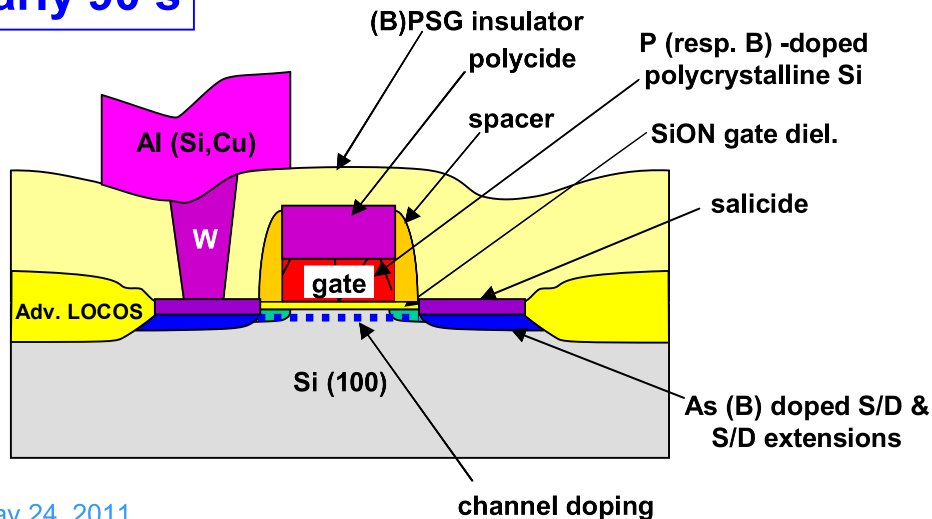
A limited number of options…

early 80's



early 90's



few materials

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	•	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	•	Rf	Db	Sg	Bh	Hs	Mt									
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

few processes

few device architectures

…but few characterization techniques

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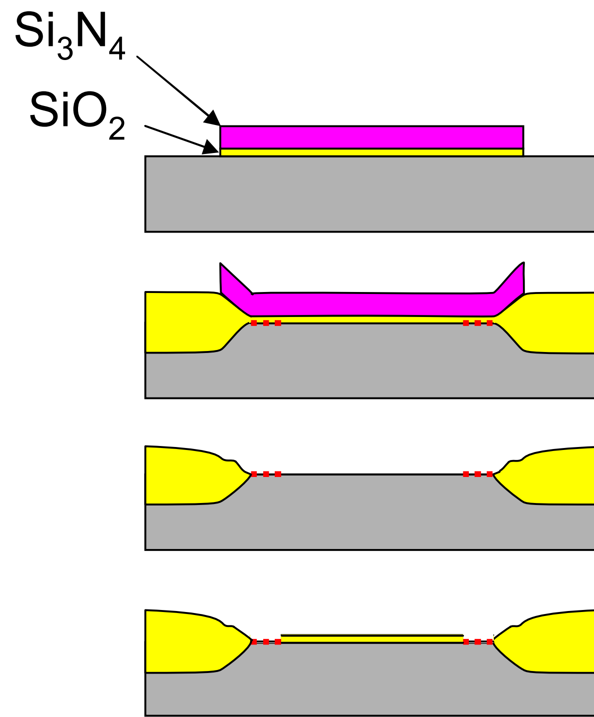
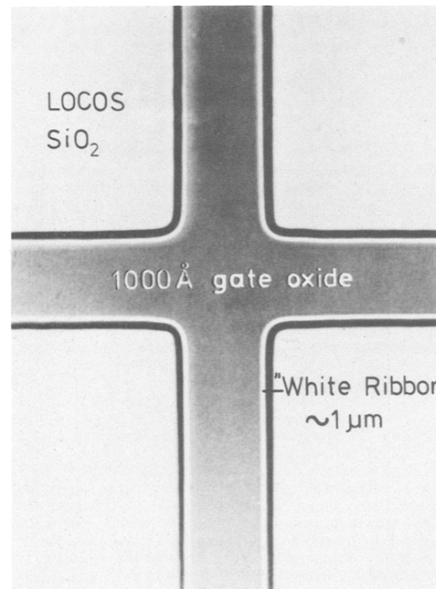
Kooi effect in LOCOS



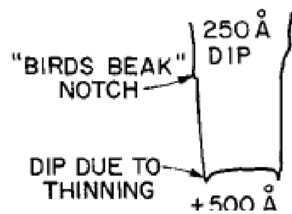


optical microscopy
≈ 0.5 µm resolution

from E. Kooi et al. JES 123 1117 (1976)

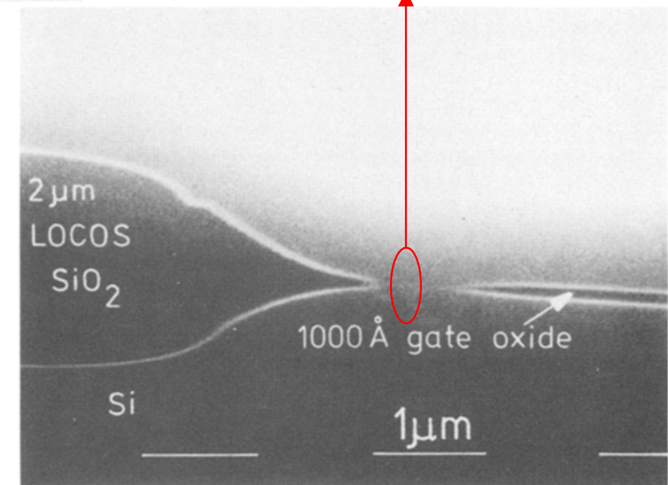
1 – 3 nm SiO_xN_x inferred from **ellipsometry** and **Auger** measurements on **full Si wafer**

"Talystep"
µm resolution



from T.A. Shankoff et al. JES 127 216 (1980)

X-sectional SEM
< 0.1 µm resolution



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Kooi effect in LOCOS

?

Si_3N_4

PAD OXIDE

ISOLATION OXIDE

200 nm

1.5μ

1 μm

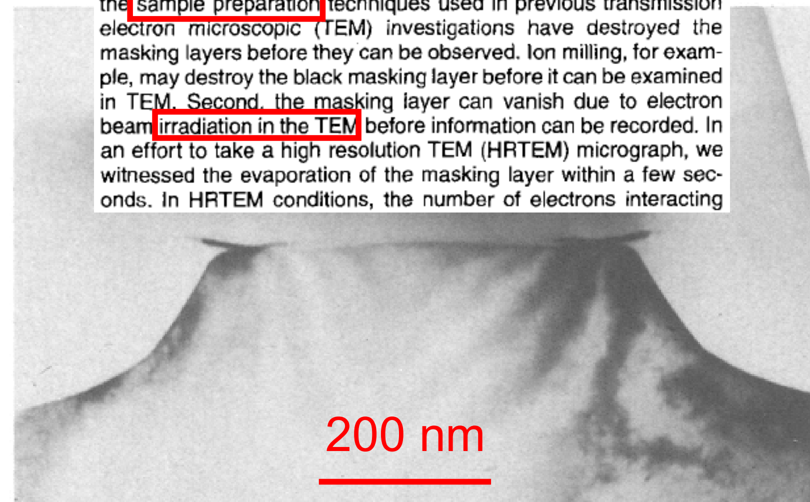
POLY Si

2.0μ

~100 % THINNING

from T.A. Shankoff et al. JES 127 216 (1980)

…and 15 years after…


oxidation masking materials and prove the model. It appears that the sample preparation techniques used in previous transmission electron microscopic (TEM) investigations have destroyed the masking layers before they can be observed. Ion milling, for example, may destroy the black masking layer before it can be examined in TEM. Second, the masking layer can vanish due to electron beam irradiation in the TEM before information can be recorded. In an effort to take a high resolution TEM (HRTEM) micrograph, we witnessed the evaporation of the masking layer within a few seconds. In HRTEM conditions, the number of electrons interacting

from T.T. Sheng et al. JES 140 L163 (1993)

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Equivalent scaling

The challenge of the introduction of new concepts

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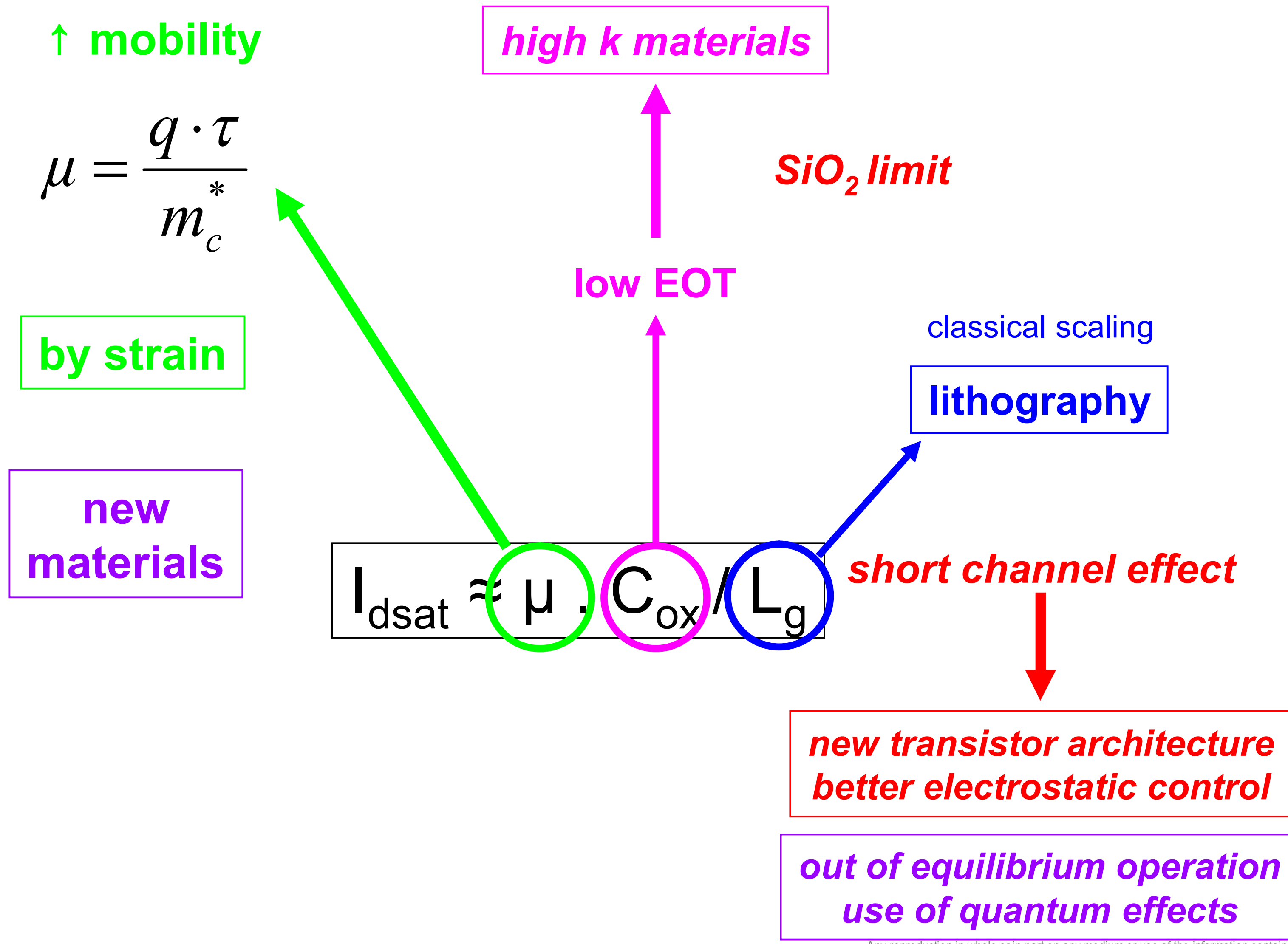
Equivalent scaling



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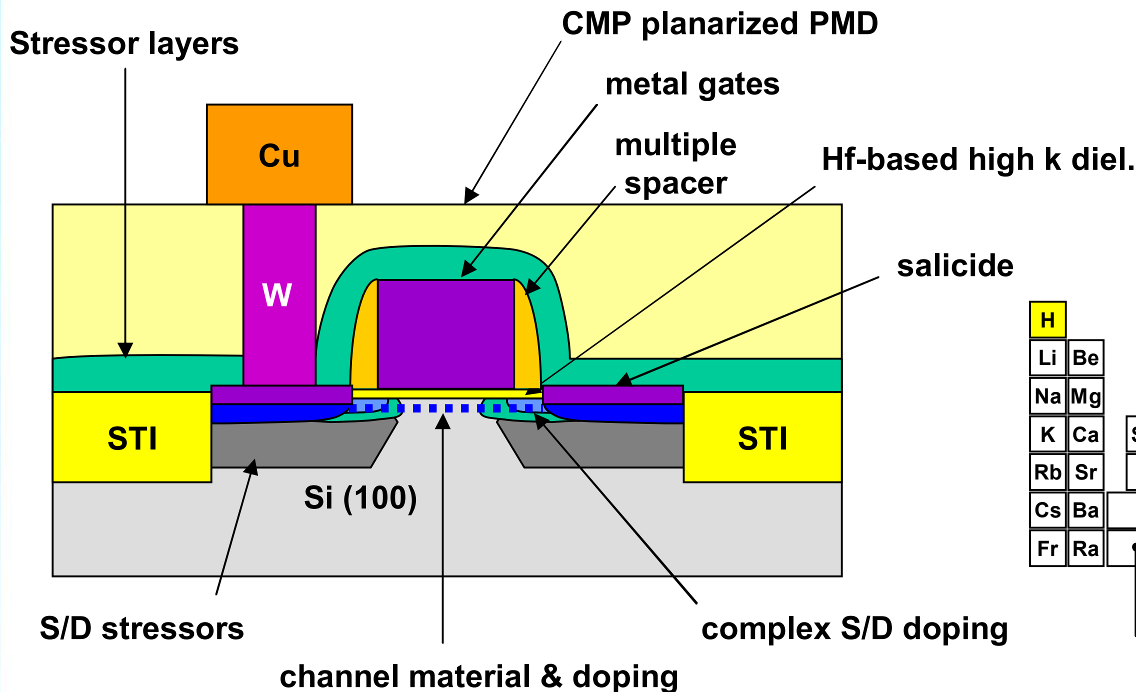
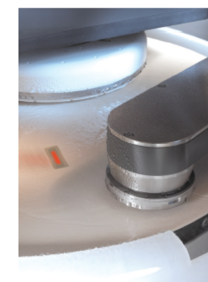
A diversity of technological options



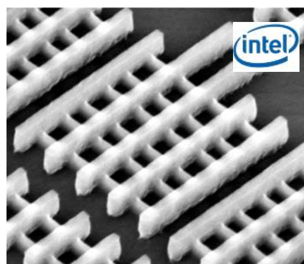
many more materials…

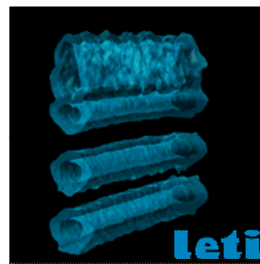
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	•	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	•	Rf	Db	Sg	Bh	Hs	Mt									
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

…processes…



…and device architectures





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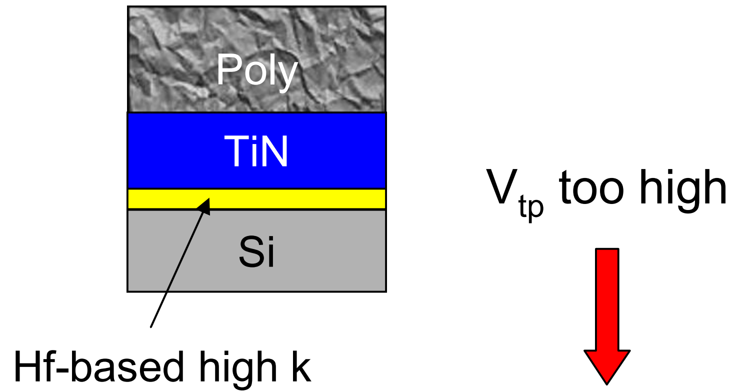
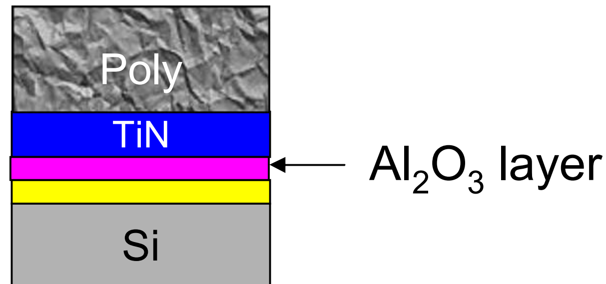
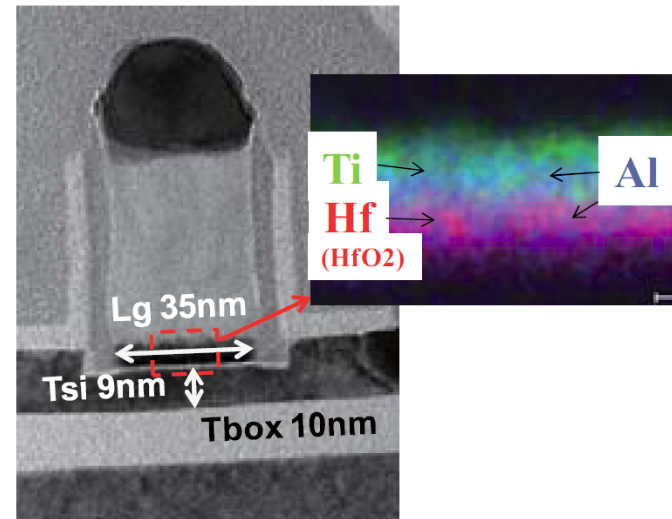
High k – metal gate characterization



V_{tp} too high



Al_2O_3 layer



less efficient with HfSiON: why?

from C. Fenouillet-Beranger et al. VLSI-TSA 2011 pp. 114–115

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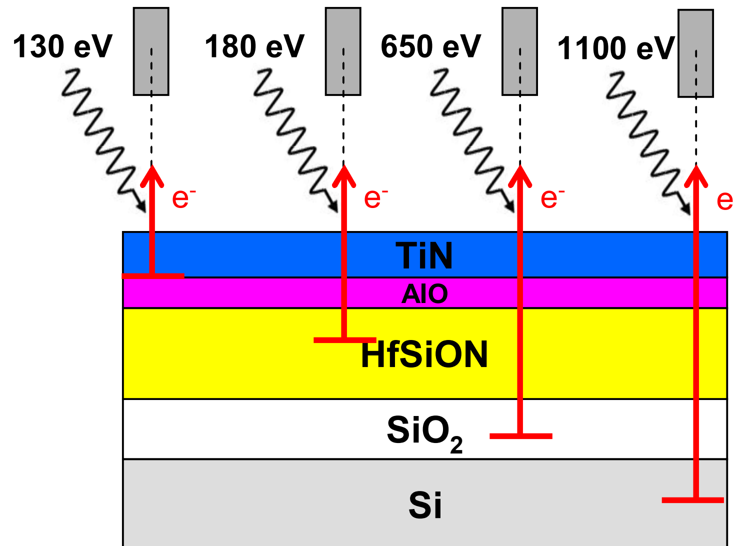
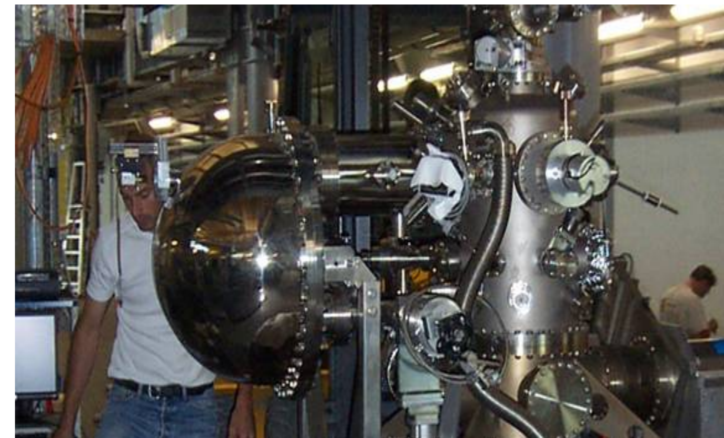
High k – metal gate characterization



Specific sample with thinner TiN

Synchrotron-based XPS

- High resolution in energy (40 < ΔE < 300 meV)
- Better sensitivity (Al detection)
- Tunable depth of analysis



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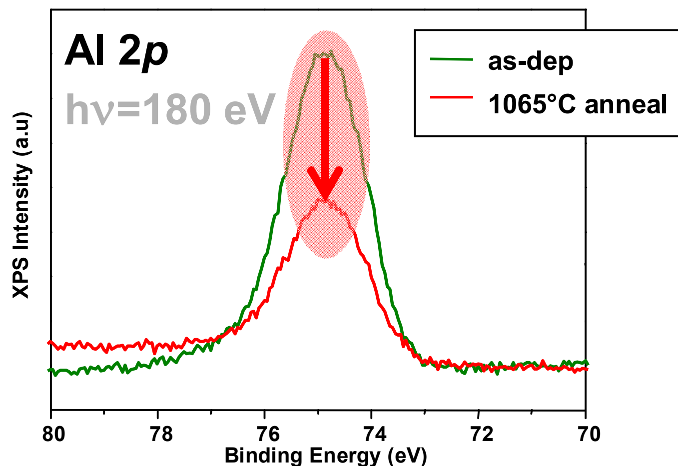
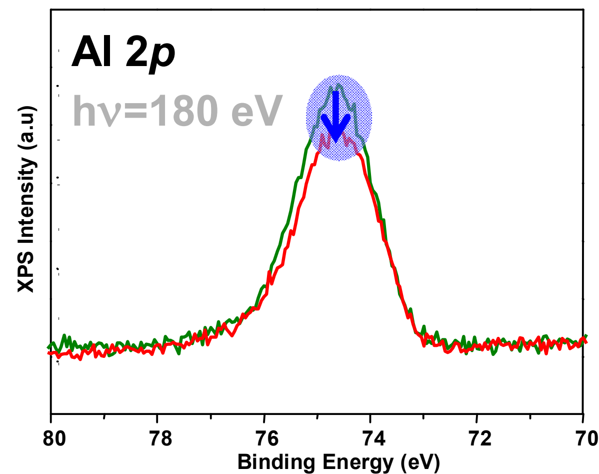
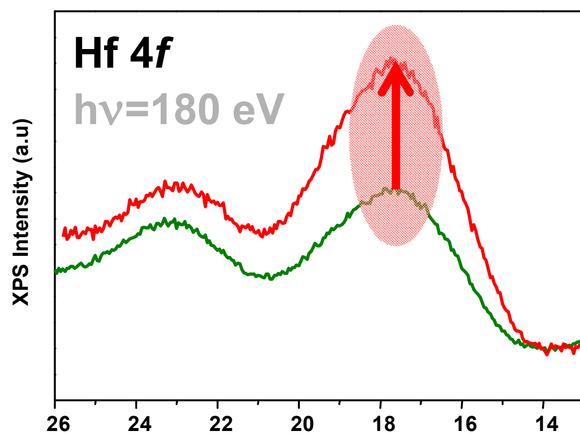
High k – metal gate characterization

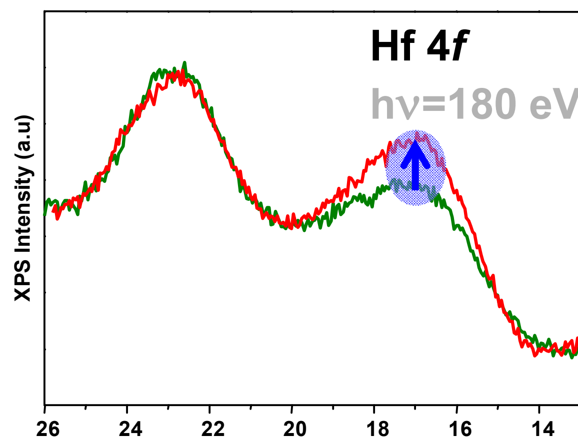
TiN
AlO
HfSiON
SiO_2
Si





TiN
AlO
TiN
HfSiON
SiO_2
Si





➔ Al diffusion through HK layer

➔ TiN as a diffusion barrier

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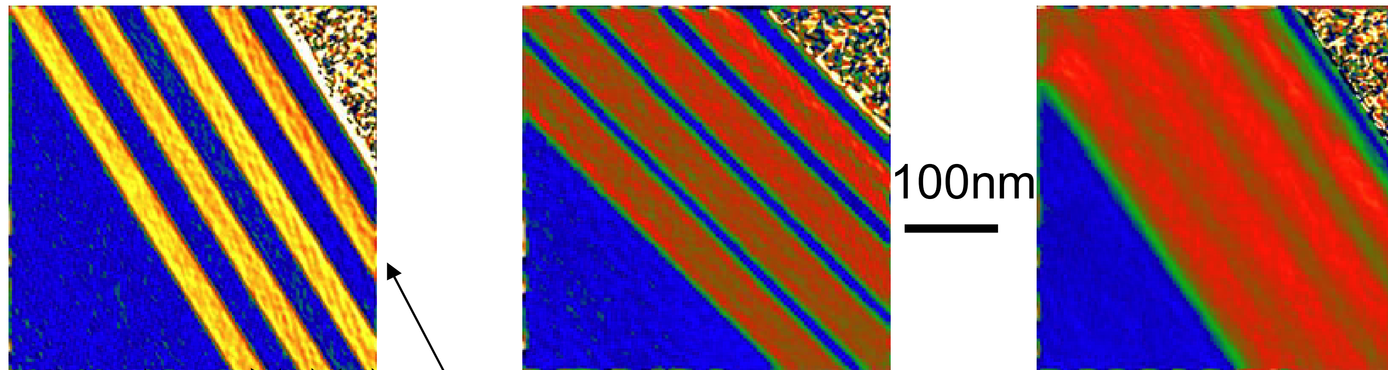
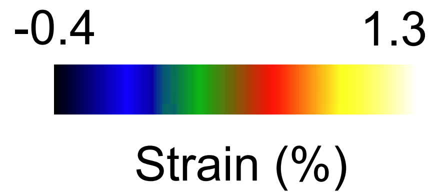
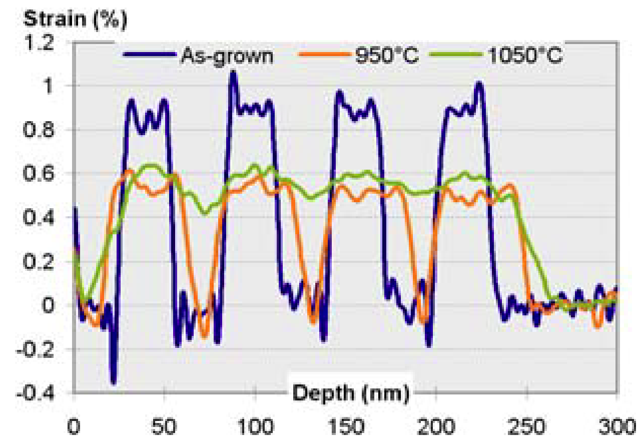
Strain

dark-field electron holography (DFEH)







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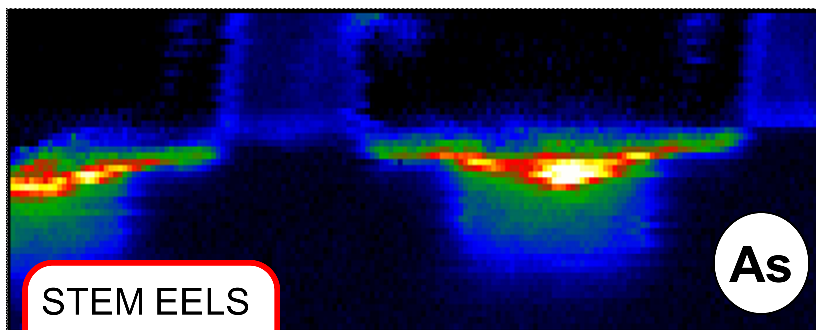
from T. Denneulin et al. FCMN 2011 poster #We-13

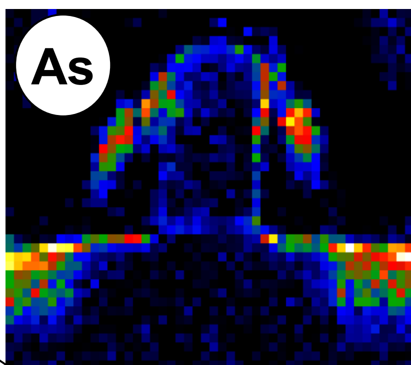
Tool improvement impact

2000

- **Standard TEM**



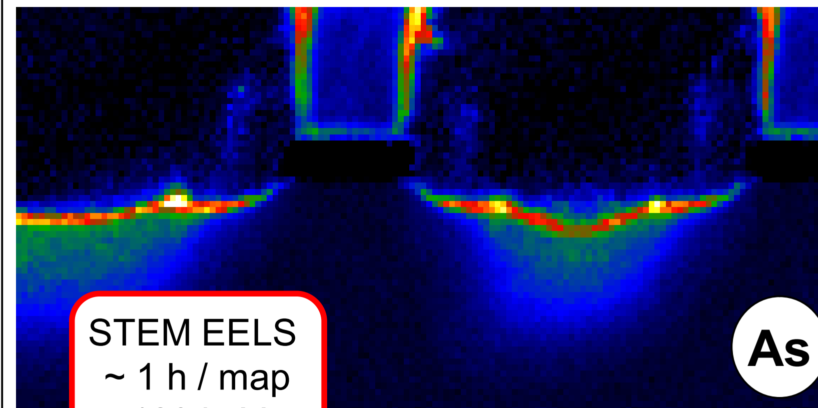
STEM EELS
~ 3 h / map
120 keV



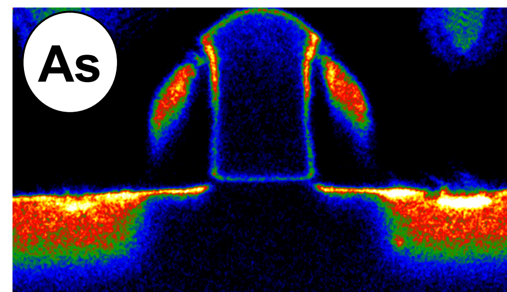
STEM EDX
~2 h / map
120 keV

2010

- **New generation TEM**



STEM EELS
~ 1 h / map
120 keV



STEM EDX
~0,5 h / map
120 keV

Courtesy G. Servanton

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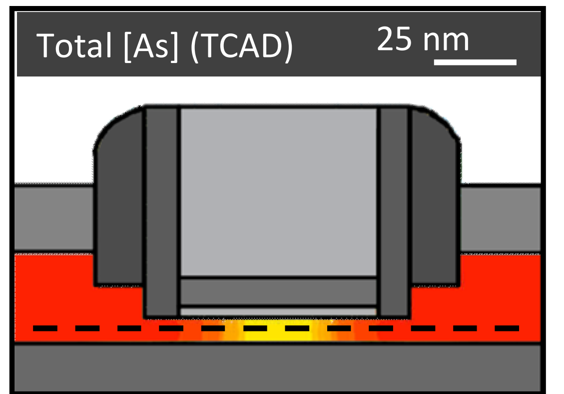
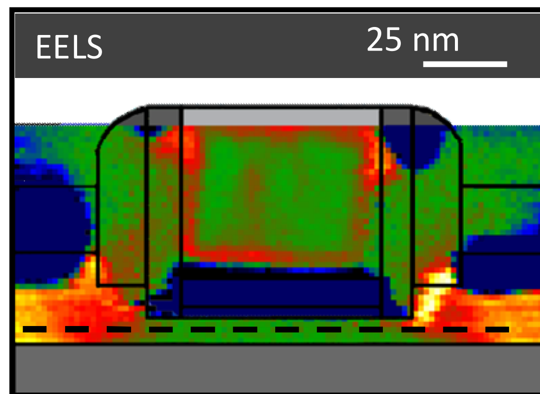
Why characterization on devices ?

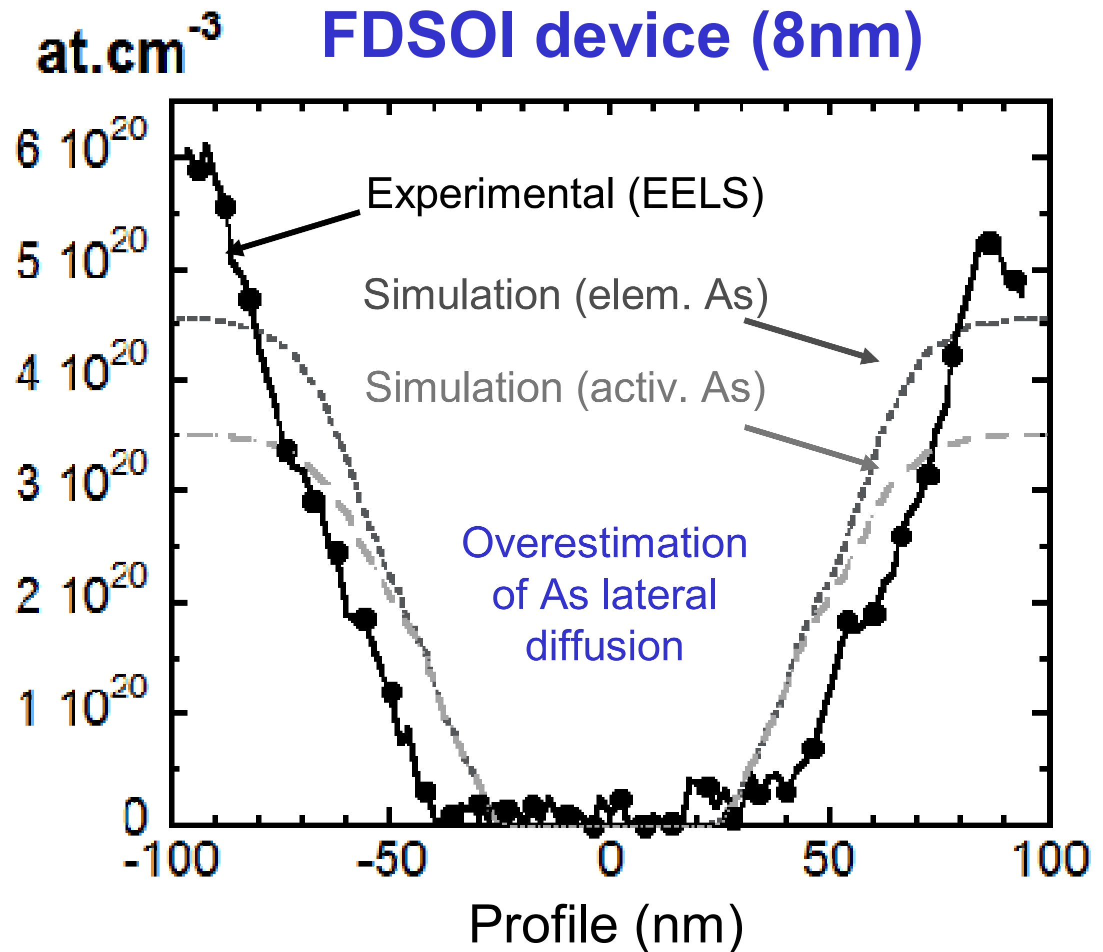


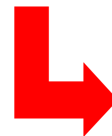
10^{10} at.cm^{-3} 10^{20} at.cm^{-3}



0% As 1.6%

FDSOI device (8nm)





Need for diffusion models adapted to confined materials

Courtesy of G. ***Servanton and C. Ailliot*** *(STMicroelectronics)*

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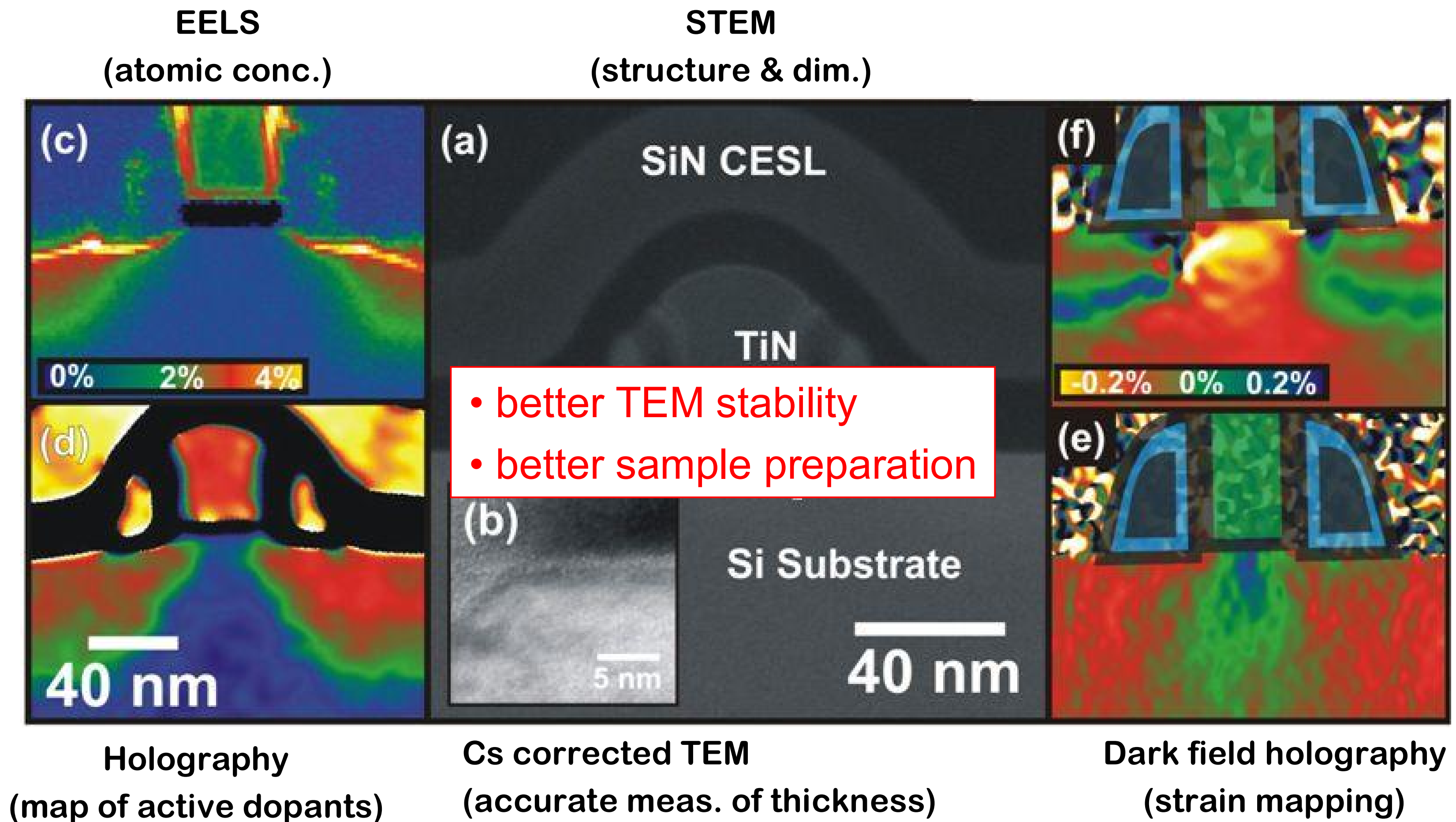
Assessing the transistor through multiple analysis

on the same sample in the same session

EELS
(atomic conc.)

STEM
(structure & dim.)



Holography
(map of active dopants)

Cs corrected TEM
(accurate meas. of thickness)

Dark field holography
(strain mapping)

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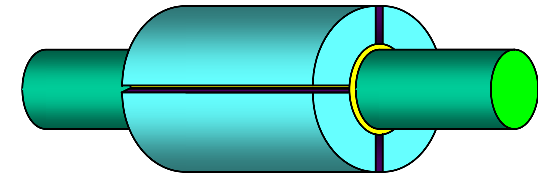
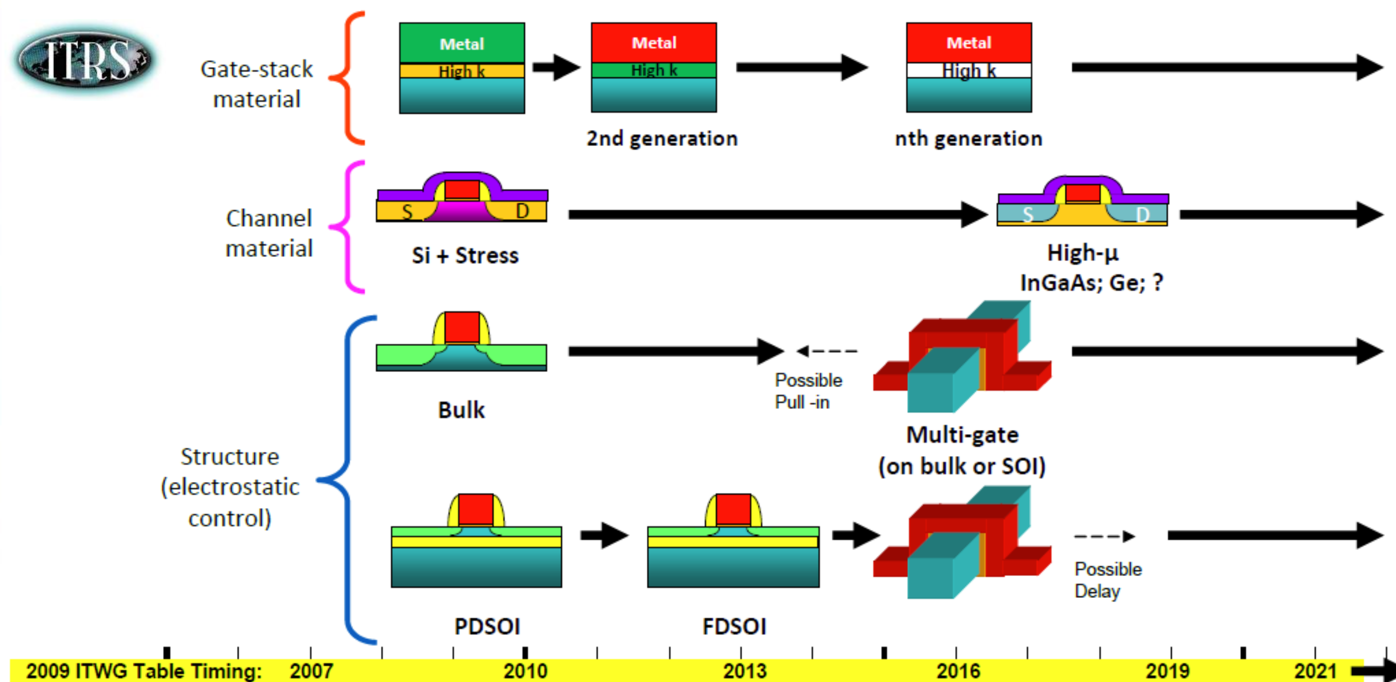
Towards the ideal device

…towards the 'ideal' MOS structure



an international roadmap…



from ITRS Winter meeting 2010

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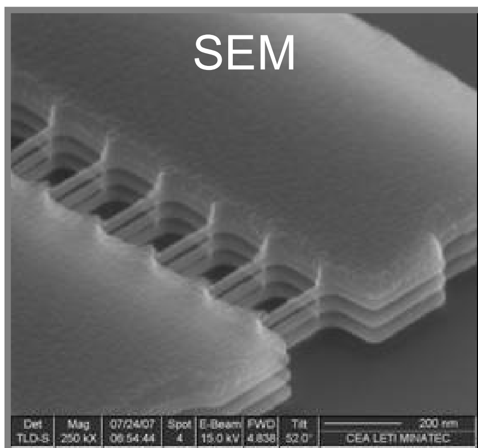
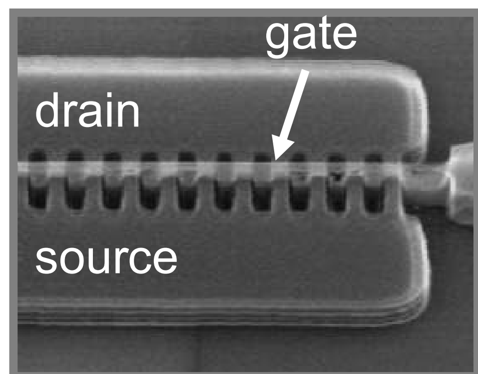
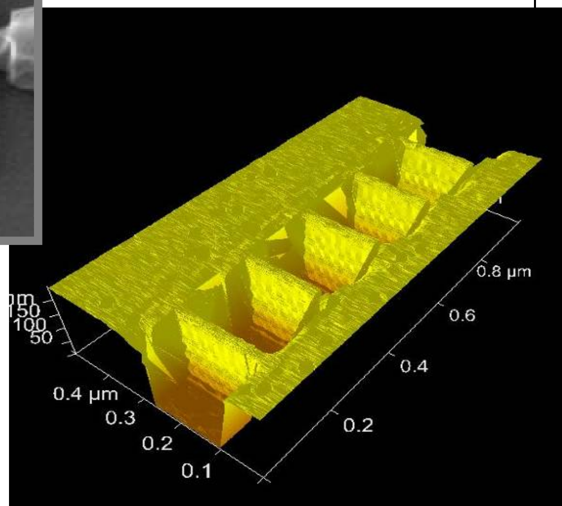
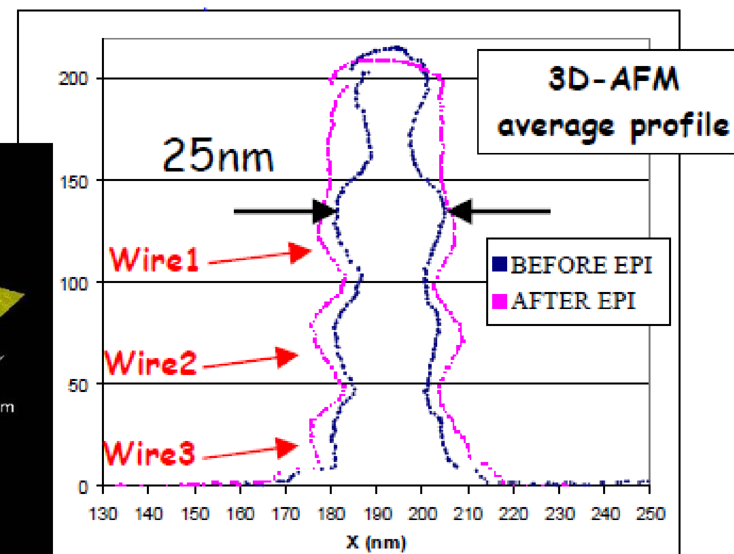
In-line control of nanowires





3D AFM for CD control





from J. Foucher et al., SPIE 2008

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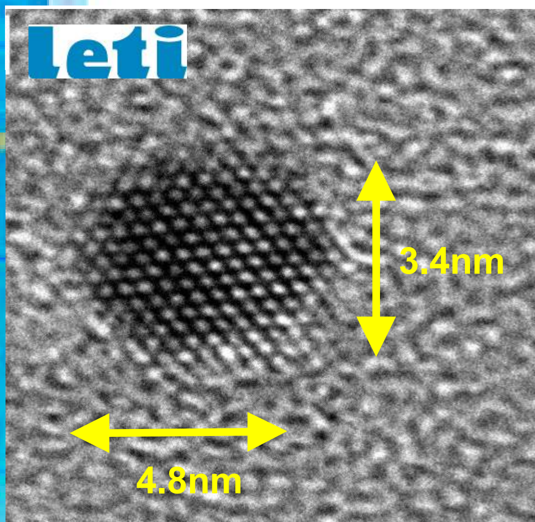
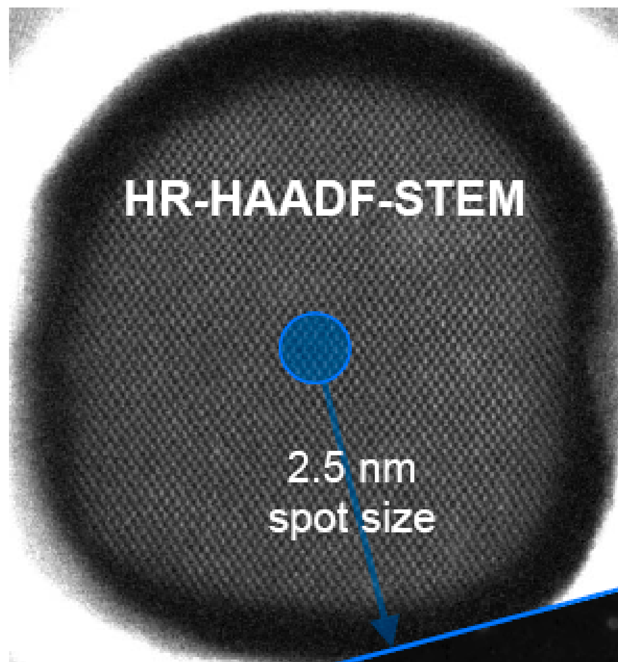
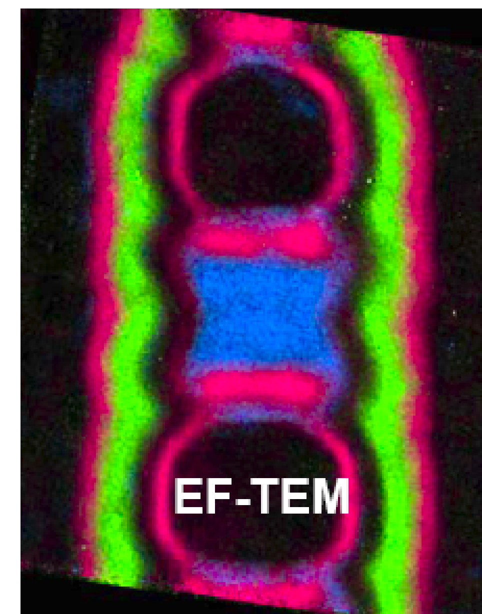
2D information from electron microscopy

■ ϕ-FET structure *C. Duprey et al., IEDM (2008)*

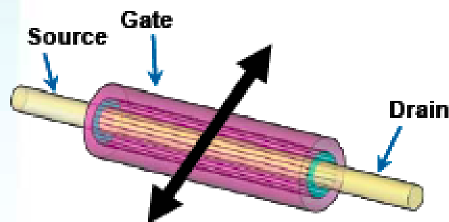


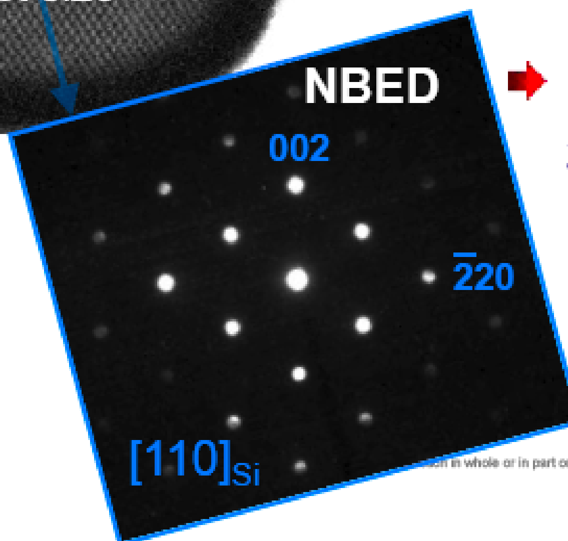
A. Hubert et al., 213th ECS symposium proc., E1 , 2008.





Courtesy M. Jublot





➡ **Conservative 3rd dimension is required**

Uppermost spatial resolution

- **Orientation**
- **Strain**
- **Chemistry**

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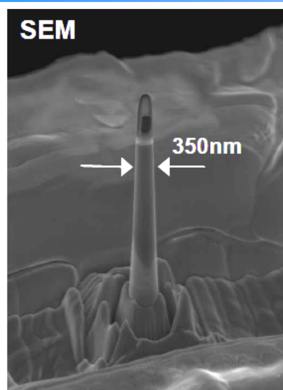
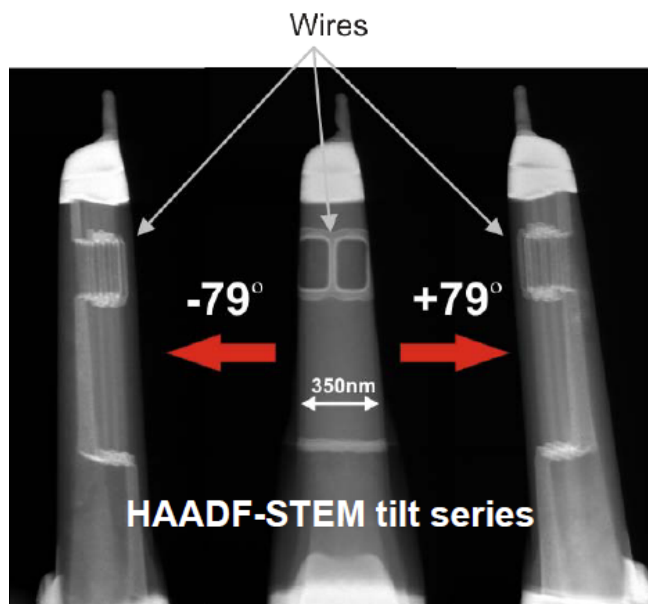
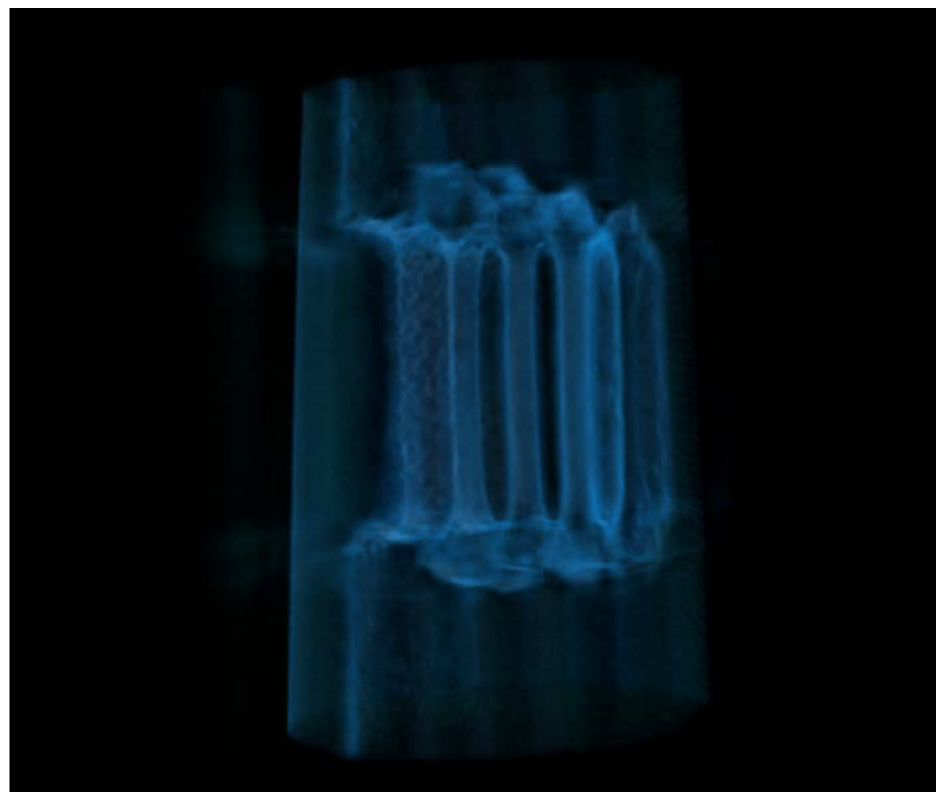
3D characterization of nanowires



appropriate sample preparation



“unrestricted” tilted view



from P. Cherns et al. FCMN 2009 poster #Th-021

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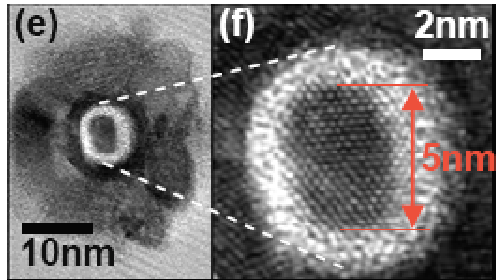
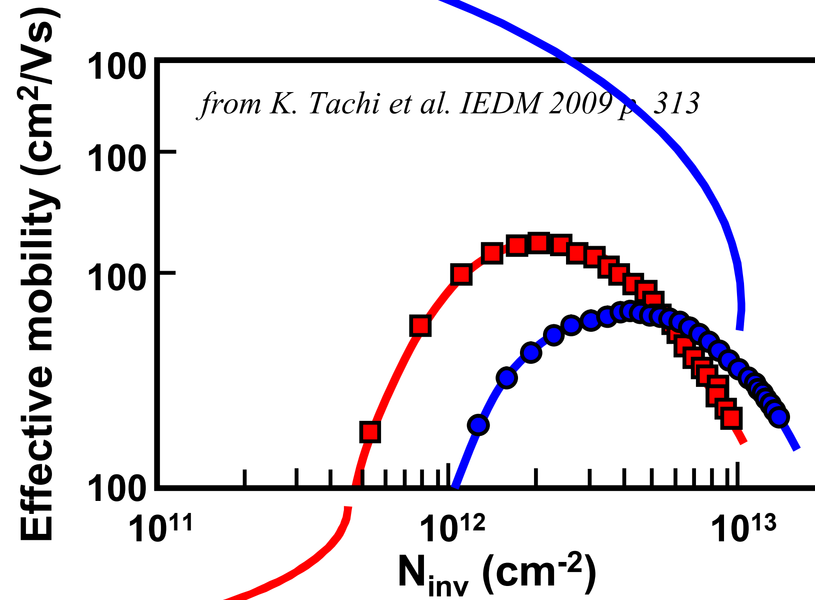
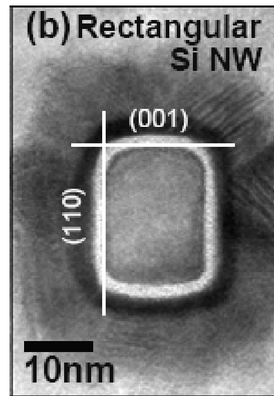
Shape-dependent effects in nanowires



w. H_2 anneal





w/o H_2 anneal

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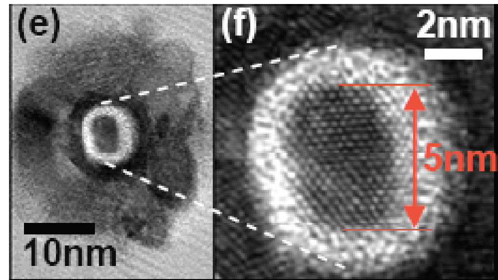
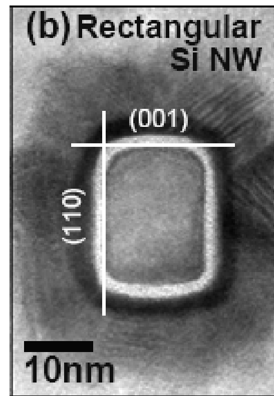
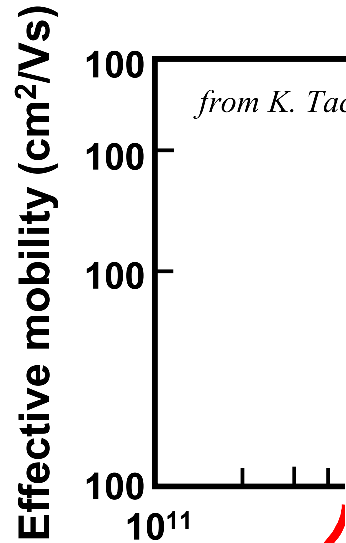
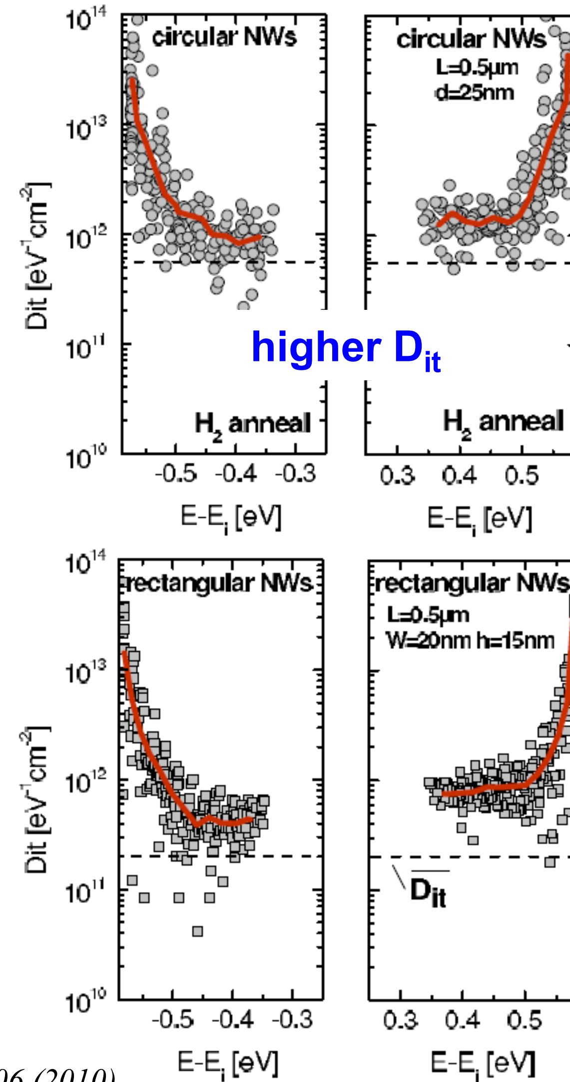
Shape-dependent effects in nanowires



w. H_2 anneal







w/o H_2 anneal

from M. Cassé et al. APL 96 123506 (2010)

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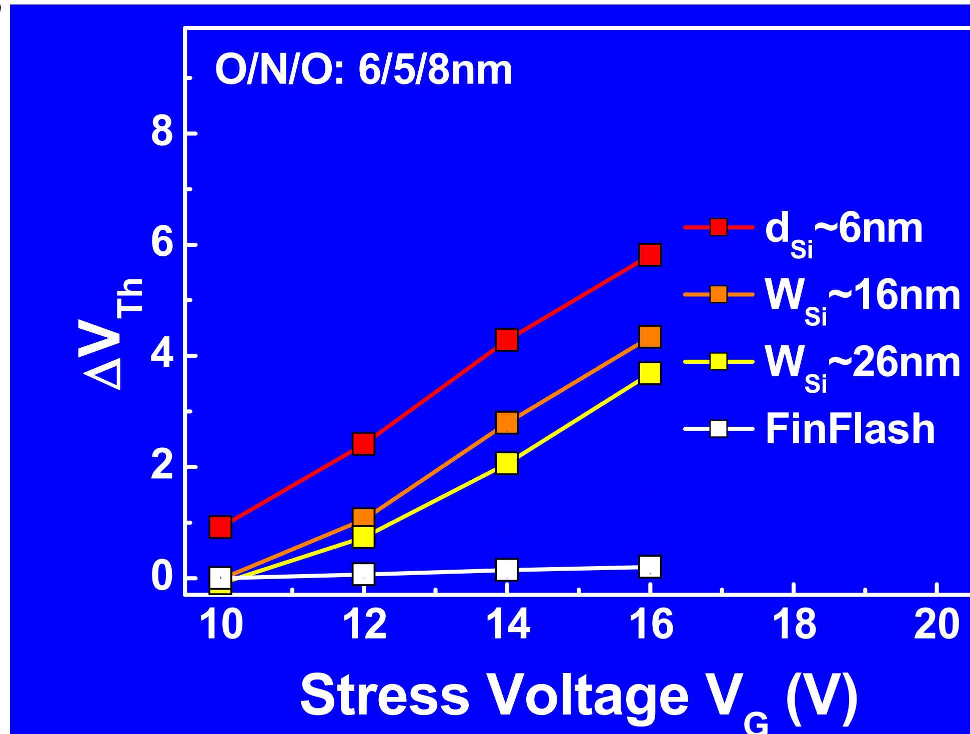
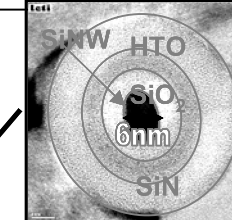
Nanowires for NVM

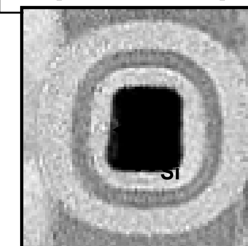
A. Hubert et al.
IEDM 09



Cylinder shape



Square shape



GAA SONOS Nanowire with small cylinder shape greatly enhances the programming efficiency

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from T. Ernst et al. ISTDM 2010

The economical challenge

It is not pure science, but…

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Spending: a gathering storm

VLSI RESEARCH INC

Where the Chip Making Industry Clicks to Find its Weather

Chip Making R&D Versus Revenues

(Worldwide in $M)

1.E+06, 1.E+05, 1.E+04, 1.E+03, 1.E+02, 1.E+01, 1.E+00

1957 1960 1963 1966 1969 1972 1975 1978 1981 1984 1987 1990 1993 1996 1999 2002 2005 2008 2011 2014 2017 2020

Total RD&E (Chip + Eq)

Semiconductor Revenues

decreasing revenue growth

increasing R&D & Capex costs

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from D.Hutcheson - 2005 Int.Conf. on Charact. and Metrology for ULSI Technol.

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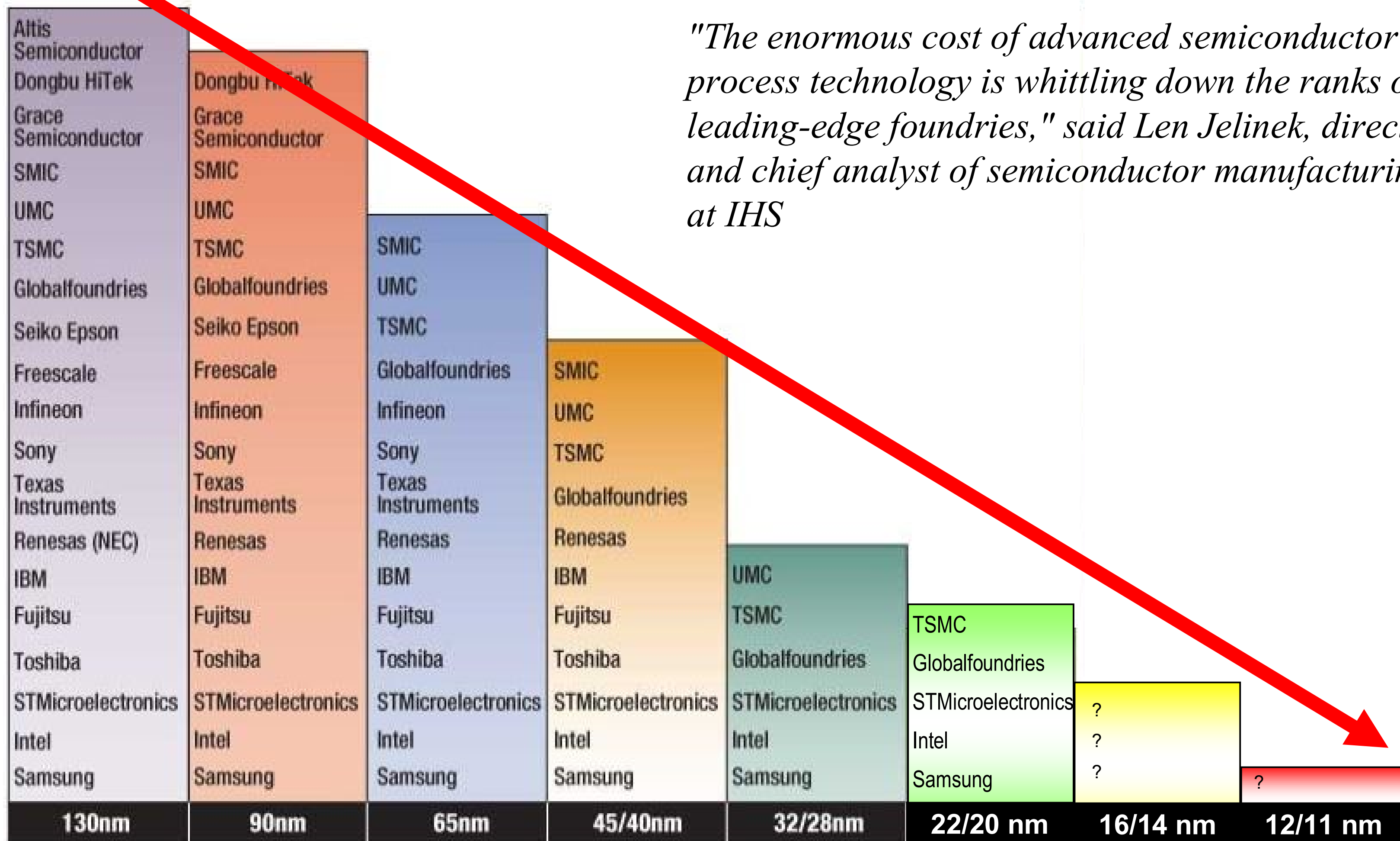
The other side of “*Moore’s Law*”



"The enormous cost of advanced semiconductor process technology is whittling down the ranks of leading-edge foundries," said Len Jelinek, director and chief analyst of semiconductor manufacturing at IHS

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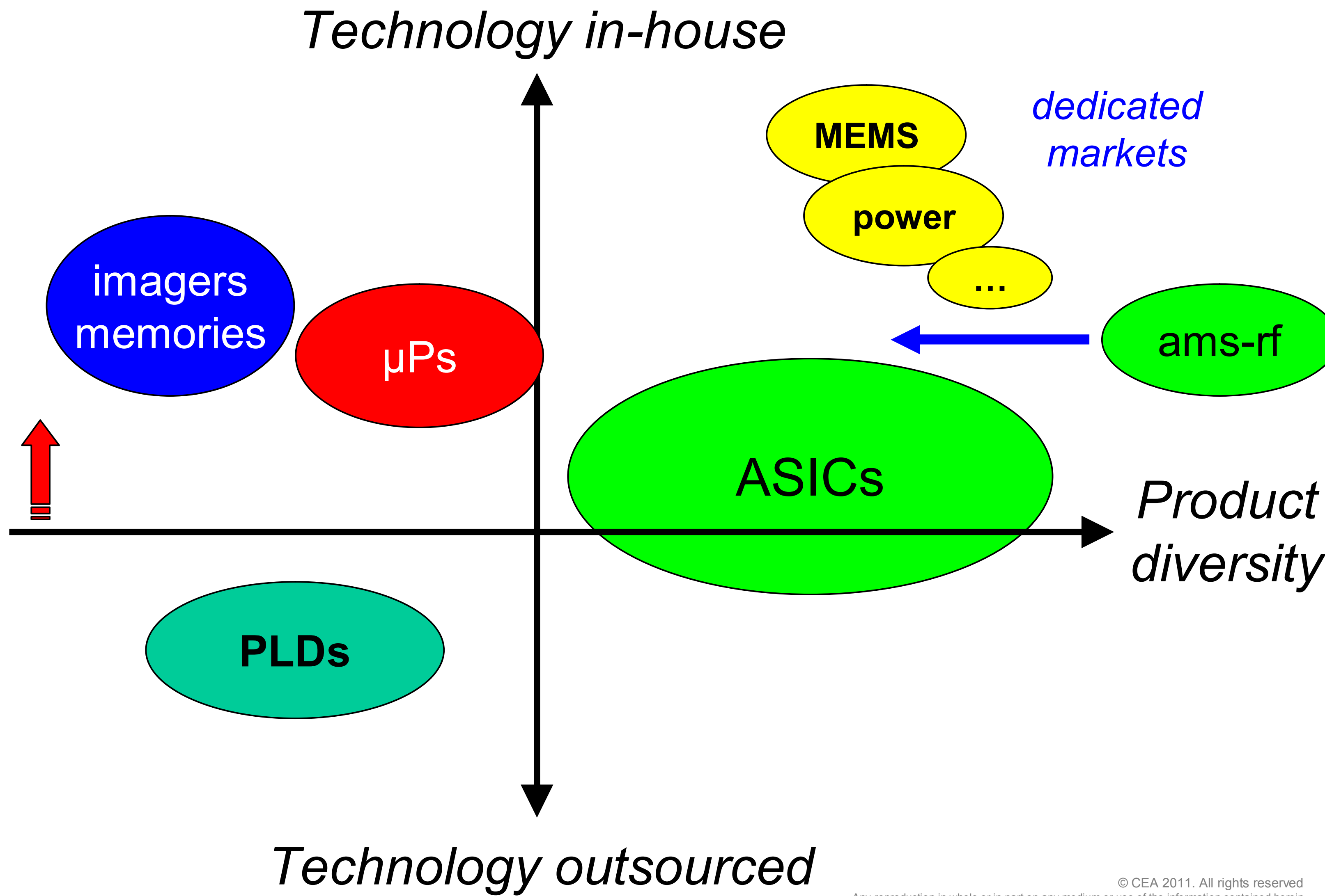
Evolution of the technology landscape



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Diversification: the *“More-than-Moore”* domain

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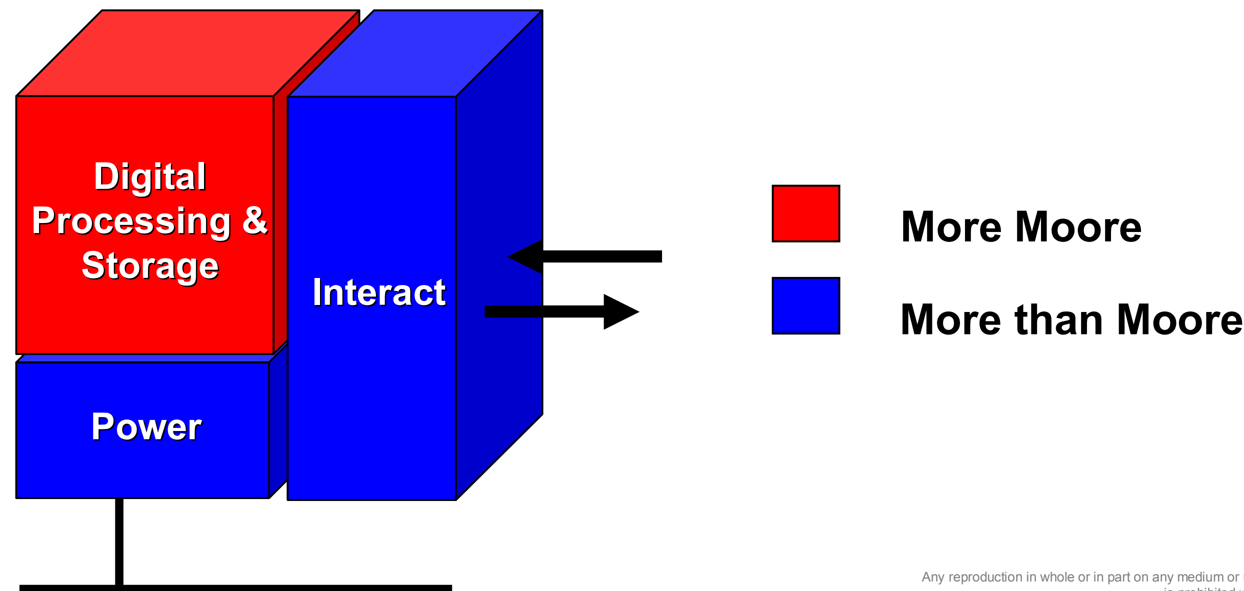
More than Moore: Functional Diversification

Short definition

Incorporation into devices of functionalities that do not necessarily scale according to "Moore's Law“, but provide additional value in different ways. The "More-than-Moore" approach allows for the ***non-digital* functionalities** (*e.g.* RF communication, power control, passive components, sensors, actuators) to migrate ***from the system board-level into the package*** (SiP) or onto the chip (SoC).



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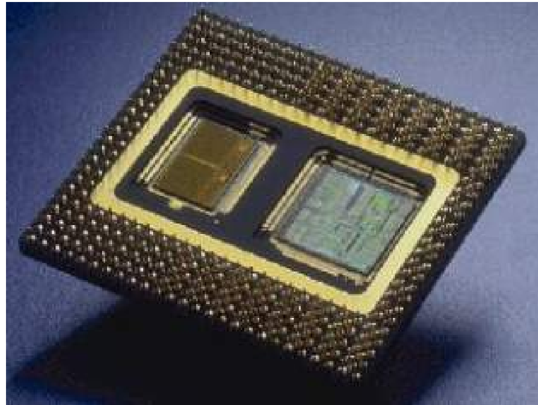
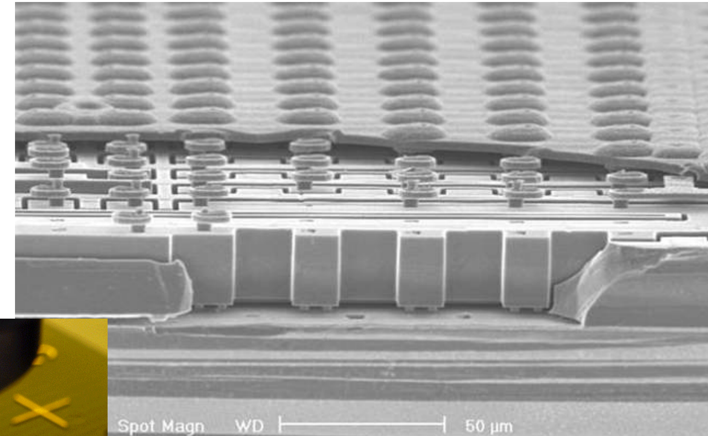
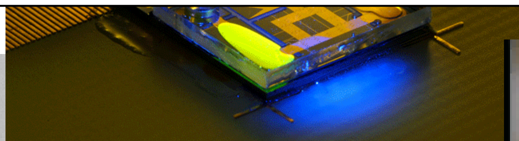
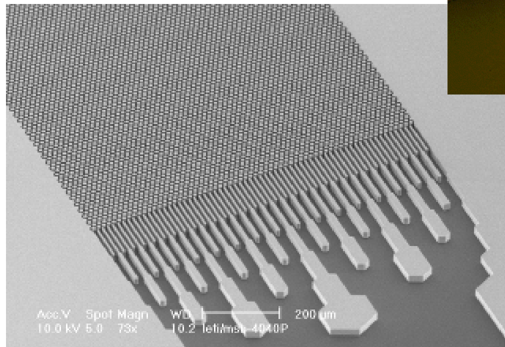
A wide diversity of new products

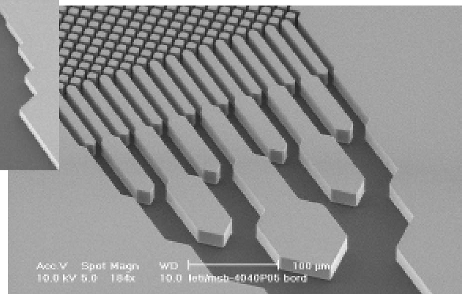


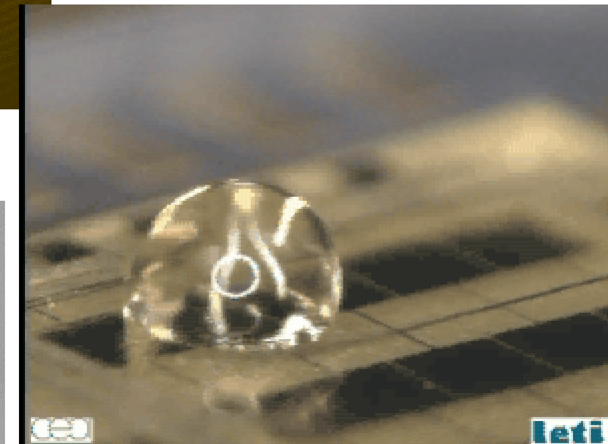




no established “CMOS-like” legacy process / device







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leti

Analog – mixed signal – rf

The importance of variability

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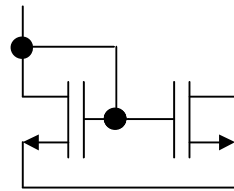
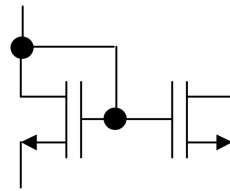
Transistor pairs as analog building blocks

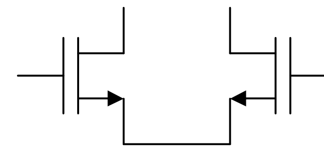
203 combinations, 8 having a design relevant function



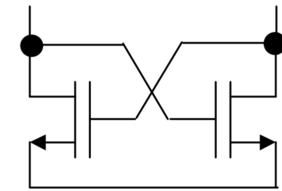
2-transistor current mirror



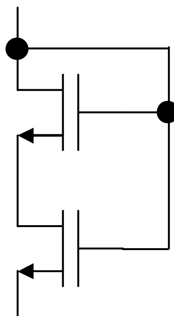
level shifter



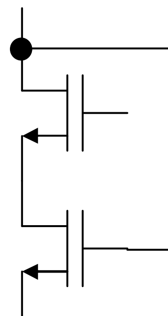
differential pair



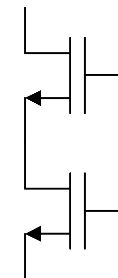
cross pair



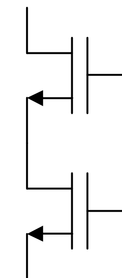
voltage reference 1



voltage reference 2



current mirror load



cascode pair

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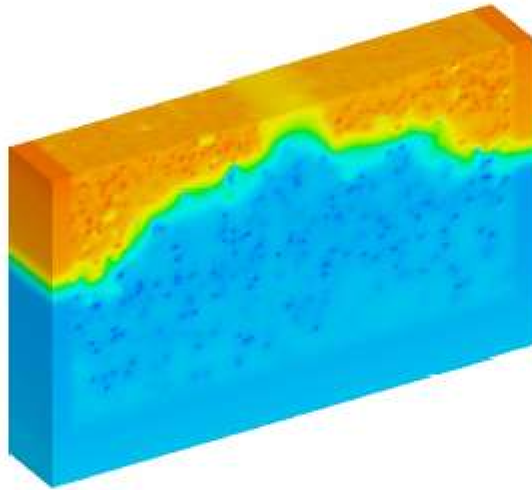
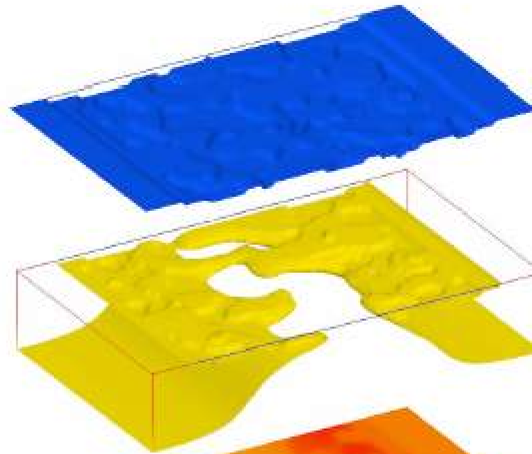
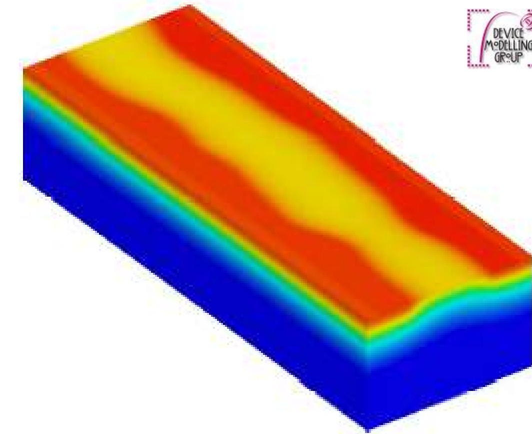
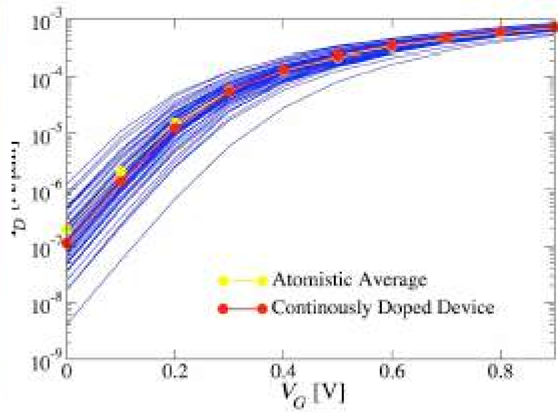
after H. Graeb, NANO-TEC Workshop (2011)

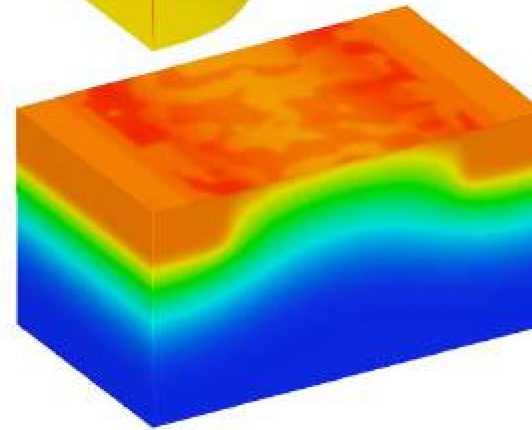
Fluctuations

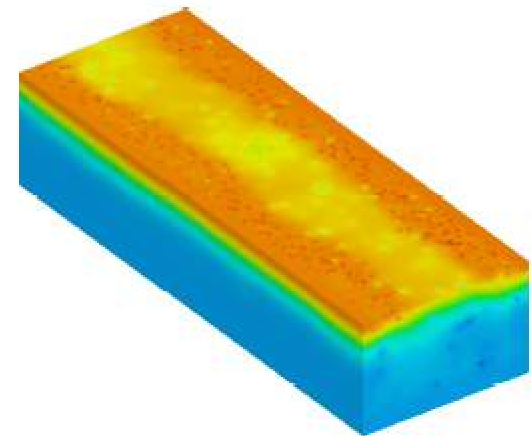












Random dopants | Interface roughness | Line edge roughness

from A. Asenov et al (2003)

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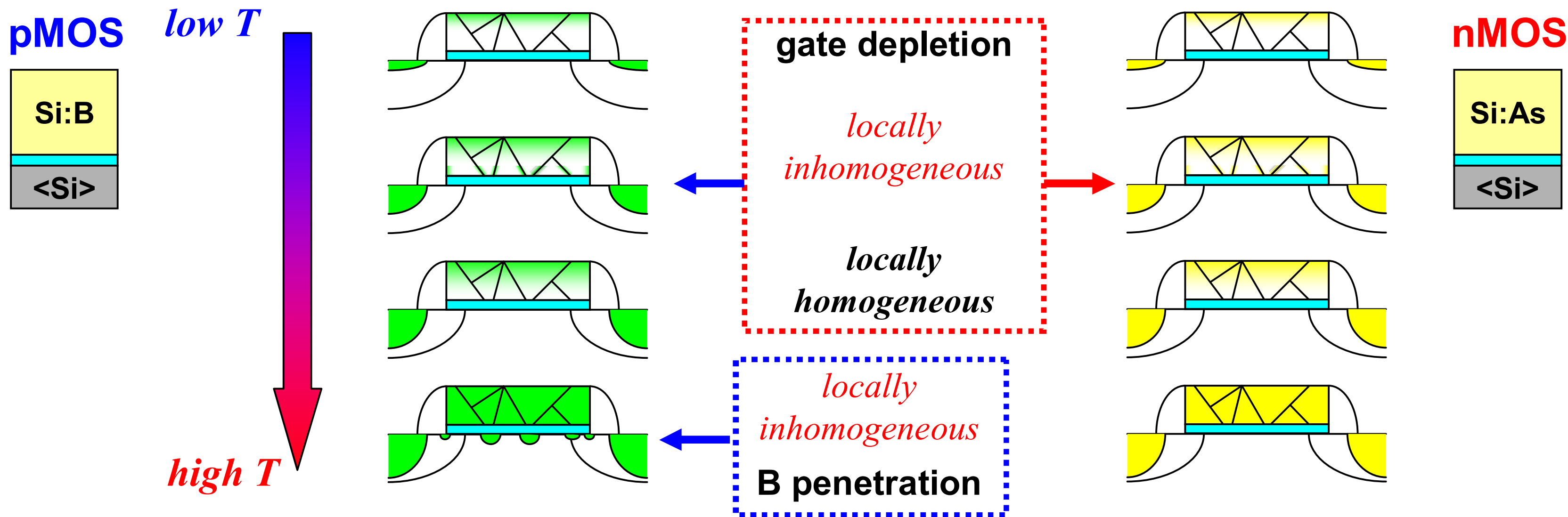
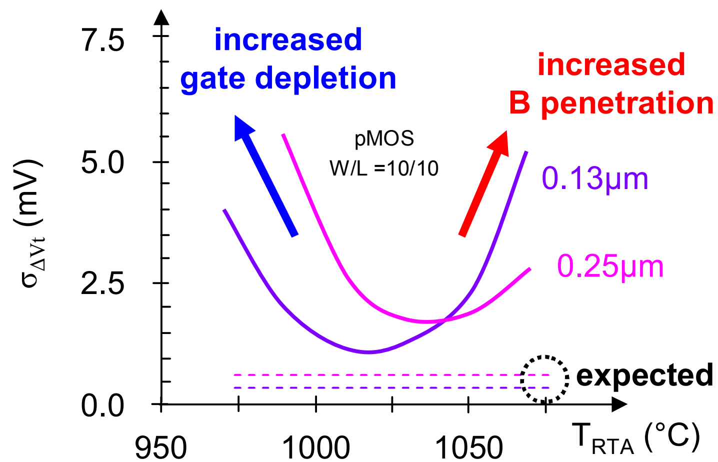
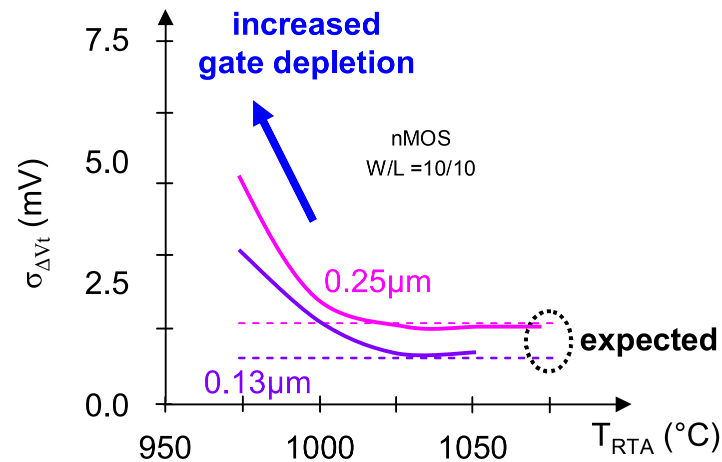
V_t matching







from H.P. Tuinhout et al., IEDM 631 (1997)

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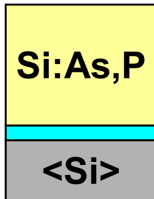
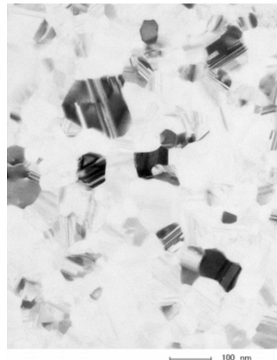
Atom Probe Tomography

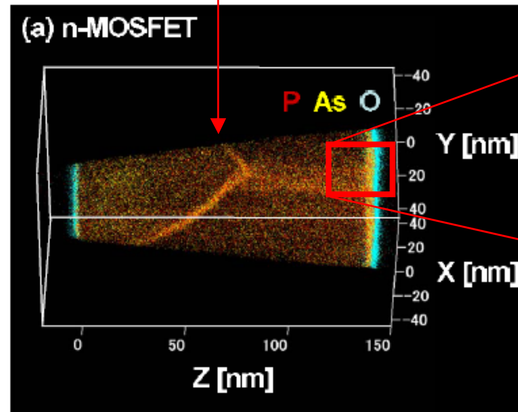
nMOS

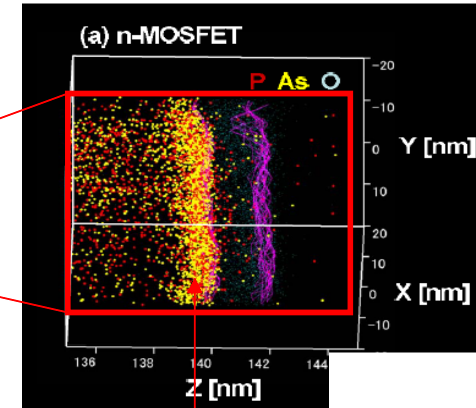


<grain size> ≈ 70nm

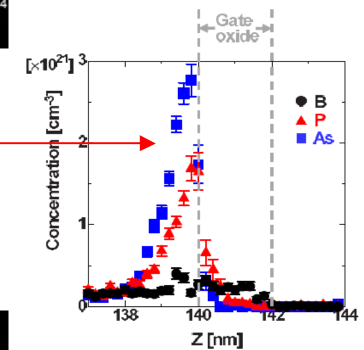


precipitation at grain boundary

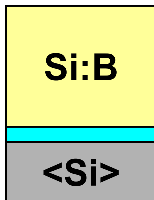




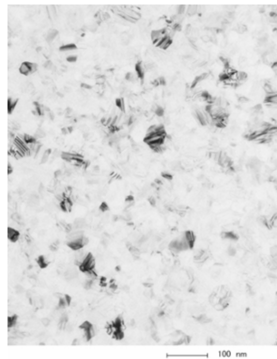
pile-up at interface

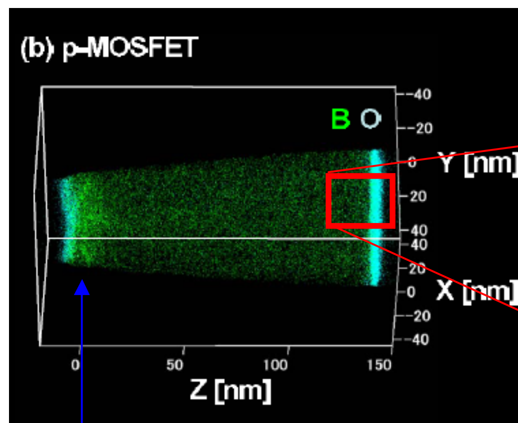


pMOS

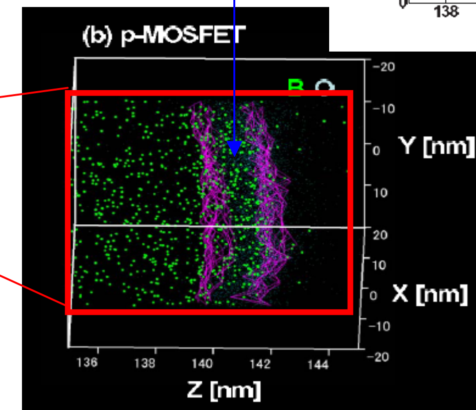


<grain size> ≈ 35nm





B in the gate oxide



exodiffusion

after K. Inoue et ql APL 95 043502 (2009)

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Healthcare systems

It is not only silicon…

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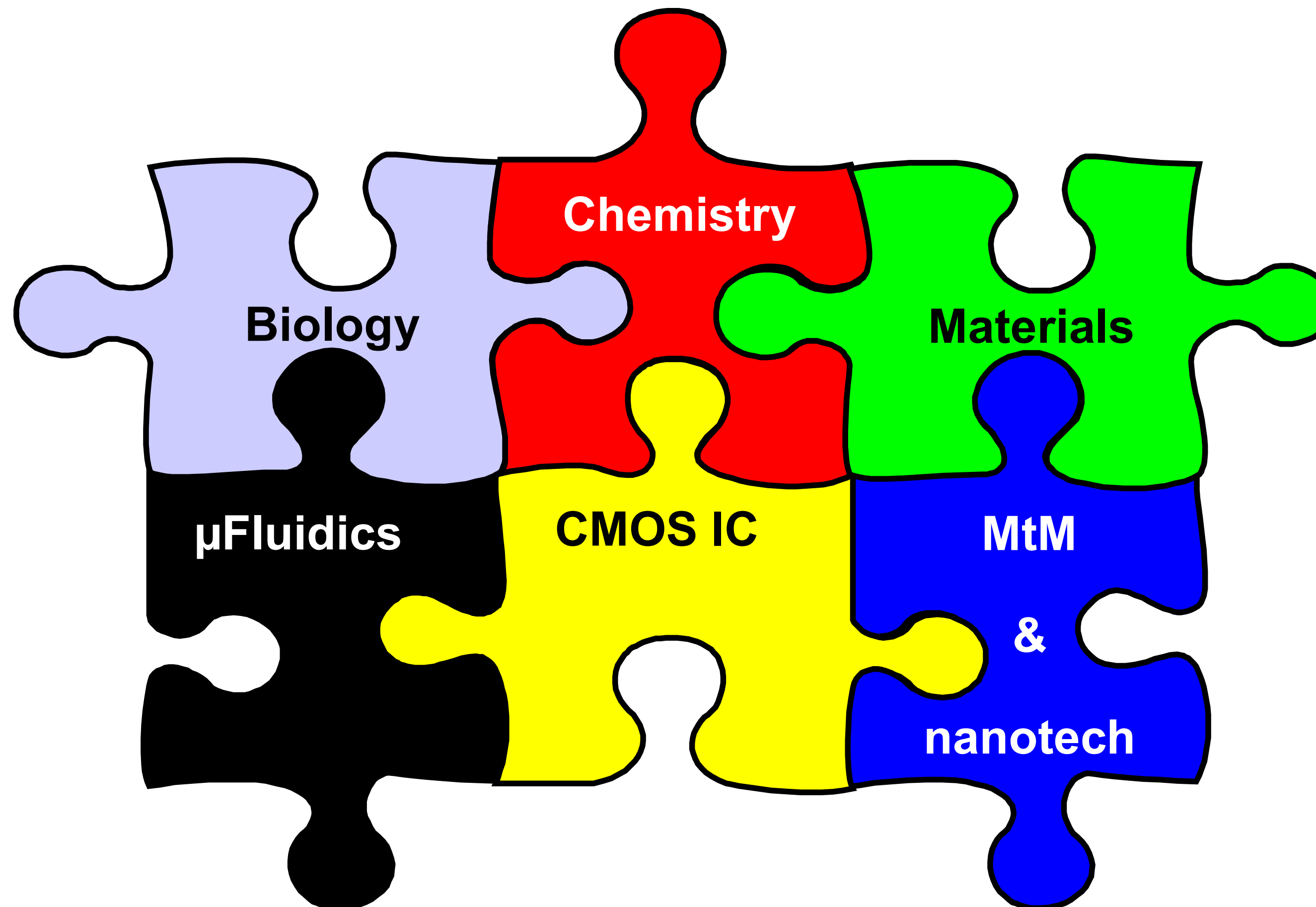
A wide technology portfolio for health



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Biosensing: an unusual world for s/c engineers

Sampling

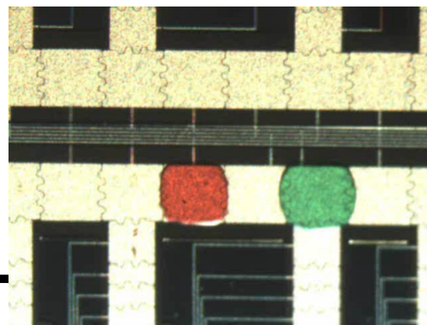
Preparation

Analysis

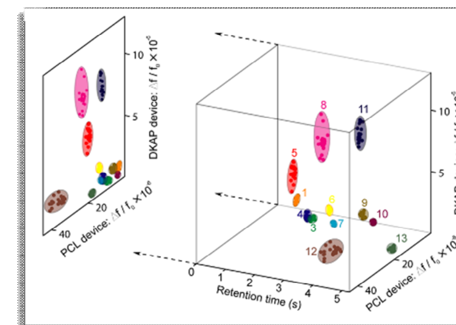
Gases
(10's l to ml)

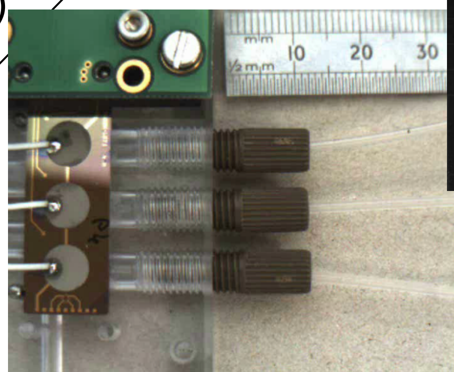
Liquids
(l to ml)

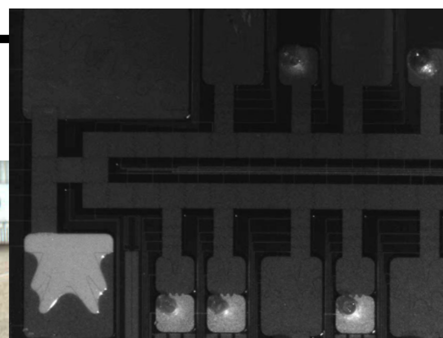
Biological
samples
(ml to µl)

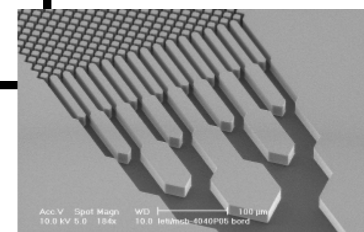


Concentration
Mixing
Purification









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Nanocharacterization challenges

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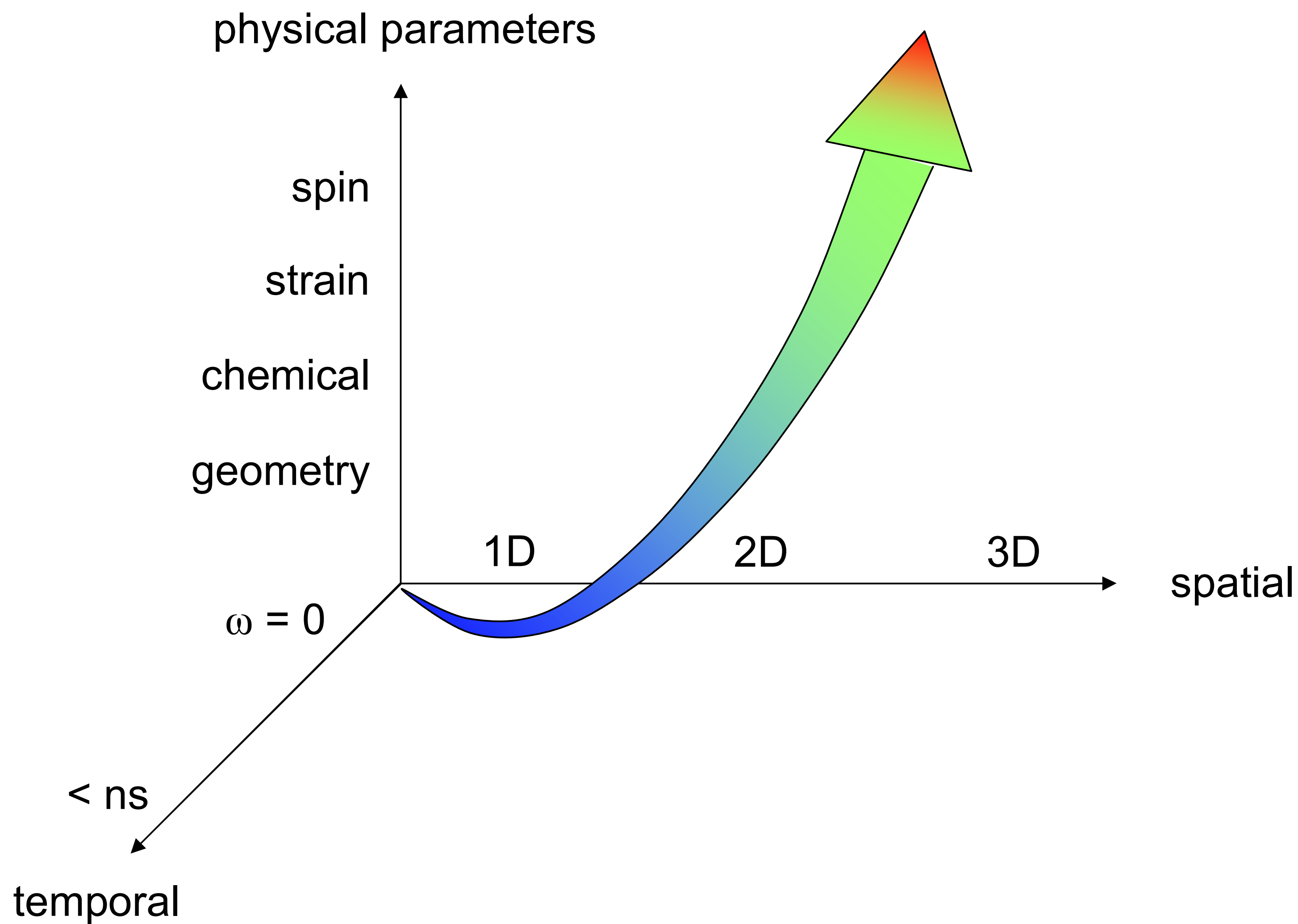
A multidimensional trend…



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Leti

…and more nano-characterization challenges

complementary set of techniques

- physical
- (bio)chemical
- electrical
- modelling

better techniques

- resolution
- sensitivity
- selectivity
- stability
- throughput

multiple scales

(nm → mm)

off-line → in-line / at-line

- non-destructive
- contamination
- cycle time
- throughput

sample preparation & observation conditions

- more complex structures
- artefact reduction
- fragile samples (biological…)

risk

image (data) ≠ reality

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Evolving R&D models

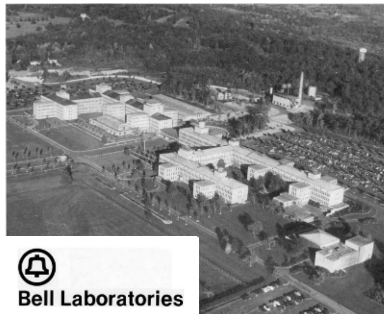
Clusters

Addressing diversity

Consortia

Cost mitigation

Central labs



Technology leadership

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Need of pooling resources together

European Photon and Neutron science campus

NanoCharacterization Center

leti

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Nano-Characterization Platform

- **~60** researchers & technicians
- **40** major characterization equipments
- **2500m²** laboratory space
- **7** Excellence Centers

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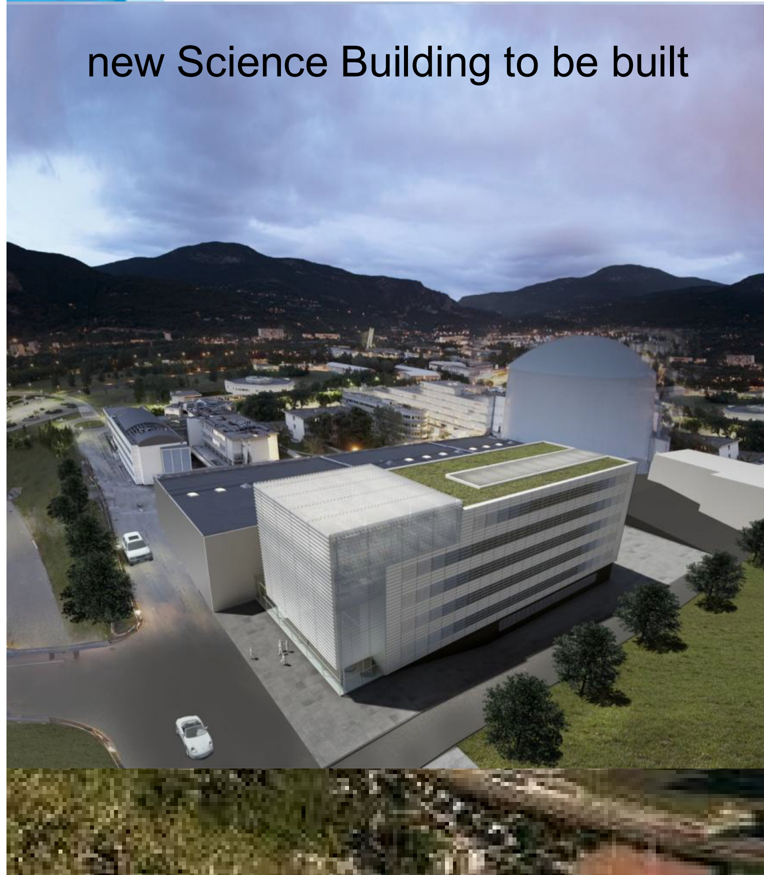
Cooperation with local expertise



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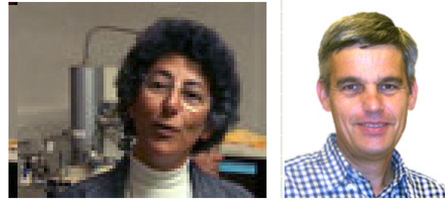

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