Nano-structure or Nano-system: Opportunities and Pitfalls

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ABSTRACT

Scaling down has revealed many new effects leading to new devices able to measure faster and more accurately than traditional devices. They also present challenges in terms of connecting to the macro-world and in reliability. In some cases the scaling works against us leading to lower performance. We should also consider reducing the size of the system, through integration and optimisation. It is therefore important to consider the benefits of miniaturisation for each application and either reduce the size of the structures in the system, or integrate the system to reduce size. This paper discusses the effects of scaling both devices and systems.

Keywords: scaling, microsystems, smart sensors

1 INTRODUCTION

Moore predicted the miniaturisation in the IC industry in the 1960's and we have seen the dramatic reduction in feature size with the improved performance [1]. For 40 years the IC industry has followed this law.

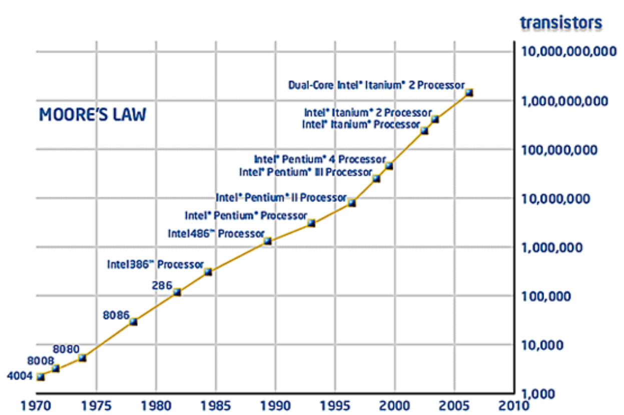

Figure 1 Moore's law and the IC industry [2]

This scaling, however, will come to an end requiring a new look at device structure and device physics. Machining has perhaps not seen such a dramatic change but scaling can be found here as well, from fine mechanics to micromachining and later to nano-machining. Fine mechanics was based on assembly techniques, whereas micromachining made use of depositions and etching. Moving to nano-machining has involved combinations of micromachining techniques (top-down) and structure growth (bottom-up).

The benefits, or drawbacks, of further scaling depend on the structure and the application and therefore we should consider both the feature size of structures and also the size of the total system. The scaling of pumps from the macro-scale to the micro-scale has led to great benefits in the bio-chemical and medical industries enabling the pumping of μl or nl of fluid. Further scaling down will probably not benefit these applications. However, nano-fluidics enables individual cell handling.

2 SCALING

In nature we see the adaptation to scale. Smaller creatures often have fine limbs and have to deal with heat loss. Larger creatures need strong limbs and have to be able to lose excess heat, a fact often forgotten in films where giant people have normal proportions. Also, as we scale down the surface area scales with L^2 and the volume with L^3. This means that nano structure have a much larger surface area to volume ratio. We can use this to our advantage if we are using the surface to capture molecules or cells, but on the other hand, this can have drawbacks since changes in the surface (such as oxidation) can considerably change the structure's operation.

When scaling, we need to consider both the individual devices and also the system to decide whether we should reduce the size. For example, with an integrated sensor, the sensor itself may be only a small part of the chip and therefore further reduction in size should only be considered if there are benefits in terms of functionality, in the same volume rather than a reduced chip size.

2.1 Accelerometer

Micro-accelerometers are usually based on a mass supported by a spring, where either the movement of mass or the stress in the spring is measured. Reducing the mass makes it more difficult to achieve high sensitivity. Examples in the literature can be found of accelerometers with high resolution (μg) use bulk micromachining where the mass is in the milli-gramme range. One device which achieved high sensitivity and low noise, combined surface and bulk micromachined in a highly symmetrical device [3]. This device is illustrated in Figure 2. Improved sensitivity to small movement can also be achieved using readout techniques such as tunnelling [4].

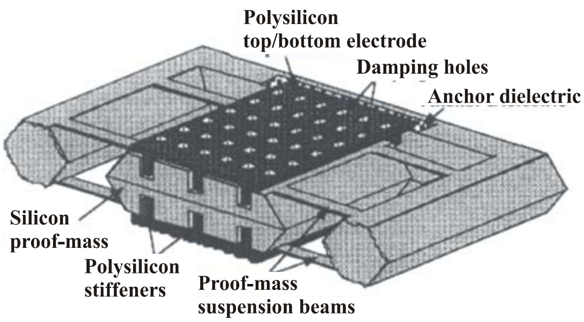

Figure 2 Micro-g accelerometer using bulk and surface micromachining [3].

An example of a complete micromachined system on a chip is the Analog Devices accelerometer, which contains all the read-out electronics and self-test on a single chip. A photograph of the chip is shown in Figure 3. Devices have been produced for ± 1g, 2g and 50g (for example). The functionality has been increased in a miniaturised package, although the accelerometer used surface micromachining and not nanomachining. This chip contain full read-out electronics and self-test.

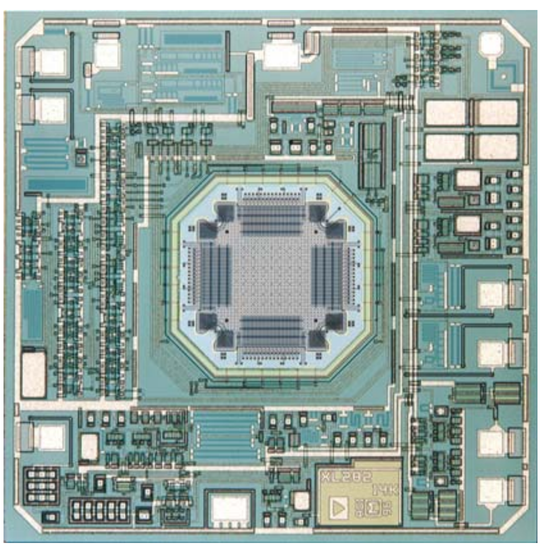

Figure 3 Analog Devices 2 axis accelerometer (reproduced with kind permission).

Surface micromachined accelerometers have proof-masses in the range of sub-μgramme and the measurement range usually ± 1g or higher [5-7]. In this case great benefit can be gained from miniaturisation of the system through integration, creating a complete systems on a chip but further miniaturisation of the device will not help. Most of the surface micromachined accelerometers are lateral accelerometers, although there are examples of vertical devices [8]. An example of such a device is given in Figure 4. Further scaling of the accelerometer would result in a higher resonant frequency but the reduced proof-mass would make it difficult to achieve a high resolution

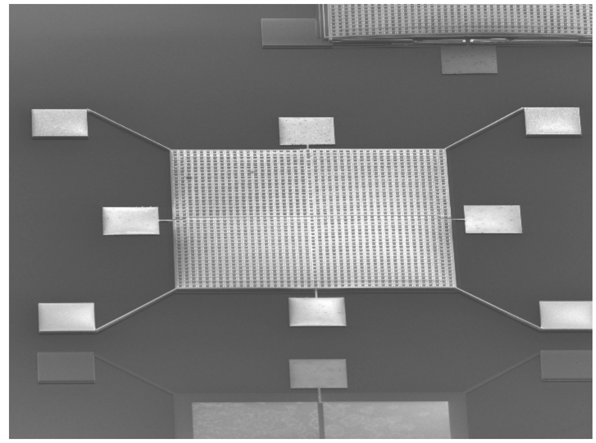

Figure 4 Vertical accelerometer using surface micromachined SiC and Aluminium [8].

2.2 Micro-pump

Miniaturisation of pumps has yielded many benefits in chemistry, biology and medicine. The ability to accurately pump μl or nl per minute can reduce cost (by using less sample) and enable studies at cell level. Activation of the pump at this scale can be, amongst others, thermal, piezoelectric or electrostatic. Miniaturisation of the system has also enabled implantable systems for medical applications. Early micro-pumps did not perform as expected due to changes in fluid properties which were not taken into account. However, understanding of fluid properties on the microscale has led to a range of applications. Most pumps are fabricated using bulk micromachining with dimensions of a few millimetres [9-10]. However, there are also examples of surface micromachined pumps [11].

2.3 Micro- nano-fluidics

The challenge with scaling fluid systems further is the increase in resistance with decreasing size. However, the benefits of nano-fluidics are that analysis at cell or molecule level can be achieved, and also the sample size can be reduced. Fluids can be drawn through the channels using electro-osmosis, to the position where they can be measured. Sub-micron distance between pillars allows DNA to be separated by length [12]. The DNA is drawn through a channel containing the pillars. The speed that the DNA travels is a function of the DNA sample length. This is achieved by forming macro-pore arrays in silicon, followed by the oxidation of the inside of the pores. Removing the silicon using TMAH leaves the oxide pillar array, where the distance between the pillars can be controlled by the oxide thickness. The resulting structure is shown in Figure 5.

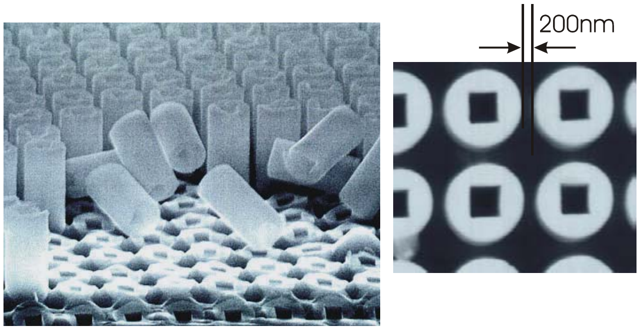

Figure 5 Oxide pillar arrays with sub-micron spacing for DNA separation [12].

Miniaturisation can bring fluid samples down to atto-litre allowing analysis of single molecules [13]. An example of such a system is given in Figure 6. The hole array containing the reaction chambers is given in Figure 7 [13].

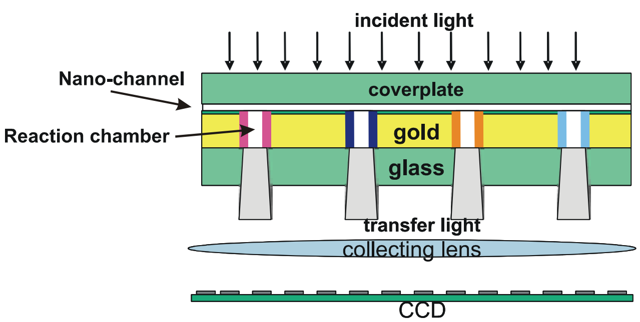

Figure 6 Schematic of the atto-litre plate device [13].

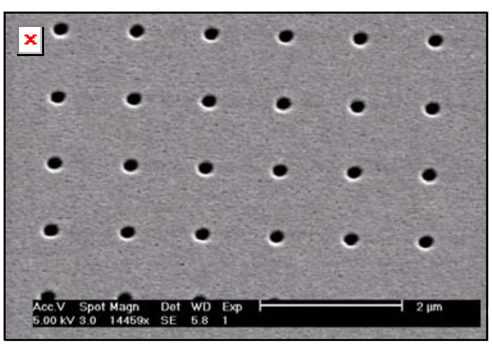

Figure 7 SEM picture of a hole-array in 200nm of Au/Pd, with the hole size of ~175nm and pitch of 1050nm

2.4 Resonators

Simple cantilevers made from epitaxial silicon can be used as vibration sensors for frequencies into the kHz range [14].

Scaling of resonators leads to higher frequencies and new applications since, for example, molecule attached to the resonator will yield a clear change in resonant frequency, or detecting force with high accuracy [15]. Further reduction in size can lead to MHz and even GHz resonant frequencies [16-18].

There are a number of issues which have to be addressed when developing these devices – reliability, actuation and sensing. Some sensing techniques do not scale well or require large equipment, not permitting a reduction in the size of the system. (Tables 1 and 2).

Sensing				
Method	***Scaling limit***	***Scal-ability***	***Inte-gration***	***Other criteria***
Capacitive	Parasitic capacitance from the device and electronics.	Micron	++	Frequency dependent on RC time constant
Optical reflection displacement	Effective reflection from the structure. Force constant of the device	Micron	--	Optical device required
Optical interferometer	Effective reflection from the structure. Force constant of the device	Micron / nano	--	Complex, precision optics required
Magneto-motive	Detectable induced electromotive force	Nano	--	Stable, high magnetic field required. Double clamped device only.
SET charge	Detectable SET source-drain current due to Coulomb blockade of the SET	Nano	+	Cryogenic temperature, double clamped devices only
piezoelectric	Effective piezoelectric signal generated. Dimension related.	Micron / sub-micron	++	Piezoelectric material required. Multilayer structure for maximum signal output.
piesoresistive	Effective piezoresistive change. Dimension related	Micron / sub-micron	++	Piezoresistive material required. Multilayer.
Tunnelling	Not device dimension related	nano	++	Small initial electrode distances. High device impedance.

Table 1 Detection techniques and their scalability.

When fabricating cantilevers on the micro-scale, the fabrication techniques are top-down techniques. Further down-scaling often requires the bottom-up approach. Structures such as nano-wires and nano-tubes have shown properties able to detect quantum effects, for fundamental studies and also new sensors [19-20]

		Actuation		
Method	***Scaling limit***	***Scalability***	***Inte-gration***	***Other criteria***
Piezo-electric	No fundamental limit for piezoeffect	nano	++	Piezoelectric material, parasitic capacitance, frequency bandwidth limit.
Electro-static	No fundamental limit for coulomb force	nano	++	
Magneto-motive	No fundamental limit for Lorentz force	nano	--	Conductive double clamped devices. Stable, high magnetic field required.
Optical-thermal	Heat capacity of the device and its heat dissipation, dimension related.	Micon/ submicron	--	Limited frequency response, optical system required.

Table 2 Actuation techniques and their scalability

3 CONCLUSIONS

Scaling from micro to nano can present many advantages but also many challenges. The advantages are very application specific. In some cases scaling can lead to greater accuracy, but in others it can actually reduce sensitivity. Therefore for each application the benefits and pitfalls of scaling need to be examined. The second aspect is that in many applications the size of the sensing device is not the issue, but the size of the system.

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