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MEMS Technology-An Overview on Scaling Advantages and Issues

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Abstract**—**In this era of “think small,” one would intuitively simply scale down the size of all components to a device to make it small. Unfortunately, the reality does not work out that way. It is true that nothing is there to stop one from downsizing the device components to make the device small. There are, however, serious physical consequences of scaling down many physical quantities. This paper will present, with the scaling mechanisms that are available in microelectromechanical systems (MEMS). It is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of microfabrication. The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters. Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move

Keywords**—** Integrated-circuit (IC); MEMS; Scaling.

I. INTRODUCTION

The miniaturization of electrical circuits and systems continues to fuel a technological revolution responsible for a $200B integrated-circuit (IC) industry, which has fundamentally changed the world economy and the way our society lives and works. Many products created by the IC industry enable the inexpensive production of extremely useful and popular electronic systems (e.g., personal computers, computer networks, instrumentation, cell phones,sophisticated electronic appliances etc).The miniaturization of nearly all other types of device and system is arguably an even greater opportunity for commercial profit and beneficial technological advances (e.g., micromechanical, microfluidic, microthermal, micromagnetic, microoptical and microchemical) [1]. However, instead of the traditional evolutionary engineering effort to reduce size and power while simultaneously increasing the performance of such a diverse set of systems, the field of microelectromechanical systems (MEMS) represents an effort to radically transform the scale, performance and cost of these systems by employing batch-fabrication techniques and the economies of scale successfully exploited by the IC industry [2]. Specifically, MEMS technology has enabled many types of sensor, actuator and system to be reduced in size by orders of magnitude, while often even improving sensor performance (e.g. inertial sensors, optical switch arrays, biochemical analysis system).

II. SCALING ADVANTAGES AND ISSUES

When miniaturizing any device or system, it is critical to have a good understanding of the scaling properties of the transduction mechanism, the overall design, the materials and the fabrication processes involved. The scaling properties of any one of these components could present a formidable barrier to adequate performance or economic feasibility. Due to powerful scaling functions and the sheer magnitude of the scaling involved (i.e., MEMS can be more than 1000 times smaller than their macroscopic counterpart).

A. Influence of scaling on material properties

When designing microfabricated devices, it is important to be aware that the properties of thin-film materials are often significantly different from their bulk or macroscale form. Much of this disparity arises from the difference in the processes used to produce thin-film materials and bulk materials. An additional source of variation is the fact that the assumption of homogeneity, commonly used with accuracy for bulk materials, becomes unreliable when used to model devices that have dimensions on the same scale as individual grains and other microscopic fluctuations in material properties. Thus, local changes in grain size and other characteristics could significantly alter the performance of MEMS produced either together (i.e., in one batch) or from batch to batch. One potential advantage of scaling MEMS to densities approaching the defect density of the material is that devices can be produced with a very low total defect count. This is one reason why the reliability of some MEMS, particularly those of simple mechanical design (e.g., cantilevers), can have better reliability than macroscopic versions [3]. However, due to the high surface-to-volume ratio of MEMS, more attention must be paid to controlling their surface characteristics. Important material properties to characterize include elastic modulus, Poisson’s ratio, fracture stress, yield stress, residual in-plane stress, vertical stress gradient, conductivity etc. Due to the flexibility of

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microfabrication, it is typically convenient to integrate microstructures that can be used to provide in situ measurements of material properties [4].Many such microstructures have been used to reveal that thin-film material properties can vary tremendously from film to film without careful process control. In fact, any high-precision and high-reliability MEMS application requires that significant effort be directed toward quantifying the precise material properties of the films being employed.

B. *Scaling mechanical systems*

From common experience we have all observed that small insects can survive a fall from a great height without significant damage and are capable of lifting objects many times their size or weight. This is due in part to the fact that mass is proportional to the volume of an object. When the linear dimensions of an object are reduced by a factor of s, the volume and hence the mass of the object is reduced by a factor of s^3. However, when a mechanical flexure (e.g., cantilever beam) is scaled down by a factor s, it mechanical stiffness,

$$k=w.t^{3}.E/4L^{3}\ldots\ldots\ldots.(1)$$

with beam width w, thickness t, length L and elastic modulus E, is only scaled down by a factor of s [14]. Clearly the mechanical strength of an object is reduced much more slowly (s) than the inertial force it can generate (s^3).

A beneficial consequence of this scaling characteristic is that MEMS can withstand tremendous accelerations without breaking or even being significantly disturbed. One extreme example is the fact that a micromechanical accelerometer survived being fired from a tank (i.e., experiencing more than a ~1,00,000 g acceleration) even though the package and surrounding components, all of larger scale, did not fare as well. A negative consequence of the diminishing significance of inertial forces on the micrometer scale is that devices requiring proof masses (e.g.accelerometers) must have motion-detection systems with a much higher sensitivity.

C. *Scaling fluidic systems*

The dynamics of fluids in microscale systems is another example of how inadequate our macroscale experience is for predicting microscale behavior. The Reynolds number, which is a measure of flow turbulence (e.g., $Re < 2000$ representing laminar flow and $Re > 4000$ representing turbulent flow), is a function of the scale of the fluidic system, as shown in equation

$$Re=\rho\cdot V\cdot D/\mu\ldots\ldots\ldots\ldots(2)$$

with density ρ, characteristic velocity V, characteristic length or diameter D and viscosity μ[5]. It is not surprising that although we commonly observe turbulent and chaotic fluid flow in most macroscopic systems, fluid flow in microscopic systems is almost entirely dominated by laminar flow conditions (i.e., as the dimensions of the fluidic system are scaled down by s, Re will also be scaled down by s and thus fluid flow becomes more laminar on a microscale). In fact, because of this behavior it is very challenging to accomplish thorough mixing in microfluidic systems.Although this behavior is expected from equation (2), actually quantifying the overall behavior of fluids on the microscale is not adequately predicted by the existing constitutive equations. Presently there are a number of efforts in the MEMS research and development community to improve our ability to model microfluidic systems.

D. *Scaling chemical and biological systems*

The scaling of chemical systems is limited by fundamental tradeoff between sample size and detection limit. Although it is typically advantageous to reduce the sample size, in a fixed concentration the total number of molecules that are available to be detected will also be reduced. Therefore, an increasingly sensitive detector will be needed but an obvious cut-off at detecting a single molecule is limiting. This tradeoff is illustrated in figure 1.

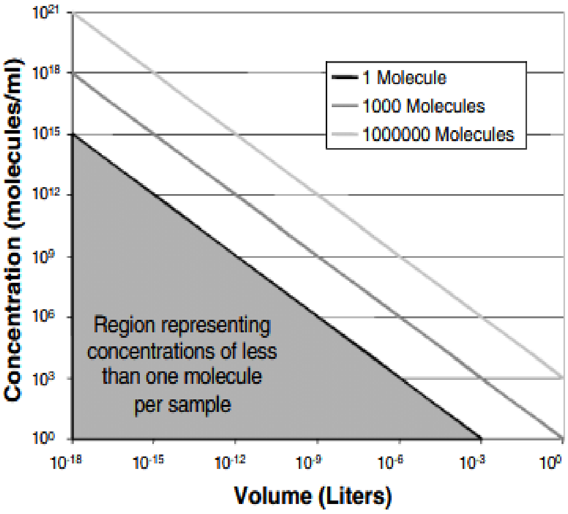

Fig 1.Tradeoff between sample size and detection limit

Most systems interfacing with biology are multidisciplinary (e.g. fluidic, electronic, mechanical etc) and thus the scaling properties of any of these components can limit the overall scaling of the system. The miniaturization of systems that interface with biology is also often limited by the application and the size of the relevant biological elements. For example, devices for manipulating cells can only be scaled down to cell-scale dimensions (e.g., typically 5–20 μm) whereas devices based on molecular function (e.g. DNA analysis)can be made considerably smaller. In addition, it has long been understood that microscopic biological organisms can overcome the detection-limit barrier, illustrated in figure 1,by using a gain mechanism (e.g., the generation of second-messenger molecules in response to the presence of a single target molecule.

E. *Scaling thermal systems*

Some of the scaling properties of thermal systems can be easily predicted by analyzing the basic relationships involved. For example, as the linear dimensions of an object are reduced by s, the thermal mass of an object (i.e., the thermal capacity times the volume) will scale down more rapidly (s^3) than the rate of heat transfer (s^2). The result is that rapidly removing the heat from a microscale object is typically a simple matter since the heat can conduct in all directions (e.g. submersed in a fluid). However, since it is easy to micro-fabricate delicate structures that only allow heat conduction along paths of very high thermal resistance, it is also a simple matter to achieve very good thermal isolation (e.g., a device on a very thin membrane supported by long and narrow tethers made of a material with a high thermal resistivity).A more careful analysis is needed to predict the thermal behavior of miniature structures when they are scaled down to sub-micron dimensions, the reason being that at these dimensions the structure and its elements are of the same scale as the quantum mechanical phonon, or lattice vibrations,responsible for carrying heat energy. It is possible to construct sub-micron-scale devices where heat conduction can be significantly curtailed in a controlled fashion.

F. Scaling electrical and magnetic systems.

Clearly the IC industry has shown that electrical systems, particularly circuits of resistors, capacitors, diodes and transistors, can be scaled tremendously with largely predictable behavior. However, a more careful analysis is needed for the case of electrostatic actuators. A figure of merit for actuators is the density of field energy U that can be stored in the gap between a rotor and stator.

For the case of electrostatic actuator, the field energy density is

U electrostatic =1/2ε·E^2 with permittivity ε and electric field E. The maximum energy density of electrostatic actuators is limited by the maximum field that can be applied before electrostatic breakdown occurs. Macroscopically this maximum field is a constant(∼3MVm−1) and the resulting energy density is only 40 J m−3.For magnetostatic actuators the field energy density is U magnetostatic =½(B^2/μ) with permeability μ and magnetic flux density B. The maximum energy density of magnetic actuators is essentially limited by saturation flux density Bsat, which is typically on the order of1Tor1Vsm−2 and the resulting energy density is 400 000 J m−3(i.e.10,000 times larger than U electrostatic for macroscopic devices).

Clearly, from the two cases above, we see that magnetic actuators can store many times more recoverable energy in the gaps between rotors and stators. Thus magnetic actuators dominate in the macroscopic world. This relative situation remains the same as devices are scaled down in size.

However,as the air gap becomes smaller fewer ionization collisions happen and a larger field can be applied before a cascade electrostatic breakdown occurs. This trend continues until the gap is made small enough so that eventually a larger voltage must be applied in order for breakdown to occur. A plot of the breakdown voltage as a function of electrode gap, known as the Paschen curve, is given in figure 2.

The consequence for MEMS is that with gaps on the order1μm, much larger voltages can be applied, that result in much larger electric fields and consequentially much larger energy densities.

The gap at which the maximum possible energy density of electrostatic actuators exceeds that of magnetic actuators is shown in figure 3 to be ∼2μm. However, if reasonable voltages are considered, a much smaller gap will be needed to achieve the equivalent energy density of magnetic actuators (e.g., ∼0.05 μm for 10 V).From figures 2 and 3 we see that the maximum energy density of magnetic actuators is not a function of air gap size.

However, practical issues, such as resistive power losses and the integration of the necessary windings, are challenges to the extreme miniaturization of magnetic actuators. In addition,the size of magnetic domains (i.e., regions of material with uniform magnetization) is typically on the scale of micrometers in soft magnetic materials (e.g., NiFe), which are commonly used to produce magnetic MEMS.

Therefore, the macroscopic assumption (i.e., the material consists of enough domains to ignore them individually and to only consider the ensemble average), will not be valid and new more complex models are needed for accurate and reliable prediction of experimental results. If magnetic MEMS are reduced to dimensions smaller than a typical domain, then the behavior will be dominated by single-domain phenomena

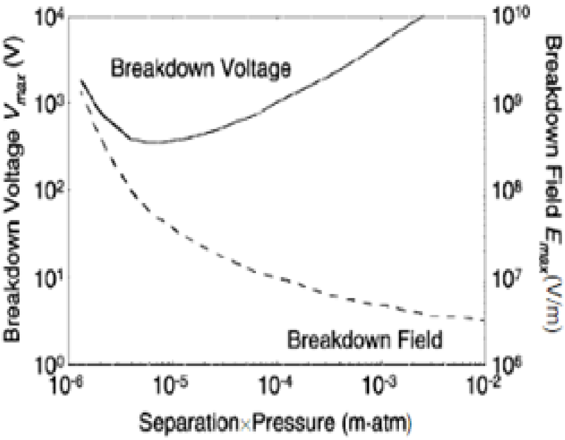

Fig 2.The Paschen Curve

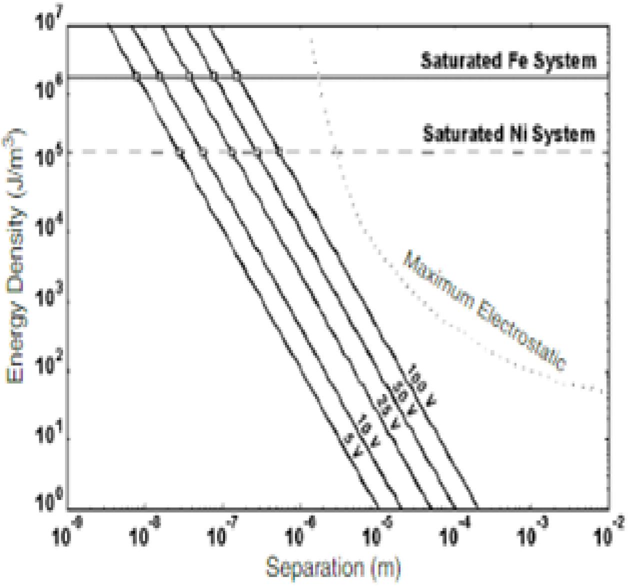

Fig 3. Comparison of electrostatic and magnetic energy densities as a function of rotor–stator gap

G. Scaling optical systems

Microfabrication techniques have already been used to produce miniaturized optical systems (e.g., LEDs, lasers, integrated waveguides, mirrors and diffraction gratings). Due to the size of the wavelength of visible light (e.g., typically near 650 nm for red to approximately 475 nm for blue), the dimensions of integrated optical components are typically not smaller than this value.The behavior of scaled optical components is well predicted by existing constitutive equations.[fresnel equation].

III. CONCLUSION

All the microelectromechanical system (MEMS) devices can be combined with integrated circuits (ICs) for operation in larger electronic systems.The potential exists for MEMS to establish a second technological revolution of miniaturization that may create an industry that exceeds the IC industry in both size and impact on society.

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