Scaling Issues and Design of MEMS

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Preface

The concept of scaling is fundamental in engineering design.

This book deals with the main issues in designing microelectromechanical systems (MEMS), taking into account the scaling item. This text includes a wide view of various types of MEMS. Moreover, the very important theme of energy supplies in MEMS has been accurately faced. Details of the design of complete MEMS are also reported, referring to the case of colonies of microrobots.

The book explores both theoretical aspects of MEMS models and experimental prototype validation. Analytical, numerical and experimental tools are widely discussed in order to give to the reader a completely clear view in understanding the main topics: to design by using 'scaling' techniques.

The topics discussed are related to the long experience of the authors in designing and in the realization of MEMS devices; the reported study is, in my opinion, at the top level in the considered area of research, moreover it establishes powerful tools to conceive emerging MEMS.

The efforts of the authors have led them to achieve a work where clearness and scientific exactness reached a perfect synchronism!

An accompanying website can be found at http://wiley.com/go/baglio_scaling

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Introduction

Accurate modelling and design of microelectromechanical systems (MEMS) cannot be adequately pursued without considering the large number of system interactions between micromechanical parts, many physical and chemical principles, analogue and digital circuits. Many research groups worldwide are effectively making progress in the computing-aided design (CAD) area, to improve significantly quality and design time. Moreover, the academic and industrial target is the definitive integration of micromechanical models with system level simulations.

Despite the fact that such a vast 'microworld' has also gained much space in several basic and advanced, academic courses worldwide, it is necessary to adopt a gradual approach in explaining such a significant quantity of interconnected concepts. Scaling issues of micromechanical systems hold an important role in this context, since almost all classical physical laws must be reviewed when the dimensions scale towards the micro- or nanoscale.

For this reason, while it is important to give a general view of MEMS designing and realization processes, each specific case, referring to the device typology, the used technology, as well as operating conditions (sensing or actuating purposes), and conditioning or driving circuits, must be accurately examined.

Scaling effects on MEMS can be in fact discussed inherently to modelling issues, designing issues, fabrication and micromachining issues. Then, even providing a complete view of scaling issues for these systems would take several efforts and involve many different competences over a relatively long time. One should start from modelling aspects, i.e. mechanical modelling, then continue with etching concepts and issues, i.e. those related to wet-etching procedures, and finally highly complex modelling or systems level simulation of such systems, including circuits.

Many research groups worldwide are not so far away from successfully realizing such aimed software supports, which could significantly improve modelling and designing efficiency in this field.

The aim of this book is that of providing a specific, somehow complementary, theoretical support to the thematic of scaling issues for microelectromechanical systems (MEMS). To do this, several different aspects inherent to the miniaturization of sensors and actuators are proposed in the various chapters, focusing on a general target that is the scaling of an autonomous microsystem.

For this reason, the content of this book covers scaling issues of devices that could be equipped on a microrobot. In this field, it is mandatory to consider scaling issues of energy sources, scaling of microactuators (which can permit the system moving or performing active tasks) and scaling of microsensors (for obtaining information on the system's status itself, or for gathering information on the surrounding environment).

As one can easily realize, also in this case it is not possible to examine all of the possible configurations for autonomous microsystems, due to the large spectrum of potential solutions, neither to define a general paradigm for modelling or designing such kinds of microelectromechanical devices. In fact, several different choices can be made in individuating optimal solutions for energy sources (thermal, electrostatic/capacitive, photo-thermo-electric, battery-powered, etc.), types of actuators (thermal actuators, electrostatic/capacitive, magnetic, piezoelectric, etc.) and particularly sensors.

For this reason, the choice of these authors was that of reporting general considerations of importance for scaling issues of MEMS and then discussing some alternative solutions for all of the three main aspects that always have to be taken into account.

Starting from Chapter 1, where a general discussion on the scaling issues of MEMS is given and related to real-device realizations, the following chapters report specific theoretical and practical issues on the scaling of actuators, sensors, energy sources and finally autonomous MEMS, e.g. microrobots.

In particular, in Chapter 2 the scaling of thermal actuators is discussed inherently to multilayer cantilever beams realized in a CMOS standard technology. In Chapters 3 and 4, the scaling of temperature and relative humidity sensors and magnetic (inductive) sensors are discussed, respectively. The vast class of micromechanical sensors is instead analysed in Chapter 5, with reference to the comparison of performance obtained with the same device realized by means of two different technologies. Importantly, in Chapter 6, the scaling issues of energy sources are considered with reference to innovative photo-thermo-mechanical and photo-thermo-electric energy supply strategies, and the combined use of both strategies is taken into account to investigate the efficiency.

Chapter 7 deals with the technologies and architectures for autonomous MEMS microrobots and reports the description of a real autonomous microsystem with a photo-thermal actuation strategy. In Chapter 8, some considerations on the non-easy ulterior moving towards the nanoscale are reported.

Finally, examples of scaling effects analyses are reported in Chapter 8, for microcantilever beams composed of two layers, together with the technical description of an open-source code realized through Matlab 6.5 for the common typologies of micromechanical devices. In particular, the aim of creating such open software instruments has been that of providing a rapid way to appreciate the effects of scaling on common microdevices that can be also operated as actuators (interdigitated combs) and sensors (mechanical plates, which could be operated as accelerometers and interdigitated combs). A user-friendly interface allows us to choose the adopted technology, the geometrical features of mechanical parts (as sustaining springs) and to evaluate the effects of scaling on the performance of devices. The implemented analytical models include static and pseudo-dynamic analysis of MEMS that are classically equivalent to second-order mass-spring-damper mechanical systems.

Since such software support is conceived to be developed and extended through the help of academic students that are introduced to MEMS, some suggestions on guidelines to be followed are provided to create interesting cultural, and therefore technical exchanges with the collaboration and supervision of authors.

1

Scaling of MEMS

1.1 INTRODUCTION TO SCALING ISSUES

The evolution of microelectronic devices has been characterized by the scaling of their characteristic feature size towards smaller dimensions. The reasons for such a scaling trend are the continuous research of better processing capabilities, which means a higher number of smaller transistors on the chip. Integrated circuits with typical feature sizes in the submicrometre range are currently fabricated and commercialized, and research is pushing such feature sizes towards the regime of a few tenths of nanometres, and even smaller.

Such an amazing revolution has not been limited only to purely electronic devices. In fact, the huge potential for lowcost and large-scale fabrication of semiconductor–microelectronics technologies has represented a very powerful and flexible platform for the conception and realization of miniaturized micromechanical structures, thus opening the way to the realization of miniaturized sensors and actuators. To these authors' knowledge, one of the earlier microelectromechanical systems date back to the end of the 1980s, at the 'Transducers' meeting in Tokyo, 1987, when the first examples of micromachined structures were presented (Gabriel, 1998).

Small mechanical features can be produced with many techniques, and several applications are well consolidated (just think of mechanical wristwatches). In such a sense, MEMS are not a novelty. What is really innovative, instead, is the fabrication process, which makes use of the

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same technologies and facilities used to produce integrated circuits. This will translate into two of the key characteristics of MEMS: lowcost, large volume batch fabrication and integration of mechanics and electronics on the same semiconductor substrate.

Having both mechanical structures and electronics, realized together on the same chip, means that simple mechanical features can be suitably functionalized and controlled in their operation by means of electronics, and that electronics can process information coming from mechanical parts. In other words, if one thinks of mechanical features on a chip as sensors and actuators, then the space of the signals the electronics can deal with will be greatly expanded, as the number of novel functionalities which can be integrated on the chip can achieve.

This is a result of the miniaturization of mechanical features and fabrication and integration with electronics. However, there is another key characteristic of MEMS that goes beyond the simple reproduction on the small scale of macroscopic, well-known, devices. This is *scaling*.

Scaling is intended as the set of effects which arise and/or change in their intensity when the dimensional scale changes by one or more orders of magnitude.

Since MEMS have mechanical features ‘sizing’ from a few millimetres down to hundreds or even tens of micrometres, there might be a 10-fold to 1000-fold shrinking in linear dimensions, compared to structures in the centimetres size range. Since the physical phenomena involved in the operation of a device may depend, in general, by the system’s linear dimensions to a certain power, the effect of such a dimensional scale change on the different parameters and laws governing the device will be weighted differently, and sometimes amazing results may arise.

As a typical example, one can report the relations among the linear dimensions, the surface and the volume of a given object, even for a simple cube for example, when its sides are isotropically scaled down by a factor of 10. The total surface of the objects then scales by a factor of 100, while its volume is 1000-fold smaller. This means, for example, that such an object will be 1000 times lighter but will experience only 1/100 of the friction when moving in a given medium.

If the object is a battery, its stored energy, which is proportional to volume, will be reduced 1000 times, while if the object is a source of radiating power, its energy transfer capability will be only 100 times smaller.

These examples may help to make clear, here, what scaling means and which consequence it has on the operation of devices. The relative influence of parameters and effects governing the operation of a given device changes when the linear dimensions of such devices are scaled down (or up). Phenomena which are commonly negligible to the macroscale may become important, or even dominant, at the microscale, and vice versa. Such changes in the relative importance of these phenomena may either favour or hamper the operation of a given miniaturized device, and this is very important to understand before facing the realization of a new device.

In all of those cases where scaling leads to advantages in the device's operation, this represents an added value for MEMS which goes beyond the simple fact of miniaturizing a macroscopic object.

There is another, maybe more important, key characteristic of MEMS. This derives from the phenomenon of 'change-of-weight', which follows a 'change-of-scale'. MEMS operate at a scale, the microscale, where the governing physical phenomena are the same of the 'macroworld', but in many cases they intervene with different weights with respect to the more common 'macroscale'. The different relative importance of physical effects and phenomena which can be experienced at the microscale allows for the conception of novel devices, which exploit different operating principles and perform better than their macroscale counterparts. In other words, MEMS may represent the enabling technology to a wider arena of potential applications which were inefficient, unfeasible or even unconceivable at the macroscale.

Such a type of regime of innovative applications and technology, which could be considered a significant portion of the 'Plenty of room at the bottom', envisioned by Richard Feynman in his historical lecture on miniaturization (Feynman, 1959), has not yet been fully explored and although many research efforts have been devoted to it.

The deep comprehension of scaling mechanisms and laws is of crucial importance for the effective development of these novel technologies and applications, since a critical and careful analysis of scaling leads to better optimized solutions, exploiting advantageous operating principles and working more efficiently. This means that scaling is an important design parameter which helps the designer in the choice of the best sensing/driving method for a given application at a given scale.

Thanks to miniaturization, integration with electronics and the phenomenon's change-of-scale, MEMS represents a technology to realize smaller, better and 'smarter' objects. In addition, scaling laws are the tool to apply such technologies in an efficient way.

A further 'shrinking' of both electronic and electromechanical devices will 'enter them' into new dimensional scales, i.e. the mesoscale and the nanoscale. Some quantummechanical effects become observable and therefore the device models must take these into account. In the case of electronic devices, some of these quantum mechanical effects may represent fundamental limits for further, future MOSFET scaling, while other effects provide the basic principles for new generations of electronic devices. In the case of electromechanical systems, this scaling step will provide higher sensitivities to the alteration of the system's physical properties, suitable instruments for the study of the new phenomena that characterize such a mesoscale and that represent the key for the comprehension of phenomena at the nanoscale (atomic or molecular scale).

In this chapter, the scaling paradigms for electronics and electromechanical devices, starting from the microscale and going down to the atomic and molecular scale, are analysed and compared.

1.2 EXAMPLES OF DIMENSIONAL SCALING POTENTIALS

In this section, some scaling effects and laws will be examined by taking into account some elementary microdevice structures.

1.2.1 Scaling effects on a cantilever beam

Consider a cantilever beam made of a given material (uniform and isotropic), having dimensions L, w and t (length, width and thickness, respectively). Let the cantilever have L along the x-axis, w along the y-axis and t along the z-axis.

Given ρ as the density of the material, the mass of the cantilever is:

$$M = \rho L w t \tag{1.1}$$

The elastic constant along the z-direction can be expressed as:

$$K_z = 12\frac{YI}{L^3} \tag{1.2}$$

where Y is the material's Young modulus and I is the cross-sectional momentum of inertia, which is proportional to wt^3.

Given l as the generic linear dimension, M scales as l^3, and K_z scales as l, or linearly with l. Let's assume the notation $M = [l^3]$ and $K_z = [l]$

to indicate that M and K_z scale with the third and the first power of the linear dimension, respectively.

For example, if one scales the linear dimensions of a cantilever by a factor of 10, isomorphically, say $l' = 0.1l$, then the corresponding scaled mass and elastic constant are, respectively: $M' = 0.001M$ and $K_z' = 0.1K_z$. This means that the 10 times linearly scaled cantilever is 1000 times lighter, but only 10 times less stiff than its non-scaled counterpart; therefore, the scaled version has an improved mechanical robustness.

A suitable excitation can drive the cantilever to vibrate at its own resonance frequency ω, which is given by:

$$\omega = \sqrt{\frac{K}{M}} \tag{1.3}$$

Therefore, it can be easily seen that $\omega = l^{-1}$, which gives for the linearly scaled cantilever, $\omega' = 10\omega$.

The vibrating cantilever may be used as a mass sensor by measuring its resonance frequency shift with respect to a reference, or 'unloaded', value ω_0, due to a change in the mass:

$$M = M_0 + m + M_0\left(1 + \frac{m}{M_0}\right) \tag{1.4}$$

where M is the total mass, M_0 is the 'unloaded' mass and m is the mass change. Thus, the resonance frequency becomes:

$$\omega = \frac{\omega_0}{\sqrt{1 + \frac{m}{M_0}}} \tag{1.5}$$

The sensitivity of the resonance frequency to mass change can be expressed as the derivative of ω with respect to m:

$$S = \frac{\mathrm{d}\omega}{\mathrm{d}m} = -\frac{1}{2}\frac{\omega_0/M_0}{\sqrt{(1 + m/M_0)^3}} \tag{1.6}$$

where $S = l^{-4}$, which means that $S' = 10\ 000S$, i.e. a linear scale factor of 10 in the dimensions of a cantilever beam leads to a 10 000-fold improvement in sensitivity of resonance frequency to mass change, which also means that smaller cantilever beams can potentially detect even smaller masses or mass changes.

The application of a force F to the cantilever tip, along the z-axis, will displace the tip by an amount δ, which can be thought of as a fraction of the cantilever's length L. F and δ are related by Hooke's law:

$$F = K_z \delta \tag{1.7}$$

Then, the force required to achieve a given displacement δ scales as $F = [l^2]$ and thus $F' = 0.01F$. The same relative displacement can be achieved on a 10-fold scaled cantilever with a 100 times smaller force.

The amount of work performed (energy spent) to displace the cantilever tip is:

$$W = F\delta \tag{1.8}$$

and this scales as $W = l^3$, which means that the energy required (actuation energy) to achieve a given relative tip displacement in a 10-fold smaller cantilever is 1000 times less than the non-scaled one.

Another example of scaling effects will be analysed by taking into account the operation of a cantilever-beam-based device as an inertial sensor. Since a cantilever beam is a suspended mass, it could, in principle, be operated as an inertial sensor to measure, for example, acceleration. Such a system can be modelled from a mechanical point of view, as a mass-spring-damper system, as represented in Figure 1.1. If the system experiences an acceleration, the mass is subjected to a force proportional to the acceleration, which is contrasted by the spring elastic reaction and the damping given by the surrounding medium. At equilibrium, the acceleration produces a net displacement of the mass position (i.e. the cantilever tip). Newton's 2nd Law gives:

$$M\ddot{x} + D\dot{x} + Kx = -Ma \tag{1.9}$$

By supposing that the acceleration a has a sinusoidal dependence on time, the previous equation can be solved in the frequency (or $j\omega$) domain:

$$-\omega^2 Mx + j\omega Dx + Kx = -Ma \tag{1.10}$$

The acceleration can be read by measurement of the displacement of the proof mass (cantilever beam) or the mechanical stress in the spring

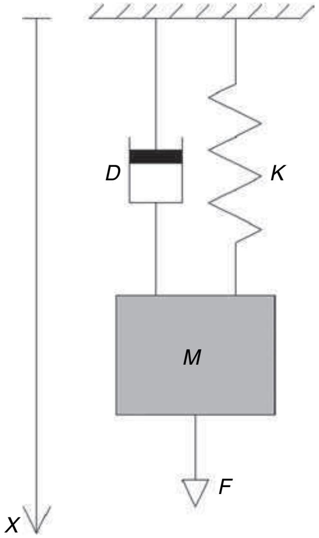

Figure 1.1 Simplified mechanical modelling of an inertial sensor as a mass-spring-damper system

(cantilever body), which is proportional to the force (acceleration); therefore, the frequency response of the system in terms of mass (tip) displacement vs. acceleration is:

$$x = \frac{-M/K}{1 + j\omega\dfrac{D}{K} - \omega^2\dfrac{M}{K}} \tag{1.11}$$

and the resonance frequency of the system is:

$$\omega_0 = \sqrt{\frac{K}{M}} \tag{1.12}$$

If the acceleration a is constant or slowly varying with time, the previous equation for the system's frequency response can be approximated by its DC value – thus:

$$x = -\frac{M}{K}a \tag{1.13}$$

The sensitivity of such an inertial sensor in terms of mass (tip) displacement vs. acceleration is, therefore:

$$S = \frac{\mathrm{d}x}{\mathrm{d}a} = -\frac{M}{K} \tag{1.14}$$

It has been shown that the spring constant for such a cantilever beam scales linearly with linear dimension and thus if the simple inertial sensor described here is isomorphically scaled down by a factor of 10, its sensitivity to acceleration has a 100-fold reduction, i.e. the same acceleration produces a 100 times smaller displacement or, with the same achievable displacement, one can measure accelerations 100 times higher; thus, scaled structures are more suitable for the measurement of higher accelerations.

The example described here highlights another advantage of scaling on a simple structure such as a cantilever beam. Of course, the overall performance of an inertial sensor, as any kind of sensor, will depend on the adopted readout strategy and circuits. However, this is of no concern for this section and, moreover, it does not affect the generality of this discussion.

Further discussions on mechanical sensors will be addressed in Chapter 5, along with some other examples and cases study.

1.2.2 Scaling of electrostatic actuators

Other basic scaling effects can be examined by taking into account different structures and/or principles. The case of an electrostatic actuator based on a parallel-plate capacitor configuration, as shown in Figure 1.2, will be considered here.

The electrostatic energy W_e stored in such a capacitor, when it is charged to a voltage difference V between the two plates is:

$$W_e = \frac{1}{2}CV^2 = \frac{1}{2}\varepsilon_0 \frac{wv}{d}V^2 \tag{1.15}$$

For a given structure and dielectric material, the stored energy is 'upper-limited' by the dielectric breakdown voltage V_b, and therefore the

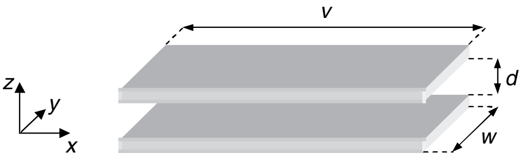

Figure 1.2 Parallel-plate capacitor

maximum energy is:

$$W_{\mathrm{e,m}} = \frac{1}{2}\varepsilon_0 \frac{wv}{d} {V_{\mathrm{b}}}^2 \tag{1.16}$$

In the case of a parallel-plate capacitor structure, the dielectric breakdown voltage can be written in terms of the breakdown electric field for the dielectric and its thickness, $V_{\mathrm{b}} = E_{\mathrm{b}}d$, and then is:

$$W_{\mathrm{e,m}} = \frac{1}{2}\varepsilon_0 wvd{E_{\mathrm{b}}}^2 \tag{1.17}$$

Since the permittivity and breakdown field are material properties, it follows that the electrostatic energy stored in a parallel-plate capacitor scales as its volume.

The analysis of scaling for electrostatic actuators allows the observation of a first phenomenon due to change of scale. In the previous discussion about the maximum voltage a dielectric layer can sustain, it has been supposed that the breakdown electric field does not depend on dimensions; this leads to a breakdown voltage which scales linearly with the dielectric thickness. The thinner the dielectric, the lower is the voltage it can safely sustain, and therefore the smaller is the energy it can store. As a consequence of such a scaling effect, miniaturization of electrostatic devices, and especially actuators, appears to be inefficient.

If the dielectric is a gaseous one, as supposed in the previous analysis, the conclusion commonly holds at the macroscale, while a significant deviation from such behaviour can be observed when the dielectric thickness approaches the micron range. The breakdown of dielectrics is an ‘avalanche effect’; thus, it appears at field values as smaller as the higher is the number of potential charge carriers that can be generated and this contributes to the effect. As the dielectric thickness is reduced, the total number of atoms or molecules contained in the gas volume decreases, and then the probability of collisions is reduced, which translates in an effective increase of the breakdown threshold. This is known as the *Paschen effect* and represents one of the phenomena that become more important in a change of scale, and in particular it allows realizing electrostatic microdevices more efficiently than one would predict on a first view. For example, a breakdown electric field of the order of 10^8 V/m has been reported for small gaps (Bart *et al.*, 1988), while the highest breakdown field measured in vacuum is reported to be 3×10^8 V/m (Madou, 2002), which are well above the 3×10^6 V/m observed at the macroscale.