THE OPTIMIZATION OF MEMS THROUGH THE DEVELOPMENT OF GENERIC MANUFACTURING PLATFORMS.

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INTRODUCTION

Since the first paper considering silicon as a structural material [1], MEMS have gained a considerable attractiveness, first in niche markets (aerospace, military), then in automotive (airbag triggering systems, and later roll-over control) and consumer industry (MEMS accelerometers and gyrometers in game consoles and mobile phones). Today they show a pervasive use in all markets sectors (industry, medical, environment…). This noteworthy development explains the high growth already observed in the multi billion dollar MEMS industry (~12B US$ in 2013) and the associated impressive annual CAGR (~12.7 %) forecast for the next few years [2]. During this past period of expansion, MEMS manufacturing technologies have undergone several changes starting with the 80's bulk micromachining technologies, moving to surface micromachining technologies in the 90's, then to SOI MEMS micromachining technologies in the 00's. Coming now at the time of technical maturity, and in a context of ambitious initiatives such as Internet of Things [3],[4] or Trillions sensors vision [5], MEMS industry is now requiring more standardization in manufacturing processes, and several initiatives are in preparation in the main R&D labs worldwide. This paper presents Leti's contribution to develop generic platforms matching the suitable MEMS technologies with different applications. Given the different levels of maturity between physical and chemical sensors, two specific approaches have been considered and Leti has today implemented two different platforms.

M&NEMS: A GENERIC PLATFORM FOR PHYSICAL SENSORS.

The maturity of most physical sensors such as accelerometers, gyrometers, magnetometers, and pressure sensors is today proved and the step further is now to have manufacturing platforms able to process all these components in a unified way, allowing to get combos (with 3, 6, 9, 10 or even 11 DoF) on single chips using a common process flow, which results in a drastic cost, size and power consumption reduction.

The basic idea underlying Leti's *M&NEMS* concept is to combine on a same device a thick MEMS layer for the inertial mass with a thin and narrow NEMS part as suspended strain gauge, allowing a size reduction of sensor without a decrease in the signal to noise ratio (SNR). This technology has been described in details elsewhere, applied to accelerometer [6], gyrometer [7], and magnetometer [8]. In all cases it consists in:

-An inertial mass, suspended at one of its extremities by a hinge anchored to the substrate

-A hinge centered with the inertia center of the mass

-A suspended nano-gauge, orthogonal to the symmetric axis of the sensor, fixed from one side to an extremity of the mass, and from the other side to an anchor. This nano-gauge is a simple silicon suspended beam used as a piezoresistive gauge

A motion of the inertial mass will induce a rotation around the hinge axis which induces an axial stress in the gauge.

For clarity, the simplified concept is exemplified in figures 1 and 2 in the case of a 3 axis accelerometer.

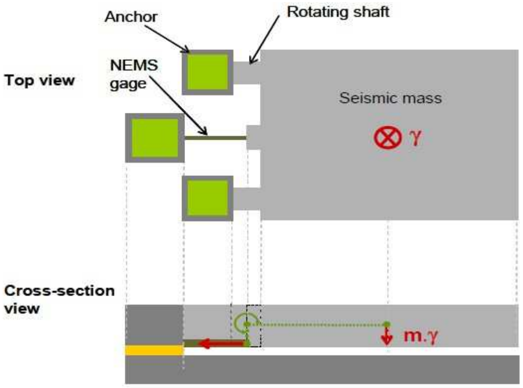


Fig. 1: Simplified structure of the M&NEMS in-plane accelerometer

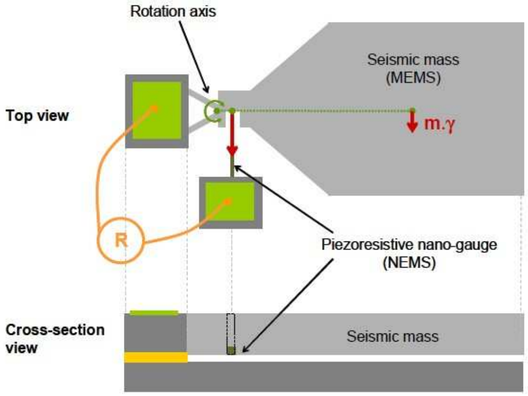


Fig. 2: Simplified structure of the M&NEMS out-plane accelerometer

This generic technology, protected by more than 20 patents, only requires 6 masks levels (packaging not included), greatly simplifies the sensors modeling and readout electronics, and exhibits the further advantage to be fully compatible with CMOS fabrication. Some characteristics of 3 axis M&NEMS sensors already prototyped and targeting consumer specs, are presented in table 1 hereafter.

For further details about the performances of the sensors, the reader is invited to consider references [6]-[8]. Besides the inertial sensors, a pressure sensor and a microphone are presently under development on the M&NEMS platform at Leti. This will open the way on the short term to 11 DoF on this platform.

The M&NEMS platform is perfectly suited for sensors fusion since the detection of piezoresistive nanogauges allows a common electronics (to which must be only added a specific circuit for the excitation part of the gyrometer).

accelerometer	• Typical size of 3-axis chip: 1mm² • Range: 10 or 50G • Dynamic range: 5000 • Linearity deviation < 0.3%
gyrometer	• Typical dimensions of sensitive element: < 0.5mm² / axis • Resolution: 0.02° /s/√Hz (limited by readout electronics noise) • 1 sensitive element / axis (avoid cross sensitivity) • Differential measurement (drift limitation) • Open-loop detection (no need matched frequencies – process control is relaxed) • Rough vacuum required (no need for getter)
magnetometer	• Typical size of 3-axis chip: 1mm² • Low power consumption (integrated permanent magnet) • Resolution: 100 nT/√Hz • Linearity range 4.5mT

Table 1: Some characteristics of M&NEMS demonstrators designed with consumer specs.

M&NEMS technology has been transferred to Tronics last year in the frame of a non-exclusive license agreement, potentially allowing other MEMS players to adopt this technology. Today, this company has successfully designed and manufactured the first batch of 6 DoF MEMS chips, with 3-axis accelerometers and 3-axis gyroscopes on a single die, as shown in figure 3.

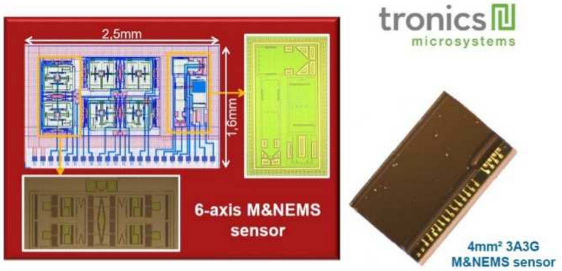


Fig. 3: Tronics first 6 DoF combo sensor.

Built on SOI wafers, with a die size of less than 4mm^2, this 6DoF MEMS chip is one of the smallest in the industry, and Tronics says further optimization will make it the smallest. Besides its size advantage, it is worth noting the piezoresistive nanowire based technology significantly decreases the power consumption and allows manufacturing of all sensor types (accelerometers, gyroscopes, magnetometers, pressure sensor and microphone) using a common process flow.

NEMS PLATFORM: A GENERIC PLATFORM FOR CHEMICAL AND BIO SENSORS.

The basic idea here is to address chemical sensors through ultra sensitive mass measurements based on the measurement of resonance frequency shifts of NEMS resonators: in the case of resonant gas sensing, the gas which is adsorbed on the vibrating beam is changing its overall mass and therefore its resonance frequency. Simple physical considerations show that NEMS resonators represent the ultimate universal mass sensor notably for gas detection [9-11], since decreasing the characteristic dimension (l) of a resonating cantilever increases both responsivity and resolution, as a function of l^{-4} and l^3 respectively. Due to their extremely small characteristic length, NEMS offers both high resolution, very short response time, and high integration. Their reduced masses allow the suspended nano-structures to vibrate at high resonance frequencies and therefore offer a good potential for ultra-sensitive gas sensing by resonant principles.

Figure 4 below quantifies the performances achievable by different resonant systems.

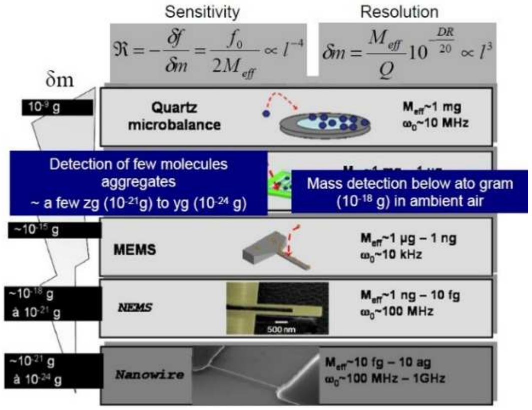


Fig. 4: Achievable performances of resonant systems.

In close collaboration with Pr M. Roukes' team in Caltech, Leti has therefore developed a NEMS platform suitable for ultra sensitive mass measurements, using different cantilever geometries and detection techniques. The crossbeam NEMS architecture [12], presented on figure 5, has been chosen based on its ability to provide a very high signal, a high SNR and a mass detection below atogram (δm = 10^{-18} g) in ambient air. Typical cantilever beam dimensions and piezoresistive nanogauges dimensions are respectively 3.2 x 0.3 µm^2 and 0.4 x 0.080 µm^2.

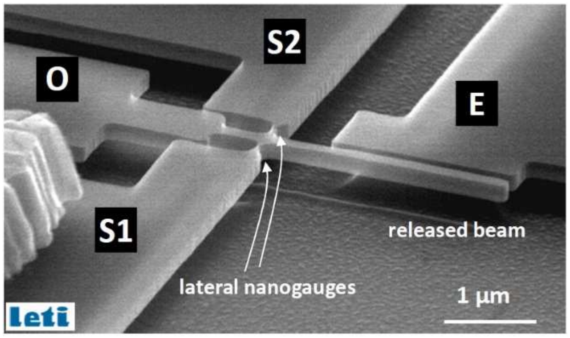


Fig. 5: NEMS Crossbeam geometry.

Designing an integrated gas analyzer providing both high selectivity and high sensitivity to a broad panel of gases still remains a major technological challenge. In the e-nose concept, the analyzer architecture is based on a sensor array, each sensor being differently functionalized with a specific layer, each one targeting one single gas in principle. However, it turns out theoretically and experimentally that this concept does not allow estimating the composition of a mixture, even with few analytes. Instead, we have proposed to improve through miniaturization a very classical approach based on the association of a gas-chromatography (GC) column and a detector. In practice, a multi-gas analyzer GC columns and crossbeams NEMS detectors has been demonstrated [11]. The GC provides selectivity by separating in time and space the gas mixture components while NEMS sequentially detect and quantify the elution peaks at the GC output. In fact, both GC column and detectors can be fabricated with CMOS-compatible VLSI silicon micro- and nanofabrication techniques, .as illustrated in figure 6.

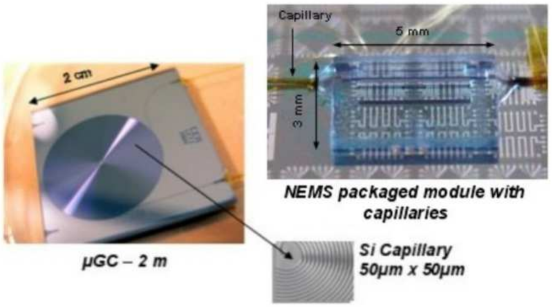


Fig. 6: miniaturized GC column and NEMS detector

Comparison of measurements performed on a test gas mixture by using both a Thermal Conductivity Detector (TCD) standard equipment (40x30x20 cm^3) and the Leti system are presented in figure 7.

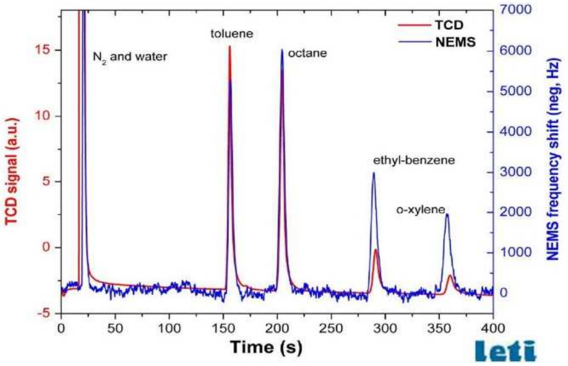


Fig. 7: Comparison of TCD and NEMS measurements.

It is shown that NEMS reach the same limit of detection, below the ppm level (in dynamic mode) and that ppb level can be achieved with pre-concentrator (e.g. for VOC measurements applications).

Based on these silicon nanotechnologies, a common Leti-Caltech start-up, APIX Technology, has been created to commercialize devices for multi-gas analysis [13]. Figure 8 presents the global system developed by APIX:

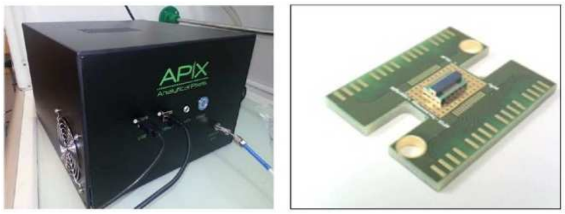
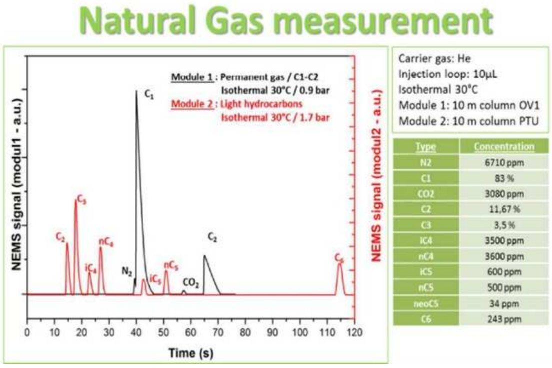


Fig. 8: nano Silicon technology based System for multi-gas analysis.

It targets applications such as petrochemicals, gas-based energy production, environment control (VOCs, Sulfur compounds, Air quality…), and portable tools for on-field measurements. Some measurements results obtained on natural gas are shown on figure 9.



Carrier gas: He
Injection loop: 10µL
Isothermal 30°C
Module 1: 10 m column OV1
Module 2: 10 m column PTU

Type	Concentration
N2	6710 ppm
C1	83 %
CO2	3080 ppm
C2	11,67 %
C3	3,5 %
iC4	3500 ppm
nC4	3600 ppm
iC5	600 ppm
nC5	500 ppm
neoC5	34 ppm
C6	243 ppm

Fig. 9: natural gas analysis by APIX

A SUPPORT PACKAGING PLATFORM

Micro and nano sytems are tied so closely with silicon processing that most of their packaging technologies are naturally derived from semiconductor microelectronics Wafer-Level Packaging technologies (and more specifically WLP with 3D interconnection for size reduction, better electrical connection and cost). However a specific customization is mandatory to take into account the constraints of mechanical and environmental protection. Particularly, in the inertial MEMS domain, well-controlled atmospheres must prevail during the entire life of the components. A support packaging platform is therefore backing MEMS and NEMS development at Leti, offering different packaging technologies (silicon or glass wafer caps, thin-film packaging) with controlled atmosphere, and possible implementation of non evaporable thin-film getters, with adjustable activation temperatures [14].

CONCLUSIONS.

MEMS and their technologies are now facing a maturity period in the area of physical sensors (inertial and pressure sensors). In parallel, the next wave will directly focus on chemical sensors with huge markets in environment, quality of life and medical markets. Although with different maturity levels, both areas require now to clearly focus on manufacturing simplification, increased integration and cost reduction. This approach must be accompanied by a strong push towards standardization. Taking into account these stringent requirements, Leti has launched two platforms matching the suitable MEMS technologies with different applications, helping industry to respond faster to the constantly growing demand in MEMS components.

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