

Bayard-Alpert Gauge Filaments: Tungsten or Thoria?

Introduction

Careful attention must be applied to the choice of filament material when selecting a Bayard-Alpert ionization gauge for a vacuum application.

The optimum choice of filament material is very application dependent, and interactions of the gas with the cathode material must be carefully considered. Filaments, in both wire and ribbon shapes, are required to (1) supply a stable electron emission current with reasonable energy input and filament temperature, (2) have reduced chemical reactivity with the rarefied environment being measured, (3) have a reduced evaporation rate at the operating temperature (i.e. long life), (4) have a vapor pressure at least one tenth of the lowest pressure that has to be measured and (5) have low levels of ionic and neutral molecule outgassing compatible with the lowest pressure measurements.

It is commonly believed that the filament in a Bayard-Alpert gauge (BAG) presents a reliability problem (especially when compared to Cold Cathode Gauges) and it is often true that the operating life of hot cathode ionization gauges is determined by filament lifetime. However, unless damaged by ion bombardment, high pressure operation, chemical reactions or severe contamination, filament lifetimes are usually in the thousands of hours (usually years).

Several attempts have been made to replace hot filaments with cold electron emitters in BAGs¹; however, no commercially available gauges have resulted from those efforts yet.

Filament Materials

Filaments are based on thermionic phenomena²- the emission of charged particles from the surface of a conductive material or compound at high temperature. The emission of charged particles depends on the **work function**³ of the material, defined as the energy, measured in eV, required to move an electron from Fermi level outside the surface. The filament materials used in BAGs can be grouped into two classes: (1) pure metals and (2) oxide-coated cathodes.

This section only concentrates on the materials commonly encountered in commercially available gauges. For information on less common materials, consult the excellent primer by Gear⁴ and the work by W. Kohl⁵.

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Among pure metals, **tungsten (W)** is used on a large scale in ionization gauge heads operated in medium and high vacuum environments. The operating temperature of tungsten cathodes is between 1900°C and 2200°C. At this high operating temperatures, contaminating electronegative gases, which would increase the work function and reduce emission levels, are rapidly evaporated from the filament surface. As a result, tungsten filaments provide more stable gauge operation compared to metal oxide cathodes. However, this advantage is usually at the expense of (1) large outgassing levels as a result of the elevated temperatures in the surrounding walls and (2) an increased reactivity with chemically active gases that react at the filament to produce other gases. Chemical reactions as well as a high vapor pressure (10^{-8} Torr at 2200K) make W a bad choice for UHV measurements.

The lifetime of W filaments, as determined by typical evaporation rates, is typically 10-20 hours at 10^{-3} - 10^{-2} Torr, and about 1000 hours at 10^{-6} Torr (gas dependent). However, accidental exposure to air and/or mechanical mishandling will damage tungsten filaments irreversibly. Tungsten is not seriously affected by hydrocarbons and halogens during operation.

Thoria-coated iridium (ThO₂Ir) filaments are the oxide-coated cathodes most commonly encountered in BAG heads manufactured in the US⁶. These cathodes are prepared by depositing a layer of thoria (i.e. thorium oxide) on a base metal of iridium by cataphoresis. The coating is then preconditioned⁷ by operation in a vacuum at about 1800°C. Iridium is the preferred substrate because it is very resistant to oxidation and does not burn out if exposed to high air pressures while hot. **ThO₂Ir** filaments are very resistant to poisoning and do not burn out if exposed for a short time during operation to a sudden inrush of air. In fact, BAGs with **ThO₂Ir** filaments are known to survive several brief exposures to atmospheric air, without any performance deterioration.

ThO₂Ir filaments operate at a “relatively cool” temperature of $\approx 1400^\circ\text{C}$, resulting in reduced outgassing and chemical reactivity with active gases when compared to W filaments. These two advantages, make **ThO₂Ir** filaments the preferred filament choice for measurements in the ultrahigh vacuum region. Most thoriated filaments are ribbon shaped to minimize heat flow to the ends which results in reduced outgassing.

Thoria coatings are very sensitive to electron and ionic bombardment. As a consequence, electron bombardment degassing must be minimized in gauge heads with **ThO₂Ir** filaments. A thorough bakeout is a better alternative in this case.

Thoria vs. Yttria: In gauges with thoriated filaments, **exposure to the alpha particles** emitted by thorium is of concern to some users. The use of yttria coated iridium filaments is recommended in those cases as an alternative(Both

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materials share very similar thermionic characteristics and behave and react very similarly when used in hot filaments) Most gauge manufacturers offer this alternative filament material as an option.

The material choice is dictated by the application. Tungsten filaments are by far the least expensive and the most popular. W is not recommended for UHV measurements due to its high vapor pressure and increased outgassing. The use of **ThO₂Ir** filaments is recommended for systems that are frequently brought to atmosphere (voluntarily or not!). **ThO₂Ir** is the only practical alternative for operation above 10^{-3} Torr. However, thoria is less stable than W in operation, and its electron emission efficiency is highly affected by hydrocarbon vapors and halogen containing compounds. This is the reason why dual W filaments (in glass tubulated gauges) are the only recommended choice for ion implantation applications⁸, where the hot cathode is routinely exposed to halogens vapors from BF₃ sources.

Some investigators⁹ have obtained results suggesting that gauges with tungsten filaments provide better stability than do gauges with thoria coated versions. The current belief is that it is not the filament material that causes the improvement, but rather the shape of the cathode. Tungsten cathodes are typically made as tight springs stretched between rigid posts that tend to move relatively little during long term use compared to the hairpin shaped or relatively unsupported ribbon shaped thoria-coated cathodes. Whenever possible opt for spring tensioned filaments in your BAG heads, particularly those with hair pin designs.

Dual filament assemblies provide security against filament burnout if the system cannot be brought to atmosphere to change the gauge. They are the most cost-effective alternative for tubulated gauges where filament replacement is not an option. Warning: Do not expect both filaments to give identical readings in a dual filament gauge unless a high accuracy gauge is being used. Simple methods for in-house replacement of tungsten filaments in nude gauges have been described in the vacuum literature as a cost-effective alternative if high accuracy and reproducibility is not a requirement in the pressure measurements performed by the repaired gauge¹⁰.

Filament Reactions

Chemical reactions at the hot filament can occur and usually belong to one of two groups: (1) thermal dissociation of gas or vapor at the hot cathode and further recombination of the resulting fragments with impurities in the gas or on the walls or (2) combination of gas with the filament material.

Chemical reactions involving the hot filament surface and the gas molecules can significantly affect the chemical composition and the total pressure of the gas environment in a high vacuum system¹¹. There is a large dependence of these reactions on the material chosen for the cathode and the type of gas in the

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environment. Some of the processes triggered by these reactions include: (1) active pumping of selected gas components, (2) outgassing of impurities into the vacuum environment, (3) thinning of the filament, and (4) poisoning of the filament surface (change in work function and emissivity).

Gases and vapor usually found in measuring systems are oxygen, hydrogen and water vapor.

Oxygen molecules react with the hot tungsten cathode and dissociate into atomic oxygen. The atomic oxygen then reacts with the carbon impurities at the surface to yield CO and CO₂. Since carbon constantly diffuses to the surface from the bulk, CO is continuously generated by this process. Even after the carbon is consumed, atomic oxygen still combines with carbon containing impurities present on the gauge walls, yielding CO.

Oxygen atoms interact with tungsten and produce oxides (WO₂, WO₃) as surface species. These species lower the work function of the material and also make the wire very brittle. These chemical processes result in the removal of oxygen from the system, therefore an ion gauge with W filament acts as a pump for oxygen.

Hydrogen molecules dissociate to atomic hydrogen in the presence of a tungsten cathode at temperatures > 800°C. The atomic hydrogen reacts with glass or metal surfaces to yield CO, H₂O, and CH₄. This fast removal of hydrogen from the gas results in anomalously high pumping speeds for hydrogen in BAG heads with W filaments.

After adsorbing a monolayer of hydrogen, the work function of a tungsten filament is significantly increased (+0.35 eV typical) and the filament must run hotter to achieve the same emission current.

Water vapor reacts with hot tungsten cathodes initiating an efficient transport of tungsten molecules to the gauge walls. This process, known as the “**water vapor cycle**”, includes several steps: (1) water dissociates at the filament into atomic oxygen and hydrogen, (2) the atomic oxygen reacts with W to form a volatile oxide that deposits on the glass walls of the gauge head as a film, (3) atomic hydrogen reduces the film back to W thus setting free water vapor, which repeats the cycle. The cathode lifetime is severely compromised by this process. CH₄, CO and CO₂ are also formed at the filament as a result of chemical reaction with water.

Hydrocarbons, such as methane and pump oils, backstreaming from vacuum pumps can dissociate on hot filaments to produce CO.

Emission of ions and neutrals

The emission of positive ions and neutrals from heated surfaces is a common occurrence that can affect the performance of BAGs in the UHV range.

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Although the positive ions cannot normally reach the collector because of the grid potential, the emission of positive ions is accompanied by a larger flux of neutrals. These neutrals can then be ionized and reach the collector giving an pressure independent current which ultimately limits the lowest measurable pressure. The evaporation of neutrals and ions can be minimized by heating the pure metal cathodes at high temperature for prolonged periods of time while pumping the gauge head.

¹ R. Baptist, C. Bieth, and C. Py, "Bayard-Alpert vacuum gauge with microtips", J. Vac. Sci. Technol. B14(3) (1996) 2119, also see US Patent 5278510 by the same authors.

² R. O. Jenkins, "A review of thermionic cathodes", Vacuum 19(8) p.359.

³ V. S. Fomenko, "Handbook of Thermionic Properties", Edited by G. V. Samsonov, Plenum Press Data Division, New York 1966.

⁴ P.E. Gear, "The choice of cathode material in a hot cathode ionization gauge", Vacuum 26(1) (1975) 3

⁵ Walter H. Kohl, "Handbook of Materials and Techniques for vacuum devices", Reinhold Publishing, 1967, N.Y., p. 486

⁶ European BAG heads usually contain Yttrium Oxide instead because of safety considerations.

⁷ J. H. Batey, "Thermal Desorption from mass spectrometer filaments", Vacuum 43(1992)15.

⁸ Eric Bopp, "Pressure measurement in ion implanters", Solid State Technology, February 2000, p. 51.

⁹ Charles Tilford, "Sensitivity of hot cathode ionization gauges", J. Vac. Sci. Technol. A 3(3) (1985) 546;

¹⁰ Michael E. Cox and J. A. Paintz, "Filament replacement for "nude" Bayard-Alpert gauges", SHOP NOTE, J. Vac. Sci. Technol. A 14(5) (1996) 2963

¹¹ P.E. Gear, "The choice of cathode material in a hot cathode ionization gauge", Vacuum 26(1) (1975) 3.