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A 3D-printed miniature magnetron gauge for ultra-high vacuum environments

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ABSTRACT

Miniaturized magnetron gauges are necessary for monitoring vacuum level in miniature vacuum chambers. This paper addresses the challenges of designing the magnetron cavity and configuring the electric and magnetic fields within it while meeting the contradictory constraints of small size and high vacuum level that make electron confinement and accumulation difficult. The resulting gauge has an internal volume of 0.3 cm^3 and is designed for and fabricated by advanced 3D printing – including direct metal laser sintering of 316 L stainless steel. Additionally, it is capable of directly attaching to a standard vacuum electrical feedthrough. A particle tracing simulation is used to assess the electron confinement for a range of operating conditions. Experimental characterization shows that the operating pressures extend from 10 nTorr (1.33 μPa) to 1 mTorr (133 mPa). The gauge current is repeatable over the characterized pressures at various values of supply source voltage, V_S, from −1000 V to −2500 V, and ranges from ≈1 nA to ≈100 μA over these pressures and voltages. The effects of V_S and pressure are examined and compared to prior work. This gauge is at least 30× smaller than commercially available magnetron gauges (e.g., a typical inverted magnetron transducer has an internal volume of 15 cm^3).

1. Introduction

For miniature systems that operate at high vacuum levels (i.e. < 1 mTorr (133 mPa)), it can be highly beneficial to monitor the vacuum level in some way because the vacuum level can be compromised with only a small amount of outgassing or leakage. To be useful in this context, a vacuum gauge must be small in comparison to the open volume of the reference vacuum cavity, and be able to operate at vacuum levels in the range of 10 nTorr (1.33 μPa) to 1 mTorr (133 mPa). As an example, the reference chambers of capacitance pressure gauges – which are used in cryogenic systems in magnetic resonance imagers, and in semiconductor processing equipment – must remain at a stable vacuum level for the capacitance pressure gauge to operate correctly. Monitoring changes in the high vacuum level within these very small reference chambers to avoid equipment failure is not readily achieved with currently available high vacuum gauges.

Miniature and microscale vacuum gauges with various working principles have been reported. However, thermal conductivity gauges (TCGs), such as the Pirani gauge, and friction gauges (FGs), such as the piezoelectric tuning fork oscillator, are not suitable for this range of vacuum. At such vacuum levels, the thermal conductivity through the gas is very small, limiting the sensitivity and resolution of TCGs [1,2]. Additionally, the gas damping induced resonance shift of FGs is negligible, because the gas damping is minimal [3]. At such vacuum levels, ionization gauges are the most effective; these gauges use energetic electrons to ionize gas molecules and produce an ion current that is inversely proportional to the vacuum level.

Ionization gauges are broadly divided into two categories. One is the hot cathode gauge (HCG); the other is the cold cathode gauge (CCG) [4]. In an HCG, electrons are constantly supplied by thermionic emission from a hot filament heated up to at least 1000 °C, and the emitted electrons are accelerated in a biased electric field to gain kinetic energy for gas ionization. In a CCG, the initial electrons are produced by background cosmic radiation or field emission. Crossed electric and magnetic fields are built across the gauge to circulate and energize these initial electrons for gas ionization, and to maintain a self-sustained electron trap with the secondary electrons produced during the ionizations [5].

The most widely used HCG is the Bayard-Alpert gauge (BAG). It consists of a fine-grid cylinder with a thin wire ion collector along the central axis; both elements are more positively biased to the filament that is located outside the grid to supply the electrons [6]. There are two major issues that limit the lowest detectable pressure of the BAG, as well as other types of HCGs. First, highly energized electrons may collide with the grid surface and cause electron stimulation desorption (ESD) [7]. This ESD can lead to desorption of grid contamination,

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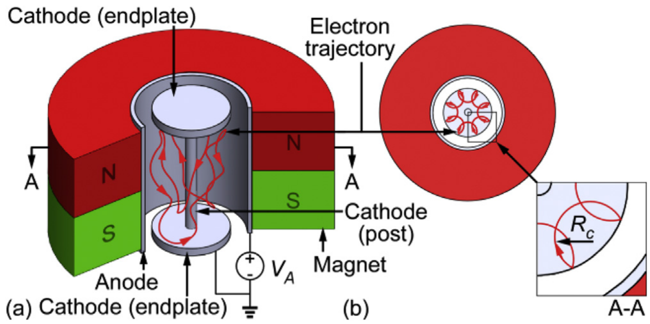

Fig. 1. The magnetron gauge consists of an anode, a cathode, and a magnet. (a) 3D schematic. (b) A-A section view. The radius of the electron cycloidal motion R_c is shown in the zoom in inset.

resulting in a current component at the ion collector that is unrelated to the vacuum level [8]. Second, the BAG has a serious X-ray effect [4]. X-ray photons can be produced at the grid when electrons strike the grid. As some of the photons arrive at the ion collector, photoelectrons can be emitted, resulting in an electron current that also has no dependence on vacuum level. As both the ESD and X-ray effects are thus independent of pressure, they limit the minimum measurable pressure of the HCGs. To extend the measurable vacuum levels, research efforts have focused on addressing these two major issues through structural refinements [7,9,10].

The magnetron gauge, as studied in this work, is a typical CCG that consists of a cylindrical anode, a central cathode, and a ring-shaped magnet (Fig. 1) [11]. The electric field is primarily radial between the cathode post and the anode. The magnetic field provided by the magnet is directed along the axis of the cylindrical anode. Electrons that encounter the crossed electric and magnetic fields are cycled between the cathode endplates with a superimposed cycloidal motion. The cycloidal motion radius R_c depends on both the magnetic field and the electron velocity component that is perpendicular to the magnetic field, as shown in Fig. 1 (b). The electron trajectories are extended by the crossed electric and magnetic fields; the gas ions, being positive and much more massive and slower than electrons, are minimally affected by the magnetic field and are consequently drawn to the cathode directly. Other types of CCGs based on similar crossed field discharges include the Penning cell type and the inverted magnetron type [12–15].

The CCGs are more suitable to incorporate within ultra-high vacuum chambers than the HCGs: First, in CCGs the ESD and X-ray effects are pressure dependent, allowing sensitivity to be maintained at lower pressures than HCGs [16]. Second, the power consumption of CCGs is usually at milliwatt or even microwatt levels, whereas HCGs are operated at watt levels because of the heated filament [17]. Third, the outgassing rate of CCGs is typically several orders of magnitude lower than that of HCGs [18], which is an important advantage for miniaturized vacuum chambers. Even the use of a microfabricated or a carbon nanotube-based field emitter array has not made the power consumption and outgassing performance of HCGs comparable to those of CCGs [19,20]. However, despite the attractiveness of CCGs for use in compact vacuum systems, most of the commercially available and recently reported miniaturized CCGs have an internal volume of at least 10 cm^3, which is too bulky to integrate with the most compact vacuum chambers [5,21–27].

This paper describes the investigation of a miniaturized magnetron gauge (referred to as the MMG). The final design has an internal volume of 0.3 cm^3, which is about 30 × smaller than the internal volume of miniaturized magnetron gauges that are commercially available. For example, the MKS Series 903 inverted magnetron transducer has an internal volume of 15 cm^3. The primary research challenge is to develop a structure in which practically achievable levels of electric and magnetic fields are able to confine electrons in a small enough volume to ensure gas ionization at practical efficiency, as an electron needs to

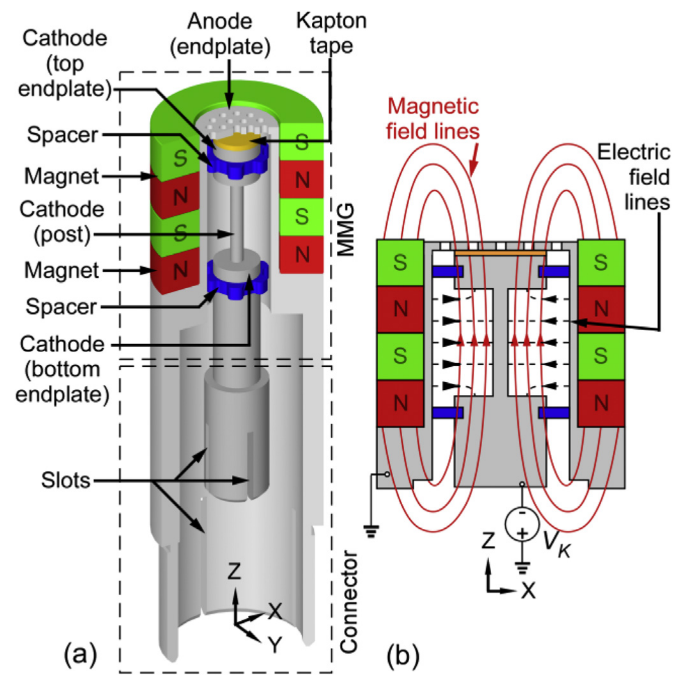

Fig. 2. (a) Schematic of the MMG geometry and connector, and (b) magnetic and electric field lines in the MMG.

travel several kilometers before a collision with a gas molecule is likely at a pressure of 1 μTorr (133 μPa) [28]. Additionally, the structure must be manufacturable and usable with existing vacuum apparatus. Section 2 describes the design and modeling of the MMG that seeks to address this challenge. Section 3 provides the experimental methods and results, followed by discussion in Section 4 and conclusions in Section 5.

2. Design and modeling

2.1. Design and structure

The MMG consists of an anode, a cathode, two spacers, and two ring magnets, as shown in Figs. 2 and 3. In this work, the MMG is integrated with a vacuum side coaxial connector for standard safety high voltage (SHV) feedthroughs as shown in Fig. 2 (a). The MMG has an internal volume of 0.3 cm^3. The connector segment, which allows reliable, precise, and quick installation, can be easily adapted for other types of vacuum fittings.

The MMG anode is comprised of a 12.4 mm long cylinder with 6.4 mm outer diameter and 5 mm inner diameter. It is capped with a 600 μm thick anode endplate perforated with multiple 600 μm diameter holes; these holes allow gas conductance through the anode and into the gauge. Two 6.4 mm thick ring magnets (K&J magnetics, RC44, magnetization direction: axial) encircle the anode. The cathode, located along the longitudinal axis of the anode, is comprised of a post with 1.0 mm diameter, capped by two 3.5 mm diameter cathode endplates that are spaced 6.0 mm apart. Two insulating spacers encircle the cathode endplates to prevent electrical shorting between the anode and the cathode. The spacers have a sawtooth periphery to facilitate gas conductance. These spacers are 800 μm thick, with inner and outer diameters of 3.0 mm and 5.0 mm, respectively. Shallow annular grooves are engraved on both cathode endplates to hold these spacers. An insulating layer is also located on top of the top cathode endplate to prevent electrical shorting.

In the MMG, the anode is grounded and the cathode is biased at a negative high voltage V_K to maintain the same electric field between the anode and the cathode as in the traditional biasing scheme. This allows the high voltage to be fully shielded inside the anode. The