7. Si MEMS

7.1 Products and Developments

7.1.1 What is MEMS?

MEMS Basics

- ***MEMS*** is the abbreviation for **Micro Electro Mechanical Systems**. It is not a good abbreviation because it omits, for example, all those microoptical, micromaterial, microchemical, or microfluidic systems that are also part of **MEMS** technology. The old-fashioned name "Microsystems" (or, to stay in touch with the spirit of the times, "Nanosystems"), would have said it all much better and simpler.
  - The word "system" is not unambiguous either. According to Wikipedia, a *"system" (from Latin "systema", in turn from Greek "συστημα"=systema) is a set of interacting or interdependent entities, real or abstract, forming an integrated whole*. OK - so an integrated circuit is a system too, because it is a set of interacting transistors, forming an integrated whole, like a memory chip? It is a matter of taste, but a the feeling is that a memory *chip* is not yet a system. If you add input and output and the interface for something that uses the memory, you might call it a memory *system*.
  - Another way of looking at it would be to equate "system" with "little machine", an entity that can do something or interacts with something else on its own.
  - A more practical point of view is simply to say that a **MEMS** *chip* is something produced on a **Si** substrate that has more functions than just microelectronics. It may *contain* some microelectronics, but it must also have some non-electronic component, be it mechanical, optical, or whatever.
  - A somewhat oversimplified but helpful point of view is that **MEMS** products invariably contain **sensors**, **actuators** or both; and that they are small (in the range of a few **µm** to a few **100 µm** across).
- **MEMS** is an "**emerging technology**", meaning that while I'm writing this, new developments undreamed off a few years ago take place, and in a few years form now this text will be outdated on many counts. Nevertheless, **MEMS** "devices" gross about **$** $5,5 \cdot 10^9$ per year in **2007**, while **MEMS** "systems" will cross the **$** $100 \cdot 10^9$ per year barrier shortly after **2010** or so (more to the MEMS market in this link). The difference between device and system is shown below.

 **MEMS** based Gyrometer="*system*".	 **MEMS** "chips", *devices*, or components

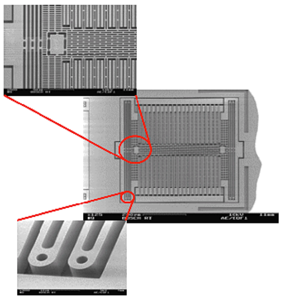
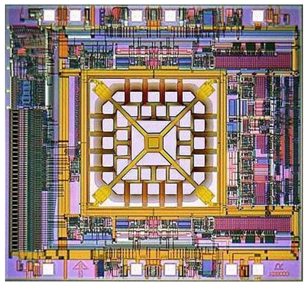
  - So be careful when numbers concerning money come up. A "system" like a car contains "systems" like gyros that contain **MEMS**-Systems and so on.
  - For all emerging technologies there is also a lot of ***hyperbole*** concerning applications and money around, and that makes it not so easy to assess what is really going on. So let's focus on the *essentials* here.
- Let's have a quick look at **MEMS products**. There are three kinds.
  - Products you most likely own (possibly without being aware of that) or experience in the world around you (possibly without being aware of that), and that you and I could buy right now.
  - Products not yet available to everyone or not ***ubiquitous***, but already marketed or just about to hit the market place.
  - Intended or projected products that may or may not make it to the market.
  - The list given below is neither complete nor does it mirror the present day (**2008**) market. It just serves to give a flavor of what is, or might be, around.

Example of MEMS Products

- What kind of **MEMS** products are on the market and possibly in your possession?
- Very prominent in this respect are **acceleration sensors**.

- If you have a car equipped with **air bags**, you need acceleration sensors and they will be based on **MEMS**.
- Knowing that, and being in Germany, you naturally type "air bag acceleration sensor bosch" into Google Pictures - and get almost nothing. Only if you follow text pages and turn to detailed product information, you may find something about **MEMS** and acceleration sensors from **Robert Bosch GmbH**; an example is shown in the link.

Here are two pictures with short descriptions from the producers of acceleration sensors (also called "**g-sensors**").

 **Bosch g-sensor** Scale ? (several **mm**)	 **MEMSIC g-sensor** Scale ? (about **1 cm**)
The common sensing principle of the accelerometers is capacitive. An acceleration in the lateral direction deflects the proof mass that is suspended by folded springs in the x-sensing element. One set of electrodes is attached to the proof mass and moves with acceleration. These movable electrodes form capacitors with two sets of fixed electrodes opposing them with a small air gap in between. The use of such a differential capacitive arrangement with two capacitors reduces the nonlinearity of the transfer function of the device. Overrange stops are implemented for shock protection that avoids the direct contact of the fingers at large accelerations. The mechanical sensitivity (in ***fF/ g***) can be adjusted by the thickness and/or the length of the springs. The differential capacitance signal is evaluated by an ***ASIC*** which is electrically connected to the sensor by chip-to-chip wire bonds. A change of C^1 and C_2 is detected and transformed into a corresponding analog voltage by a capacitance/ voltage converter. (Image courtesy of Bosch) .	MEMS-Based Accelerometer MEMSIC's dual-axis thermal accelerator is a MEMS-based semiconductor device that works conceptually like the air bubble in a construction level. The square in the middle of the chip is a resistor that heats up a gas bubble. The next larger squares contain **thermal couples** that sense the location of the heated bubble as the device is tilted or accelerated. (Image courtesy of MEMSIC, Inc.) .

- The first thing we learn from the pictures is that obviously two quite different principles are used for measuring acceleration. The second thing we learn is that both accelerometers are quite complicated little things; the **MEMSIC** one evidently coming with some integrated microelectronics around the actual sensor in the center of the device.

Accelerations sensors are not restricted to cars and airbags, of course. Your car might have some electronic *system* that keeps it from ***skidding*** and ***rolling*** when you move on ice and snow or negotiate a curve with too much speed. This "***ESP***" system (or whatever cute abbreviation your car manufacturer use for that) needs **MEMS** to tell it that something is not as it should be, and this includes information about acceleration.

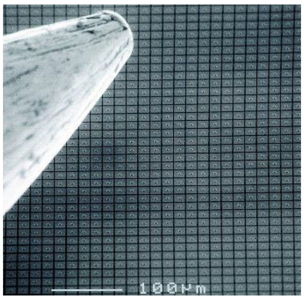
- Pretty much everything that flies (air crafts, rockets, missiles, unmanned aircraft (drones), balloons, war heads, ...) need accelerometers; in particular for calculating where you are or how fast you are.
- More and more "***gadgets***" contain accelerometers, like Nintendo consoles for measuring movement and tilt to complement its pointer functionality. Sports watches for runners may contain accelerometers to help determine the speed and distance for the runner wearing the unit. A small number of modern notebooks and cell phones ("iPhone") feature accelerometers to automatically align the screen depending on the direction the device is held.

Besides sensors for *linear* or translational acceleration, cars with an **EPS** system (and anything that flies) will also need sensors for angular movements, or ***gyroscopes***.

- The market for linear accelerometer and gyroscope chips is around $\$\,650 \cdot 10^6$, with single chips going for roughly **$ 20**. The market is expected to grow massively, driven by cost reductions and the many uses coming from ever more sophisticated gadgets as explained above.
- We will look at gyroscopes in more detail in the next module, so nothing more about accelerometers here

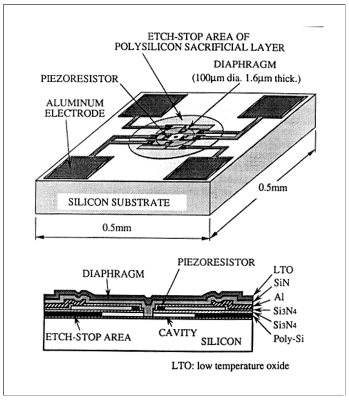
The next **MEMS** device - or better ***OMEMS*** device (an abbreviation that is sometimes used), is the "**Digital Micromirror Device**" from Texas Instrument (***TI***) called "**Digital Light Processing**" (***DLP***). A **DLP** chip is the "heart" of the **beamers**, a *product* virtually non-existing **10** years ago and by now (**2007**) quite ubiquitous.

- The **DLP** chip (or the principles behind it) was invented in **1987** by **Larry Hornbeck** and made it to the market around **1996**. Ten years later, in **2006**, according to **TI** a grand total of **10 · 10^{6}** chips have been sold. Not a lot, if you compare it to memory chips or microprocessors, but still an unparalleled success for a rather outlandish device back in the final days of the second millennium. Here it is:

 Courtesy of Texas Instruments	 Courtesy of Texas Instruments
The **DLP** chip - looks like a mirror.	**DLP** chip close up with the tip of a needle

- All you see by looking a the chip directly is a mirror. Only if you look closely (with a microscope), you realize that this mirror consists of something like **1 280 · 720=921 600** separate small (about **15 µm · 15 µm**) mirrors that can move independently.
- Exactly how it works (with more picture) is explained in a separate module. Note that in this example **MEMS** is another **enabling technology**; there is simply no other way to do what a **DLP** chip can do.

The last major and rather common **MEMS** product is the **pressure sensor**. Not something you use conscientiously, but something that is quite important in many existing products and machinery and probably inside several things you do use. In fact, measuring the pressure of gases and liquids is about as common as measuring the temperature - there is a tremendous market for this out there!



- Moreover, there would be an even larger market for **MEMS** pressure sensors if they could be used in in places where they would be very useful, but face major problems. Inside your car tires, for example, or even inside *you* - if you suffer from high or low blood pressure. The problem, of course, about to be solved right now, is how to supply power and how to interface the sensor with the outside world (at negligible cost, of course).
- The picture shows one kind of **MEMS** pressure sensor (probably from Toyota). We recognize a few by now familiar materials like **Si**, **Si_3N_4**, **Al** and **poly-Si**, but also new parts like "piezoresistors".
- The working principle is easy to guess - words like "***diaphragm***", "cavity" and and "piezoresistor", if taken together, should make it quite clear.

If you give the matter a bit more thought, you will start to realize that there is a tremendous diversity of requirements for pressure measurements, just given as alternatives:

1. Gas - liquids.
2. High pressures - low pressures.
3. At room temperature or at extremely high or low temperatures.
4. In a ***benign*** or corrosive environment.
5. With high or low demands on accuracy.

- Just consider the **4th** point. A pressure sensor is always exposed to the medium the pressure of which it is supposed to measure. How about ***liquid manure***? If you want to run a large biogas facility automatically, you must measure the pressure inside your (more or less) liquid ingredients.
- How about measuring the pressure inside a car engine at working temperatures? Well, if it is done at all, it will not be easy. If you use a **MEMS** device consisting of **Si**, **Si_3N_4**, **SiO_2**, and so on, it might be able to take the heat, but you cannot integrate electronics on this chip because *transistors* can't. This teaches us that **MEMS** may not be the answer to *all* your system needs but must compete with other solutions to a given problem.

- Finally. let's just list some more products, possibly not yet on the market or not yet of monetary importance. It is a save bet, however, that during *your* professional life as an engineer, you will see most of those products around - and a lot more, not even imagined by now. We will just give some catch words with a few explanatory lines. More to all of that you will learn in a separate lecture course and in the links given
- ***RF MEMS*** or "radio frequency microelectromechanical systems".
  - "***RF***" here includes frequencies in the higher **GHZ** region (in German it would be ***HF***=high frequency). If you consider that just making a switch that opens and closes a **GHZ** circuit is a non-trivial enterprise because your parasitic capacities more or less short-circuit everything, you get the idea why **MEMS** could be useful.

    Class Exercise: *How large is the resistance of a **1 pF** capacitor at **10 GHZ**?*
  - What **RF MEMS** can do is to produce high quality switches, varactors (variable capacitors or reactances), high ***Q*** capacitors and inductors, resonators, filters and phase shifters, couplers and power dividers; offering the advantages of improved isolation, lower power dissipation, and reduced cost, size, and weight. **RF MEMS** is seen as being on the verge of revolutionizing wireless communication, but presently is mostly investigated at universities.
- **Optical MEMS** (besides the **DLP** chip).
  - While the **DLP** chip is digital, i.e. the mirrors have only two positions, analog mirrors with precisely adjustable positions and two axes would allow to project any picture via scanning a Laser beam. Other intended applications are displays, ***IR*** imagers, spectrometers, bar code readers, maskless lithography, adaptive optics, head-up displays, and so on.
- **BioMEMS** and **Microfluidics**
  - Put a drop of blood (or any other body liquid) on the appropriate **BioMEMS** chip, and it will give you either a full analysis ("lab-on-chip") or answer a particular question (do I have Aids?). Grow and connect neurons on a **bioMEMS** chip, or use it to re-connect nerves. Implant an artificial retina into the eyeball of the blind, or the proper device into the ear to allow hearing for the deaf. Micropumps under the skin soon might deliver continuously the proper amount of a drug according to some sensor (a huge improvement of the quality of life for people with diabetes!).
  - There is no end to keen visions here, and all of the above is being vigorously pursued at present
- Then there are **specialties**.
  - Reading and writing heads for memory discs. Relatively simple devices but accountiung for a large part of the MEMS market.
  - "Silicon microphones" are, if you like, very special pressure sensors. Consider that small and cheap microphones are needed in amazingly large quantities - there is one in every cell-phone.
  - Nozzles for ink-jet printers. Many very small nozzles in parallel for faster and more precise printing are being investigated and might enable "printing on demand" on a large scale.
  - Control of package shipping, where **MEMS** shock sensors would rest inside packages to monitor time and any type of damage that may occur while the package is in transit.
  - **MEMS** Oscillators, replacing the good old "quartz crystals", flow sensors, finger print sensors. And so on ....
- Like with any emerging technology, it is rather hard to figure out what is fact (in the sense that a product exists or will come into the market for sure) and what is fiction (in the sense that it would be nice to have, but is too expensive or that it can't really be made).
  - Time will tell and *you* will see.
- What can be predicted with certainty, however, is that feature sizes will shrink. Things will tend to become smaller for the same reasons as in microelectronics: More chips per ware=more performance per Dollar.
  - That will necessitate some rather outlandish materials science or rather quantum physics. A taste of what's around the corner can be found in the link.