Microelectromechanical sensors for measuring gas pressure

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Abstract
New prototypes and concepts of micro sensors for measuring gas pressure have been developed by using the fabrication technologies for Micro Electro Mechanical Systems (MEMS). The realization of such microstructured sensors requires sophisticated fabrication processes such as thin film deposition, photolithography and etching techniques. This approach of MEMS sensors for gas pressure is demonstrated by few examples, such as micro-Pirani gauges, resonant vacuum micro gauges and micro spinning rotor gauges.

Keywords: MEMS vacuum gauges; Micro-Pirani gauges; Micro spinning rotor gauge; Resonant vacuum micro gauge; Micromachining

1. Introduction
Users require inexpensive, reliable sensors compatible with modern signal processing circuitry. One answer to this demand may be provided by microsensors, notably based on silicon with on-chip circuitry fabricated by using the integrated circuit (IC) technology. Indeed, a variety of microsensors and microactuators fabricated by standard semiconductor technologies have been demonstrated [1-4]. On-chip circuitry, high reliability and low cost batch-process fabrication are the advantages offered by IC technology for sensors. New prototypes and concepts of microstructured vacuum sensors have been developed by using these technologies for MicroElectroMechanical Systems (MEMS). This approach is demonstrated by few examples: i) Micro Pirani chips with resistive or thermoelectric detection principle, ii) Resonant vacuum micro sensors, iii) Micro spinning rotor gauges.

2. Semiconductor IC technology and micromachining for vacuum microsensors
Thermal based thin film vacuum sensors (chapter 3) require small thermal conductance of the substrate in order to minimize the substrate’s thermal bypass. Sensors with high sensitivity can be realized with substrate membranes (few 100 nm thick) of siliconcarbide, siliconnitride or siliconoxide. Furthermore, new types of capacitive vacuum sensors can also be realized by using very thin membranes with high mechanical stability. The fabrication of such membranes can be performed by silicon micromachining. Sensor films for thermal based vacuum sensors are realized by PVD or CVD processes and photolithographic patterning on these membranes.

Silicon micromachining is based on anisotropic etching of silicon by using etchants like KOH, EDP or by dry reactive ion etching (RIE) with gases like SF₆. The very different etch rates in the various crystallo-graphic directions of silicon enable the preparation of well defined geometrical structures [5-7]. For example, the KOH etch rate \( R(100) \) of the (100)-silicon planes is much higher than the etch rate \( R(111) \) of the (111)-silicon planes with a ratio \( R(100)/R(111) \approx 400 \). Boron doped silicon can be used as an etch-stop layer, since the etch rate is reduced by few orders of magnitude at high boron concentrations.

The preparation of thin membranes by anisotropic etching is demonstrated in Figs. 2 and 3. Mask layers of \( \text{SiO}_2/\text{Si}_3\text{N}_4 \) are deposited on the front and back side of a silicon wafer by LPCVD or PECVD processes. These layers are resistant against anisotropic etchants like KOH or EDP. Micropatterning of the back side mask layer is performed by photolithography and wet chemical or plasma etching (RIE) of the \( \text{SiO}_2/\text{Si}_3\text{N}_4 \) films.

Fig 1: Anisotropic etching of (100)-silicon wafers (left) and relation between mask opening \( a \) and membrane width \( b \) (right) for a (100)-silicon wafer with thickness \( d \)
These mask openings with precisely defined width \( a \) determine the areas, where the (100)-planes of the (100)-silicon wafer are exposed to the etching process. (111)-planes are not substantially etched by the anisotropic etchants. Therefore, the shape of the etching groove is determined by the mask opening and the orientation of the (111)-planes with respect to the (100)-planes. A quadratic mask opening leads to a pyramid-shaped etch groove (Fig. 3) with side-walls of (111)-planes. Since the angle between the (100)- and (111)-planes is 54.7°, a quadratic mask opening with an edge length \( a \) results in the formation of a quadratic membrane with an edge length \( b = a - \frac{2d}{\tan(54.7°)} = a - \sqrt{2}d \).

**Fig. 2:** Etch grooves of a (100)-silicon wafers after anisotropic etching with KOH (left) and schematic of the formation of a thin SiO\(_2\)/Si\(_3\)N\(_4\) membrane (right)

Thin cantilever beams can also be structurized by the anisotropic etching technique. Etch resistant mask layers have to be patterned by photolithography on (100)-silicon wafers. Convex corners of these mask layer are underetched (Fig. 3), since (411)-planes show a high etch rate, comparable with that of (100)-planes. The etch process stops at (111)-planes (side-walls of the etch groove) after completion of the cantilever beam undercutting [8].

**Fig 3:** Preparation of thin cantilever beams by anisotropic etching of convex corners: orientation of Si crystallographic planes with respect to the mask layer (left) and incompletely underetched mask layers, which will form thin cantilever beams [8]

**Surface micromachining with sacrificial layer technology [9]**

Bulk micromachining means that three-dimensional features are etched into the bulk of crystalline materials. In contrast, surface micromachined features are built up, layer by layer, on the surface of a substrate. Dry etching defines the surface features in the x-y plane and wet etching releases them partially from substrate by undercutting. In surface micromachining, shapes in the x-y plane are unrestricted by the crystallography of the substrate. The nature of the deposition processes involved determines the very flat surface of micromachined features (sometimes called 2.5D features). An excellent thermal insulation of surface micromachined features can be achieved by wet chemical etching of so-called sacrificial layers.
3. Thermal based vacuum microsensors

Thermal vacuum sensors (Pirani gauges) are based on the principle that heat transfer between a hot wire and surrounding is proportional to the number of molecules (and hence to the pressure) transferring the heat, when the mean free path \( l \) of the gas molecules is larger than the distance between hot wire and ambient. In the high pressure range \( (p > 10 \text{ mbar}) \), where the mean free path \( l \) becomes very small compared to this distance, the thermal conductivity is almost independent on pressure. At low pressures \( (p < 10^{-3} \text{ mbar}) \) the thermal power, transferred by the gas molecules, becomes very small compared to radiation and conduction of the hot wire. Therefore, conventional Pirani gauges show low sensitivity in these two pressure ranges. In contrast to these Pirani tubes, in a micro Pirani gauge \([10-14]\) the heat transfer takes place between an extremely thin heated membrane and the surrounding. The thin membrane \((100 - 800 \text{ nm thick})\) is realized by silicon micromachining as described in chapter 2 by using SiO\(_2\)/Si\(_3\)N\(_4\) films. Heating is performed by a meander-shaped metal thin film heater (Al, Au, Pt) in the centre of the membrane. With such a micromechanical design and thin SiO\(_2\)/Si\(_3\)N\(_4\) membranes the pressure-independent conductances can be reduced to \( \approx 10^{-6} \text{ W/K} \) and therefore, the sensitivity in the low pressure range can be increased. Two detection principles have been realized:

i) a resistive sensor chip (Fig. 4), where a thin film heating/measuring resistor is arranged in the centre of membrane together with compensation resistors on the bulk silicon rim. Short response time \((5 \text{ ms})\) high sensitivity (Fig. 5) at low pressure and small power consumption \((0.25 \text{ mW})\) are outstanding features of the chip, which is bakeable up to 350 °C.

ii) a thermoelectric sensor chip (Fig. 6), where a meander-shaped thin film serves as heater of the membrane area and a thin film thermopile detects the membrane temperature as a function of gas pressure. Fig 8 shows the sensor output voltage as function of N\(_2\) pressure by applying a constant heating power of 84 µW.

In order to increase the sensitivity of the micro Pirani chips in the high pressure range, the conductance by gas can be enhanced employing a bulk silicon "microcap" (lid) on the chip (Fig. 7). Applying this lid, the distance between heated membrane and "ambient" can be considerably reduced and therefore the thermal conductivity remains a function of pressure even in the atmospheric pressure range. In order to achieve this pressure dependence, the distance should be few microns. Such distances can be realized precisely by anisotropic etching of \((100)\)-silicon wafers with KOH etchant at 80°C. This measure leads to a heat exchange between membrane and lid across a small gap, instead of the free convection heat exchange with the surrounding gas. Fig. 8 demonstrates the effect of various gap dimensions and shows the increasing sensitivity of the sensor in the high pressure range with decreasing gap width. Fig. 9 shows a micro Pirani chip integrated in a standard TO5 carrier with a vacuum filter mounted into the TO5 cap.

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**Fig. 4:** Resistive micro Pirani chip with meander-shaped heating/measuring resistor on SiO\(_2\)/Si\(_3\)N\(_4\) resistive micro Pirani chip in the low pressure range, membrane and compensation resistors on bulk Si rim (chip size 2x2 mm\(^2\), response time 5 ms)

**Fig. 5:** Signal voltage as function of pressure for a resistive micro Pirani chip measured with Wheatstone bridge voltage supply of 1 V.

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**Fig. 6:** SEM picture of a thermoelectric micro Pirani chip (size 3x3 mm², response time 10 ms)

**Fig. 7:** Cross sectional view of a micro Pirani chip with silicon lid for increased sensitivity at $p > 10$ mbar

**Fig. 8:** Output voltage $U$ (mV) as function of pressure $p$ of thermoelectric micro Pirani chips (Fig. 6) for various gap distances (heating power 84 µW).

**Fig. 9:** Micro Pirani chip integrated in standard TO5 housing with vacuum particle filter

Very small and well determined distances between heated surfaces and surfaces at ambient temperature, which increase the sensitivity of micro Pirani gauges in the high pressure range, can also be manufactured by surface micromachining with sacrificial layer technology, described in chapter 2. Figs. 10 and 11 show a schematic and a SEM picture of a resistive vacuum sensor, fabricated by using this technique [15]. The meander-shaped resistor is deposited and patterned on a thin membrane of CVD oxide. Spacing between this membrane and the substrate (heat sink) of only 2 µm has been performed by wet chemical etching of an aluminium sacrificial layer of 2 µm thickness. The sensor shows a high sensitivity in the pressure range from $10^{-1}$ mbar to 1000 mbar.

**Fig. 10:** Cross sectional view of a micro Pirani chip, fabricated by surface micromachining, before etching of sacrificial layer

**Fig. 11:** SEM picture of a micro Pirani chip with high sensitivity at atmospheric pressure, fabricated by surface micromachining [15]

### 4. Resonant vacuum micro gauges

Fig. 12 represents a resonant vacuum micro gauge [16] consisting of a 250 µm by 150 µm clamped-free cantilever beam, which represents the micro resonator. It is excited electrothermally and the vibrations are detected using n-doped polysilicon resistors, integrated in the suspended cantilever. The damping (inverse
quality factor $Q$ of such resonant cantilevers due to gas friction is a function of pressure. The quality factor $Q$ can be evaluated from the 3 dB-bandwidth at resonance. Fig. 13 shows the quality factor as function of pressure for 250 µm by 150 µm (triangles) and 300 µm by 200 µm (circles) clamped-free beam resonators.

5. Micro spinning rotor gauges

The magnetically-suspended spinning rotor vacuum gauge (SRG) [17-19] has become an important instrument for the precise measurement of vacuum pressure, since the calibrating relationship, i.e. the factor between pressure and the rotor deceleration, can readily be calculated in terms of the molecular weight and temperature of the gas concerned. A conventional SRG contains a small sphere (diameter 4-5 mm), magnetically-suspended and accelerated by coils and rotating in a tube with a distance $d \approx 4$ mm to the tube wall. The conventional SRG shows a inferior sensitivity for low pressures ($p < 10^{-5}$ mbar), since the deceleration due to gas friction becomes small compared to residual terms in the decay rate, arising mainly from various inevitable tiny imperfections.

![Fig. 12: SEM photograph of a 250 µm by 150 µm clamped-free beam resonator](image1)

![Fig. 13: Quality factor $Q$ as function of pressure $p$ for two types of beam resonators](image2)

Concepts of miniaturization as discussed above can also be applied in order to increase the sensitivity range of spinning rotor gauges. The new concept is based on the application of microfabricated discs (instead of spheres) and of electrostatic instead of magnetic driving forces (Fig. 14). Electrostatic suspending/driving forces are superior to magnetically ones in the field of microactuators with geometrical dimensions in the µm-range. The microdisc with thickness $t = 50$ µm and a diameter of 500 µm has been fabricated by using established SU-8 thick resist technology [20].

![Fig. 14: Schematic setup of a micro SRG (left) and components (microdisc, electrodes, Si housing) of the device (right)](image3)

Electrodes on the microdisc has been structurized by deposition of thin Au layers and photolithographic patterning. The microdisc is located in a disc-shaped silicon housing (diameter = 600 µm, depth = 90 µm) which is prepared by deep RIE of silicon. Top suspending/driving electrodes are formed on a thin glass substrate, which is used for sealing of the silicon housing by anodic bonding. The effect of miniaturization has been calculated by using the classical theory of deceleration arising from gas friction. For a disc-shaped rotation body the deceleration can be described by
the mean velocity of the gas molecules and $\rho$ the mass density, $\omega$ the rotation frequency, $r$ and $t$ the radius and thickness of the disc, respectively, $\bar{c}$ the mean velocity of the gas molecules and $\sigma_t$ the momentum accommodation coefficient. The deceleration of a conventional SRG amounts to $-\dot{\omega}/\omega = 0.043 \cdot p/(s \cdot mbar)$ for a steel sphere ($\rho = 7.8 \ g/cm^3$, $r = 2 \ mm$). According to Equ. (1), the deceleration of a micro SRG is $-\dot{\omega}/\omega = 5.1 \cdot p/(s \cdot mbar)$ for a SU-8 disc (density $\rho = 1.5 \ g/cm^3$, thickness $t = 50 \ \mu m$, radius $r = 250 \ \mu m$) in $N_2$ atmosphere at room temperature ($\bar{c} = 470 \ m/s$). Therefore, the sensitivity range of a SRG can be extended two orders of magnitude down to pressures of $10^{-7} \ mbar$ as a result of miniaturization.

At high pressures ($\rho > 1 \ mbar$) the sensitivity of a conventional SRG is low, since the mean free path $l$ becomes small compared to the distance $d$, and therefore, the viscosity and deceleration by gas friction, becomes almost independent on pressure. On the other hand, small distances $d$ of about 10-20 $\mu m$ between the rotating disc and the housing can be realized for the micro SRG, which will increase the sensitivity range also at high pressures up to 100 mbar. However, the big deceleration of microdiscs at high pressures requires new detection mechanisms for the frequency decay rate.

### 6. Conclusion

Microstructured vacuum gauges enable the extension of the sensitivity range for various conventional vacuum gauges such as Pirani gauges and SRG due to their low thermal conductances and small dimensions compared to the mean free path. Established MEMS fabrication technologies offer the chance for their reliable and cost-effective batch-process fabrication. Reliable chip parameters (as consequence of batch-process fabrication) permit a simple exchange of chips without additional gauge calibration. Small size of the devices, their low power consumption and short response time open new fields of applications for these gauges, e.g. in medicine, consumer market (test of vacuum isolations), in complex MicroElectroMechanical Systems or as transferable calibration standards.

### References

[1] P. Krummacher, H. Ogouy, Sensors and Actuators, A 21-23 (1990) 636-638
[2] T. Nakamura, K. Maenaka, Sensors and Actuators, A 21-23 (1990) 762-769
[3] H. Baltes, A. Nathan, in: Sensors, Vol. 1, T. Grantke and W.H. Ko (eds.) Weinheim: VCH (1991) 195
[4] J. Kramer, P. Seitz, H. Baltes, in: Transducers 91 Digest of Techn. Papers, New York: IEEE (1991)727
[5] H. Seidel, L. Csepregi, A. Heuberger, H. Baumgärtel, Anisotropic Etching of Crystalline Silicon in Alkaline Solutions-Part I, Orientation dependence and Behavior of Passivation Layers, Jour. Electrochem. Soc. 137 (1990) 3612-3626
[6] H. Seidel, L. Csepregi, A. Heuberger, H. Baumgärtel, Anisotropic Etching of Crystalline Silicon in Alkaline Solutions-Part II, Influence of Dopants, Jour. Electrochem. Soc. 137 (1990) 3626-3632
[7] F. Völklein, T. Zetterer, Praxiswissen Mikrosystemtechnik, Vieweg, Wiesbaden (2006)
[8] G.K. Mayer, H.L. Offereins, H. Sandmeier, K. Kuhl, Jour. Electrochem. Soc., 137 (1990) 3947
[9] R.T. Howe, Polycrystalline Silicon Microstructures, in C.D. Fung, P.W. Cheung, H.W. Ko, D.G. Fleming (eds.), Micromachining and Micropackaging of Transducers, Elsevier, New York (1985)
[10] F. Völklein, W. Schnelle, Sensors and Materials, Vol. 3 (1991) 41-48
[11] A.W. van Herwaarden, D.C. van Duyn, J. Groeneweg, Small-size vacuum sensors based on silicon thermopiles, Sensors and Actuators A, Vol. 25-27 (1991) 565-569
[12] A.W. van Herwaarden, P.M. Sarro, J. Vac. Sci. Technol., Vol. A 5 (1987) 2454-2457
[13] P.K. Wenig, J.-S. Shie, Rev. Sci. Instr., Vol. 65 (1994) 492-499
[14] O. Wenzel, C.K. Bak, The MicroPiraniTM: a solid-state vacuum gauge with wide range, Vakuum in Forschung und Praxis 4 (1998) 298-301
[15] A. Häberli, Compensation and Calibration of IC Microsensors, Ph. D. Thesis ETH-Zürich (1997), Diss. ETH No. 12090
[16] O. Brand, Micromechanical resonators for ultrasound based proximity sensing Co, Ph. D. Thesis ETH-Zürich (1994), Diss. ETH No. 10896
[17] J.W. Beams, D.M. Spitzer, J.P. Wade, Spinning rotor pressure gauge, Rev. Sci. Instrum. 33 (1962) 151
[18] J.K. Fremerey, Spinning rotor vacuum gauges, Vacuum 32 (1982) 685
[19] J.K. Fremerey, The spinning rotor gauge, J Vac Sci Technol A3(3) (1985) 1715
[20] C.-H. Lin et al., Jour. Micromech. Microeng. 12 (2002) 590-597