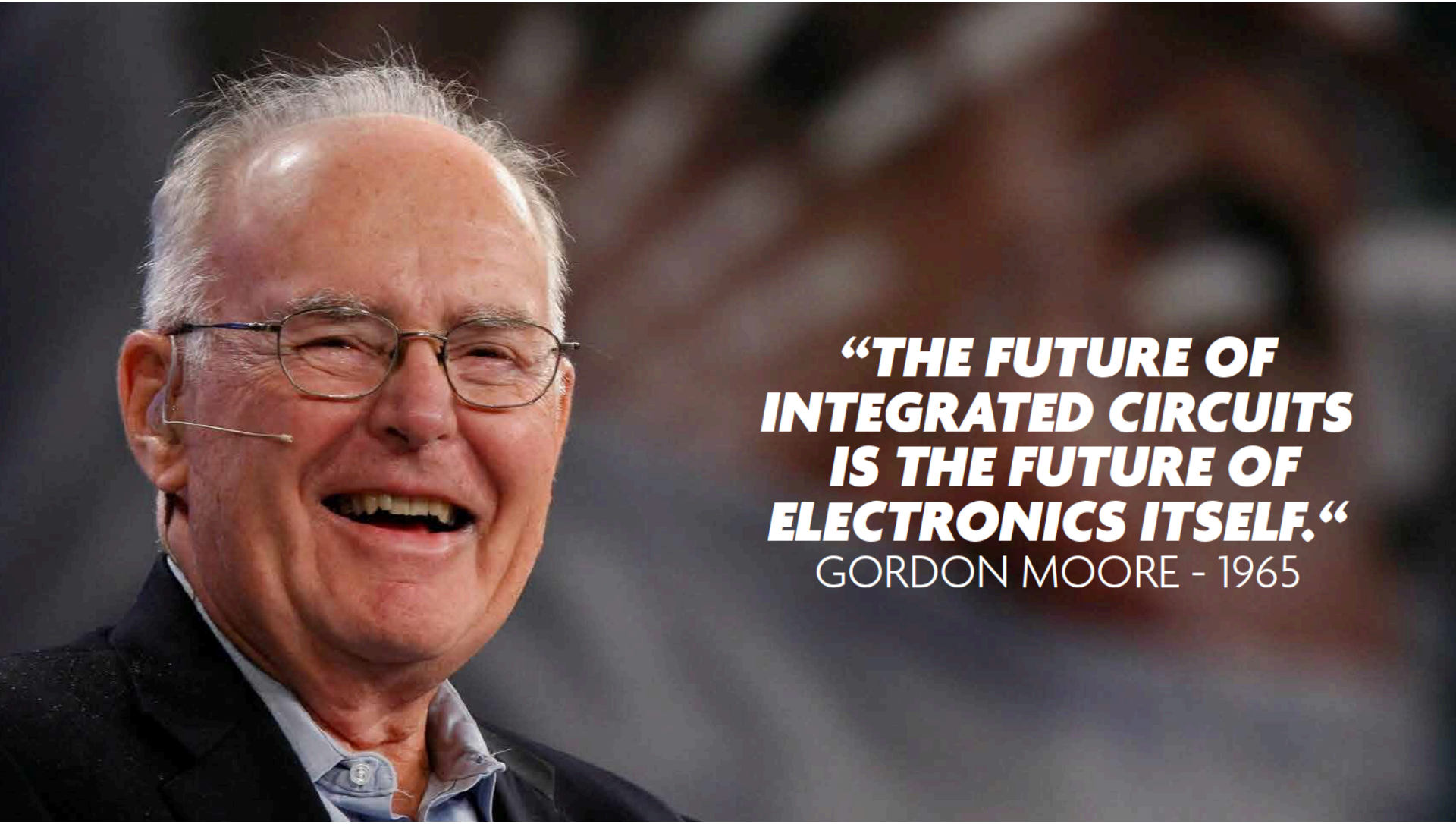
Report on IMEC International Technology Form

Brussels, May 24-25th, 2016

Trends and drivers for integrated circuit technology

W. Snoeys, CERN

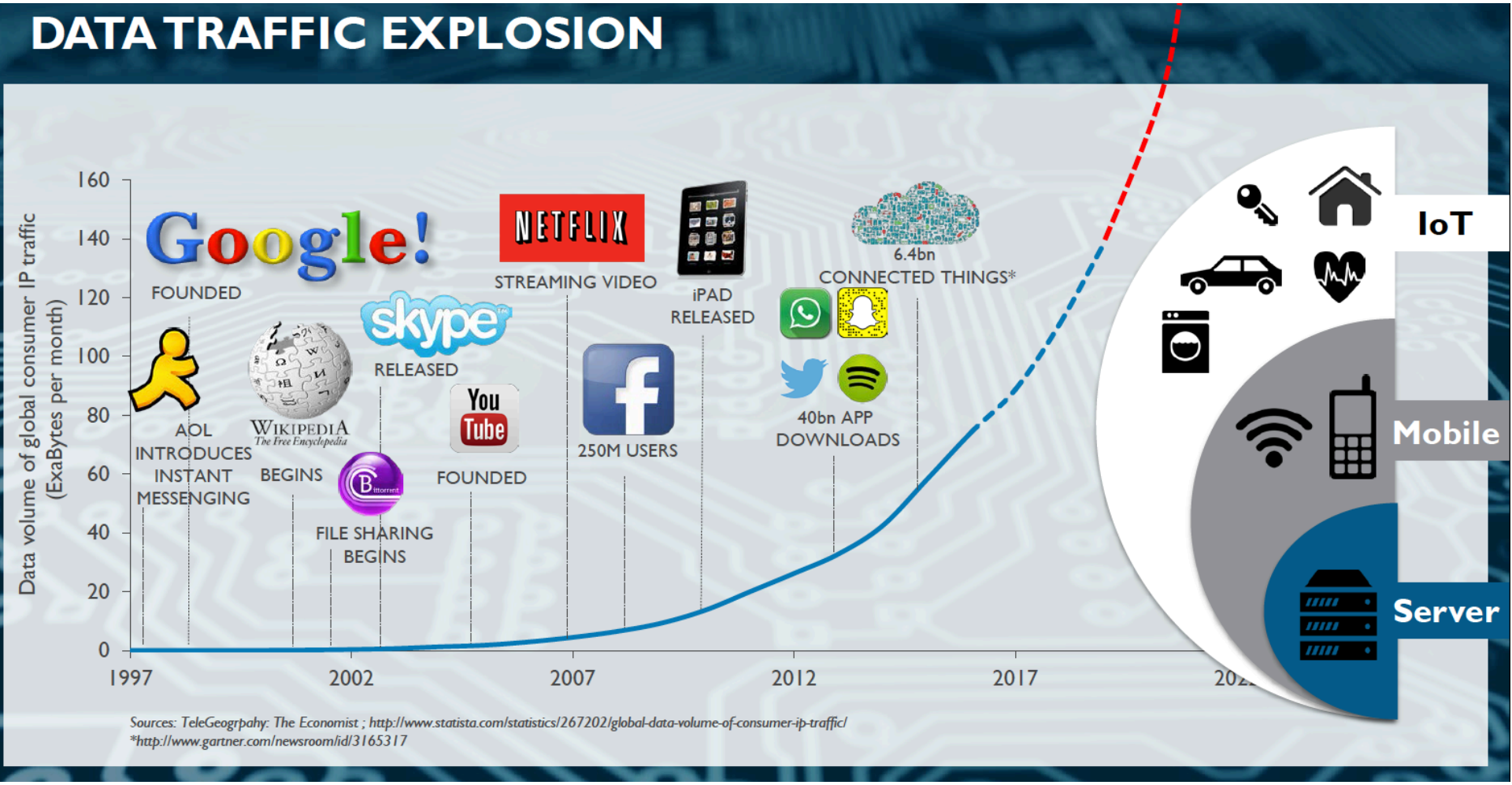


Gordon Moore – 2016 Imec Lifetime of Innovation Award

CMOS Scaling

New drivers

DATA TRAFFIC EXPLOSION



IoT wave

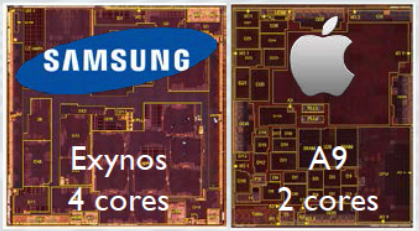
APP wave

PC wave

NEW APPLICATIONS DRIVE CPU REQUIREMENTS

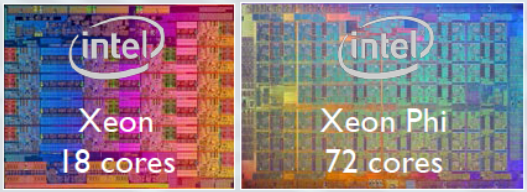
Micro-controller
Performance **100 MHz**
Power **1 mW-100mW**
Memory **<1 MByte**

28 nm



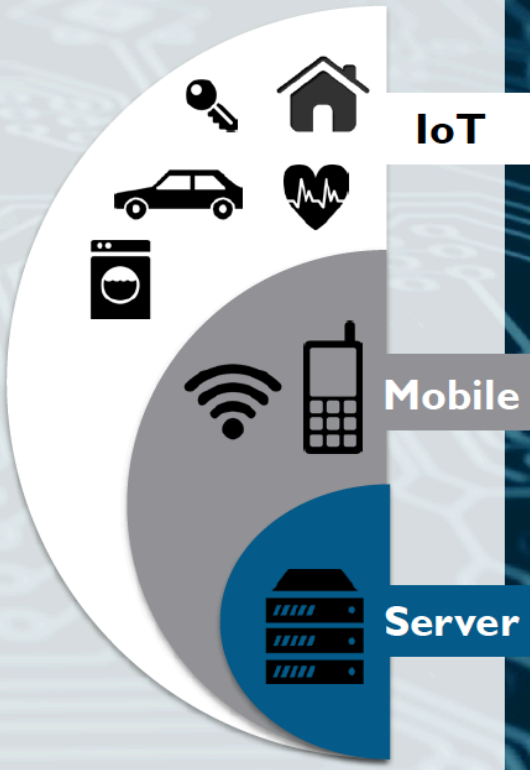
Cores **4**
Performance **1 GHz**
Power **100 mW-10W**
Memory **1-4 MByte**

14 nm



Cores: **8-16 (72 for HPC)**
Performance **4 GHz**
Power **100-500W**
Memory **16-40MByte**

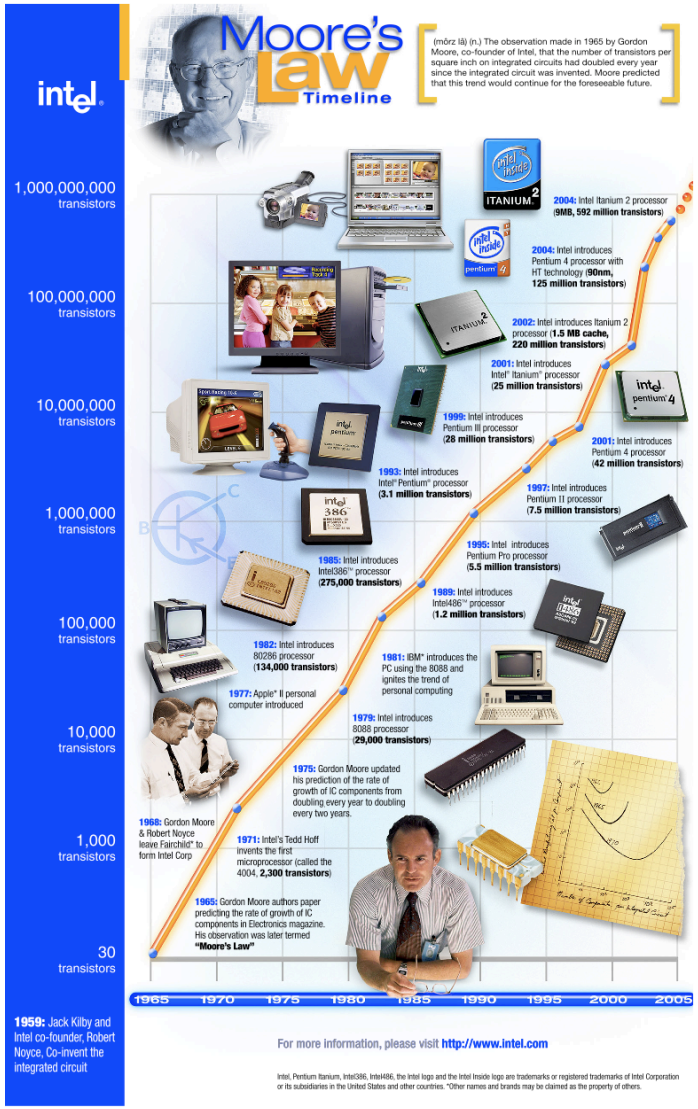
14 nm



... DRIVING TECHNOLOGY DIVERSIFICATION

Transistor scaling

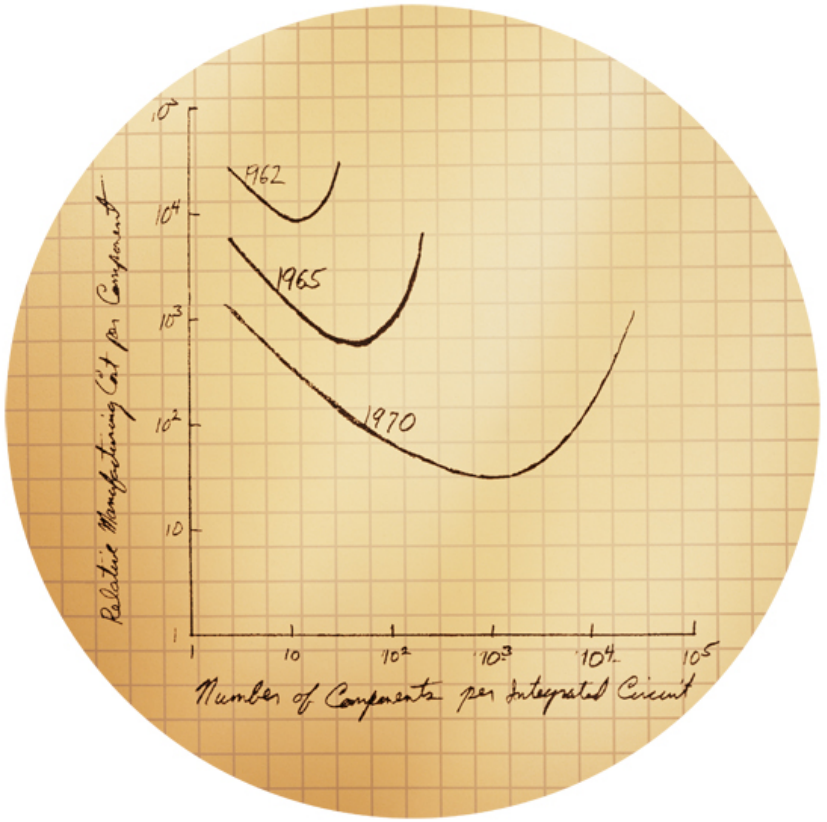
Smaller More Faster Less power



Moore's law

'The number of transistors per integrated circuit increases exponentially with time

'(doubling roughly every two years)'



Bob Dennard

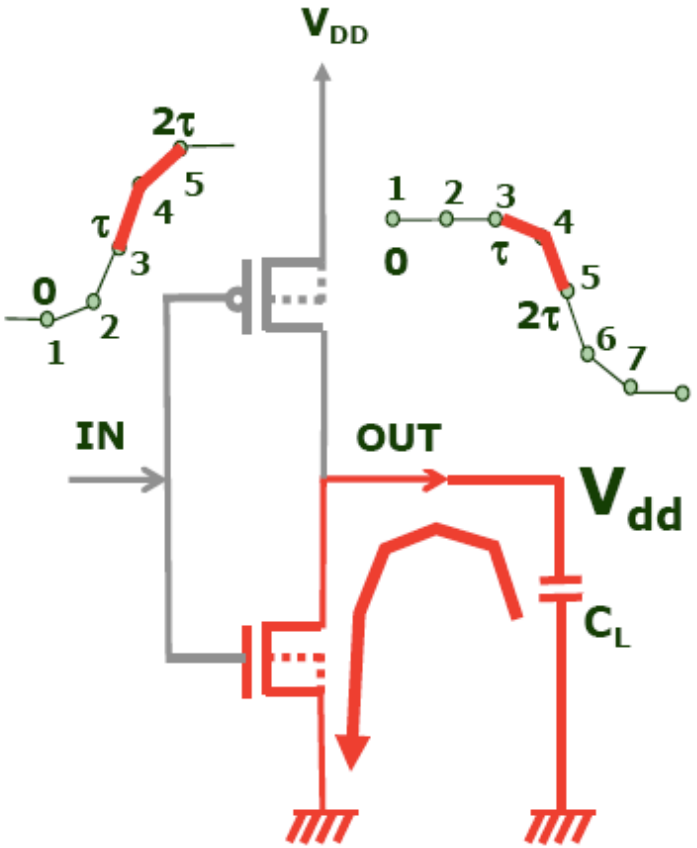
Constant power density scaling

Not always possible

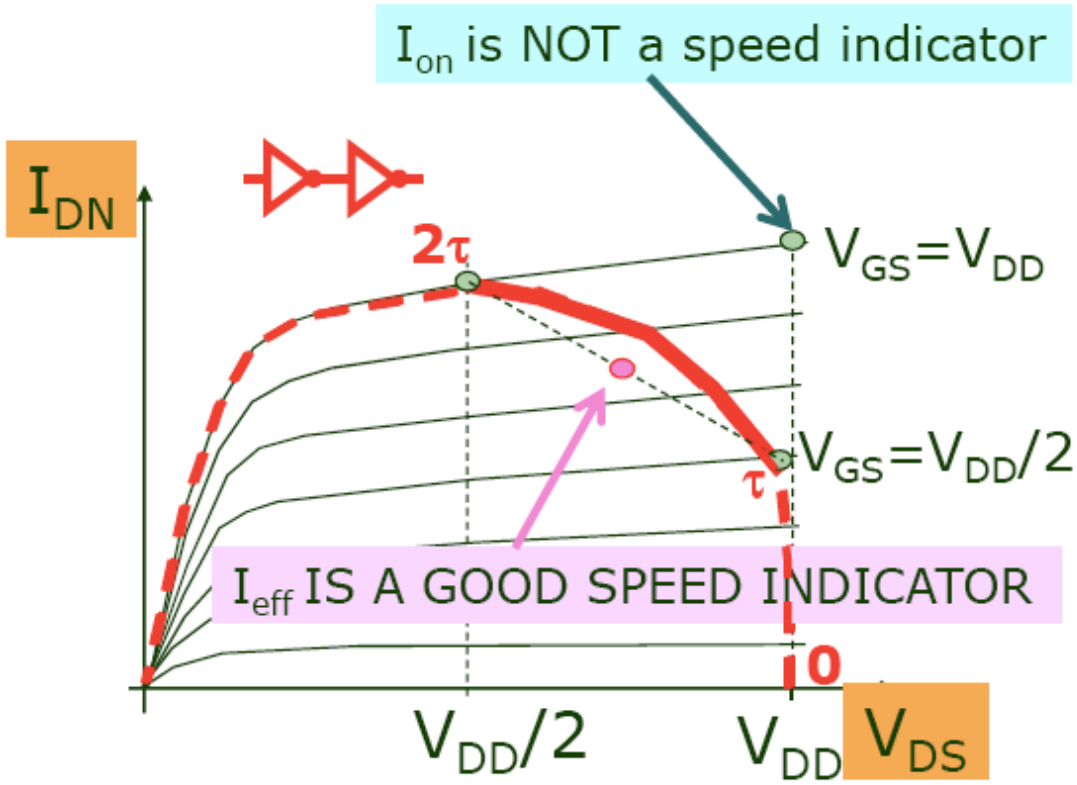
Trouble until new game changer is found.

Transistor performance metrics (T. Skotnicki)

SWITCHING TRAJECTORY WHEN CHARGING /DISCHARGING THE LOAD



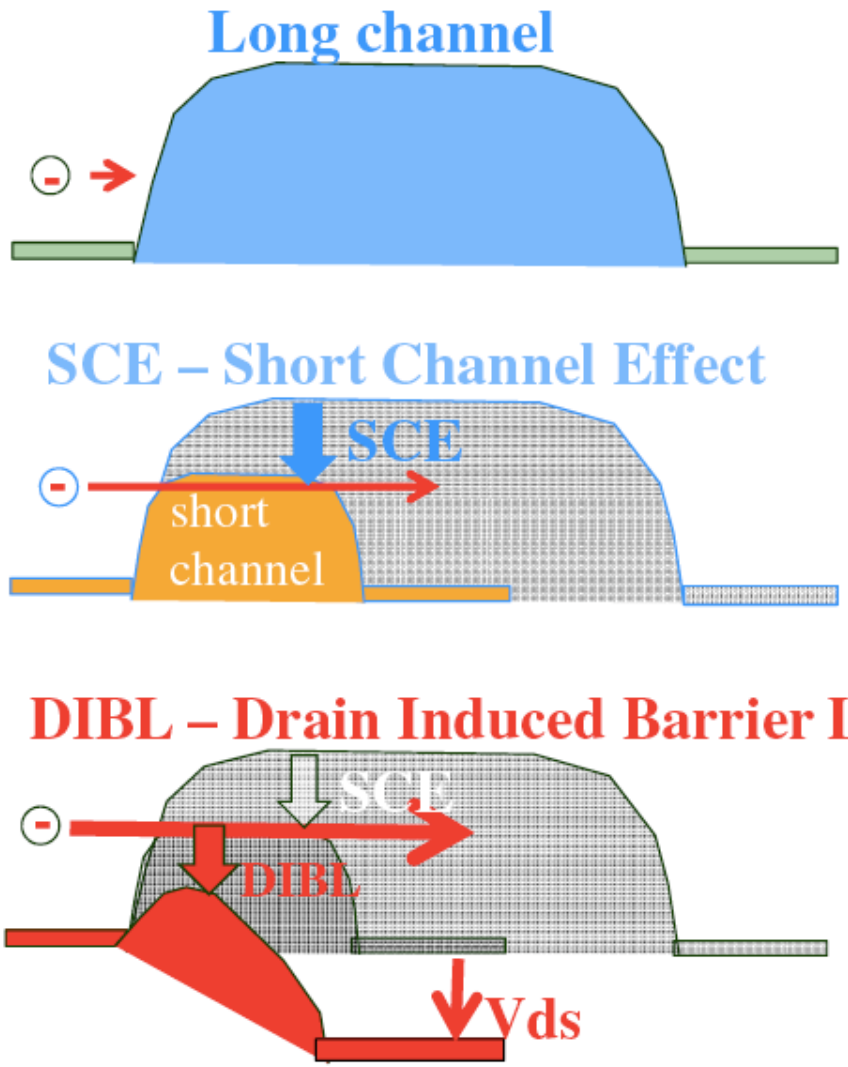
Example of CHARGING

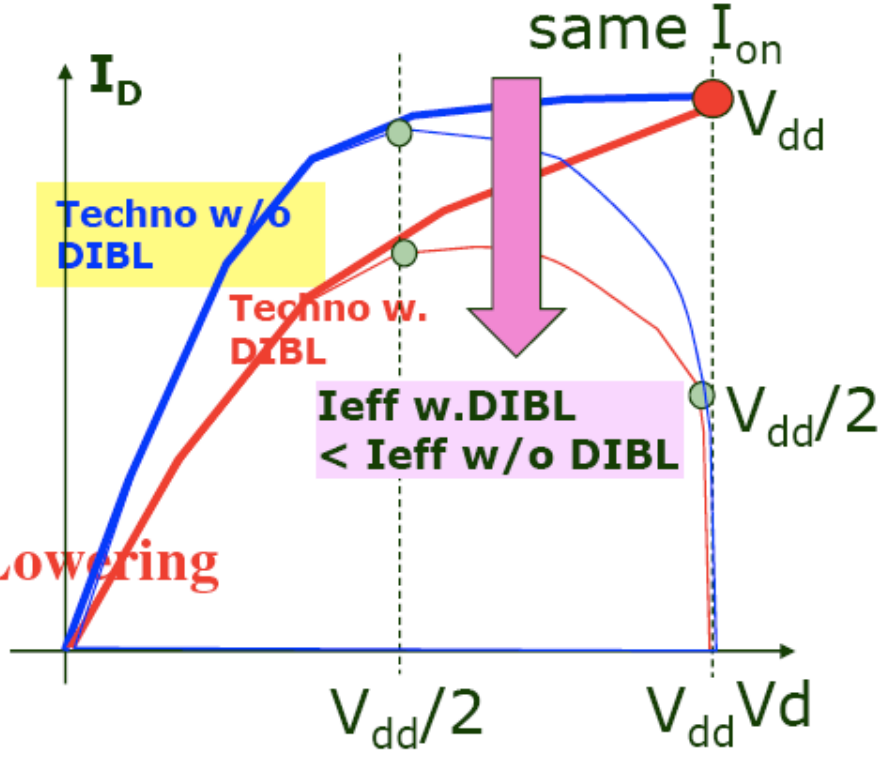


$$I_{eff} = \frac{1}{2}\left[I\left(V_G = \frac{V_{dd}}{2}; V_D = V_{dd} \right) + I\left(V_G = V_{dd}; V_D = \frac{V_{dd}}{2} \right) \right]$$

Ref.: M.H. Na et al., IEDM 2002, p.121.

Importance of Drain Induced Barrier Lowering

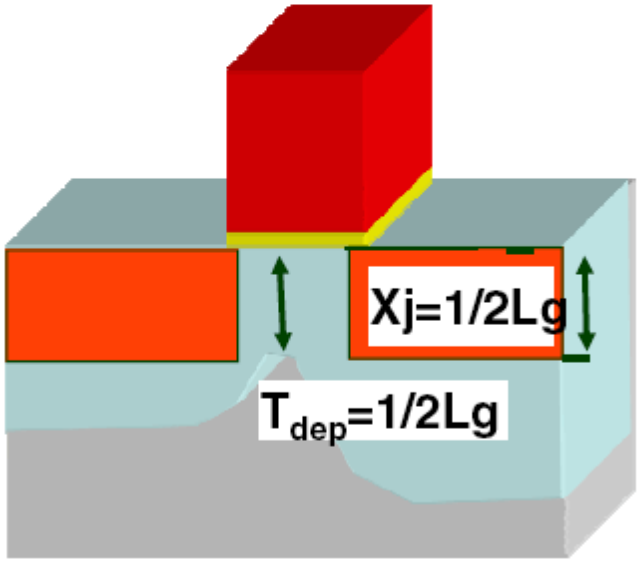




WHY DOES THE PLANAR MOSFET FAIL ?

(Ref.: *T. Skotnicki, et al., Electron Device Letters, Vol 9, N° 3, 1998*)

$$DIBL = 0.80 \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \left(1 + \frac{X_j^2}{L_{el}^2} \right) \frac{T_{ox}}{L_{el}} \frac{T_{dep}}{L_{el}} V_{DS}$$



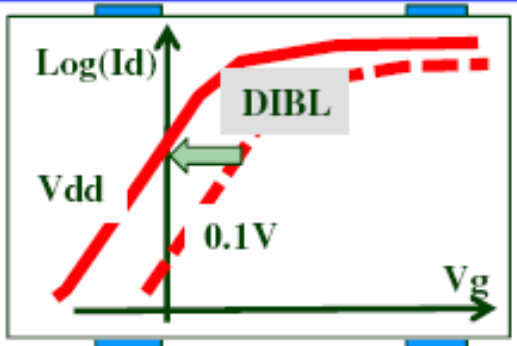
Suppose : Lel=2/3Lg

$$2.4 \left(1 + \frac{3^2}{4^2} \right) \frac{1}{20} \frac{3}{4} 1V = 140mV$$

REF.: T. Skotnicki, invited paper ESSDERC 2000, pp. 19-33, edit. Frontier Group

Who does better than bulk ? (T. Skotnicki)

$$DIBL = 0.80 \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \left(1 + \frac{X_j^2}{L_{el}^2}\right) \frac{T_{ox}}{L_{el}} \frac{T_{dep}}{L_{el}} V_{DS}$$



BULK

T_{dep}=3/4Lel

Xj=3/4Lel

140mV/V

T_{ox} +2A

ε_{si} +15%

III-V

210mV/V

T_{dep}=Tsi+λTbox

Xj=Tsi ≥6nm

ETSOI

110mV/V

FDSOI

UTBB

80mV/V

T_{dep}=Tsi/2

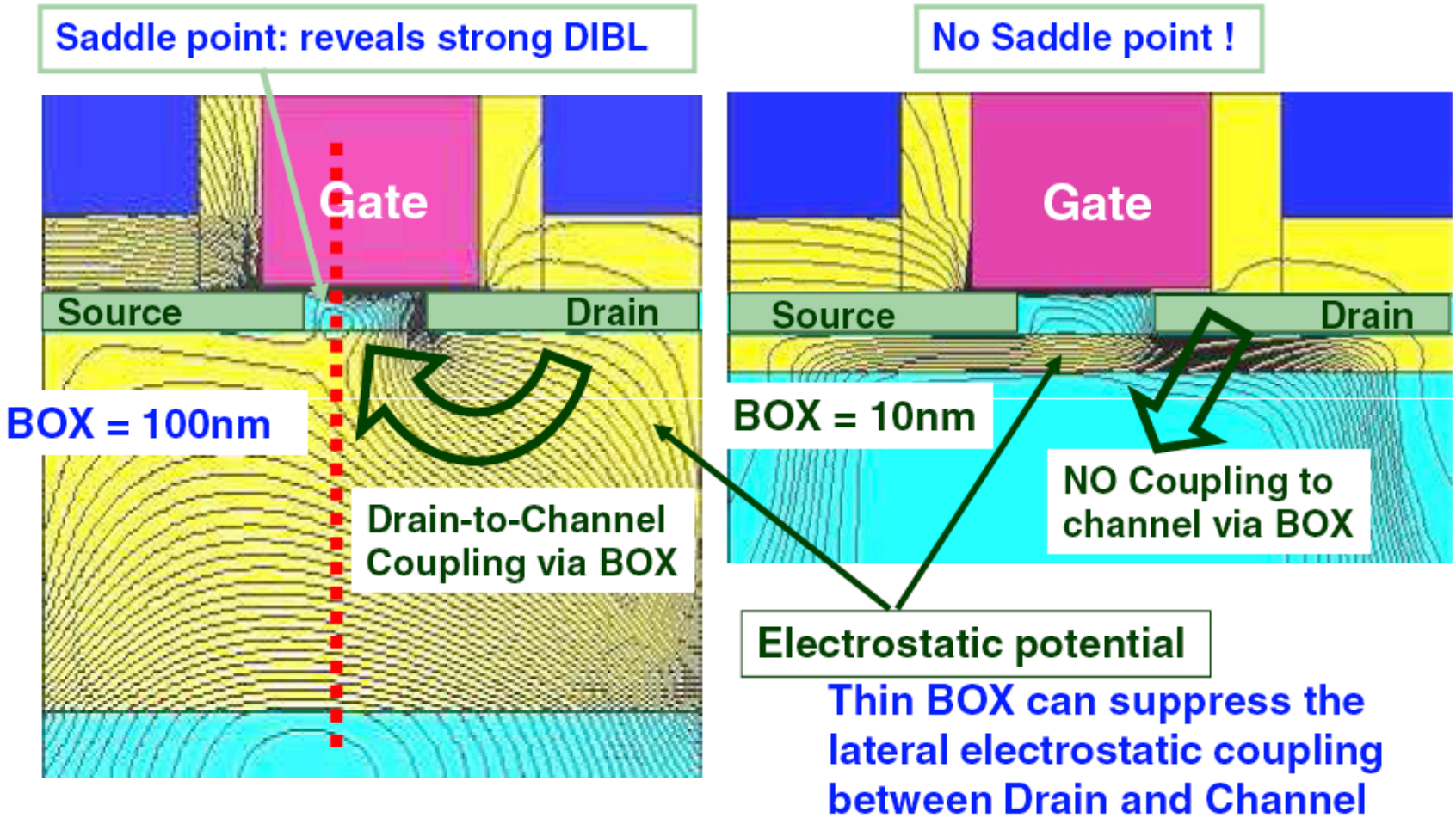
Xj=Tsi/2

Tsi ≥ 10nm

FinFET

70mV/V

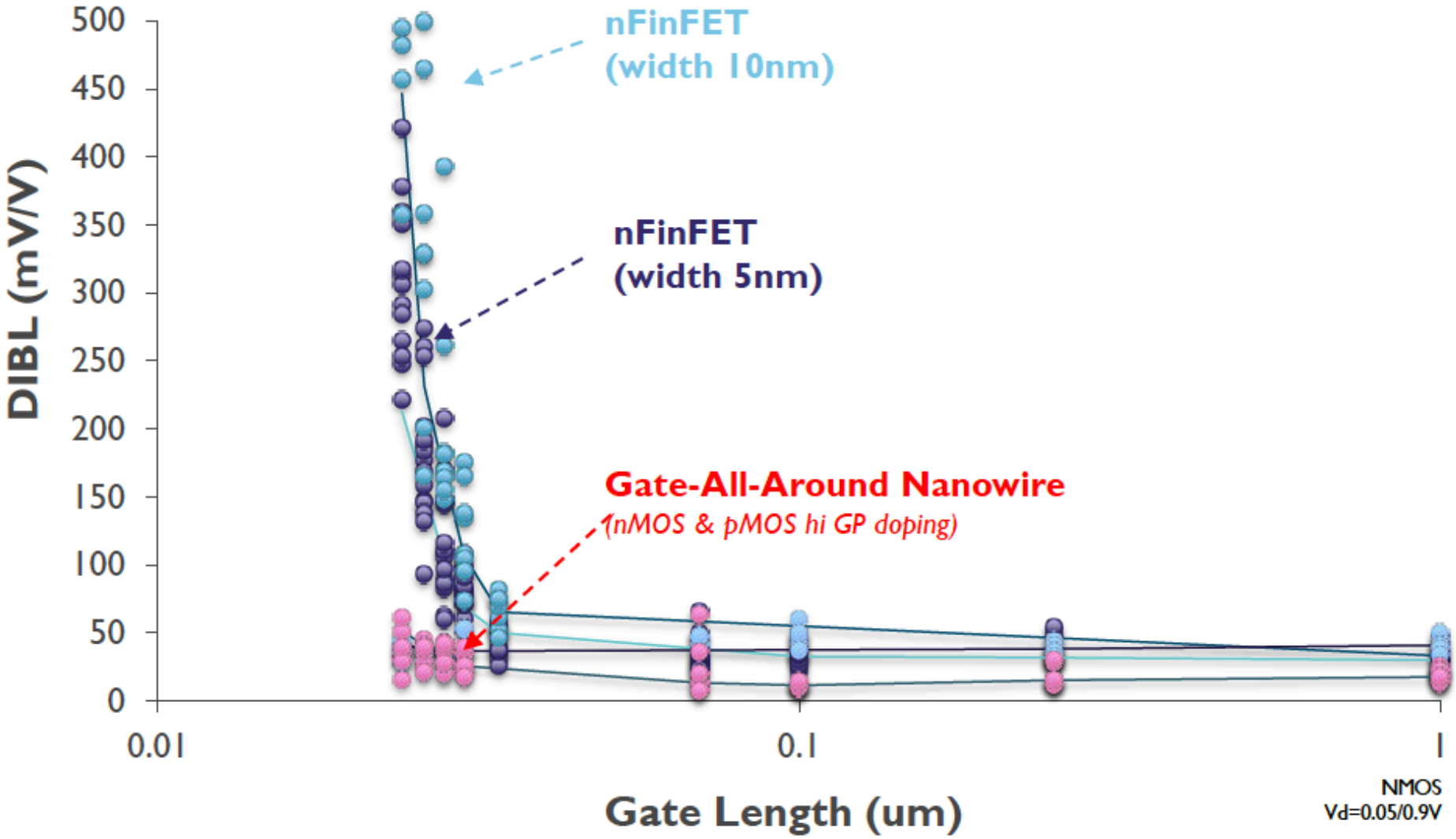
SOI: Why thin buried oxide ?

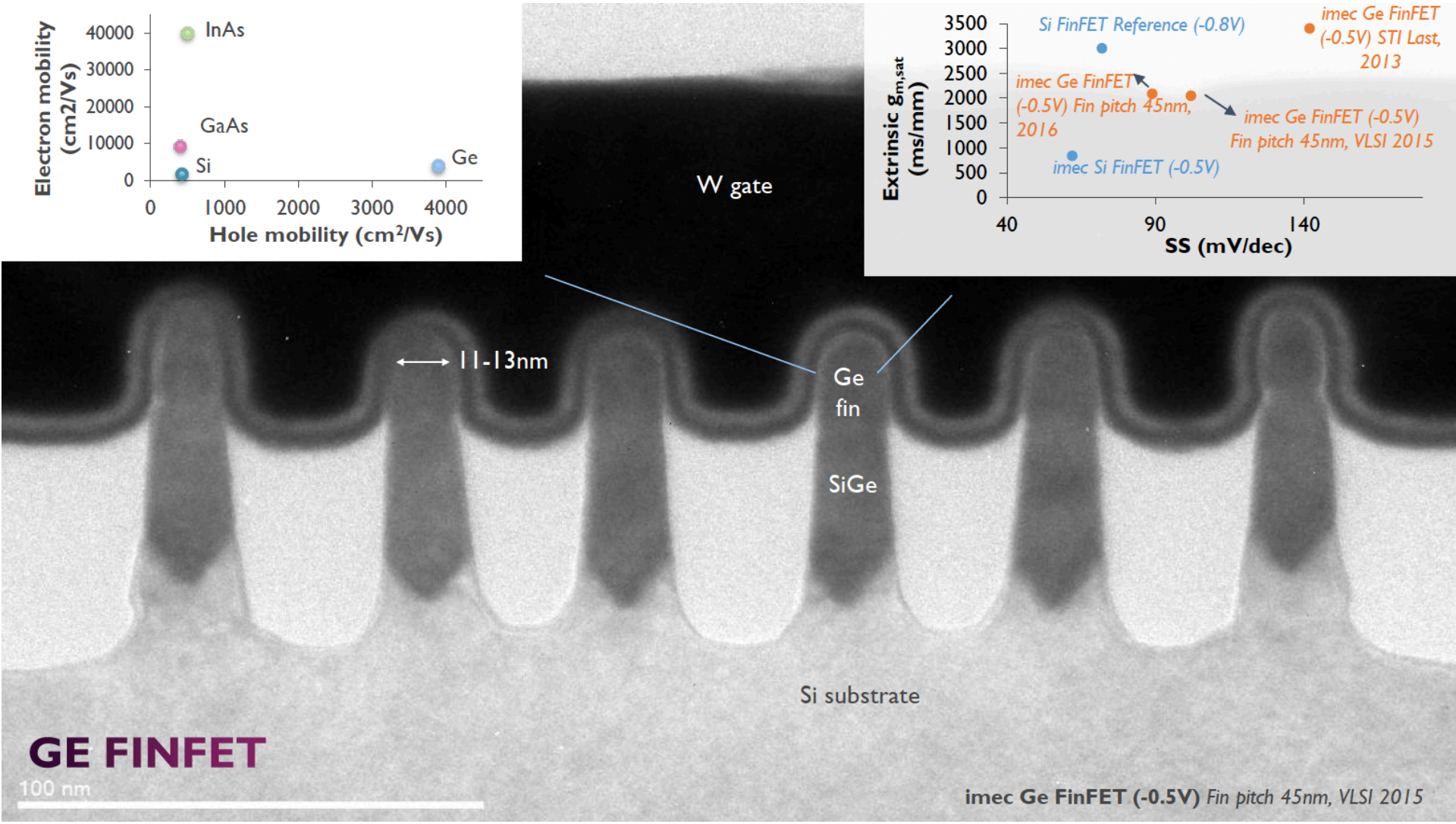


REF.: T. Skotnicki et al., ECS Symp, SOI Techn. & Dev XI, edit S. Cristoloveanu , 2003

Avoid drain-to-channel coupling to reduce Short Channel Effects and Drain Induced Barrier Lowering

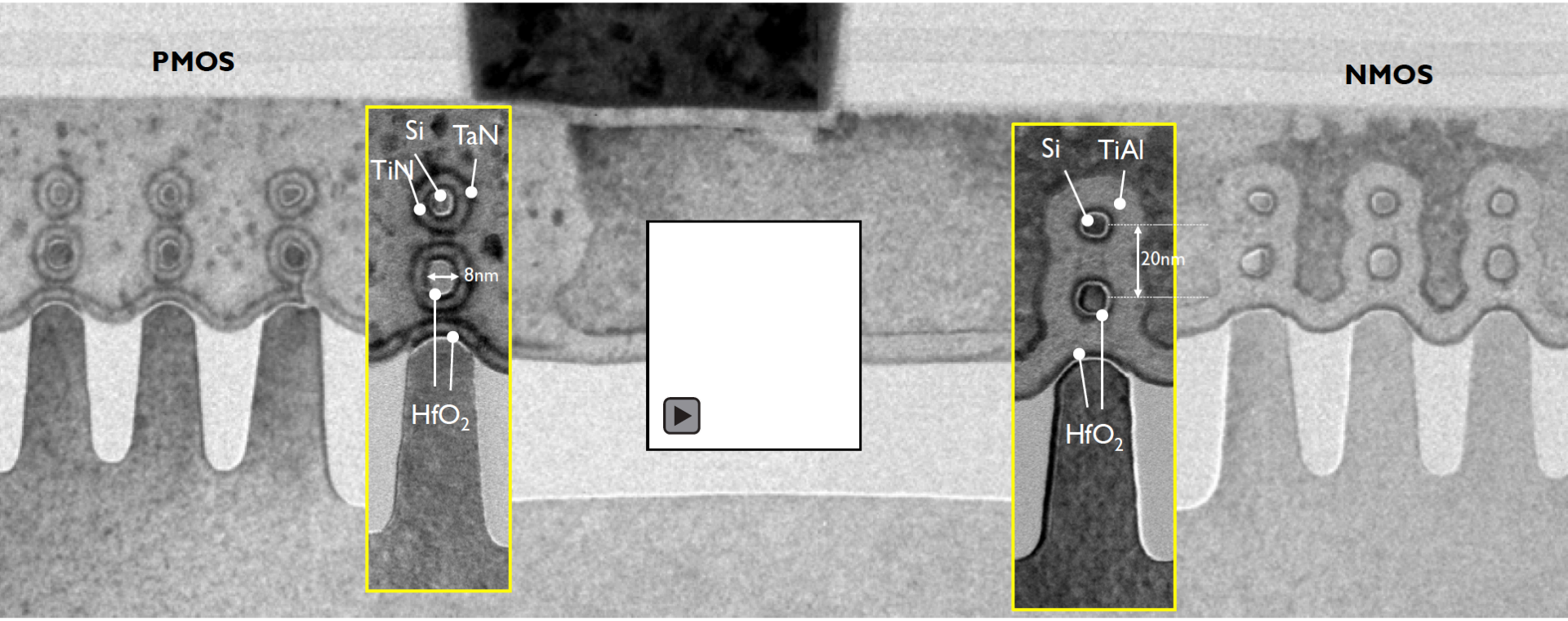
Transistor Electrostatics -> new devices




Electron mobility (cm2/Vs)
40000
30000
20000
10000
0
InAs
GaAs
Si
Ge
0
1000
2000
3000
4000
Hole mobility (cm²/Vs)
W gate
11-13nm
Ge fin
SiGe
Si substrate
GE FINFET
100 nm
Extrinsic gm,sat (ms/mm)
3500
3000
2500
2000
1500
1000
500
0
Si FinFET Reference (-0.8V)
imec Ge FinFET (-0.5V) STI Last, 2013
imec Ge FinFET (-0.5V) Fin pitch 45nm, 2016
imec Ge FinFET (-0.5V) Fin pitch 45nm, VLSI 2015
imec Si FinFET (-0.5V)
40
90
140
SS (mV/dec)
imec Ge FinFET (-0.5V) Fin pitch 45nm, VLSI 2015

SI GATE-ALL-AROUND NANOWIRES (GAA)

CMOS INTEGRATION



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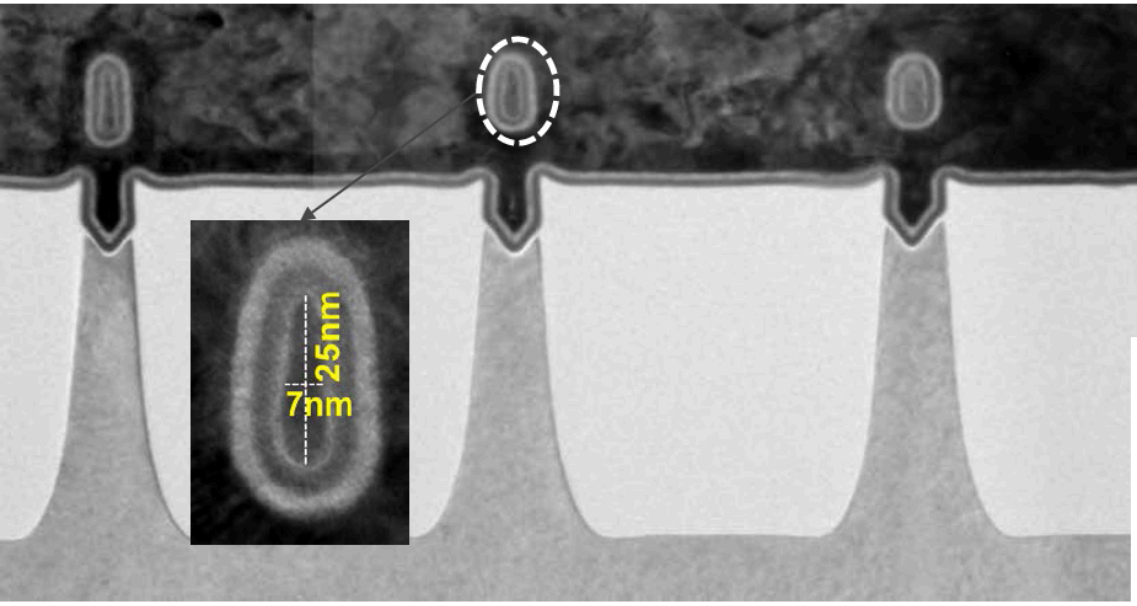
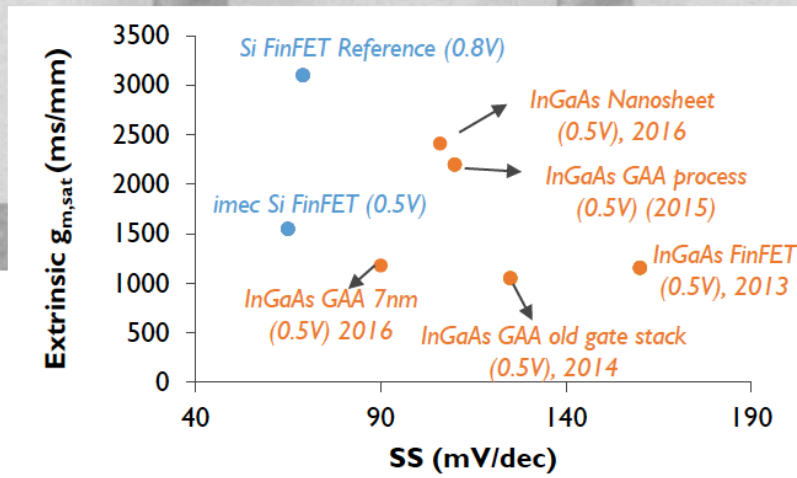
Transistor Electrostatics

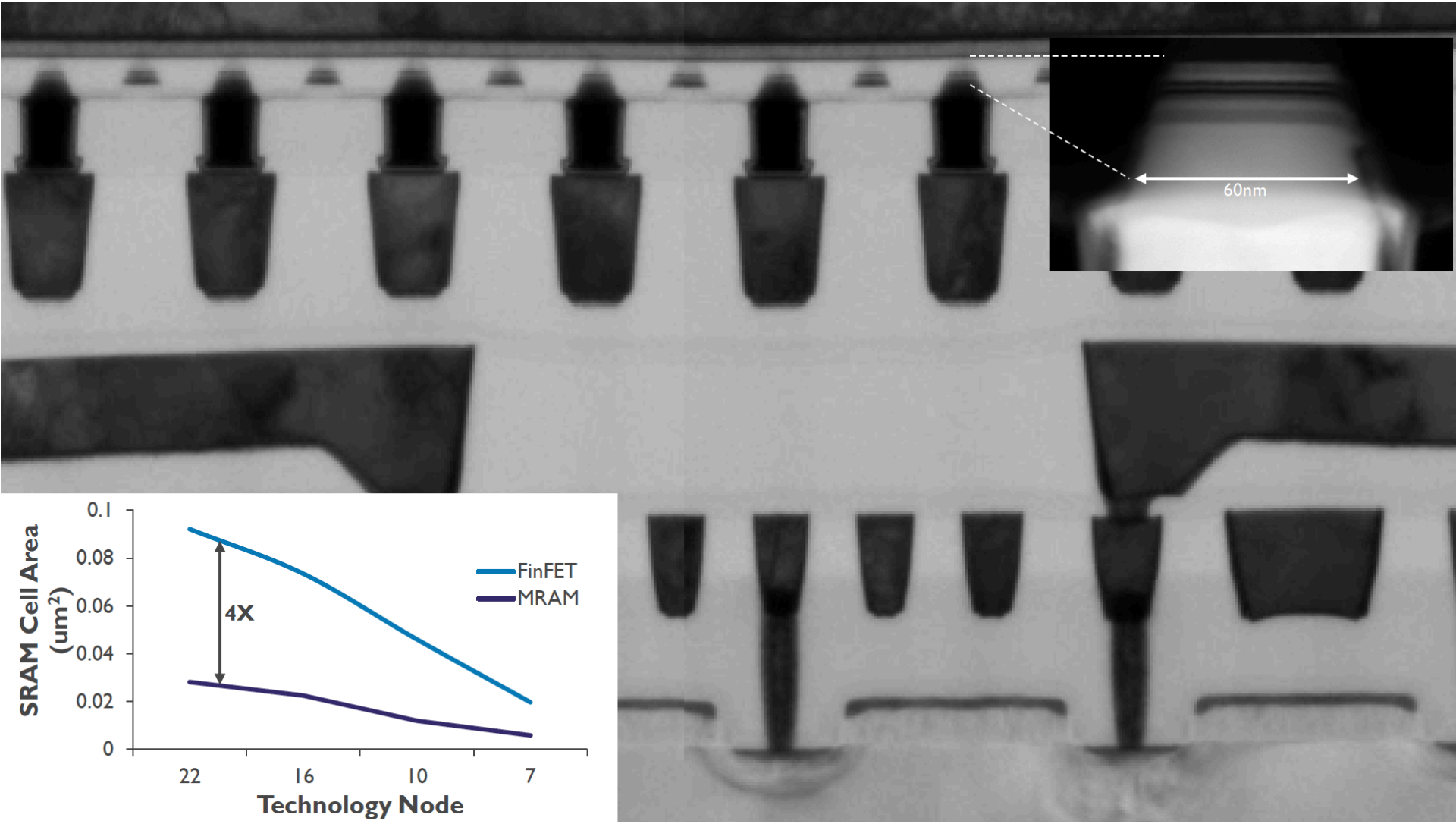
III-V GATE-ALL-AROUND NANOWIRES (GAA)

SUB-10NM DEVICES OBTAINED

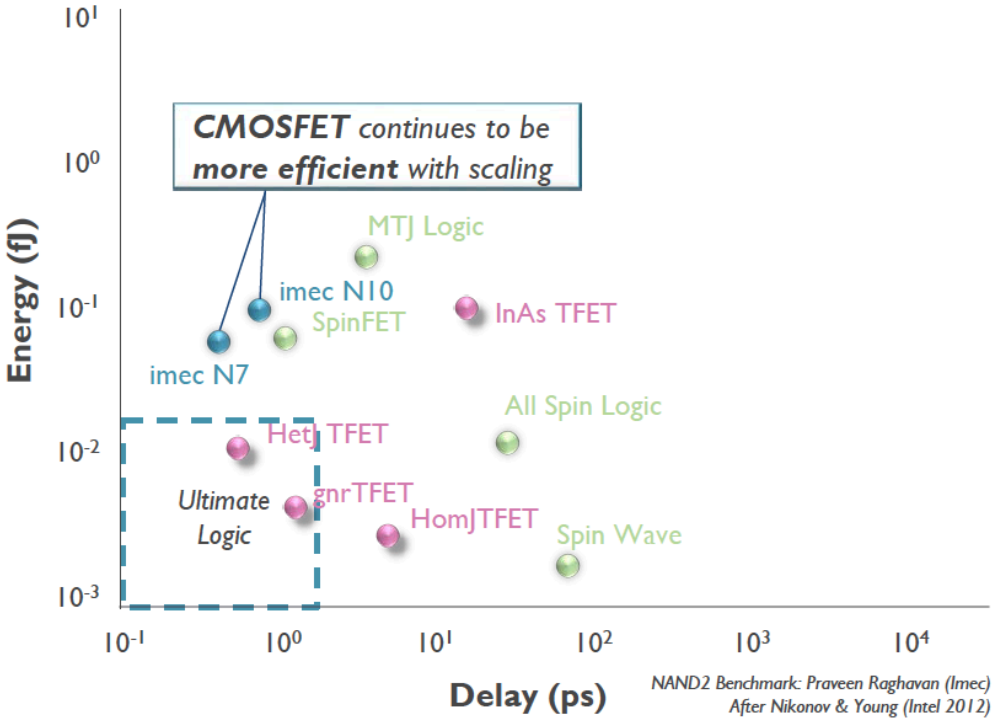


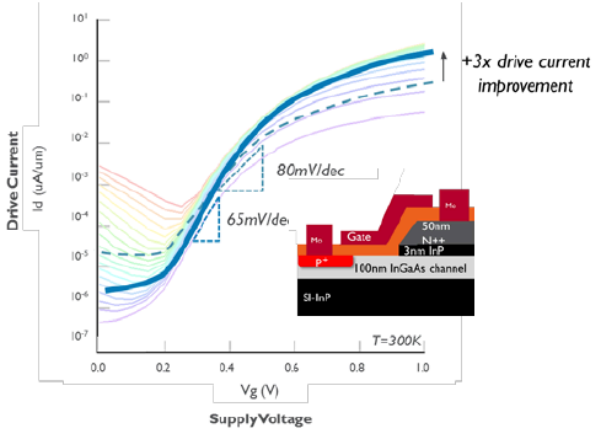


SRAM – MRAM offers density advantage

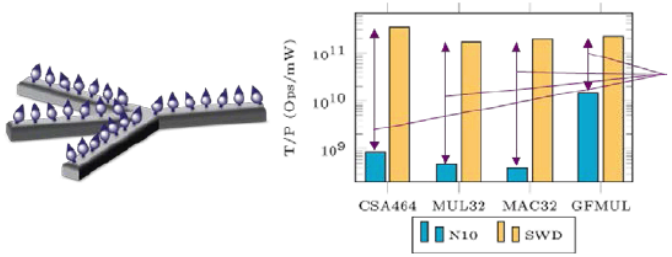


FINDING THE NEXT SWITCH





Tunnel FET can provide 3x drive current improvement



Spine Wave Majority Gates allow for 100x Energy efficiency improvement

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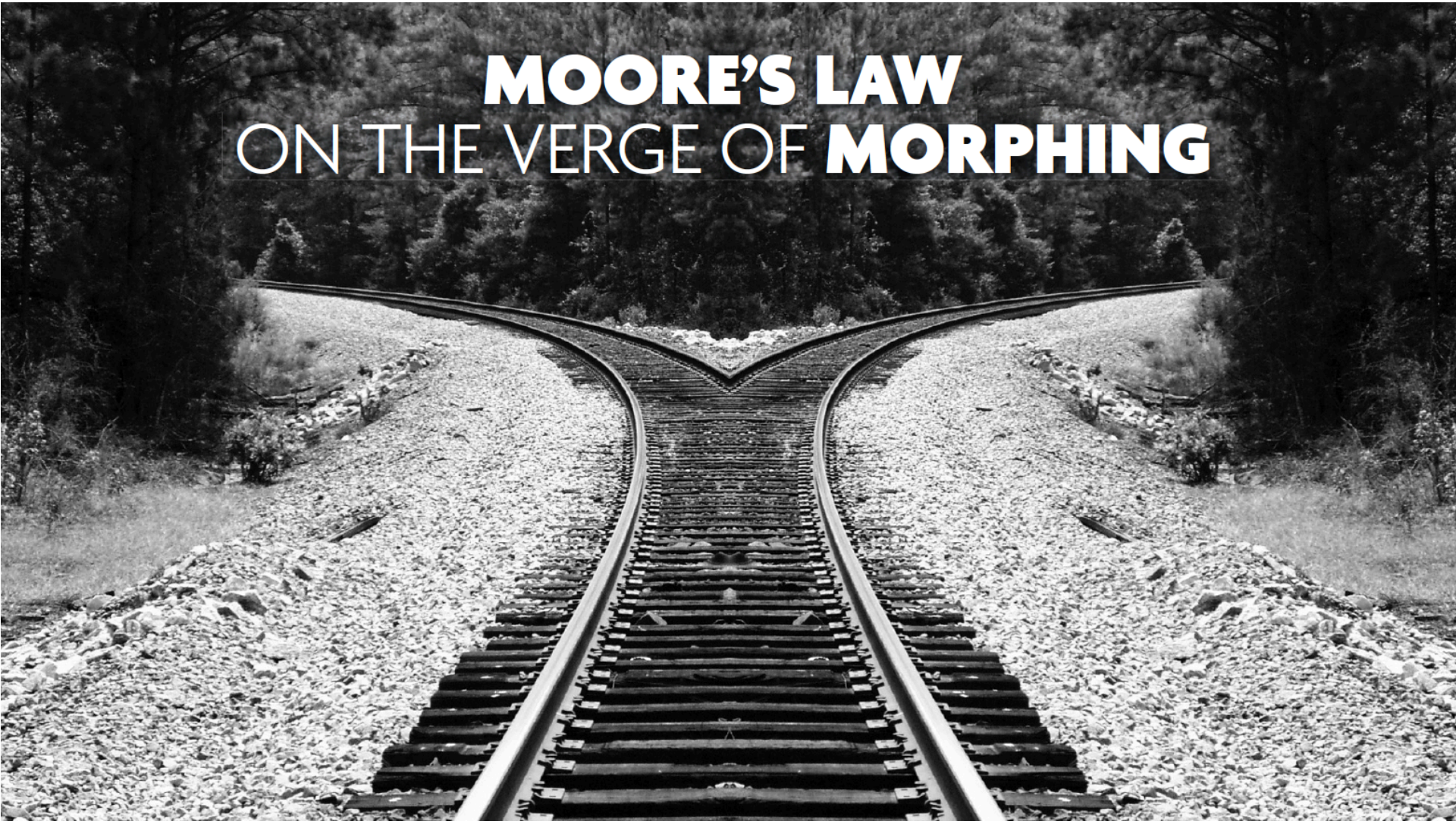
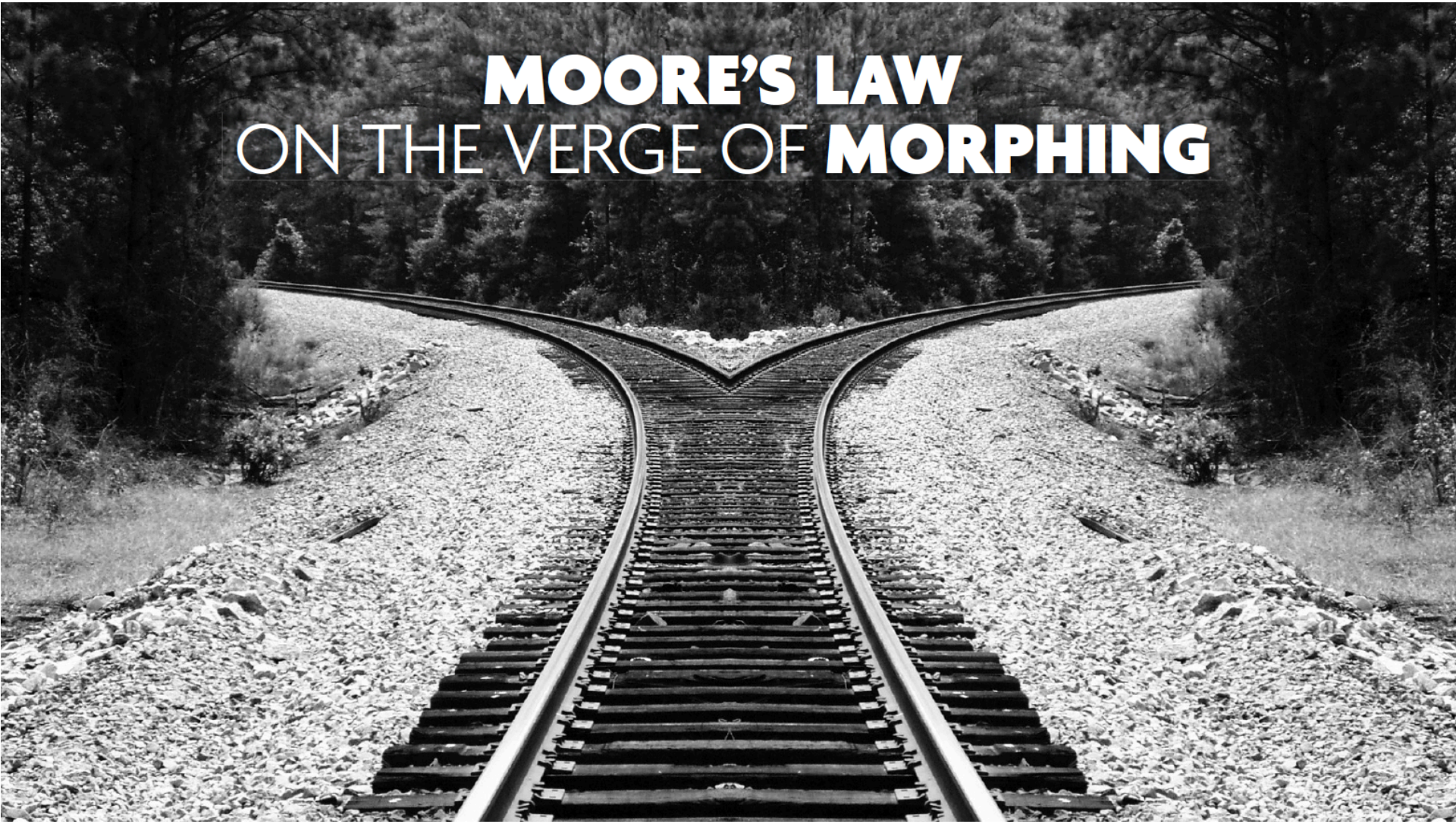

MOORE'S LAW
ON THE VERGE OF MORPHING

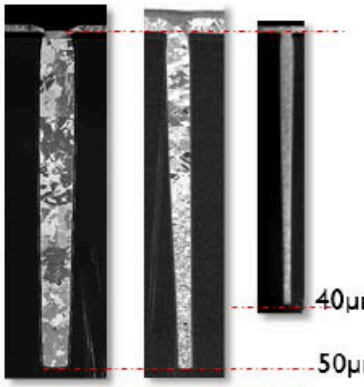


2D will saturate…

Use the third dimension

imec

Through-Si-Via (TSV)

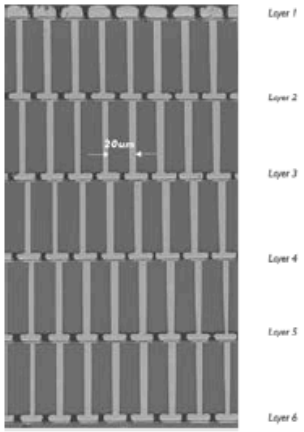


5µm Ø, 50µm deep AR 10:1

3µm Ø, 50µm AR 17:1

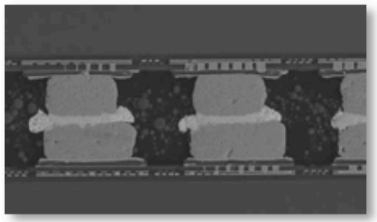
2µm Ø, 40µm deep AR 20:1

Multi-Layer Stacking (N=6)

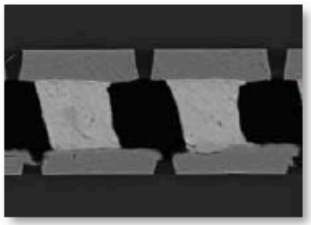


⇒ 5x50µm TSV
⇒ 20µm pitch

Ubump scaling

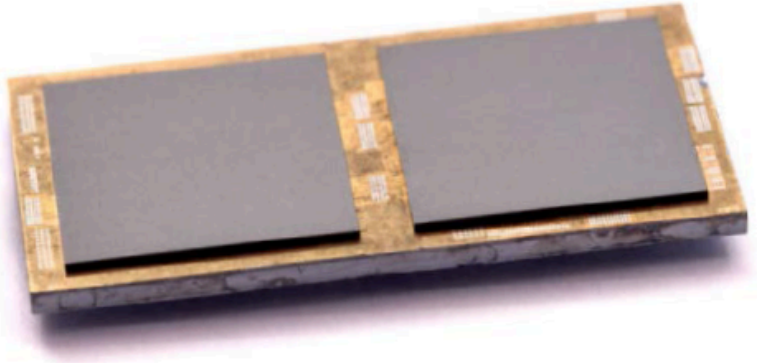


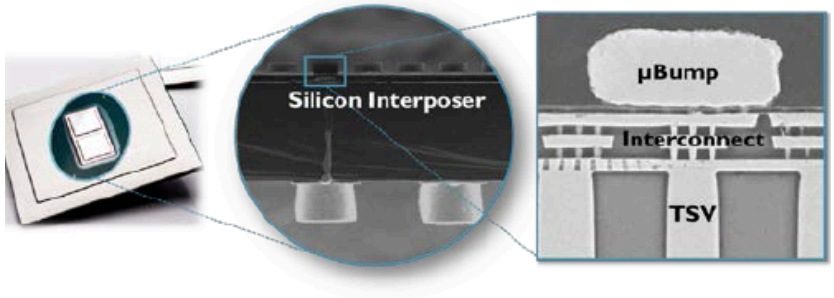
20µm µbump pitch



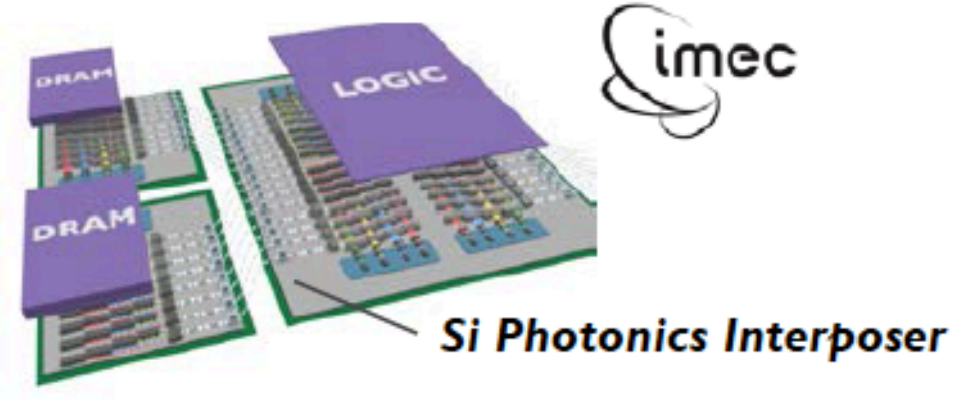
⇒ 10µm µbump pitch

Si Interposer

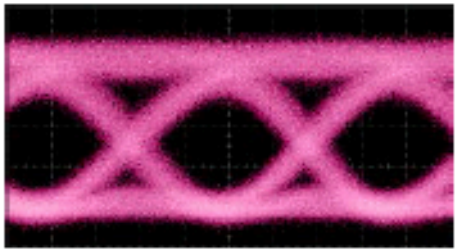




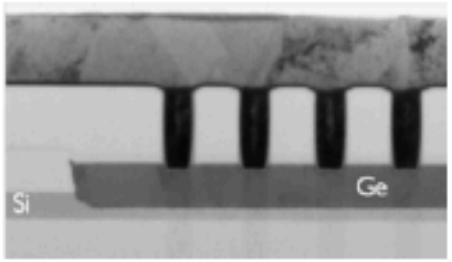
Use the third dimension

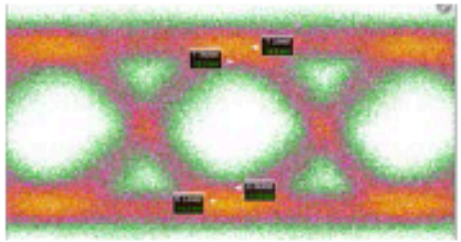


50G Modulators



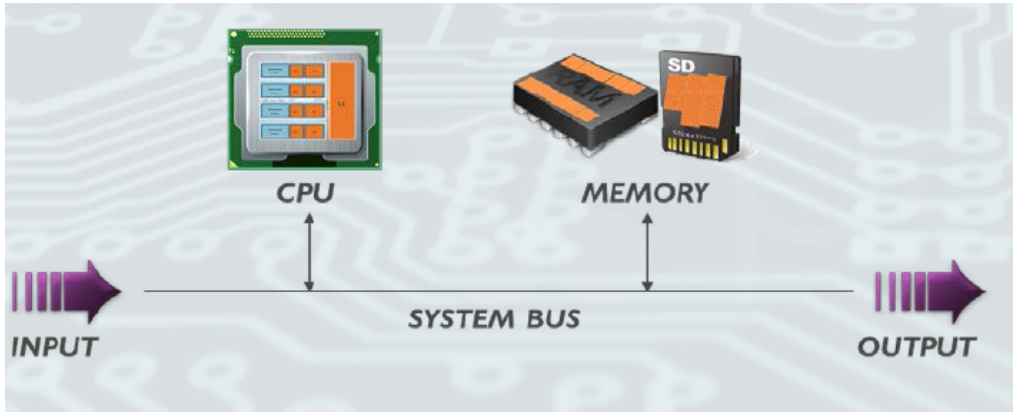
50G Photodetectors





50Gbps Eye Diagrams

Architectures



- Evolution to large number of CPU's operating in parallel
- Increase of connectivity

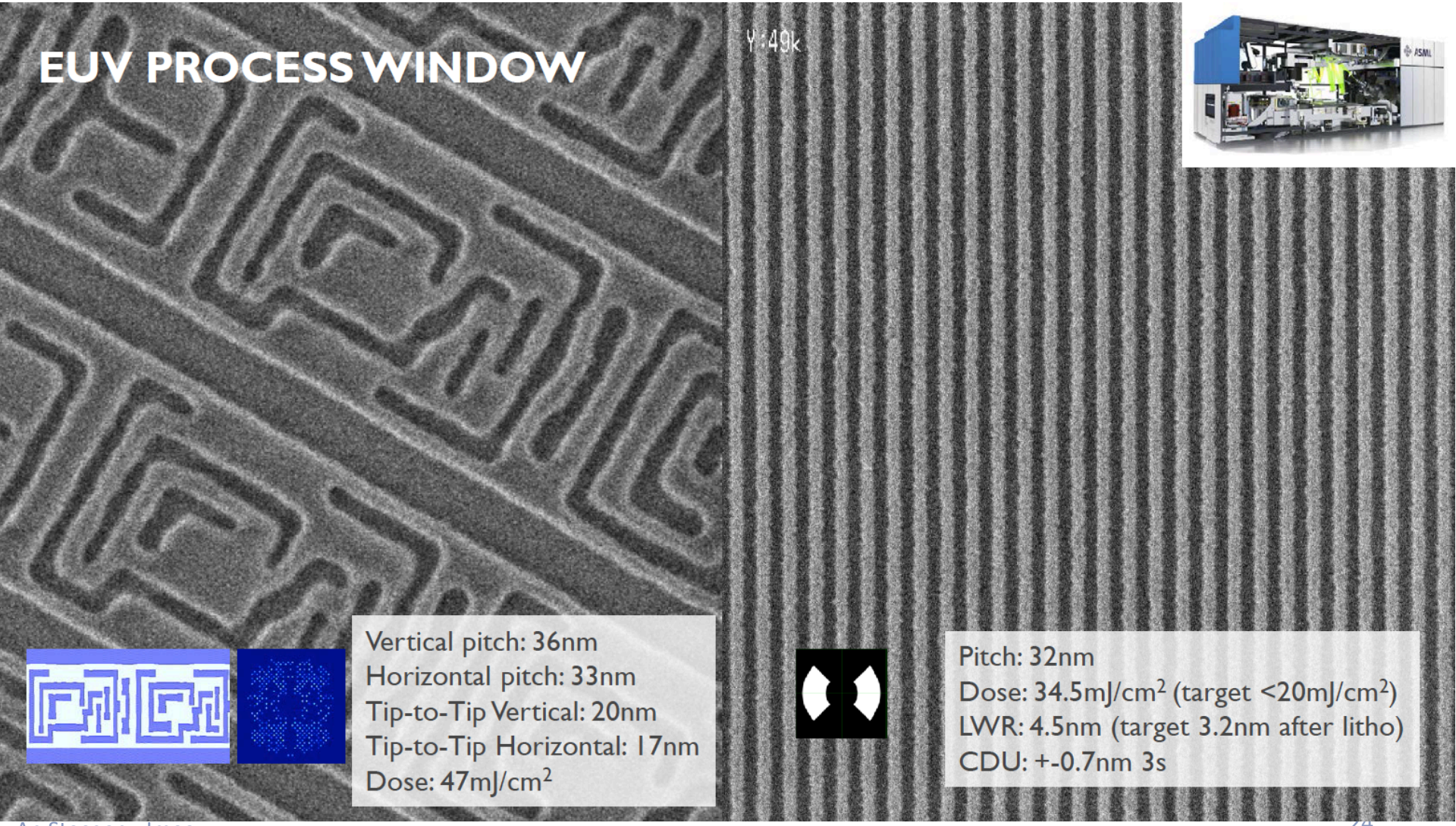
- Taking inspiration from neurons in the brain with synapses to 10-15000 other neurons. Mimic this interconnectivity in hardware
- Example RRAM

Technology enablers

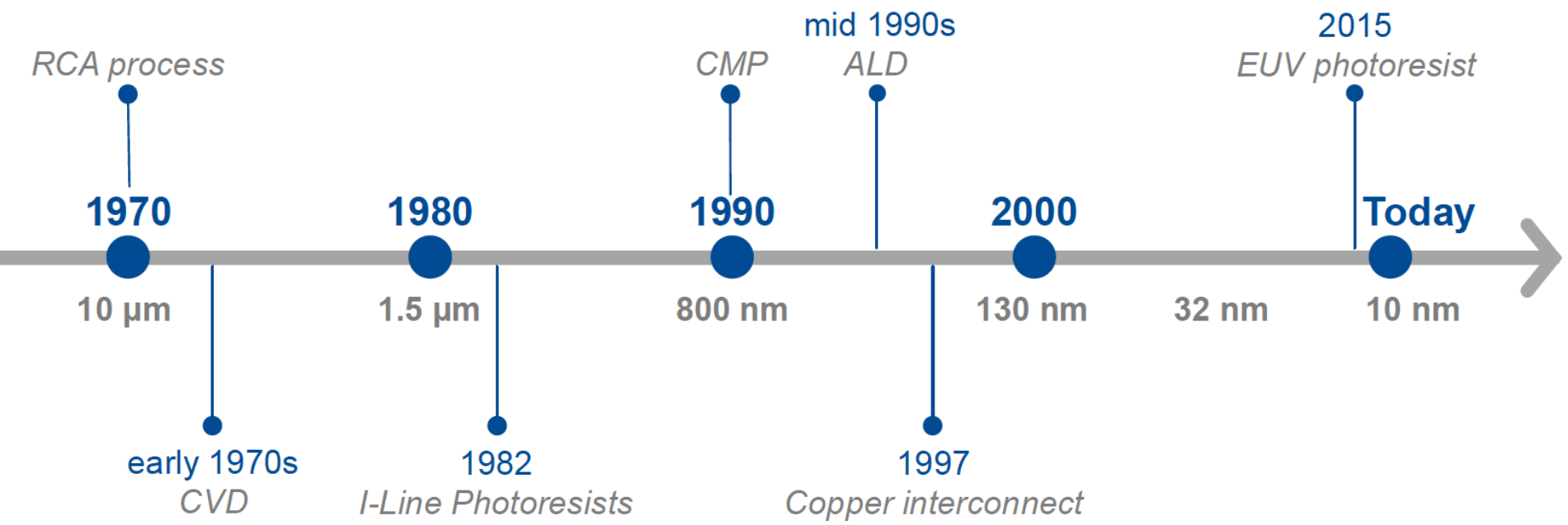
A few examples

EUV now coming on-line (finally)

perspectives for cost and processing time savings on large die for some time to come

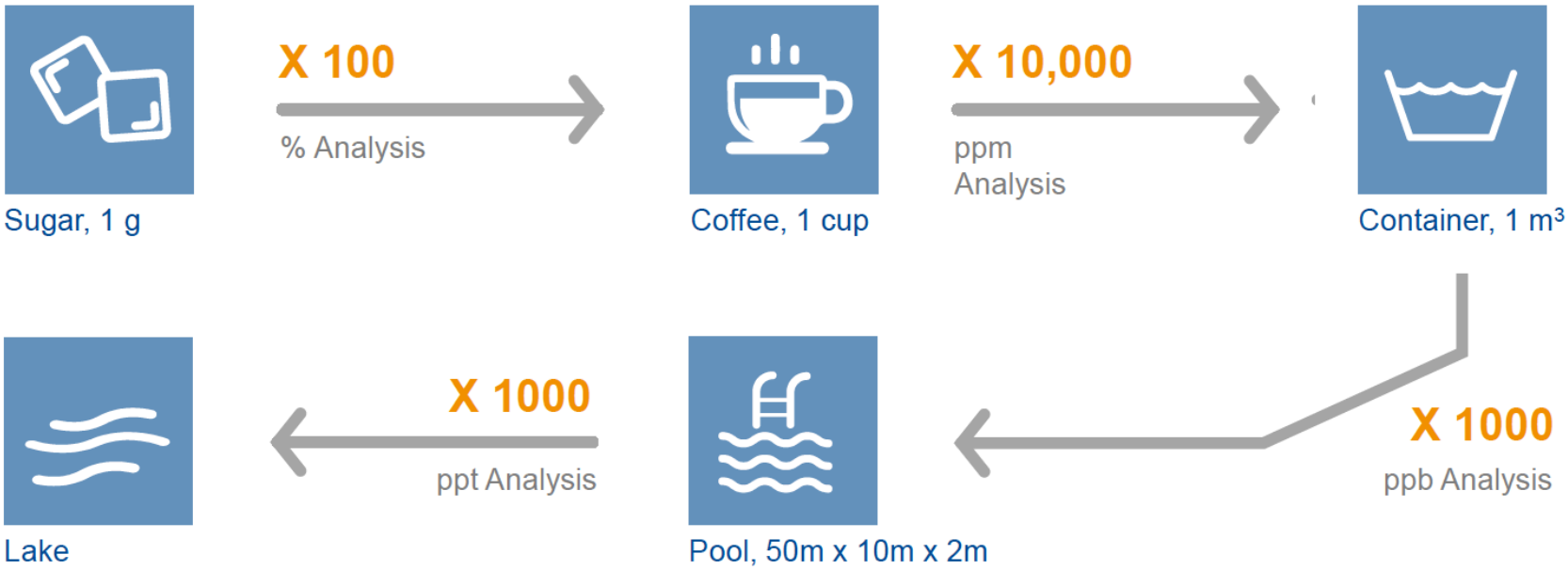


Chemistry is a strong driver of the digital innovation



2

Defect-free preparation of nm-scale structures enabled by ultrapure chemicals

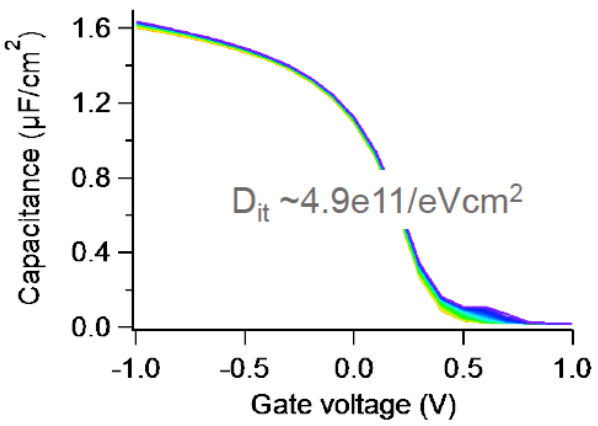


Top grades reach levels below 100 parts per trillion (ppt)

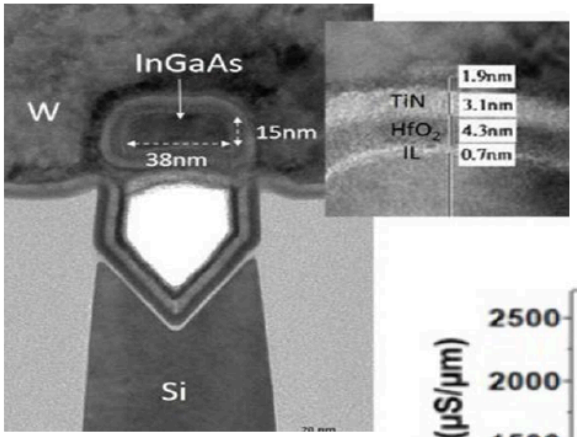
8

EXTENSION OF HFO2 ON NEW CHANNEL MATERIALS

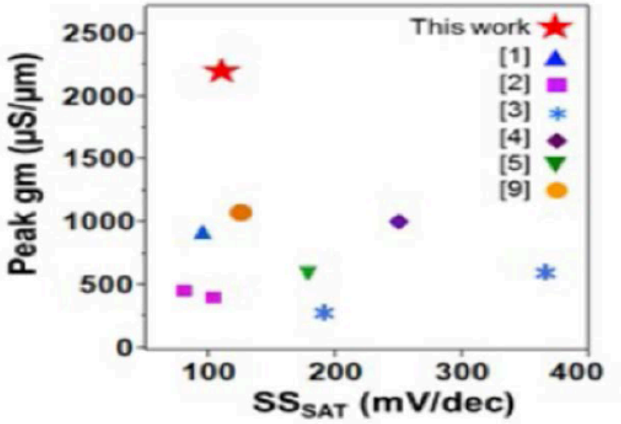
SiGe Channel Passivation



III-V Channel Passivation

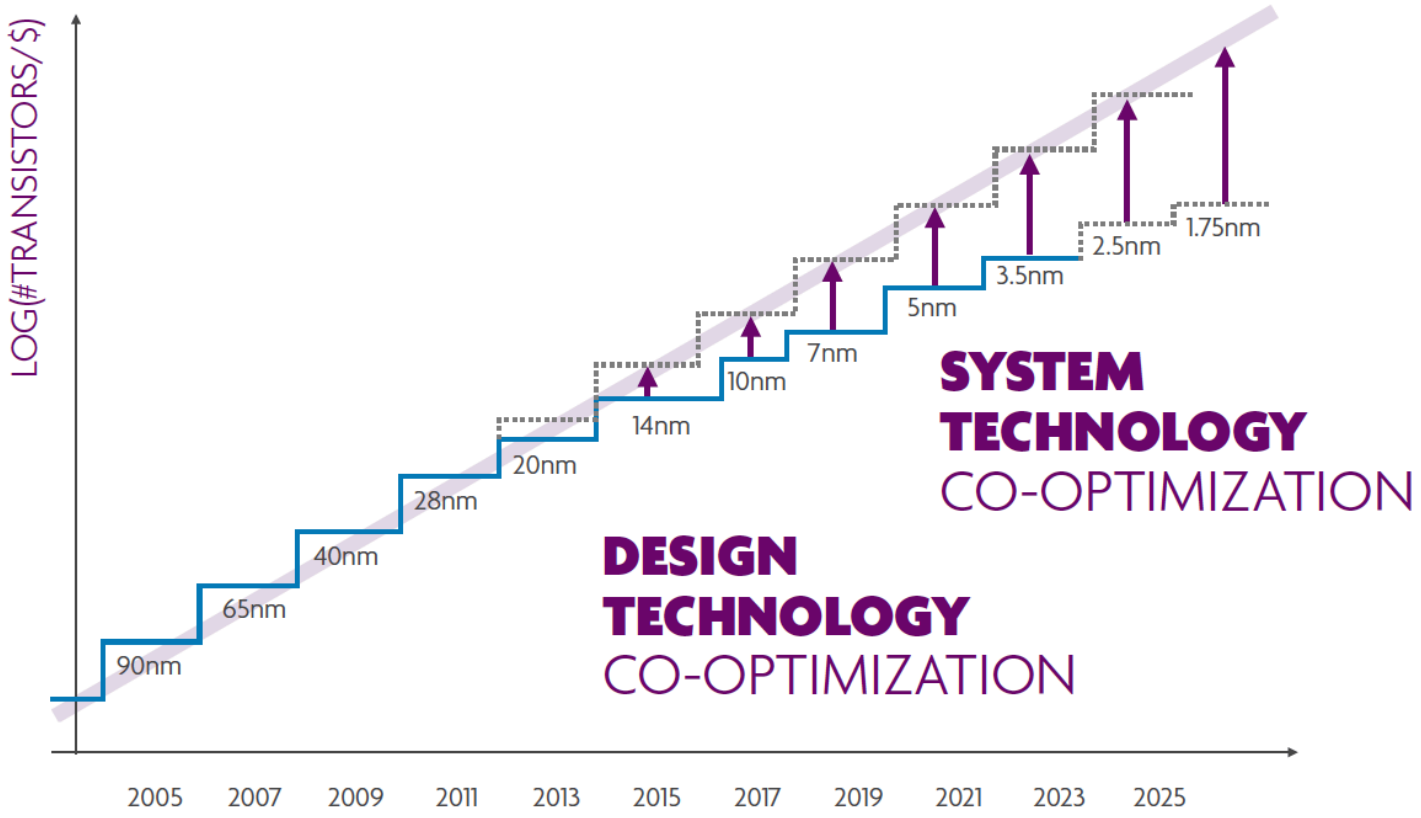


ASM-IMEC JDP
© 2015 IEEE



- ALD passivation of strained Si(50%)Ge achieves D_{it} < 5e11/eVcm² with HfO_2
- ALD passivation on InGaAs nanowire shows record mobility with reasonable sub-threshold slope

Left: ASM
Right: IMEC, earlier published in N. Waldron, et. al., paper S31P01, Proc Int. Electron Devices Meeting (Washington DC, Dec. 7-9, 2015)



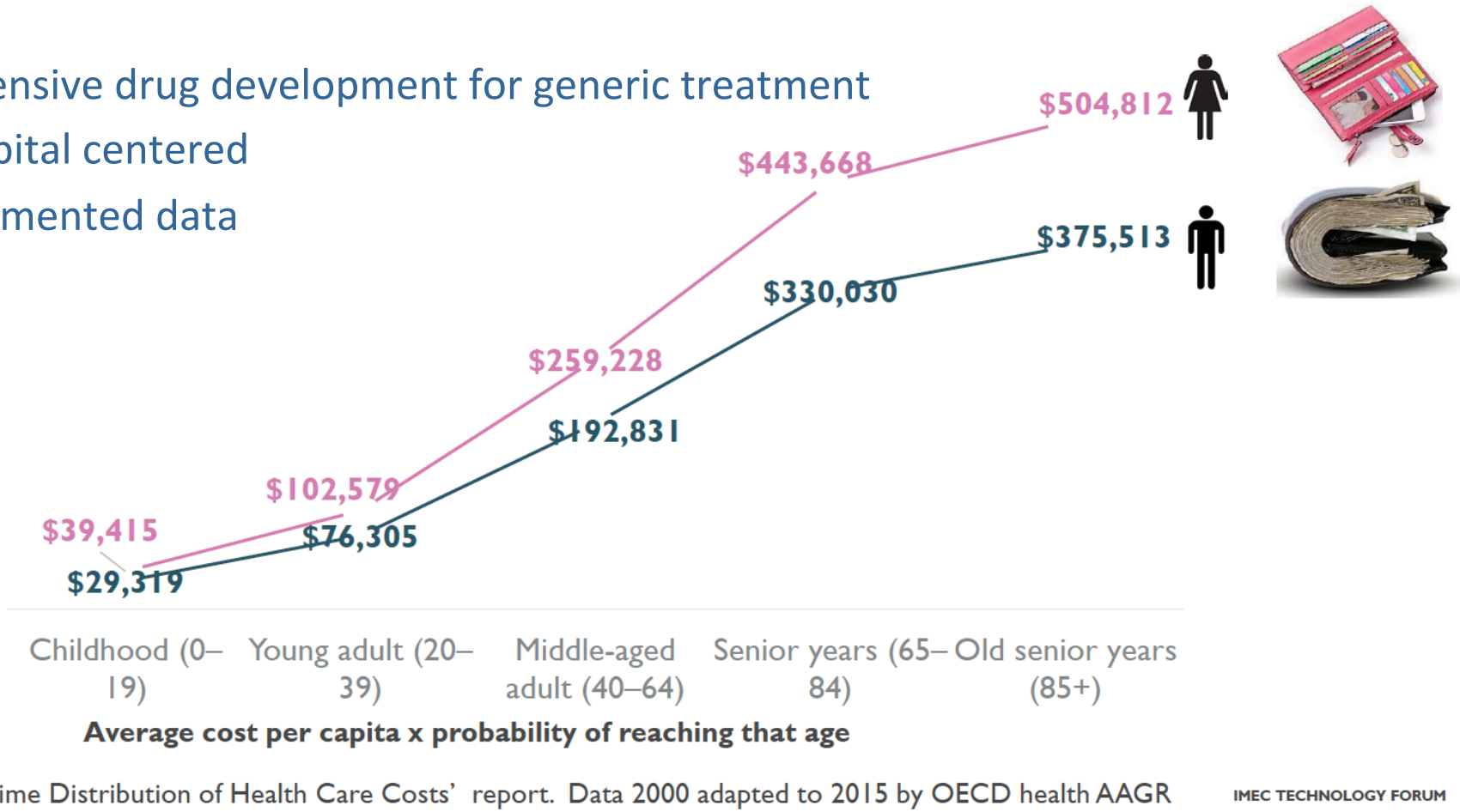
New applications and opportunities

- Healthcare towards precision medicine
- Automotive towards smart connected cars
- Energy
- Internet of Things

Precision Medicine

YOUR LIFETIME COST TABLE

- Expensive drug development for generic treatment
- Hospital centered
- Fragmented data



Based on:
'The Lifetime Distribution of Health Care Costs' report. Data 2000 adapted to 2015 by OECD health AAGR

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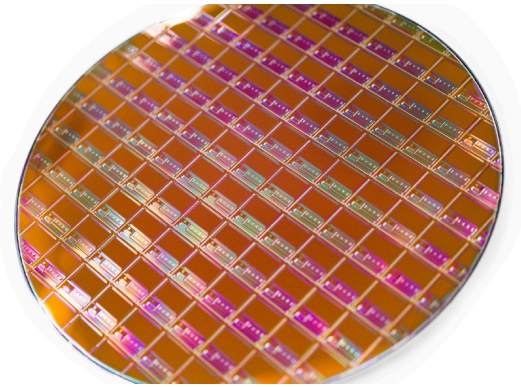
Could do much better:

- Personalized drug fabrication on demand
- Remote monitoring/treatment
- Connected databases

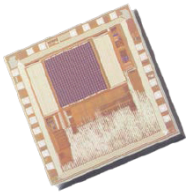
Healthcare towards precision medicine

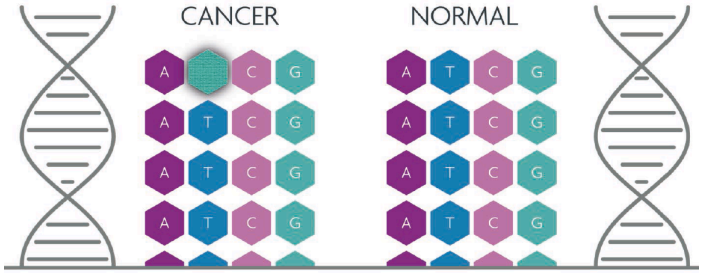
3X SMALLER
7X FASTER
2X LOWER COST



PACIFIC BIOSCIENCES

Product launched on 1st of Oct 2015
... enabled by custom photonic chip developed at imec





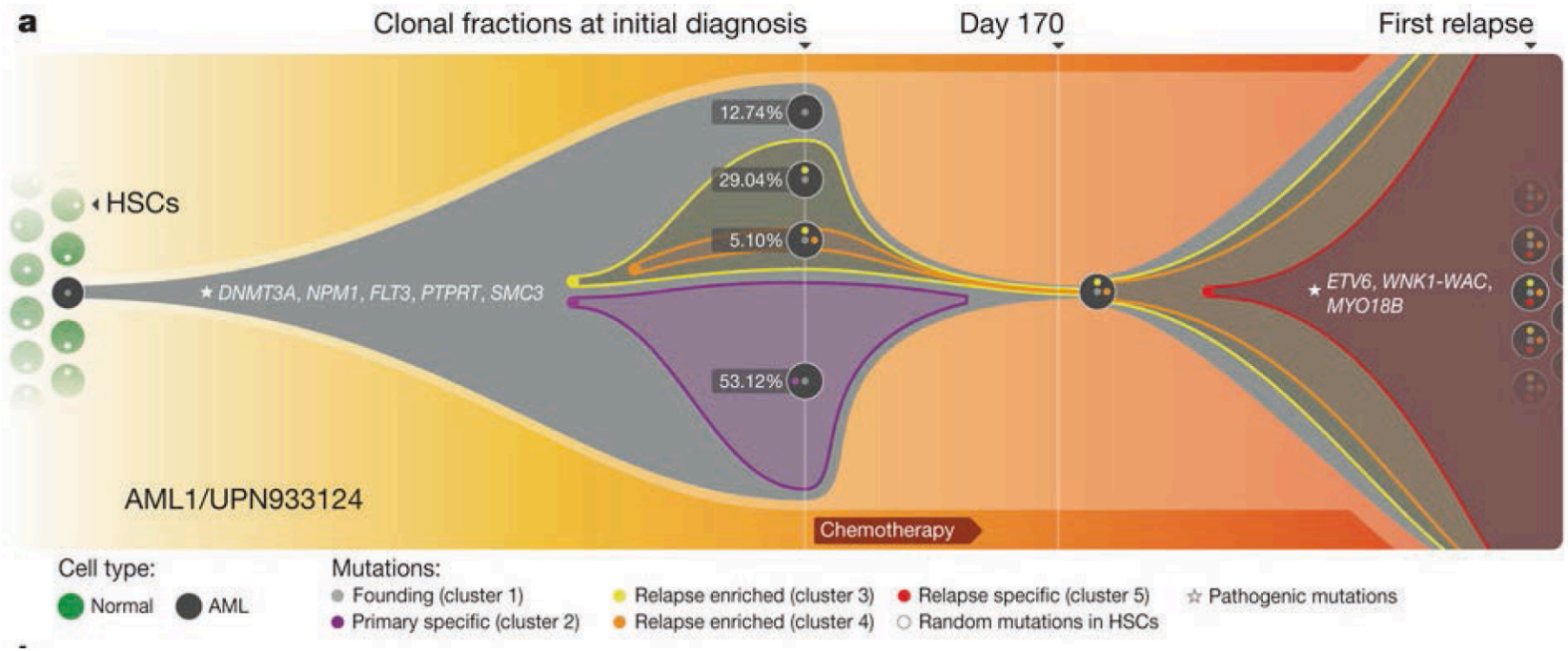
- DNA sequencing:
- From many weeks to a few days, from many millions $ to a few thousand $
- Silicon enables integration, mass production and lower cost
- Every person is unique:

  From generic to specific treatment

DNA SEQUENCING IN THE CLINIC

EXAMPLE: RELAPSING LEUKEMIA CANCER PATIENT

DETAILED FOLLOW-UP OF AML LEUKEMIC PATIENTS USING TARGETED HIGH-THROUGHPUT, DEEP (590-FOLD) SEQUENCING DEMONSTRATE THAT RELAPSE IS ASSOCIATED WITH NEW MUTATIONS SHAPED BY THE CHEMOTHERAPY



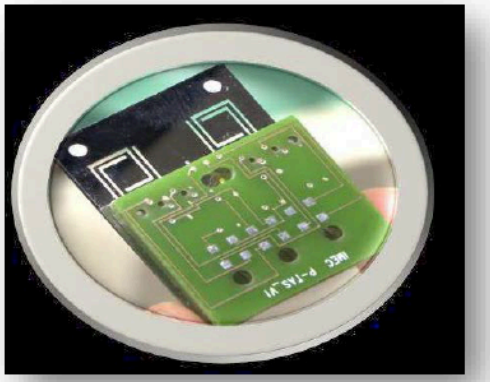
"CLONAL EVOLUTION IN RELAPSED ACUTE MYELOID LEUKAEMIA REVEALED BY WHOLE-GENOME SEQUENCING," NATURE 481, 506-510 (2012)

IMEC TECHNOLOGY FORUM

Need multiple genome-sequencing

TOTAL TIME TO SEQUENCE IS STILL 2 WEEKS AND PRODUCES ~ 300 Gbytes of data
ADVANCED CLINICAL CENTERS HAVE 0-5 SEQUENCING MACHINES

FAST SAMPLE PREP



MICROFLUIDIC CHIP SOLUTIONS TO MAKE SAMPLE PREPARATION EFFICIENT

FAST SEQUENCING

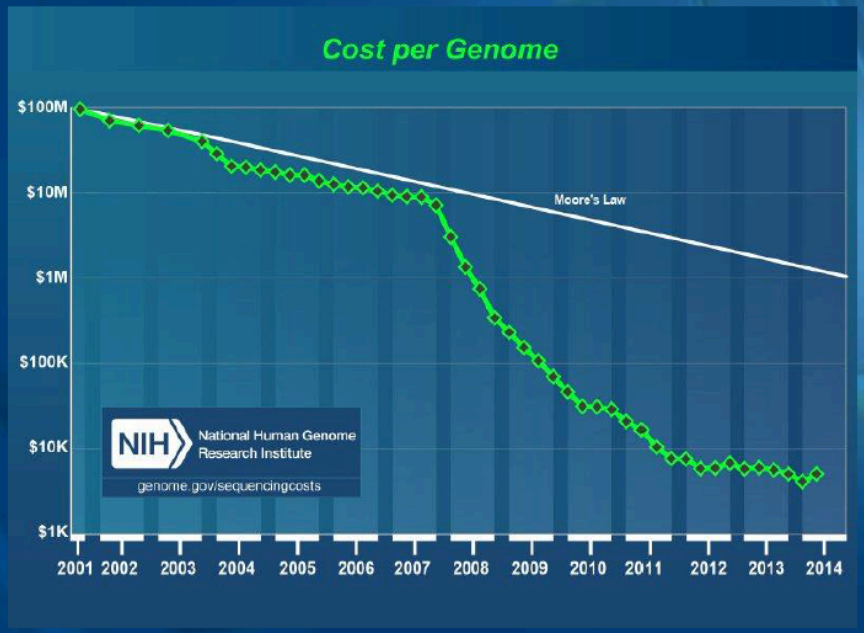
CHIP SOLUTIONS TO READ OUT HIGH THROUGHPUT LONG READ SEQUENCES

FAST DATA ANALYTICS

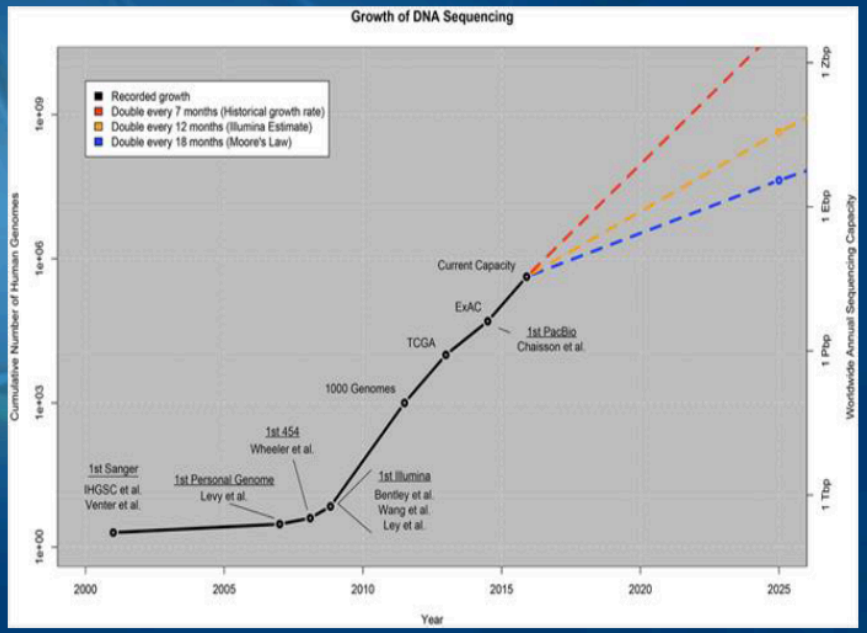
HIGH PERFORMANCE COMPUTING SOLUTIONS TO MAKE SENSE OUT OF DATA

TRENDS

Cost is dropping

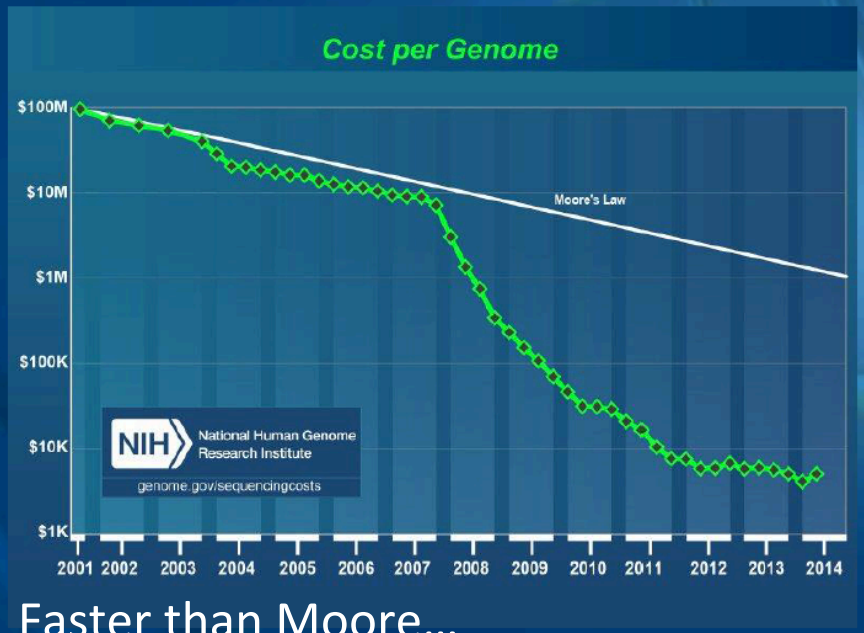


Data is Growing



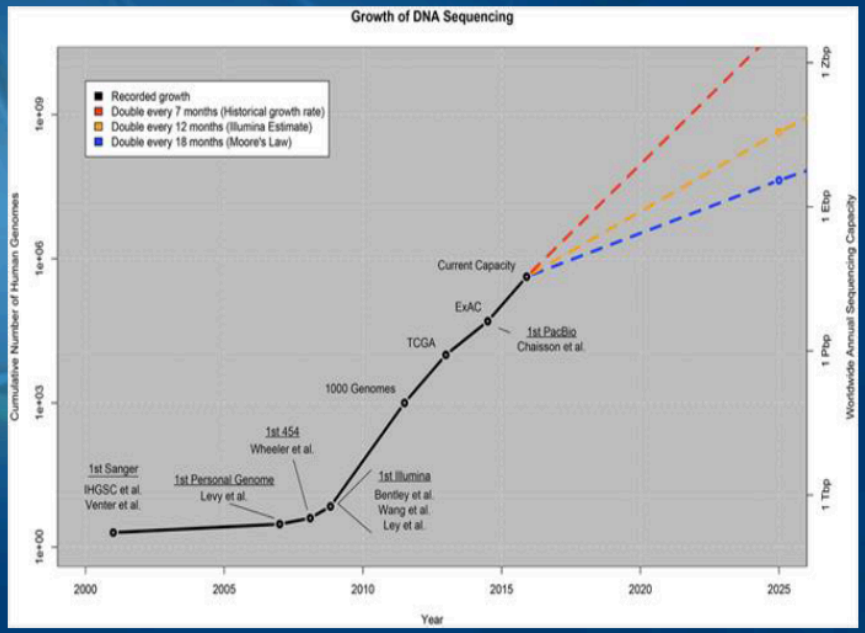
TRENDS

Cost is dropping



Faster than Moore…

Data is Growing



thanks to Moore !

MAIN COMPUTING CHALLENGES

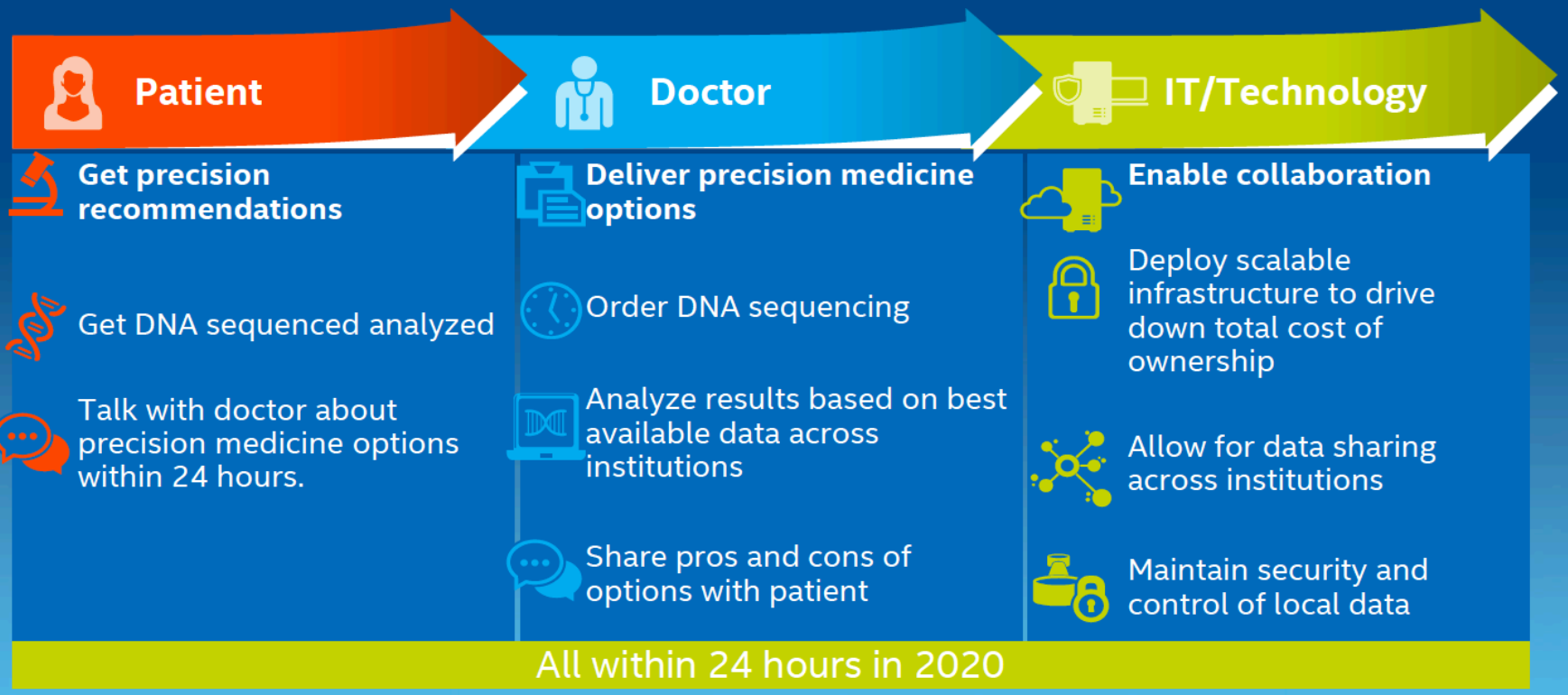
intel experience what's inside

4 % of data currently in research

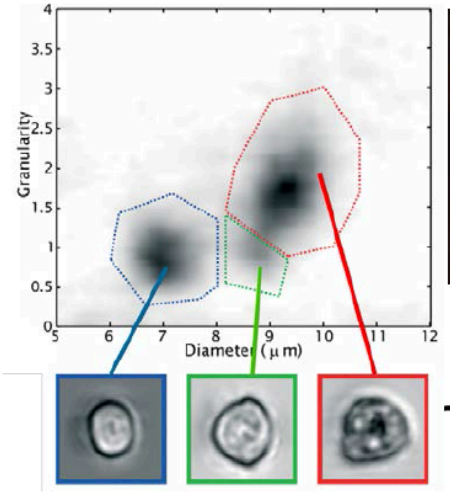
96 % of data stuck in institutions

- Too large to move
- Protected

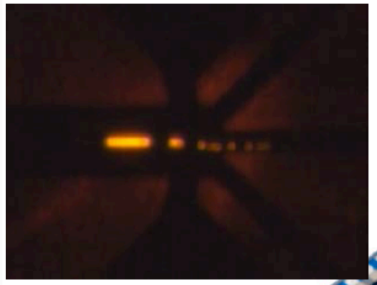
ALL-IN-ONE-DAY GOAL – A CHALLENGE FOR MEDICAL AND TECH INDUSTRIES



IMEC KEY TECHNOLOGY FOR CANCER DIAGNOSTICS



Lensfree imaging of blood cells



Specifications:

- NEW: 5000 cells/sec/channel achieved
- Sorted purity: >98%
- Multichannel: 1 mm^2 / channel
- Easier to use than conventional equipment

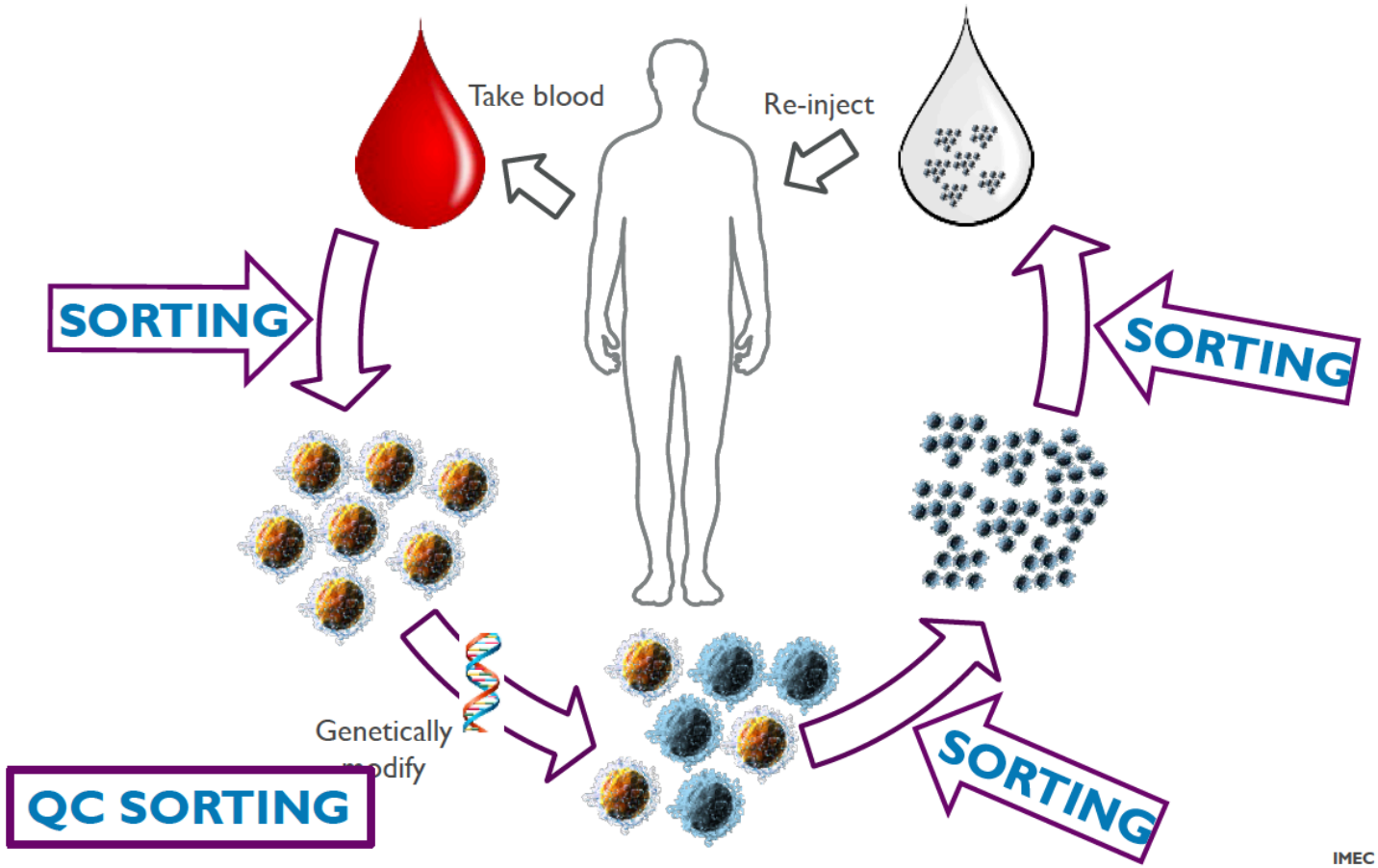
NEW: COMBINE LENSFREE IMAGES and FLUOMARKERS for ACCURATE detection of RARE CELLS

TECHNOLOGY FORUM

9 out of 10 cancer cells can be detected from the blood

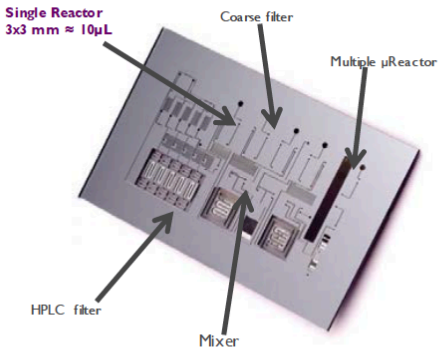
CELL BASED IMMUNOTHERAPY

FIGHTING DISEASE WITH OWN IMMUNE SYSTEM

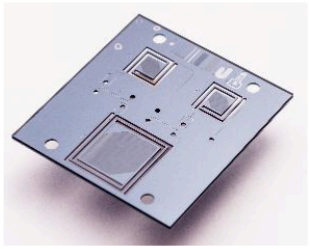


Micro-machined sorting chips can accelerate the process to within practical timelines and make it affordable.

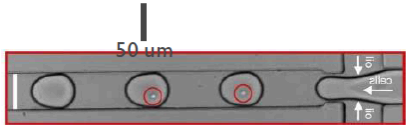
AUTOMATED MINIATURIZED WORKFLOWS



5-plex SNP detection with integrated sample preparation



PCR reactors are optimized for fast thermal cycling



High speed on-chip droplet generators for high throughput testing

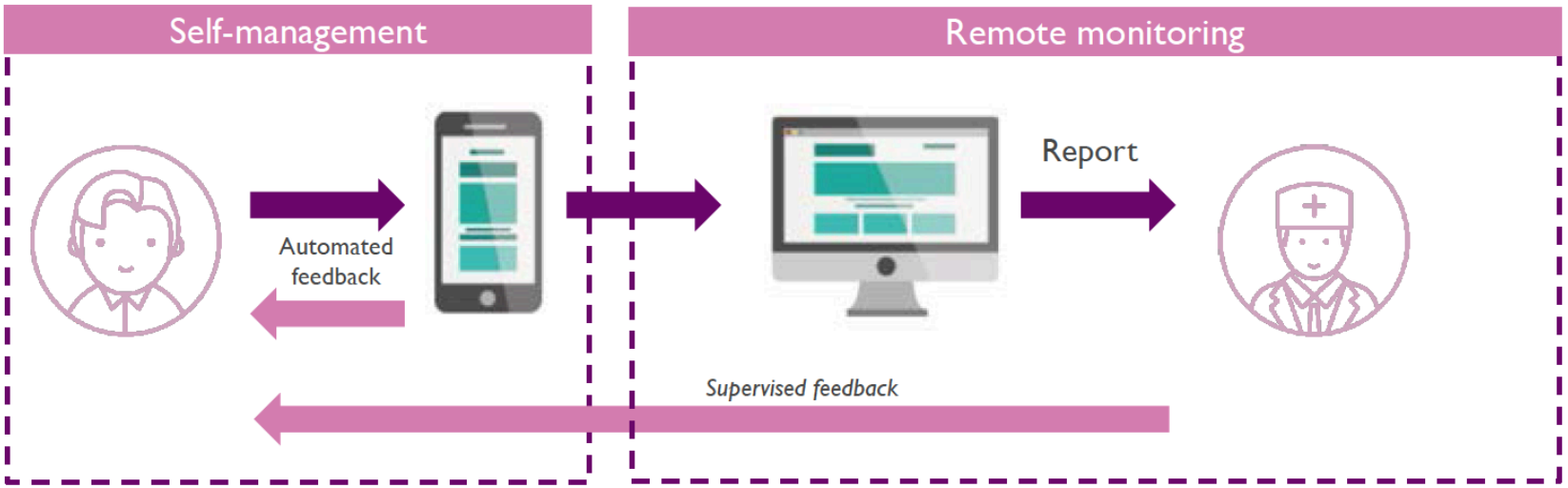
FEATURES

- COMPACT, INTEGRATED SAMPLE PREPARATION: SAMPLE-IN, DATA-OUT
- ON-CHIP FILTERS, MIXERS, DILUTION, LYSIS, DNA/RNA EXTRACTION, HPLC FILTER CAN BE COMBINED IN ONE WORKFLOW
- MULTIPLEX AND PCR REACTION CHAMBERS: 40 CYCLES IN <3 MINUTES
- MINIATURE SAMPLE CHAMBER TYPICALLY HOLDS 2 µL SAMPLE + REAGENTS
- ACCURATE TEMPERATURE CONTROL WITH INTEGRATED HEATERS AND SENSING
- INTEGRATED DROPLET GENERATION FOR ddPCR: REPRODUCIBLE DROPLET GENERATION DOWN TO 30pL DROPLETS, FAST GENERATION UP TO 20,000 DROPLETS PER MINUTE PER CHANNEL

IMEC TECHNOLOGY FORUM

Micro-machined sorting chips can accelerate the process to within practical timelines and make it affordable.

Wearable devices

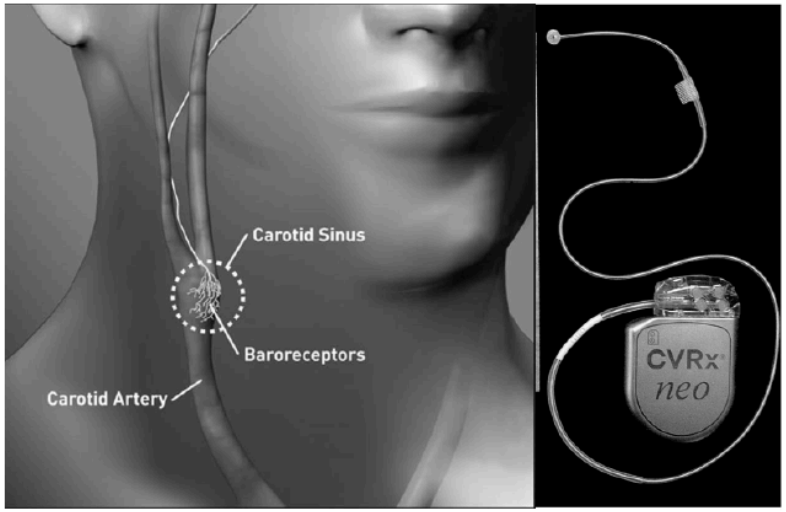


Patients using wearable sensors & smart devices…

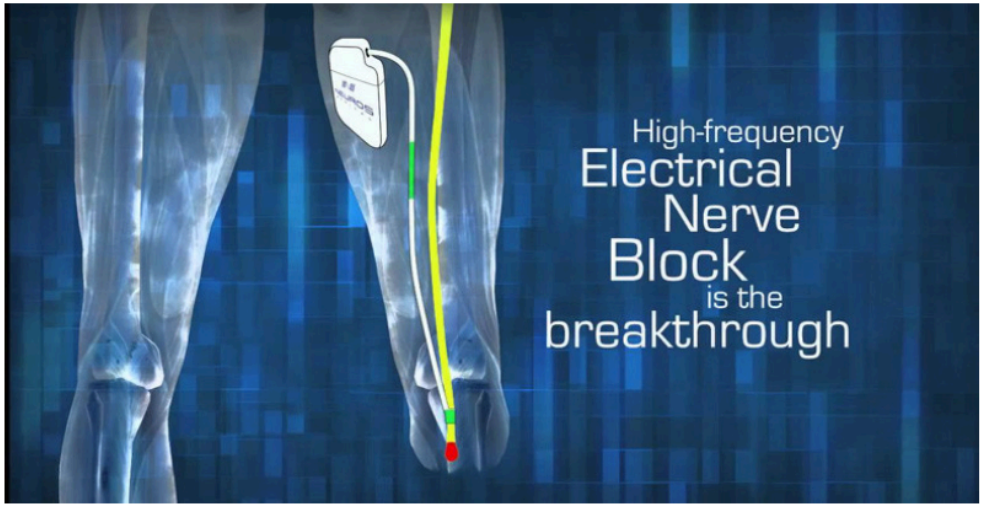
… to provide doctors with actionable information

Precedent: writing and erasing signals in peripheral nerves

Electrical Stimulation of Carotid Sinus Nerve



Electrical Nerve Block for Phantom Limb Pain

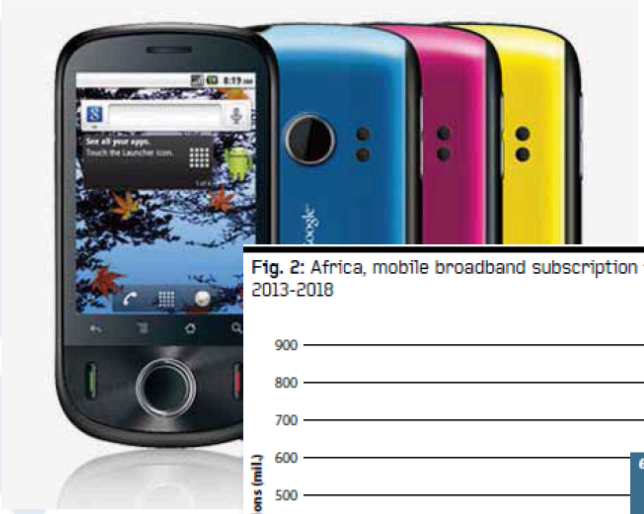


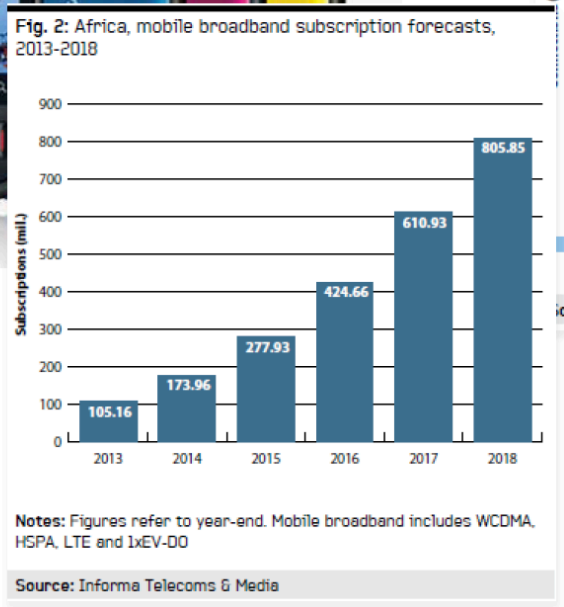
Source: CVRx; www.fescenter.org

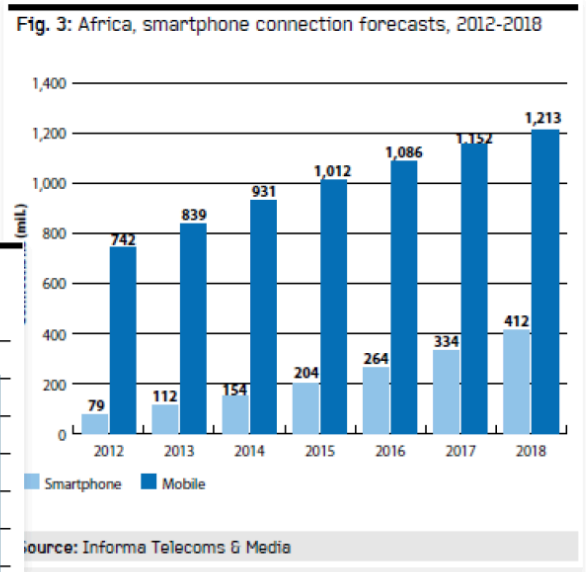
Need miniaturization but also new techniques for the interfaces and powering

- Blocking inside the body needs 10s of mW
- Wireless ?
- Grain of rice size devices…

Low-cost smartphones - key enabler of data in Africa







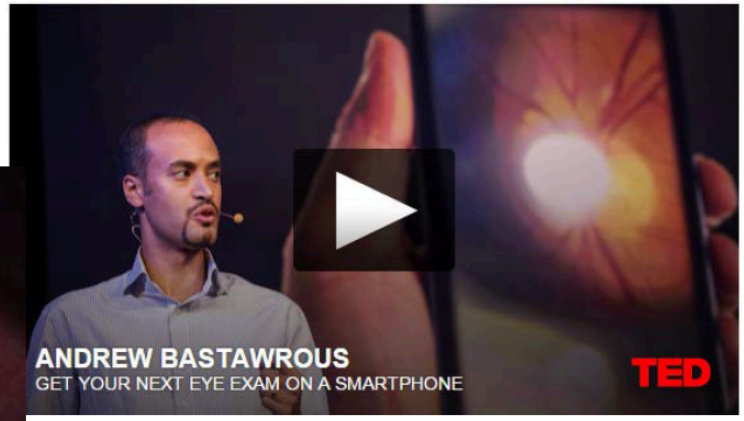
LONDON SCHOOL of HYGIENE &TROPICAL MEDICINE

Remote diagnosis

Studying blindness – there's an app!

peek

Professional eye exams from your smartphone



2012 Max Perutz Science Writing Award winner, **Dr Andrew Bastawrous** (MRC Research Fellow at the International Centre for Eye Health at the LSHTM)

"This is potentially a game changer"
Peter Ackland, CEO International Agency for the Prevention of Blindness

"Good news for developing countries. Curing blindness is going mobile"
Bill Gates
Bill & Melinda Gates Foundation

"It could really make a difference to the problem of screening in schools"
Dr Hillary Rono, Opthalmologist, Ministry of Health in Kenya

Tech4Good Award for Digital Health 2014
Tech4Good Awards

Digital Design of the Year Winner 2014
London Design Museum

Low cost smart phones key enabler in Africa

Mobile lab

Photo: European Mobile Lab/Tommy Trenchard

&TROPICAL MEDICINE

Automotive

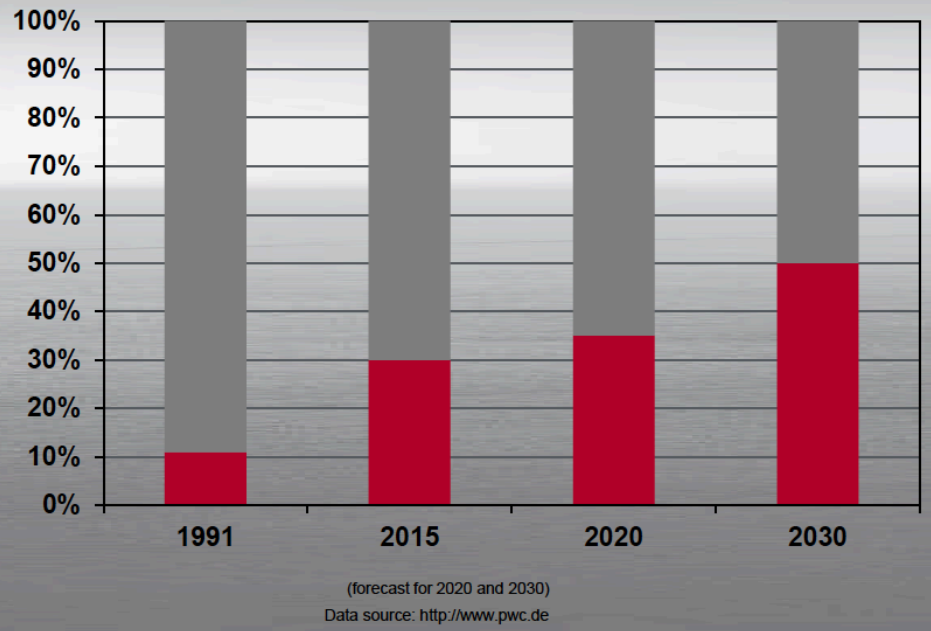
AUTOMOTIVE NEEDS AN UPGRADE

- Towards smart mobility connected driver-less cars
- Advanced sensor systems
- Smart signal processing: detection – positioning – identification
- Car = most intelligent robot in our daily life

Value Share of Electronics

Outlook

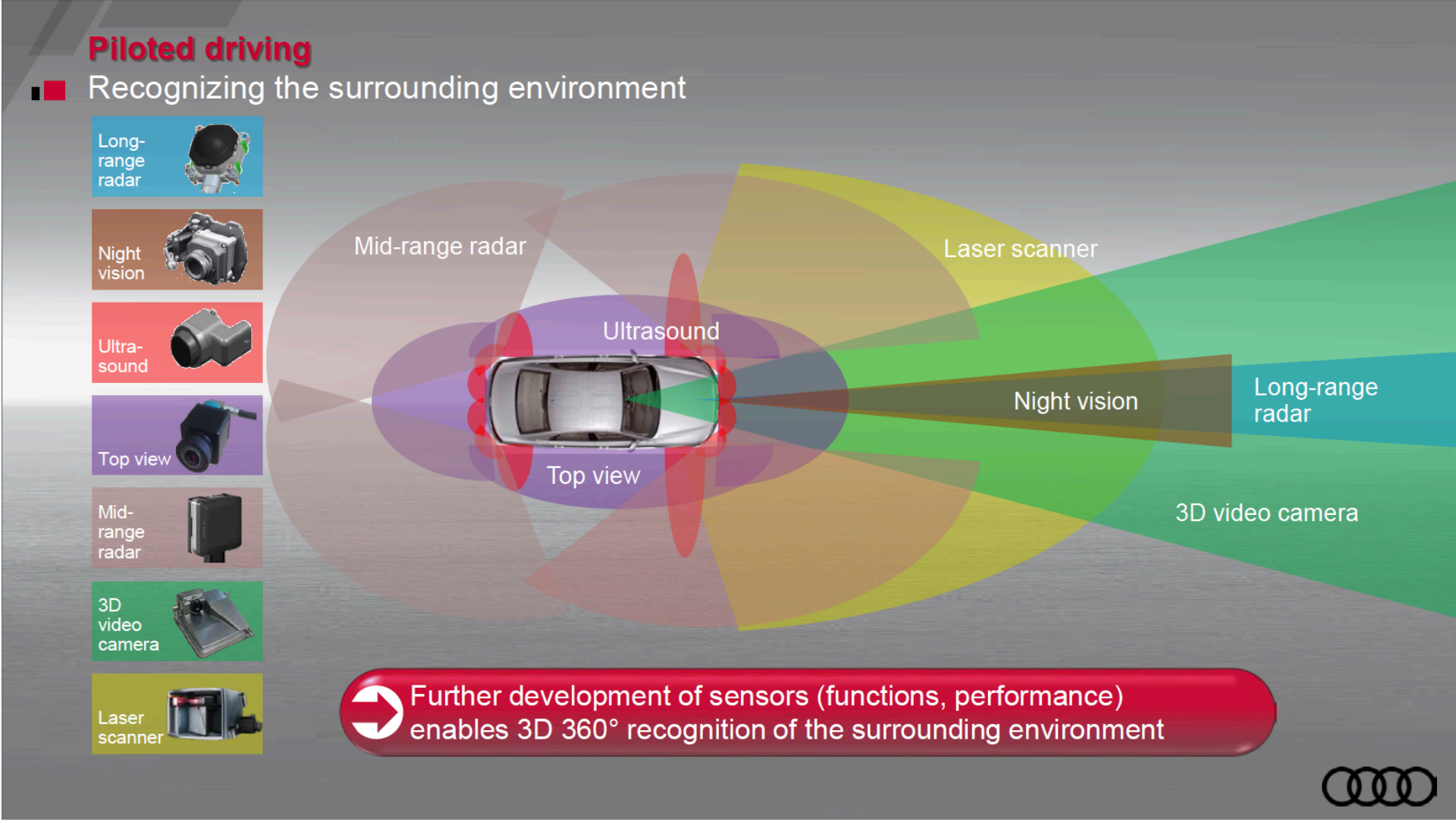
Electronic components share of vehicle production cost



in addition:

- continuously **increasing** number of **lines of software code**
- continuously **increasing** amount of **data traffic** within and from/ to the vehicle

80 % of innovations due to semiconductors



Advanced sensor systems

CMOS RADAR ON CHIP

HIGH RESOLUTION

LOW POWER

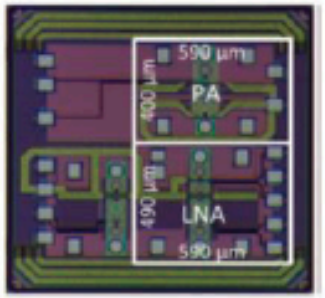
LOW COST

SMALL SIZE

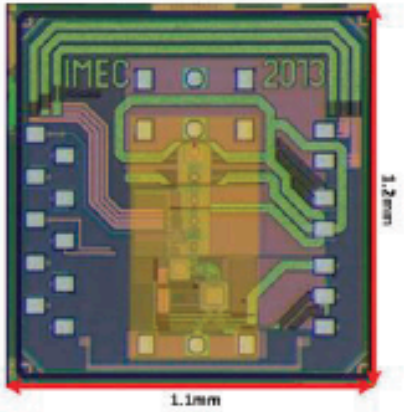
LEVERAGING STANDARD FOUNDRY TECHNOLOGY

- 28 nm CMOS
- 79 GHz
- Integrated with antenna's in 3x2 cm^2 module (chip much smaller)
- Challenge is rejection of direct couplings between TX and RX
- Going to 140 GHz would allow integrating the antenna in the chip.

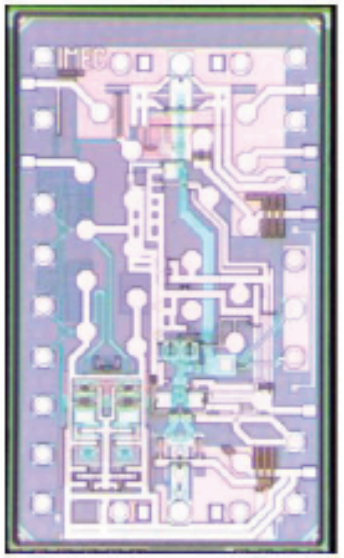
PA & LNA



Transmitter



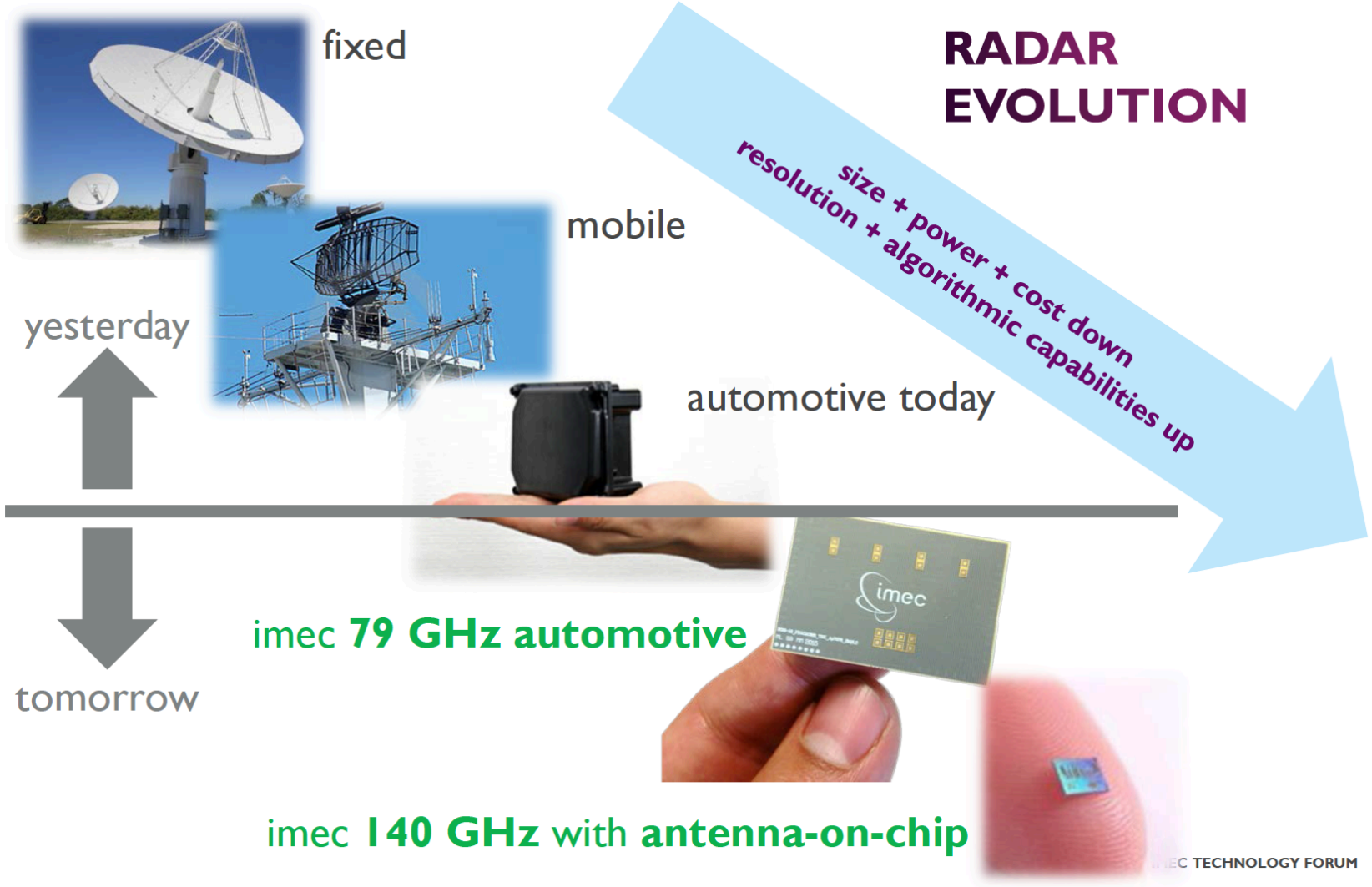
Transceiver



28nm CMOS key components and full systems

P. Wambacq, W. Van Thillo et al.

- Journal of Solid State Circuits Vol. 49, no. 12, December 2014
- Journal of Solid State Circuits Vol. 51, no. 5, May 2016
- ISSCC


RADAR
EVOLUTION
size + power + cost down
resolution + algorithmic capabilities up
fixed
mobile
automotive today
yesterday
tomorrow
imec 79 GHz automotive
imec 140 GHz with antenna-on-chip
imec
TECHNOLOGY FORUM

Audi connect

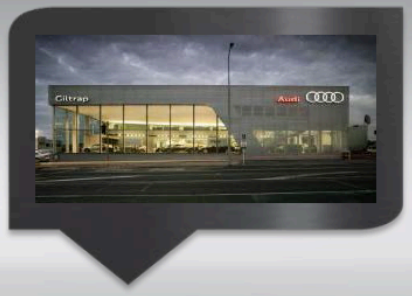
Functions

The vehicle

is connected within itself

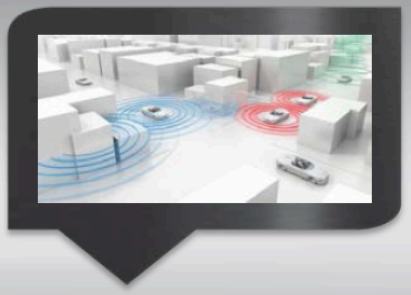
Stage 1

Connected Infotainment



Stage 2

Car2x Communication



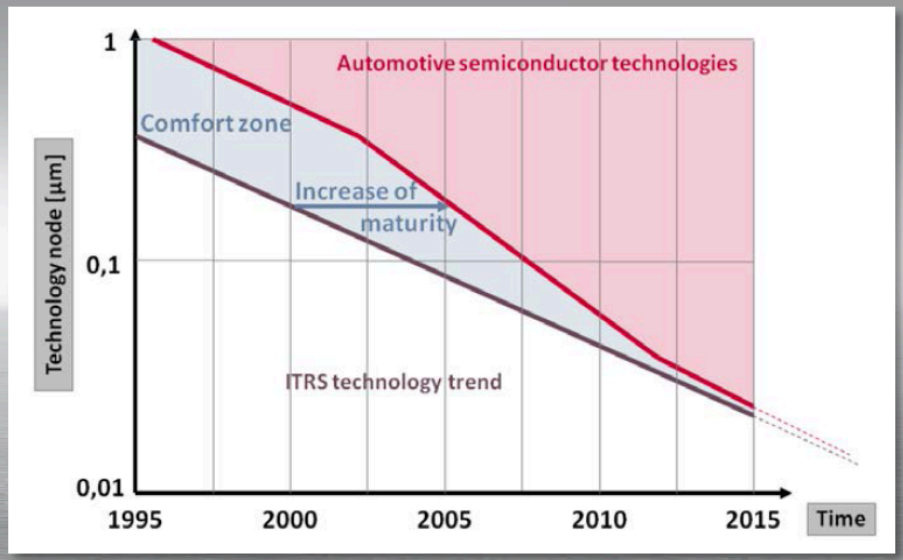
Stage 3

Swarm Intelligence

last decade: vehicle became connected within itself
this decade: vehicle connects seamlessly with the world

Infotainment & Audi connect

Shortened innovation cycles



- **Shortened innovation cycles** closed to consumer industry
- Increasing demand to **use technologies from the consumer world**
- Time **gap to consumer** is **getting shorter** and shorter
- **Reduced "comfort zone"** for automotive applications

Early adoption of new technologies in Automotive to enable new customer functions

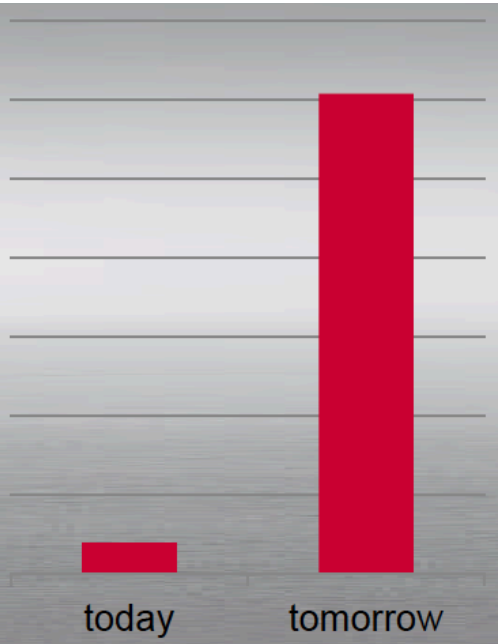
- It is about **enabling new technologies and not to prohibit** them
- **Synchronizing** the **speed of innovation and reliability** is a key challenge

Fully autonomous driving

"Does your car have any idea why my car pulled it over?"

Fully autonomous driving

- **Today**: **8,000h** on-time
  (approx. 1.5h per day, 15 years)
- **Tomorrow**: **121,500h** on-time
  (approx. 22.5h per day, 15 years)

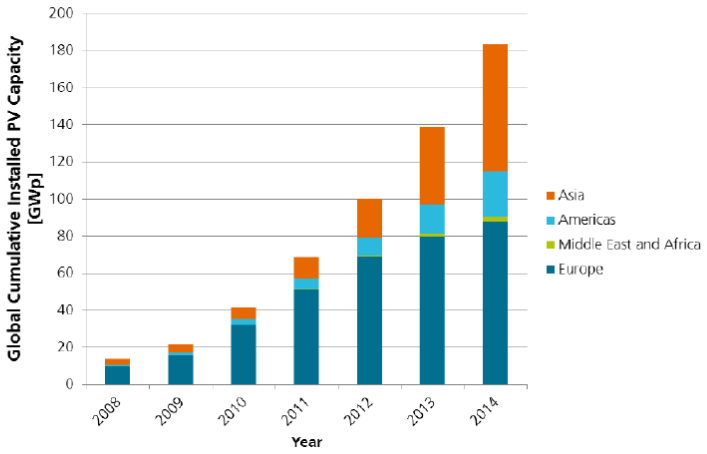


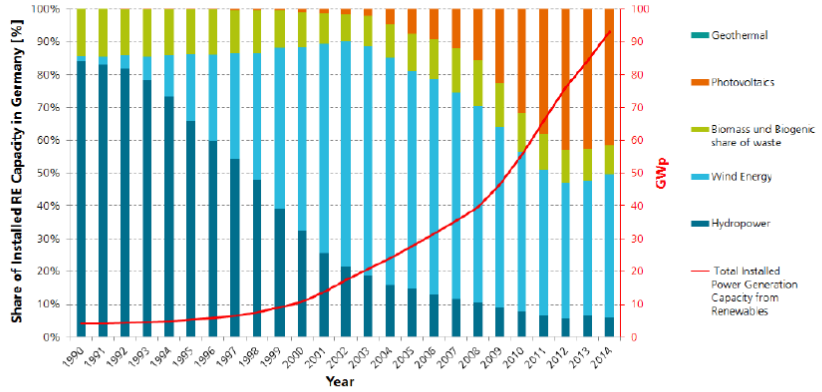
Energy

Energy and photovoltaics (PV)

GLOBAL PV: 2014/2015 IN A NUTSHELL

Top 3 markets	China largest market	Global capacity added	Global installed capacity	Market growth	Electricity produced
China Japan USA	15 GW	>50 GW	235 GW	Mainly growth in Asia and US	World 1% Italy 8%





In 2014 about 28% of the electricity in Germany was generated by renewable energy (RE) sources according to BMWi.

Preliminary data 2014: BMWi; 2013: BMWi / AGEE-Stat. Up to 2012 Data: BMU, BDEW. Graph: PSE AG 2015

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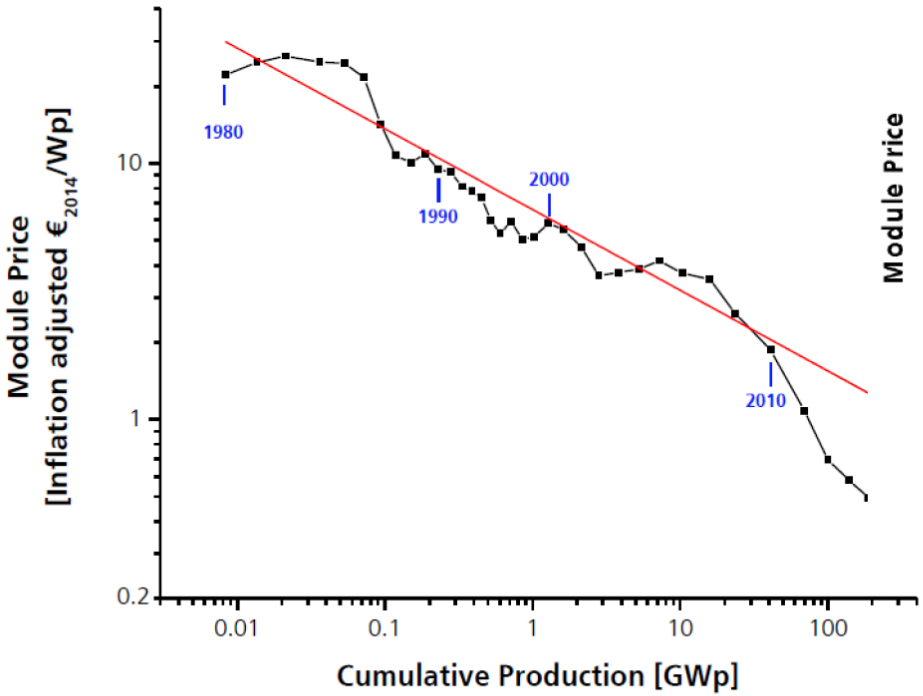
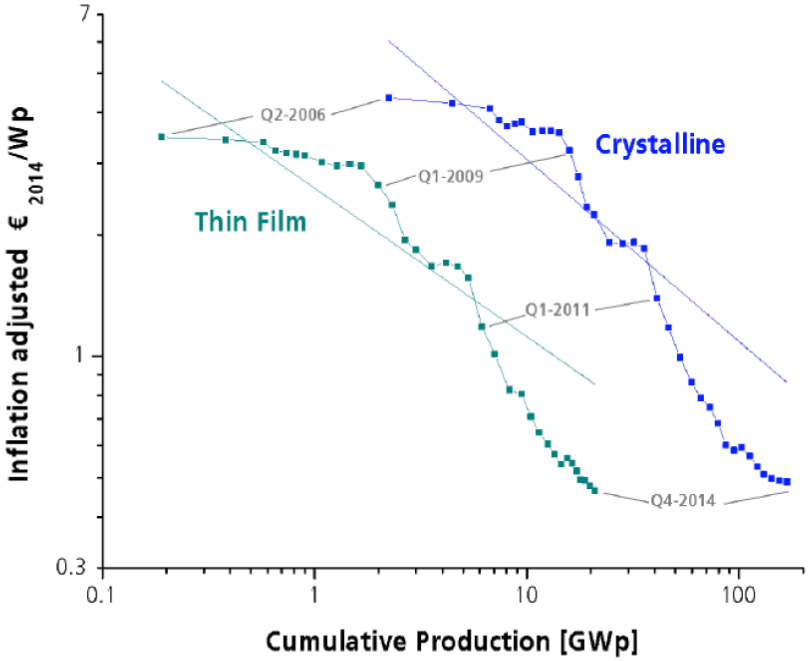
PRICES HAVE COME DOWN BY A FACTOR OF 10 SINCE 2005

STABILIZATION FOR THE NEXT 2-3 YEARS





Data: from 2006 to 2010 estimation from different sources : Navigant Consulting, EUPD, pvXchange; from 2011 to 2014: IHS. Graph: PSE AG 2015

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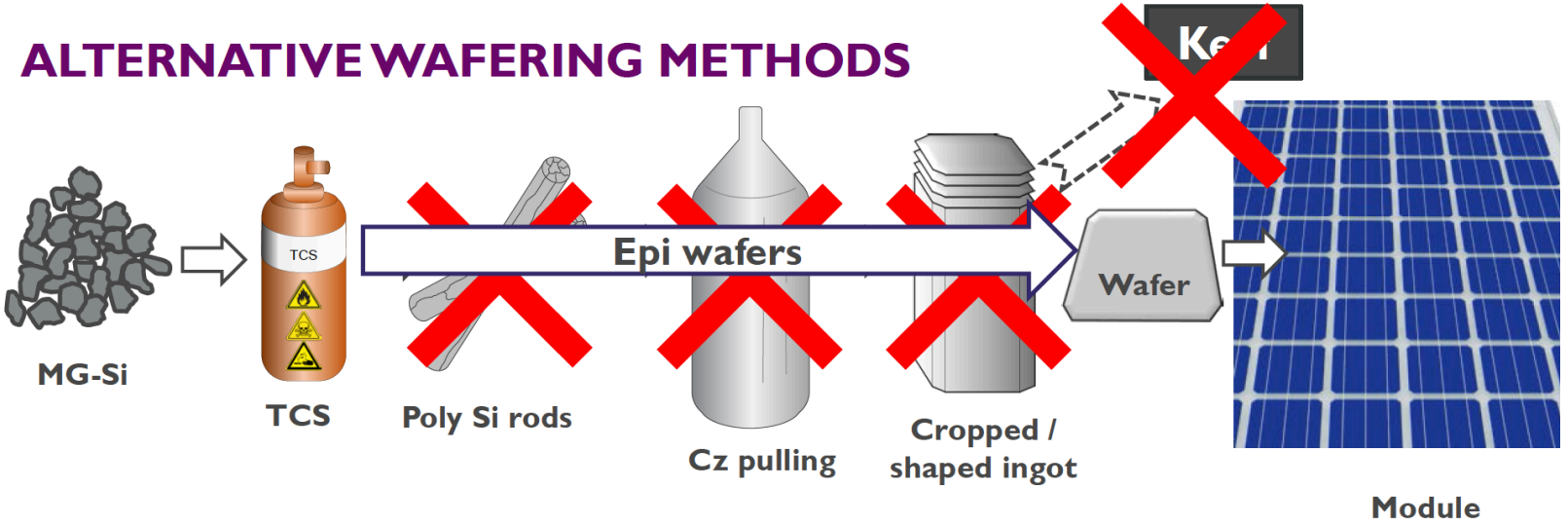
ALTERNATIVE WAFERING METHODS



③ Direct crystallization of wafers from gas

② Direct crystallization of wafers from melt

① Kerf-free wafering of Si ingots

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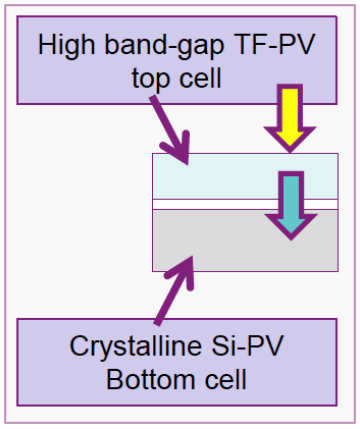
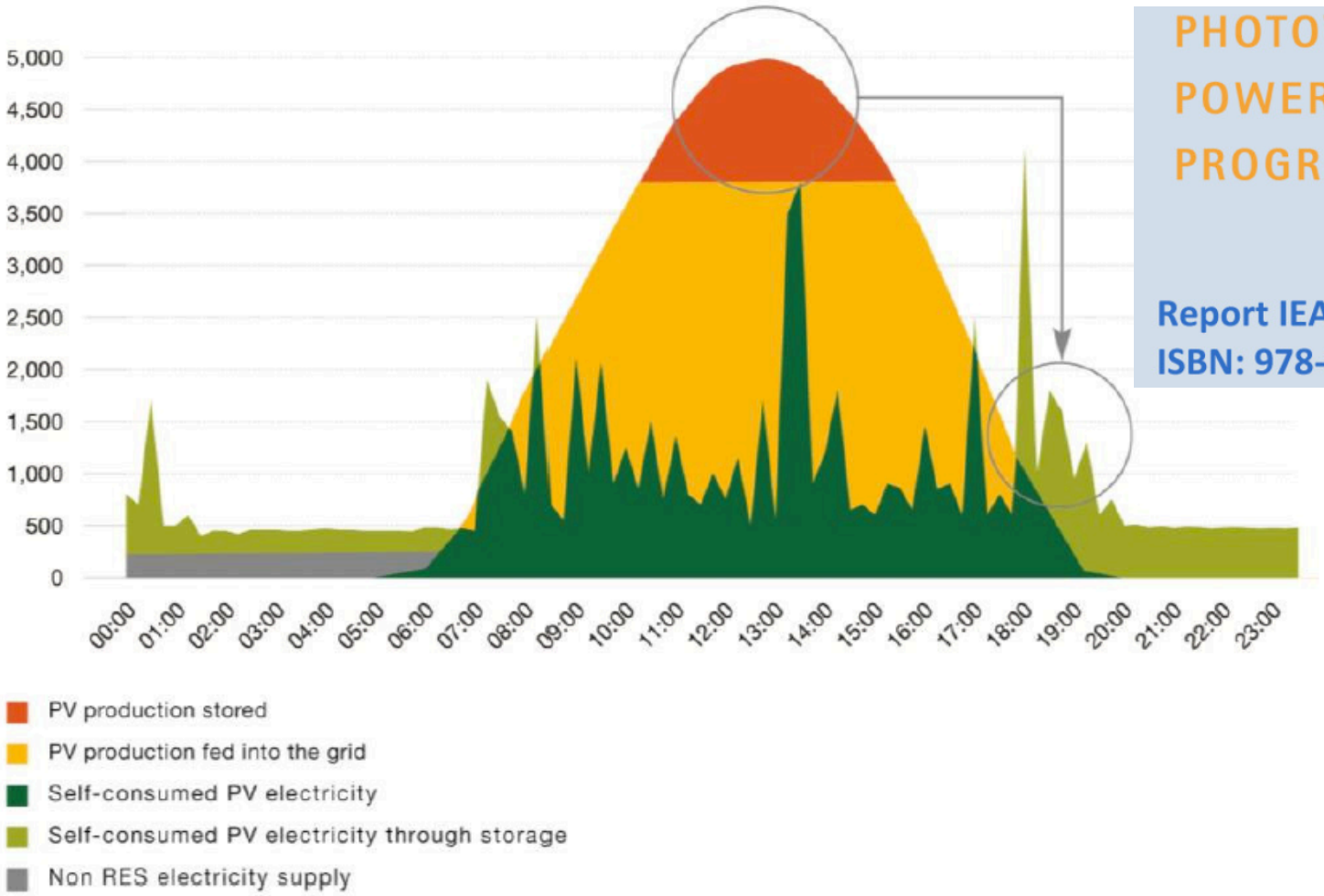
Direct epitaxial growth from gas



Towards higher efficiency:

- Stacked cells (thin film + crystalline)
- Perovskites

Energy storage



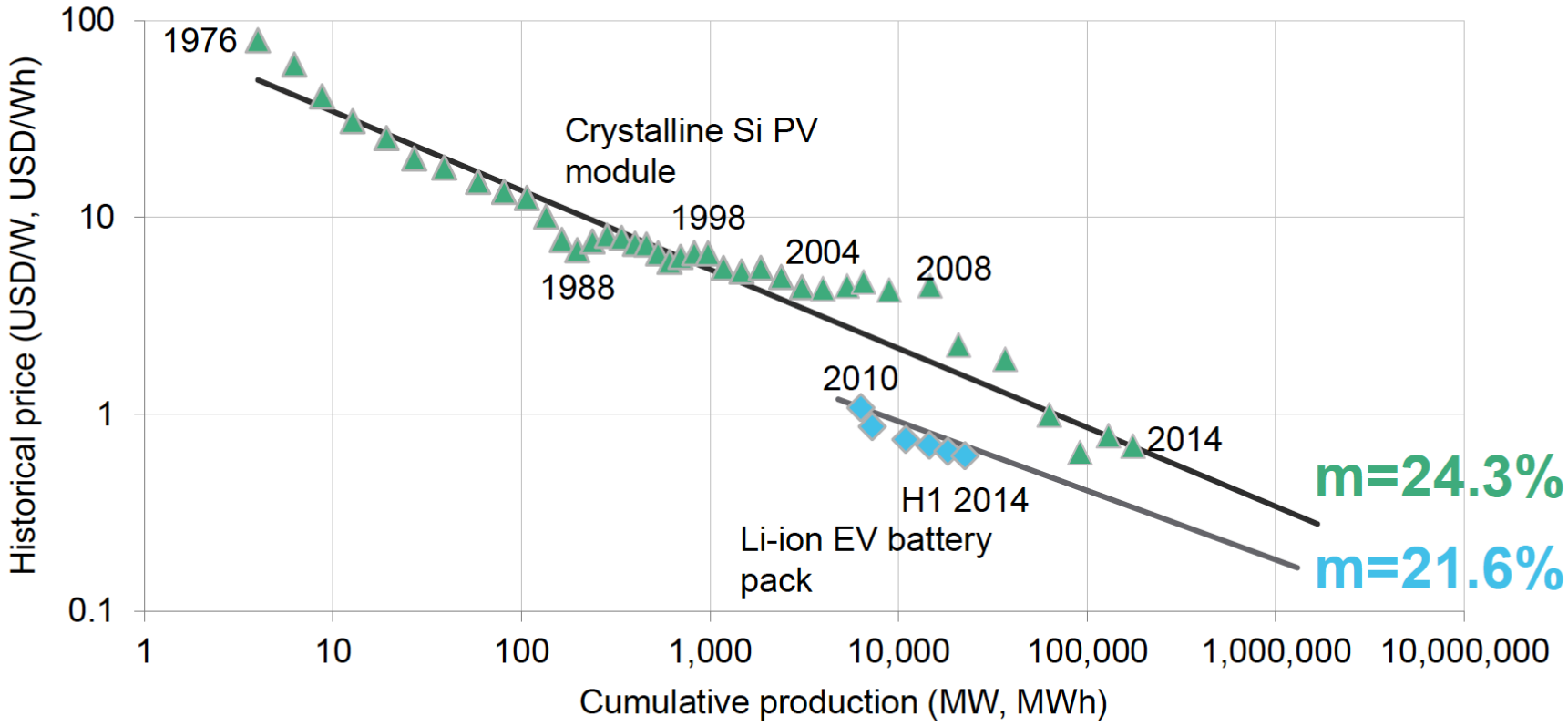
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Report IEA PVPS T14-03:2014
ISBN: 978-3-906042-24-4

Shift generation peak to consumption peak

LITHIUM-ION EV BATTERY EXPERIENCE CURVE COMPARED WITH SOLAR PV EXPERIENCE CURVE

Bloomberg NEW ENERGY FINANCE

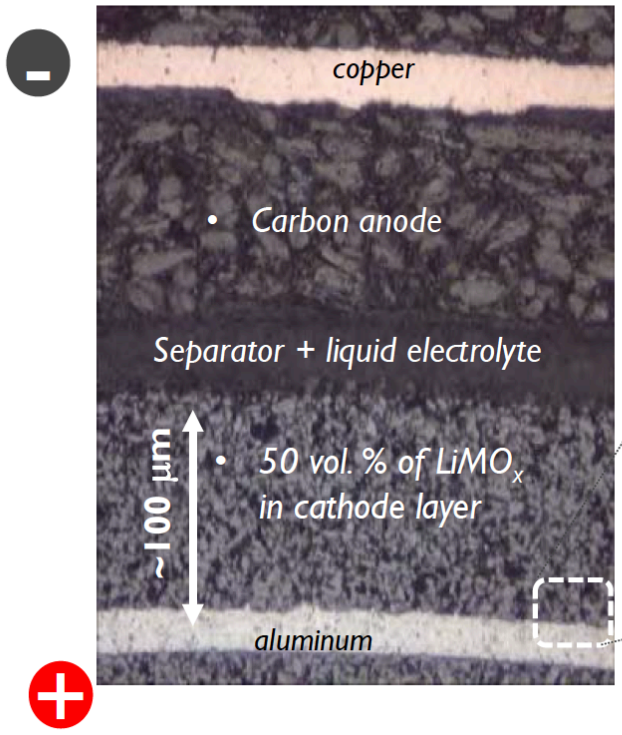


Note: Prices are in real (2014) USD.

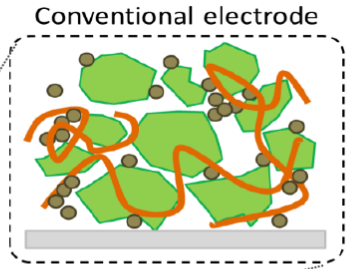
Source: Bloomberg New Energy Finance, Maycock, Battery University, MIIT

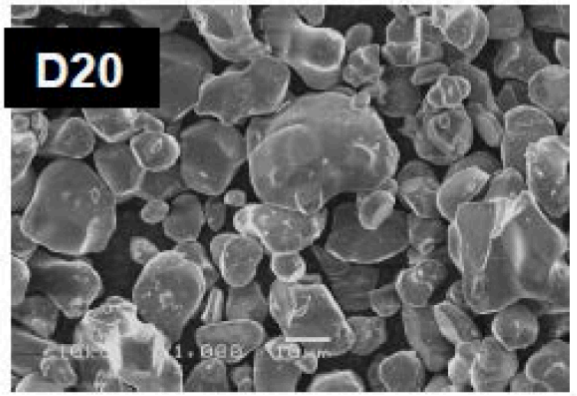
LOOKING TO BATTERY TECHNOLOGY TODAY

BASED ON MICRON-SIZE PARTICLES AND LIQUID ELECTROLYTES

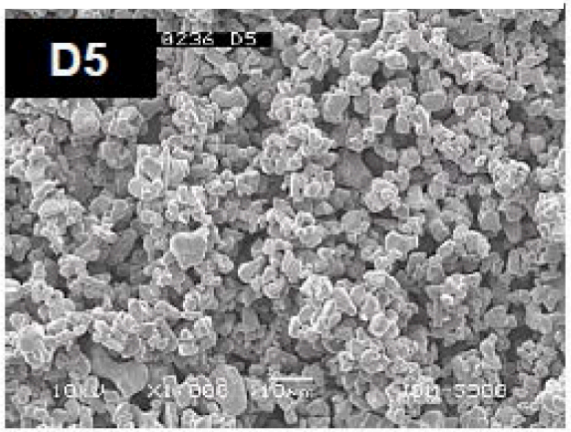


Particle-based Li-ion battery electrode fabricated with micron-sized powder





20µm



5µm

imec

27

- Nanoparticles for enhanced rate performance
- Imec is working towards solid-state Li-ion batteries for local short term storage to improve energy density, reliability and safety

Nearly Zero Energy Buildings and the reality of energy markets

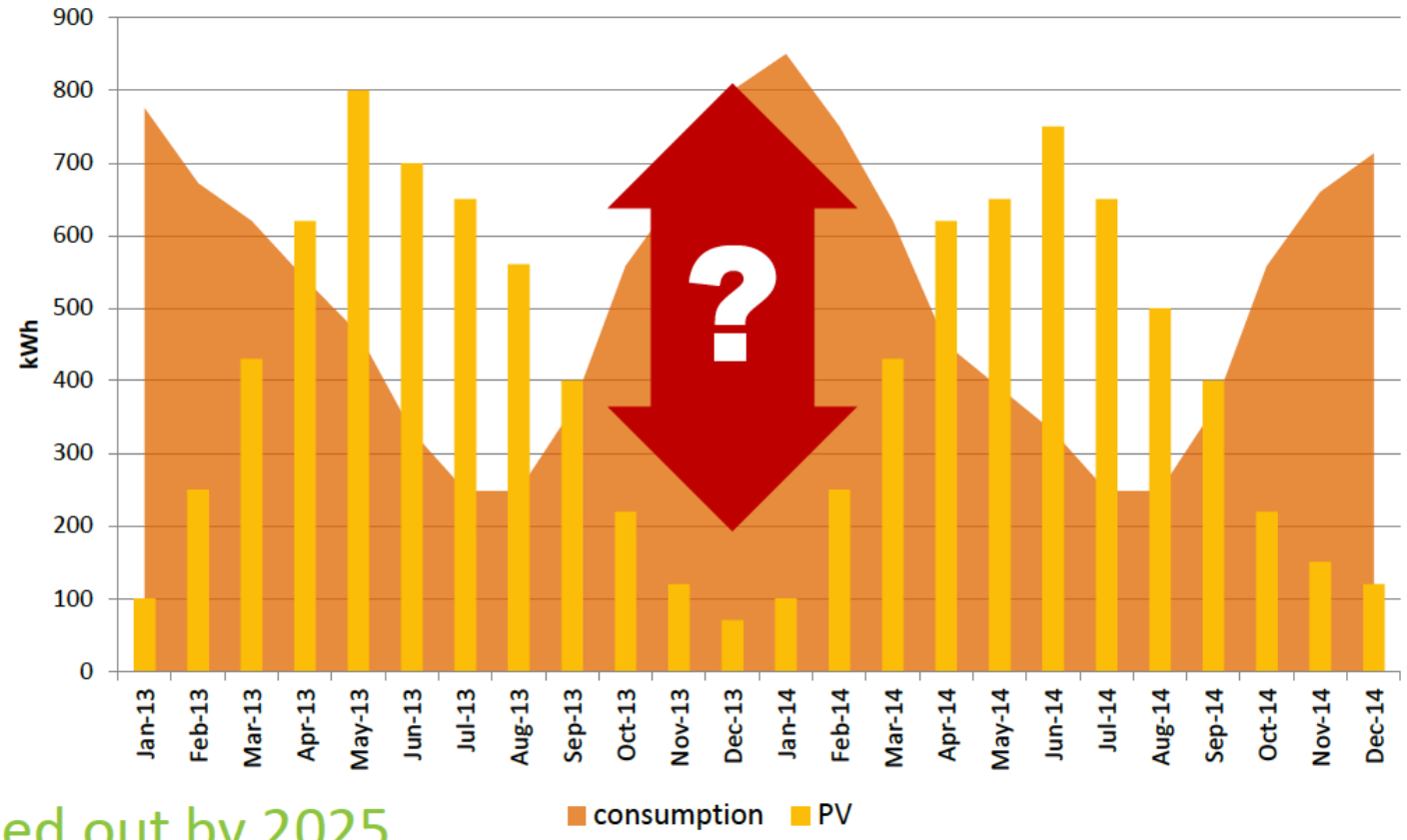
Long term storage ?

Insulation

Ventilation

Heat pumps

+ PV



Nuclear phased out by 2025

Currently no investments in gas plants

Biomass: 200M€/year subsidies for 400 MW plant

Internet of Things

Internet of Things – Analog Devices

Traditionally specialized in interfacing real analog world to the digital world

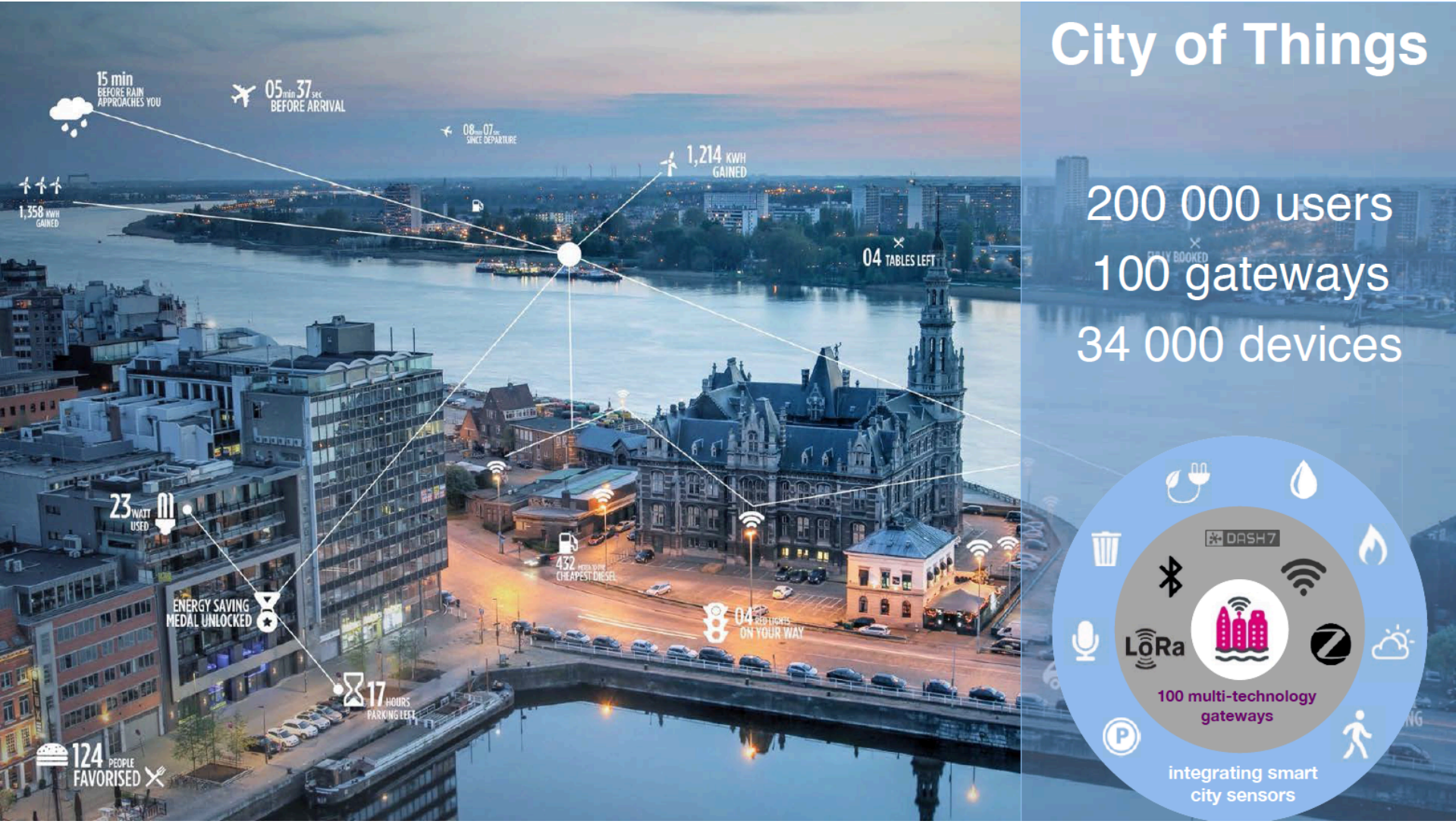
Definition of IoT: a signal chain extending to the Cloud

Trend towards more intelligence on the sensing node

"transmit wisdom not data"

Required technologies not yet mature: chip scale sensors, energy harvesting, ultra low power techniques, …

System architecture critical and very different for different applications.



- Antwerp: Testbed for IoT
- Need to develop ecosystem
- Data storage

iMinds

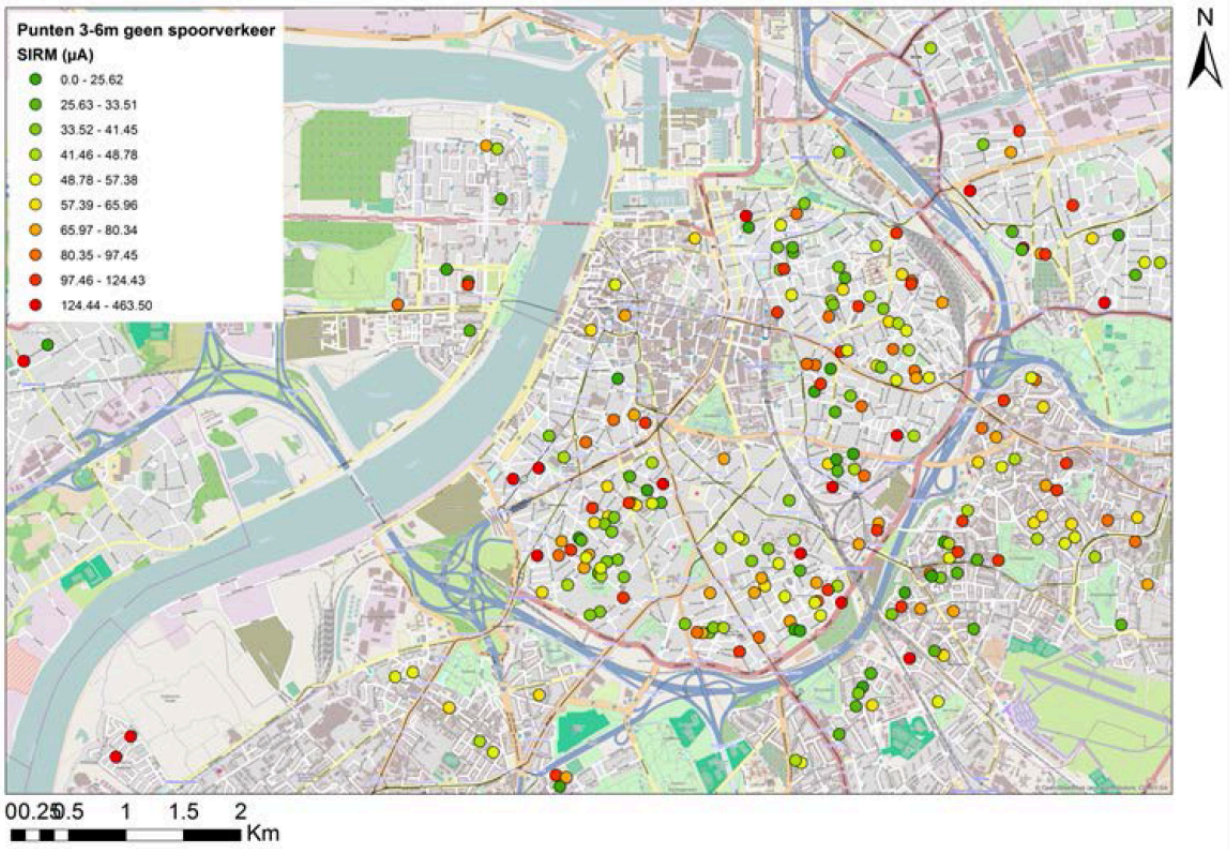
iMinds


Wagen 1
Wagen 2
bpost
iMinds
imec

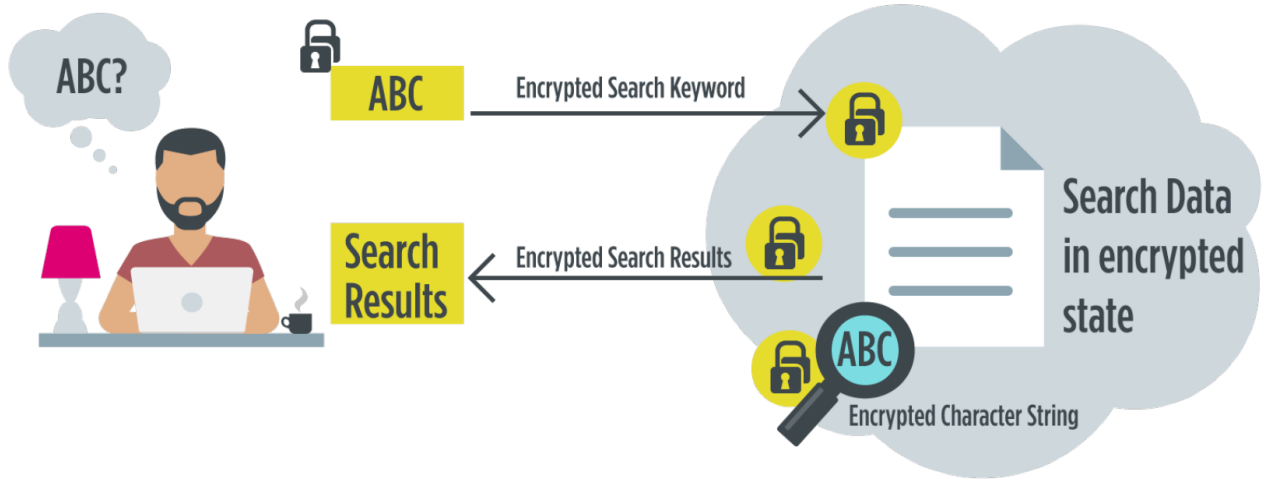
Air quality monitoring using strawberries

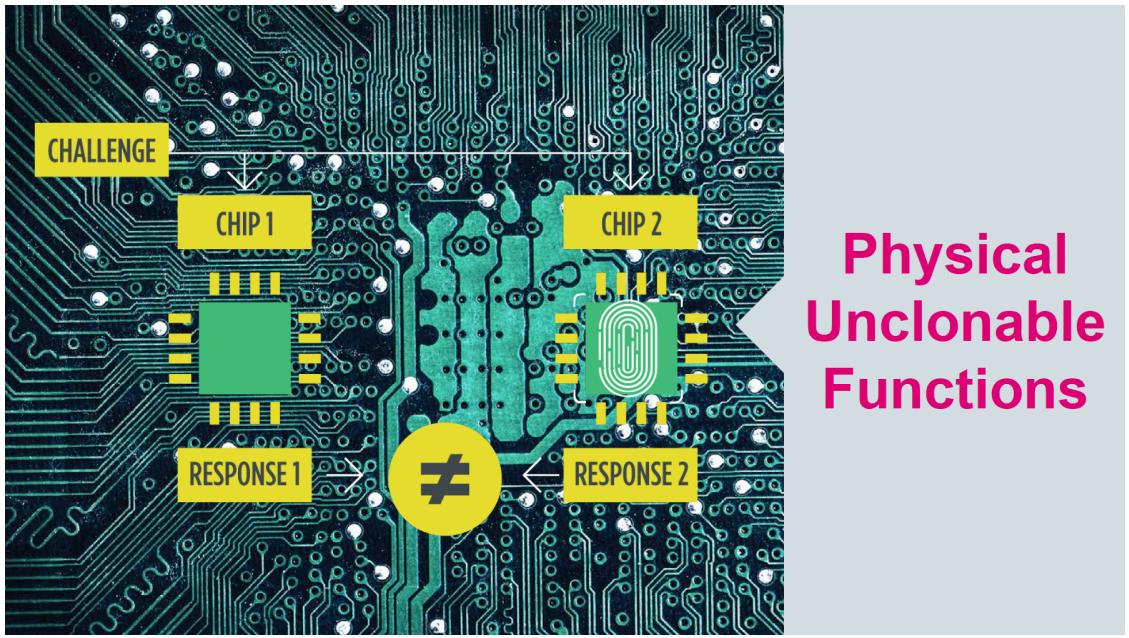
iMinds

Air quality monitoring using strawberries



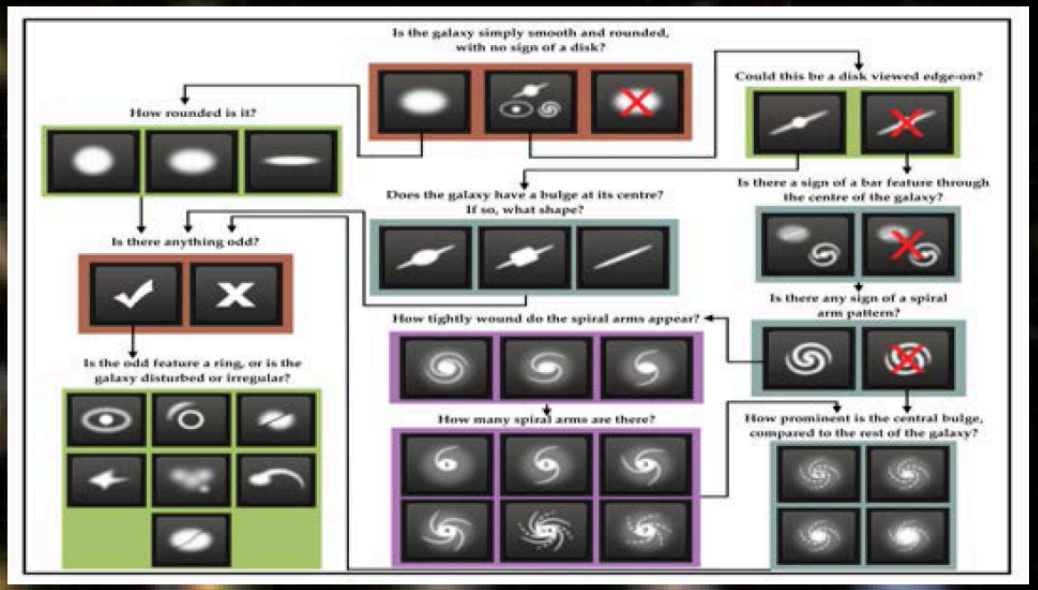
Distributed trust: data encryption





Artificial Intelligence

AI for classification of galaxy images



iMinds #1 out of 326 teams

Kaggle Competition: *http://benanne.github.io/2014/04/05/galaxy-zoo.html*

“ *The question of whether machines can think is about as relevant as the question of whether submarines can swim.* ”

- Edsger Dijkstra, 1984

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Everything connected - Distributed Trust - Distributed intelligence

Conclusions: CMOS scaling

- Data explosion (PC – App - IoT)
- Finfet and nanowire transistors
- Moore's law continues but with expansion to 3D
- Architectures
- PC and mobile market saturate, new applications emerge

New applications

Medicine

- DNA sequencing accelerated by micro-machined chips enables individualized precision medicine, early detection and monitoring saves significant cost
- Wearable devices – portable labs – mobile phone

Automotive

- 80 % of innovation in semiconductors
- Sensor systems – connectivity
- Fully autonomous driving

Energy

- PhotoVoltaics: better efficiency and cost reduction
- Batteries for short term storage

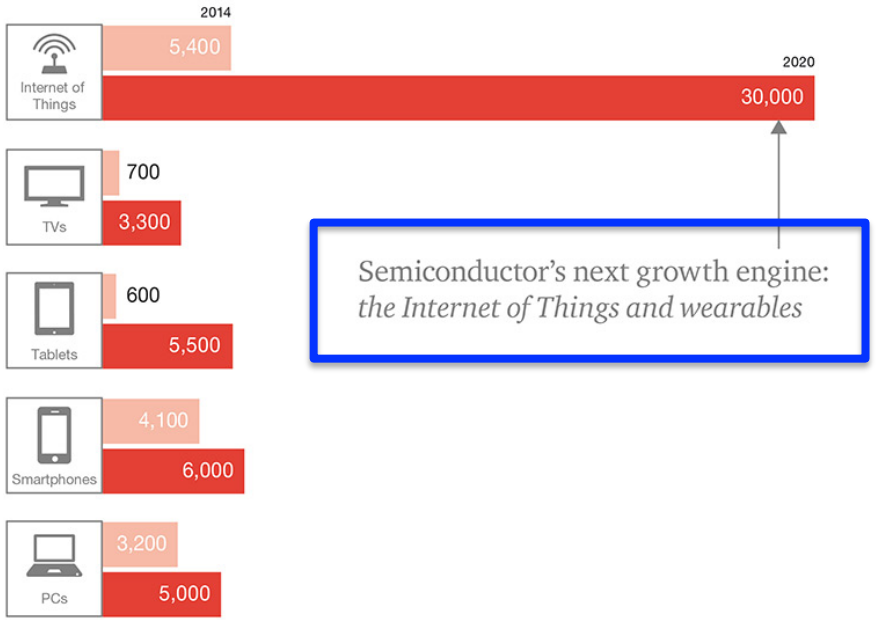
Internet of Things (IoT)

- Smart sensor systems
- Encryption
- Artificial Intelligence and data

The IoT is expected to drive a massive increase in connected devices and revenue growth across multiple industries.

Connected devices by 2020

in millions

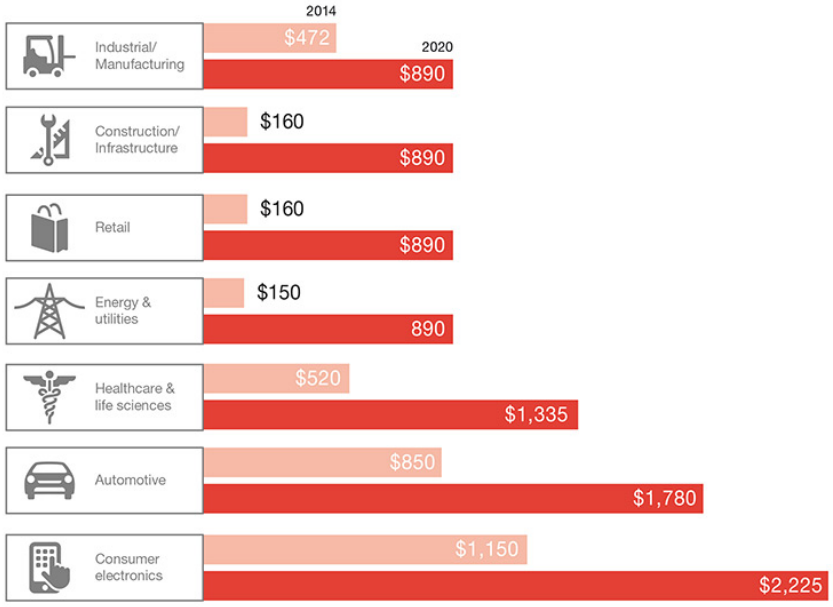


pwc

For more information, please visit:
pwc.com/iot

IoT market by 2020

US$ billions



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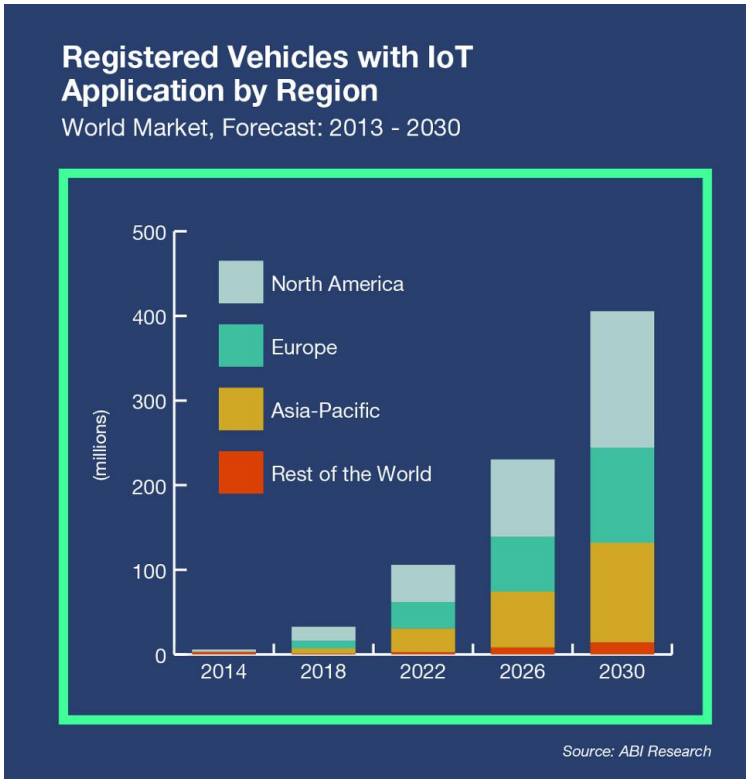

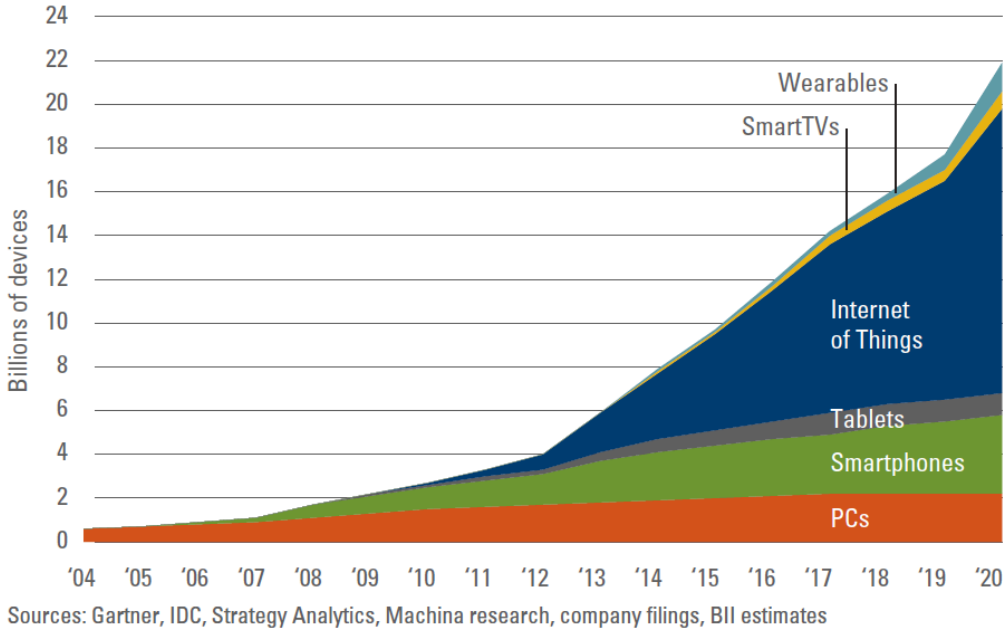

Source: AlixPartners

Also:

- Tipping point : 50 B investment in digital healthcare in the last 18 months (Georgia Papathomas – J&J Pharmaceuticals)

Thank you !