

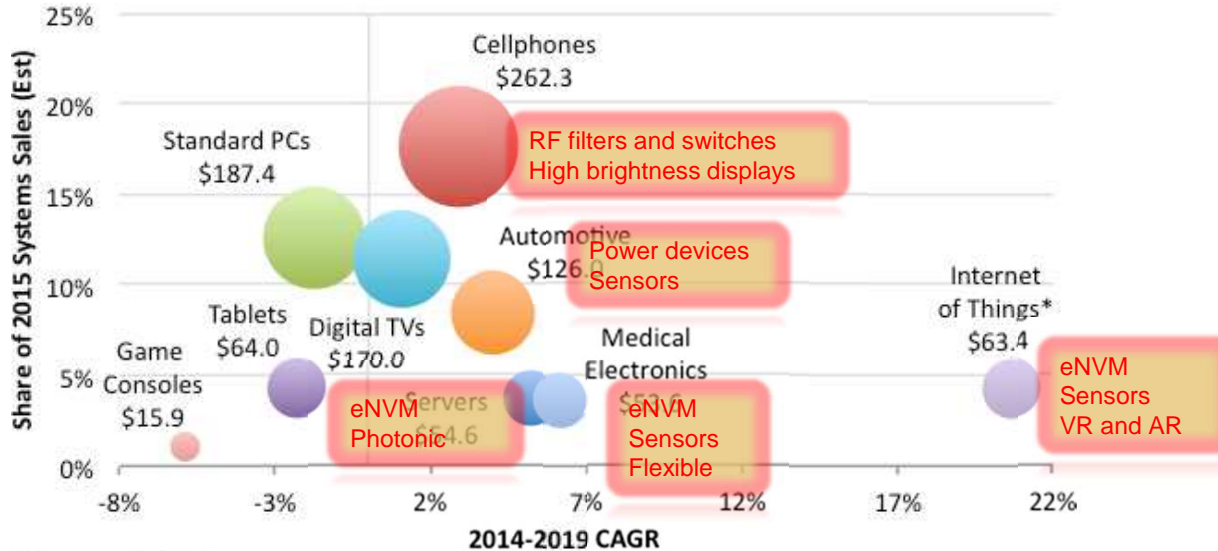


NEW SENSORS: EMERGING CONCEPTS AT NANOSCALE

Thomas Ernst

SENSORS ARE KEY IN GROWING MARKETS

End-Use Systems Markets (\$B) and Growth Rates



- IOT
- Medical
- Automotive
- Cellphones

*Covers only the Internet connection portion of systems

Source: IC Insights

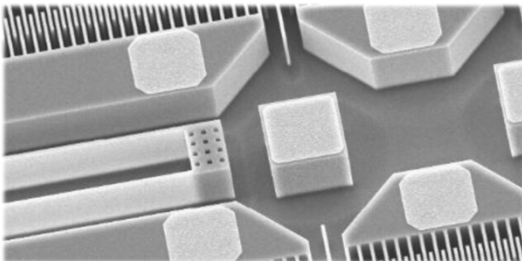
Global Sequencing Market by Product Type, 2014-2020 (\$Millions, Source: BCC Research)

Product Type	2014	2015	2020	CAGR% 2015-2020
Sequencing instruments, reagents & consumables	2,778.00	2,981.30	4,686.50	9.5
Sequencing services	2,527.20	2,869.80	9,122.50	26
Total	5,305.20	5,851.10	13,809.0	18.7

CEA-LETI THE LEADING MEMS & SENSORS R&D LAB WORKING FOR INDUSTRY



- 30+ years experience on MEMS
- 200+ people: **World's Largest MEMS R&D Institute**
- All 8" and 12" MEMS technologies in-house



- 330-patents portfolio in the MEMS / NEMS field



- 25 ongoing industrial collaborations
- 20+ industrial transfers
- 7 startups created

tronics

APIX
ANALOGICAL PIPETS

Wavelens

Primo1D
The 1-D Thermal Company

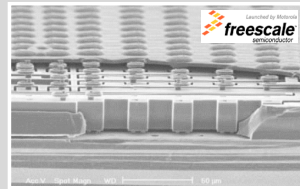
enerbee

elichens

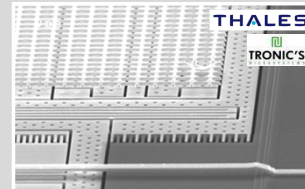
mir sense

SENSING BACKGROUND AT LETI

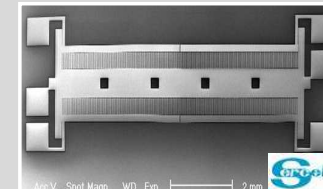
Inertial Sensors



3-axis Accelerometer



3-axis Gyroscope

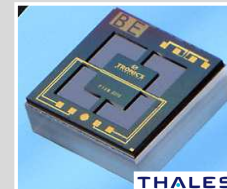


Geophone

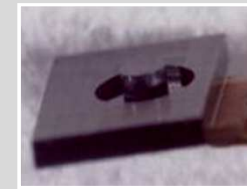
Pressure sensors



Capacitive pressure sensor

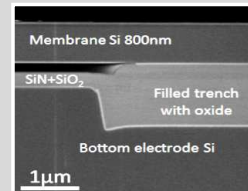


Piezoresistive pressure sensor



3-axis force sensor

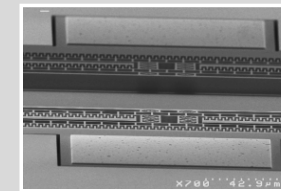
Acoustic sensors



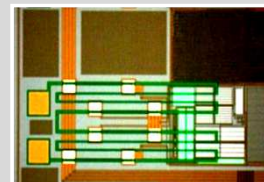
cMUT



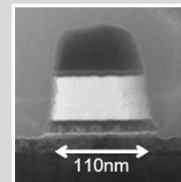
Microphone



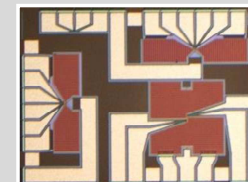
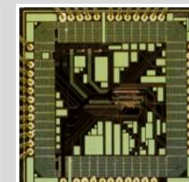
Magnetic sensors



Above-IC GMR sensor



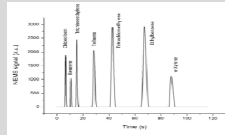
TMR sensor and resonator



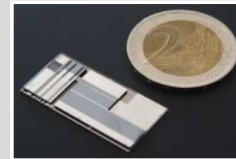
3-axis Compass

SENSING BACKGROUND AT LETI

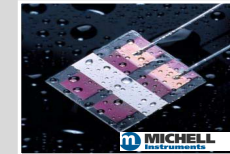
Gas sensors



NEMS-based + μ GC gas sensor

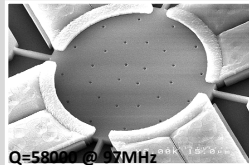


μ -TOF Mass-spec for NRBC

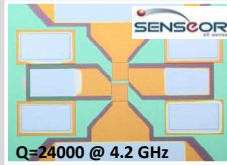


Humidity

RF-MEMS

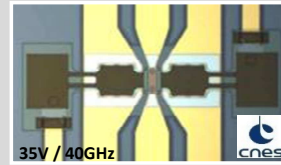


Q=58000 @ 57MHz



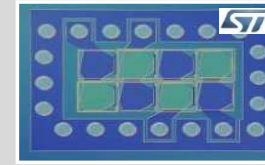
Q=24000 @ 4.2 GHz

High-Q resonators (Si and HBAR)



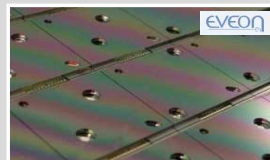
35V / 40GHz

Micro-switch

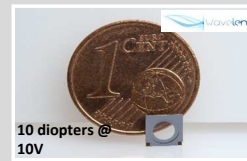


BAW filter

MEMS Actuators

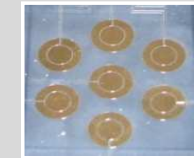


Micro-valves



10 diopters @ 10V

PZT-based Variable Lens



PZT ultrasonic transducers
(Digital-loudspeaker, pMUT)

Energy harvesting



200 μ W/cm³ @ 200 Hz

Piezoelectric AlN harvester



1cm³ / 10 μ W @ 20 Hz

Electret-based harvester



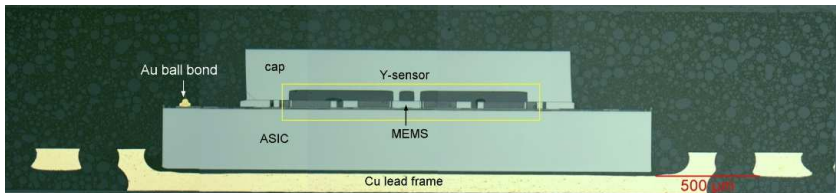
1cm² x 1mm
1mW @ 60rpm (1Hz)

Breakthrough concept

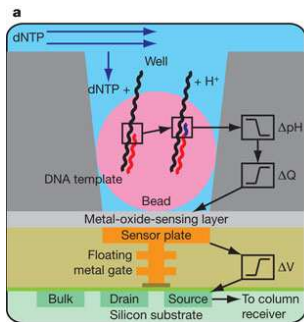
CEA- LETI : WORLDWIDE INDUSTRIAL MICROSYSTEMS PARTNERSHIPS



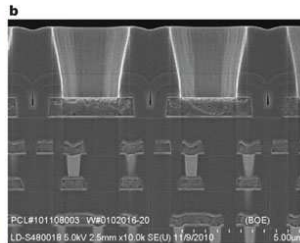
SENSING ON CHIP



InvenSense (source: Chipworks)



ThermoFisher
SCIENTIFIC

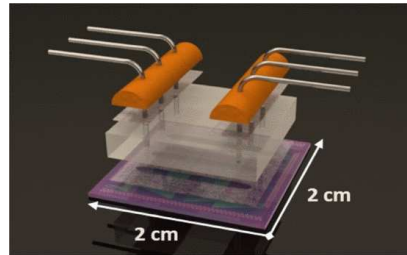
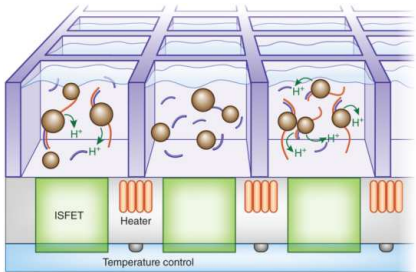


ION torrent
(Source: Nature)

- Best Signal/Noise ratio
- Reduced losses
- Reduced packaging cost
- Co-integration needed when thousands of sensors read independently

(DNA sequencing)

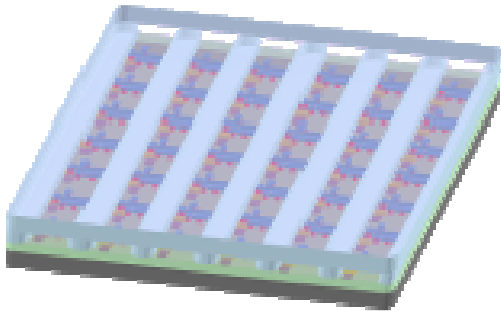
WHY NANO-SENSING ?



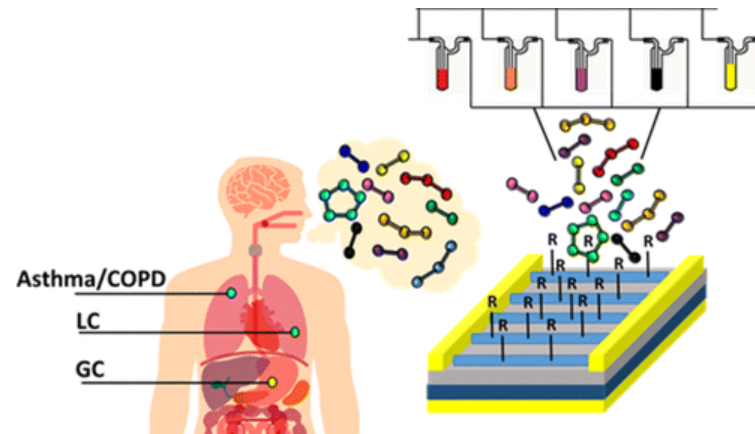
- Very high sensitivity (single molecules)
- Ultra-dense arrays of sensors
- Interactions with chemicals, light etc. at nanoscale.

DRUG Monitoring: Nature Method, Guiducci et al.
EPFL / LETI / Univ. Udine

Carmignani et al., VLSI TSA 2016 LETI



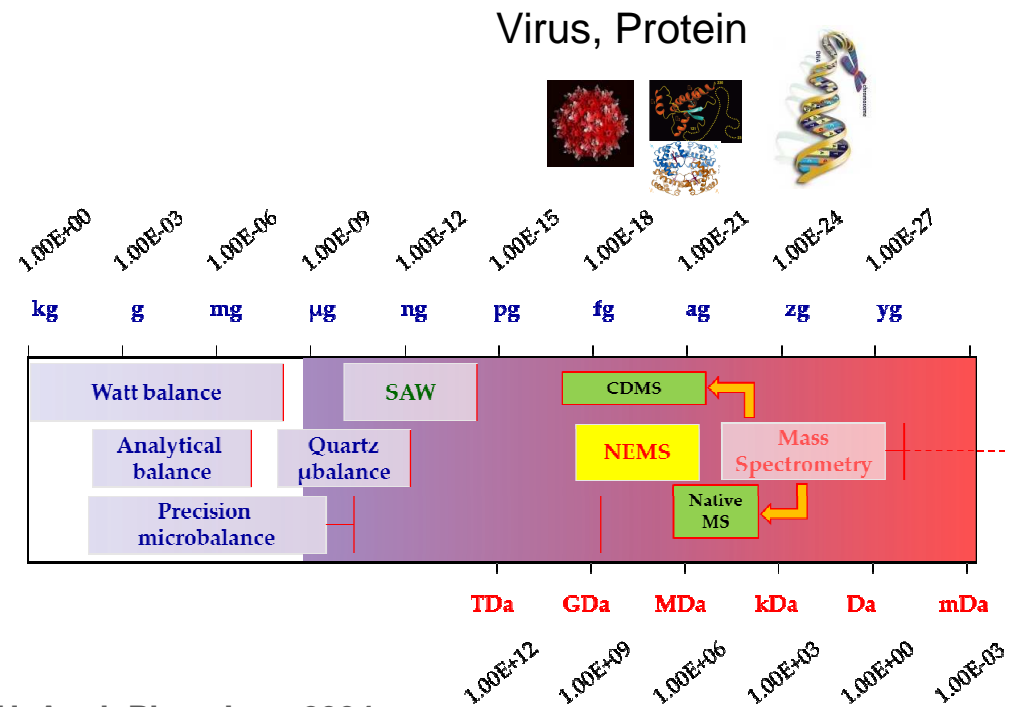
Complex gas sensing
LETI, IEDM 2011



Breath Monitoring (lung cancer)
ACS Nano 2017 (consortium)

MASS SENSING WITH NEMS

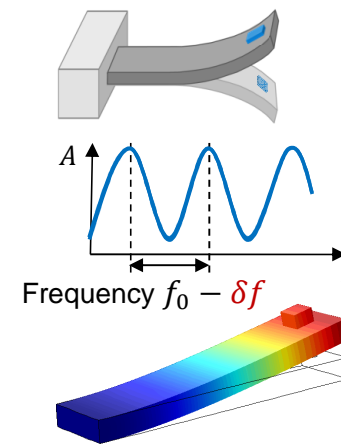
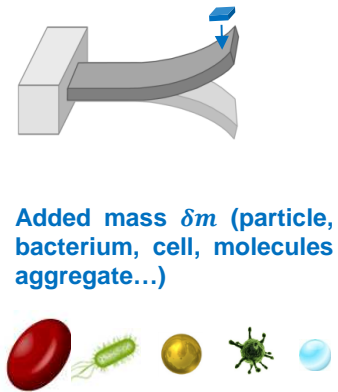
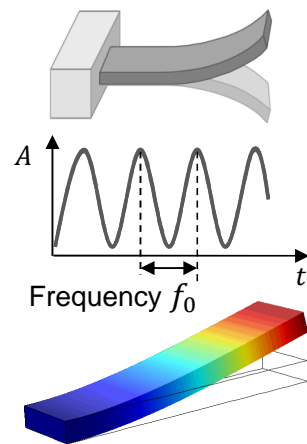
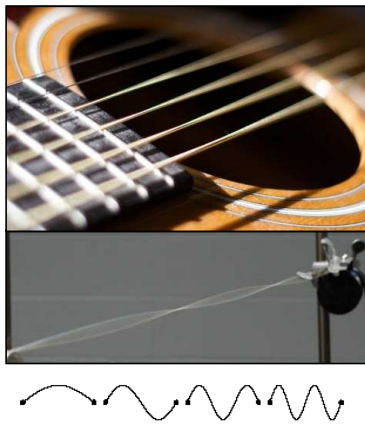
- NEMS detect single particles (requires multi-mode operation)



KL Ekinci et al., CALTECH, Appl. Phys. Lett. 2004
 M. S. Hanay et al. , CALTECH, LETI, Nature Nanotech. 2012

HOW DOES IT WORK?

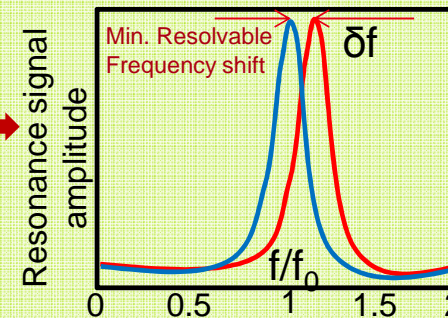
Precision mass measurement with micromechanical resonators



Actuation
(resonance)

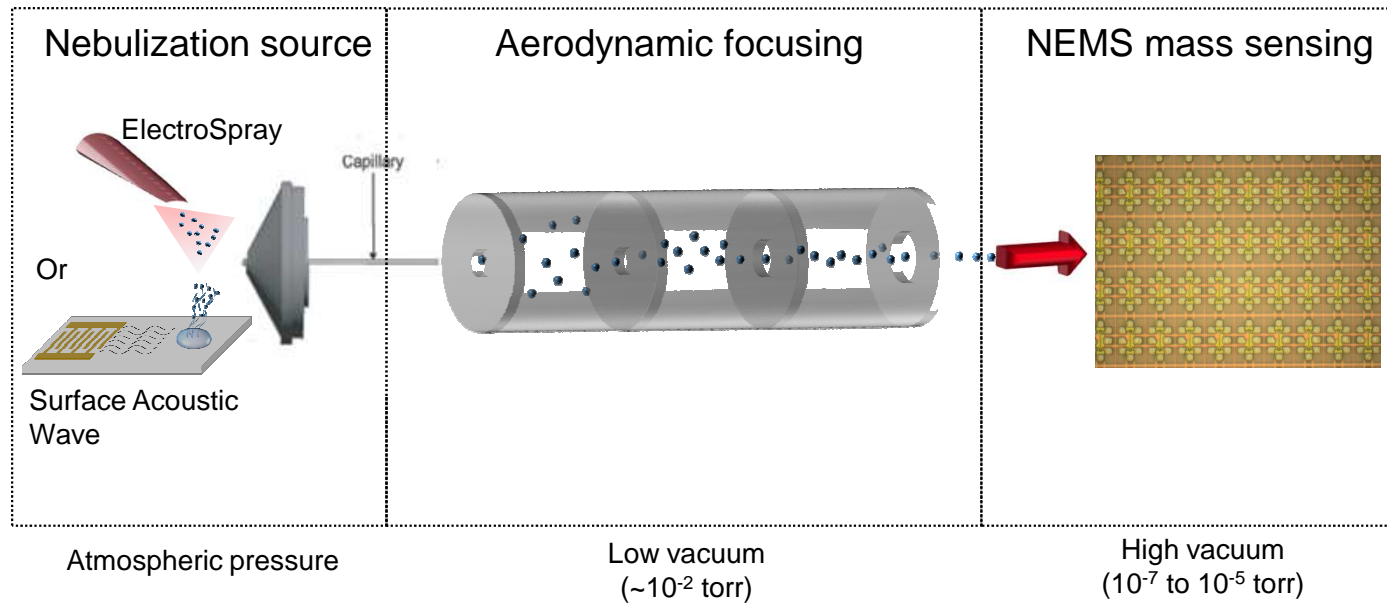
MEMS / NEMS
mass sensor

Added mass δm

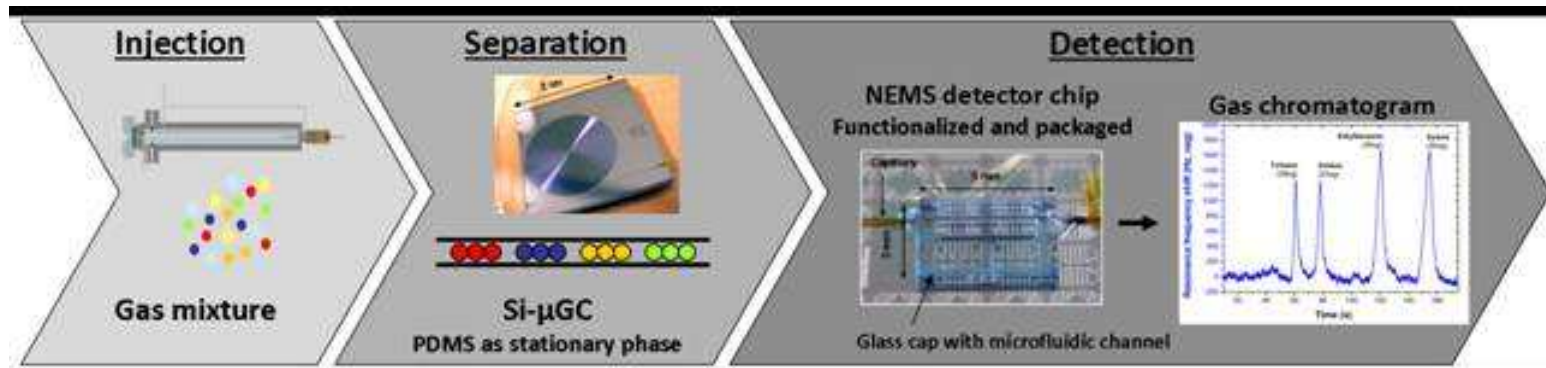
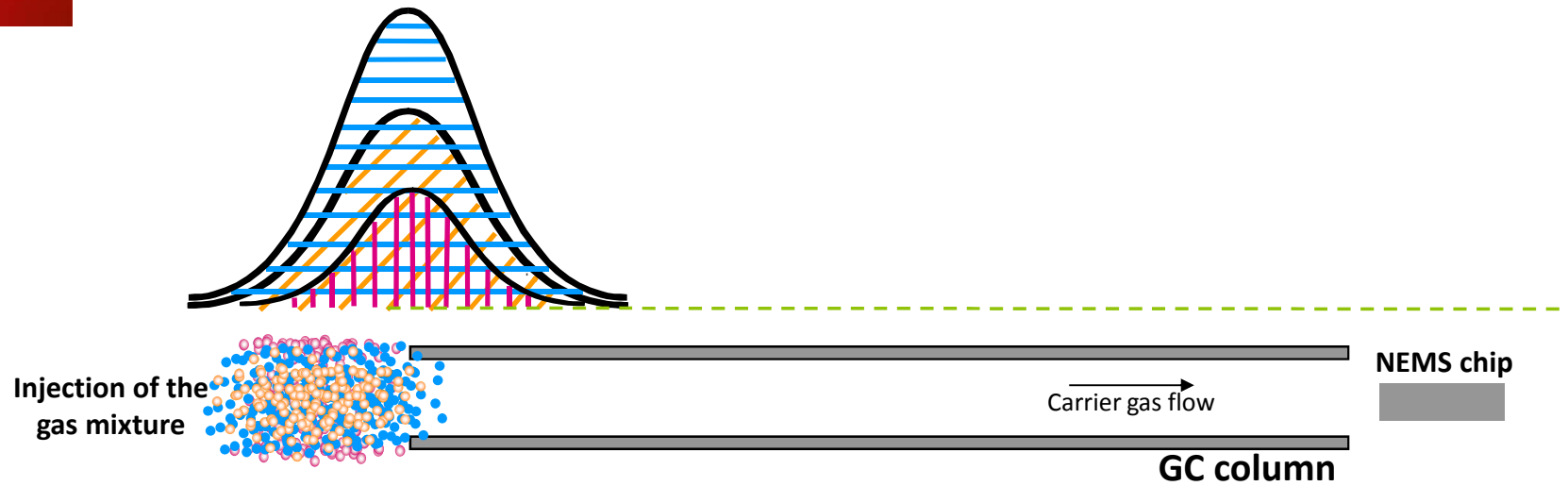


Signal processing
(measuring δf to
determine δm)

MASS SPECTROMETRY WITH NEMS



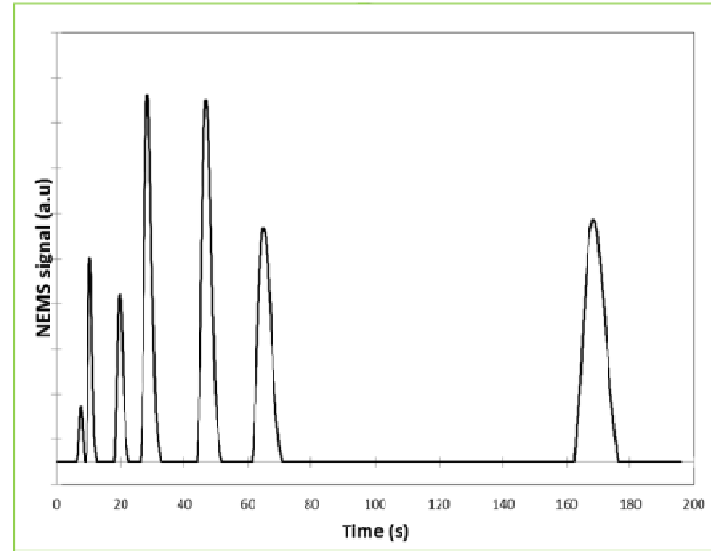
GAS SENSING WITH NEMS



HUGE VOLUME REDUCTION OF EXISTING SYSTEMS

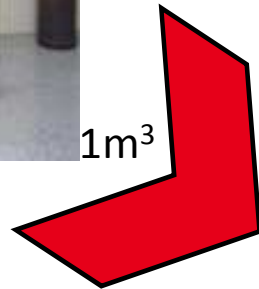


1m³



Carrier gas: He at 1mL/min
Injection loop: 10µL
Isothermal 70°C / 0.9bar
Module : 2 m column OV1

Type	Concentration
Chloroform	100 ppm
Benzene	100 ppm
Trichloroethylene	100 ppm
Toluene	100 ppm
Tetrachloroethylene	100 ppm
Ethylbenzene	100 ppm
o-Xylene	100 ppm



1L

15 cm

10 cm



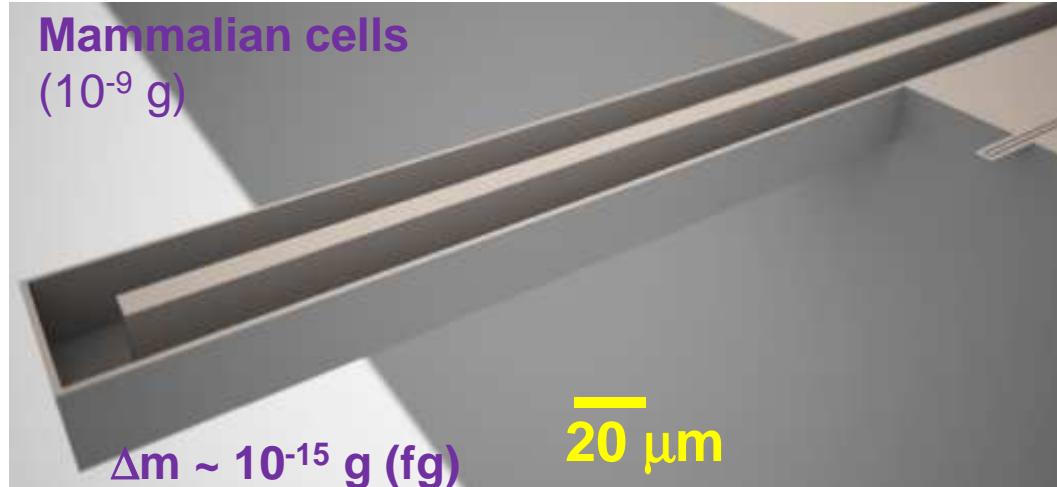
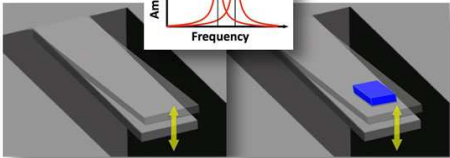
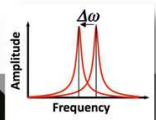
SOURCE: www.apixanalytics.com

SUSPENDED MICROCHANNEL RESONATOR (SMR) FOR DIAGNOSTICS

- A new paradigm, bringing the target inside the device

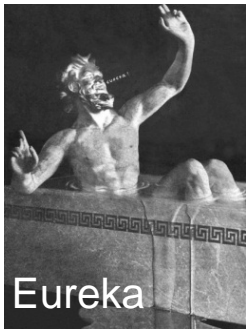


$$\Delta f \propto \frac{1}{\delta m^{1/2}}$$

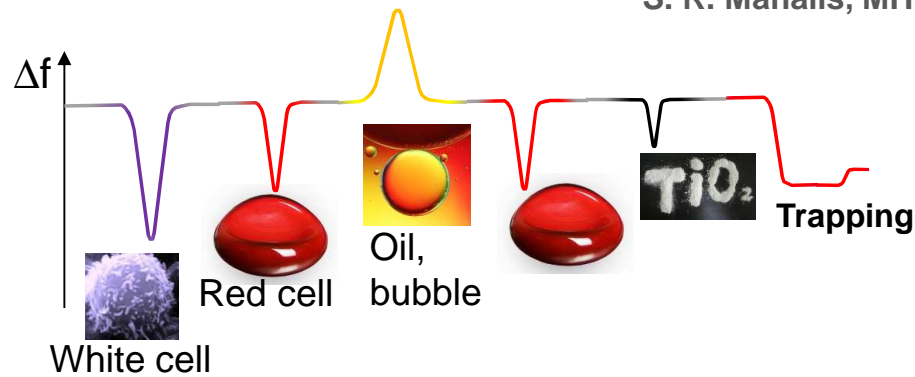
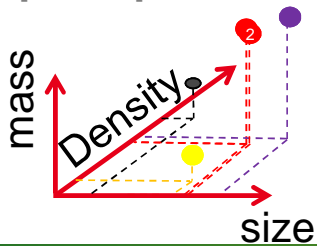


N Cermak et al, MIT, LETI, Nature biotech 2016

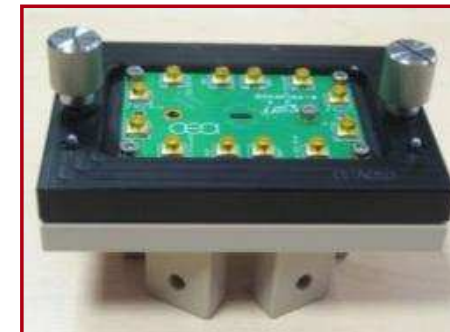
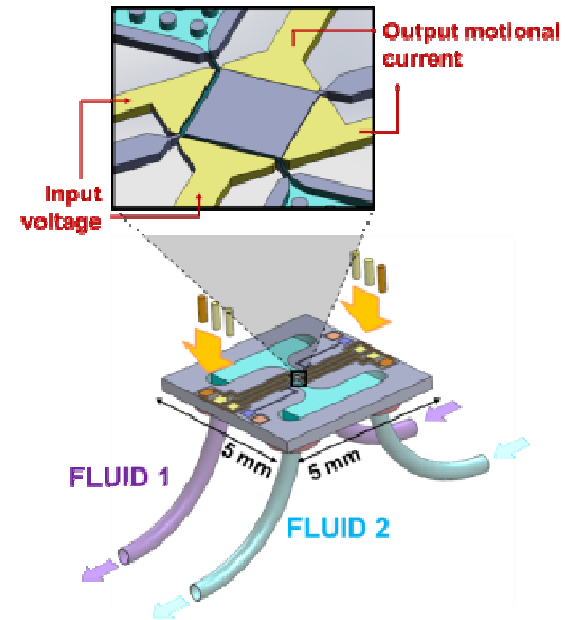
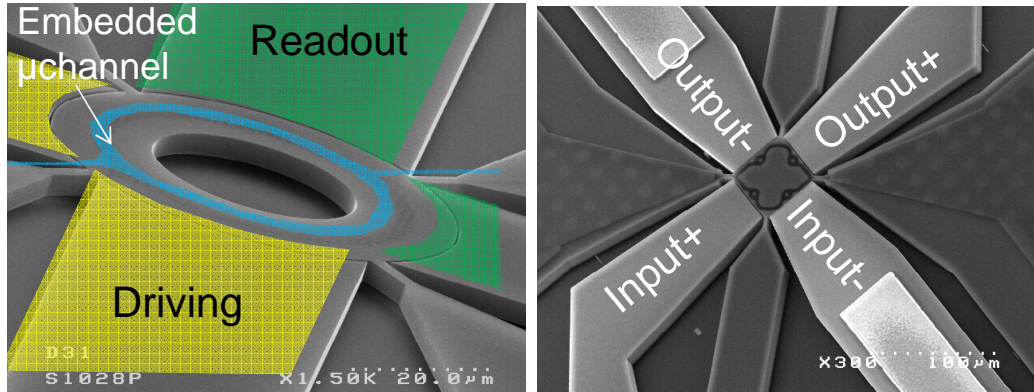
S. R. Manalis, MIT, APL 2003



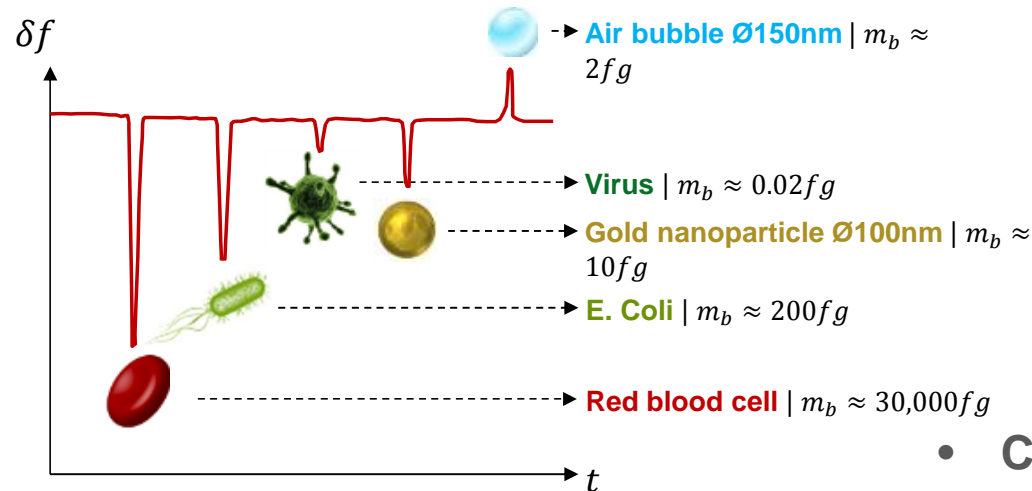
Archimedes' principle



LETI SMR TECHNOLOGY



- Typical resolution $\sim 1 \text{ fg} = 10^{-18} \text{ kg}$
- Dynamic range = a few 10nm to 5 μm



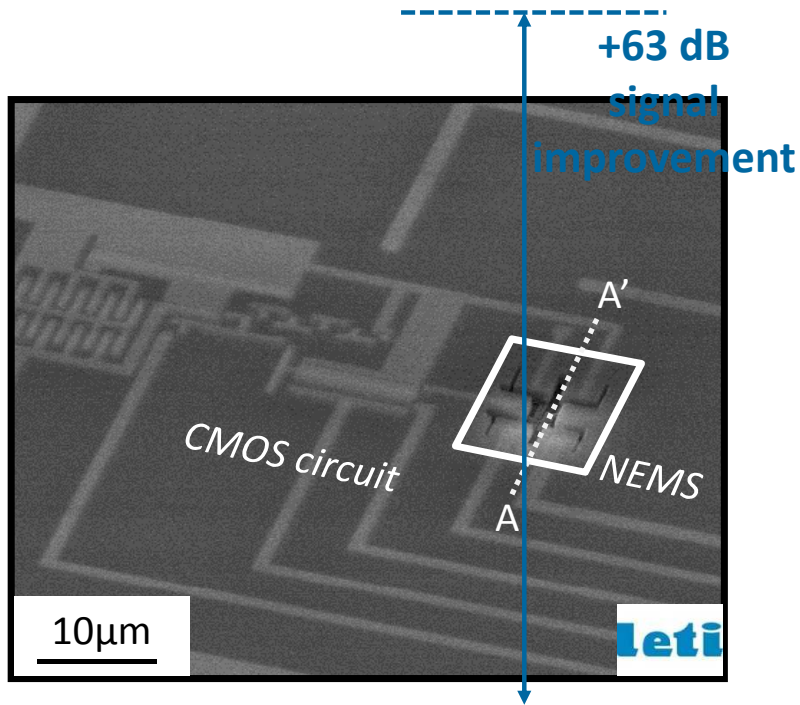
C. Hadji et al, LETI, IEEE MEMS 2017

- Customized plug and play platform = fast connection



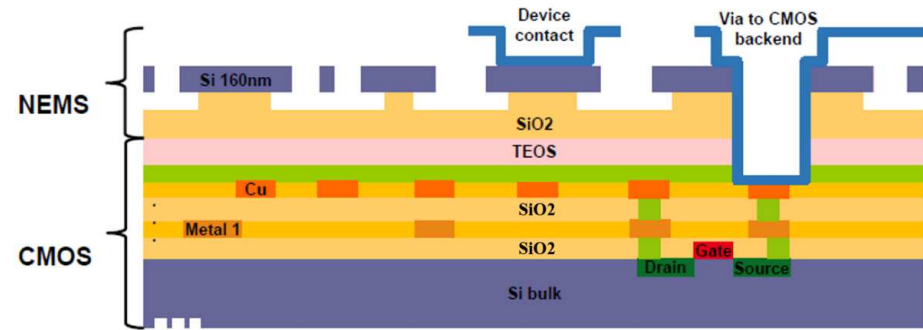
CO-INTEGRATION WITH CMOS

ON FD SOI FRONT-END

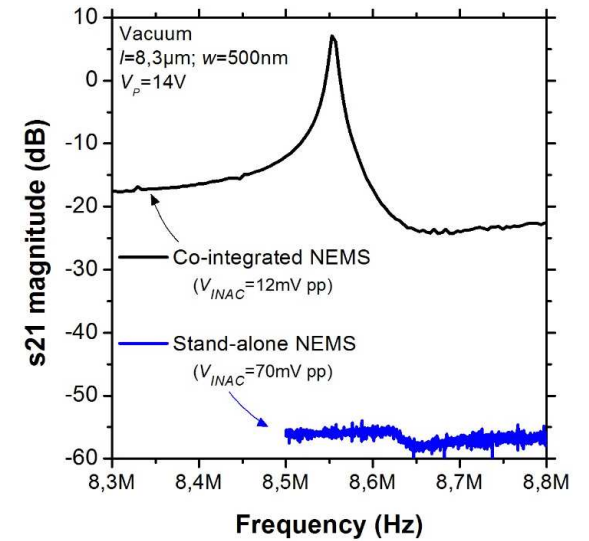


J. Arcamone et al., IEDM 2014

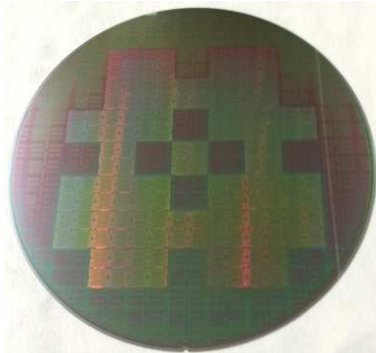
ABOVE CMOS (MONOLITIC)



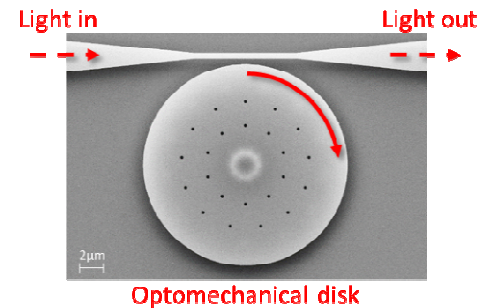
Ouerghi et al., IEDM 2014,2015 LETI
T. Ernst et al. ESSDERC 2015



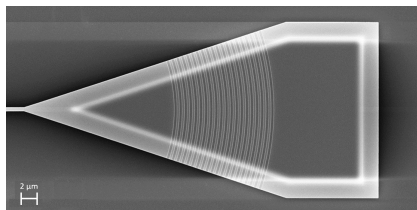
TOWARD VERY HIGH SENSITIVITY WITH OPTOMECHANICS



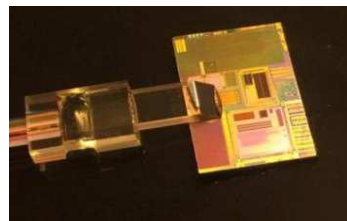
- 200mm SOI wafer
- 120000 optomechanical resonators



Silicon photonics bricks :



Optical grating coupler



Optical packaging

- Optical Q up to 1 million
- Thermal noise resolved up to 500MHz
- Displacement sensitivity $< 10^{-17} \text{ m.Hz}^{-1/2}$

CONCLUSION

Leti prepares the long-term future of MEMS companies

- Innovation at all levels (materials, processes & devices)
- Broad range of applications and potential markets
- Short-term applicative projects coexisting with advanced research

MEMS R&D partner with unique versatility

- Design & process
- Packaging & characterization,
- Readout electronics & system integration

AKNOWLEDGMENTS

- **CEA- LETI** :
J. Arcamone, S. Hentz, T. Alava, G. Jourdan, V. Agache, L. Duraffourg,
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L. Hutin, Jose-Luis Munoz, E. Rolland, C. Tabone, C. Plantier, I. Ouerghi,
C. Carmigni, W. Ludurczak
- **CEA- INAC** :
Ariel Brenac
- **BIG** :
C. Masselon S. Dominguez
- **APIX Analytics** :
P. Andreucci, P. Puget, E. Colinet
- **MIT** :
Pr. S. Manalis
- **CALTECH** :
Pr. M. Roukes



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