Zero Power Technology as Enabler of Future Smart Wearables

Adrian M. Ionescu, EPFL

Summary

The Big Picture

- Global challenges
- Trillion of sensors planet
- Next exponential technology:
  - Zero Power Smart Systems

Wearable technology for a Smarter Life:

- Sensing, wireless communication, energy scavenging
- More than monitoring… feedback and prevention

Conclusions

Global challenges

- Healthcare, environment, energy

Sustainable care

Personalized medicine

Safer transportation

Need of technologies for humanity,
improving Quality of Life and fostering economic growth

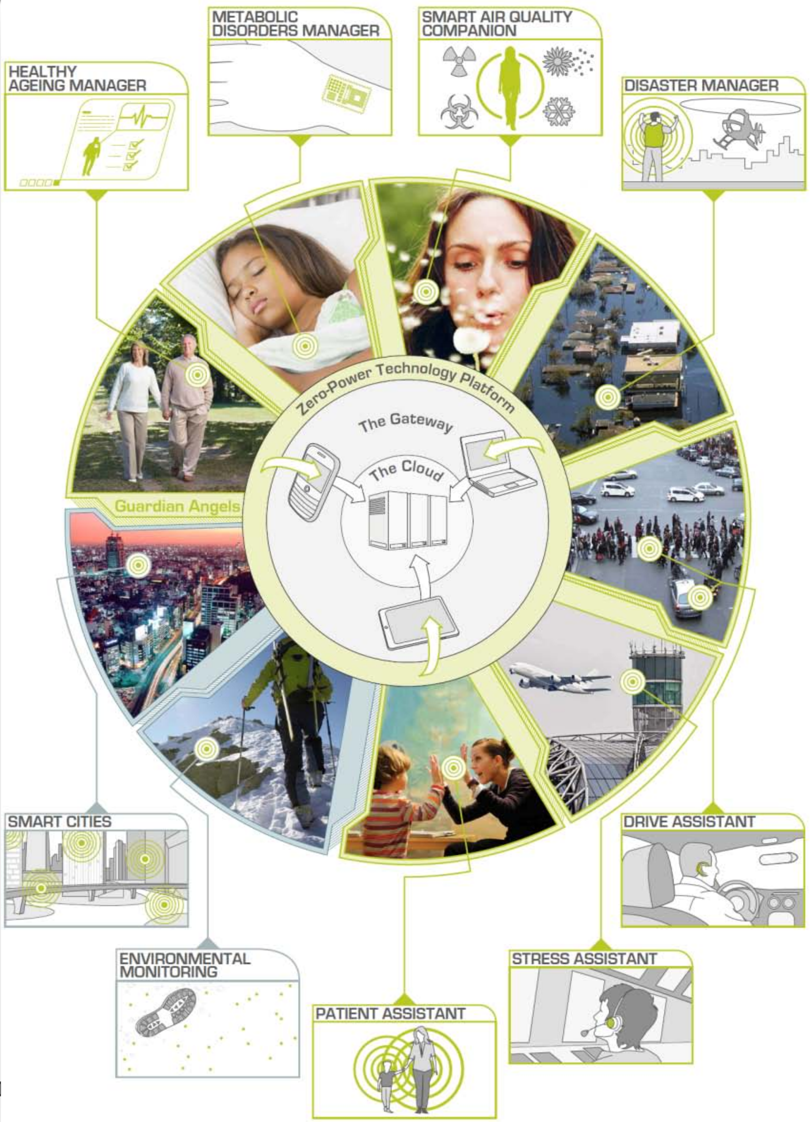
Disaster management

Reduced food waste

Pollution monitoring

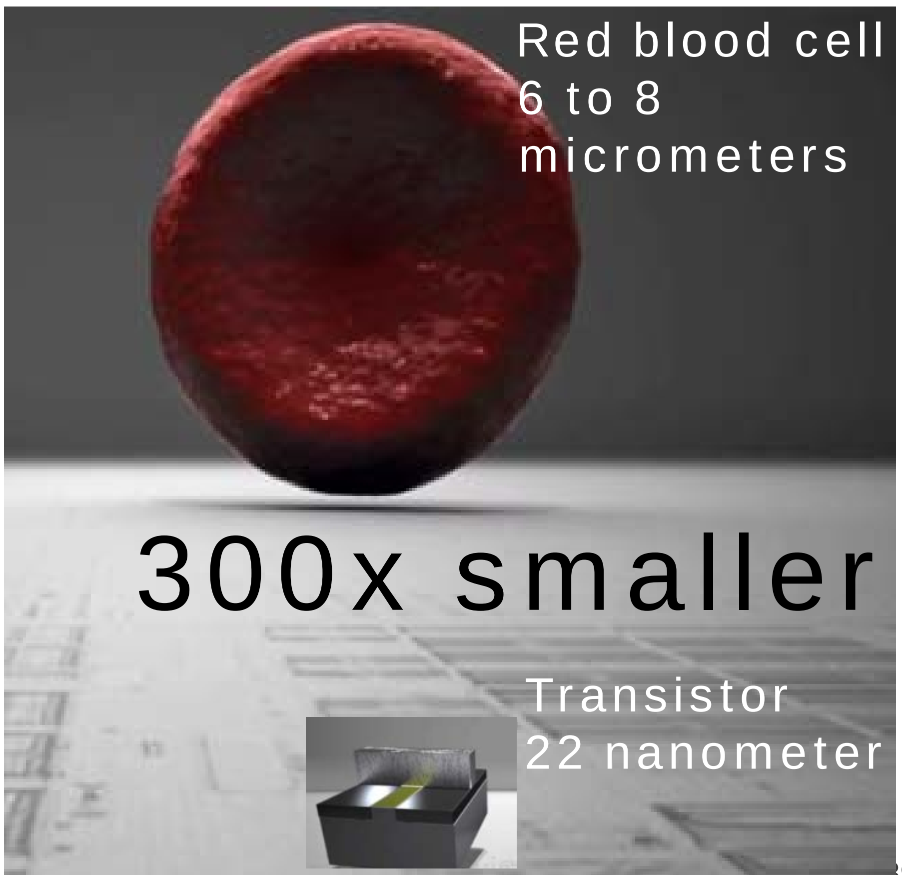
Computing at the edge of the cloud

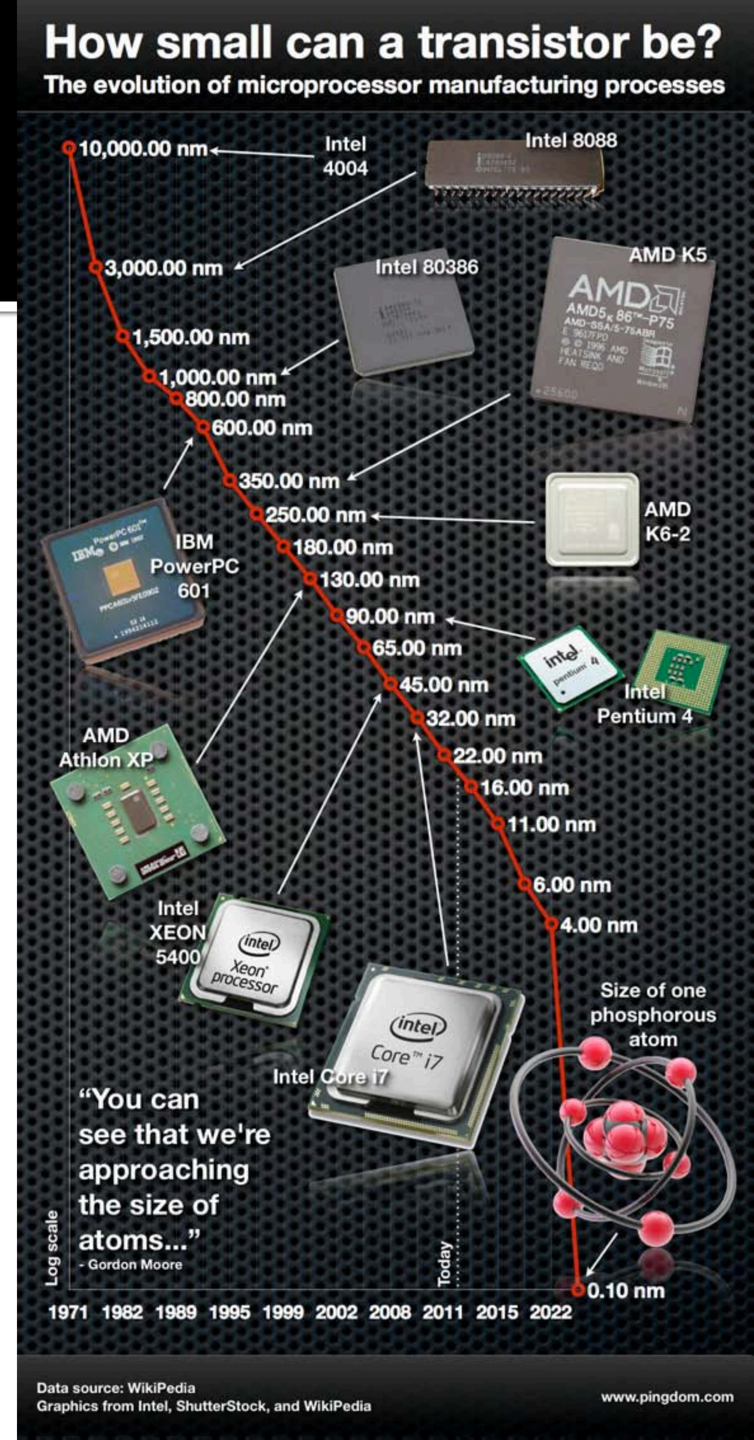
- More than infotainment...
- Internet-of-Things (IoT) calls for the deployment of trillions of tiny wireless devices
- New Quality of Life by ethics driven sustainable services with invisible technology



>2000: Nano Era

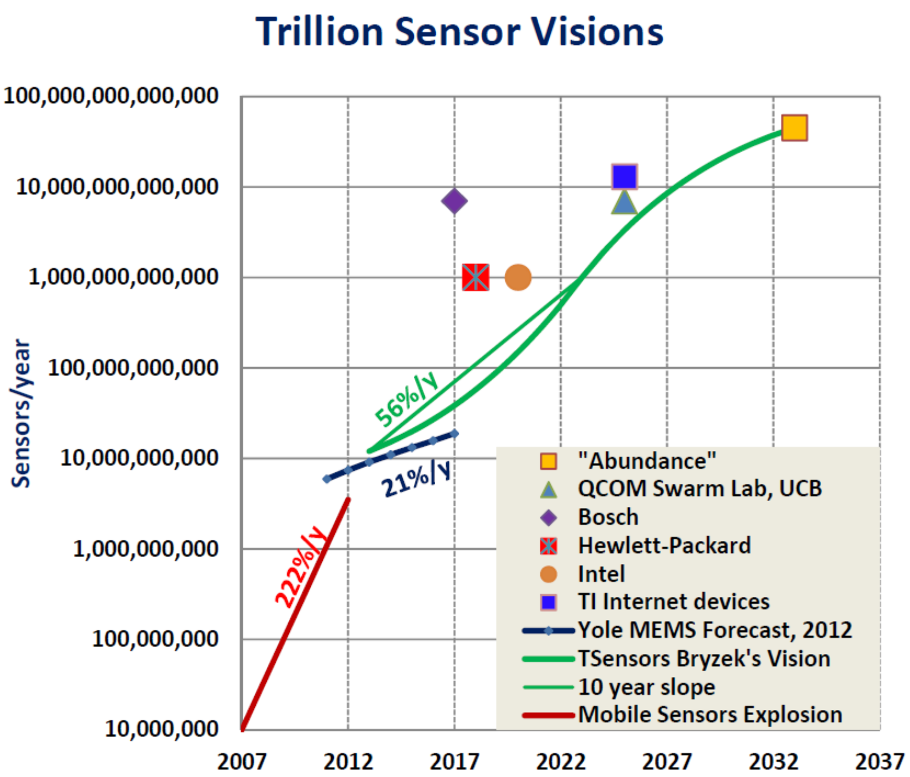
- Size of a transistor < 100nm
- Today: 3D 22nm transistors

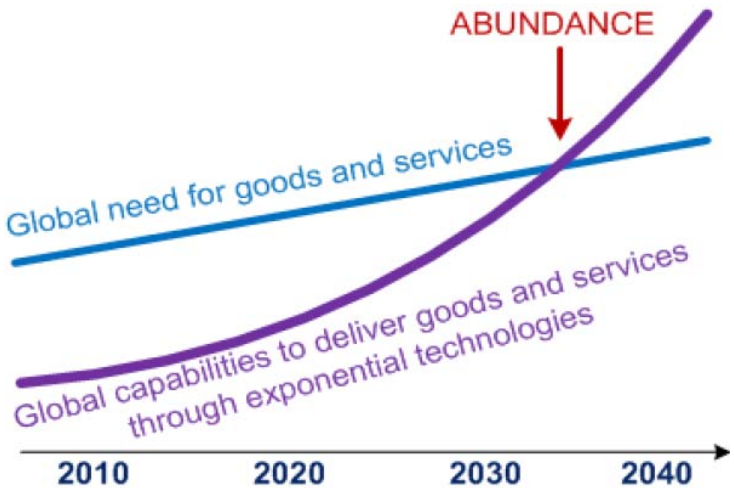




>2007: Trillion of sensors?

- 2007: the iphone!!!
- .. But no Trillion Sensors anticipated by market research companies
- Concept of abundance

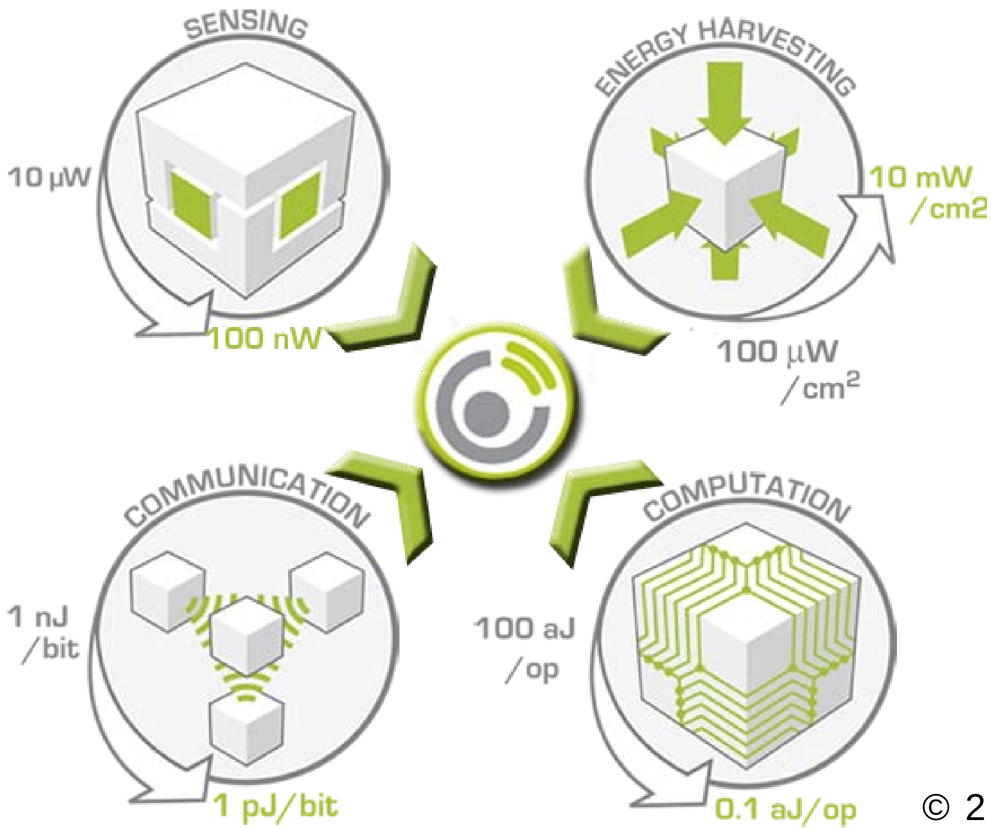




Zero-Power Smart Systems form the next Exponential Technology for a Smarter Life

What is Zero-Power?

- Zero-Power technology: enabler of Autonomous Smart Systems Systems



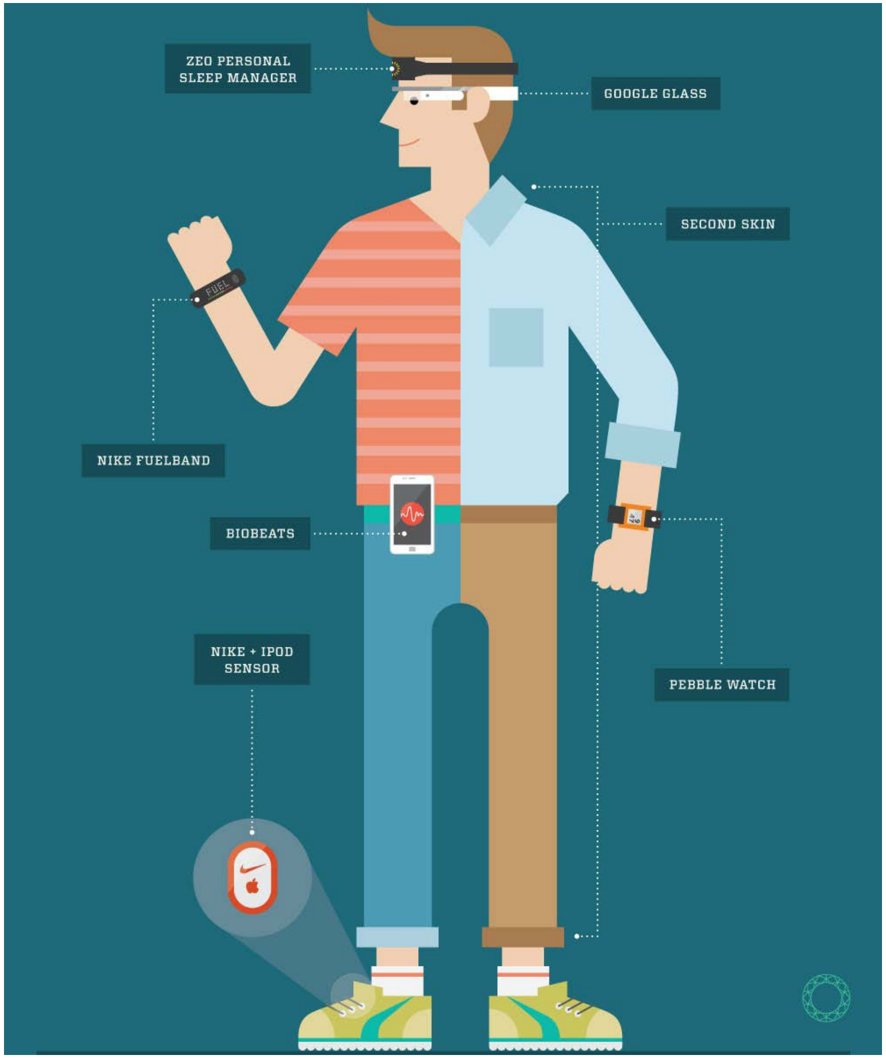
- x 1000 more energy efficient bit computation
- x 1000 more energy efficient bit transmission
- x 100 more efficient energy harvesting

10 years ahead industrial roadmaps

© 2012: Guardian Angels for a Smarter Life

Wearable technology: sense your body

- Technology to be worn on the user's body for an extended period of time, significantly enhancing the user's experience
- Four wearable categories:
  - Fitness and Wellness
  - Healthcare and Medical - require approval, monitor vital signs and augment senses.
  - Industrial and Military
  - Infotainment



Wearable technology: sense your environment

Environmental related diseases:

AIR

WATER

- RESPIRATORY INFECTIONS: Globally more than 1.5 million deaths annually from respiratory infections are attributable to the environment, including at least 42% of lower respiratory infections and 24% of upper respiratory infections in developing countries.
- CANCER: environmental causes also account for an estimated 31% of global lung cancer burden.
- CARDIOVACULAR DISEASES: 2.5 million people die every year from cardiovascular disease attributable to work-related stress as well as chemical, air pollution, and environmental tobacco smoke exposures.
- DIARRHOEA: about 1.5 million deaths per year from diarrhoeal diseases are attributable to environmental factors; WHO recently estimated that 88% of all cases of diarrhoea globally were attributable to water, sanitation and hygiene.
- MALARIA
- INTESTINAL NEMATODE INFECTIONS
- HEPATITIS B and C
- TUBERCULOSIS
- ...

A schoolgirl with a face mask for protection from smokestack pollution emissions of factories in her neighbourhood in the eastern Mediterranean region.

Credit: Munir NASA/UNEP/Still Pictures

CAN ENVIRONMENTAL AND HEALTH CO-MONITORING HELP AT GLOBAL SCALE?

Anatomy of a Wireless Smart Sensor Node

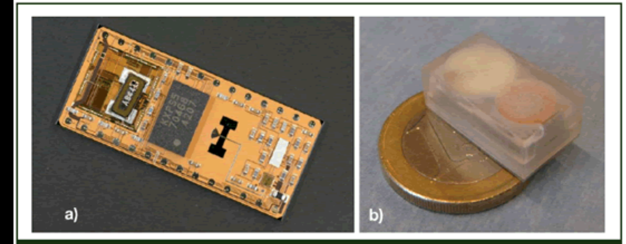
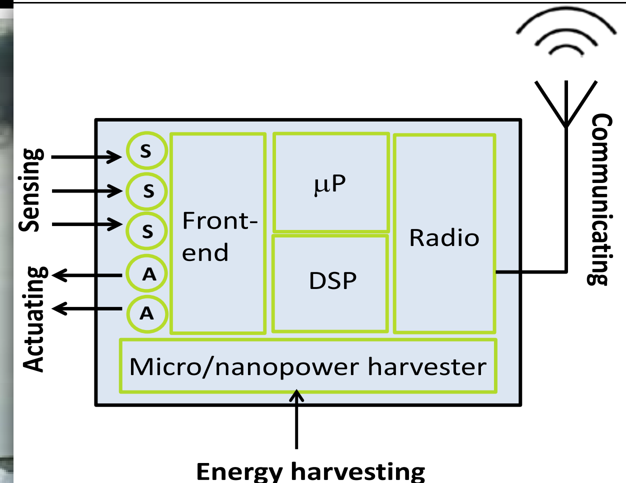


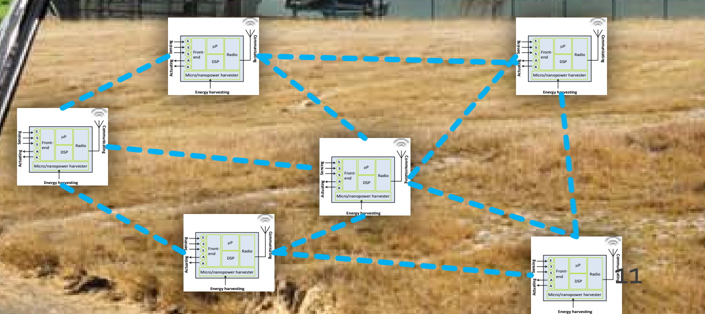
Figure 5. e-CUBES 3D Integrated TCI Substrate for Wireless Sensor Node Fabricated at Fraunhofer IZM and Final Health and Fitness Demonstrator Assembled at Philips Applied Technologies



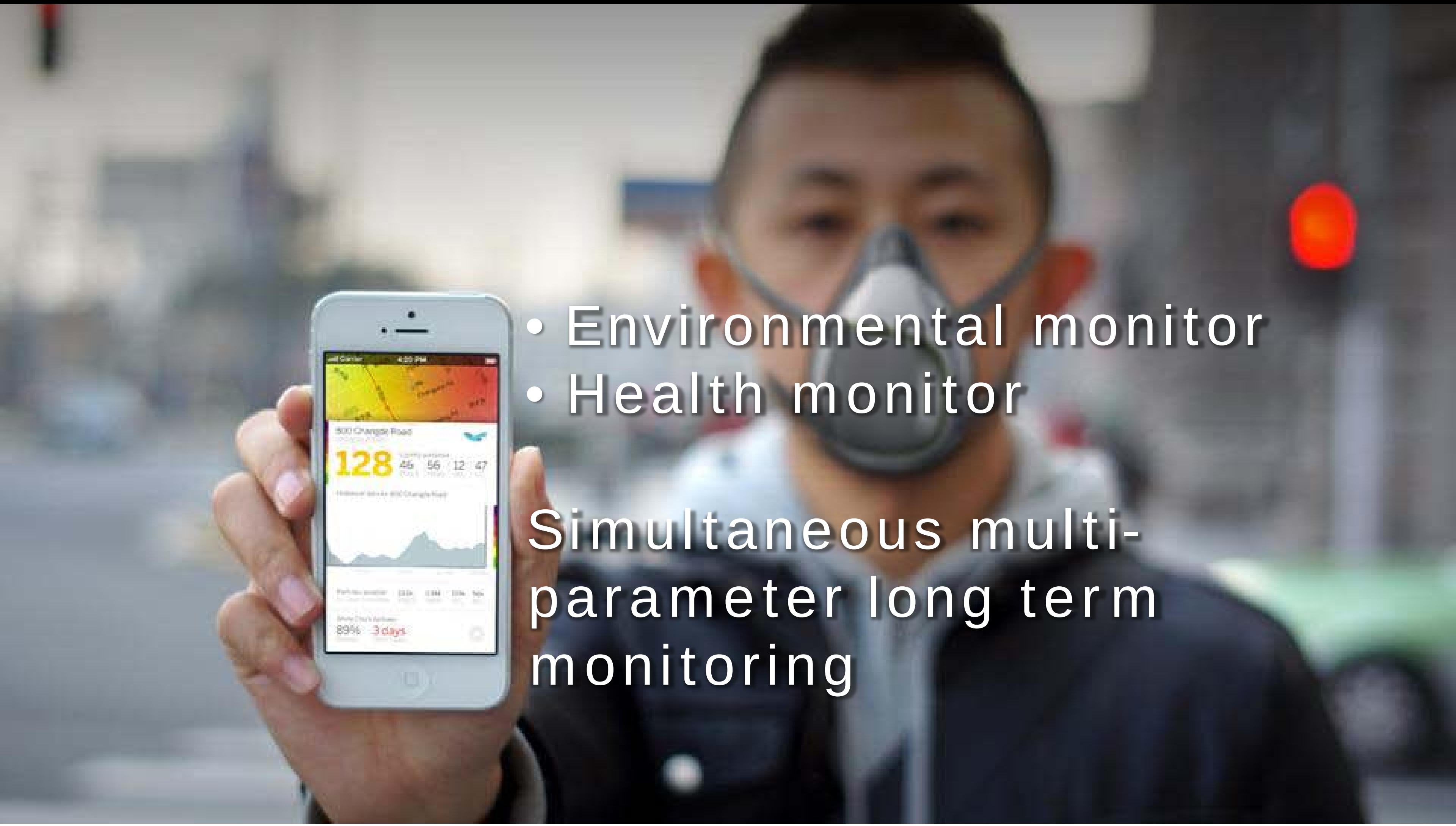
Wireless Sensor Nodes, a key emerging monitoring technology for:

- Environment
- Health
- Infrastructure
- Agriculture
- Weather

- How small can be? ~cm^3 to mm^3
- How much energy? ~100microWatt



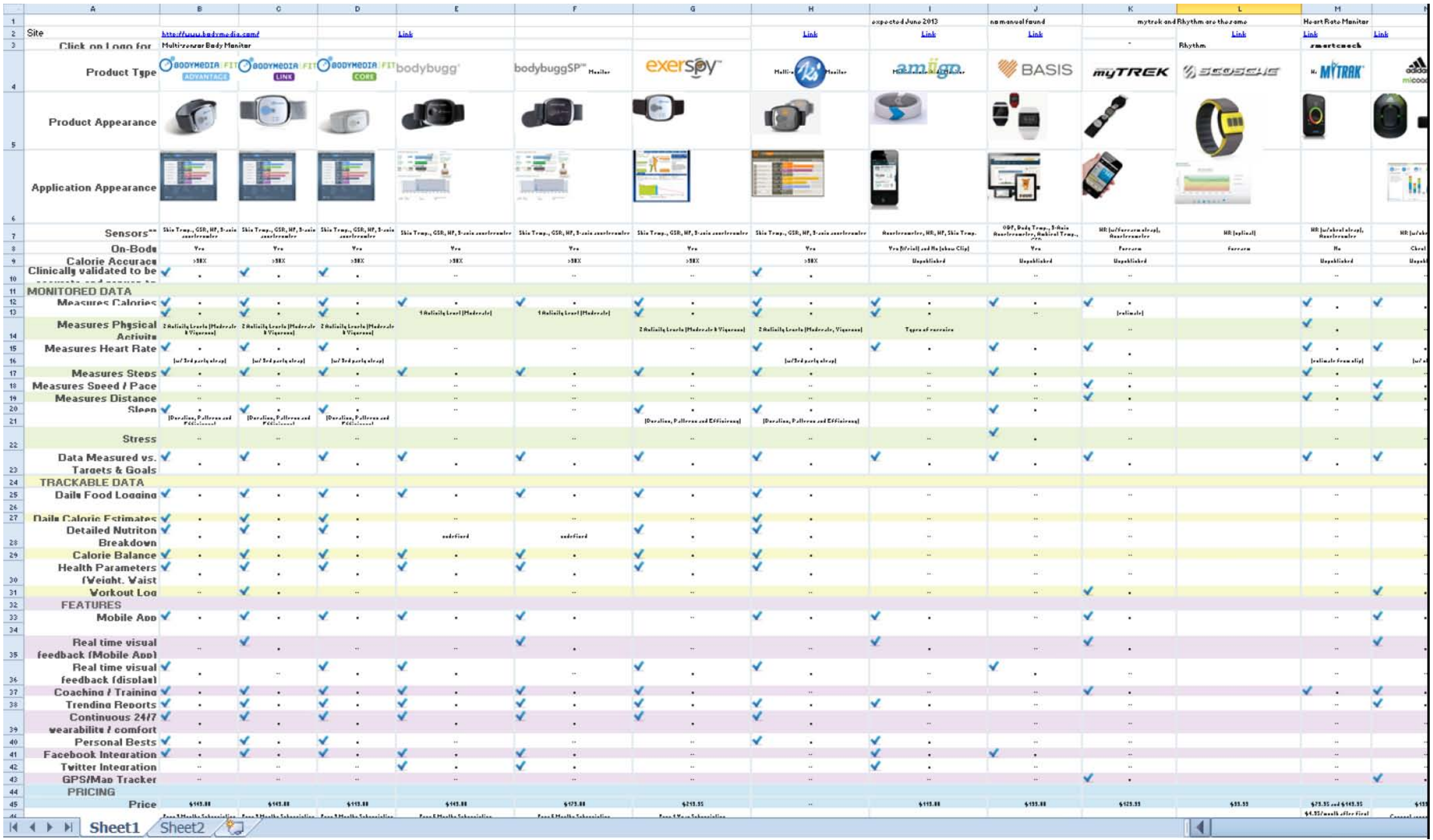
One person = One Wireless Multi-Parameter Sensor Node



- Environmental monitor
- Health monitor

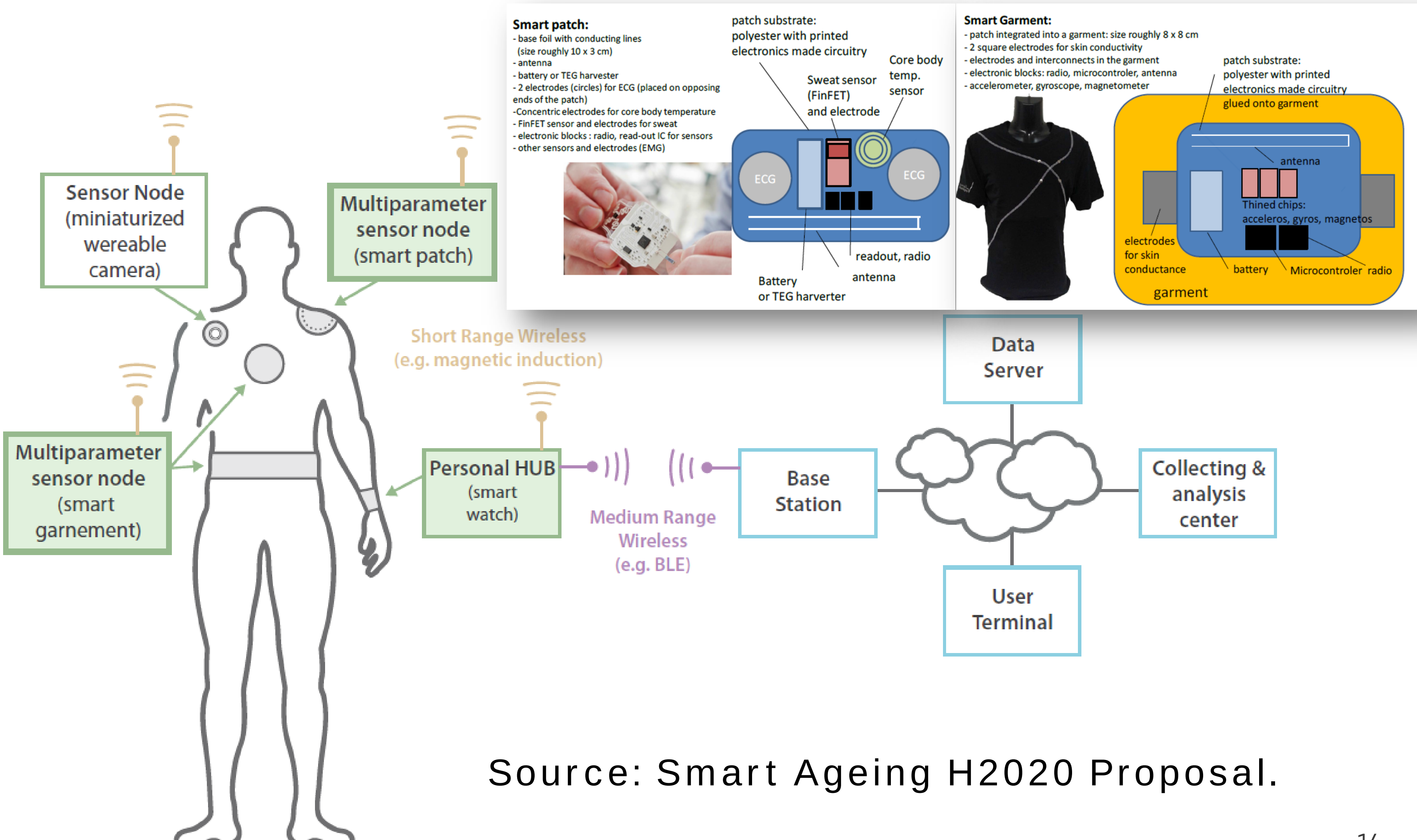
Simultaneous multi-parameter long term monitoring

Wearable technology revolution has started!



Source: Rudy Lauwereins, IMEC.

Wearable system architecture



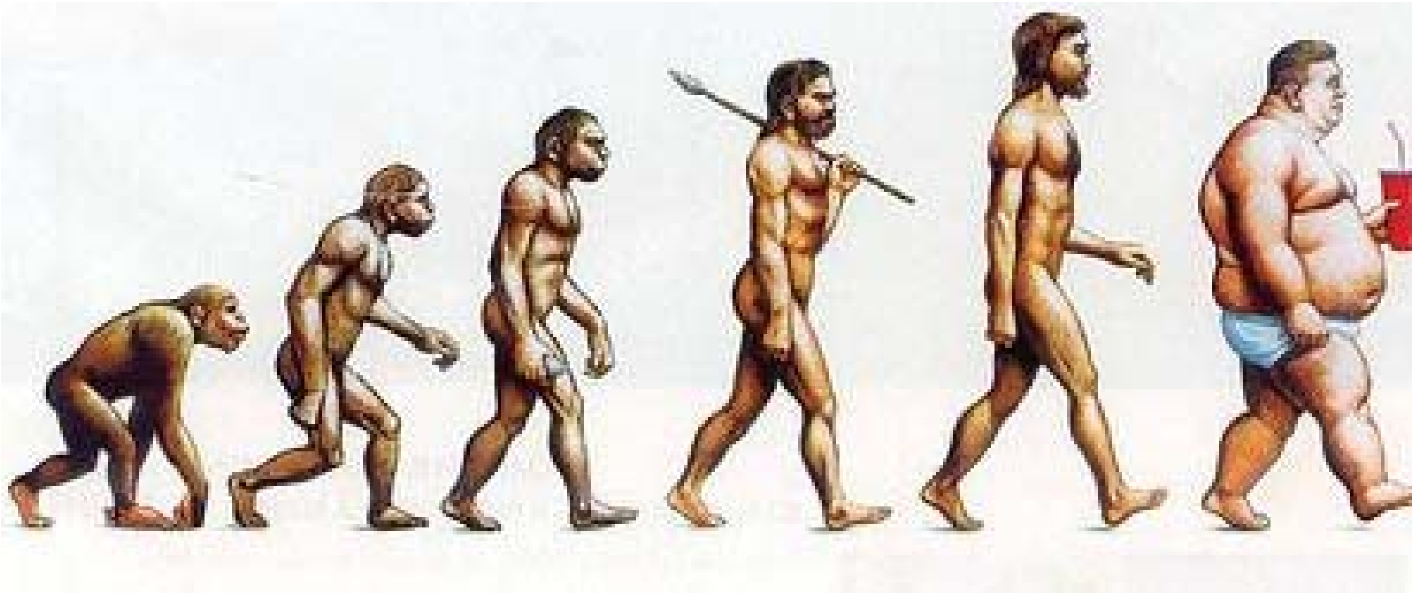
Source: Smart Ageing H2020 Proposal.

Feedback channels

- Encourage and motivate on an objective basis!
- Feeback channels:
  - Physical activity
  - Mental activity
  - Nutrition
  - Hydration
  - ...

  for behavior change!

The effect of evolution on behavior and energy expenditure



18kCal/kg/day 4kCal/kg/day

Can wearable smart system technology help?

Behavior engineering

- Quality of Life involves behavior change

supported by Smart Systems

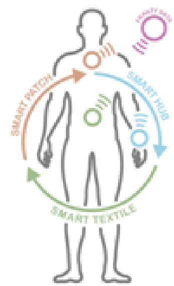
How healthcare can really benefit?

- Wearable smart systems can help by
  - Sensing and diagnosing complex situations in real life
  - Long-term autonomy and data fusion
  - Interact with both the patient and the environment
  - Quality of life: tool for behavior engineering
  - Improving security and safety
  - Better decisions in real life

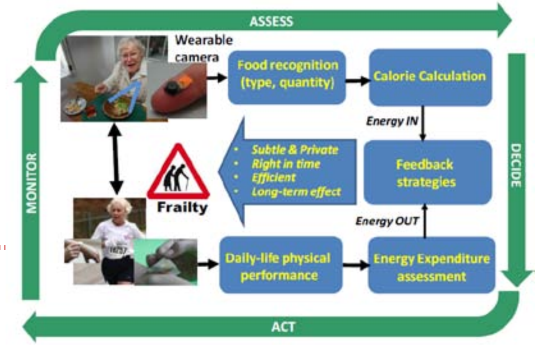
A key component of Care Cycle!

Care cycle and wearable smart system technology

Assesing and preventing frailty



Healthy
Frail
Pre-frail



Feedback
- real-time
- context-aware
- post-monitor on innovative channels

***Low Power Wearable Technology Platform:**
- multi-sensing
- low power processor
- body comms
- energy autonomy
- hetero-integration
- middleware

***Advanced signal processing**
***Cloud storage & machine learning**

MONITORING & ASSESSMENT

Self — Health professional

Smart System

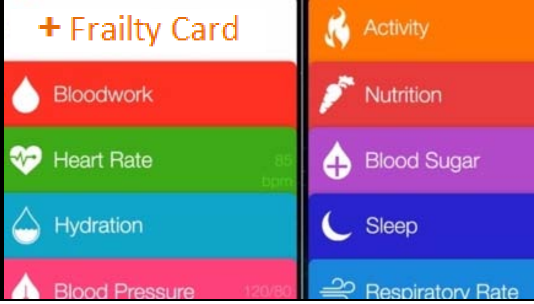
Follow-up
Intervention
Complementary tools (nutrition, diet)

Personal Health Record

Electronic Health Record

Big Data

Activity & energy expenditure monitoring

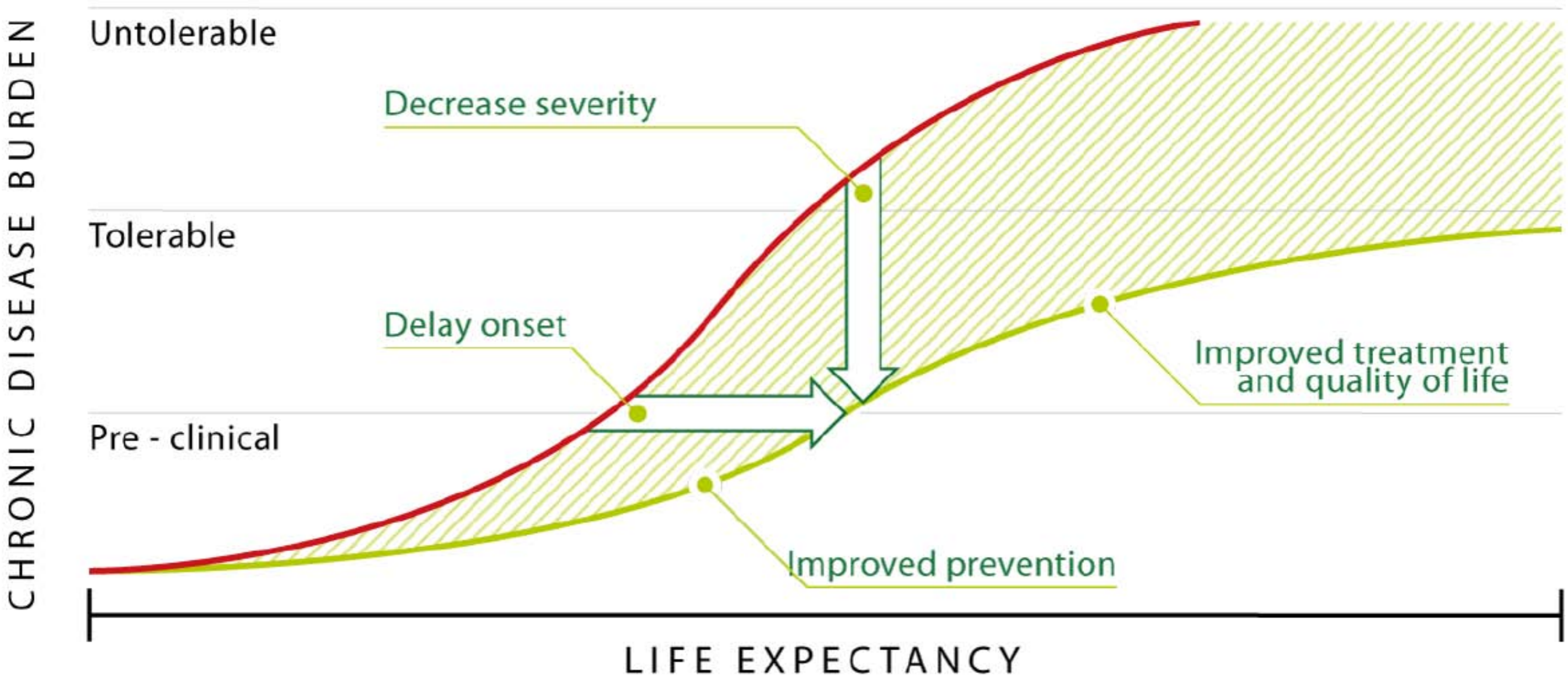


- Individualized Assessment on Smart Hub
- Physical Activity monitoring with smart garment:
  - Accelerometer, Gyro
  - 24/7 activity recognition and energy expenditure estimation
- Physiological signals with multi-parameter smart patch:
  - ECG, heartbeat
  - Respiration
  - Bio-impedance
  - Skin temperature
  - Bio-chemical sensing

Paradigm change:
a sustainable healthcare strategy based on prevention enabled by future zero-power smart wearable technology

Benefits

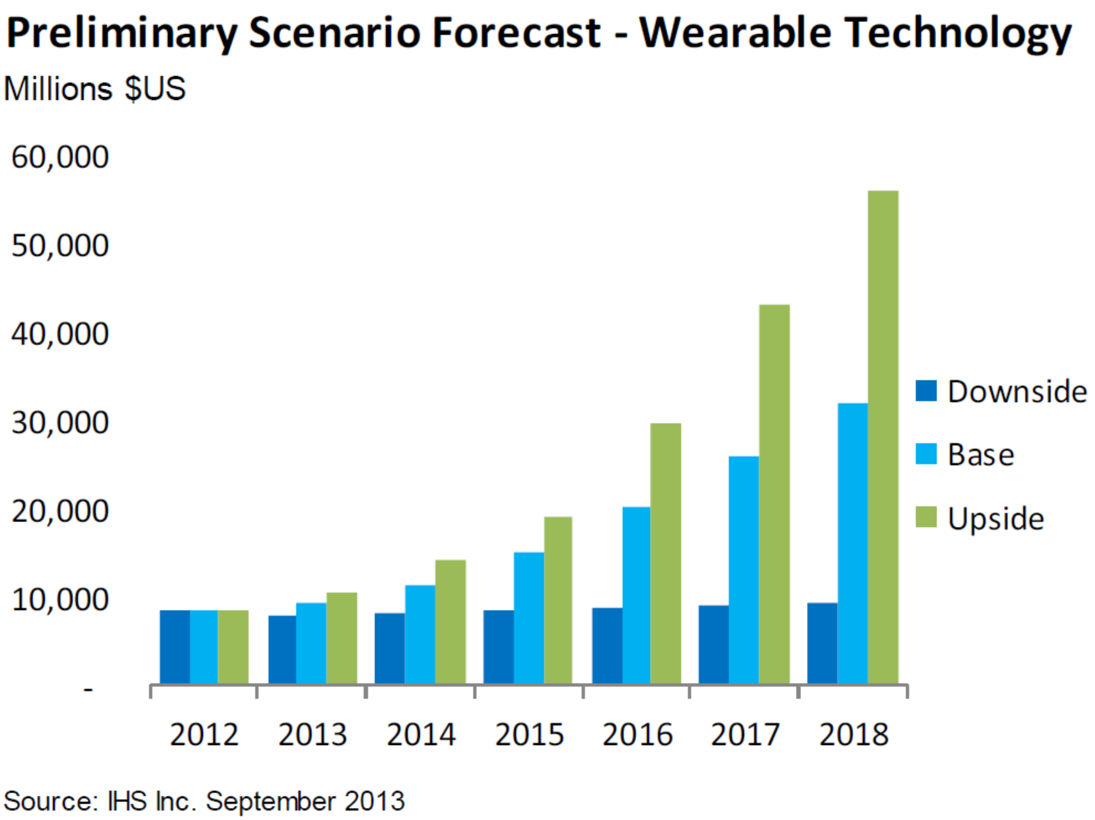
- Quality of Life, sustainable



World market for wearable technology

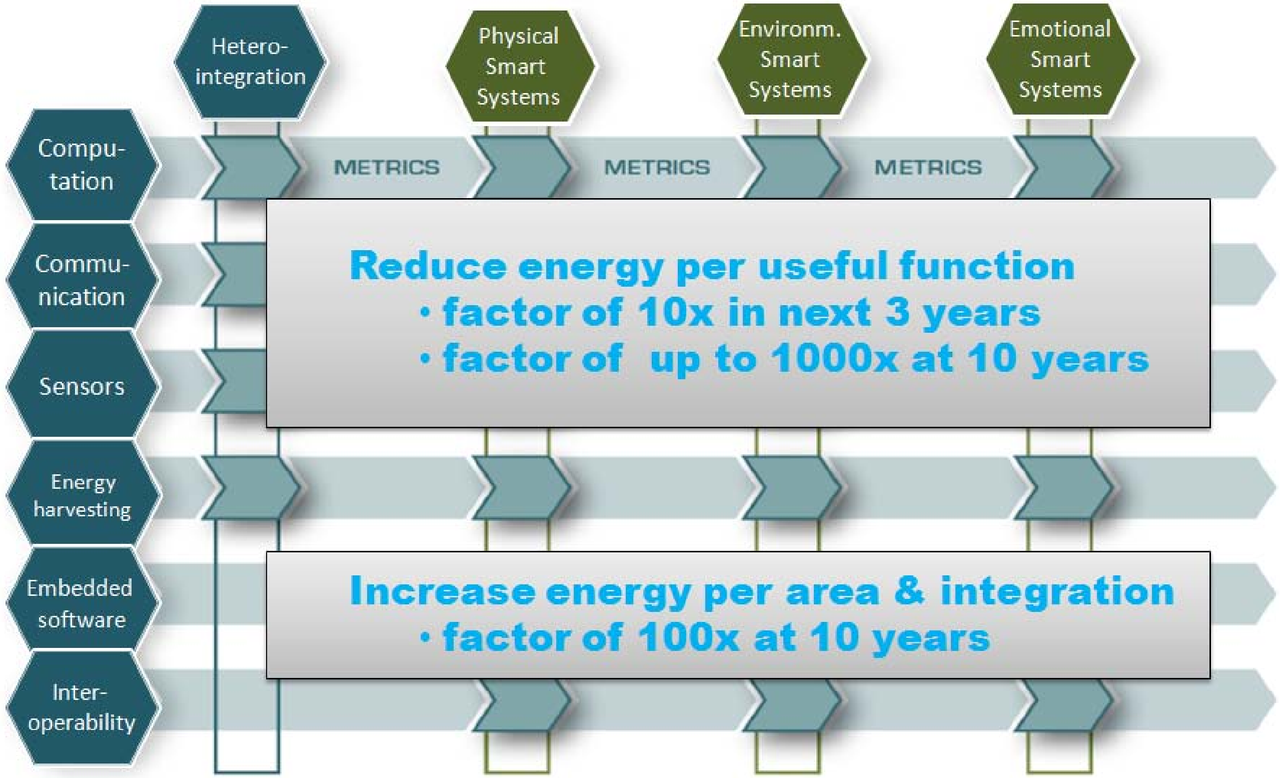
- Present:
  - Infotainment
- Future:
  - Social
  - Health
  - Sports & Fitness

Worldwide health expenditure growing 7% annually (7.3TUSD in 2012)

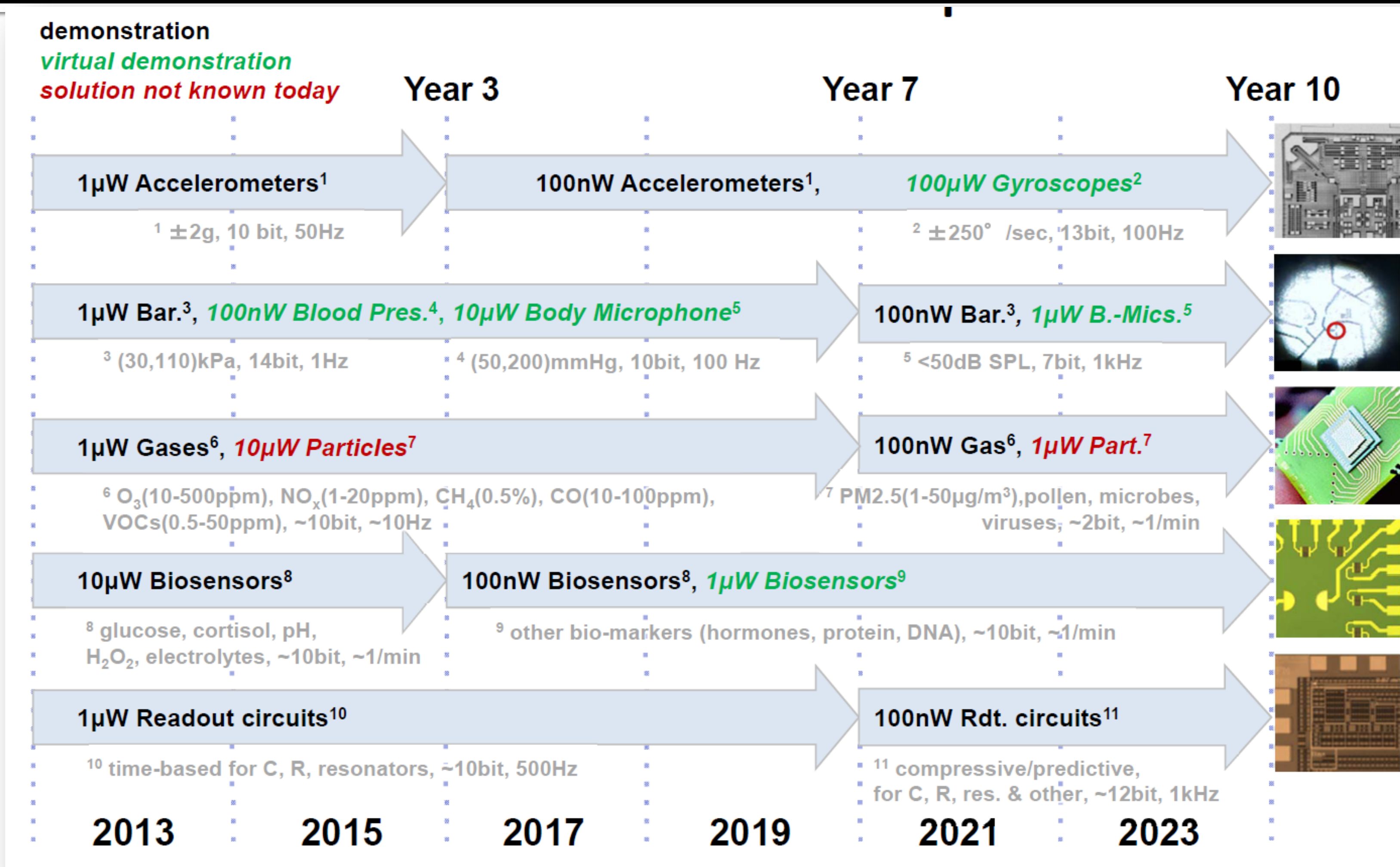


Key enabling technologies

1. Low power multi-parameter sensing
2. Low power communications
3. Energy scavenging and storage
4. Heterogeneous integration: on-foil (flexible substrates) and 3D



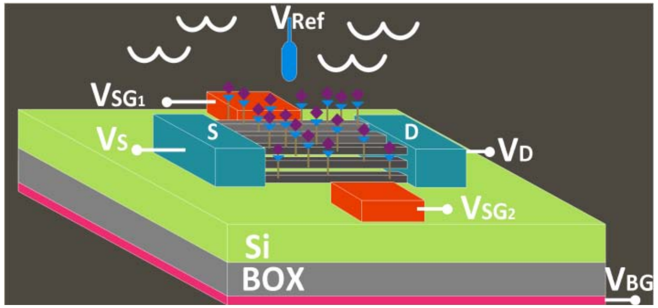
Low power sensor roadmap

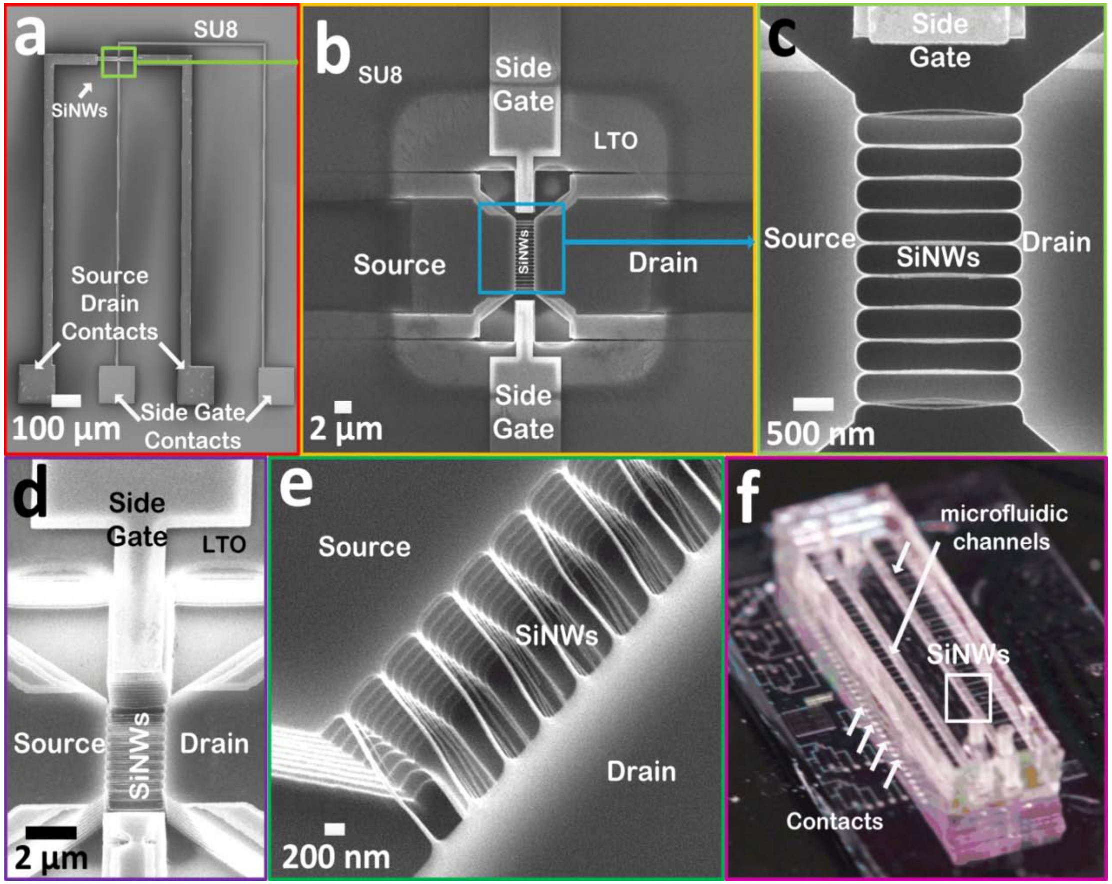


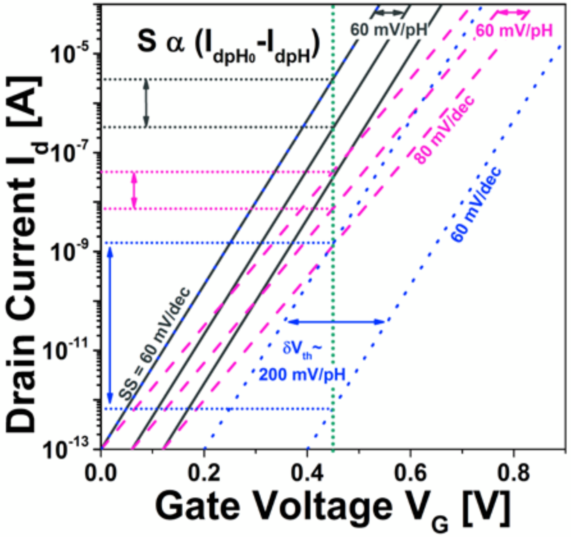
Source: Guardian Angels Flagship, C. Hierold.

Integrated nanowire array biosensors

- 3D stacked silicon nanowire pH sensor
- Low voltage (sub-1V), low power



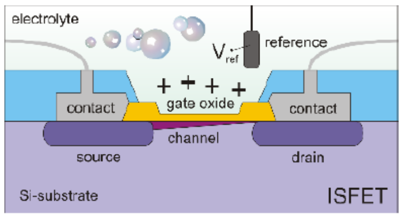


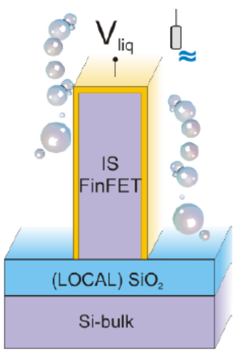


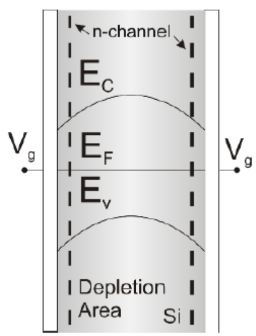
E. Buitrago et al, VLSI-TRI 2014.

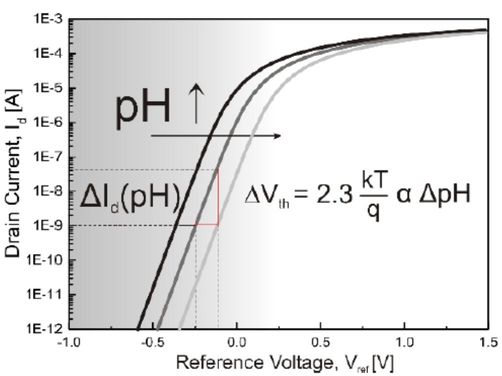
Sensing with computing technology

- Liquid-gate FinFET
- High-k: important for sensitivity and stability

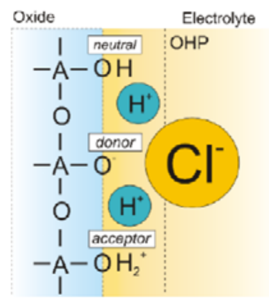








$$V_{th} = E_{ref} - \Psi + \chi^{sol} - \frac{\Phi_{Si}}{q} - \frac{Q_D}{C_{ox}} + 2\phi_f$$



$$|\Delta\Psi(pH)| = \alpha \cdot 59 mV/pH$$

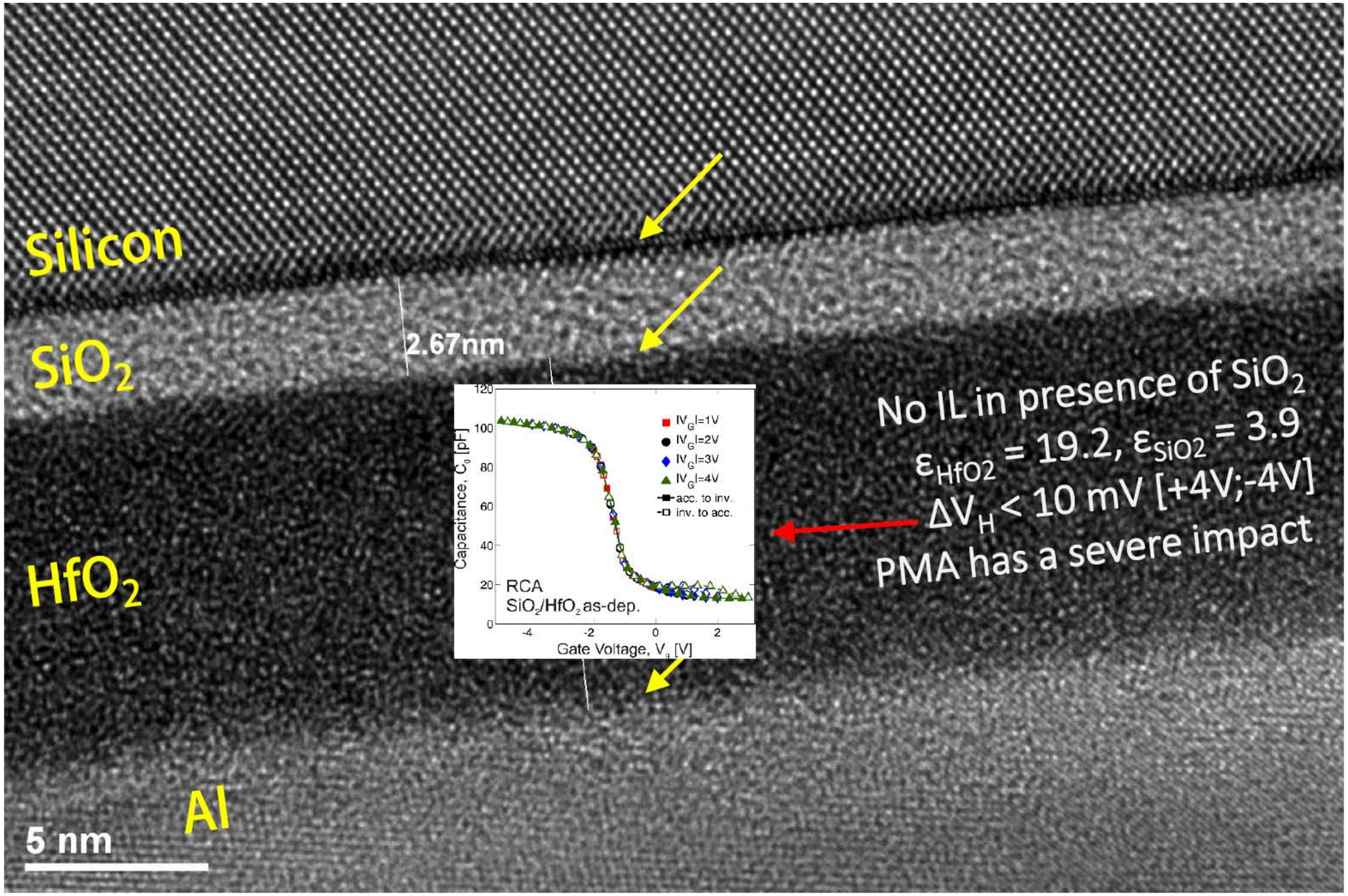
$$\alpha = \frac{\beta}{\beta + 1}$$

$$\beta = \frac{2q^2 N_S (K_a K_b)^{1/2}}{kTC_{DL}}$$

- Only oxides with **high N_S** can provide $\Delta V_{th} \sim 59$ mV/pH

Oxide	K	ΔV_{th} [mV/pH]
SiO_2	3.9	35-41 [38–40]
Si_3N_4	7	46-55 [40, 41]
Al_2O_3	9	52-58 [19, 36, 40]
Ta_2O_5	22	56-58 [24, 42]
HfO_2	25	57 -59 [43]

Hysteresis-free FinFET biosensor



No IL in presence of SiO_2

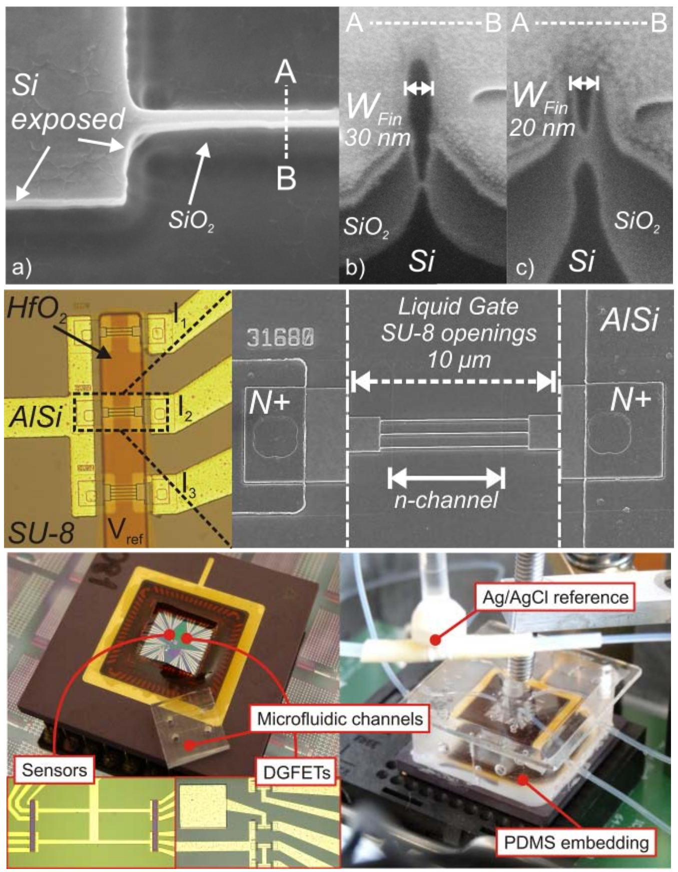
$\varepsilon_{HfO2} = 19.2$, $\varepsilon_{SiO2} = 3.9$

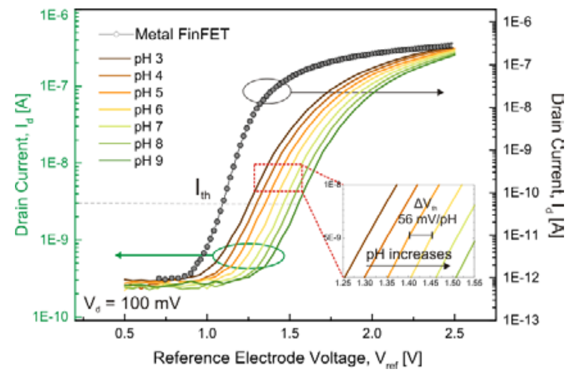
$\Delta V_H < 10$ mV [+4V;-4V]

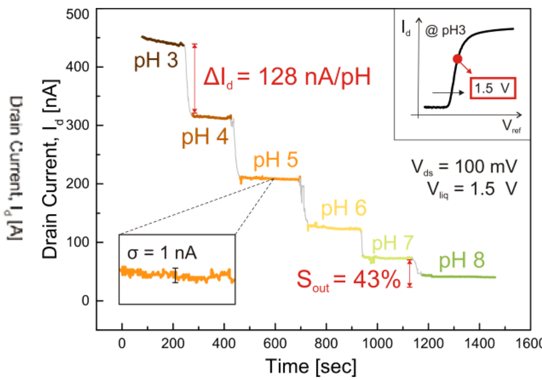
PMA has a severe impact

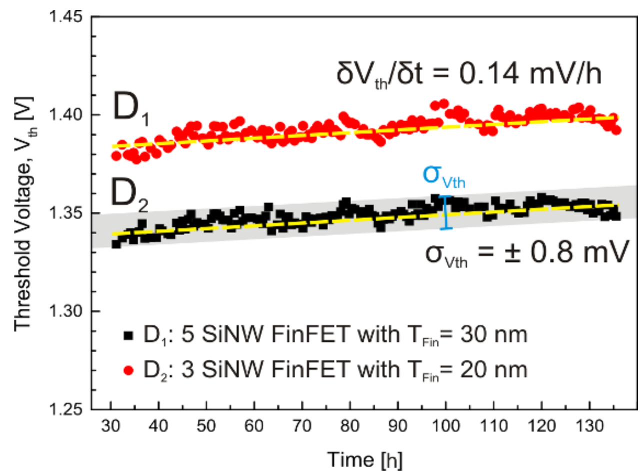
FinFET bio-sensors

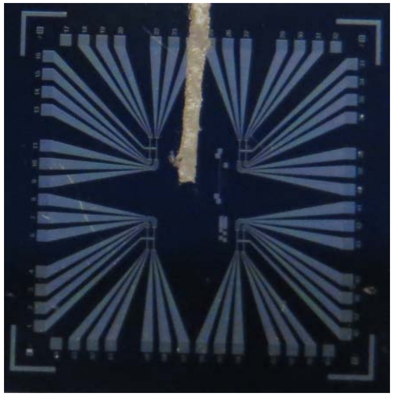
- Full-scale pH and protein low power sensors
- Intel processor-like technology: convergence







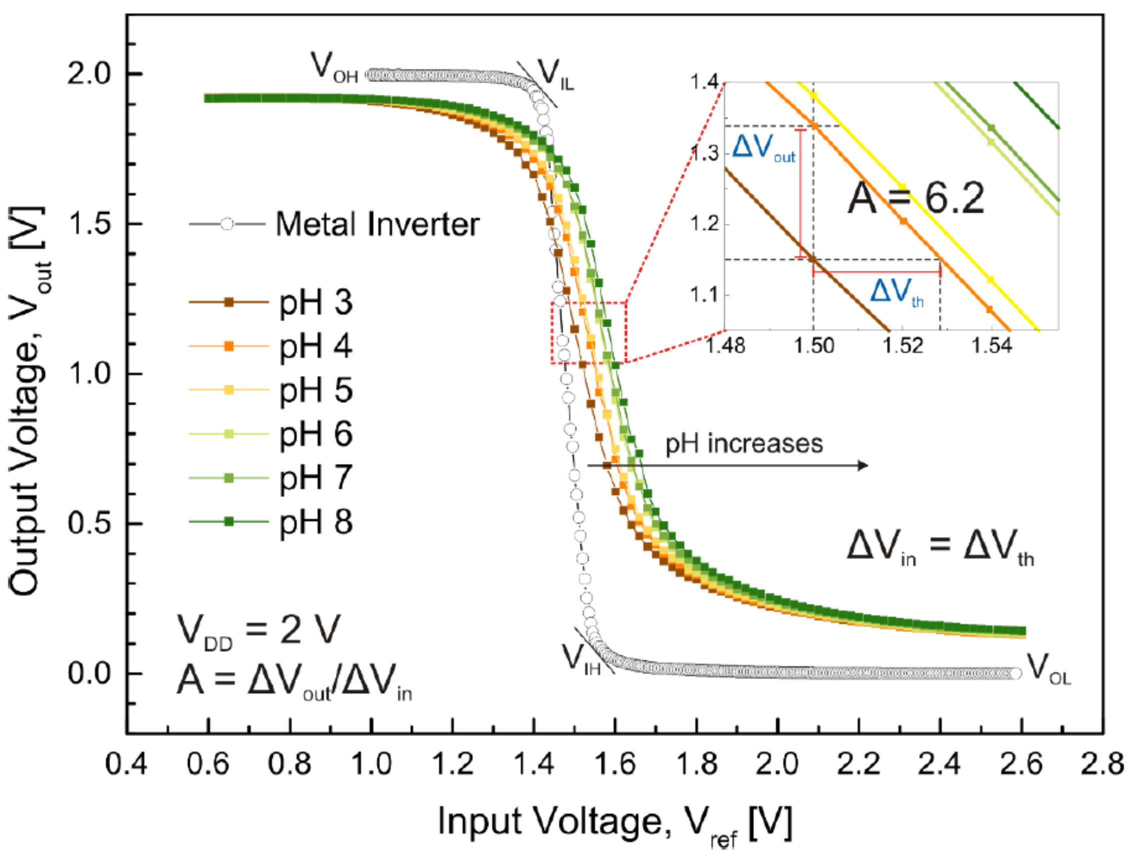




Smart patch die

S. Rigate et al, MEMS 2014.

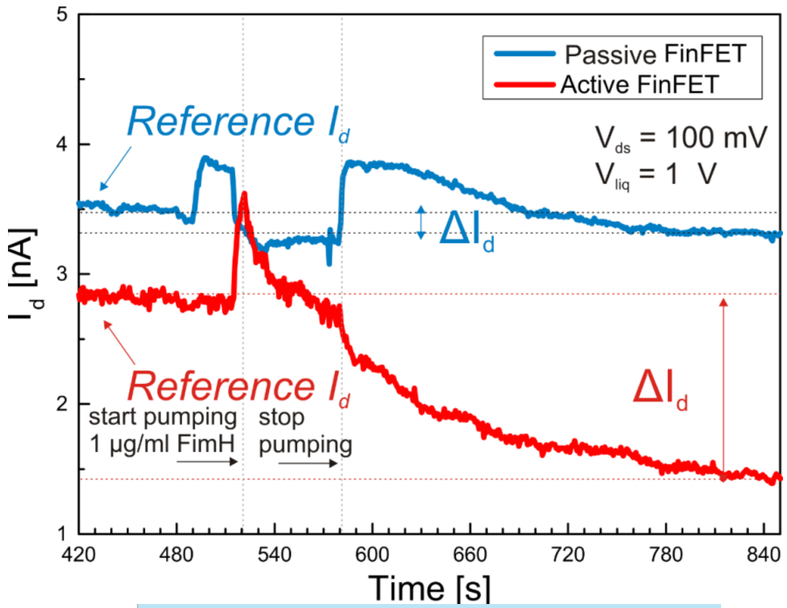
FinFET inverter sesnor

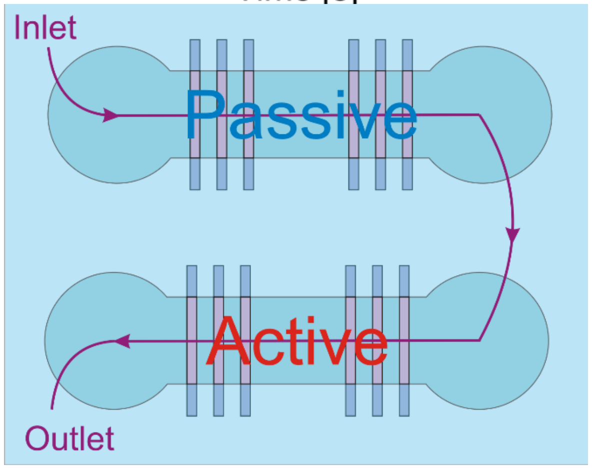


	FinFETs-based Amplifier		
pH	ΔV_{in}[mV]	ΔV_{out}[mV]	**A = $\Delta V_{in}/\Delta V_{out}$**
3-4	30	185	**6.2**
4-5	6	40	**6.6**
5-6	27	174	**6.5**
6-7	5	31	**6.2**
7-8	16	102	**6.4**
	≈ 17 mV/pH	**≈ 107 mV/pH**	**≈ 6.4**

FimH protein sensing

- FimH detection: early detection of FimH-expressing E. coli : antiadhesive treatment
- Functionalization(Uni Basel): APDMES silanization+ amine-reactive esters
- HEPES buffer solution at pH = 8

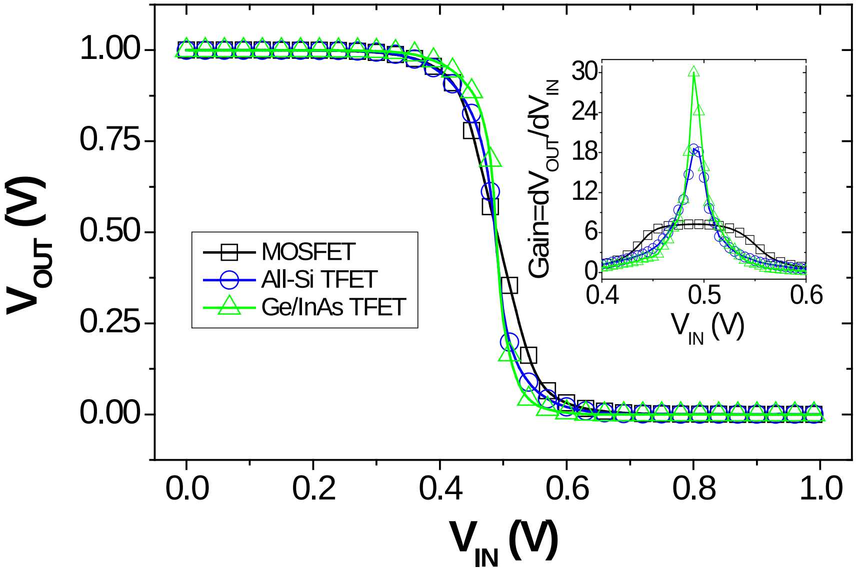


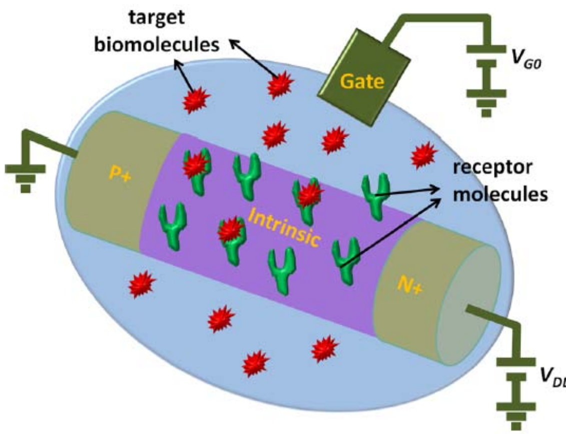


Towards Tunnel FET biosesnors

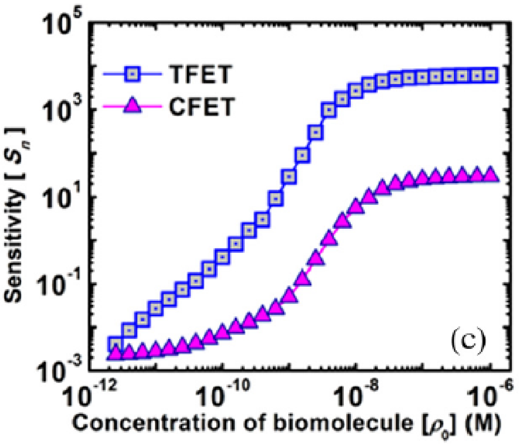
C-Tunnel FET versus CMOS INVERTER-SENSOR:

- Lower voltage, more gain
- Better noise margins
- Speed not a limitation

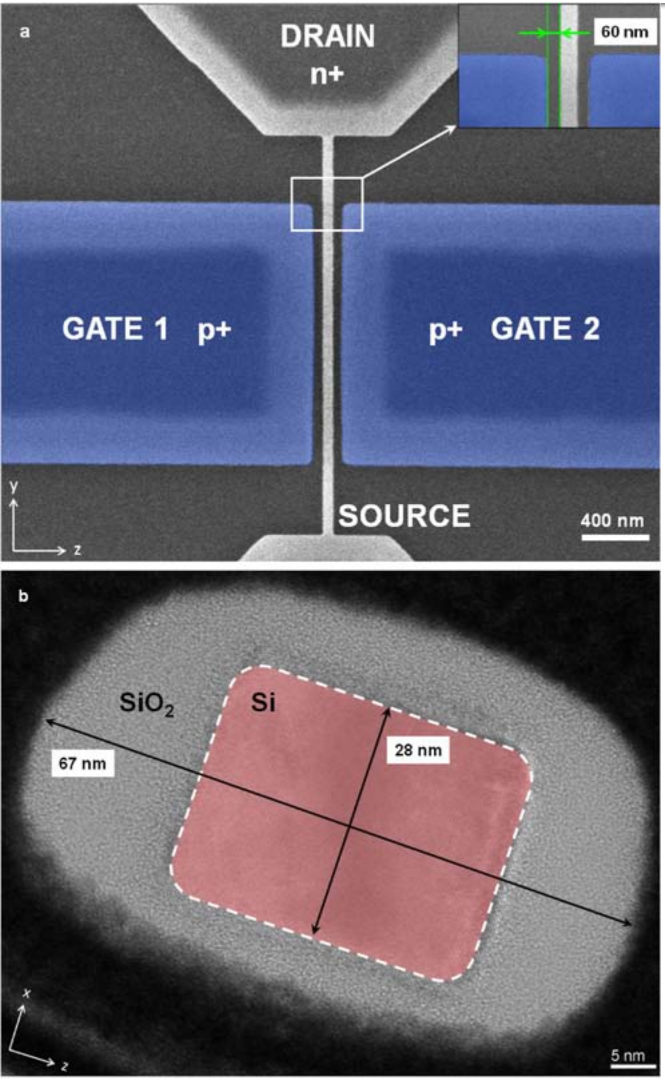




Improved sensitivity of TFET compared to CFET:



Active Integrated Nano-Electro-Mechanical Balance

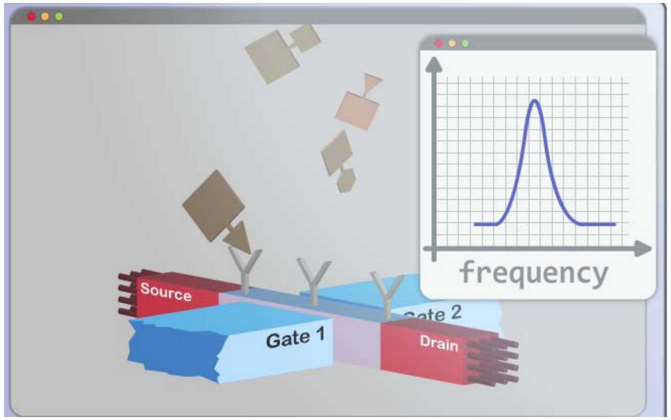


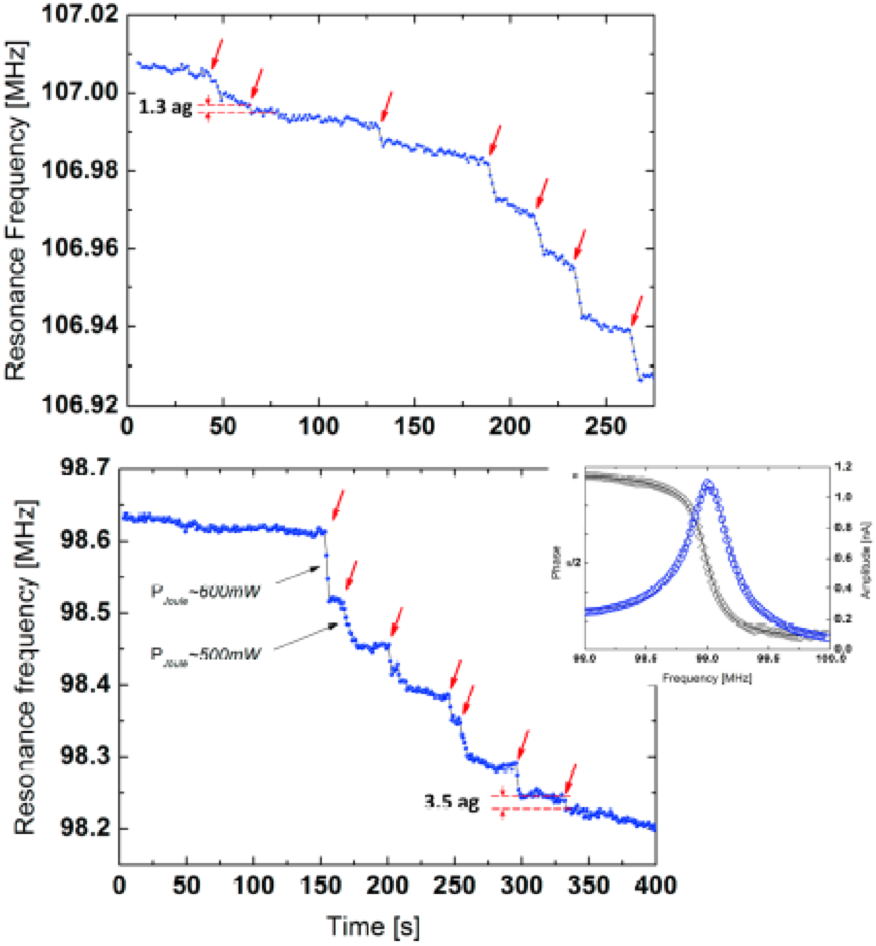
A transistor in a guitar string

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}}$$

- Bartsch, S.T. Dupre, C. Ollier, E. Ionescu, A.M. Device Research Conference (DRC), 2012
- Bartsch, S.T. , A.M. Ionescu, IEEE JEDS 2014.

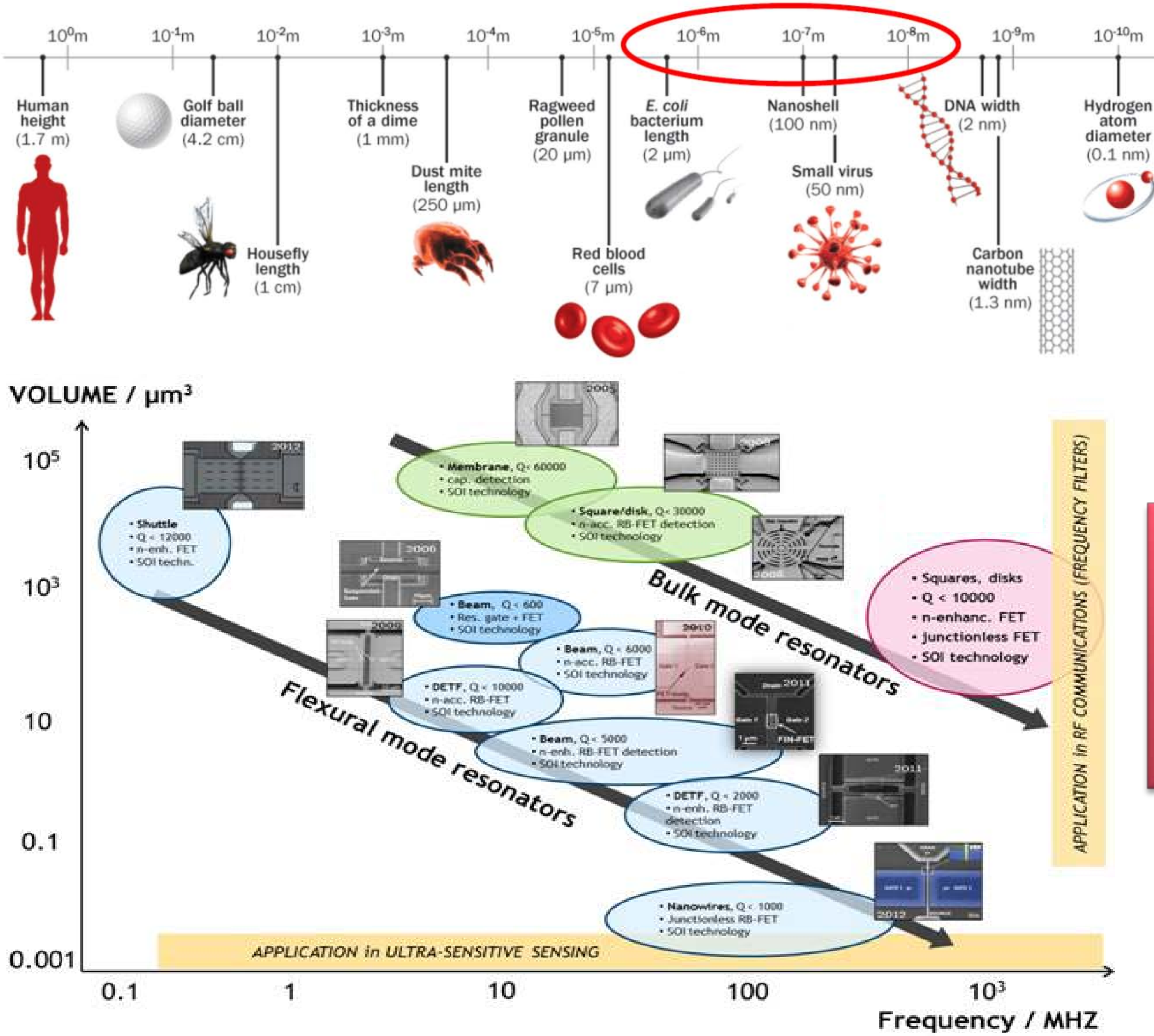
200MHz junctionless FET mass balance





- Mass accretion of 1.3 ag (top) detected: corresponds to approx. 4000 gold atoms
- Scalable to detect ~10 atoms
- Applications:
    - biomarkers for early cancer detection
    - integrated gas sensors
    - integrated particle sensors

Resonant nano-electro-mechanical transistors: roadmap

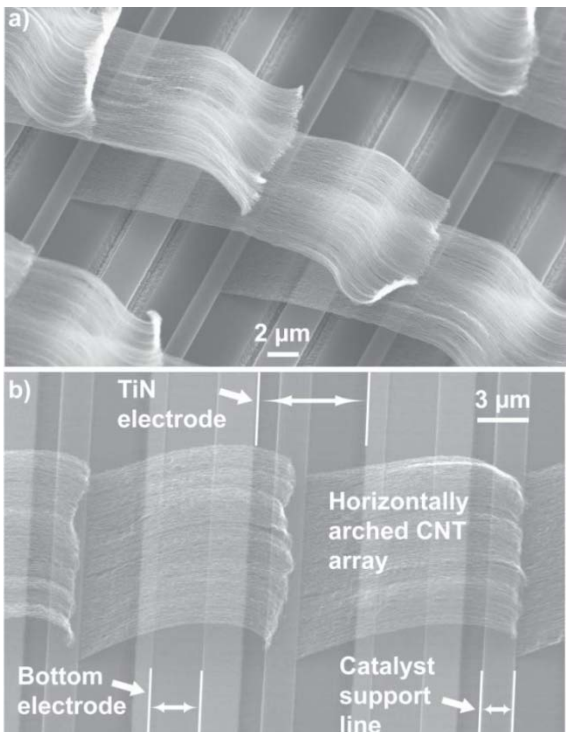


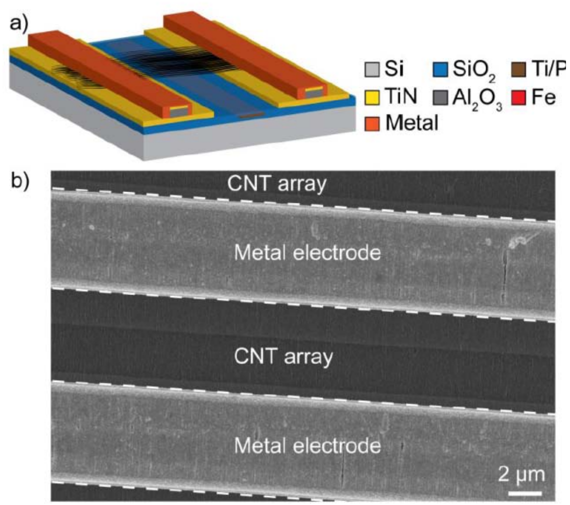
Sensors:

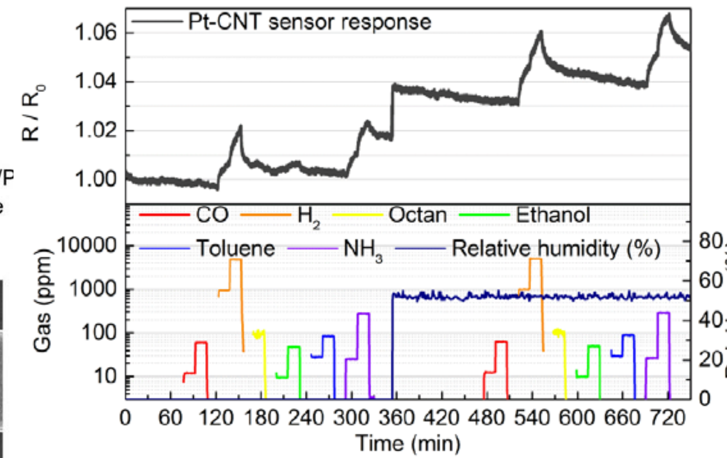
- Gas
- Particle
- Bacteria
- Viruses

Carbon Nanotube (CNT) gas sensors for air quality

- High-yield, in-situ integration of Horizontal CNT Arrays
- Selectivity strategies: chemoresistors, chemocapacitors, # contact metals.

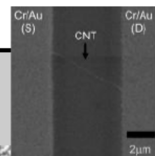
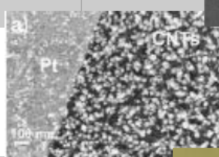
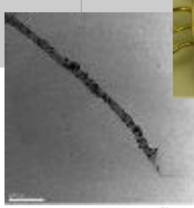
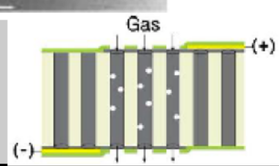






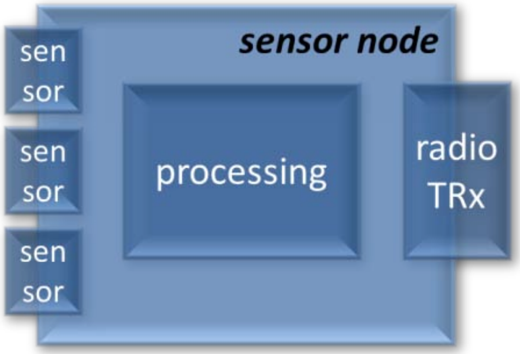
Sensor metal	Gases				
	H_2	Ethanol	Toluene	NH_3	H_2O
Pt	+	+	0	+	+
Pd	+	0	0	+	+
Au	0	0	-	+	0

CNT sensor performance

Targeted Analyte	TLV or regulations	Sensor Picture	Best LoD reported for bare CNT, resistive sensor.		Nanolab CNT sensors	Literature ultimate LoD
Ethanol	200 ppm		300 ppm	Someya et al.	**10 ppm**	1.3 ppm*
NO_2	3 ppm		10 ppb	Valentini, santucci et al.	**50 ppb**	100 ppt
H_2	4 %		N/A		**0.1 %**	~10 ppm
Toluene	50 ppm		500 ppm	Sayago et al.	**5 ppm**	1.2 ppm*
NH_3	25 ppm		5 ppm	Quang et al. Jung et al.	**1 ppm**	100 ppb

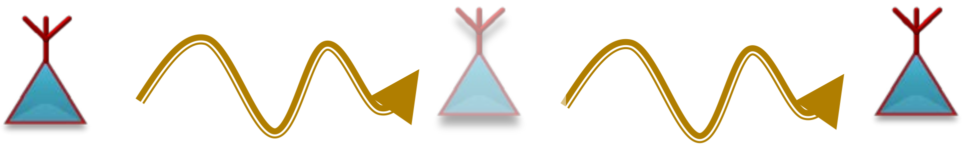
H. Guerin, PhD thesis 2014, EPFL.

Challenges for wireless technologies



Mitigation by distribution of the 1000x factor:

- system level techniques
- access technologies
- algorithmic, protocol level techniques
- radio front-end innovations
- enabling device & fabrication technologies

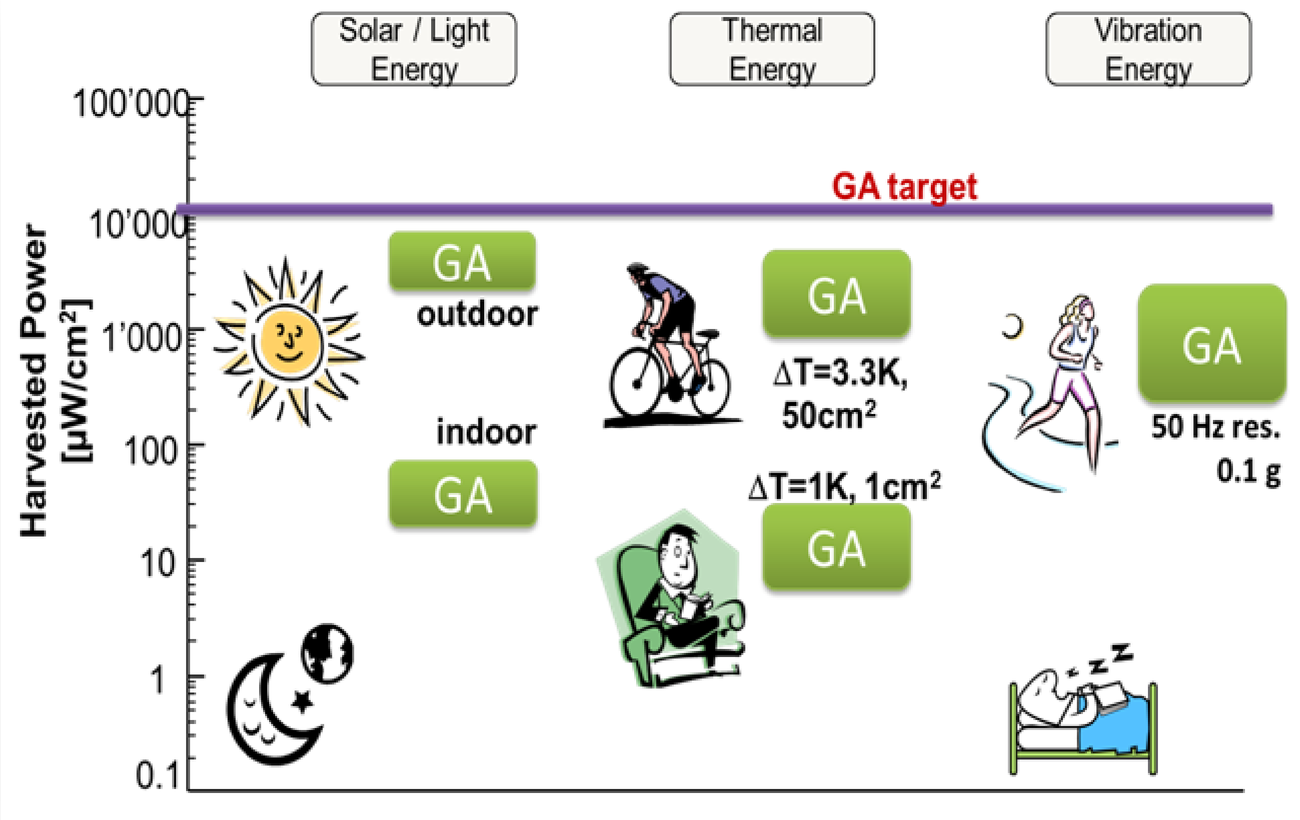


Energy / useful bit = 10 pJ @ 2m which is 1000x less than SoA

(1) transmit energy + (2) transmitted energy + (3) receive energy

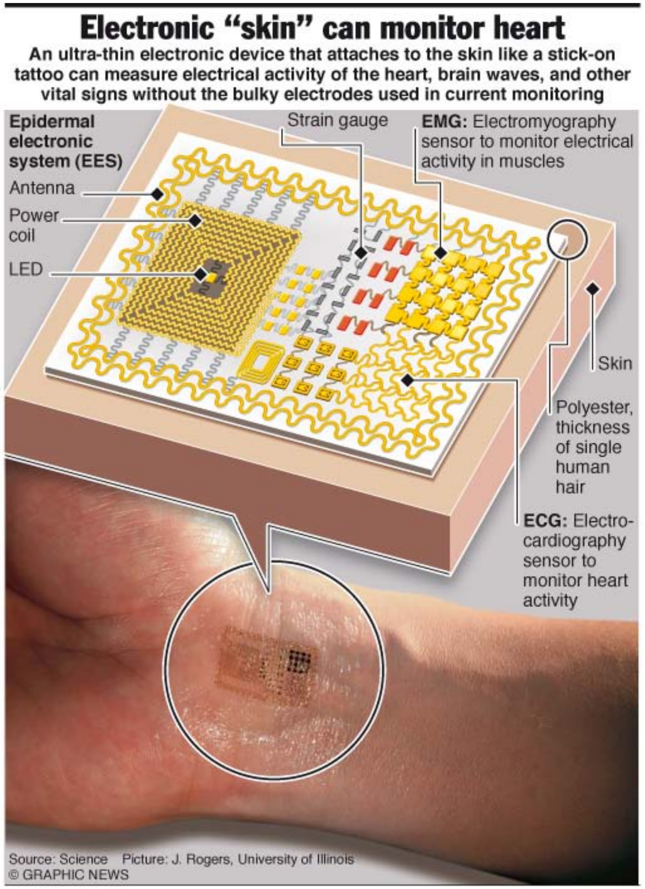
Energy harvesting

- Dynamic, real life, requirements
- Multiple harversting interfaces, storage, power management

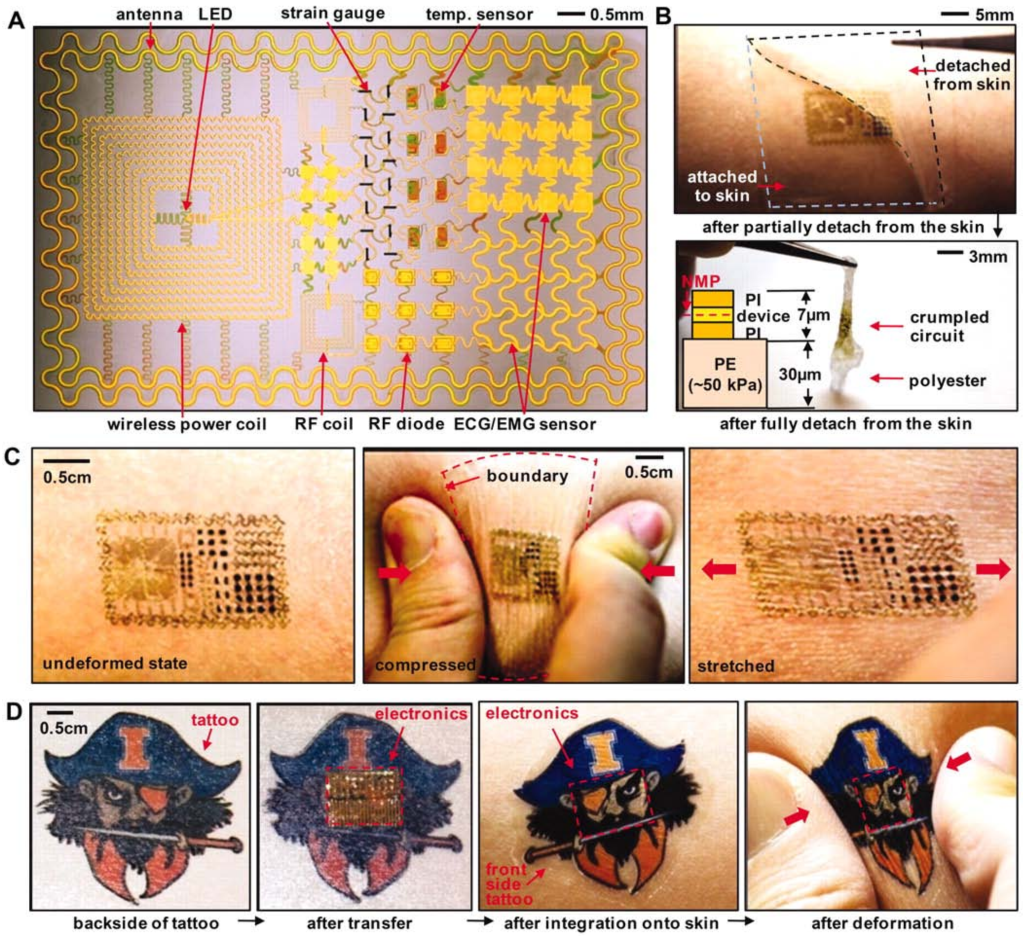


Epidermal electronics

- Future smart patches for healthcare



John A. Rogers, Science, 2011.



Conclusions

- Wearable Technology revolution has started
- Zero-Power technology enables combined healthcare and environmental autonomous monitoring:
  - Non-obtrusive, non-invasive, wearable
  - Wireless: one person = one multi-parametric physical and environmental dynamic node
  - Long-term monitoring
  - Capable to generate Big Data smartly structured for data mining
  - Included feedback channels: activity, nutrition, hydration, etc.
  - Prevention strategies