Chapter 3.3

MICROSYSTEM TECHNOLOGY FOR AMBIENT INTELLIGENCE

Geert Langereis
Philips Research Eindhoven
geert.langereis@philips.com

Abstract Sensor systems using microsystem technology are essential components to make our daily environment responsive. Microsystem technology enables widespread use of distributed systems with sensory inputs due to intrinsic low costs, low power, a high integration level, and small size.

Keywords ambient intelligence (AmI); micro electromechanical systems (MEMS); microsystem technology (MST); miniaturised total analysis systems (μTAS); system-in-package (SiP)

1. DEFINITION OF MICROSYSTEMS

Before starting a discussion on the impact of microsystem technology (MST) for ambient intelligence (AmI), it is essential to define the field of technology. The original concept of micromachining has evolved towards a broad scope, which could not have been foreseen in the early days, not even by the visionary survey of Richard Feynman [1, 2].

At the end of the 1970s and the beginning of the 1980s, the field of micro electromechanical systems (MEMS) originated from silicon technology. It was seen as the next logical step from integrated electronics towards surface-micromachining and bulk-micromachining integrated with control electronics. Already in an early phase, people managed to make micropumps in silicon for moving fluids. This initiated the trend towards microplumbing on wafer-scale by the creation of fluidic channels. Since then the term *microsystem technology* (MST) has become more common than solely MEMS.

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Scientists realized that fluid handling became even more interesting when (bio)chemical and physical sensors were integrated with the fluid handling system. The result is the trend towards a *Lab-on–a-chip* also known as *miniaturized total analysis systems* (μTAS).

Current problems in the field of microsystems are with respect to packaging the system, hence the commonly used name *system-in-package* (SiP). SiPs are the solution for chemical–mechanical sensor and actuator systems including industrial manufacturing and packaging concepts.

Even besides the broadening from the mechanical domain towards chemical and fluidic systems, I would like to widen the scope further. The sensory enablers for AmI do not necessarily have to be created using silicon technology. The SiP approach gives us the opportunity to package different types of technologies. Technologies which are sometimes more suitable with respect to costs, manufacturability, and performance can easily be integrated into a single package. The result is an omni-disciplinary field of physical domains and manufacturing technologies enabling the creation of smart interfacing nodes between microelectronics and our environment.

2. WHAT DO MICROSYSTEMS MEAN FOR AmI?

According to the Cambridge International Dictionary of English [3] the word *intelligence* means *The ability to understand and learn and make judgments or have opinions that are based on reason*. Let us have a closer look at the properties this dictionary attributes to the concept of intelligence.

Obviously, the ability to learn refers to *sensors* for collecting data. However, the definition is more specific than just referring to the collection of data. It requires an intelligent system to be capable of *making judgments* based on the sensor readings. For ambient intelligence this implies that sensor systems must be integrated with electronics for *data processing*. System designers will read *making judgments after reasoning* as retrieving signals from a noisy background, pretreatment of the data, and combining sensor readings in order to output reliable information.

But what is the consequence of putting intelligence in our environment, for example to create AmI*? When integrating reasoning sensors in our equipment and surroundings of daily life, these sensors should be small, numerous, and cheap. Therefore, miniaturization is essential, just as multiplicity and a high level of integration of all system components. Integration of sensor

*When using the word "intelligence" to refer to the level of adaptation in our environment, a direct consequence is that an "Ambient Intelligence Quotient" (AIQ) can be defined. The regime should be clear: when an igloo has the AIQ of a moron, the Home-lab at the High-Tech Campus in Eindhoven comes close to the 150.

systems in all types of materials, from fabrics to plastics, in all thinkable form factors requires the development of new fabrication technologies in new materials. Besides a direct consequence on the sensing element, the packaging method is exposed to specific AmI constraints as well. So, for AmI we need small devices, integrated with electronics into SiP solutions. This is exactly what was defined as being the microsystem mission in Section 1.

3. MICROCOSMOS

An amazing view on the boundless world of insects can be seen in the movie *Microcosmos* by Jacques Perrin [4]. This movie shows the industrious life of tiny little creatures filmed with macro-lenses in order to create a bug's eye view.

While observing the activities of insects on a millimeter scale, we may notice some remarkable things. The body of a swallowtail butterfly is huge with respect to its fragile legs. We can see a beetle rolling a stone of twice its size at tremendous speed. Surface tension makes water boatmen walking on the water and helps the carnivorous sundew plant to cover a grasshopper completely with a film of digestive juices. We can actually see a droplet of water evaporating. But the most surprising, however, is the water spider who collects air bubbles to make an under water nest in which it nibbles its freshly caught water flea.

Although they live in the same physical world as ours (i.e., where all the laws of physics are equal to ours), the viewer is over and over again deceived by his mechanical expectations. Our preciously built-up common sense of mechanics is fooled by ants and bugs!

What happens is that, although the physical laws are the same, the proportionality of physical effects differs. While surface tension can roughly be ignored in the centimeter and meter scale, it cannot be done so in the millimeter scale. A small water droplet evaporates at a rate that is significant with respect to its volume. The large stone appears to be lighter to the beetle than a rock of two meters would be to a human.

This movie can be the inspiration for every MEMS designer. It proves that while designing MEMS, we should abandon our common sense and reconsider the laws of physics.

4. SCALING AND MINIATURIZATION

The mismatch between our macroscopic mechanical sense and what is observed in the millimeter range can be physically explained by evaluating the art of scaling [5].

An example is shown in Figure 3.3-1. A cubic mass of size R^3 is suspended by a beam of length L, width b and thickness d. Due to gravity, the beam deflects and the mass displaces by a distance Δy. The mass of the cube is given by $m = R^3\rho$ with ρ the density of the cube material (we neglect the mass of the beam for simplicity). The spring constant of the beam is given by [6]

$$k = \frac{Ebd^3}{4L^3} \tag{3.3-1}$$

with E the Young's modulus. The force on the spring is equal to the force induced by gravity $F = k\Delta y = mg$ resulting into

$$\Delta y = \frac{\mathrm{m} \cdot \mathrm{g}}{k} = \frac{4\mathrm{g}\rho}{E}\frac{R^3L^3}{bd^3} \tag{3.3-2}$$

with g the gravity constant. When reducing the size of the structure of Figure 3.3-1, which means that each linear dimension is decreased by a factor of for example 0.1, the mass reduces by the power of three and the spring constant by the power of one. The result is that the deflection Δy does not reduce by a factor of 0.1, but by 0.1^2. Apparently, small structures appear to be stiffer. This is the reason that the body of a butterfly can be supported by legs, which are relatively thin with respect to the legs of larger animals.

A more general overview of scaling can be given by considering a certain relevant length S in physical structures. This length can be the length of an arm, the distance of an air-gap, or the thickness of a mem-

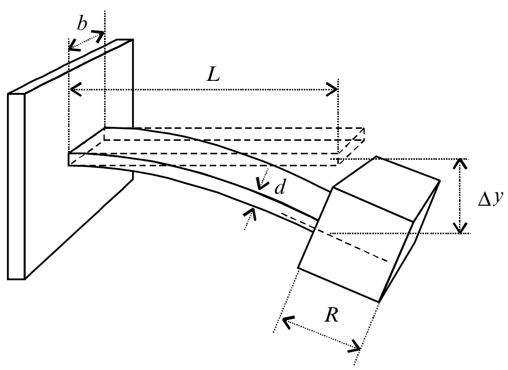

Figure 3.3-1. Deflection of a mass on a cantilever beam.

Table 3.3-1. Scaling laws.

Physical phenomenon	Scales with size S
Capacitor electric field	S^{-1}
Time	S^{0}
Van der Waal's forces	$S^{1/4}$
Diffusion	$S^{1/2}$
Size/velocity	S^{1}
Bending stiffness	S^{1}
Surface	S^{2}
Thermal loss	S^{2}
(Muscle) strength	S^{2}
Electrostatic force	S^{2}
Friction	S^{2}
Volume/Mass	S^{3}
Inertia	S^{3}
Magnetism	S^{3}

brane. As seen in the example above, masses of objects are related to volumes and therefore proportional to S^3. Bending strengths of beams are proportional to S as we have seen from Equation (3.3-1). The pulling strengths of beams and muscles are commonly proportional to their cross section S^2.

Capacitive transducers have the advantage that when reducing the air-gap, the capacitance and plate-to-plate force increases as S^{-1}. Very suitable for miniaturization, even when realizing that the capacitance decreases with S^2 as a function of the plate size. An example is the capacitive microphone, which needs an electret at normal scale to supply the hundreds of volts of biasing voltage. At micron scale the operational point can be biased from a simple low voltage power supply.

For magnetic transducers the situation is worse [7]. Assuming a constant current density through a wire or coil, the magnetic flux is proportional to S^3. For permanent magnets the scaling is proportional to the volume S^2.

More scaling rates are summarized in Table 3.3-1[†]. From top to bottom the phenomena are more dominant at a larger scale. MEMS devices are typically characterized by phenomena in the S^2 and lower domains. This means that magnetism, inertial forces, and masses are of lesser significance than surface tension, electrostatic forces, friction, and diffusion.

However, Table 3.3-1 does not say exactly at what dimension a certain phenomenon becomes prevailing. This depends on all specific geometries

[†] Note that some scaling powers are arguable depending on the configuration. For example, a force due to magnetic flux can be said to scale with S^3, although the magnetic force between two current carrying wires scales with S^4

and material properties. For certain phenomena there are some guidelines. In the field of microfluidics, the dimensionless Reynold's number is an indicator of whether flow is laminar or turbulent [5]. For large Reynold's numbers, convective and inertial forces dominate as we are used to with large objects in water. For small Reynold's numbers, on the other hand, viscosity is so large that transport of, for example, heat in the medium depends on diffusion rather than on convection. This will be the case in channels in the micron range.

Although time does not scale with size as a first order approximation, a smaller device will have a larger throughput. Microsystems will be faster in their response and consume less analyte in case of chemical systems. Diffusion based transport enables quick responses without the need for mechanical convective systems. This has resulted in static micromixers without moving parts [8]. Due to the fast diffusion processes, thermal and electrochemical actuation are new options for the creation of mechanical actions [9]. Another example of an application profiting from fast diffusion due to downscaling is the amperometric ultramicroelectrode [10].

5. OVERVIEW OF MST SENSOR TECHNOLOGY

Not all MEMS and SiP technology was created with AmI in mind. Whatever the motivation for the development was, miniaturization, manufacturability, and cost reduction must have been part of the goals. The result is a broad portfolio of sensory systems, which are available for giving our environment its sensing organs. All equivalences to the human sensory inputs are available: smell (e-nose), hearing (microphones), taste (chemical sensors), sight (camera), touch (temperature, pressure, and movement sensors). The following sections do not give an exhaustive list of devices covering all sensory inputs, just some highlights are picked out which indicate trends in this field.

5.1. Silicon Micromachining

Bulk silicon micromachining started with the development of anisotropic silicon etching in the 1960s to create free hanging masses and membranes. It took until the early 1980s before surface micromachining using sacrificial layer etching was developed. The step from bulk micromachining to surface micromachining enabled the fabrication of mechanical structures in the micron range and so the concept of MEMS was born. In the 1980s, MEMS using surface micromachining became a hype and this period was characterized by fancy SEM pictures of micromotors and gearwheels created using silicon sculpturing. Practical usefulness was initiated by some examples of MEMS dies with integrated electronics. A striking illustration of the trend in early MEMS is the difference between the bulk-micromachined accelerometers of 1979 [11] and the integrated surface micromachined equivalent of 1982 [12]. The step towards a commercial product took until 1991 when analog devices revealed its first MEMS-based silicon accelerometer with integrated electronics, the ADXL-50 [13].

Silicon accelerometers with integrated electronics have occupied the automotive market as the sensory input for airbag actuation. The automotive market has been a profitable playground for multiple MEMS applications. Currently various types of gyroscopes, air pressure sensors (airco, tire pressure, etc.) and flow sensors have entered the market.

Besides the automotive market, the second largest market is found in the application of nozzles for inkjet printing. First publications originate from the late 1970's [14]. Some manufacturers include the silicon inkjet nozzles in their cartridges, which include a high-tech technology in a disposable product.

In terms of shipment and revenue, the largest growing business at this moment in the field of MEMS devices is the RF-MEMS business with an annual growth rate of 148.5% for the shipment and 54.9% for the revenues [15]. The reason is that RF-MEMS appear to increase power efficiency and allow for reconfigurable networks in radio-frequency (RF) applications. Designing voltage-controlled oscillators, tuneable filters/antennas and adaptive impedance matching circuits requires the combination of a large tuning range, high quality (Q) factors and low switching voltages [16]. MEMS technology appears to be very suitable for accomplishing this. Common RF-MEMS technology uses metal parts for the conductors and air-gaps for the capacitors. This results in lower losses and better on/off ratios than with semiconductor solutions.

At this moment, 85% of the components in the RF section of a mobile phone are passives. These passives generally consume significant space and are therefore less suitable to be implemented in the same process as the active electronics. As a solution, a technology platform is developed which combines the passive components onto a single high-resistivity silicon substrate [17]. This passive chip can be integrated with an active chip into a single SiP solution, which can have a size reduction of up to 50% with respect to conventional technology. The technology used for this is the PASSI™ technology shown in Figure 3.3-2.

It is the result of optimizing electrical performance, mechanical performance, cost of manufacturing, and process compatibility to the existing

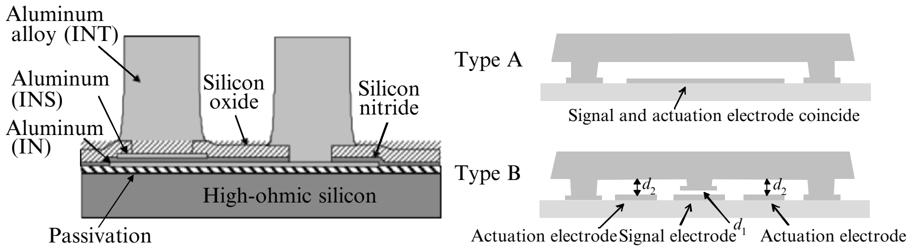

Figure 3.3-2. PASSI$^{\circledR}$ cross-sectional artist impression (left-hand) and arrangements into two types of capacitive MEMS structures (right-hand).

IC manufacturing infrastructure. The PASSI$^{\circledR}$ process stack consists of a high-ohmic silicon substrate and three aluminum layers with several silicon-dioxide and silicon-nitride insulation layers. The top aluminum layer is a 5 μm thick alloy and has a very low sheet resistance of 6 mΩ. It is therefore very suitable for defining interconnects, coplanar waveguides and high-Q inductors.

By selective sacrificial layer etching of one or more of the passivation layers, free hanging structures are made with two different air-gap sizes (right-hand of Figure 3.3-2). The lateral geometry is optimized to create good-quality RF-switches and tuneable capacitors as shown in Figure 3.3-3.

When the technology of dry etching macropores into silicon is added to PASSI-like processes, trench capacitors [18] can be realized with a high density of over 30 nF/mm^2. Such local capacitors are very suitable for supply-line decoupling in the GHz-regime in RF wireless communication. Breakdown voltages of over 30 V are realized, which show superior performance over conventional SMD implementations.

The PASSI$^{\circledR}$ technology is finalized by wafer-level encapsulation using a solder-sealing technique [19]. With such techniques, a cover is soldered

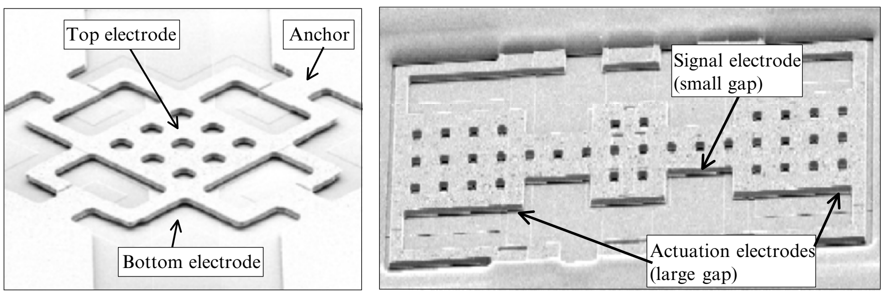

Figure 3.3-3. SEM pictures of a typical MEMS switch (left-hand) and a dual gap tuneable capacitor (right-hand).

on the wafer to cover the devices. In the soldering ring, a small hole is maintained through which air can be pumped out or through which a filling gas can be submitted. In a soldering reflow step the ring is closed subsequently. Thereafter, wafer dicing has become less critical.

So, surface micromachining has evolved into advanced systems like the RF-MEMS platforms for the creation of smaller circuits with better performance than conventional technology, optimized with respect to manufacturability. The PASSI™ technology places the passive components on the optimized PASSI-die while the active control electronics is on a conventional semiconductor substrate. Both dies are integrated into a single package.

5.2. Chemical Sensors

Generally speaking, chemical sensors consist of a selector part and a sensor part. The selector part determines a selectivity for a certain chemical or biological substance. Specific anticipation in the selection part results into modulation of a physical quantity in the sensor part which subsequently converts it into an electrical signal [20].

This two-stage set-up of chemical sensors results in typical key problems. Quantitative data from chemical and biological sensors are hampered by phenomena like drift, temperature changes and other interfering environmental conditions. The change in the selector part of the chemical sensor must be measured with respect to a certain reference. We have to deal with references in time and space. For example, electrochemical measurements require a closed electrical loop. This loop exists partially in the world of electrons and partially in the world of ions. When measuring the phenomena occurring at one ion/electron interface the interferences at the other ion/electron interface should remain unaffected. This is the problem of a reference in space, which requires the design of a proper reference electrode.

On the other hand, the reference in time is subject to drift. Interfering factors like temperature/pressure changes and diffusion of interfering gasses and chemical substances will cause an electric signal, which cannot be distinguished from the signal of interest.

Both types of reference problems can be cancelled out for a short period of time by means of calibration. To do this, the sensor must be placed in a known reference environment. With a one-point calibration we can cancel out effects like drift, with a two-step calibration we can determine the sensitivity as well.

However, there are more options which simplify the problem of drift under certain circumstances. One option is to use a stimulus-response measurement in which the local environment is disturbed deliberately in order to learn from the response due to this disturbance. In that case, the drift of the sensor has become less critical since the problem is shifted to applying a known disturbance, which is generally easier to realize in a microsystem.

The key problems with chemical sensors are illustrated by the biography of the *ion sensitive field effect transistor* (ISFET [21]). From that overview we can read between the lines that the search for market applications of the ISFET is guided by the development of methods to define a decent reference and to calibrate the system. One smart solution is the coulometric microtitrator as developed at the University of Twente [22] where electrochemically generated H^+ or OH^- ions are used to control the local pH in the vicinity of an ISFET. The result is a titration curve from which the end point is detected from a nonlinearity in the pH response. In that case, the pH sensor calibration is less critical since quantitative information is obtained from the integrated current as supplied to the generator electrode.

A more fundamental and systematic description of differential sensor-actuator systems is given in literature [23]. It shows that besides solving reference and calibration problems, differential measurements and stimulus-response measurements give access to the detection of new parameters in some cases.

A review on chemical sensors in general was published by Janata et al [24].

5.3. Fluid Handling and Tubes

The advantage of silicon chemical sensors is that they can be used to analyze tiny volumes. The small volume of analyte results in a fast response. This is especially convenient for DNA analysis where the analyte is scarce and expensive and where many samples have to be analyzed sequentially or in parallel. Operation of the analysis should be simplified by implementing the fluid handling in a microsystem. Such a microsystem is referred to as μTAS or *lab on a chip* [25].

A typical μTAS comprises:

- A fluidic channel system for analyte transport and sample manipulation.
- Reaction chambers, separation columns, calibration and washing liquid storage containers.
- An electrical layer.
- (Bio)chemical sensors and physical sensors (pressure, temperature, etc.).
- Sample insertion system.

- A user friendly and easy to manufacture packaging concept.

Channels and reaction chambers can be made by dry or wet etching on silicon substrates or glass [26]. In the early days of fluid handling, MEMS micropumps were proposed [27]. Later on, the advantages of miniaturization were adopted by using the electroosmotic flow principle [28]. Electroosmotic flow uses the charge double layer, which is present on the interface of a fluid and the surrounding walls to apply an electric force to the bulk fluid. One advantage is that the flow profile is uniform while it is parabolic with a pressure initiated flow. Electroosmotic fluidic systems can be used to split and join streams without using fragile moving parts.

All types of chemical assay can be carried out in fTAS approaches. Separation techniques like electrophoresis and chromatography can be miniaturized on a wafer. Sample insertion is shown in various ways, for example using microdialysis probes [29].

5.4. Optical Systems

The classical example of optical applications for MEMS are the digital micromirror devices (DMD's). These devices consist of 800 up to 1 million reflective plates having a size of $16 \times 16\,\mu m^2$ each. The mirrors can be tilted electrostatically by angles of up to 10° in order to reflect light from an incident source. The result is that pixels can be projected on a screen using nonpolarizing optics at a very high speed. The product is on the market by DLP™ products, a division of Texas Instruments [30].

Micromirrors benefit from miniaturization by means of the speed of the mechanical actuation. Mechanical actuation, however, suffers from wearing and material fatigue. This is not the case when mechanical motion is initiated by electrowetting principles, which appear to be very suitable for optical applications.

Electrowetting is the principle of liquid manipulation using electrostatic forces. If a volume of an aqueous liquid has a cross-section of the order of millimeters, it can be manipulated in shape and position. The Duke University in North Carolina has shown some interesting results with fluid transport using electrowetting [31, 32].

An example of an optical application of electrowetting is the variable-focus liquid lens [33] as shown in Figure 3.3-4. A cylindrical housing is used which is coated on the inner side with a transparent conductor, shielded from the liquid by an insulating hydrophobic coating. The cylinder is filled with two immiscible liquids having a different refractive index. One of the liquids is electrically conducting, for example an aqueous salt solution, the other is insulating, for example a nonpolar oil. If both liquids

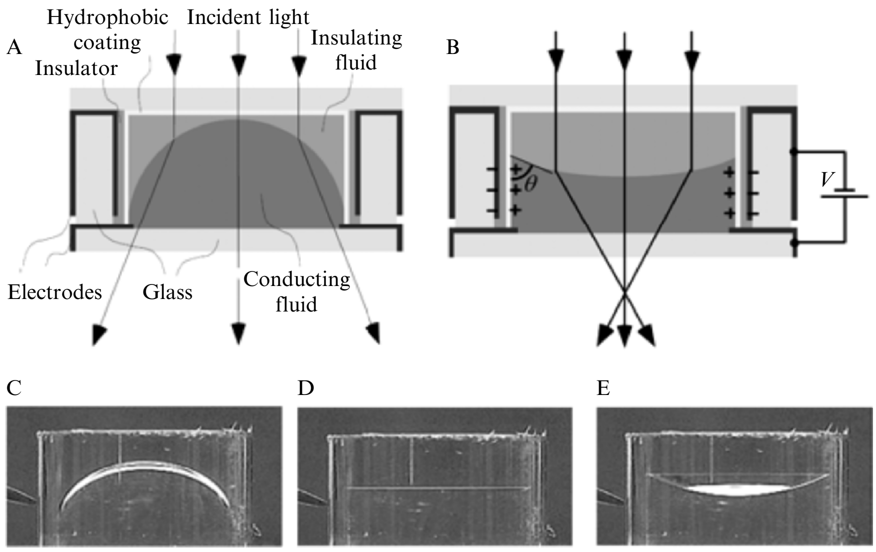

Figure 3.3-4. Schematic representation of the variable-focus liquid lens (A)–(B) and photographs showing the controllable meniscus (C)–(E).

have equal densities the shape of the meniscus is perfectly spherical, independent of orientation. A second electrical contact is made in the transparent bottom, which contacts the conductive fluid.

When a voltage is applied, charges accumulate in the wall electrode and opposite charges collect near the solid/liquid interface in the conducting liquid. The resulting electrostatic force effectively lowers the solid–liquid interfacial tension and with that the contact angle θ. Figure 3.3-4 (C) to (E) are snapshots of video frames of a 6 mm diameter lens taken at voltages of 0, 100, and 120 V. The switching speed is in the milliseconds range.

For camera applications, the adjustable lens can be integrated with corrector lenses, a CCD chip and control logic into a packaged image sensor. Typical applications of such devices are in the field of portable personal consumer electronics like PDA's and mobile phones where the increasing number of pixels requires lenses with adjustable focal distances.

Another example of the electrowetting principle for optical systems is the electrowetting display [34]. As shown in Figure 3.3-5, a colored oil film can be contracted into a localized droplet by applying a voltage. The transparent electrode yields a perfect reflective pixel principle when placed on a white background. When used in a full color system, the reflectivity is four times higher than in an LCD (67% versus 17%). A second advantage

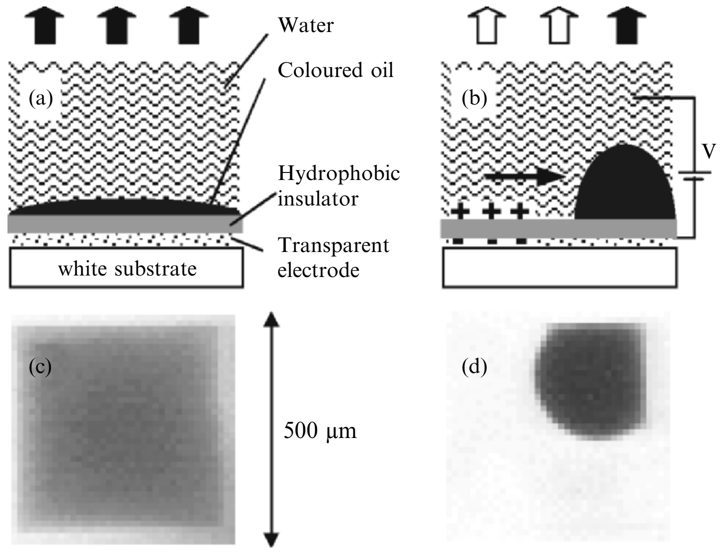

Figure 3.3-5. Electrowetting display principle. (a) No voltage applied, therefore a colored homogeneous oil film is present. (b) Voltage applied, causing the oil film to contract. Top row, diagrams; bottom row, photographs.

over an LCD is the wide viewing angle. Typical switching speeds below 10 ms are measured which is sufficient for a full motion display.

5.5. System Approaches

With respect to the academic MEMS work in the early days, publications in the field of MEMS have grown with respect to adaptation to the application. A good impression of present day work on MEMS can be obtained by scanning the special issue of the proceedings of the IEEE on biomedical applications for MEMS and microfluidics [35]. The presented microsystems are still illustrated by ingeniously fabricated three-dimensional structures, but the articles describe a real problem in the medical world and present an integrated microsystem providing a solution taking manufacturability and operability into consideration.

Consider the field of MEMS microphones. Common MEMS acoustical transducers are based on capacitive principles. An intrinsic problem of a capacitive transducer is the high output impedance, which requires dedicated preamplifiers placed close to the sensing device. The obvious solution is to design a technology in which the microphone and the preamplifier can be realized in CMOS technology on the same silicon die. Several examples are published [36, 37], where the latter one is a comprehensive approach to realize acoustical systems capable of measuring sound, on-chip data processing and sound radiation.

However, the inconsistency of these approaches is the mismatch of technologies. A CMOS process is a high yield process with over thirty masks optimized for small area microelectronics. A silicon MEMS microphone is expected to have a lower yield due to the anisotropic or dry back-etch and sacrificial layer etching. In addition, microphones consume considerable wafer surface which is acceptable because they are realized using typically five mask steps. The combination of a MEMS microphone with CMOS electronics does not combine the best of two worlds, but adds the weaknesses of both. The result is a relatively risky microphone process with the costs of CMOS electronics per unit of surface.

A better solution would be to choose optimized technology for both the microphone and active chip. Both dies can be packaged into a SiP, where the separation of high-impedance sensing element and preamplifier is still small. This is shown by Microtronic [38] where a CMOS die and a silicon MEMS microphone are packaged by flip-chip mounting onto a silicon carrier. The matching of technology to application (a separate MEMS and CMOS process) and separating technologies over two dedicated foundries is commercially much more attractive than the single-chip approach.

So, the SiP approach is a method to match technologies. We have already seen another example in Section 5.1 where the PASSI™ process was introduced as a base layer in which passive components and MEMS structures are integrated in order to flip-chip a CMOS dye onto it.

Combining several systems in a single package is not only interesting because of cost reduction but also creates new operational possibilities. In Section 5.2 the advantage of stimulus-response measurements for solving reference problems in chemical sensors was clarified. In that case, joining sensors and actuators added a value to the individual devices. Using multiple sensors in a system and combining the readings of the sensors might even yield more information. For example, N sensors can give information on $N + M$ parameters in case the M parameters have some correlation with the measured N parameters. In some cases the new parameters couldn't even be measured directly. This principle is called *polygraphy* or *multivariant analysis*. A descriptive example is the situation where multiple simple human-body sensors are measured (respiratory rate, skin resistance, skin temperature, skin potential, and heart rate) while the person under test is asked to shoot a target [39]. From the combined sensor readings we can see whether the test subject hit or missed the target!

Sensors in a miniaturized system usually give very local information, which reduces some disturbing effects. By adding actuators in the same

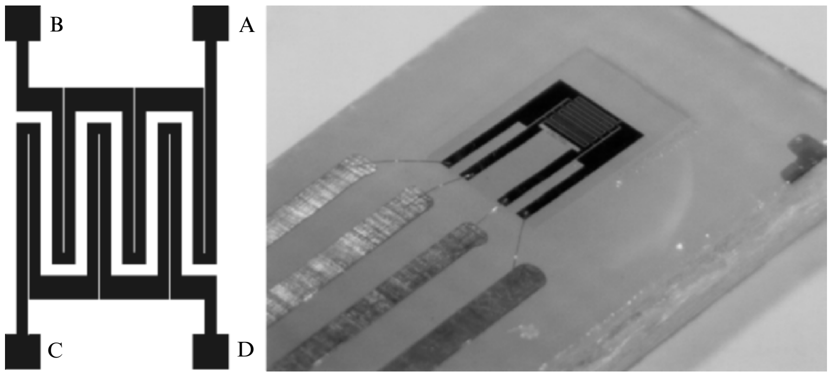

Figure 3.3-6. Integrated sensor-actuator structure: schematic functional representation (left-hand) and photograph of a packaged realization (right-hand).

local environment polygraphic sensor-actuator systems are made. The benefits of polygraphy, localization and sensor fusion are illustrated by the simple single sensor-actuator device [40] of Figure 3.3-6. The multi-purpose sensor structure consists of two meandered platinum wires on a glass substrate. The active area is $1 \times 1\,\text{mm}^2$ while the length of the meanders can be up to 10 mm. The glass substrate with the metal structure is packaged onto a PCB and covered by an epoxy resin, except for the active area of the sensor, to create a dipstick probe. The probe was intended to be used to characterize aqueous solutions, especially laundry washing processes where rigid sensor structures are essential.

Three direct sensor modes can be distinguished. Between pads A and B (or C and D) a resistive path is present which functions as a temperature sensor. The two separated meanders can be switched as an interdigitated finger structure, which is a common geometry for electrolyte conductivity measurements. Finally, when using the whole surface of $1 \times 1\,\text{mm}^2$ relative to an external large counter electrode, chrono-amperometric bleach detection is possible or potentiometric titration of weak acids.

Besides the three direct sensor modes, there are two actuator modes. The first one is the electrolysis mode where the electrode surface is used to generate H^+ or OH^- ions from water in order to control the local pH. The second one is the use of the resistive meanders for local heating.

The possible combinations of actuator modes with direct sensing modes result into a matrix of stimulus-response measurements. We can think of anemometric measurements to determine flow or turbulence by a time-of-flight or cooling down principle. From the relation between conductivity and temperature we can deduce information on specific ion concentrations under certain conditions [29]. It might be even possible to do a coulometric precipitation titration of Ca^{2+} with conductometric endpoint detection in order to determine the water hardness.

So, by applying several signals (DC, AC, transient, etc.) in different configurations to the single structure of Figure 3.3-6 and extracting the proper signal we can deduce multiple parameters from the polygraphic data set.

6. MICROSYSTEM PACKAGING

The academic world has shown many inventive creations of silicon sensors [41]. What is omitted in almost all cases is a solution for the packaging. Nowadays, more and more solutions are provided for packaging devices with entries to the outside world [42, 43].

In some integrated systems, the package is part of the system. This is the case with the integrated track pointer as developed at Philips Research. On the left hand side of Figure 3.3-7 a cross-sectional drawing of the track pointer is given. A silicon substrate comprises signal processing electronics and planar integrated magnetoresistive (MR) sensors. The tilt of a ferrite stick can be measured with these MR sensors.

Conventional technologies suffer from drift and hysteresis when using piezoresistive sensors, or metal fatigue when using the capacitive principle. The packaging solution of the MR principle is robust and can withstand the tremendous horizontal forces it is exposed to by the user. The integra-

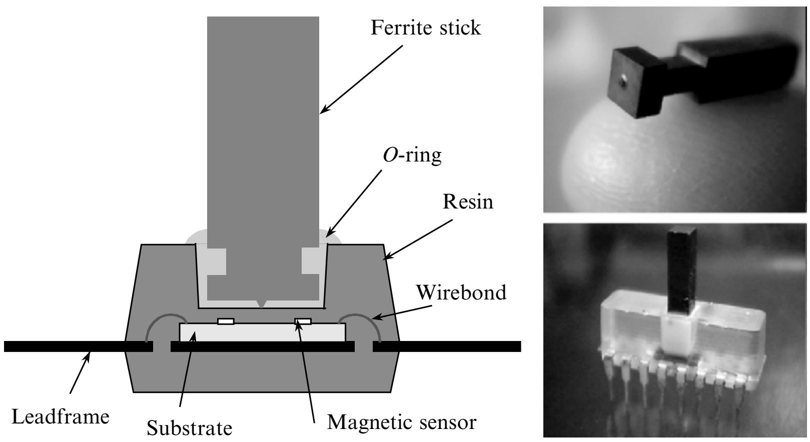

Figure 3.3-7. Integrated track pointer in DIL housing.

tion of the magnetic sensors on a chip allows us to integrate the preprocessing electronics in the same SiP product.

The chip of the integrated trackpointer does not have any free hanging structures like some other mechanical MEMS. Therefore the chip can be cut and handled just like integrated electronic chips. This is less trivial with chips containing free hanging structures. Those structures are damaged easily during sawing and handling of the wafer.

If possible, micromachined devices are packaged on a wafer scale, before separation. Waferscale packaging can be used to fill enclosures with special gasses or to create vacuum chambers [19]. Packaging on wafer scale solves the problem of sawing and handling fragile micromechanical chips.

7. MATERIALS AND PRODUCTION: WHAT ENABLES MST?

The applications of microsystems mentioned above are very diverse with respect to the processes used to realize them. Even two virtually similar surface micromachining processes will differ a lot due to individual constraints on the construction. Without standardization of microsystem processes and packaging, we have to reinvent the basics over and over again. Although batch-processable micromachined devices have the opportunity to become cheap components in all AmI, most applications are low volume products at this moment. Due to the bad uniformity in micromachining silicon processes it is very hard to ramp the applications up to the levels AmI requires. With more standardization we could use multiproject wafers to reduce development time.

However, there are some MEMS technology platforms that are more or less accepted as basic technology, at least within certain fields of application. First is the use of silicon on insulator (SOI) wafers, which are very suitable for surface micromachining. A SOI wafer is preprocessed to have a buried oxide layer and a relatively thick, up to 20 μm, epitaxial silicon layer on top. By etching trenches and holes in the epilayer and subsequently removing parts of the buried oxide layer by wet or dry etching, free hanging structures are created easily. Since the free hanging structures on SOI wafers have considerable mass they are popular for lateral accelerometers [44].

An alternative is the HEXSIL [45, 46] technology that is specifically designed for MEMS devices. With this technology, trenches are etched in a silicon wafer and filled with nickel by electroless plating. A sacrificial oxide layer enables release of the nickel structure to obtain free hanging structures. High resistive parts are made by using undoped polysilicon instead of the nickel. The silicon wafer acts as a mould and can be reused.

Both bulk-micromachining and surface micromachining processes are offered by foundry services like Europractice [47]. Experiments can be done on multiproject wafers and the design and development process can be completely outsourced.

Substrate transfer technology [48] (STT) is the technology where a SOI wafer, including electronics in the epilayer, is bonded onto a glass substrate. The resistive substrate of the SOI wafer is subsequently removed in order to have electronic circuits on a low loss carrier. This is a very beneficial method for low-loss RF applications and is illustrated in Figure 3.3-8.

A subsequent development of STT is the technology where the adhesion to the glass substrate is made by a polyimide layer with a weak adhesion layer facing the glass. In this case, the stack can be peeled off of the glass substrate and a flexible foil containing the electronics remain.

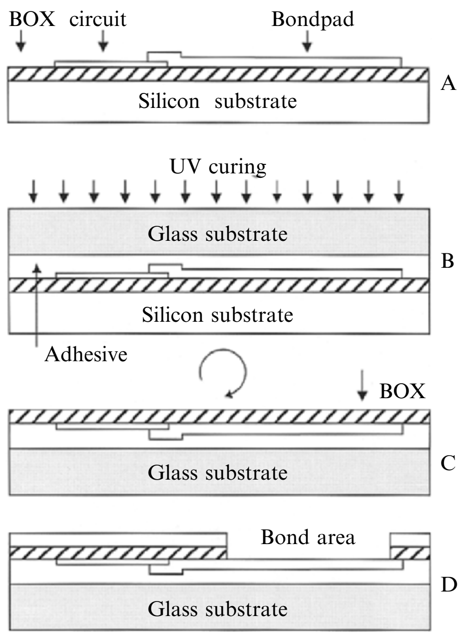

Figure 3.3-8. Schematic cross-section of the transfer of an SOI wafer to a glass substrate. (a) Fully processed SOI wafer. (b) Curing of adhesive by UV exposure through the glass substrate. (c) Removal of the silicon substrate selective toward the buried oxide. (d) Optional deposition of a scratch protection layer and opening of bondpads.

An active RF-tag of size $3 \times 3\,\text{mm}^3$ that can be coiled and bent was demonstrated [49]. This technology, which is not yet optimized for MEMS applications in the sense of micromechanical devices, is extremely valuable for AmI. It combines the opportunity of batch processing with flexible solutions, which can be placed on and in almost any application.

8. MEMS MODELLING

Besides MEMS technology for packaging and realization, successful development depends on the quality of design and test equipment. In this section, a brief overview is given on the method of MEMS modeling.

8.1. Lumped Elements Method

The best method to start calculations on MEMS structures is to use lumped element methods. With lumped element methods, entities of all physical domains are represented in a single formalized network. This yields optimum transparency of transduction principles, where electrical circuit theory can be applied to optimize and calculate performance parameters. The theory is known as *dynamical analogies* or *systems theory* and is as old as the existence of electrodynamic transducers [50–52].

This method will be illustrated using the example of the mass on a cantilever (see Figure 3.3-1). To make it a two-domain physical transducer, an electrostatic actuator is added as shown in Figure 3.3-9. Assume the mass and the cantilevers to be good conductors. The counter electrode is placed at a distance y_0 to create a parallel plate capacitor.

The starting point is the definition of a state variable, a *flow* and an *effort* in each physical domain. The flow is defined as the derivative in time of the state variable and the effort is defined as the cause of the flow. In the electrical domain, the state variable is the charge q. This makes the flow to

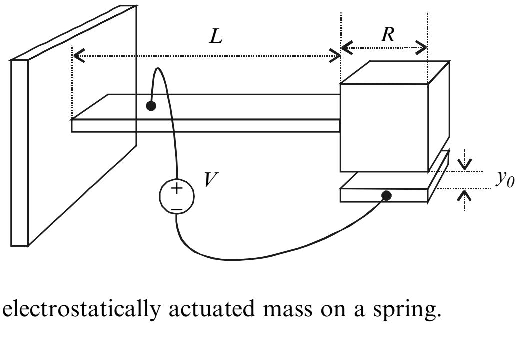

Figure 3.3-9. An electrostatically actuated mass on a spring.

be the electrical current $i = \mathrm{d}q/\mathrm{d}t$ and the potential the effort since it is the cause of an electrical current. In the mechanical domain we may consider translation as the state variable, resulting into force as the flow and speed as the effort[‡].

For a selection of physical domains the state variables, flows, and efforts are given in Table 3.3-2.

In the SI system, the product of effort and flow is the power in Watts. Energy can be stored in either a capacitive or an inertial buffer or be dissipated in a resistive element, satisfying the equations:

$$\text{flow} = C\frac{\text{d(effort)}}{dt},\ \text{effort} = L\frac{\text{d(flow)}}{dt}\ \text{or effort} = R \cdot \text{flow} \qquad (3.3\text{-}3)$$

respectively. Besides the one-port elements R, C, and L, there are also two-port elements like transformers and gyrators.

Now we can derive an equivalent circuit for the electrostatically actuated mass on a spring of Figure 3.3-9. The system is driven by an electric potential source $u(t)$. The source has an electrical internal resistance R_e that is loaded by the impedance of the capacitance C_e. This is shown at the electrical side of Figure 3.3-10.

Transduction from the electrical to the mechanical domain is modeled by an ideal transformer. In a certain regime, where the system is biased by a voltage V_{Bias}, the transduction is linear and satisfies $u = T_{\text{EM}} \cdot F$ and $v = T_{\text{EM}} \cdot i$. The transduction coefficient $T_{\text{EM equals}} y_0^2/(\varepsilon_0 R^2 V_{\text{Bias}})$.

On the mechanical side, the compliance of the beam C_{M} [equal to k^{-1} as given in Equation (3.3-1)], the mass M_{M}, and a certain mechanical friction with air R_{M} are incorporated into the model. These components are placed in series since they are exposed to the same velocity v.

From a circuit analysis we can understand the behavior of the system. The voltage source is not only loaded by the impedance due to the electrical parts R_e and C_e, but also by the mechanical parts R_{M}, C_{M}, and M_{M}. This is due to (electromechanical) coupling acting in two directions, back and forth. The idealized part of the coupling is modeled by the ideal transformer. The frequency response can be derived from the model. There will be a resonance due to the mass and the spring at $f_{\text{res}} = 1/[2\pi\sqrt{(C_{\text{M}} M_{\text{M}})}]$. At lower frequencies where the effect of C_e is negligible, the transduction from input voltage $u(\omega)$ to mass velocity $v(\omega)$ is given by

[†]This is the *impedance* equivalence which opposes the more commonly used *mobility* analogy where it is just the opposite way (speed is *flow* and is force is *effort*) since mechanical impulse is considered as the state variable. These conventions are called *dual* and result in mathematical interchangeability of the associated buffers.

Table 3.3-2. Summary of state variables, signals and components in several physical domains.

Physical domain	State variable	Effort	Flow	Resistive	Inertial buffer	Capacitive buffer
Electrical	Charge $\boldsymbol{q}$ **[C]**	Potential $\boldsymbol{u}$ **[V]**	Current $\boldsymbol{i}$ $[A]$	Resistor $\boldsymbol{R}$ **[Ω]**	Coil $\boldsymbol{L}$ **[H]**	Capacitor $\boldsymbol{C}$ **[F]**
Mechanical	Translation $\boldsymbol{x}$ **[m]**	Force $\boldsymbol{F}$ **[N]**	Velocity $\boldsymbol{v}$ **[m/s]**	Friction **[N·s/m]**	Mass **[kg]**	Compliance **[m/N]**
Acoustical	vol. displ. $\boldsymbol{x}$ **[m]**	Pressure $\boldsymbol{p}$ **[Pa]**	Vol. velocity $\boldsymbol{U}$ $[\mathbf{m^3/s}]$	Resistor $[\mathbf{Pa \cdot s/m^3}]$	Mass $[\mathbf{kg/m^4}]$	Compliance $[\mathbf{m^3/Pa}]$
Magnetic	Flux $\boldsymbol{\Phi}$ **[VS]**	Mmf $\boldsymbol{M}$ **[A]**	Potential $\boldsymbol{u}$ **[V]**			
Thermodynamical	Entropy $\boldsymbol{S}$ **[J/K]**	Temp. $\boldsymbol{T}$ **[K]**	Entr. flow $\boldsymbol{f_s}[\mathbf{J/s \cdot K}]$			

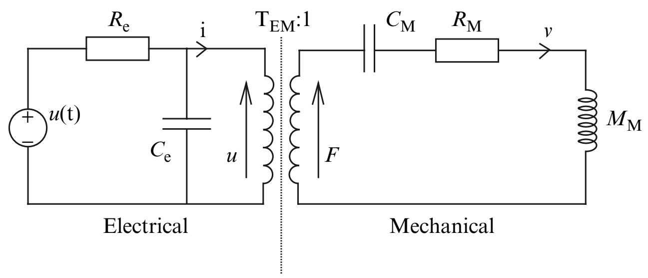

Figure 3.3-10 Equivalent model for the electrostatically actuated mass on a spring.

$$v(\omega) = T_{EM}^{-1}\left(\frac{R_e}{T_{EM}^2} + \frac{1}{j\omega C_M} + R_M + j\omega M_M\right)^{-1} u(\omega) \qquad (3.3\text{-}4)$$

which shows how the method of lumped elements easily helps us to develop mathematical models.

When the model of Figure 3.3-10 shows too much disagreement with observations, we have to refine the model by adding more components. For example, oscillating modes in the cantilever are not implemented in the model, but could be included by adding *LC* circuits. At any time, the lumped element model is linked phenomenologically to reality.

8.2. Finite Elements Method

The values of the lumped elements are not straightforward to be determined in all cases. This can be due to the fact that an element represents a phenomenon, which cannot be localized intuitively and that it represents a nonlinear effect, or that it is difficult to be represented in a single element. Examples are cases where all the vibrational modes of a plate have to be considered, when the shape of a structure is very complicated or when there is no analytical solution to a certain nonlinear differential equation. In that case modeling must be based on the motional differential equations directly.

The finite element method (FEM) is based on spatial segmentation of a structure where each segment is described by its coupled differential equations. Software packages like ANSYS, COSMOS, CoventorWare, and FEMLAB are available for numerical evaluations and provide graphical representations of the results.

However, this method has several drawbacks. The finite element method is a low-level interpretation of the physical behavior. To combine them into macroscopic overviews of device characteristics, large capacity with respect to memory and calculation speed is required. It is very hard to maintain the systems overview since the links between physical domains have become invisible. In many cases, the designer has to limit himself to a FEM analysis of only a part, one or two domains, of the problem to limit the complexity of the problem. To understand the relation between design parameters and performance in FEM analysis it has become the skill of the scientist, rather than the power of the tool as we have seen with the lumped element method.

9. SUMMARY AND CONCLUSIONS

Based on the overview of technology presented in this chapter, we can summarize the advantages of microsystems with respect to AmI as six key benefits:

- Microsystems are the small domain interfaces enabling AmI. They are small, will *fit in anything* and act in their position as a reasoning transduction node.
- The devices are realized using batch processing which results in cost reduction and better uniformity. Since this *multiplicity* reduces costs, we can put even more of them in everything.
- New features are facilitated by *scaling* physical phenomena. Think of the static micromixers without moving parts, the ultramicroelectrodes and all the new things enabled by electrowetting.
- Scaling down and batch processing does not necessarily result in poor or fragile devices. On the contrary: MEMS devices especially are *high-end*, consume less power and are robust when designed properly.
- An array of sensor elements and sensor/actuator fusion enables multivariant analysis and *stimulus response measurements*, which is beneficial with respect to deriving new and otherwise inaccessible parameters and increases measurement reliability.
- The SiP approach considers the matching of technologies in order to optimize development time, yield, cost efficiency, and functionality. A sensor has become more than a single sensing element, it comprises signal conditioning and a package suitable for PCB mounting.

Considering these benefits, one might wonder why microsystem technology, especially MEMS sensors, has penetrated only in limited fields of application. The question is what the limiting factors are for the success of micromachined products. A cautious onset for a list of explanations is:

- Silicon foundries have to make structural changes in their fleet of equipment for the relatively new technologies like surface micromachining and microfluidics. Some typical MEMS materials are not appreciated in existing plants, which requires additional structural changes.
- To have a freshly designed MEMS product welcomed at one of the silicon-foundries, persuasive precalculations are needed. However, the MEMS technology platforms are relatively new resulting in ambiguous cost estimations, which hamper the process of acceptation.
- There is no satisfying set of universal microsystem processing technologies. Unification would speed up the design process and enable more flexible use of foundry services.
- Microsystem technology requires multidisciplinary skills from the design, development, industrialization, and manufacturing teams. In the first three teams, dealing with the edge of several physical domains has become common practice. At production sites, however, introducing disciplines besides microelectronics require adaptation of a mindset and the installation of equipment to check standards in the field of the application.

As shown in Section 2, the definition of AmI maps perfectly onto the aim of the SiP approach. From this consideration we may conclude that microsystem technology, besides CMOS technology, is the most important enabler for AmI. However, it is fair enough to say that AmI is a challenge for microsystem technology. This appears to be a more reasonable view since at this moment the development and acceptance of AmI is partially limited by the limited availability of cheap sensor and transducer technologies. Nevertheless, we must realize that microsystem technology, like MEMS, is not the goal but is the method to design the consumer products of the future.

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