FABRICATION METHOD AND PACKAGING

Summary

This chapter presents an overview of several micromachining techniques and methods that are used to make Microflowns. The focus will be on micromachining in general, fabrication methods (deposition, etching, etc.) and what materials are used to create a Microflown. Several structures that were made in the “MESA kitchen” will be presented [1]. Furthermore a general idea will be given of production methods, the micro machining research issues and how a half-inch Microflown is packaged.

Introduction

The Microflown is made using microtechnology, which is a follow-up of microelectronics that started its revolution after the invention of the transistor by Shockley in the Bell laboratories in 1947. In years, the size of the transistor decreased and integrated circuits came on the market. The size of sensors and actuators (S&A) created by means of fine mechanical techniques became the bottleneck for further miniaturisation of devices and time consuming steps were carefully examined in order to reduce them. With the spin-off of the microelectronics it was found that it was possible to create micron sized mechanical structures and the micromechanics became an important field within the S&A groups.

In first instance, micromachining techniques include the basic processing steps of IC technology, namely thin film deposition, doping, lithography, and etching. In addition, special etching and bonding processes were incorporated that allowed the sculpturing of three-dimensional microstructures.

The micromachining may be divided in: *downsizing* of existing machinery, *improvement of existing products* due to the enhanced precision of the micromachining production techniques and at last the creation of *new products* due to the new production possibilities.

Micromachining is downsizing

In first instance sensors and actuators were miniaturised but held the same functionality as their bigger “brothers”. Examples of downscaling are for example miniature motors, pumps, valves, or gears.

The first example that is shown in Fig. 3.1, is the electrostatic axial gap **wobble motor.** This type of motor consists of a disk that is elevated by a little tip in the middle. Stator poles, that generate a pulling force, are located underneath the rotor. Experiments have shown that micromotors can successfully drive gear trains and slider gear racks. Micromotors with a radius of 100µm were driven at voltages between 15–25V, which theoretically gives driving torques of 10-25pico-Nm (1 pico means 1/1000.000.000.000). Driving frequencies ranged up to 500Hz for motors with four stator poles, which is equal to a rotational speed up to about 10rpm. Wobble motors with integrated gear linkages have been driven for a few minutes. No investigation of their lifetime and failure mechanism has been performed yet.

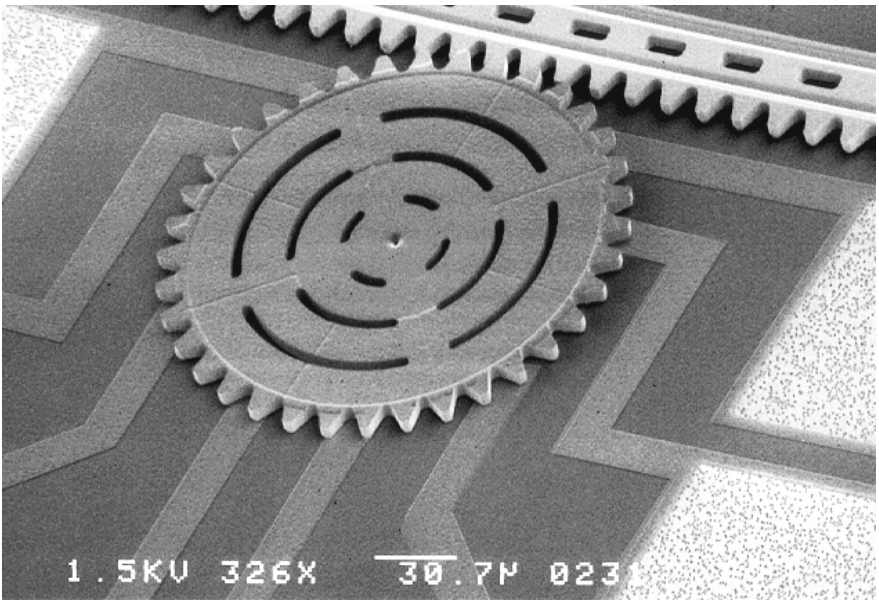

Fig. 3.1: SEM Photo of a slider that is operated with a (Wobble) motor (Rob Legtenberg [2]).

Fig. 3.2 shows the slider and the rails in more detail. One can observe that with the use of micromachining, objects can be made with a very high precision.

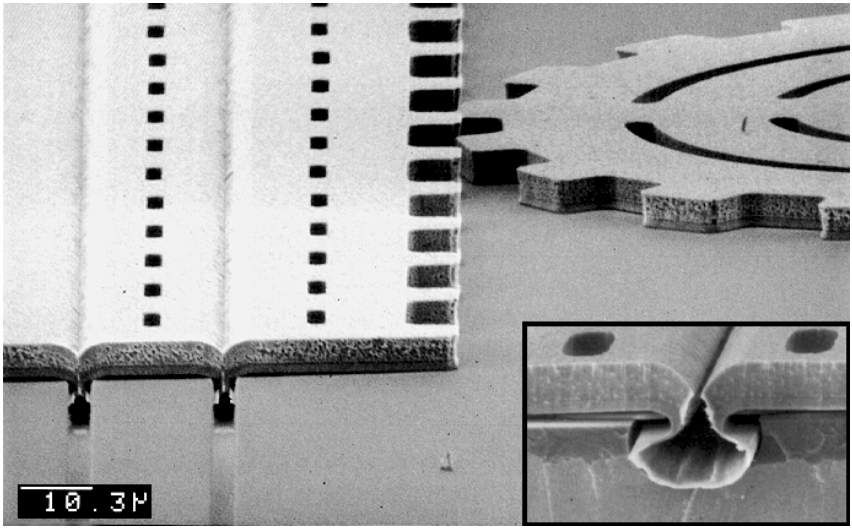

Fig. 3.2: SEM Photo of a slider that is moved by a gear, in the right corner an enlargement of the rails is shown (Erwin Berenschot [2]).

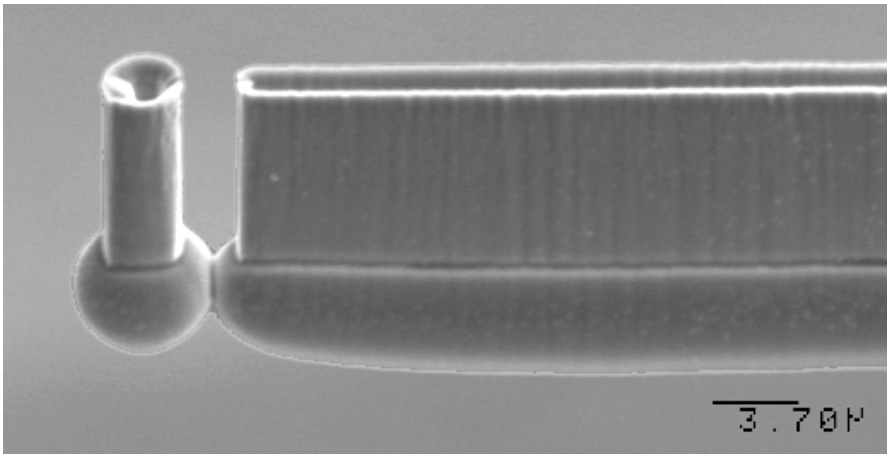

Fig. 3.3: SEM Photo of a micro-pipette (Cristina Rusu, Ronny van ‘t Oever [5]).

Another example of downsizing is the realisation of a **micro-pipette**. It is made using a so-called buried channel technology (see Fig. 3.14). This fluid-handling device has a length of 130μm, a width of 5-10μm, a round opening of 1μm and can expense the tiniest amounts of liquid. Here it was used to study mechanical and structural properties of DNA molecules.

Micromachining is accuracy and reproducibility

In other cases micromachining technology made it possible to create components with higher accuracy and reproducibility than with conventional fabrication techniques. Examples of structures that were made for these features are for example nozzles which are used for ink jet printers or a vaporiser part that is used in a sprayer to relief asthma patients.

A membrane filter is one example that is made at the MESA Research Institute. It has millions of exactly the same pores, see Fig. 3.4. The membrane thickness is 0.1μm and the pores can be made with diameters down to 0.1μm.

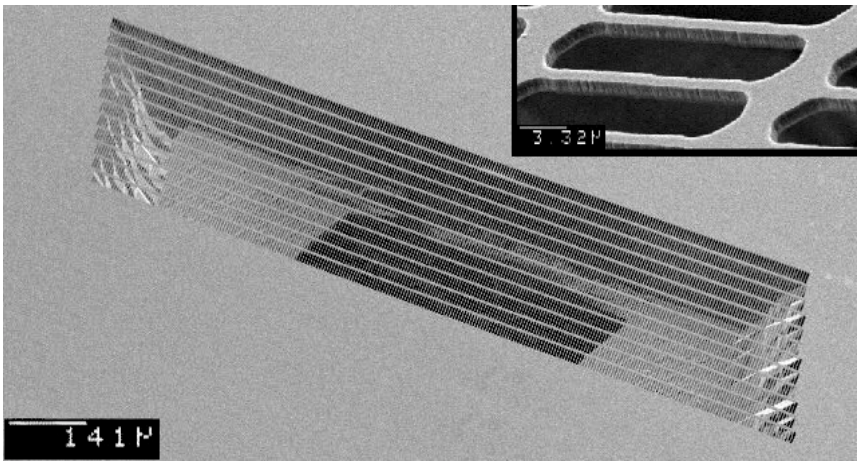

Fig. 3.4: SEM photo of a micro sieve. It consists of millions of identical rectangular holes with slightly curved corners. The black hole that can be seen through the sieve is the exhaust drain. In the right corner an enlargement of the holes is shown. This particular sieve is used for beer filtration (Stein Kuiper [3]).

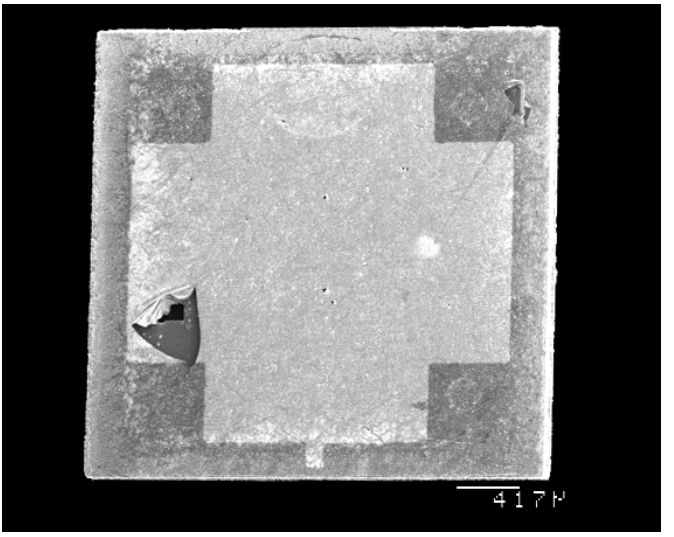

Fig. 3.5: Front of the silicon microphone (Ad Sprenkels). The membrane is partly removed so that the “acoustic holes” become visible [4]. (see also chapter 2, Fig. 2.7: A cross-section of a condenser microphone)

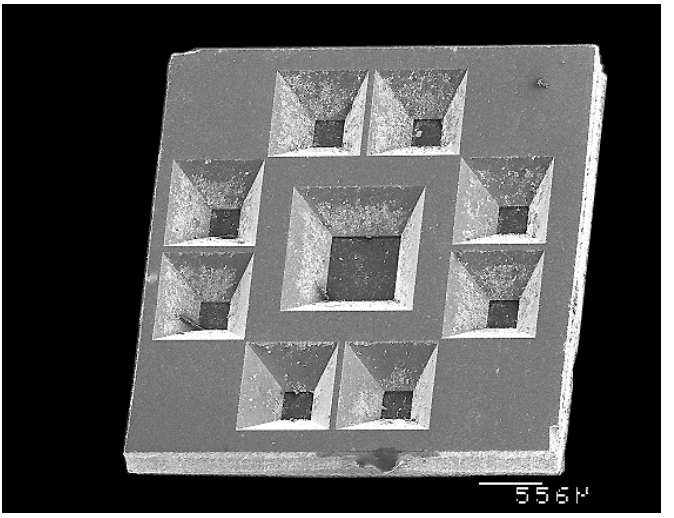

Fig. 3.6: The back of the silicon microphone showing nine “acoustic holes” (Ad Sprenkels, 1992).

The silicon microphone is another example of micromachining technology that became available due to the high reproducibility possibilities.

One of the first micro-machined electret condenser microphones was made at the University of Twente in 1985. The 1.5μm-thick membrane is stretched 42μm from the backplate. The electret-material of the microphone (that measured $3\times3mm^2$) was silicon dioxide (glass) in stead of the commonly used Teflon and it is charged up to an equivalent of 300V. Electron microscope pictures show the front (Fig. 3.5) and back (Fig. 3.6) of the microphone.

The microphone that is shown in Fig. 3.5 and Fig. 3.6 does not have a back-chamber yet. Four years later a prototype of this microphone was developed. It already operates for eight years now and has, if it is not packaged, a frequency response that is flat (ripple 1dB) from 10Hz up to 15kHz with a sensitivity of about 60mV/Pa. If packaged in such way that it becomes suitable for hearing aids, the sensitivity drops to 15mV/Pa and the frequency response will be flat from 150Hz up to 7kHz. The build-in preamplifier (CMOS transistor used as impedance tranducer) is also made at the University of Twente. The selfnoise of the microphone plus preamplifier is about 28dB(A).

Micromachining initiates new possibilities

New micromachining techniques enable the manufacturing of very small structures. This initiates the development of new products. One of the sensors that can operate only due to the small dimensions and thus the micromechanic sculpturing capabilities is for instance a resonating flow sensor. A beam of 600×200μm is stretched over a channel that is etched in the silicon, see Fig. 3.7. The resonator is kept at resonance with a feedback loop. The resonant frequency shifts as result of a mass flow.

The Microflown is another example of a sensor that originated due to micromachining techniques. It is a complete new sensor that only operates if it is made in these small dimensions. If made bigger it would not be sensitive for sound waves anymore. The Microflown itself consists on only two parallel and closely spaced tiny wires that are heated by an electrical current, and a support structure of some kind. These wires are therefore made of a material that is electrically conducting and temperature sensitive. Compared to the previous examples, Microflowns are very easy to make. This may be one of the reasons that the product

development went so fast (it took five years from invention to the first commercial available half-inch ICP probe).

When air flows across the sensors, their temperature change, which alters the electrical resistances. This electrical resistance variation is the output signal. The sensitivity for sound is depending on the temperature sensitivity of the sensors. It is therefore important to find materials that are (apart from good mechanical properties) very sensitive for temperature variations.

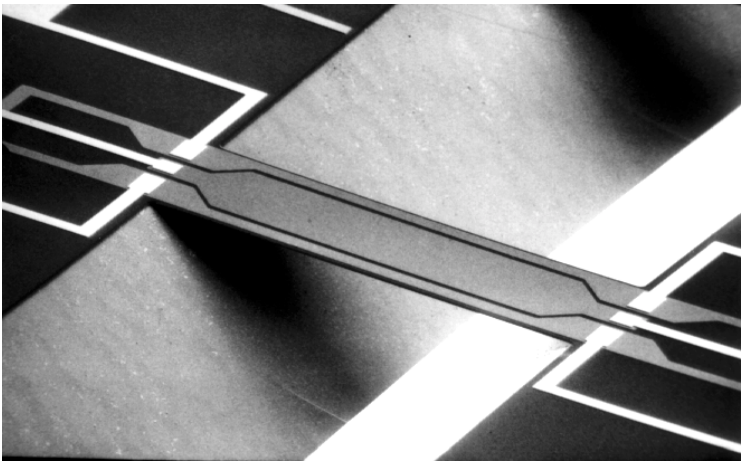

Fig. 3.7: SEM Photo of a resonating flow sensor, the length of the beam is 1mm (Siebe Bouwstra).

Three types of Microflowns

The Microflown has been successfully realised in three variations, a cantilever, a bridge and a through-the-wafer type. The Microflown was originated from a bridge-type of mass flow sensor, see Fig. 4.6 and Fig. 1.8. The first Microflown that fabricated as a cantilever type, see Fig. 1.9. At that time it was thought that the sensing-wires had to be free in the sound wave. The package gain effect however showed the opposite: the wires should be close to a rigid boundary. And to create a high corner frequency (i.e. sensitivity for high tones) the wires should be made as thin as possible. This is why the bridge type was used again: for improved

mechanical stability (to allow thinner sensor) the wires should be clamped at two sides, see Fig. 3.9.

Later on the through-the-wafer type of Microflown was investigated. Initially it was intended to create a three-dimensional Microflown, see Fig.77 in part B2: "*3D p**u** sound intensity probe*". The packaging of this 3D-probe is rather tricky and therefore such probes still are realised using three separate Microflowns. However, the advantage of a through-the-wafer type of Microflown is that the packaging can be realised in a more precise manner, see further chapter AIII "package gain". Another advantage of the through-the-wafer type of Microflown is that soldering can make the electrical connections. In this way the (quite time consuming) wirebonding can be avoided and a connector can directly be connected, see Fig. 3.10.

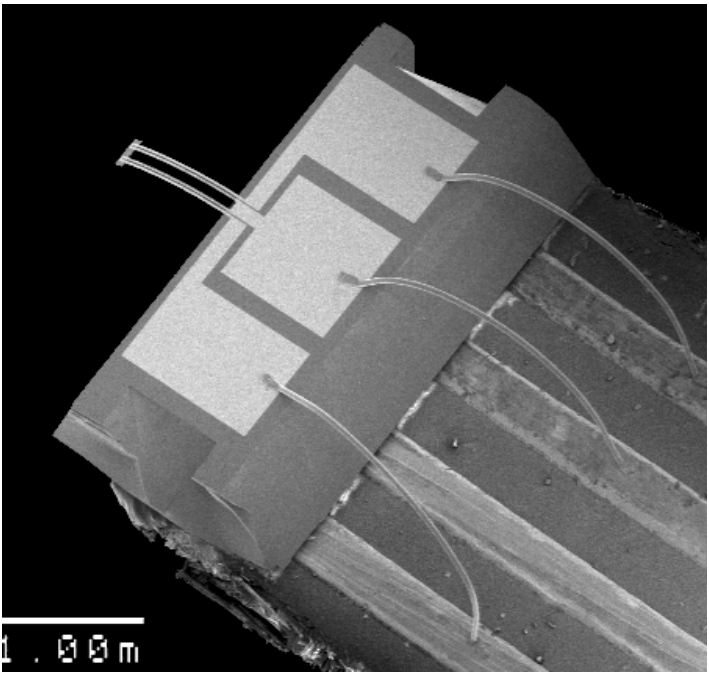

Fig. 3.8: SEM photo of a cantilever type of Microflown.

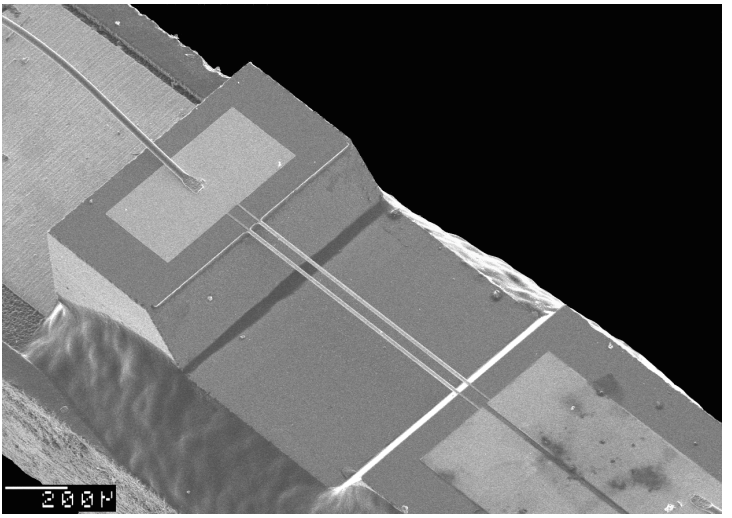

Fig. 3.9: SEM photo of a part of a bridge type of Microflown. At the top of the sample a wire-bond is visible. The sample is glued on a printed circuit board, the glue can be seen at the side of the sample. This type is used nowadays in the commercial products.

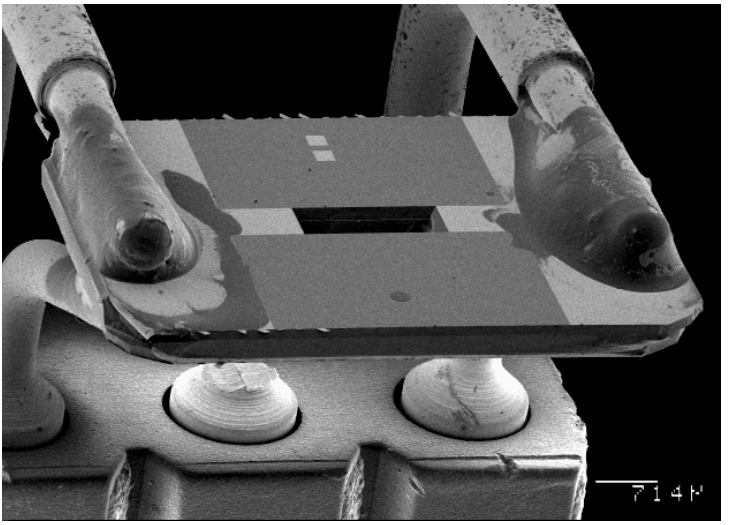

Fig. 3.10: Photograph of a through-the-wafer type of Microflown soldered on a connector. The silicon bulk now acts as a package (gain).

Fig. 3.8 shows a cantilever type of Microflown. The three wire-bonds that take care of the electrical connections are clearly visible. The wire-bonds are connected to the platinum bondpads. The two wires that sticking out are the sensors of the Microflown. To get an understanding of the electrical path, the tip of the two sensors is shown in Fig. 3.12. It shows how the electrical part of the sensors is designed. The sensors are 600μm in length, 15μm in width and have a thickness of 500nm silicon-nitride plus 200nm platinum. As can be seen at the sides, the sensor is diced by breaking.

The bridge-type of Microflown is shown in Fig. 3.9. The length of the sensors is 1mm, the width is 5μm and the thickness is 200nm platinum plus 150nm silicon-nitride. For dicing, this type of Microflown is sawed.

Micromachining production steps

The fabrication of Microflowns in a cleanroom requires a certain number of standard process steps. The three types of Microflowns are made in slightly different ways, here the process steps are given to create a cantilever type is given:

- Standard cleaning
- LPCVD Nitride deposition
- Lithography
- RIE etching of silicon nitride layer
- Lithography
- Sputter deposition of the sensing layer
- Wet chemical etching
- Dicing (sawing/breaking)

Before any process is allowed to start, wafers need to be cleaned. This is to avoid contamination of equipment and also to be sure that processes are starting with fresh wafers.

After the cleaning, a thin (300nm) silicon-nitride layer is deposited on the waver. This layer is used as a mask for the wet chemical etching and as a carrier for the sensors (Fig. 3.11a).

The wafer is now completely covered with a silicon nitride layer and on one side, a photolithographic (or photoresist) layer is deposited. This layer is deposited as a liquid on the wafer that is spinning at a certain speed. The rotation speed and viscosity of the photoresist liquid define the thickness of photoresist. The wafer is now heated to harden the

photoresist. After that, the wafer with photoresist is put under a mask and illuminated. The pattern that is illuminated will be removed by the development of the photoresist layer.

To create the sensors and bondpads, a (200nm) platinum layer is deposited with a sputter technique. This layer will be the actual sensor layer and will be used as bond-pads to establish electrical connections on the printed circuit board. The platinum layer is patterned with a lift off technique: only where the photoresist layer is removed the platinum layer will remain (Fig. 3.11b).

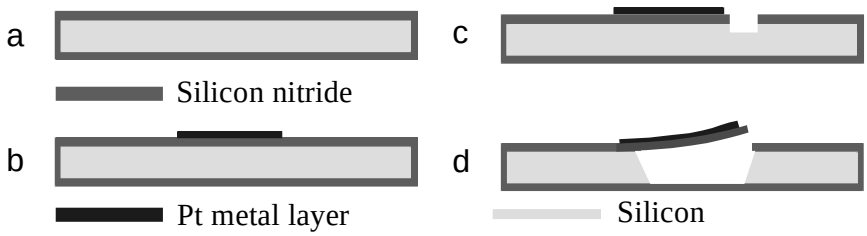

Fig. 3.11: Schematic production steps of the cantilever Microflown.

When the patterned platinum layer is ready, the silicon nitride layer is etched to create a path for the wet chemical etchand to create the channel and set the cantilevers free. Before this can take place, again photolithography step has to be completed. The place where the photoresist layer is removed, the silicon nitride layer will be removed too. The silicon nitride layer is removed by reactive ion etching (RIE) (Fig. 3.11c).

Wet anisotropic wet chemical etching (KOH) will create the channel and will set the cantilever bridges free (Fig. 3.11d). An example of the etch behaviour of KOH is shown in Fig. 3.15.

The bridge type of Microflown is made in a similar manner. First the silicon nitride layer is deposited, the platinum layer is sputtered and patterned and RIE etching patterns the silicon nitride. Now an extra wet isotropic wet chemical etching step has to be included to etch under the sensor wires. An example of isotropic echting is shown in Fig. 3.14. After this step wet anisotropic wet chemical etching (KOH) will create the channel.

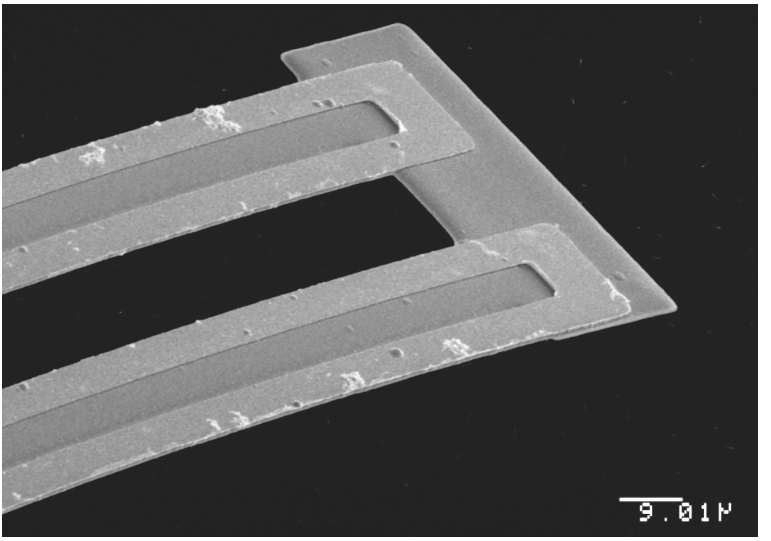

Fig. 3.12: Just to get a feeling: the tip of a cantilever type of Microflown. It is showing the 200nm platinum sensor layer on top of the 300nm silicon nitride carrier layer.

The through-the-wafer type of Microflown is made almost the same as the bridge type. The difference is that now the wafer is processed on two sides. One wire is created on the front side and the other on the back of the wafer. The standard process steps will be discussed in more detail now.

Standard cleaning

To ensure that the silicon wafer is absolutely clean, all processes need a wafer cleaning before the production process is carried out. The cleaning process is required to keep the oven tubes for thermal oxidation and diffusion free of metals. The standard cleaning processes leave the wafers with a thin oxide film (“native oxide” with a thickness in the range of nano-meters).

LPCVD Nitride deposition

The second standard process step is the deposition of a thin film of silicon nitride. Since the standard cleaning leaves a layer of “native

oxide", just before the nitride deposition the waver must be de-oxidised with a 5% HF solution.

The abbreviation "LPCVD" means: Low Pressure Chemical Vapour Deposition. In the LPCVD process a gas is fed through a pipe which contains wafers at elevated temperature at a low pressure. The silicon nitride is deposited from a mixture of dichlorosilane (SiH_2Cl_2) and ammonia (NH_3) at temperature of 800-850 ^{o}C at 0.15mBar pressure.

Photolithography

The photolithographic process includes a mask that defines transparent and non-transparent areas on it. Since for patterning transfer light is used, the minimum feature size feasible is defined by the wavelength of the light (resolution is about 1μm). The patter transfer from the mask to the substrate requires the following steps:

- Photoresist spinning. The photoresist layer is deposited as a liquid on the wafer that is spinning at a certain speed. The rotation speed and the viscosity of the photoresist liquid define the thickness of photoresist.
- Prebake (typically 1 minutes at 90°C). After this step the photoresist is a solid layer.
- Illumination in a mask aligner. The mask aligner allows precise alignment of the mask with features on the substrate and the crystallographic orientation of the silicon wafer.
- Postbake (depending on the resist, normally 1 minutes at 120°C). This step is performed to harden the photoresist layer.
- Development. The illuminated parts of the photoresist layer will be removed in this step.

Sputter deposition metal layer and lift off

In this deposition processes high-energy ions hit the substrate and sputter material from the target. This material is deposited on the substrate. Usually argon (Ar) ions are used to generate a plasma between the target and the substrate. The target is negatively charged, so the argon (Ar) ions impinge of the target and not on the substrate which is grounded or floating. An important advantage is that the adhesion of the sputter deposited films is generally much better than for example vapour deposition. This is due to the high kinetic energy of the sputtered atoms

when they reach the substrate. The atoms penetrate a bit into the substrate.

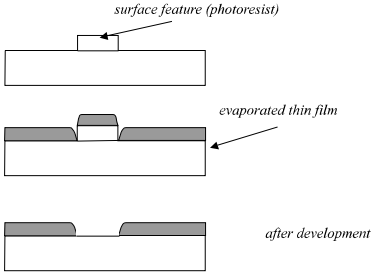

Fig. 3.13: Lift off process.

The parts where the photoresist is removed, the metal layer is sputtered on the wafer. The metal layer that was sputtered on top of the photoresist will be removed at the same time when the photoresist is dissolved. This method of metal patterning is called “lift off”

Wet Chemical Etching

Wet chemical etching is the oldest silicon micromachining technology. Two ways will be mentioned here: isotropic and anisotropic wet chemical etching. The chemistry of this etching is still debated and poorly understood. In Fig. 3.14 the results of etching silicon through a mask using anisotropically and isotropically etching solutions are shown.

The etching is performed to create the channel under the sensors of the Microflown. For the bridge type it is not possible with anisotropic etching to etch under the sensors. To be able to etch under the sensors an isotropic etching step is necessary.

Isotropic etching means that the silicon is etched in all directions. So to etch under a sensor with a width of 5-micron a 2.5-micron (the sensors is under-etched from both sides) isotropic etching step is required.

After this step the channel of the Microflown is anisotropically etched with a KOH-solution. The KOH-solution temperature is at about 70°C and maximum etch rates are a few μm per minute. It will take several hours to create the channel.

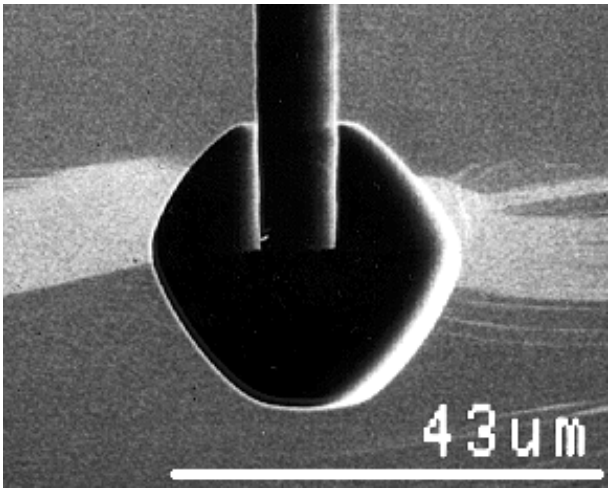

Fig. 3.14: Etchpit formed by isotropic etching silicon through a trench of silicon nitride (Micromachinist Meint de Boer).

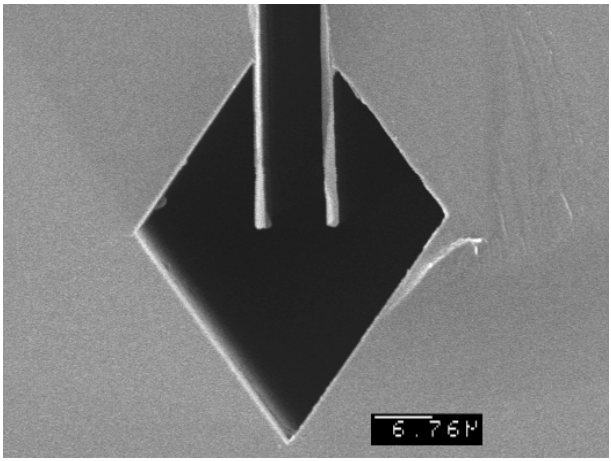

Fig. 3.15: Etchpit formed by anisotropic etching silicon through a trench of silicon nitride (Micromachinist Meint de Boer).

RIE etching of silicon nitride layer

The only practical way to pattern the silicon nitride layer is RIE etching. The abbreviation RIE means reactive ion etching, which is a form of plasma-assisted etching. The basis of this etching is that a gas glow discharge is used to dissociate and ionisate relatively stable molecules. In this state they form chemically reactive and ionic species. A chemistry is chosen such that volatile products are formed that react with the solid to be etched.

Micromachining research issues

This paragraph describes what the research issues regarding the micromachining development of the Microflown. Five research issues can be distinguished:

1) The quest of the best sensor material. The Microflown is a thermal sensor and therefore the transduction quality is directly proportional with the sensor material's ability to react on temperature variations. First the sensors were made of gold. The melting point however was relative low and many Microflowns were (literally) liquidated. Platinum proved to be a better sensor material due to its high melting temperature. The adhesion on the silicon nitride was an important issue. If deposited directly on the nitride layer it came off during the KOH etching. If on the other hand an adhesion layer was used, the thermal properties were ruined. A lot of experimenting was required to find the optimum thickness of the adhesion layer. Nowadays the very temperature sensitive germanium and silicon are under investigation. To be able to use these materials, the process schemes have to be altered (the last step, KOH etching, etches the germanium and silicon).
2) Search for new types of Microflowns. The first "Microflown" was a regular bridge type mass flow sensor. However at the beginning it was believed that the sensor wires had to be free in the sound wave to improve the acoustic quality of the Microflown. For this the cantilever type of Microflown was designed, see Fig. 3.8 and Fig 1.7. To improve the frequency response, the sensor wires had to be made thinner and this caused a lower mechanical stability. To improve the reduced stability, a supporting structure was made, see Fig. 3.16.

Later on, when the package gain was discovered, the cantilever type turned out unnecessary because the wires had to be near an obstacle, see chapter AIII “package gain”. The bridge type of Microflown was used again. Much effort was taken to create very thin wires, 200nm is the standard nowadays. The latest developments is the through-the-wafer type of Microflown. For this design, the wafer has to be processed at two sides. The advantage is that the package (gain) can be made with much higher accuracy and reproducibility.

3) Dicing of Microflowns. The dicing of cantilever types was done by breaking, this can be seen in Fig. 2.15 and Fig. 3.8. This way of dicing is however not possible for the bridge types. These types are diced by sawing. Again, a long development route had to be discovered because the normal sawing procedure destroyed the Microflowns sensors. The through-the-wafer type of Microflown can not be sawed since sensor wires are located on top as well as under the wafer. So this type of Microflown has to be etched free and taken out of the wafer by hand.
4) Design of simple and stable process schemes. Even the slightest variation in a design or materials choice may result in a complete different outcome. For instance the golden sensor material had to be replaced by an other material. Of all the metals only platinum, aluminium and palladium survived the process steps. In operation, the aluminium sensors burned into the non-conducting aluminium-oxide and resistance of palladium did not vary with temperature. Many different ways (about 20) of making Microflowns were tested and only three ways turned out to be well performing. One process design involves: process design, mask design, mask making, actual execution of the process steps, trouble-shoot Murphy’s errors, dicing, mounting on printed circuit board, wirebonding and acoustic testing. It takes about three months to fulfil one process design step.
5) Electrical connections are normally made by wirebonding, see for example Fig. 3.8 and Fig. 2.15. It is a simple and reliable way of making the electrical connections between the sample and the printed circuit board. The method is widely used in the IC industry but in case of the Microflown is not very satisfying. In contrast to many electrical microchips, the Microflown has to be in contact with the open air directly. The fragile wirebonds therefore are being protected by an epoxy. Furthermore the all wirebonds have to made by hand, three wires per Microflown. All together the wire bonding is a time

consuming process step. Other ways of making the electrical connections, such as soldering directly on the sample, are being investigated. First attempts can be seen in Fig. 3.10.

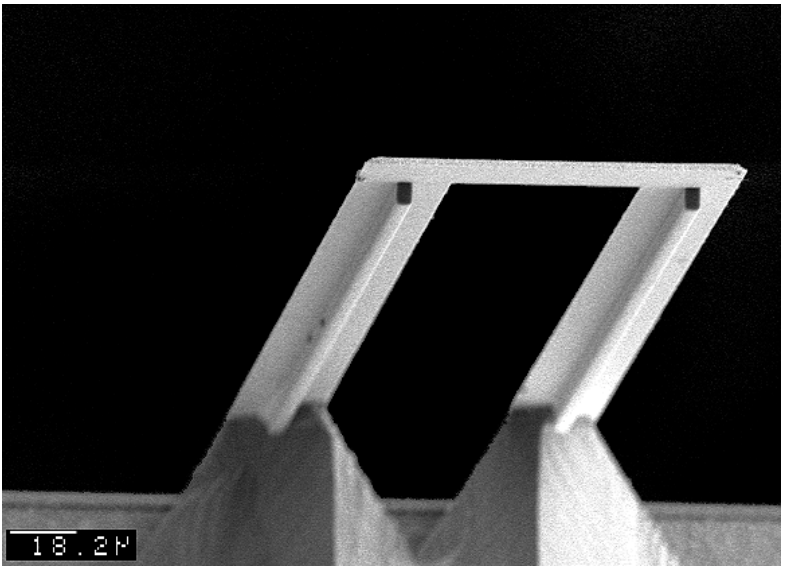

Fig. 3.16: SEM Photo of supporting structures under the cantilever type of Microflown (Twan Korthorst).

Packaging

Packaging is one of the uncultivated parts in the field of micromachining. In case of the Microflown, the packaging should be designed in such way that the sound can reach the sensors and at the same time it should protect against other influences like force (touching the sensors will destroy them), acceleration (dropping) moisture (sweat, rain), (dust) particles and possibly DC flow (wind). Moreover the Microflown should be packaged in such way the package gain is optimal.

Of course, different applications require different packages, connectors and preamplifiers; it should all fit in. In this paragraph the packaging of the half-inch ICP particle velocity probe is portrayed.

Nowadays, for measurement purposes the half-inch ICP probe is used most commonly. Considerations for the size of this package are that it

should be similar to a half-inch pressure microphone. This is required to get good acoustic measurements results; if the probe had a different shape, the sound intensity probe (the combination of a ½" sound pressure microphone and a Microflown) becomes not symmetrical and measurements are not satisfactory. The electronics are designed in such way that it can be used with the standard 4mA ICP protocol, see further chapter 4.

The first step is the production of Microflowns in a cleanroom. This results in approximately 1500 Microflowns that are diced, but still in a wafer. The Microflowns are optically inspected (about 1 to 5 percent is broken) and taken out of the wafer. These Microflowns are glued on a small printed circuit board (PCB). The next step is the wirebonding and the protection of the wirebonds with epoxy. The Microflowns on a PCB are electrically tested and when approved, acoustically tested.

These tested Microflowns (on a PCB) are used for many different applications. Here the ½" ICP Microflown will be used as an example.

The head of the probe consists on two aluminium parts and two stainless steel cylinders. The two cylinders are squeezed in to the top part and the assembly is glued in the other part. After that, the Microflown is glued in to the head of the probe with cyanoacrylate. The Microflown in the head is tested electronically to check if the Microflown is not damaged in this procedure. Now the position of the Microflown inside the package is checked by an acoustical check of the is package gain. When positioned correct, the PCB is fixated with filling glue at the bottom part of the head of the probe.

After this, the PCB is electrically connected to the (tested) preamplifier. The preamplifier is soldered to a BNC connector and the head of the probe, the preamplifier and the BNC connector are glued to the stainless steel cylinder. The probe is acoustically calibrated and ready to use.

If a sound pressure probe is incorporated in the half inch housing, the BNC two-wire connector is not sufficient anymore. In this case a 7-pins LEMO connector is used.

References

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