Hot vs. Cold Ionization Gauges

Every modern high vacuum and ultrahigh vacuum system relies on some form of ionization gauge for pressure measurements under 10^{-3} Torr. There are currently two competing ionization gauge technologies to choose from - the hot cathode gauge (HCG) and the cold cathode gauge (CCG). This application note is designed to help vacuum users choose between the two competing ionization technologies. Each gauge type has its own advantages and disadvantages. The best choice requires careful consideration of the operating characteristics of both gauges and is dependent on the application.

In This Application Note

Introduction

Every modern high vacuum and ultrahigh vacuum system relies on some form of ionization gauge for pressure measurements under 10^{-3} Torr. There are currently two competing ionization gauge technologies to choose from which are viable means for pressure measurements between 10^{-2} and 10^{-10} Torr:

1. In the hot cathode gauge (HCG) ionizing electrons from a thermionic cathode are accelerated by suitable electrodes into an ionizing space.

2. In the cold cathode gauge (CCG) ionization is caused by a circulating electron plasma trapped in crossed electric and magnetic fields.

In both cases, the electrical current resulting from the collection of the positive ions created inside the gauge is used as an indirect measure of gas density and pressure.

This application note is designed to help vacuum users choose between the two competing ionization technologies. Each gauge type has its own advantages and disadvantages. The best choice requires careful consideration of the operating characteristics of both gauges and is dependent on the application.

For more detailed information on this subject consult the following publications:

1. J. M. Lafferty, Ed., "Foundations of Vacuum Science and Technology", p. 414, section 6.9., John Wiley and Sons, NY, 1998. Note: This is an excellent book recommended for any high vacuum question.

2. R. N. Peacock, N. T. Preacock, and D. S. Hauschulz, "Comparison of hot cathode and cold cathode ionization gauges", J. Vac. Sci. Technol. A 9(3) (1991) 1977.

3. R. F. Kendall, "Cold cathode gauges for ultrahigh vacuum measurements", J. Vac. Sci. Technol. A 15(3) (1997) 740.

4. R. F. Kendall, "Ionization Gauge Errors at Low Pressures", J. Vac. Sci. Technol. A 17(4) (1999) 2041. Note: Great paper that compares the performance of both gauges, particularly at low pressures.

5. Vic. Comello, "Should your next ion gauge run hot or cold?", R&D Magazine, p. 65, Nov. 1997.

6. Eric Bopp, "Pressure measurement in ion implanters", Solid State Technology, February 2000, p. 51. Note: The special gauging requirements of ion implant applications are nicely discussed in this article.

7. J. H. Singleton, "Practical Guide to the use of Bayard-Alpert Ionization Gauges", J. Vac. Sci. Technol. A 19(4) (2001) 1712.

Hot-Cathode Gauges (HCG)

The majority of commercially available HCGs are of the Bayard-Alpert design and are compatible with the IGC100 controller.

A Bayard-Alpert gauge (BAG) boils electrons from a hot filament and accelerates them toward a cylindrical grid cage. As the electrons traverse the space enclosed by the grid, which is fully open to the vacuum chamber, they collide with gas molecules ionizing some of them. A fine wire located at the center of the ionization volume collects the resulting cations producing a current proportional to the gas density at the gauge. At constant temperature, the collector current is linearly related to the gas pressure.

The useful operating range of a conventional BAG extends between 10^{-3} and 10^{-10} Torr, corresponding to an impressive seven decades of dynamic range. Special gauge designs are available to extend the lower limit to 10^{-11} Torr for UHV applications, or the upper end to 10^{-1} Torr for process applications.

The strict linear dependence of collector current on pressure is one of the most important advantages of HCGs over the competing ionization technology. It is generally possible to approximate the 'collector current vs. pressure' response of a BAG to a straight line and calculate pressures from a single linear proportionality factor (i.e. sensitivity factor) stored in the gauge controller. A sensitivity factor calibrated at mid-range, can be used for accurate and reproducible pressure measurements between 10^{-9} and 10^{-4} Torr. Deviations from linearity typically amount to less than ±25% over the entire useful dynamic range of the gauge, with the biggest deviations taking place at the operating limits.

BAGs are generally considered to be more accurate, stable and reproducible than CCGs. Under controlled vacuum conditions, the reproducibility of a BAG calibration can be as good as 2% through a year of uninterrupted operation. Repeatability is 1-2%, limited by uncontrollable random sensitivity variations. However, not all BAGs are created equal and gauge-to-gauge and long-term stability variations are to be expected from commercial devices used in 'real' systems. Measurement accuracies better than ±50% require calibration of the individual gauge response. High accuracy gauge designs have recently become available that guarantee better than 3% measurement accuracy following calibration against NIST standards. Calibrated, high-accuracy BAGs combined with high quality controllers, such as the IGC100, are commonly used as transfer standards in high vacuum gauge calibration laboratories.

BAG readings are gas dependent due to varying ionization efficiencies, and are usually calibrated for nitrogen gas (argon is also a popular choice in semiconductor processing). Gas correction factors, readily available from the vacuum literature, can be used to correct the gauge readings for other gases.

Any BAG, depending on its past history of operation and the precise atmosphere in the vacuum system, can act as either a source (outgassing) or sink (pumping) of gas. Its operation can cause significant changes to the gas composition in the system. The relative importance of these effects depends upon the overall vacuum system characteristics and operating conditions. For example, changes in pressure and gas composition due to pumping or outgassing will be relatively more significant in a small UHV system with low pumping speed, than in a large industrial vacuum chamber with large diffusion pumps. Similarly, any pressure gradient between the gauge and the main chamber will depend upon the conductance of the tube connecting the two, and will be zero when the gauge is inserted directly into the chamber (i.e. nude BAG).

The power requirement of a typical filament for 1 mA emission is between 10 and 15 W. This is enough to cause thermal degassing from the gauge elements and surroundings that affect the reliability of low pressure measurements. It is possible for gas composition and pressure in even a large vacuum system to be dominated by gases released from a single HCG and its immediate surroundings when such a gauge is not properly degassed.

HCGs encounter most of their problems at $\approx 10^{-10}$ Torr where the X-ray limit, electron stimulated desorption (ESD) and outgassing set a limit on the usefulness of the gauge. Degassing and bakeout of the gauge can minimize the effects of ESD and outgassing. The ultimate accuracy of a BAG may be seriously compromised in the absence of a bakeout and/or degassing. The X-ray limit provides a residual collector current comparable to the ion signal from 10^{-10} Torr of gas in conventional gauges. Special nude gauge designs, with reduced collector and grid wire diameters and closed-end grids, are required to reduce the magnitude of that residual current into the 10^{-11} Torr level.

Reactions of the gas molecules with the hot filament can seriously affect the composition of the gas, and the reliability of the pressure measurements, in a BAG. This effect must also be accounted for in high accuracy measurements at low pressures.

Gas permeation through the glass envelope, particularly of He and other light gases, must be considered in UHV systems at base pressure, and provides another good reason to use all-metal gauges in those applications.

The operating life of a HCG is frequently determined by the filament lifetime. This is, by far, the main reason why high vacuum users choose 'filament-free' Cold-Cathode Gauges (CCGs) over BAGs. However, unless damaged by ion bombardment, high pressure operation or chemical effects, filament lifetimes can be many thousands of hours, thus filament life is not an important consideration in most cases. This is especially true with ThO_2Ir filaments and when smart controllers, such as the IGC100, which protect the gauge from overpressures.

There is always a delay between turning on a HCG and obtaining a meaningful reading. It is necessary to wait for thermal equilibrium of the gauge and its surroundings. Depending on the pressure to be measured, and the history of the gauge, stabilization can last from minutes to weeks, and might require bakeout and/or degassing to reach completion.

A good quality controller, such as the IGC100, must always be part of a BAG measuring system. Controllers have been known to add as much as ±15% inaccuracies to BAG readings. The electronics required to run a BAG are generally (1) more complicated, (2) require more power, and (3) are bigger in size than those required to operate CCGs.

BAGs have safety hazards associated to them that must be considered during gauge selection and operation. Glass envelope gauges can break and/or implode violently resulting in the danger of flying glass. Gauge walls can get hot and cause burns. The risk of electrical shock is always present and can be deadly in some cases. All these risks are easily eliminated by proper system design, including glass shields, suitable connector cables and good grounds.

Cold-Cathode Gauges (CCG)

Several varieties of CCGs are used for vacuum measurements including the Penning, the magnetron, the inverted magnetron and the double inverted magnetron.

All CCGs utilize crossed electric and magnetic fields to trap electrons. The high voltage ranges from 2-6 kV and the magnetic field 1-2 kG. The electron plasma, responsible for ionization, originates from the random release of an electron at the cathode caused directly, or indirectly, by a cosmic ray, field emission, a photon, radioactivity or some other event. A discharge slowly builds inside the ionization volume to the point where the entry of new electrons into the plasma is limited by space charge repulsion. At pressures below 10^{-4} Torr, the discharge is practically a pure-electron plasma. The electrons move in cycloidal jumps, circling about the anode, and during part of each jump they have sufficient energy to ionize gas molecules through electron impact ionization. The probability of collision is proportional to the gas density. The slow ions generated, are quickly captured by the cathode. The current generated by this ion collection process is measured and used as an indirect indication of gas density and pressure.

The typical operating range of a CCG is between 10^{-2} and 10^{-9} Torr. With very special precautions, the lower end has been extended into the 10^{-11} Torr for some special gauges, but only with marginal accuracy. Claims that commercially available CCGs will measure total pressures below 10^{-9} Torr should be treated with extreme caution!

The upper pressure limit of the CCG is reached when the current becomes so large that heating and sputtering from the electrodes becomes a problem. This sets a usual limit of 10^{-4} Torr. However, several tricks are commonly implemented to extend the useful upper pressure into the 10^{-2} Torr range. At the other end of the pressure range, CCGs have been used down to 10^{-11} Torr but only under very carefully optimized conditions and with very limited accuracy.

The ion-induced current is not linearly related to the pressure in the chamber. Rather, the relationship is exponential and complicated by the presence of spurious discontinuities in the current vs. pressure characteristic. The number and size of discontinuities depends on gauge design, with the inverted magnetron being the least susceptible to this problem. Gauge-to-gauge variations among seemingly identical gauges are often observed and it is not unusual to observe discontinuities disappear between successive calibrations. Elimination of discontinuities has been a major challenge to designers of CCGs since their conception. The non-linear relationship between current and pressure is a disadvantage that complicates the reliability of pressure measurements, particularly below 10^{-9} Torr. Between 10^{-4} and 10^{-9} Torr the exponent is usually fairly constant, close to 1.0 and hidden from the user by a logarithmic detector or look-up table. Somewhere between 10^{-9} and10^{-10} Torr the exponent often shifts suddenly to higher values (1.25 or higher). This sudden *and spurious* change in exponent requires special precautions to account for the more pronounced logarithmic response, and only marginal accuracy is generally possible below 10^{-9} Torr. No standard method for dealing with currents below the magnetron knee is available as of this writing.

CCG readings are gas dependent and the gas correction factors are *not* the same as for HCGs.

There are few results in the vacuum literature on the accuracy, stability and repeatability of CCGs. In general, CCGs are considered to be less accurate than HCGs and are not recommended as high vacuum transfer standards. Repeatability is about ±5%, and sensor-to-sensor matching is within 20-25% for inverted magnetrons. Manufacturers often specify accuracies within a factor of two for new (and clean) gauges. Whenever higher accuracy is required, the specific tube/controller combination must be calibrated against a transfer standard such as a spinning rotor gauge or high-accuracy BAG. Calibration is more complicated than in HCGs because of the non-linear 'current vs. pressure' response and the presence of discontinuities in the calibration curve. Stable operation appears to be possible over periods of several years under clean, low pressure vacuum conditions. However, contamination can cause failure of a CCG just as a HCG. Pump oil is polymerized by the discharge and forms insulating films on the electrodes. Metal vapors, caused by sputtering, can cause insulator leakage. Most CCGs can be disassembled and serviced by the user in the field to restore them to normal operation when they become contaminated.

CCGs respond very quickly to pumpdowns. In general, they arrive at stable readings faster than HCGs during pressure cyclings between 10^{-3} and 10^{-7} Torr. There is also no filament to burn out. The absence of a hot filament also makes outgassing much less of a problem.

Outgassing rates are typically very much lower and more predictable than for HCGs. Degassing is not necessary since the input power is very low and there is no internal heating to cause localized outgassing. Measured pumping speeds are also low (comparable to those of HCGs) so that pressure measurement errors are generally insignificant, provided adequate tubulation to the vacuum system is provided. Residual currents are not a problem at UHV levels in CCGs which are essentially free of X-ray and ESD effects. In applications requiring frequent pumpdowns to low pressures with little or no opportunity for degassing, the readings of a CCG may be significantly closer to true chamber pressures than HCG readings. CCGs are often preferred over HCGs for critical applications such as material outgassing studies.

Sensitivity to externally produced magnetic fields is typically far lower than for unshielded HCGs and usually not a problem under normal laboratory conditions.

Concerns about stray magnetic fields from modern CCGs are mostly unfounded. Inverted and double inverted magnetron gauges reduce stray field to only a few Gauss. Addition of shielding sleeves further reduces stray fields to levels comparable with background effects in a typical laboratory. Special applications, such as electron microscopes, might still require careful experimentation with the exact location and orientation of the gauge even after shielding is in place.

On the downside, CCGs can be hard to start. The discharge in a CCG does not start (i.e. strike) the moment the high voltage is applied. The 'striking' time varies from gauge to gauge. This delay ranges from seconds at 10^{-6} Torr to hours at 10^{-10} Torr. Auxiliary 'strikers' consisting of (1) edge emitters, (2) radioactive sources or (3) UV lamps are often included in modern gauge designs to reduce this problem greatly. Striking is not a problem if the CCG can be turned on during pumpdown before the pressure reaches 10^{-5} or 10^{-6} Torr. A gauge also starts quickly if charges from any other source of ionization can reach the gauge. Once a CCG strikes, the readings are meaningful within a few seconds, faster than the time it takes a HCG to stabilize after a filament emission is established.

The circulating electron current and energy are determined by the gauge construction and its fixed operating parameters - they cannot be controlled by the user! This is a big difference from the HCG operation where most parameters can, and usually are, accessible to the user from the controller.

The electronics required to operate a CCG are usually much simpler and less expensive than those for HCGs. The CCG controller supplies only the high voltage required, and it measures the current in the same loop. Small permanent magnets are used to set the magnetic field. The amount of current in the high voltage power supply is usually limited to 0.1 mA so that danger of serious electric shock is reduced. It is generally possible to enclose the gauge assembly and low-power (i.e. <1 W) electronics into a package not much bigger in size than a tubulated BAG.

CCGs are usually of all-metal construction, and are not hot to the touch.

Conclusions

HCGs and CCGs are both capable of measuring pressures between 10^{-2} and 10^{-10} Torr. They both produce gas dependent readings. Their pumping effects are of similar magnitude and negligible in the presence of adequate (i.e. >10 Ls^{-1}) tubulation to the vacuum system.

The ultimate accuracy of the BAG is better than the CCG. However, due to increased outgassing, a bakeout and/or degassing are often required to achieve the full advantage with the HCG. In most cases, a longer delay is also required to obtain a stable reading from a HCG. For applications involving continuous pumpdowns to low pressures, without an opportunity to degas or bakeout, a CCG might be the best choice to follow chamber pressure in real time.

HCGs are more easily calibrated than CCGs because of their linear response to pressure. Spurious discontinuities in the calibration curve can also affect readings of CCGs; however, this is rarely a serious problem in modern inverted magnetrons.

The filament life often limits the useful lifespan of a HCG; however, in most applications, filament lifetime is several years of continuous operation.

Starting the CCG can be delayed, particularly at low pressures; however, this is not a serious problem if strikers are built into the gauge to shorten the delay. CCGs can also be turned on at higher pressures during a pumpdown.

Careful consideration of the effects described in this note should help you choose between the two competing ionization gauge technologies.