Wearable physical & physiological low-power sensors

D. Flandre, N. André, T. Delhaye, T. Walewyns, L. A. Francis

Université catholique de Louvain (UCL)
ICTEAM Institute, Electrical Eng. (ELEN)

Convergence WP1 partners :

G-INP, UCBM, IUNET, EPFL, GreenTeg

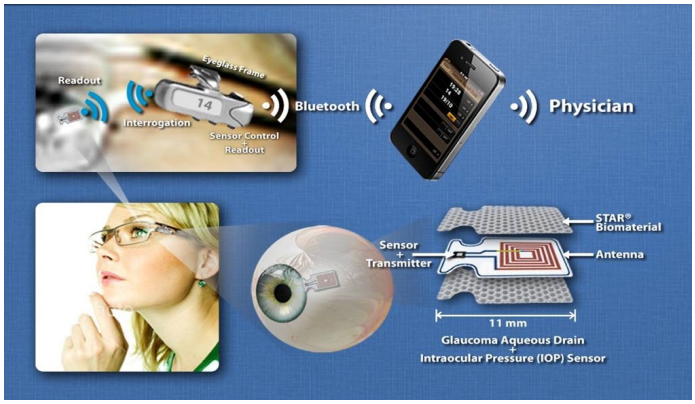
Developments in CONVERGENCE WP1

- Activity tracking
  - UCBM : ECG-like sensors based on 3 capacitive electrodes
  - IUNET : gait disorders with 3D accelerometer, magnetometer and gyroscope
  - UCL : Strain sensor for body deformations (muscle activity)
- Body temperature measurement
  - UCL : Ultra-thin sensor for skin temperature
  - EPFL / GreenTEG : 3 temp-sensor patches on skin and algorithm to derive core temperature (vs ingestable pill)
- Breath monitoring
  - G-INP and ams-UK : Gas chemiresistive sensors for disease
  - UCL : Breathing pattern with condensation sensor
- Sweat analysis :
  - ISFET nanosensors in EPFL and G-INP

Outline

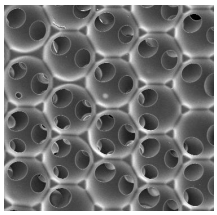
- Ultra-low-power sensing and circuit blocks
  - Starting case in UCL : implantable eye pressure system
  - Challenges, Innovative concepts, Specific technologies
- UCL Developments within CONVERGENCE
  - Strain sensor for body deformations
  - Ultra-thin sensor for skin temperature
  - Breathing pattern sensor
- Conclusions & Perspectives for WP1

1. Ultra-low-power sensing and circuit

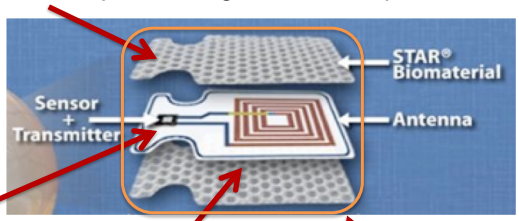


- Glaucoma management IOP microsystem that combines therapeutic and diagnostic benefits in one ophtalmologic implant for long-term monitoring
- Regional project with iStar, Rosselini and U. Liège

1.1 Challenges



STAR® Biomaterial :
'sweet-spot' precision-pore geometry
for anti-fibrotic, pro-healing, biomimetic performance !



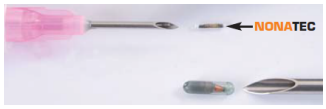
MEMS Pressure Sensor :
Highly-sensitive in 0 - 70 mmHg range
with 0.5 - 1 mmHg precision !

Wireless power / data transfer :
mm^3-inductive coupling => all circuit blocks ≈ 100 µW
for sensor read-out and communication distance of a few cm !

Prototype assembly and validation :
Biocompatible materials and packaging techniques !

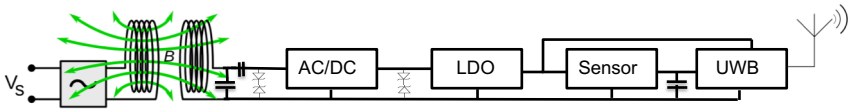
1.2 UCL concepts, technologies & blocks

Towards miniaturization :
Capsule < 8mm length x 1.2mm diameter



- **Inductive coupling @ 1 or 13.56 MHz using ferrite coil** (< 4mm long)
  - Vs. higher frequencies (900MHz – 5GHz for mm-size antennas) :
    - less absorption by body tissues
    - record coupling efficiency when multi-turn + ferrite core @ cm-distance
    - record ULP AC/DC rectifier power efficiency

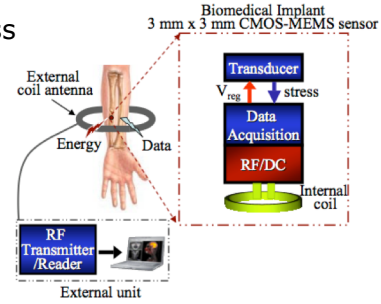
- **SOI technology** for single-chip solution, i.e. enabling monolithic integration of all system blocks in 4 x 1 x 0.5 mm^3 with highest performance
  - AC/DC rectifier and voltage regulation with CMOS ULP
  - MOSFET-based piezoresistive pressure sensor + oscillator interface
  - Ultra Wide Band pulse data transmission with on-chip antenna



2. Strain sensor: In-body applications

BioImplantable MEMS Array Bone Stress Sensor *[J. Fernando Alfaro, PhD Thesis, 2007]*

3 x 3 mm² Si chip
Measured strain (ΔL/L) ~ 1-100 ppm
For E_{bone} = 100 MPa



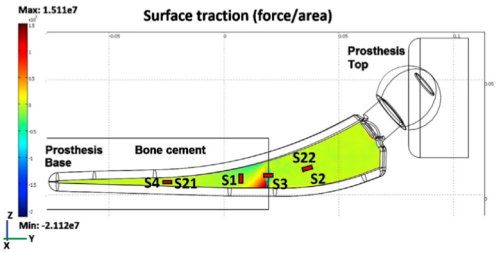


Fig. 1. Simulated stress distribution for the hip-joint prosthesis with solicitation along *y*. The horizontal rectangle indicates the placement of the cement.

Piezoresistive sensors for force mapping of hip-prostheses *[Correia et al, S&A-A, 2013]*

Si thin film piezoresistors with Gauge Factor ~ 28 (i.e. GF = ΔR/R / strain)

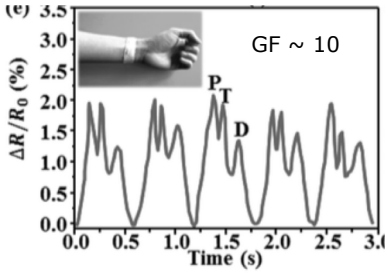
2. Strain sensor: On-Body applications

Many stretchable sensor on hands, limbs, knee…
for strain from 0.5% to >100% exceeding practical Si limits

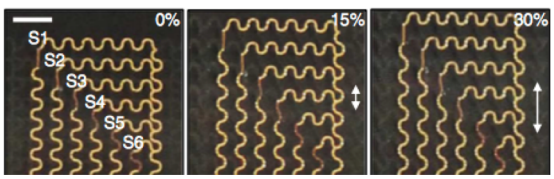
Silicon gauge Ok for subtle movements,
up to about 0.2% deformation…

Or embedded in polyimide sheets with stretchable electrodes

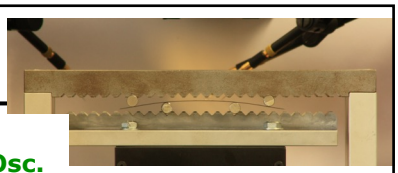
Carbonized Cotton Fabric for High-Performance Wearable Strain Sensors [Zhang et al, Adv. Funct. Mater. 2017]



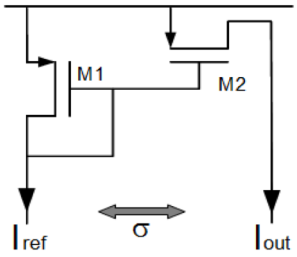
Stretchable Si nanoribbon electronics for skin prosthesis [Kim et al, Nature Com. 2014]
…with GF ~ 200



2.1 CMOS strain sensor



UCL : PMOS Mirror as Current Source of on-chip Current Controlled CMOS Ring Osc.

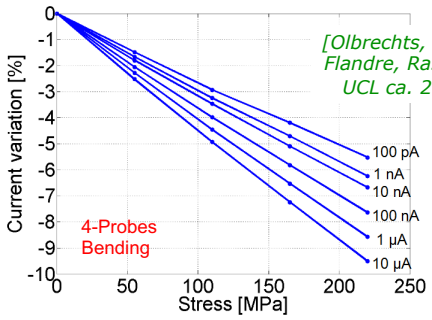


$$I_{out} \cong \left[1+\left(\pi_{PMOS\perp}-\pi_{PMOS//}\right)\cdot\left(\sigma_{xx}-\sigma_{yy}\right)\right]\cdot I_{ref}$$

with $\sigma = E_{Si}.\varepsilon$

- 5 % / 100 MPa

+ 5 % / 100 MPa



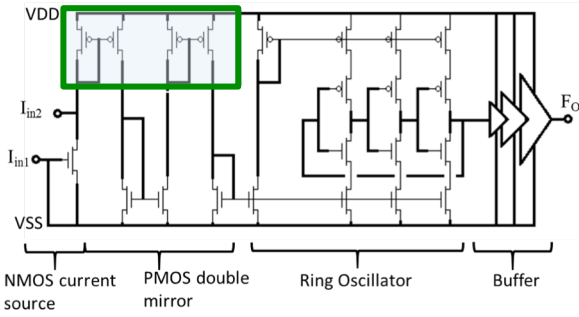
[Olbrechts, Rue, Flandre, Raskin, UCL ca. 2010]

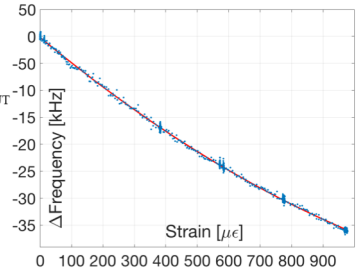
Much lower power consumption (here < 10µA @ 1.6 V) than piezoresistive gauges (typ. mA @ several V)

Much easier read-out circuit (no amplifier or ADC as for std piezo or capacitive sensors)

2.2 CMOS strain sensor circuit

Membrane for pressure sensors or Full chip thinning for strain





[Al Kadi Jazairli et al., IRSP 2016]

Vdd = 1.2 - 1.6 V

≈ 10-100 µW power consumption (90% in output buffer)

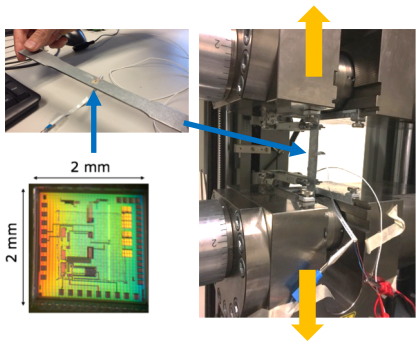
Freq. Output :

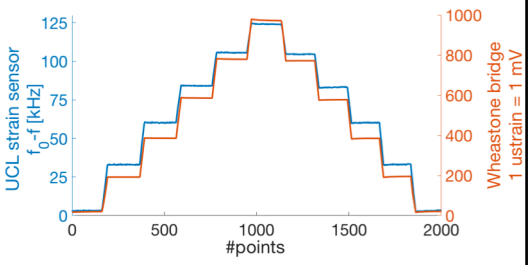
2.5 – 300 kHz

- ✓ high gauge factor: 400
- ✓ sensitivity: 300 ppm/µε
- ✓ precision: 5 µε

2.3 CMOS strain sensor circuit demos

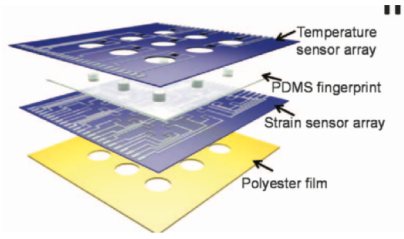
- Dogbone test sample on Zwick traction machine
- Reference: std metallic strain gauge on kapton (GF = 2)
- Chip – glued with Epo-tek P1011S

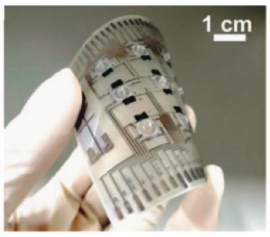




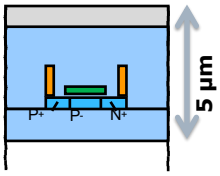
3. Ultra-thin temperature sensor

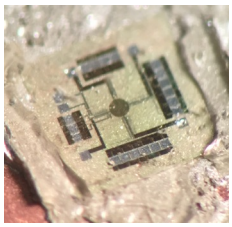
Artificial e-skin sensor arrays *[Harada et at, ACS Nano 2014]*





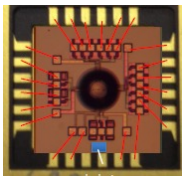
UCL concept :
- **SOI lateral thermodiode**
  (Accurate, Low power)
- **Thinned down to a few µm by XeF_2**
  (Fast, CMOS compatible, Highest Si:SiO_2 selectivity, Moderate cost)



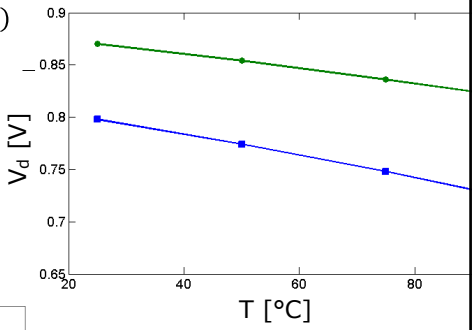


3.1 SOI thermodiode characterization

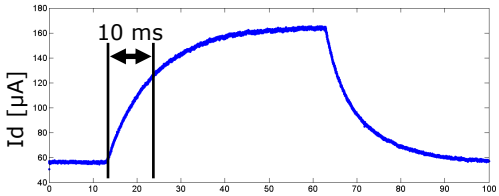
- Constant current mode, embedded microheater



$$V_d = V_0 - d(T - T_0)$$
$$d = \frac{V_0 - V_d}{T - T_0} \approx 1\ mV/K$$



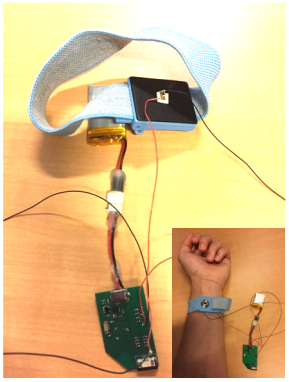
- Constant voltage, Pulsed mode

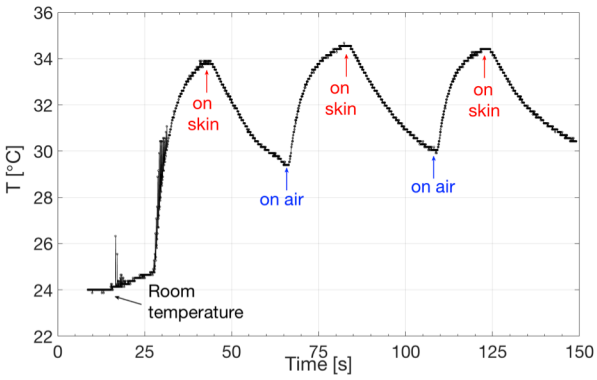


Low thermal mass,
Intrinsically fast

3.2 SOI thermodiode demonstration

With CEA-LETI platform

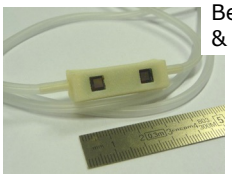




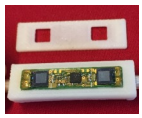
Data each 50 ms
Diode of 20 x 20 µm²
on 2 x 2 x 0.4 mm³ chip

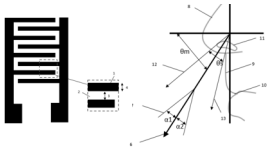
4. Breathing pattern sensor

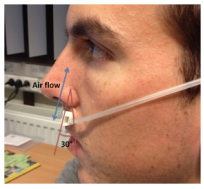
UCL Concept : Measurement of **condensation during exhalation** and **forced drying during inhalation** through capacitive detection based on **interdigitated microelectrodes**



Below nose : One sensor per nostril // airflow & read-out interface IC

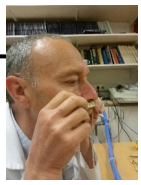




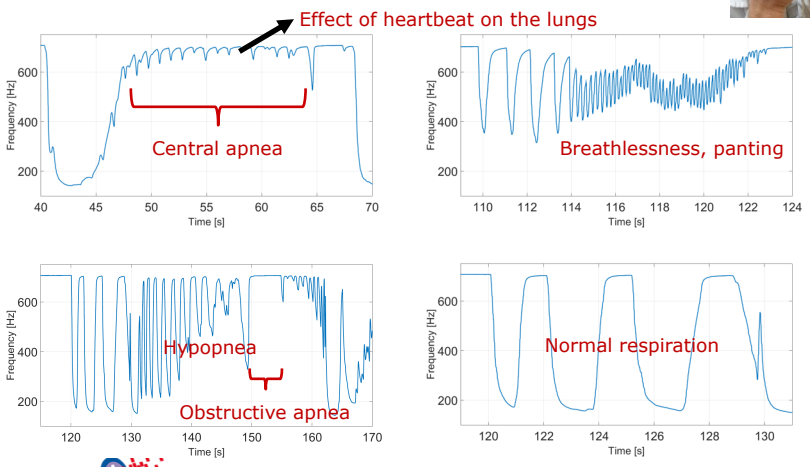


Principle	Power	Footprint	Range	Precision	Readout	Maturity	Apps
Condensation between interdigitated µelectrodes	<200 µW with readout	5x5x0.5 mm³ (unpackaged die) 35x10x12 mm³ (housing)	2000 pF (readout dynamic range)	0.1%, up to 1 kHz sampling (readout)	Constant DC charge current scheme	TRL6-7, prototypes validation (ongoing)	Breath pattern monitoring (respiratory envelope)

4.1 Breathing pattern tests

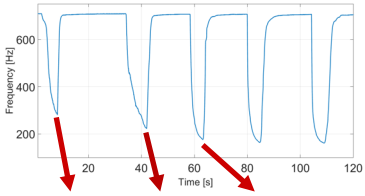


Reproduction of dyspnea phenomena by Prof. Liistro, UCL Saint-Luc Hospital, Belgium



4.2 Breathing volume tests

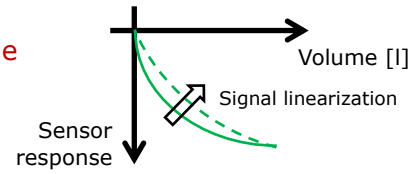
Test with artificial breath simulator setup based on a 3 liters syringe and nozzles







~ 1 l ~ 2 l ~ 3 l volume



Ongoing development:
Microheater implementation to control the condensation

⇨ New applications in spirometry, COPD diagnosis, etc. through respiration amplitude recovering

Conclusions

Liu Y et al, "Flexible, Stretchable Sensors for Wearable Health Monitoring: Sensing Mechanisms, Materials, Fabrication Strategies and Features", Sensors 2018, 18, 645

Table 1. Detectable indicators in health monitoring.

WP1

Indicator	Position	Measured Parameter	Possible Application
Motion	Hand	Strain, Pressure	Rehabilitation, gesture identification
	Limb	Strain	Rehabilitation, sport training
	Foot	Pressure	Gait detection, sport training
	Throat	Strain	Phonation and deglutition detection
	Face	Strain	Expression identification
Skintemperature	The whole	Temperature	Wound healing, physiological status, Clinical diagnosis
Heart rate/ECG/pulse	Chest, wrist, neck, finger tip	Strain	Detection of Heart failure and cardiovascular disease
Respiration	Chest Nostrils	Strain Pressure, Humidity	Detection of cardiac arrest, apnea, emotional control
Metabolism	Sweating area, oral cavity, eyes	Constituent of biofluids	Evaluating the body status by the appearance & concentration of lactic acid, alcohol, electrolytes, pH

Perspectives : Convergence scenarios

		Ready for integration on flexible demonstrator	Longer term integration
Active life scenario	Electrocardiogram	UCBM: ECG with wireless communication (size: 20cm² and power consumption: 0.01W). Available by July 2018.	-
	Muscle activity	UCL: strain gauge integrated with readout and buffer which can be glued on a flexible foil.	-
	Motion tracking	EDI: outsourced motion tracking devices already integrated in Demo#1.	-
	Sweat analysis	EPFL: ISFET based measurement of pH and K^+, Na^+ ion concentration in sweat with microfluidics and low power readout. Available by February 2019.	GINP: Si nanonet-based sensors for hormone and protein detection in sweat, very first integrated devices expected in January 2019 but adaptation to aptamer-based detection will still have to be validated.
	Breath analysis	UCL: detection of water condensates which gives e. g. information on breathing frequency. Available: small rigid device to be located below the nostrils, wired to the communication box (presently zigbee communication with computer which can be connected to a platform via Bluetooth).	GINP: detection of acetone in breath using ZnO nanonets based chemiresistors integrated on micro-hot plates. Could be used to detect the transition between sugar consumption to fat consumption during intense activity.
	Skin temperature	UCL: temperature measurement available. Could be integrated on a flexible foil. The same readout as the one developed for WP2 should be used.	-
	Core body temperature	EPFL/GreenTEG: sensor ready using algorithm to correct measurement from environmental temperature variation. Can be located on forehead, chest or upper arm. Algorithm can be adapted by GreenTEG for different locations.	-
Frailty scenario : additional specific sensors	Muscle activity	IUNET: involuntary interruptions of movement such as motion freezing in Parkinson's disease, full device with sensor, readout, data analysis available.	IUNET (not reported because not mature enough): surface electromyography for the detection of very small voluntary or involuntary muscle activities.
	Breath analysis	-	GINP: detection of acetone in breath using ZnO nanonets based chemiresistors integrated on micro hot plates. Could be used for diabetes monitoring.

Sensor readiness for integration

	Principle	Power	Minimal Footprint	Sensitivity	Precision	Readout	Maturity
Pressure sensor	pMOSFET strain gauges embedded on a membrane	~10 µW (7 µA @ 1.6 V) for transducer only ~100 µW with off-chip read-out buffer	2x1x0.3 mm^3 for unpackaged die (4 pins required)	700 ppm/mbar	2 mbars	Ring oscillator + CMOS buffer (*)	TRL4, proof-of-concept lab
Strain sensor	pMOSFET strain gauges	60 - 120 µW with off-chip read-out buffer	1x1x0.005 mm^3 for unpackaged die (4 pins required)	300 ppm/µε	5 µε	Ring oscillator + CMOS buffer (*)	TRL5, certified lab tests
Tempera-ture sensor	Ultra-thin SOI thermodiode	60 µW	0.1x0.3x0.005 mm^3 for unpackaged die (2 pins required)	1-2 mV/°C @ const. I	0.5°C without averaging	Voltage divider + ADC	TRL 6, tested in relevant environment
Breathing sensor	Condensation between interdigitated µelectrodes	< 200 µW with readout	5x5x0.15 mm^3 (unpackaged die) 35x10x12 mm^3 (housing)	2000 pF (readout dynamic range)	0.1%, up to 1 kHz sampling (readout)	Constant DC charge current scheme (MPR121**)	TRL 7, field prototype validation (ongoing)

(*) frequency-dependent digital signal to be interfaced off-chip with µcontroller / ** see datasheet