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MEMS and Nanotechnology

by

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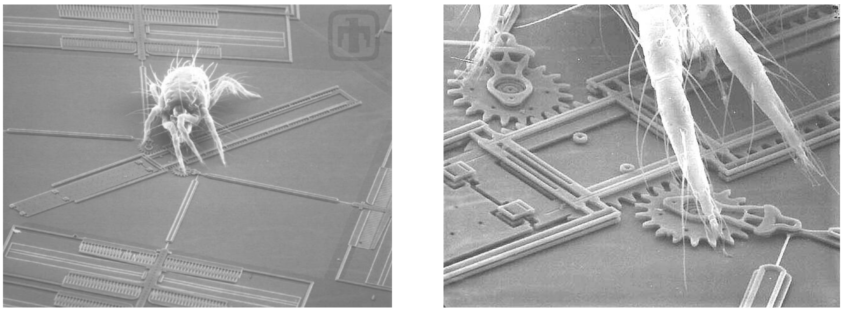


Figure 1: Spider mite on MEMS assembly

Contents

1 Introduction

MEMS, microelectromechanical systems, are sensors and actuators realized at microscale, thus offering the opportunity for integration into applications that require high performance as well as high precision but at the same time do not provide much space.

The impuls towards this development was already given in December 1959 when Richard Feynman offered a prize of $1000 for building a working electrical motor, each side smaller than $\frac{1}{64}$ of an inch (approx. 0.397mm). This size had been specified, because Mr. Feynman believed that producing a device that small would necessitate an entirely new approach to engineering and assembly techniques. The challenge was met in 1960 by William McLellan, who built the motor, to Mr. Feynman's surprise and disappointment, by hand. Also, he only started working on it in June when he realized that nobody else had made it. The wires, for example, Mr McLellan fabricated by rolling an already thin wire between two microscope glass slides until it was as thin as a human hair. Using his microscope as well as a sharpened toothpick to push the pieces into place and some hairs of a fine artist's brush as tweezers Mr. McLellan surely didn't offer the revolutionizing methods Mr. Feynman hoped for, but in the end a considerable public interest in miniaturization had been stirred up, hence pushing researches in this field till finally MEMS as we know them became possible. Of course nowadays nobody uses thoothpicks for MEMS assembly anymore.

The fabrication methods used today will be introduced in chapter 5. Before that there will be an overview of some important active principles as well as the introduction of different microscaled sensors and actuators that are commonly used.

2 Definition of MEMS & NEMS

2.1 What is MEMS?

Microelectromechanical systems are microscale mechanics integrated on a silicon chip. Their mode of operation basicly derives from the transformation of mechanical motion into electricity, thermal energy or even light and vice versa. While the transfer from motion to electrical signals is usually found in sensors, the possibilities to turn other forms of energy into kinetic energy is used in actors. Considering the tiny size of MEMS there are seldomly found joints. Non transversal and non rotational motion is mainly performed by deformation of flexible components, such as thin cantilevers, beams or membranes.

The mechanical components of MEMS are integrated with C-MOS-circuits, which provide the possibility to drive actuators or evaluate signals gained by sensors.

2.2 What is NEMS?

Current researches not only deal with fabricating microscale but also nanoscale devices. Those nanoelectromechanical systems, NEMS, are expected to provide the possibility to even measure forces and displacements at a molecular scale. Still, not everything that is labeled nano really contains nano. When it is time to apply for research funds, structures several micrometers in size soon shrink to sensational ”only several thousand nanometers small”. However hard the border is to define, the active principles of both, MEMS and NEMS, are very similar if not the same, so chapter 4 of this paper will basicly deal with existing MEMS devices.

But concerning electromechanical designs that are actually a few tens of nanometers in size, there are still a few obstacles to overcome.

2.3 Problems with NEMS-technology

Looking at current transistor fabrication tendencies one can easily see the fact that it is possible to create structures some nanometers in width or layers only a few atoms thick. Nevertheless, just scaling down a MEMS layout is not enough. You have to consider the fact that the number of atoms forming a cantilever, beam or membrane decreases according to the volume. A cantilever half as long, high and thick as a reference cantilever only contains an eighth of the atoms. As a result a considerable big number of atoms are surface or near surface atoms. Together with the unavoidable interference with surrounding molecules this may lead to a change in physical qualities. For example: you want to use the piezo-resistive effect in a thin layer of silicon. But as a result of the little thickness all the Si-atoms react with oxygen, and suddenly you get isolating glass instead of semiconducting silicon. Furthermore some additional physical effects have to be considered, like the increased influence of adhesion. If, for example, two pieces that are supposed to work as capacitive electrodes attract each other, this will induce a short-circuit, which on the one hand makes measurement impossible and on the other hand would destroy the NEMS device.

Another problem is that NEMS can respond to masses of single atoms, consequently a sensor could respond to the impact of molecules, e.g. dust, which leads to mismeasurement. In addition it is important not to forget that the desired measurement of small deflections or forces also means small output signals. Those signals may be hard to distinguish from thermally induced noise.

So before NEMS can be effectively realized, engineers, designers and production standards have to meet some challenges. The engineers have to consider additional effects that have been irrelevant for microdevices. Designers have to find new approaches not only to avoid the sticky adhesion problem, and production and packaging have to take place in an extremely clean environment.

3 Active Principles

This chapter will introduce some of the most common active principles, that can be found in MEMS and NEMS devices to transform energy.

3.1 Thermal Transduction

Thermal transduction is a well known principle, which is used in different macroscopic applications but can also be applied in microscale systems. Thermal transduction is based on the effect that materials expand when being heated. It makes sense to describe a microcantilever's thermal behaviour by two parameters: First, of course, change in length, which can be calculated as $\Delta l = \alpha \cdot l \cdot \Delta T$, where α is the material's thermal coefficient. The second would be the so-called block force F_b, calculated as $F_b = EA \cdot \alpha \cdot \Delta T$, where A is the cantilever's cross-sectional area and E its Young's modulus. If a force, which is equivalent to the block force, applies a pressure on the cantilever's tip, there will be no expansion although the material is heated. This has to be considered when the cantilever is supposed to move or push something.

The same principle can be applied similarly when using membranes (cp. droplet generator, chapter 4.2.2).

An example for a common application of thermal transduction existing in micro- as well as in makroscale is the bimetal actuator.

Concerning the advantages and disadvantages, the big advantage of thermal transduction is the fact, that large forces and displacements can easily be achieved. Unfortunately it looses some value when the large necessary input energies are taken into consideration. Also this form of actuation or sensing only reaches very low frequencies. Much more effective transduction methods are piezo and electrostatic transduction.

3.2 Electrostatic Transduction

Electrostatic transduction can be multiply applied. When parallel plate movement occurs, there is a change in the distance between two condenser plates. Comb finger movement changes the effective area of the capacitor. In both cases the change in voltage is measured. From these oscillations the change Δx or ΔA, and consequently the desired value ($x, \dot{x}$, ...) is derived by software or integrated C-MOS logic. The applied equations are:

$$\Delta U = -Q\frac{x}{\varepsilon \Delta A}$$

$$\Delta U = Q\frac{\Delta x}{\varepsilon A}$$

While comb finger movement is used in comb structures to generate a movement, parallel plate movement can be used to induce as well as to sense movement.

There are two evident advantages of electrostatic transduction, namely the fast response, and the easy integration with C-MOS.

3.3 Piezo-Resistive Effect

A further popular effect is the piezo-resistive effect. It occurs in materials with non-rotational symmetric elemental cells. Compressing or expanding of such materials results in an unbalanced shifting of charges and a drop of voltage, respectivly. Thus a very simple sensor can be realized. On the other hand, connecting a piezo-element to a voltage source results in the reverse effect: expansion or contraction of the element. This is taken advantage of as actuators in several printers for example. A piezo-resistive element's quality is described by the so-called gauge factor, which describes the ratio of change in resistance – calculated by voltage and current – and change of length. The gauge factor basicly tells if the voltage drop resulting from compression is positive or negative. Since the piezo-resistive effect also appears in doped silicon it is also used in MEMS – which are commonly structured in silicon. E.g. a piezo layer (silicon with $10^{19} cm^{-3}$ boron or phosphorus atoms) grown at 560°C can attain maximum gauge factors of -40 in the case of p-doping and +20 in the case of n-doping, respectively.

4 Types of MEMS

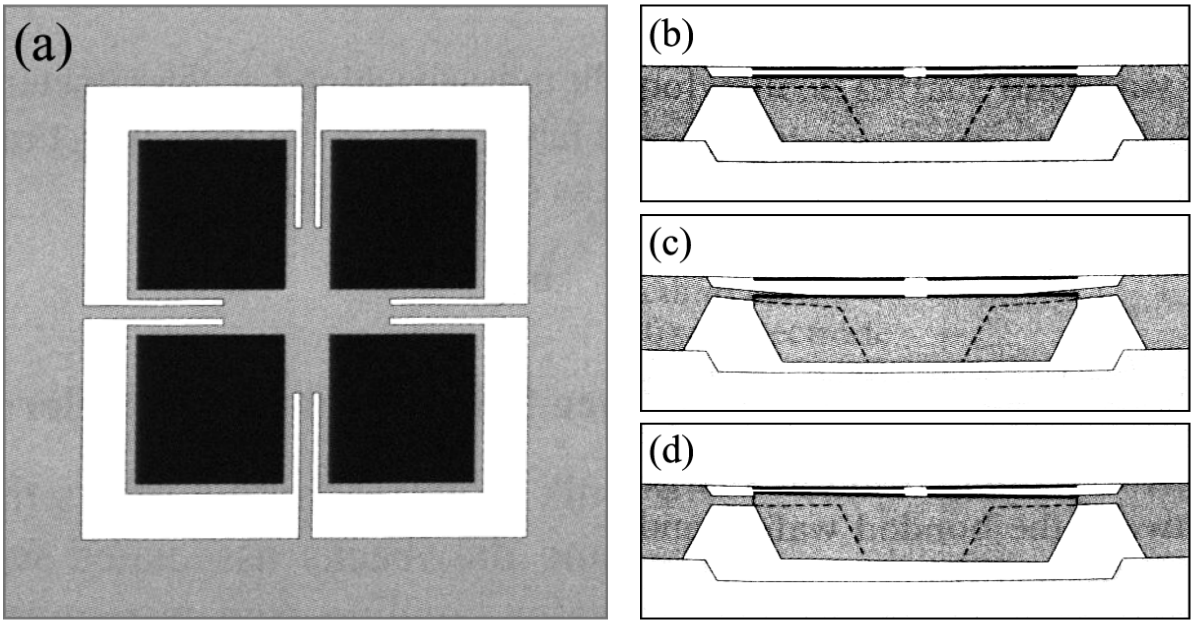
4.1 Sensors

4.1.1 Accelerometers

Nowadays there are uncountable applications for MEMS accelerometers: in automotive systems they activate savety systems or are used to implement vehicle stability systems. In laptops they serve in hard disc protection systems, so that in the case of dropping the read and write head can be positioned savely in order to avoid impact on sensible sectors. Futhermore they find a huge market in robotic systems.

A simple MEMS accelerometer is designed as a mass suspended by one to four thin silicon beams to a reference frame. The mechanical equivalent to this design is a spring-mass-damper-system, with the beams operating as "springs" and "dampers". When accelerated, the proof mass is displaced against the stiffness of the beams, thus lengthening the very same. The displacement of the proof mass or the lengthening of the silicon beams can be measured by different means. One possibility is of course to use strain gauges on the suspension beams. But this simple method is also suboptimal, because there can only be achieved one direction of sensitivity. A much better method is to realize a proof mass with four capacitive electrodes on it (cp. figure 2).

Acceleration in vertical direction causes an equal change in capacitance for all four electrodes. Whereas acceleration in horizontal direction causes the proof mass to tilt, thus increasing the air gap for two of the capacitors, while at the same time decreasing it for the others. By evaluating the change of voltage for each capacitor the three-dimensional acceleration vector can be easily derived. Although these types of accelerometers are more complicated in fabrication than those mentioned before, they are more favoured, because they are sensitive to all three dimensions of space.



(a) proof mass with four capacitive electrodes

(b) neutral position, (c) accelerated vertically, (d) accelerated horizontally

Figure 2: Three-axis MEMS accelerometer

4.1.2 Gyroscopes

MEMS-gyroscopes are usually vibratory gyroscopes, which means they contain a vibrating mechanical element, the proof mass. It is caused to vibrate by impressing an alternating voltage on the attached comb drives. Figure 3 shows a gyroscope with two proof masses, that vibrate in opposite direction to avoid unbalance. Thanks to the Coriolis effect this arrangement can now detect rotation around the axis that is parallel to the wafer surface and perpendicular to the direction of the vibration's motion. When the gyroscope rotates around the described axis the Coriolis acceleration causes the proof mass to vibrate in the direction perpendicular to the wafer's surface, according to the equation $\vec{a} = 2\vec{\omega} \times \vec{v}$. This form of vibration can be detected by capacitive electrodes underneath the proof mass and on the wafer surface, respectively. The applied measurement principle is the parallel plate movement described in chapter 3.2 on electrostatic transduction. The measured alternating current or voltage allows to derive the rotational speed.

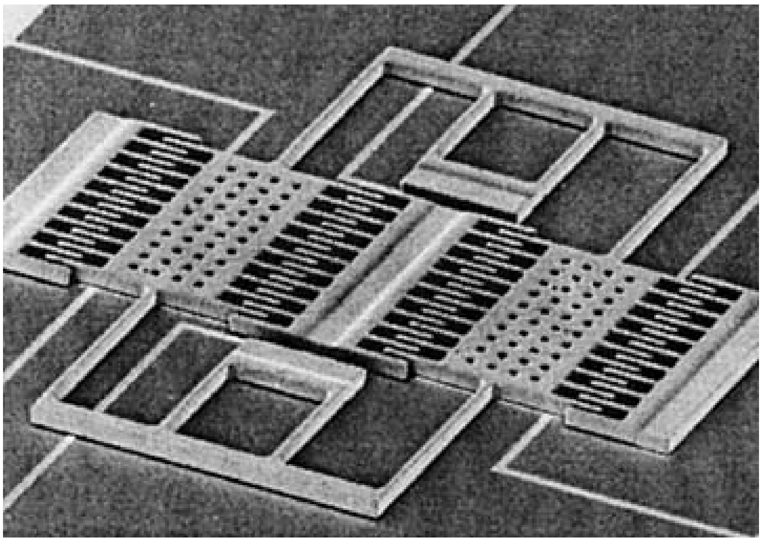


Figure 3: vibratory gyroscope with two proof masses

4.2 Actuators

The applications for MEMS actuators are as multifaceted as the devices they are used in. The following chapter will try to give an overview of some different MEMS actuators and their fields of application.

4.2.1 Micromirrors

One of the applications for micromirrors is in phase modulation systems for devices using coherent light. Again the parallel plate movement is used, this time in order to create an attracting or repelling force between two capacitor plates. The mirror, e. g. a thin gold layer, is located on top of the upper, moveable plate. By moving it up or down some tens of nanometers the optical way of the reflected light is shortened or lengthened, thus changing its phase.

A further possible application for different forms of micromirrors is in optical switches, where either single mirrors or arrays of hundreds of them are installed. By tilting the mirrors a beam of light can be directed towards the desired position. The front page picture shows such a single mirror, that is driven by a microengine (cp. chapter 4.2.3).

4.2.2 Droplet Generator

The request for printers that manage extremely high resolutions has already lead to a considerable spread of MEMS technology in common ink jet printers. Different solutions have been found by different companies, including several piezo approaches as well as evaporating some ink in order to accelerate other ink near the nozzle. A further method to realize a droplet generator is shown in figure 4.

A membrane is heated for some microseconds and tries to expand. When the critical stress is reached it buckles, thus abruptly diminishing the volume of the ink chamber in front

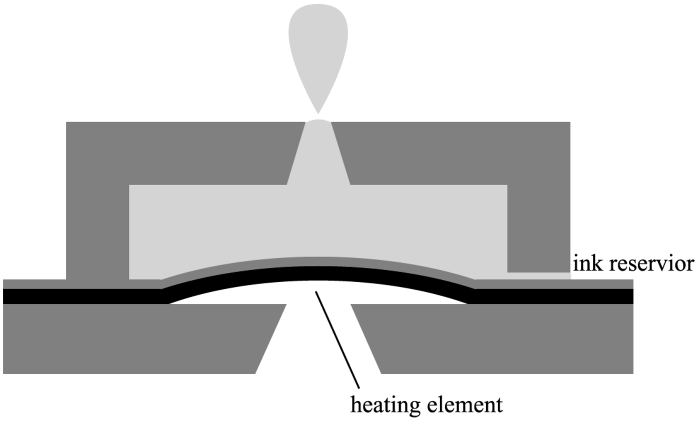
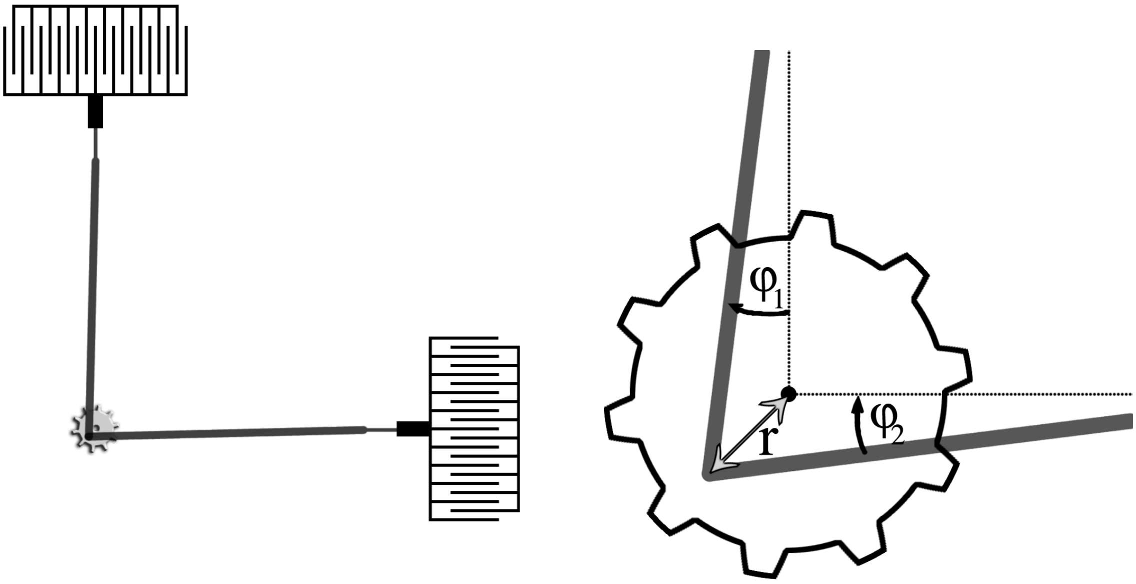


Figure 4: droplet generator

of the nozzle. An ink droplet is shot out, reaching speeds of about $10ms^{-1}$. Then the membrane is cooled down again and takes its initial position. Ink from the ink reservoir flows into the chamber filling it up and the process can be repeated. This kind of droplet generator is able to achive rates of 1.8 to 5 kHz, depending on the geometry and the desired drop speed.

4.2.3 Microengines

Like for most applications, there are several different ways to realize a microengine. The engine I would like to introduce is electrostatically driven (cp. figure 5 (a)).



(a) electrostaticly driven microengine (b) gear wheel

Figure 5: Microengine with gear wheel close-up

It uses two comb drives to create perpendicular forces. The comb drives are excentricly connected to the gear wheel by beams, that have a short thinner part working as a spring. This part allows the beam to bend. The method of operation can be compared to that one of a normal scaled engine. The linear force created by the comb drives is translated into a torque which causes the gear wheel to turn. The torque of a single electrostatic actuator calculates as

$$M_i = F_i \cdot r \cdot |sin\varphi_i|$$

F_i is the linear force, r the distance between gear wheel hub and linkage and φ the angle as given in figure 5 (b). Because of the gear wheel's small mass and the resulting lack of inertia two linear actuators are required to overcome the top and bottom dead centre.

4.2.4 Micropumps

MEMS can even fullfill their purpose in medical science. For example, the micropump schematically shown in figure 6 may be implanted in patients needing constant medication. It consists of a microchamber, which is connected to the reservoir of liquid medicine. The chamber's volume can be changed by a piezo actuator which deflects the upper shell. The result is a changed pressure inside the chamber. Membranes with small holes in certain areas serve as valves. The pump's working mechanism can now be described as follows: In order to fill the chamber with liquid a low pressure is created, allowing the valve between reservoir and chamber to open. When the chamber's volume is diminished during the next step the first valve closes and the valve between chamber and vein opens and the medicine streams out.

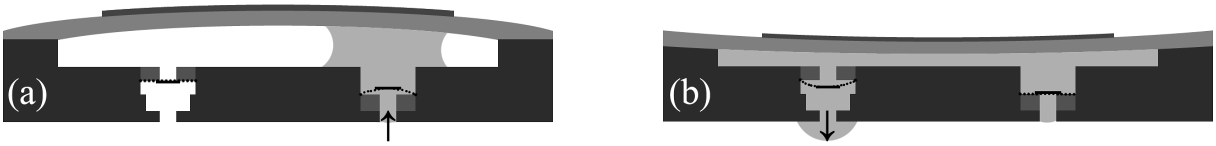


Figure 6: micropump, (a) chamber fills with liquid, (b) liquid gets pumped out

Of course this micropump can also be used in other applications than medical, but whatever its purpose is, the flow rate can be easily controlled by the frequency that drives the piezo actuator.

5 Fabrication

Fabricating MEMS is a challenge of its own. The basic process can be divided into the following steps: growing an epitaxial layer, and covering it with photo resist, which at the same time serves as protectional layer; structuring the photo resist; etching of the undesired parts not protected by the remaining resist; and for finish, removing the resist layer. The difficulty is to create three-dimensional structures by repeating this process over and over again. This requires exact layouts and high precision. Besides this, further difficulties and problems can occur during the fabricating process. Chapter six will give a short overview of some of them.

5.1 Epitaxial Growth

Most MEMS are made from silicon wafers. Depending on the type of layer one wants to grow on the wafer during the first step of the fabrication cycle, different methods are used: For example in MEMS technology many membranes are glass-membranes, since glass-layers (SiO_2) are very easy to create on silicon (Si). The common process for this is thermal oxidation. The wafer's surface is simply oxidated in a heated, evacuated chamber with oxygen supply. A further popular application for glass is as sacrificial layers, which will be explained later.

An allround process is the chemical vapour deposition (CVD). Again the wafers are positioned in an evacuated chamber with gas supply. They are now heated directly, so that the flowing in gases mainly react on the wafer's surface, thus growing the desired layer. This method also allows, depending on the chosen gases, to grow organic layers or even doped silicon layers. Using the gases phosphine (PH_3) and silane (SiH_4) will result in n-doped silicon for example.

Metal layers, which are required for mirrors or contact electrodes, are deposited by thermal evaporation. A so-called target, which consists of the desired metal, is heated until it evaporates. The material then condensates on the wafer, which is positioned near the target. The method of choice for evaporating valuable metals like gold or platinum is shooting an electron beam at it – this way only very little metal is required, compared to other heating methods.

5.2 Photolithography

When the epitaxial layer has reached the desired thickness the photo resist can be deposited on it. During the next step the photo resist is exposed to light through a mask. The mask has transparent areas, that are shaped like the desired structure. Depending on the type of resist, either the translucent areas give the shape of the areas that are supposed to remain on the wafer, or the black ones do. That is to say there are two kinds of photo resist: positive and negative resist. Positive resist becomes porous, when exposed to light, negative resist hardens. Due to diffraction effects the minimum structure width that can be achived when using ultra violet light is approximately $1\mu m$. If smaller structures are desired, the use of x-ray or e-beam exposure is required. After exposure the more porous parts of the resist can easily be removed. The material under the remaining photo resist is now protected while the rest can be removed by etching.

5.3 Etching

During the etching process the unprotected silicon or the freshly deposited layer of different material is being removed, leaving only those areas intact that are covered with resist. It is necessary to choose a resist that is not affected by the applied etching method, or at least not attacked at the same order of magnitude as the material that is supposed to be etched away. The choice of photo resist heavily depends on the method that is chosen to take the material away. Basicly there are two different ways of etching: chemical and physical. While the first means to dissolve the material by changing it into soluble or volatile substances, the latter doesn't change the chemical structure of the material but removes atoms or pieces by using physical force.

An example for chemical etching would be silicon wet etching, e. g. by potassium hydroxide (KOH). As the name already says it is a process for etching silicon. Due to the crystal structure of silicon it is not etched isotropicly, which means the silicon is not taken away at the same rate in each direction. Surface atoms of the <100>-crystal-plane have fewer bonds into the silicon than surface atoms of the <111>-plane. This results in the effect that the <100>-plane is etched 30 times faster than the <111>-crystal-plane. Simplified, one can observe an etching stop as soon as an <111>-plane is uncovered. Figure 7 illustrates this effect:

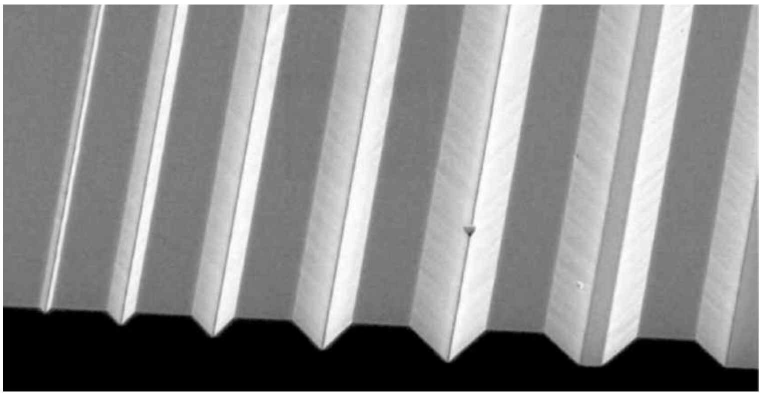


Figure 7: silicon wet etching with potassium hydroxide

the inclined walls are <111>-planes while the wafer surface is <100>-plane. On the bottom of the last channeling the horizontal <100>-plane is not entirely vanished. If the process had been continued, the channels would have gained the same shape as the left ones. The chemical reaction for silicon wet etching is

$$Si + 2OH^- + 2H_2O \longrightarrow SiO_2(OH)_2^{--} + H_2.$$

A second popular method is reactive ion etching. It reaches good rates by combining chemical and physical etching. In order to etch silicon for example, chlorides and fluorides like CCl_4 or SF_6 are used. While flourine and chlorine ions react with silicon resulting in volatile substances, the heavy carbon or sulphur ions impact on the surface, thus physically removing silicon. Please note, that also the protective layer over areas, that are not supposed to be removed, is attacked by the ion impacts. Consequently this etching process has to be stopped before it is completely destroyed.

A third, very important etching process (chemical) uses hydrofluoric acid (HF). That is an acid being very agressive towards ceramics and glass, which is the reason for storing it in plastic containers. Its importance for MEMS processing is based on its ability to completely remove oxidated silicon while at the same time leaving the rest of the used materials intact. This allows us to create chambers or separated structures like gear wheals by using glass as placeholder. Those layers, that are removed again completely, are called sacrificial layers. In a process where sacrificial layers are removed no protective layer is needed. Also HF-etching is isotropic, so that such a layer would be undercutted very soon.

6 Problems with the Fabrication

During this whole fabricating process different problems can occure. They state a big challenge for engineers and make clear, how strict the demands for cleanness during fabrication are, even when only working at microscale. That is because almost all problems directly result from contaminations. The two basic forms of contamination which are especially dangerous are microscopic contamination and molecular dirt. Molecular dirt can be the oil fog from vacuum pumps for example: For many processing steps a high vacuum is required or a low pressure would be of advantage, but still the used pumps may not be perfectly oil-tight and leaking oil can condense on the wafers' sufaces and form a microscopic film. As a result the adhesion of layers deposited afterwards is extremely degradated and those layers are probable to detach later, which, of course, would destroy the MEMS-device.

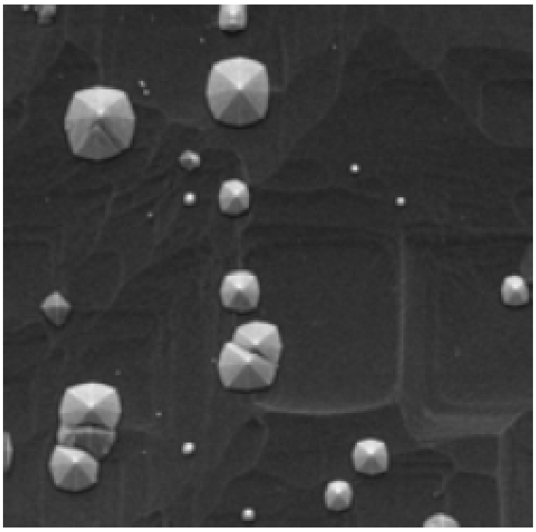


Figure 8: hillocks developed during silicon wet etching

The second mentioned form of contamination, the microscopic contamination, usually is dust. Either dust that is introduced because of insufficient cleanness, or dust that is created during a fabrication step. Besides the problems mentioned in chapter 2.3, dust can also be a problem during fabrication. Remember the peculiarity of KOH-etching for example, and imagine a dust grain falling onto the $<100>$-chrystal-surface. By this grain a part of the plane is blocked and beginning from this point the $<111>$-crystal-planes are being uncovered. The resulting pyramid-like structures, so-called hillocks (cp. figure 8), can cause unbalance in gear wheels or become serious problems, when absolutely smooth surfaces are required.

Besides this, many other obstacles can appear during the fabrication process of MEMS, the bandwidth reaching from material impurities to misalignments, when forming three dimensional structures by "stacking" thin layers.

Concluding, one can say that MEMS and NEMS already support powerful applications, but also hold further great opportunities for the future, if we manage to get all the little difficulties under control.

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