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Nano Electro Mechanical Devices for Physical and Chemical Sensing

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The emergence of MEMS in consumer applications has dramatically increased market perspectives but also puts very strong constraints on cost and integration issues. Addressing these issues through further size reduction is not always relevant as it does not allow maintaining a correct signal to noise ratio (SNR) for the ubiquitous capacitive MEMS sensors. Different solutions are presented here according to the nature of the signal to be sensed: For physical sensors a new concept mixing a micron sized proof mass and a nano-sized detection structure is described. For chemical sensors, the reduction in size actually presents some advantages in terms of high resonant frequency, reduced gas damping, and high sensitivity to applied forces or added mass. Application of nano-resonators to gaz sensing is depicted.

Developed originally at the end of the 80's, Micro Electro Mechanical Systems (MEMS) have by now given rise to a mature industry generating this year almost a 10 billion US$ turnover: Silicon micromachining techniques made possible the realisation of ultra-miniature and low cost sensors that allowed the deployment of airbags in cars (MEMS accelerometers are used there to measure the deceleration related to an accident), and more recently, new functions in smart phones.

This deployment in large volume applications has triggered interest from large semiconductor industries (STM, TI, Freescale…) and a strong competition towards lower cost and higher integration: The new Grail of the industry is the realization of a 9 Degrees of Freedom sensor, combining the measurement in the 3 directions of space of acceleration, rotation speed and earth magnetic field.

As inspired by the semiconductor industry, an obvious answer to these needs is to further decrease the size of the sensors, from Micro to Nano Electro Mechanical Systems (NEMS). However, even taking apart the technological challenges, this is not that simple as physics laws are not always in favour of scaling down: A simple homothetic size reduction does not allow maintaining a correct signal to noise ratio (SNR). As it will be seen here, different types of sensors require different approaches.

Nano size detection for physical sensors.

As mentioned before, inertial sensors are becoming one of the most ubiquitous sensor today, with applications in industrial, automotive or consumer applications. Further miniaturization is highly sought, as it allows both to decrease the cost (proportional to the surface of silicon) and increase integration (mandatory in portable applications such as smartphones, tablets…). However simple reduction of the seismic mass affects the sensitivity and reduces the nominal capacitance (95% of commercial MEMS accelerometers use capacitive detection), thus reducing signal to noise ratio (SNR). To overcome these limitations, a new design and a new detection mode have been investigated, giving birth to the nicknamed M&NEMS concept. The basic idea is to combine on a same device a thicker MEMS layer for the inertial mass with a thinner and narrow NEMS part for detection [1].

- In the case of an accelerometer, the structure consists in:

- An inertial mass, suspended by one of its extremities by a hinge anchored to the substrate.
- A suspended nano-gauge fixed from one side to an extremity of the mass and from the other side to an anchor. This nano-gauge can be a simple silicon suspended beam used as a piezoresistive strain gauge [1], or a vibrating beam, in the case of a resonant accelerometer (both transduction means can be equally used).

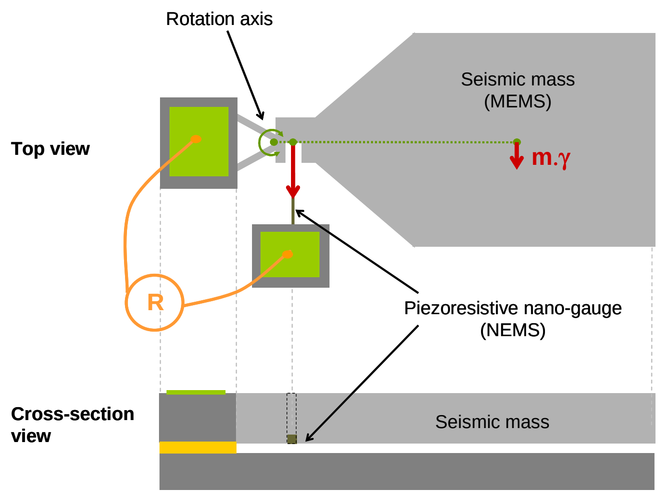
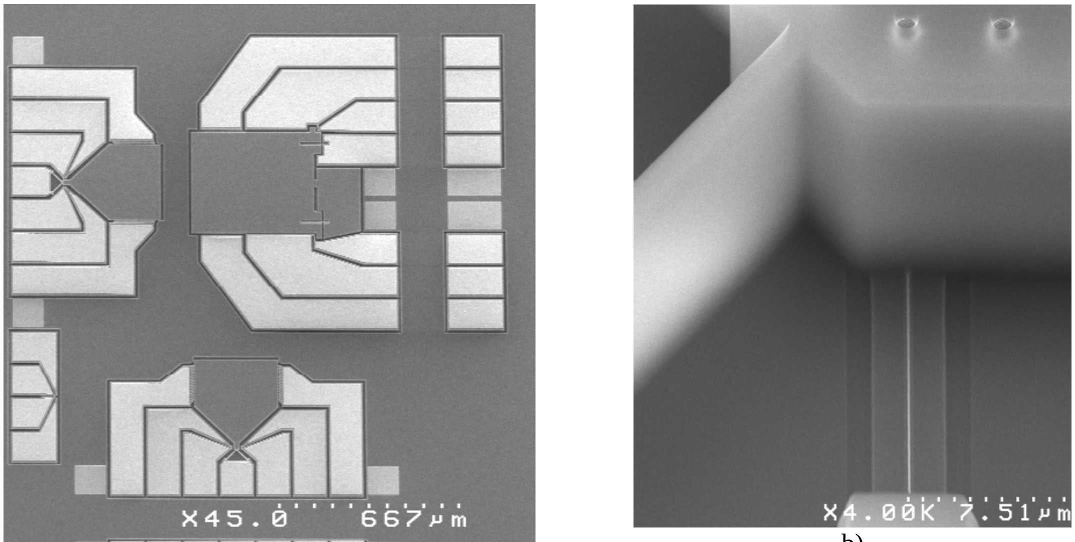


Figure 1: Structure of the M&NEMS in plane accelerometer.

The main advantages are:

- The use of piezoresistive nano gauges allows high efficiency of the transduction thanks to high stress concentration effect (very small cross-section of the silicon nanowire gauge), and a lever arm effect achieved by appropriate design.
- In-plane and out-of-plane detections are easily achieved on the same wafer as well as co-integration of multi-sensors (accelerometer, gyroscope, magnetometer and pressure sensor)
- Differential measurements allows minimization of thermal drift and non linear behaviour.

This ease of design allied with a significant gain in MEMS surface area for similar performances makes this technology very suitable for multi axis inertial sensors. In a first step, 3D accelerometers have been integrated in a single chip. Figure 2 shows an example of 3 axis accelerometer based on M&NEMS technology, with a magnification of the X/Y unit and of the associated nano-gauges. The typical dimensions of sensitive elements are below 0.4mm² per axis.



a) b)

Figure 2: a) 3 axis accelerometer base on M&NEMS technology b) magnification of the X/Y unit and of the associated nano-gauges.

A 3-axis gyrometer based on the well known tuning fork design has also been realized. Compared to state of the art MEMS gyrometer, the Coriolis force detection is done by suspended Si nanowire piezo-resistive gauge instead of the classical capacitive detection [2]–[4]. This M&NEMS concept of gyrometer enables the realization of extremely compact single-chip 3D gyroscopes while maintaining high performances: for consumer or automotive applications a size of the mechanical part of 0.5mm²/axis can be obtained while standard gyroscope sizes are higher than 1-2mm²/axis. The same concept has been recently adapted to a 3-axis magnetometer [5], therefore paving the way to the realization of an integrated and miniaturized 9 DOFs sensor.

Nano size detection for chemical sensors.

Down scaling MEMS sensors to nanometer dimensions present some advantages: Along with the small dimensions come low power consumption, potential high resonant frequency, and quality factors, fast response time and high sensitivity to applied force, external damping or additional mass. This makes NEMS particularly suitable for gas or, more generally, mass sensing.

Gas or bio sensors based on NEMS are formed of nano-resonators covered with a biocompatible layer suitable to adsorb the specific gas to be detected. As the resonance frequency of the NEMS resonator is function of its total mass, an additional mass causes a shift of the resonant frequency. The gas concentration is then evaluated by the measurement of the frequency shift (Figure 3)

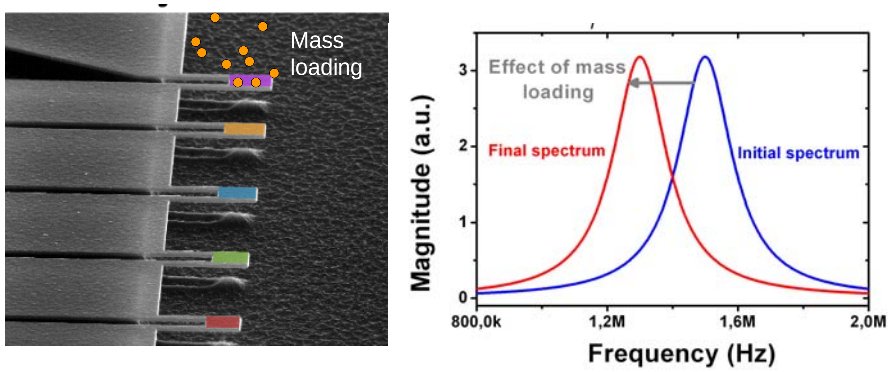


Figure 3: Frequency shift of NEMS resonators due to mass loading

Orders of magnitude improvement in mass sensing resolution has been demonstrated compared to other classical gravimetric sensors such as quartz crystal microbalance (QCM), surface or bulk acoustic wave (SAW, BAW), flexural plate wave (FPW) devices, and other microscale mechanical resonators [6].

This improvement stems from NEMS resonators miniature total mass, very high resonance frequency, and remarkable frequency stability. Gas sensors containing NEMS structures are thus one of the most promising ways for ultra-sensitive multi-gas sensor [7]. Down scaling of NEMS is particularly interesting for mass sensing and mass spectroscopy [8] because of the exceptional mass resolution achievable with ultra high frequency (UHF) NEMS resonators in vacuum medium.

The NEMS resonators have been realized using a top down approach, based on VLSI integration on 200 mm wafers: Advances in lithography techniques allow the realization of structures close in size to those achieved with bottom-up synthesis methods. The first realization has shown more than 2.5 million NEMS on the same wafer with a density approaching 60 000 resonators/mm² (Figure 4).

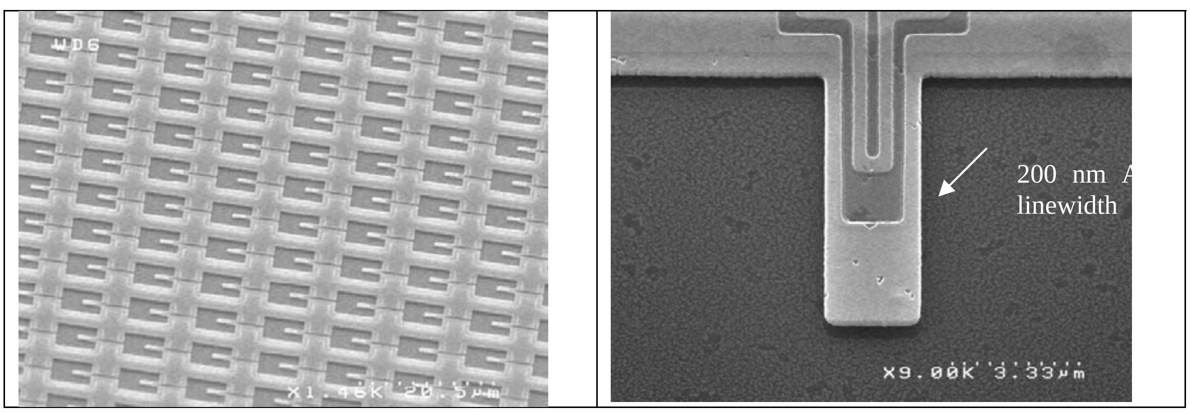


Figure 4 : a) Array of NEMS resonators and b) detail of a single resonator – Out of plane displacement configuration

Both in plane and out of plane (Fig 4 b)) resonators have been realized. Piezoresitive detection has been extensively explored as it seems an effective transduction principle at these dimensions. Electrical characterizations carried out on Out-of-Plane nano-resonators show that 600 zg/Hz mass response can be obtained [7]. An original mechanical structure –so called “cross-beam”- has also been proposed [9], embedding top-down nanowires (see Figure 5). It is based on suspended p^{++} doped piezoresistive nanowires connected in a symmetric bridge configuration to a resonating lever arm. The differential bridge architecture provides intrinsic signal amplification and background suppression. With this design, an outstanding mass sensitivity of 17 zg/Hz (1zg=10-21g) has been measured, corresponding to a mass resolution in air of 700 zg.

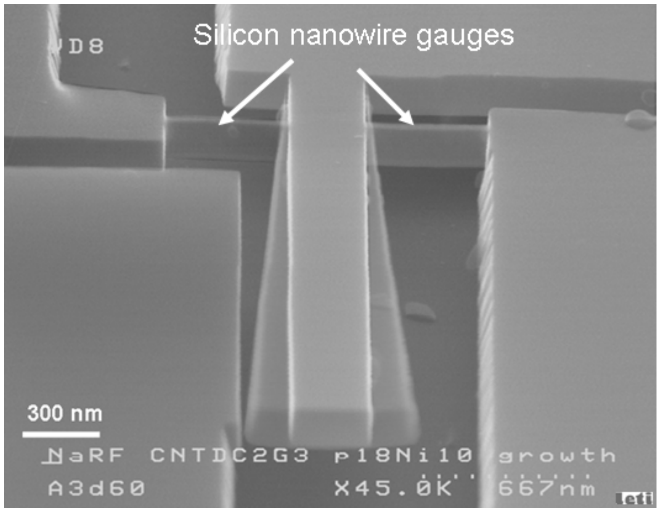


Figure 5 : SEM picture of a single resonator – In plane vibration .

Integration of these individual resonators in a system including gas chromatography column, and arrays of resonators with different fonctionalization layers pave the way towards miniaturized multi gas sensors. The GC provides selectivity by separating in time and space the gas mixture components while detectors sequentially detect the elution peaks at the GC output. Both GC column and detectors can be fabricated with CMOS-compatible VLSI silicon micro- and nanofabrication techniques. This system features state-of-the-art experimental results in terms of limit of GC-mediated gas detection: Figure 6 depicts a chromatogram obtained when coupling NEMS resonators to a 2m long capillary column. For each peak, the limit of detection (LOD) in terms of injected mass at the column input is below the ng level. This is at the state-of-the-art when compared to a Thermal Conductivity Detector (TCD) which is the detector used in currently existing miniaturized GC systems.

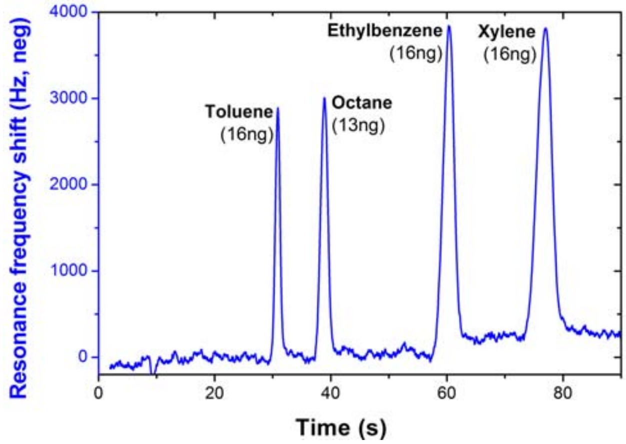


Figure 6: Chromatogram measured by a crossbeam NEMS placed behind a standard 2m long capillary column (at 50°C). Brackets indicate the amount of analyte injected into the GC column.

Besides performances, NEMS provide unique advantages compared to TCD: they do not require Helium as a carrier gas, clean air can be used what is much easier to implement a portable system. Furthermore, the parallel use (with NEMS) of different sensitive layers further increases the degree of separation of a gas mixture [7].

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