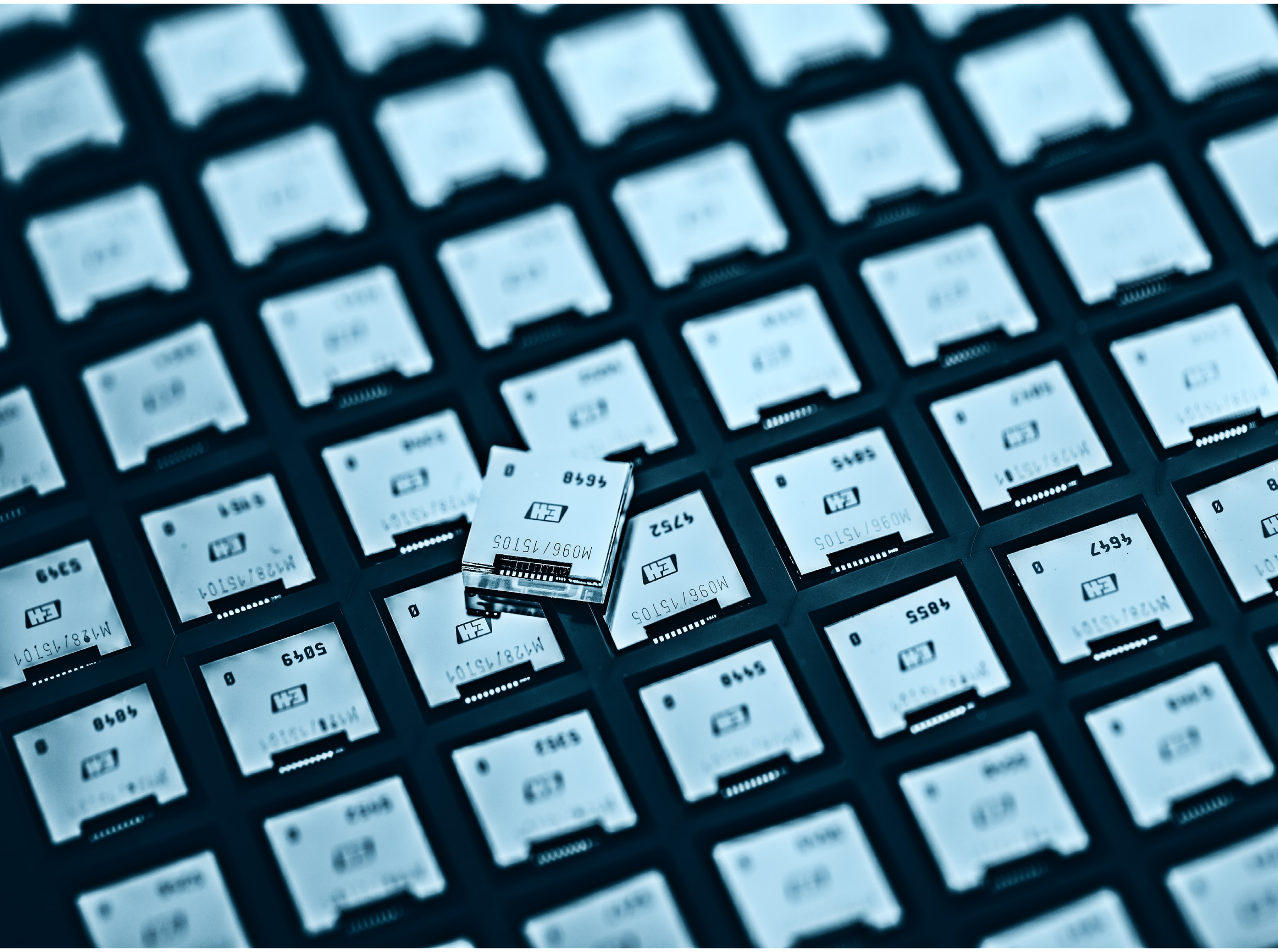
Density measurement basics

Training document (MEMS-CHIP)



Basics of density measurement

At a glance

This section gives you a first insight into the basics of density measurement. You will learn that density is a temperature and pressure-dependent substance property which is often specified with the unit kg/m^3 or lb/ft^3. The density value is required for determining concentration, average molecular weight and content. For finding the density of gases, it must be noted that this density depends on the respective pressure. The density of liquids depends on the temperature.

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What is density?

Density is a physical property of a substance that is dependent on temperature and pressure. It provides information on how heavy a substance is. If the mass of two substances of the same quantity is compared, the substance with the higher weight has the higher density.

The density ρ (rho) is defined as mass m per volume V.

Density formula

$$\rho = \frac{m}{V}$$

Substances can occur as pure substances, mixtures or compounds. If the masses of the individual substances per unit volume are added together, the result is the density of a mixture of substances:

Density formula of mixtures of substances

$$\rho = \frac{1}{V}\sum_i m_i$$

ℹ Conversion into SI units:
$1\ kg/m^3 = 1000\ g/m^3 = 0.001\ g/cm^3$
$= 0.000001\ kg/cm^3$

The SI unit of density is kilograms per cubic meter (kg/m^3).

The US unit of density is expressed in pounds per cubic foot (lb/ft^3).

There are also product or industry-specific units. For example, the degree Oechsle (°Oe) or the degree Brix (°Bx). The units indicate the density or sugar content of must or sugar/water solutions.

ℹ The density depends on pressure and temperature.

Due to thermal expansion and compressibility, the density of a substance is influenced by the prevailing temperature and pressure. These influencing variables have a greater or smaller effect on the density, depending on whether the substance is a solid or a fluid.

The degree of temperature and pressure dependence is much higher for fluids than for solids. In order to obtain a precise density indication, the associated **temperature** and **pressure** must be known, especially with fluids.

ℹ The volume and the density change with a change in temperature and/or pressure. The mass always remains the same.

While the density and volume of a substance change due to the influence of temperature and pressure, the mass always remains constant. If the volume is reduced due to the influence of pressure and/or temperature, while the mass remains constant, the density will increase.

Temperature and pressure influence on the density of some liquids at t_{ref} = 20 °C and p_{ref} = 10 bar

Substance	Density ρ (t_{ref}, p_{ref}) (kg/m³)	Density ρ (t_{ref} +1 °C, p_{ref}) (kg/m³)	$\Delta\rho$ (ΔT = 1 K) (kg/m³)	Density ρ (t_{ref}, p_{ref} +1 bar) (kg/m³)	$\Delta\rho$ (Δp = 1 bar) (kg/m³)
Gases					
Helium	1.634	1.629	-0.006	1.80	0.163
Air	11.92	11.88	**-0.04**	13.12	**1.2**
CO_2	19.10	19.02	-0.08	21.14	2.04
Methane	6.70	6.68	-0.02	7.39	0.69
Liquids					
Propane	500.52	498.95	-1.57	500.80	0.28
Water	998.62	998.41	**-0.21**	998.66	**0.04**
Ethanol	790.22	789.36	-0.86	790.30	0.08
Pentane	626.86	625.89	-0.97	626.99	0.13

Source: NIST Reference Fluid Thermodynamic and Transport Properties Database

The table shows that the density of gases hardly decreases at a temperature change of one Kelvin. With air, it only decreases by approx. 0.04 kg/m³. With the MEMS chip, such a change might not be clearly detected. However, if the pressure is increased by 1 bar, the gas density in the example of air increases by 1.2 kg/m³. The density of a liquid, on the other hand, hardly changes at all due to a pressure change of 1 bar.

ℹ In order to be able to compare substances better, the density of a substance can be converted into a so-called standard density or into a specific density.

The **standard density** (also referred to as **"reference density"**) indicates the density of a substance or mixture of substances at a certain temperature and pressure. It enables better comparability of different density values with each other. The following **standard conditions** for temperature t_n and pressure p_n are frequently used in the listed industries:

Standard conditions for standard densities in different industries

Industry	Temperature$_n$	Pressure p_n
Physics	0 °C	1.01325 bar
Chemistry	0 °C	1.000 bar
Oil & gas	15 °C/60 °F	1.013 bar
Medicine	37 °C	Air pressure
Laboratory	20 °C	1013 mbar

Source: based on https://de.wikipedia.org/wiki/Standardconditions

The standard density of substances or mixtures of substances can be taken from so-called density tables. Examples of density tables can be found here, amongst other sources:

- **Alcohol**: Standard OIML R 22
  "International Alcoholmetric Tables" dated 1973
  (http://www.oiml.org/en)
- **Sugar**: Standard ICUMSA
  "Densimetry and Tables: Sucrose -Official; Glucose, Fructose and Invert Sugar - Official ICUMSA Method SPS-4" dated 1998
  (http://www.icumsa.org)

- **Water**: PTB notices
  Wagenbreth, H.; Blanke, W.: "The Density of water in the international system of units and the international practical temperature scale" dated 1968 and
  Bettin H.; Blanke W.: "The density of water as a function of temperature after the introduction of the 1990 International Temperature Scale
- **Gases**: NIST DATABASE
  "NIST Reference Fluid Thermodynamic and Transport Properties Database"
  (http://www.nist.gov)

The **specific density *d***; also known as relative density, describes the ratio of two density values. The density of a substance is compared with the respective standard density or another reference variable (e.g. air). The specific density is a dimensionless quantity.

Calculation of specific density *d*

$$d = \frac{\rho}{\rho_{air}}$$

What are density specifications required for?

Density is a standard value for the characterization of substances and mixtures of substances and is therefore frequently used in the analysis and synthesis of substances.

The density value makes it possible to derive various parameters which allow conclusions to be drawn about the composition of a mixture or a compound.

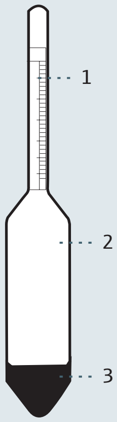
Very often the density is used to determine the **concentration** of a substance in an aqueous solution. The quantitative amount of a (pure) substance in a mixture can be specified in volume percent, mass fraction or as substance quantity concentration.

In addition, the quality of a mixture of substances or a compound of substances is often determined by the **mean molar mass**. The mean molar mass can also be determined with the help of density and enables a characterization of natural gas, for example.

Which measuring methods are available for the determination of density?

There are numerous devices and measuring methods with which the density of a substance can be determined. With the MEMS chip, the **resonator density measurement** is used as a relatively new principle. Typically, however, even today older measuring methods such as **areometer**, **pycnometer** and **buoyancy considerations** are used.

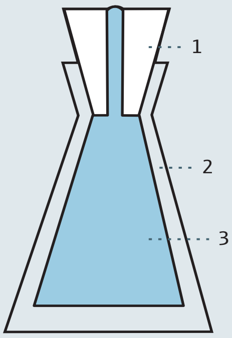
Measuring methods for the determination of density



Areometers are often used for measuring the density of liquids. These glass floats are placed in the liquid and sink until the buoyancy forces of the test liquid are in equilibrium with the areometer weight. The density of the liquid can be derived from the immersion depth of the float.

Source: Liquid density measurement overview articles 2002
Prof. Dr. G. Hradetzky (Merseburg University of Applied Sciences)
Prof. Dr. K.-D. Sommer (PTB Braunschweig)

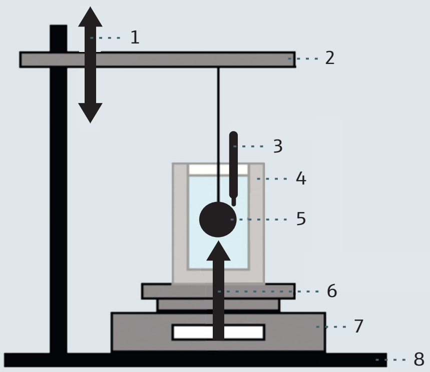
1. Reading scale
2. Floatation body
3. Sinker



Pycnometers are weighing vessels which are first weighed empty and then with the liquid or solid to be measured. The density can be calculated from these two values.

Source: http://www.physik.uni-halle.de/Lehre/Grundpraktikum/anleitungen/Pharma-Heft-11.pdf, Martin-Luther-Universität Halle-Wittenberg

1. Stopper with capillary
2. Piston with grinding
3. Sample liquid

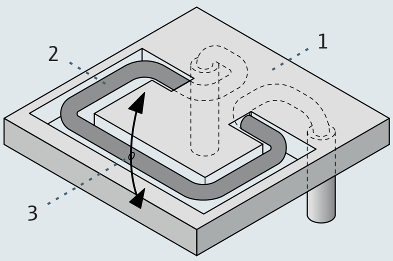


With the help of the buoyancy principle, the measurement of density is also possible with **buoyancy weighing**. A sinking body is immersed in the liquid to be measured and its buoyancy is measured using a balance. The quotient of buoyancy and sinking body volume gives the density of the liquid to be calculated.

Source: Article "New measuring method for areometers by direct buoyancy force measurement" in WeighAhead (issue 10, 2004), Christian Buchner and Dietmar Steidl, Federal Office for Verification and Measurement (BEV)

1. Calibration
2. Lifting device
3. Sinking body
4. Container with liquid
5. Temperature measurement
6. Buoyancy
7. Balance
8. Base

Measuring methods for the determination of density (continued)



The Omega chip is a **resonator densimeter**. In this method, a resonator moves while maintaining contact with the respective liquid. The vibration frequency is measured, which depends on the density of the liquid.

Source: Technical Information "DLO-M1", TrueDyne Sensors AG

1. Clamping fixture
2. Resonator with test liquid
3. Measurement of vibration frequency

Comparison of density measuring methods

	Areometer	Pycnometer	Buoyancy weighing	Resonator densimeter
Substance type	Liquids	Solids and liquids (low-viscosity)	Solids and liquids	Gases and liquids
Field of application	Laboratory, process	Laboratory	Laboratory, partly process	Laboratory, process
Measuring uncertainties	0.02 to 5 kg/m³	0.02 to 0.5 kg/m³	0.001 to 0.5 kg/m³	0.005 to 10 kg/m³
Traceability	⊞ Direct measurement	⊞ Direct measurement, traceability via volume release	⊞ Direct measurement	⊟ No direct traceability
Procedure	⊞ Relatively easy procedure ⊟ Inflexible measuring method	⊟ Complex measuring method	⊞ Relatively simple procedure	⊞ Very simple procedure
Temperature requirement	⊟ Homogeneous temperature required	⊟ Careful temperature checks necessary	⊟ Exact temperature problematic	⊞ Simple temperature setting
Measuring result	⊞ No drift	⊞ Exact results, no drift	⊞ Very accurate results	⊞ High-precision results ⊞ Rapid results ⊞ Continuous measurement
Influencing factors	⊟ Measuring problems due to evaporation ⊟ Segregation ⊟ Reading error ⊟ Large sample quantity necessary		⊟ Measuring problems with high viscosity ⊟ Measurement under pressure difficult	⊞ Measurement under pressure possible ⊟ Measuring problems with high viscosity, bubble formation, impurities ⊟ Limited measuring range

Notes:

The resonator density measurement

At a glance
In the previous section we learned about the basics of density measurement and the definition of density. This section is dedicated to the vibration method which is also used by density sensors for density measurement. This method also has some advantages and disadvantages, which are explained in detail.

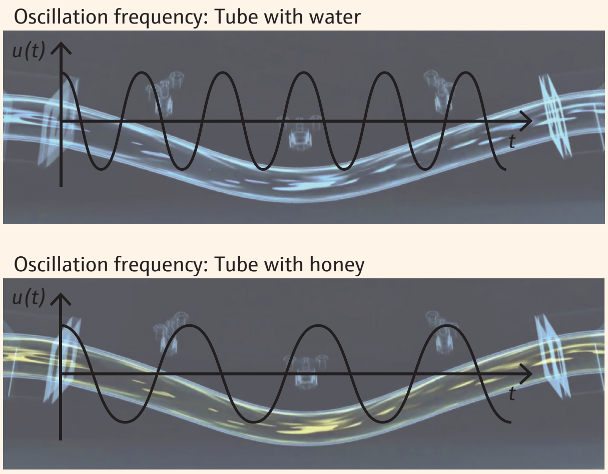
Contents

- How does the resonator density measurement work?
- What are the benefits?
- What are critical influencing factors (disadvantages)?
- When is the resonator density Measurement requested?
- Determination of methane number in gas engines to increase efficiency.

How does the resonator density measurement work?

With the resonator density measuring method, the density **is measured indirectly by a frequency** determination. The liquid to be measured is filled into a tube (resonator) which is set into resonance vibration. The resulting oscillation frequency, which depends on the density of the liquid and the rigidity of the resonator, now provides information on the density. The higher the vibration frequency, the lower the density of the liquid.

Liquid density/vibration frequency dependence



Source: TrueDyne Sensors AG, flexural resonator animation

The properties of the resonator (e.g. stiffness) depend on temperature and pressure. These dependencies are determined on the basis of calibration measurements and compensated for by the measuring instrument. The only remaining variable that can be influenced is thus the density of the liquid.

The following equation illustrates the relationship between density ρ of the liquid, the properties of the resonator (constants A and B) and the oscillation frequency f:

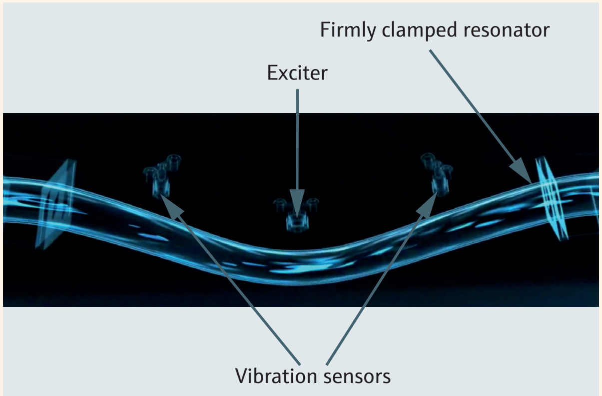
Relationship between medium density ρ and vibration frequency f

$$\rho = A + \frac{B}{f^2}$$

How the resonator measuring device works:

- Resonator is firmly clamped at both ends.
- Exciter causes the tube to vibrate.
- Vibration sensors detect the vibration frequency.

Design of a resonator measuring instrument



Source: TrueDyne Sensors AG, flexural resonator animation

The shape and materials of the resonator are not fixed. Thus, the resonator can be either a round tube or a square tube.

What are the advantages?

The **straightforward handling** which goes hand in hand with the low complexity of the testing techology, is one of the greatest advantages of the resonator density measurement. The density is measured after the medium has been added without any further adjustments having to be made. Reading errors can be excluded, as the density value is shown on a digital display. Temperature control of the medium is not required; instead, the temperature is measured in situ. In addition, the extraction of an exact volume is not required.

The **miniaturization** of the technology that is possible means that only **small sample quantities** are needed for reliable density determination. This feature is particularly relevant for expensive media. The use of small sample quantities also makes it easier to determine the medium temperature for density measurement.

The measurement can be performed in a closed system and thus **under pressure**. This is particularly relevant for certain media such as alcohol-water mixtures or gases. Without the appropriate pressure, such media would volatilize, leading to incorrect measuring values.

Finally, the measuring results are available in an **extremely short measuring time**.

Resonator measuring instruments can also be used for a **continual measurement** with flow directly in the process.

What are critical factors (disadvantages)?

The method **does not allow direct traceability**, i.e. the measured density cannot be compared with the national standards (kg and m^3) for this measured variable. The reason for this is that the density is calculated using a measured frequency. At least two reference media with known density are required for the calculation. Traceability is therefore only possible via these two reference media.

The measuring sensitivity is influenced by the nature of the measuring tube. The smaller the **dead weight of the measuring tube**, the lower its influence on the frequency and the higher the measuring sensitivity. Conversely, measuring low medium masses with a simultaneously high dead weight of the measuring tube is problematic.

The mechanical properties of the resonator are changed by **pressure and temperature influences**. As a result, the frequency also changes. These dependencies can be compensated for by calibrations with different pressure and temperature points.

In addition, the frequency is also dependent on the **viscosity** of the measuring liquids. This can give rise to further measuring uncertainties.

Air bubbles in the measuring liquid can also lead to measuring errors. This is not the case if degassing is carried out before the measurement.

The measuring result can be falsified by **contamination** of the resonator. An indication that the resonator is clean is reading the correct air density when empty.

Where is the resonator density measurement used?

Resonator density measuring methods are particularly suitable for measuring the density of liquids in industries with different accuracy requirements in the laboratory and process:

- In the oil and gas industry, e.g. for determining calorific value, energy content or composition.
- At filling stations for settlement of the correct value and determining foreign particles.
- In transport for settlement of the correct value and to check the medium.
- In aircraft refuelling for optimizing the filling quantity to the flight distance.
- On engine test benches to test for constant fuel quality.
- Etc.

Which versions of resonator densimeters are available?

Examples: Resonator densimeters

Densimeter series DIMF 2.1: Density measurement for process measurements from Bopp & Reuther

Unit dimensions: approx. 650 x 450 x 150 mm
Source: http://www.bopp-reuther.de/

Densimeter DMA 5000: Laboratory densimeter from Anton Paar. Universal instrument with highest precision (0.000005 g/cm³).

Unit dimensions: 482 x 340 x 231 mm
Source: http://www.anton-paar.com

UGC-Densitometer: Densimeter for process measurements from AMETEK

Unit dimensions: approx. 450 x 200 x 100 mm
Source: http://www.ametekpi.com

MEMS density module: Densimeter for integration into TrueDyne Sensors AG modules.

Unit dimensions: 66 x 30 x 15 mm
Source: www.truedyne.com

Notes:

MEMS technology

At a glance
In the previous section we got to know the vibration measuring method. This section deals with the establishment of MEMS technology at TrueDyne Sensors AG. The technology has brought about the MEMS sensor, the heart of which is an oscillating silicon measuring channel. Compared to conventional resonator technology, it combines numerous advantages. These range from its small size and a wide range of applications to the exact determination of the density of gases, even at low pressure, and an extremely fast reaction time.

Contents

- What is MEMS technology?
- Where are MEMS technologies used?
- How is the Omega chip structured?
- What opportunities does MEMS technology offer?

What is MEMS technology?

MEMS stands for **M**icro-**E**lectro-**M**echanical **S**ystems. The technology combines microelectronic and micromechanical components in a complex microsystem based on silicon semiconductor technology.

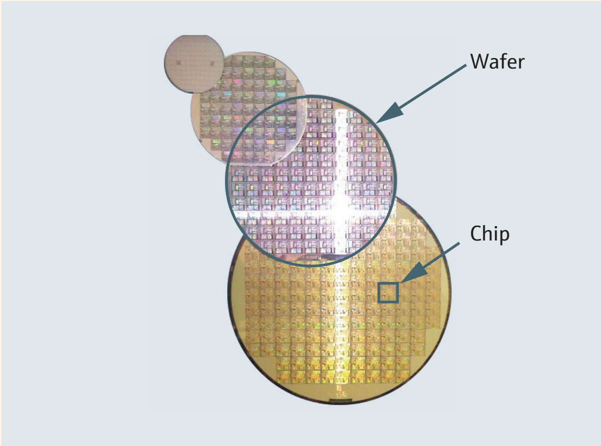
For the **semiconductor technology**, several electronic components are structured on a semiconductor substrate (often made of silicon) using various process technologies, e.g. photolithography and thin-film technology, and assembled into a chip. Since the individual steps for the production of a chip are very complex, these steps are multiplied and several chips are produced simultaneously. This is done with a circular or square, disc-shaped **wafer** which consists of the material of the required substrate.

Semiconductor technology allows for the **miniaturization** of electronic circuits, which in classic electronics consist of mechanically manufactured components. One **TrueDyne Sensors AG MEMS chip** not only includes **electronic** but also **mechanical** and **fluidic functions**.

Due to the high demands on the individual components, a TrueDyne Sensors AG MEMS chip is usually not limited to a silicon substrate. Instead, **diverse materials** are used for the different components, which are brought together using various assembly and connection techniques. [1]

1 Source: Praxiswissen Mikrosystemtechnik, F. Völklein und T. Zetterer, 2006, Vieweg+Teubner Verlag

Circular wafer



Source: https://de.wikipedia.org/wiki/Wafer

Where are MEMS technologies used?

MEMS technologies are becoming increasingly important. They are used in the most diverse areas and are omnipresent in our everyday life. MEMS systems are increasingly used in **automotive industry applications**, e.g. for theft protection, airbag control or vehicle rollover detection systems. In addition, they are used in the **mobile communications sector** for navigation, display orientation or mobile gaming. There is also great application potential for microfluidic systems in **medical engineering**, especially in biomolecular analytics. Keywords here are **lab-on-a-chip** or **BioMEMS**.

How has MEMS technology developed at TrueDyne Sensors AG?

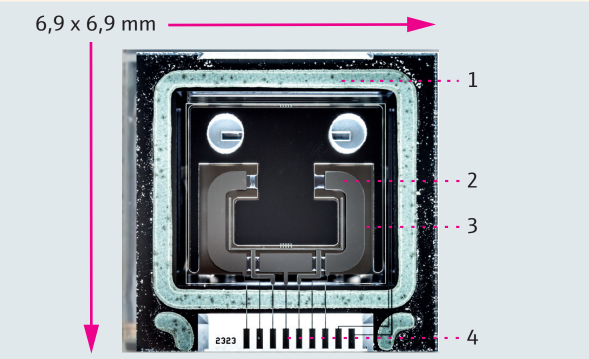
For several years, TrueDyne Sensors AG has been working on the development and implementation of the **Coriolis measuring principle** as a fluidic microsystem or as MEMS chip. The fluidic channel required for the Coriolis measuring principle is formed from a silicon substrate and integrated into a MEMS chip.

This system has not proven itself effective for measuring the flow rate at TrueDyne Sensors AG. However, it has been shown that the vibrating silicon channel can be used very effecticely as a **resonator densimeter** .

How is the TrueDyne Sensors AG MEMS chip constructed?

Nowadays, a TrueDyne Sensors AG MEMS chip is very small, no more than **6.9 x 6.9 x 1.5 mm** in size. It contains electronic components, a fluidic measuring channel and a temperature sensor.

TrueDyne Sensors AG MEMS chip



Source: DLO-M1 launch documents

1.Thin-film temperature sensor
2.Measuring channel
3. Vacuum
4. Electrodes

The TrueDyne Sensors AG MEMS chip is manufactured using a total of four wafers:

- Two silicon wafers form the **measuring channel**. The measuring channel is formed using plasma etching technology. For this purpose, half of each channel is etched into a silicon wafer. The channel is created by connecting the two halves (bonding method).
- A glass wafer contains metallic **electrodes**, fluidic openings and the **temperature sensor**.
- Another silicon wafer is used to package the measuring channel in a **vacuum**. This allows the measuring channel to oscillate without air damping.

What opportunities does MEMS technology offer?

Numerous advantages and new areas of application are available due to the **miniaturization** (measuring channel = 0.5 µl volume) and the **material qualities** (silicon) of the channel.

Miniaturization is gaining ground particularly in applications where **small sample quantities** and a **compact structure** are of great importance.

The thermal and mechanical properties of silicon mean that a **powerful sensor** is also provided.

Silicon is a good conductor of heat. The channel is therefore **not exposed to large temperature differences**. The temperature information required for density measurement can thus be determined precisely and easily.

The mechanical properties of silicon are also advantageous for density measurement. The **low deadweight** and the **low rigidity** of the silicon channel mean that a very **high measuring sensitivity** is achieved. This property is particularly important for light liquids and **gasses**. Thus, a gas measurement with **low pressure** (the currently specified pressure range is between 1 and 20 bar) can still be carried out with a high (level of measuring) sensitivity.

The silicon channel can vibrate at a very **high frequency**. This leads to a **short measuring time** and makes the measuring signal independent of external, mechanical interference vibrations.

Notes: