THE BASICS OF PRESSURE MEASUREMENT
AND CAPACITANCE MANOMETERS

PROBLEM

The accurate and precise measurement of pressure and vacuum is critical to the maintenance of control over many of the fabrication processes in the production of electronic, photovoltaic and other semiconductor devices. It is therefore important to understand the way that pressure and vacuum are measured and the advantages and limitations of the different instrumental options for determining pressure.

BACKGROUND

Vacuum and Pressure Measurement

There are many systems for pressure measurement; it is therefore important to understand the meaning of the different pressure metrics. One such metric, familiar to most in the USA, is psi or "pounds per square inch". Using this metric, atmospheric pressure at sea level is

measured at 14.69 psi. For comparison, the European and Asian pressure measurement systems defines atmospheric pressure as 1.0 bar. Another metric is "inches of water". This metric is often used to report barometric pressure in US weather forecasts. The unit refers to the height of a submerged column of water that is supported by atmospheric pressure; using this metric, atmospheric pressure is 406.8 inches H_2O (at 4°C). Occasionally, this unit of measure is used for vacuum measurements in industrial processes.

The metric most commonly used for vacuum measurement, however, is the Torr, equal to 1 mm Hg. It represents the barometric pressure that is needed to raise the height of a sub-merged column of mercury by 1.0 millimeter. Atmospheric pressure equals 760 Torr. A derivative of the Torr often used in semiconductor process vacuum measurements is the millitorr or 1/1000th Torr. Vacuum greater than 1.0 millitorr are usually expressed as

Atmospheres	PSI (Absolute)	Inches H_2O	Bar	mbar	Torr/mm Hg	mTorr	kPa
100	1469	Not Used	100	Not Used	76,000	Not used	1.0E+04
10	146.9	4068.0	10	Not Used	7,600	Not used	1.0E+03
1	14.69	406.8	1	1,000	760	Not used	101.325
0.1	1.47	40.68	0.1	100	76	Not used	10.132
0.01	0.15	4.068	0.01	10	7.6	7,600	1.013
1.0E-03	Not Used	Not Used	1.0E-03	1	0.8	760	0.101
1.0E-04	Not Used	Not Used	1.0E-04	0.1	7.6E-02	76	0.010
1.0E-05	Not Used	Not Used	1.0E-05	1.0E-02	7.6E-03	7.6	1.0E-03
1.0E-06	Not Used	Not Used	1.0E-06	1.0E-03	7.6E-04	0.8	1.0E-04
1.0E-07	Not Used	Not Used	1.0E-07	1.0E-04	7.6E-05	7.6E-02	1.0E-05
1.0E-08	Not Used	Not Used	1.0E-08	1.0E-05	7.6E-06	7.6E-03	1.0E-06
1.0E-09	Not Used	Not Used	1.0E-09	1.0E-06	7.6E-07	7.6E-04	1.0E-07

Table 1 - Pressure and vacuum scales

scientific notification, (e.g. 5.0 x 10^{-6} Torr). Vacuum and meteorological measurements in the European and Asian system usually divide the bar into 1/1000th's to create the millibar.

The SI (International System of Units) metric for pressure is the Pascal (abbreviated Pa), named for the French mathematician and physicist Blaise Pascal. It is defined as a measure of force per unit area equal to one Newton per square meter. Atmospheric pressure in SI units is 1.01325E+05 Pa. Barometric pressure in weather forecasts outside of the US are often reported in kilopascals (kPa).

Table 1 shows a comparison of the most common pressure and vacuum scales.

Vacuum Gauges

There are many different kinds of commercial pressure and vacuum gauges. The major types of gauges include:

- **Mechanical gauges:** These use some form of mechanical linkage or diaphragm arrangement that does not require electronics. The arrangement physically moves an indicator needle that shows the pressure or vacuum.

- **Thermal gauges:** Commonly referred to as Pirani, thermocouple, and convection gauges, these function on the principle that the thermal conductivity of a gas varies with pressure. An electrically heated wire is the sensing element in a balanced electronic circuit. The rate of heat loss from the wire varies with the thermal conductivity of the gas and thus is its pressure. This variation requires a change in one of the circuit's electrical characteristics (current, voltage, or power) to maintain the circuit balance.

This electrical change is sensed and reported as pressure/vacuum.

- **Strain-based gauges:** Commonly used in positive-pressure applications. They employ a thin diaphragm with a strain-sensing electronic circuit mounted on its backside. A change in pressure causes the diaphragm to deflect producing strain that is detected by the sensor.

- **Capacitance manometers:** Commonly used for pressure/vacuum measurement. They rely on the change in capacitance between a diaphragm and powered electrode.

- **Column-type manometers:** These use a liquid whose height in a closed column changes with pressure.

- **Ionization vacuum gauges:** These rely on ionization of the ambient gas molecules and measurement of the corresponding ion current. The ion current is directly correlated with the vacuum pressure in the chamber.

Table 2 shows a comparison of the different types of pressure/vacuum gauges. No single gauge can meet every measurement requirement in every process.

	Mechanical Gauges	Thermal Gauges	Strain Gauges	Capacitance Gauges	Column Gauges	Ionization Gauges
Pressure/Vacuum Range (atm)	-1 to 500	10^{-6} to 1	-1 to 500	10^{-8} to 200	1 to 10	10^{-12} to 10^{-5}
Gas Sensitivity	None	High	None	None	None	High
Accuracy	Poor to Good	Fair	Fair to Good	Excellent	Good	Fair
Need for Mains Power	No	Yes	Yes	Yes	No	Yes
Electrical Output	No	Yes	Yes	Yes	No	Yes
Corrosion Resistance	Poor	Fair	Good	Excellent	Poor	Poor
Physical Size	Good to poor	Good	Excellent	Excellent	Poor	Fair
Overall Safety for Personnel	Fair	Poor	Fair	Good	Poor to Good	Fair
Relative Cost	Fair to Excellent	Good	Fair to Excellent	Fair	Fair	Fair

Table 2 - Relative performance of major pressure gauge types

Capacitance Manometers

Capacitance manometers are electro-mechanical gauges that can measure both pressure and vacuum. The capacitance gauge translates a pressure-modulated movement in a thin diaphragm into an electrical signal proportional to the pressure. Figure 1 shows the major components of a commercial capacitance manometer. The pressure sensor is the thin diaphragm that is exposed to the pressure or vacuum being measured via the inlet tube. An electrode, typically a ceramic disk with conductive pathways, is mounted in the reference cavity behind this diaphragm. It is powered with an electrical signal (either AC or DC). Pressure differences between the process and the reference cavity deflect the diaphragm slightly, changing the distance between it and the electrode. Variations in this distance produce variations in the capacitance between the diaphragm and the electrode and this variation, in electrical signal, is proportional to the pressure change. This signal is amplified by the on-board electronics and output to the device's electrical connector for transmission to pressure indicators and process controllers.

Since differences in the capacitance signal are produced by physical changes within the manometer and not by changes in the gas properties, pressure measurements by the capacitance manometer are independent of the composition of the gas being measured. Thus, a capacitance manometer's output doesn't change if the gas composition in the process changes. In many chemical and thin film processes, the chemistry can change on a second-by-second basis; capacitance manometers thus provide a critical advantage in such processes.

There are two basic types of capacitance sensors:

- Absolute capacitance manometers in which the reference cavity is evacuated to high vacuum so that the pressure measurements will always be referenced to vacuum.

- Differential capacitance manometers that do not have a reference cavity – just a tube or passage that can be connected to any pressure or vacuum source. These manometers read the difference in pressure between the inlet tube and the reference cavity at the backside of the electrode. They are routinely used as safety switches and for airflow pressure drop measurements.

Capacitance manometers typically read pressure or vacuum over a four-decade range; i.e. from 1000 Torr to 0.1 Torr.

Like all precision electromechanical devices, capacitance manometers require exact calibration at the time of manufacture. As well, they must be periodically re-calibrated to maintain the specified accuracy and performance. If the user doesn't regularly recalibrate a capacitance manometer in accordance with the factory recommendations, there is a risk that the process which the manometer monitors could shift outside its "window" of performance. Obviously, this can cause reduced productivity or, in extreme situations, complete shutdown of a process line.
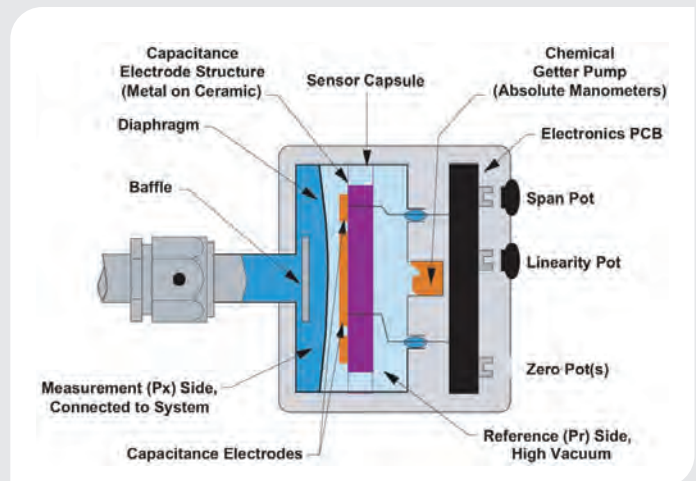

Figure 1 - Capacitance manometer schematic showing the internal components and functional zones

Calibration of capacitance manometers is not always well understood by users, so a brief explanation of the most important terms used to describe calibration is helpful.

- **Reference Standard:** A very accurate pressure or vacuum measurement instrument used to calibrate other such instruments.

- **Accuracy:** The absolute difference in measurement between a manometer and the reference standard used for calibration. Common specifications are usually in units such as percent of reading or percent of Full Scale.

- **Linearity:** The actual capacitance output produced by the sensor is not sufficiently linear to be used for measurement purposes. Therefore, the manometer electronics (whether digital or analog) are designed to linearize this output to an ideal standard. Linearity measures how well the electronics have done this task – typically specified as a percent of Full Scale.

- **Repeatability:** A measure of how closely the capacitance manometer can achieve the same output for the same pressure over a period of several different process runs. Some manometer manufacturers (including MKS) include repeatability in the accuracy specification, but not all do so. Users should ask their manometer supplier to define this term if it isn't specifically called out.

- **Resolution:** The minimum pressure that the manometer can actually measure. If the manometer is an analog model and a digital input is needed, a high-resolution analog/digital conversion (at least 14-bit) is almost always required; otherwise, the A/D resolution will determine the pressure measurement resolution – not the manometer's resolution.

- **Zero and Zero Offset:** Zero refers to a condition that occurs when the manometer output is adjusted to read zero at (a) either the lowest obtainable pressure in the system, or (b) a pressure lower than the resolution of the capacitance manometer. Zero shifts may occur over time changing this position and introducing a shift in the overall output of the manometer. Such shifts must be removed for acceptable accuracy. If

the system can reach a base pressure lower than the manometer's resolution, then the output of the manometer can be adjusted to its minimum output. However, if the minimum system pressure is above the resolution of the manometer, then a permanent zero offset must be used to determine the correct system pressure. The existence of a zero offset or zero drift is NOT always an indicator that the unit needs recalibration because a change in the zero position only rarely affects the actual manometer calibration.

Capacitance manometers are frequently used as reference devices for other types of gauges (i.e. they are the calibration standard against which other products are measured). An unheated 1000 Torr capacitance manometer has an accuracy specification (which includes repeatability) of about 0.25% of Reading. This can be compared with an accuracy of 5-25% of Reading for a Pirani or thermocouple gauge of the same range – an improvement of 100x. Thermal or mechanical gauges should never be used to calibrate a manometer – the manometer is far more accurate.

The overwhelming majority of capacitance manometers in service today provide an analog output signal such as 0-10 VDC, 0-5 VDC, 0-1 VDC, or 4-20 mA. In most of these products, the output signal is linear with the pressure. For example, if a capacitance manometer has a 0-10 VDC output, the pressure at 5.00 VDC will be 50% of the product's Full Scale range; at 1.00 VDC output, the pressure is 10.0% of the Full Scale range; and so on.

Recently, user requirements have led to the development of capacitance manometers with digital communications. The communications can be based on DeviceNet™, Profibus®, Ethernet, ModBus, or serial protocols depending on the application.

MKS Baratron® capacitance manometers (Figure 2) are highly accurate and repeatable, insensitive to gas composition, compact, and easily interfaced with most process tools. MKS manufactures its manometers

almost exclusively using nickel-based alloys such as Inconel®, Incoloy® and others. This makes them very resistant to corrosion when the materials are matched to the process (particularly for halogens and oxidants). The overall manometer sensor construction is critical for operator safety; MKS' sensors are fully welded and 100% leak-checked prior to assembly. In the event of a failure of the diaphragm (extremely rare), the process gases are completely contained within the sensor, preventing escape to the outside environment. No other pressure or vacuum gauge offers that level of safety.

Figure 2 - MKS Baratron® capacitance manometer

CONCLUSION

This note contains an overview of the different measurement systems and metrics in common use for the measurement of pressure and vacuum. The different types of instrumentation appropriate for pressure/vacuum measurement have been described and compared with each other. Capacitance manometers have been examined in detail and found to be the most accurate and repeatable measurement devices currently available. Capacitance manometers' characteristics and use as reference standards are described in some detail. This note presents MKS Instruments' Baratron solution for capacitance manometer applications, detailing the particular features that make the Baratron manometer a superior solution.