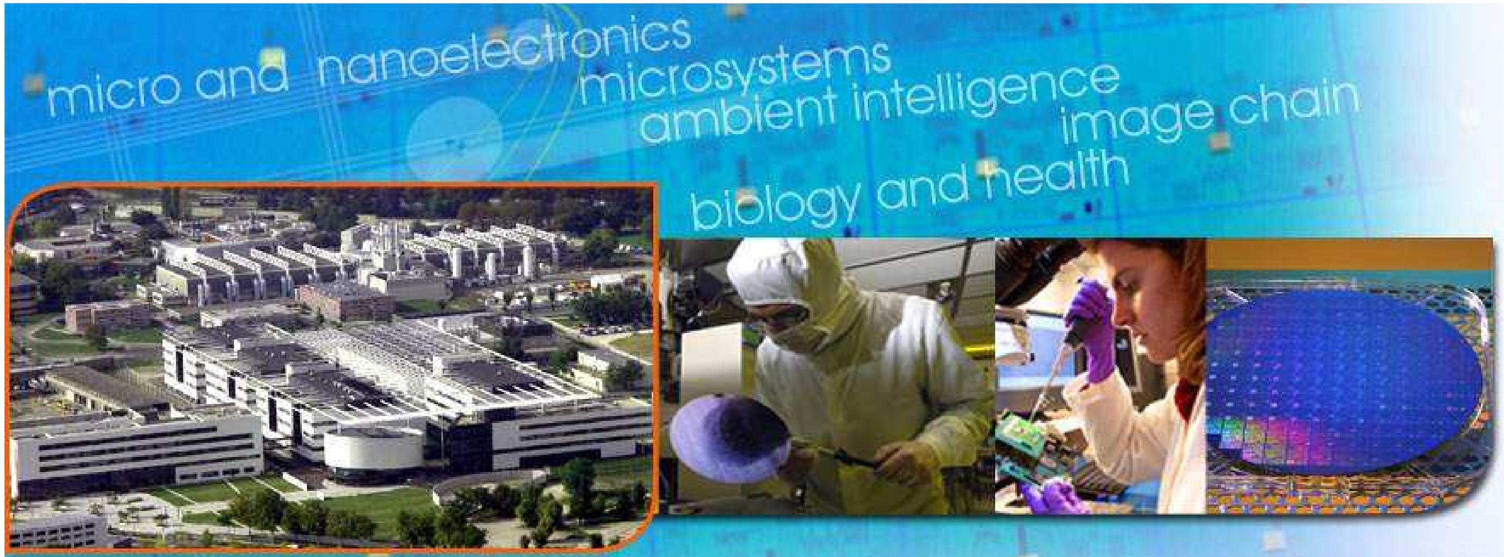
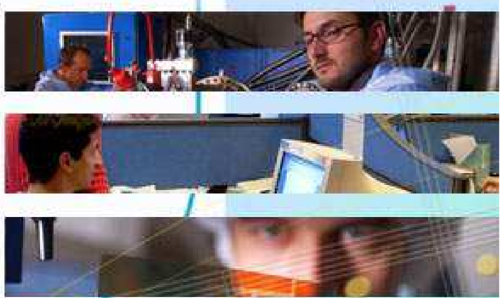



2011

# From NEMS to Nanowires and their Front-End co-integration with CMOS for enhanced sensing performances

**IS-AHND 2011 / NEMSIC**
Tokyo - Japan
October 5, 2011

**Eric OLLIER et al.**



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# Outline

- Introduction
- Technological platforms in NEMSIC
  - Sensing application
  - Power management application
- Examples of Devices fabricated in NEMSIC
  - Sensing application
  - Power management application
- Conclusion

# NEMS&Nanowires…more than miniaturization of MEMS

## Motivations :

- NEMS/nanowires devices in thin Si layers
  - Benefit of NEMS (miniature size, low power, high resonance frequency&quality factor, NEMS arrays, sensing networks)
- NEMS/nanowire-IC integration : monolithic integration, 3D approaches…
  - Reduce cost, size and power consumption
- Toward new applications :
  - Low-cost & RF applications : nano-accelerometers, nano-resonators
  - New applications : **mass sensor (gaz and bio sensors), NEMS switches**, SGFET, memory,…

## Issues :

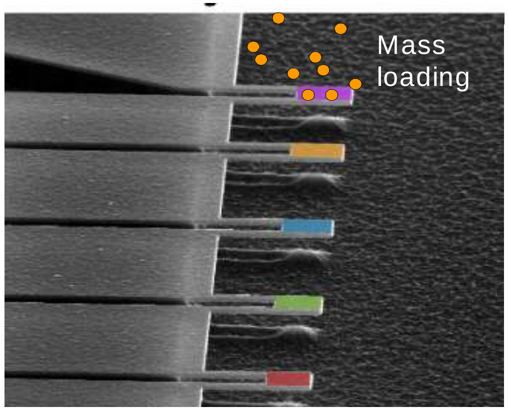
- NEMS/nanowires challenges in physics : quantum phenomenon (Casimir force, charge quantification), noise processes, transduction & detection
- Transduction principle: capacitive, MOS (SG-FET, planar), piezo-resistance…
- Manufacturing of NEMS/nanowires in thin Si layers, packaging
- Characterization of NEMS/nanowires (morphology, electrical…)

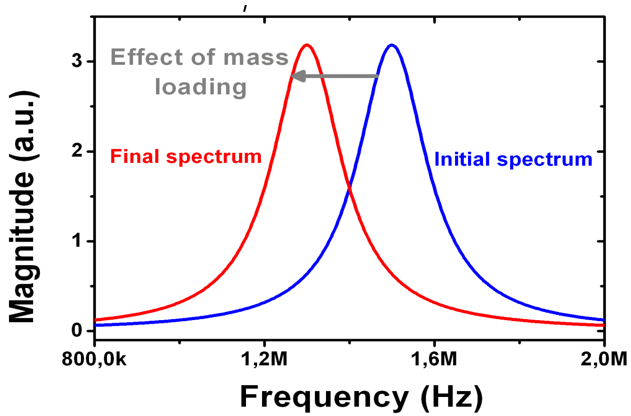
# NEMS for mass-sensing

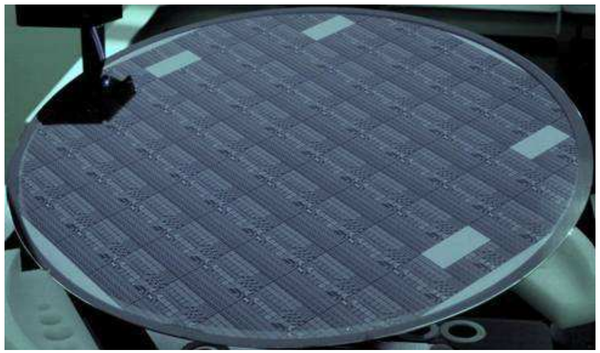
## NEMS resonators for ultrasensitive mass detection

Shift of NEMS resonant frequency caused by mass loading

Various functionalizations to enhance selectivity (multi-gaz sensing)



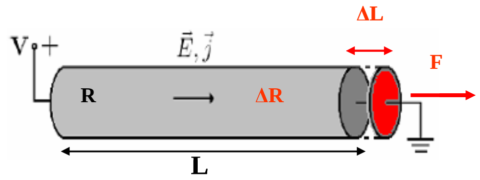



*First 200 mm wafers with 3.5 millions NEMS (Caltech-LETI Alliance)*

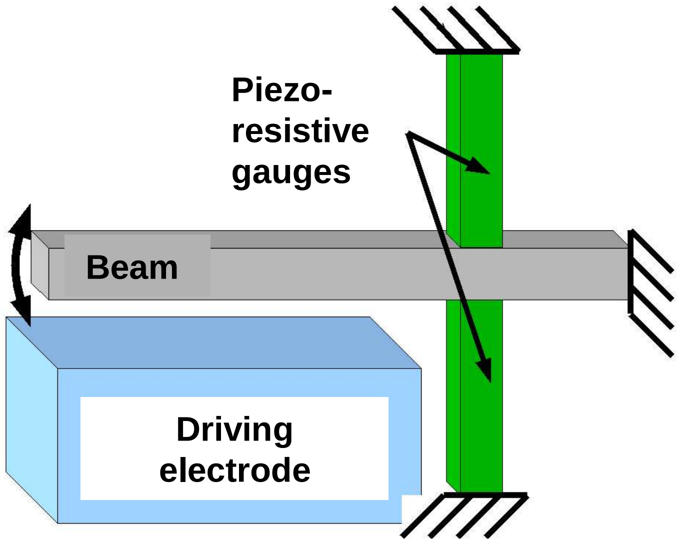
**CMOS process – Micro electronics tools – 200mm wafers**

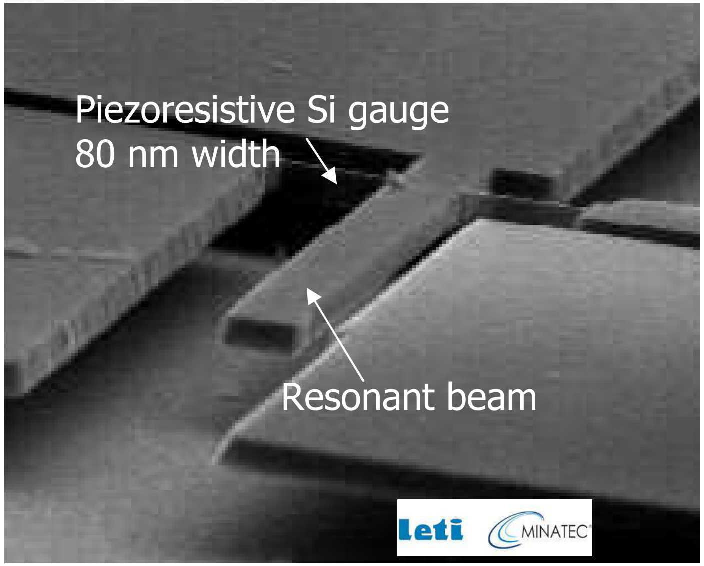
# NEMS for gaz sensing at CEA-LETI

## In-Plane piezo-resistive nano-resonators for gaz sensors




Gauge factor $\gamma = \dfrac{dR/R}{dL/L} = \dfrac{dR/R}{\epsilon}$



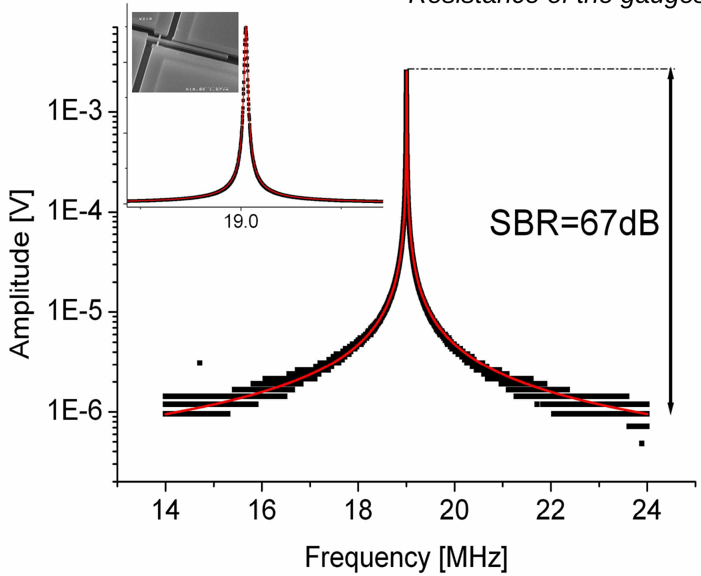




*« In-plane nanoelectromechanical resonators based on silicon nanowire piezoresistive detection », E. Mile et al., Nanotechnology 21, 165-504, 2010*

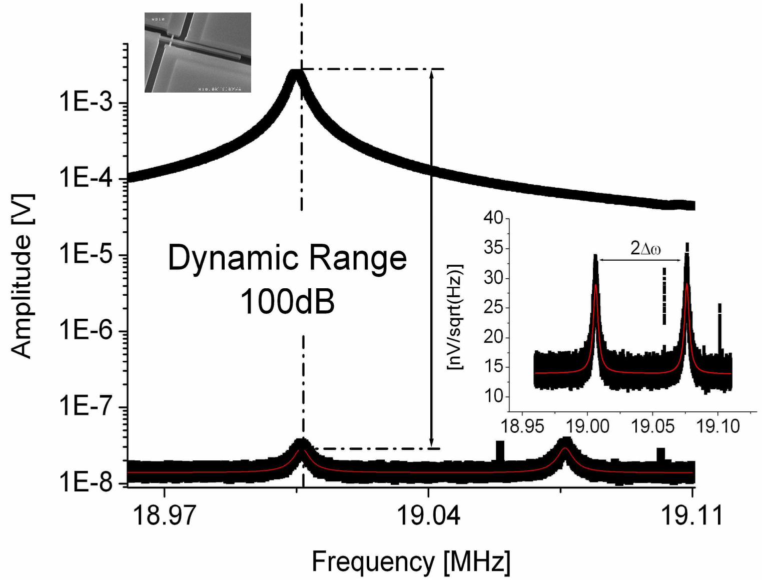
# NEMS for gaz sensing at CEA-LETI

## In-Plane piezo-resistive nano-resonators for gaz sensors

*Resistance of the gauges ~1kΩ / Gauge factor $\gamma$ ~ 40*




*Vdrive=1.5V; Vbias=1.5V; Vacuum <1 mTorr*
*Displacement 10 nm at Vdrive 3mV*




*Vbias=1.5V – Noise computed for 1Hz-bandwith*

**- Fr 19.16MHz ( 2% dispersion around 200mm wafer)**
**- Q 5000-10000 in vacuum / Q 200 in air**
**- SBR 67dB thank to:**
*** geometrical decoupling (driving electrodes and piezoresistive gauges)**
*** frequency decoupling (down-mixing measurement)**

**- Noise floor very low and dominated by thermomechanical and electronic noise, rather than Johnson noise**

**Mass 140 fg, Q-factor of 5000, DR 100 dB → Allan deviation 1.5x10$^{-9}$ over 1s-integration time**
**→ Potential mass resolution of ≈0.3 zg at room temperature and at 20 MHz**

*« In-plane nanoelectromechanical resonators based on silicon nanowire piezoresistive detection », E. Mile et al., Nanotechnology 21, 165-504, 2010*

# From NEMS to Nanowires …

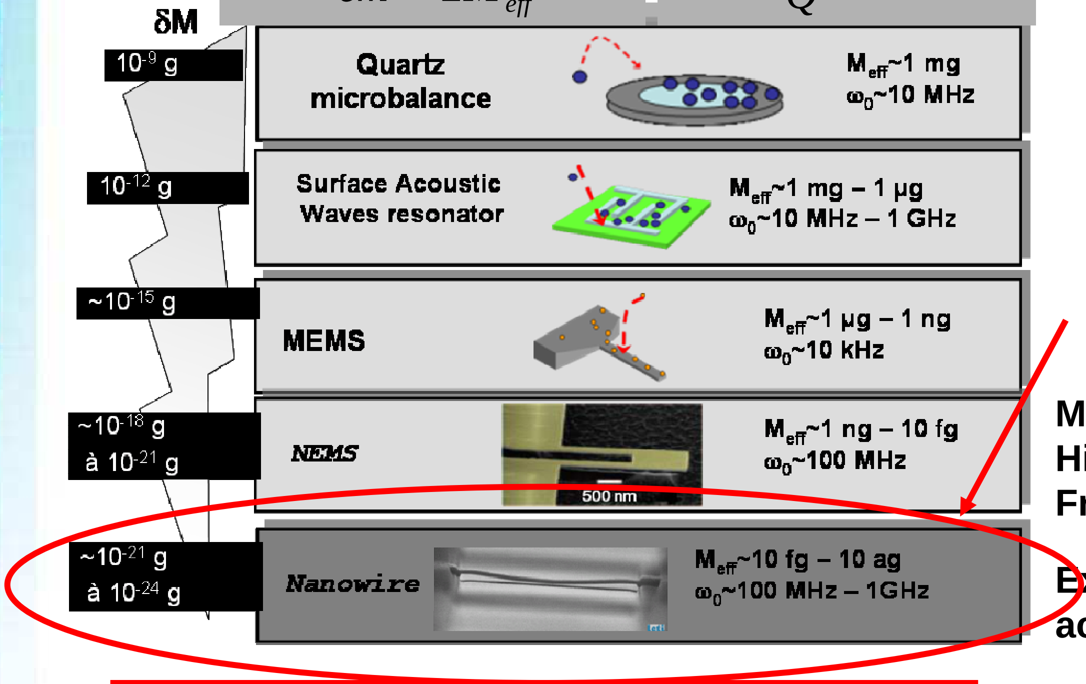
## NEMS/Nanowires resonators for ultrasensitive mass detection

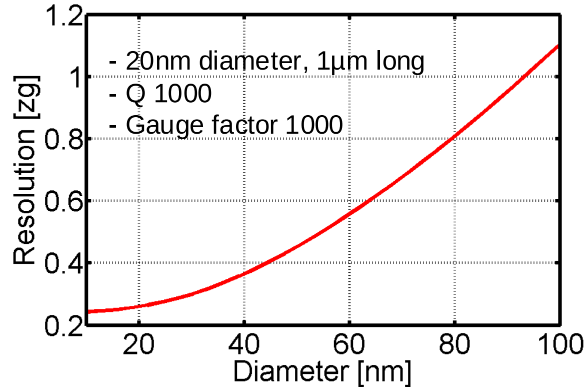
**Sensitivity**

$$\Re = -\frac{\delta f}{\delta m} = \frac{f_0}{2M_{eff}} \propto l^{-4}$$

**Resolution**

$$\delta m = \frac{M_{eff}}{Q} 10^{-\frac{DR}{20}} \propto l^{3}$$




**NEMSIC**

**Miniature total mass**
**High resonant frequency**
**Frequency stability**

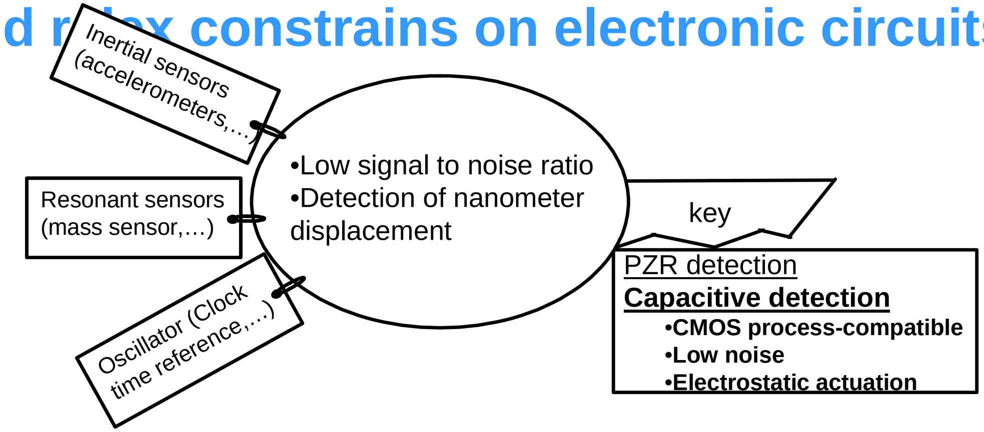
**Exceptional mass resolution achievable with UHF NEMS resonators**

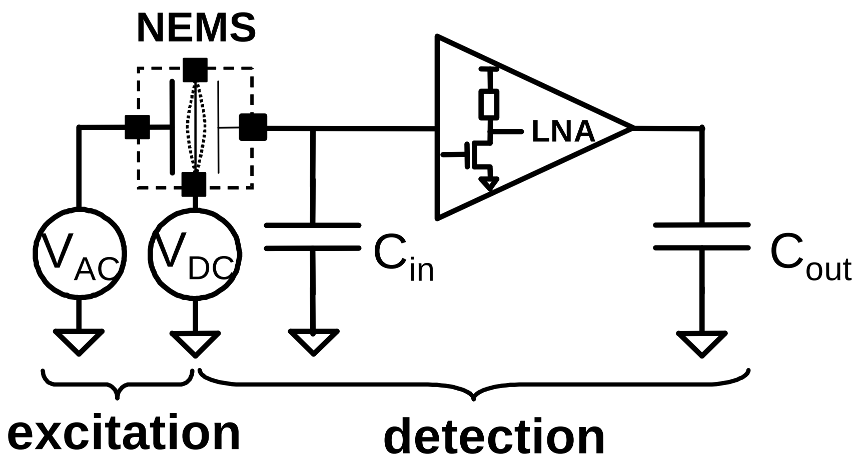
Detection of few molecules aggregates
~ a few zg ($10^{-21}$g) to yg ($10^{-24}$ g)

**Nano-resonators can enable few molecules mass detection in gaz or liquid environments**

# Need for Integration of NEMS & Nanowires with CMOS

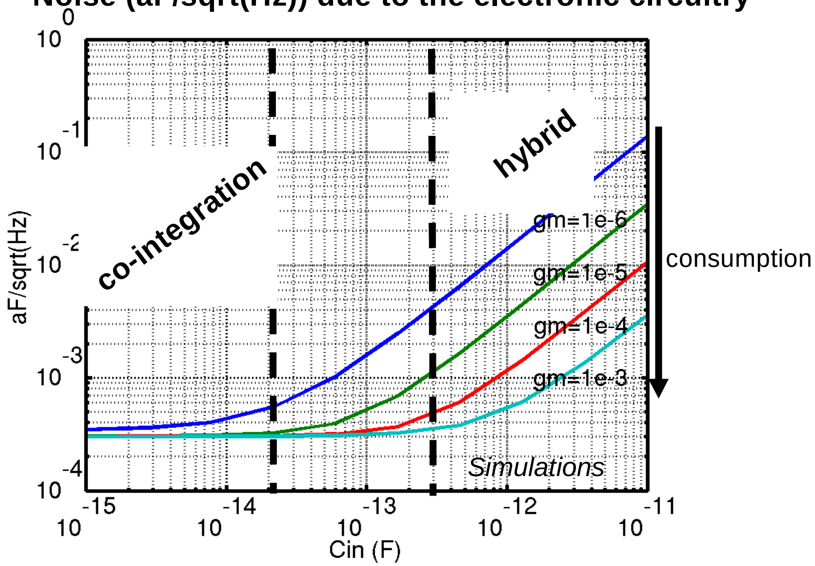
## Integrated transistors help transduction at nano-scale and relax constrains on electronic circuits




Cin sum of interconnecting capacitances, LNA input capacitance, NEMS capacitance

**Noise (aF/sqrt(Hz)) due to the electronic circuitry**



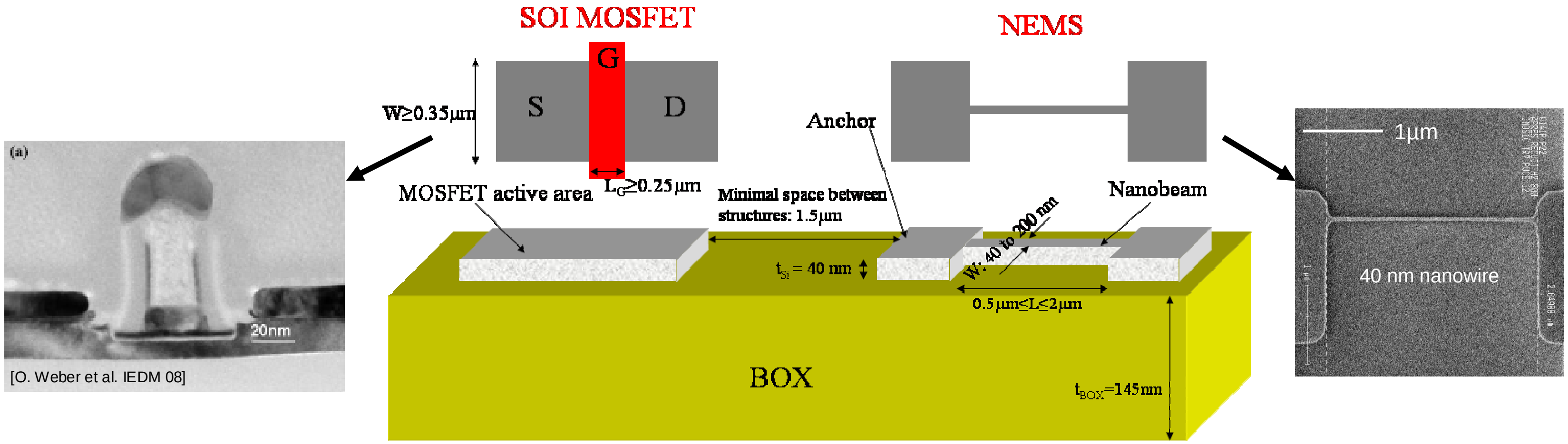

## NEMS-CMOS integration allow to "suppress" Cin leading to improved detection performance together with low power consumption

*"Ultra-Sensitive Capacitive Detection Based on SGMOSFET Compatible with Front-End CMOS Process" , E. Colinet et al., IEEE Journal of Solid-State Circuits, vol. 44 (1), 2009, pp. 247-257*

# Technological platforms developed in NEMSIC

## General considerations

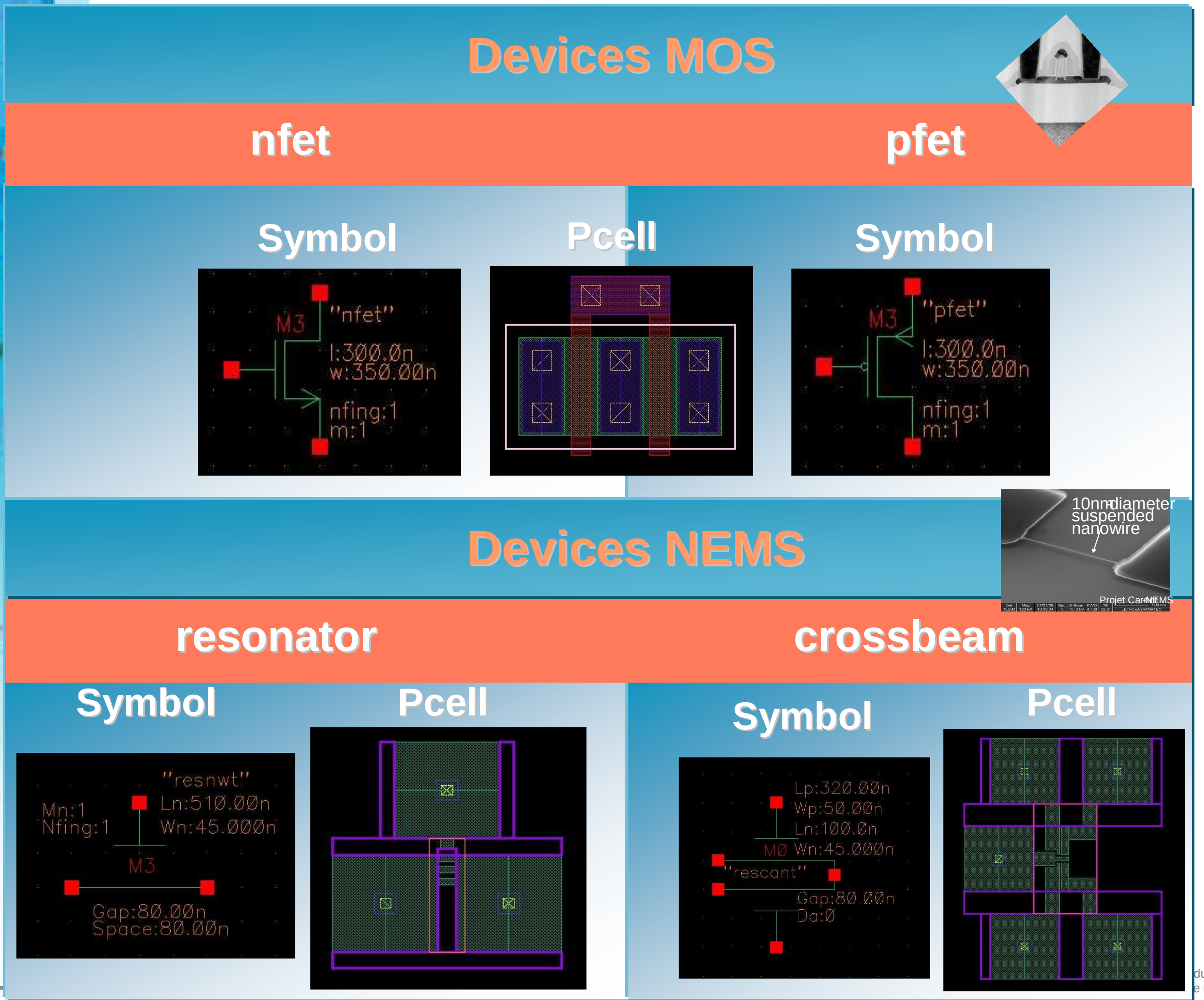
- Role of CEA-LETI in NEMSIC WP5: Advanced Technological Platforms for NEMSIC
- Integration of Nanowires + CMOS transistors on the same wafer
  - Nanowires: Diameter 40-50nm
  - Transistors: FDSOI technology
- SOI technology
- DRM & DK provided to partners to enable electrical simulation and layout
- Two dedicated platforms in CEA-LETI/MINATEC 200mm clean-rooms:
  - 1 for Sensing devices
  - 1 for Power Management devices
- Issues:
  - Combine FDSOI technology and Nanowire technology
  - Open the platforms to the partners (EPFL, Univ of Southampton, LETI)



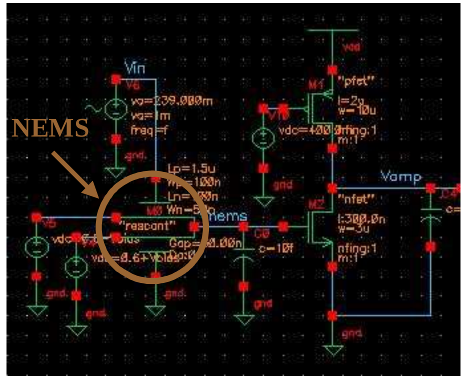
[O. Weber et al. IEDM 08]

# DRM and DK for Nanowire - FDSOI integration

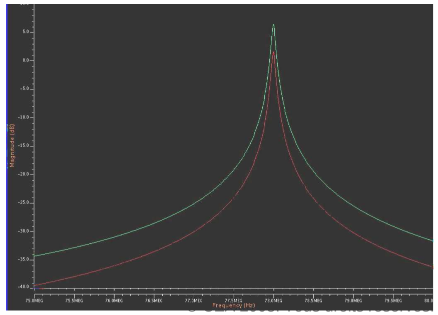
## Design Kit for Nanowires - CMOS integration on FDSOI technology




**Design-Layout**
**Electrical simulation ELDO**
**Physical verif & Layout Finishing**

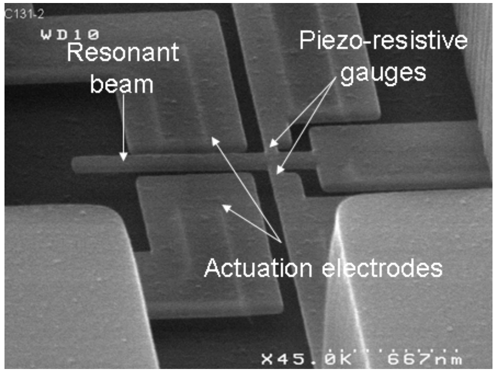



*Amplificator*



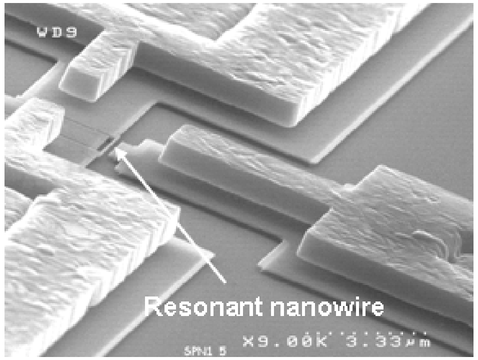
# Stand-alone and Co-integrated ultra-scaled Si NEMS (LETI)

**Cross-beam structures with electrostatic actuation and piezo-resistive detection**



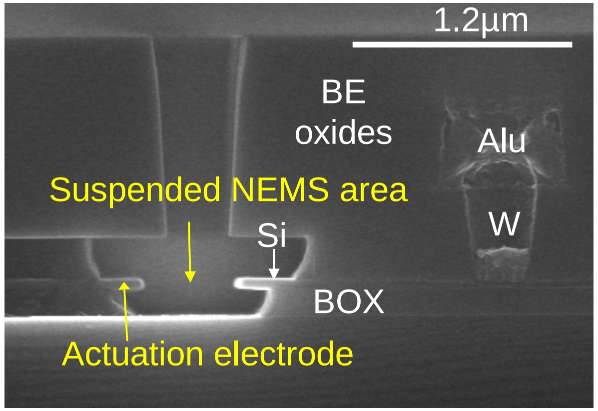

SEM view of stand-alone ultra-scaled Si NEMS
(beam width 80nm, gauges 30nm wide, Si thickness 40nm)

**Nanowires structures with with electrostatic actuation and piezo-resistive detection**




SEM view of stand-alone ultra-scaled Si nanowire
(beam width 40nm, thickness 40nm)

**NEMS-CMOS co-integration will enable direct measurement of NEMS resonators**



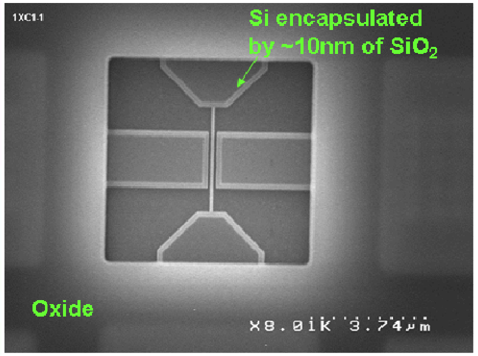

NEMS (nanowire 40x40nm cross-section) embedded in CMOS process

***Electrical results will be reported later***

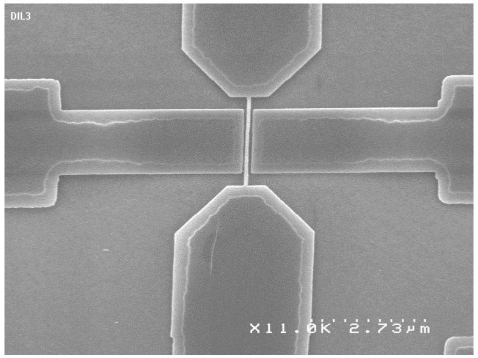
# Fabrication of devices designed by NEMSIC partners

## EPFL

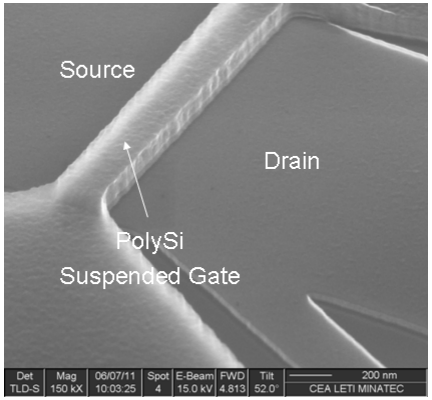
Vibrating Body FET
(VBFET)

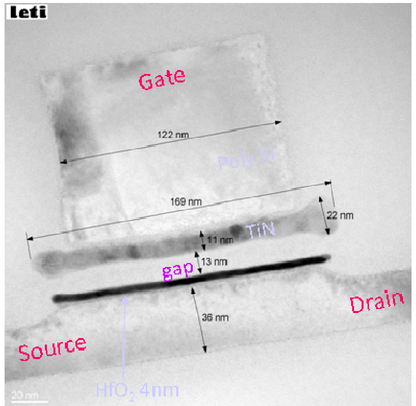



Vibrating Junctionless FET
(JFET)



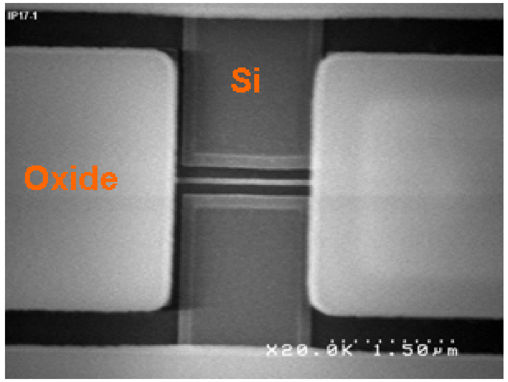

Suspended gate switch
(Power Management)




## Univ of Southampton

Lateral Suspended Gate FET
(SG-FET)




***Please refer to talks given by EPFL and Univ of Southampton***

# Conclusion

- NEMS & Nanowires are very attractive because of their intrinsic advantages and because they offer the possibility of innovating approaches for the sensors field and the CMOS industry
  - Compactness and low cost
  - Low power consumption (simplified analog circuit associated with NEMS)
  - Good SNR (reduction of parasitics essential for NEMS/Nanowires)
- Convergence of Nanowires and CMOS technologies is a real opportunity
  - Down-scaling favorable to benefit of the advantages of NEMS/Nanowires
  - Arrays necessary for high performances and new generation of sensors
- NEMSIC aims to demonstrate benefit of Integration of Nanowires & CMOS
  - Stand-alone Nanowire-based devices
  - Innovative devices like Mixed Nanowire-Transistor devices by EPFL (VB-FET, SGFEt for power management) and Univ of Southampton (Lateral SG-FET)
  - Fully integrated Nanowire-based structures with CMOS (FDSOI) by LETI
  - CEA-LETI: fabrication of advanced devices on 200mm NEMS-FDSOI platforms
- Practical applications targetted in NEMSIC:
  - Resonant devices for gaz sensing (& bio applications)
  - Devices for power management in CMOS industry

## Acknowledgement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  - EC for NEMSIC project (Nanowires)
- Collaborations (NEMS)
  - Carnot-Caltech program
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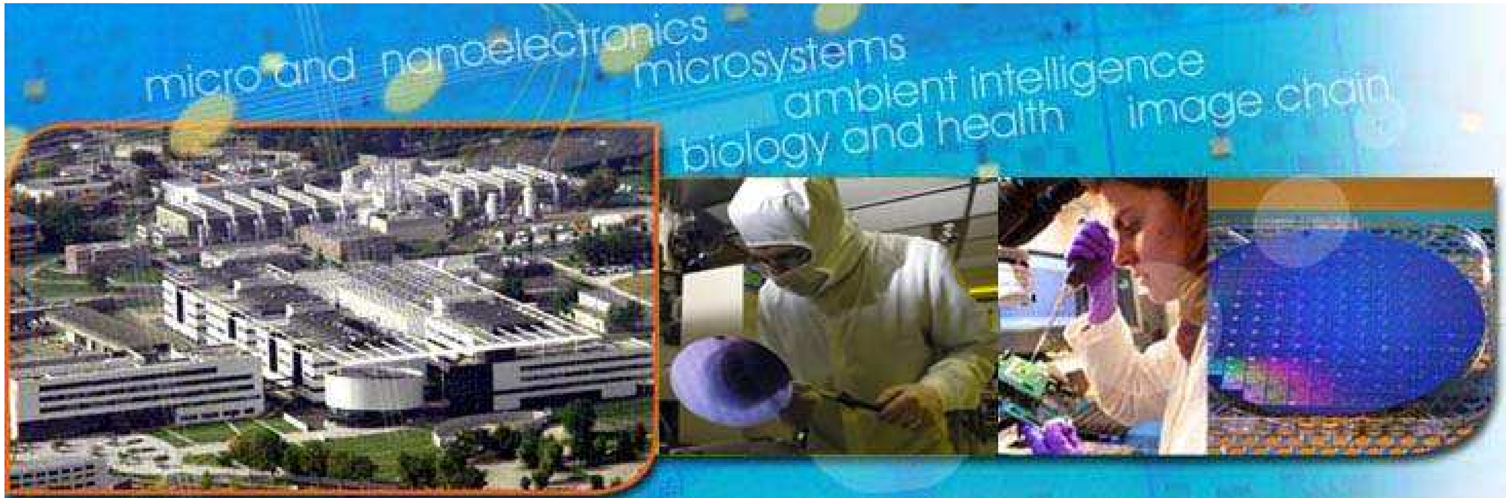
  - Leti 200 mm clean rooms staff


- Corresponding author: Eric Ollier, Eric.Ollier@cea.fr




# Innovation for industry

Loyalty
Entrepreneurship
Team work
Innovation

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