MEMS and NEMS

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This paper is about the impact of scaling on the system performance of mechanical inertia sensors and first activities towards nano mechanical sensors. Permanent cost pressure will result in continuous efforts to integrate more functions into further miniaturized systems. As a consequence microsystems (MEMS) may also incorporate functional nano devices such as carbon nanotubes in the future. Therefore an overview of recent activities for the application of carbon nanotubes with a focus on mechanical sensors is provided.
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Introduction

Requests for further miniaturization of microsystems may certainly result in serious efforts to integrate nano scale functional devices in microsystems. New materials with new properties on the nano scale will emerge. In this paper, limitations for microsystems scaling and current research activities in the field of nanostructures are discussed in general and first proposals to realize mechanical sensors based on carbon nanotubes (CNT) are introduced in particular. This paper is mostly about mechanical sensors and systems on the micro and nano scale.

After more than 20 years of microsystems research and development it seems inappropriate to include a definition of microsystems once again. But due to some evolution of these definitions over the years it should be mentioned that microsystems or MEMS (both phrases are used as synonyms) are considered in this paper as systems that involve electronic and non-electronic elements and functions on the micro scale. This may also include sensing functions, signal acquisition and processing, control, actuation, display functions and means for performing chemical and biochemical interactions. The system aspects comprise also system partitioning, (V)LSI of non-electronic elements, calibration, signal-to-noise-ratio, stability, reliability and first of all assembly, packaging and test. This definition follows in most points the one given by Senturia [2]. Prominent examples of such microsystems and products are TI's DMD™ device [3], ADI's inertia sensors [4] or Infineon's surface micromachined integrated pressure sensors [5], [6].

Consequently, a definition for nanosystems follows: Nanosystems involve electronic and non-electronic elements and functions on the nano scale for sensing, actuation, signal processing, display, control and / or interface functions.

Today there are yet not many examples available that might fulfill this definition of nanosystems. Two examples might be IBM's "Millipede" [1] and Samsung's field emission display based on carbon nanotubes [7] the function of which is defined by electron emitting CNTs sealed in a flat vacuum package that also incorporates the picture generating phosphorus layers at a distance of 200 µm from the CNTs. Besides Samsung other companies like Motorola and Sony have been engaged in the development of field emission displays (FED). An excellent overview and summary of the state-of-the-art is provided by Itoh [8].

Scaling of Capacitive Force Sensors

Cost issues are in the foreground of the discussion about miniaturization. Researchers and product developers are spending tremendous efforts to further miniaturize integrated systems. They even accept the fate that in some cases, miniaturization does not support the physical system function per se. This is one of the most important differences between microelectronics and microsystems: While in microelectronics miniaturization and further integration, following Moore's Law, have succeeded in better performing transistors and systems until recently (smaller, faster, cheaper), inertia sensors do not benefit from scaling in general.

Table 1 summarizes the analysis of the system performance of three generalized and simplified examples of MEMS, i.e. pressure, acceleration and yaw rate sensors [9]. The performance is discussed with respect to scaling.

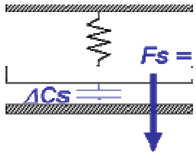
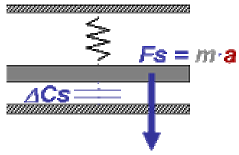
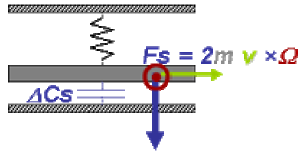
	Pressure p	**Acceleration a**	**Yaw rate Ω**
			
Sensing force	$F_s = \alpha^2 A_0\, \mathbf{p}$	$F_s = \alpha^3 m_0\, \mathbf{a}$	$F_s = 2\alpha^4 m_0 v_0\, \mathbf{\Omega}$
SNR_{opt} $x/\alpha d_0$=const.	~ 10log (const. α^2)	~ 10log (const. α^2)	~ 10log (const. α^2)
SNR_{opt} $\omega_{0,mech}$=const.	~ 10log (const. α^{-2})	~ 10log (const. 1)	~ 10log (const. α^2)

Table 1: Influence of miniaturization and scaling on system performance for pressure, acceleration and yaw rate sensors [9]. $\alpha < 1$ is the scaling factor for the dimensions of these simplified sensor models.

The signal-to-noise-ratio (SNR) at the output of a virtual ground amplifier is taken as a measure of the performance of all three systems. For comparison reasons all sensors, even the pressure sensor, though it would not be straight forward to realize, are assumed to be differential capacitive sensors, forming a capacitive bridge at the input of the amplifier. The following evaluation also applies if one of the sensor capacitors is fixed and considered as a reference sensor (reduced sensitivity).

All three sensors measure a sensing force F_s as a result of the physical unit applied that displaces the sensing electrode against a spring force. The change of the distance to a counter electrode is measured by the change of the respective capacitance ΔC_s.

Equation (1) gives the SNR of the sensor systems in dependence of the capacitance change and a number of constants that depend on technology, only. Furthermore, the sensor capacitance C_s is assumed to be smaller than the parasitic capacitances C_{par} of the setup, even in case of monolithic integration of MEMS and the circuit.

Numerous constraints exist when scaling a particular device, including design, process and electro-mechanical considerations. Most of them are design specific and therefore cannot be considered from a general viewpoint, but two constraints are common to all measurement systems, namely the minimum required measurement range and the minimum required measurement bandwidth. While the scaling of the mass is predefined by the scaling of the geometrical dimensions, the spring constant is considered as a free design parameter. Its choice has to satisfy these two constraints.

$$SNR_{opt} = 10\log\left(const_{tech}\frac{\Delta C_s^{\ 2}}{C_{par}}\right) \tag{1}$$

$$C_s << C_{par}, \qquad const_{tech} = \frac{9\mu V_{in}^{\ 2} V_{d,sat}}{4k_B T B_{el} L^2}$$

B_{el}:	Electrical bandwith	μ:	Carrier mobility
V_{in}:	Input voltage	L:	Gate length
k_B:	Boltzman constant	$V_{d,sat}$:	Saturation voltage
T:	Absolute temperature		

In the case of an open loop system (case $x/\alpha d_0$ = const. in Table 1) the minimum required measurement range, which is related to the maximum relative displacement, dominates the choice of the spring constant.

Force feedback systems (case ω_{mech} = const. in Table 1) can overcome this limitation, if the feedback force can handle the measurement range. Then the minimum required mechanical bandwidth, which determines the noise bandwidth, determines the choice of the spring constant.

The results of scaling on the pressure and inertia sensors are achieved by substituting for ΔC_s in Eqn. (1) with expressions achieved by scaling down the sensors' geometry (Table 1) It is obvious that in general scaling of inertia sensors will reduce the system performance of miniaturized systems ($\alpha < 1$ is the scaling factor for the dimensions of these simplified sensor models). Only in the case of force feedback systems with reduced spring constants compensating for the reduction of size and mass accelerometers are scaling invariant. Pressure sensors are less sensitive to scaling, or may even improve, if the thickness of the sensor's membrane can be easily scaled down (reducing spring constant).

In concluding this section about scaling, it is shown that at least in the case of yaw rate sensors miniaturization will not improve the sensor's performance per se. There are possible solutions available that will help escape this scaling trap. These solutions will be implemented by complex system designs.

Nano Mechanical Sensors

CNT integration into MEMS for actuation and electrical interfacing has been proposed to characterize the electro mechanical properties of nanotubes [11], [12]. Figure 1 shows the realization of that kind of a test stand [13]. A single walled carbon nanotube (SWCNT) is assembled between two fixed Ti/Au electrodes (50 nm thick). AFM cantilevers can be used to apply forces and bending moments on the suspended SWCNT by deflecting the released cantilever structure. It is obvious that this kind of MEMS structures can also be used as electromechanical interfaces for CNT based mechanical sensors. Figure 2 shows clearly the embedded carbon nanotube (CNT).

Current research on CNT based nano transducers could be classified roughly in two categories: (i) Sensors that take advantage of the small dimensions of the tube to interact with structures and surfaces on atomic and molecular level and (ii) sensors that take advantage of unique (e.g. electronic) properties of nanotubes to interact with the macroscopic environment.

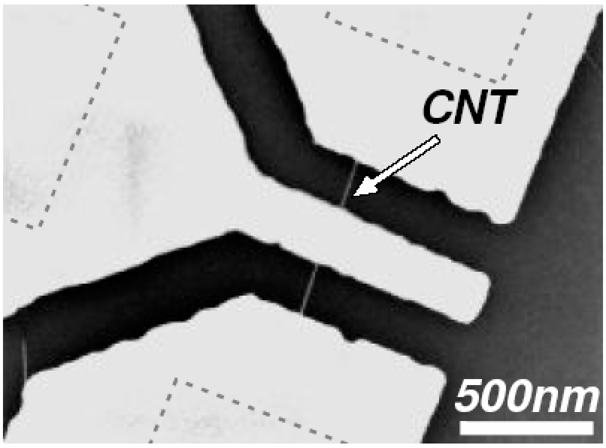


Fig. 1: SEM image of a suspended single walled carbon nano-tube, contacted by two fixed electrodes and a released cantilever (50 nm Ti/Au). The dashed lines indicate anchor areas [13].

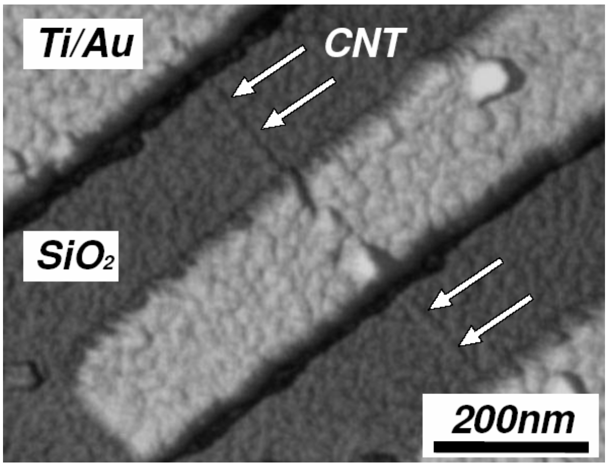


Fig. 2: AFM image of a contacted single walled carbon nanotube (diameter approx. 1.2 nm) on 1.5 µm SiO_2 before HF release. Gold electrodes on top are 30 nm thick [13].

Important representatives of the first category (i) are CNTs that are used as AFM probe tips [14]. CNTs are placed on the tips of conventional AFM probes either by manipulation or direct catalytic growth. The effective radii of those CNT tips are reported to be in the range of 3 nm (SWCNT) – 6 nm (MWCNT) [15] and at least of half size of etched silicon tips. An increase in lateral resolution of up to 70% was achieved by imaging gold nanostructures compared to the resolution achieved with silicon tips. Additional advantages are the typical high aspect ratio of the cylindrical CNT that is advantageous for imaging narrow and steep features and the elastic buckling of the tube above a low critical force that avoids the damage of the device under test (e.g. organic and biological samples). Furthermore it was shown [16] that the CNT tip's end can be modified to create probes that can sense matter on the molecular level by very distinct chemical functionality.

Mechanical sensors of category (ii) are reported in the area of strain sensors. A substrate (matrix) material (e.g. polymer) is filled with CNTs and investigated by Raman spectroscopy [17]. In SWCNT the position of the D* Raman band strongly depends on the strain transferred from the substrate to the nanotubes. The spatial resolution of the measurement is around 1 μm and is limited by the spot of the Raman laser. This method is used to measure stress fields around defects in polymers and tensile strain in materials.

A new approach to apply SWCNTs as stress sensors on the macro scale is reported in [18]. SWCNTs mixed with DMF (N,N-dimethylformamide), filtered and dried, resulting in a 10 μm thick film of randomly orientated SWCNT bundles (buckypaper) is fabricated and attached to a device under test. The resistance of the CNT layer is measured by a four point probe technique. The measured voltage shift is proportional to the applied stress or strain. Unfortunately there is no discussion about the performance of those CNT strain sensors compared to conventional strain gauges. However, the authors claim that the described approach allows incorporating CNTs directly into various materials (e.g. composites) to realize integrated strain sensors.

Very recently a PMMA-based micro pressure sensor was reported [19] using bulk multi walled CNTs as piezoresistive sensing elements. The MWCNTs are attached to gold electrodes on top of the membrane by AC electrophoretic manipulation of the nanotubes. By applying pressure to the membrane the tubes are strained and the resistance of the tubes is increasing. The gauge factor of the tubes is estimated and reported to be 235.

The direct integration of CNTs into MEMS devices could result in the next generation of nanotransducers for the evaluation of mechanical loads. To realize these nanotransducers, it is mandatory to control and reproduce the assembly, or better the growth, of nanostructures from one point of catalyst to another. Self assembly of nanostructures instead of structuring by photolithographic means will be the preferred process technology approach for manufacturing of these structures. Recently [20], [21], field assisted growth of CNTs was demonstrated to control the alignment of CNTs between two separate areas of Fe catalysts on silicon or molybdenum electrodes, respectively.

Fabrication of nanostructures by means of self-assembly instead of planar photolithography and etch steps will reduce fabrication complexity and costs significantly. In concluding this section about nanosystems one should emphasize that nanosystems are not just miniaturized microsystems. New process technologies towards self-assembly and the utilization of new sensing principles based on quantum effects will help to avoid the scaling trap of microsystems. Basic research is needed to integrate nanostructures into MEMS on wafer level to characterize performance based on statistical data and to provide defined electrical and mechanical interfaces of nanostructures to the micro and macro world.

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