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Radioisotope-powered ion gauge with super high stability, long life, and large sensitivity range from ultrahigh vacuum to high pressure

Yuerui Lu and Amit Lal[a)]
SonicMEMS Laboratory, School of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853

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The authors report the radioisotope-powered ion gauge (RPIG) using the safe, low activity, planar radioactive ^{63}Ni beta thin-film source as the cold cathode. RPIG has both high stability and long lifetime with ^{63}Ni half-life of 100.1 years. The authors experimentally demonstrate an ultrahigh sensor dynamic range, from high vacuum (10^{-6} Torr) to high pressure (10^{3} Torr), which is the largest sensitivity range among all the reported pressure sensors. With high source stability independent of temperature, and its self-powered nature, RPIG is a promising candidate for pressure measurement, which needs extreme low temperature or high temperature, in microsystems where power consumption and system complexity need to be minimized. © *2010 American Vacuum Society.* [DOI: 10.1116/1.3483579]

I. INTRODUCTION

Ionization gauges are widely used in the semiconductor industry as high-vacuum gauge, which can be classified into hot and cold cathode gauges, depending on the method of generating electrons. Conventional hot cathode ionization gauges, using thermally generated electrons, have serious outgassing problems, while cold cathode ionization gauges, using a glow discharge to generate free electrons, suffer from the requirement of a few kilovolts to function and the instability of the glow discharge at low pressures. Moreover, ion gauges do not work for vacuum pressures above 10^{-3} Torr, which is important for semiconductor processes, such as reactive ion etching and sputtering. In the case of miniature vacuum systems (1–10 cm^3), power and volume dedicated to an ion gauge are highly limited and are often the performance limiting component of portable vacuum instruments. Attempts at realizing miniature ion gauges have utilized nanostructures to amplify emitted electron flux imaging on gaseous atoms to measure ionic current. Recently, promising nanostructured emitters, such as carbon nanotubes[1,2] (CNTs) or HfC-coated CNTs,[3] are used as the cold cathode, which can reduce the voltage to hundreds of volts to realize a stable electron flux. However, the degradation of the field-emission current leading to short lifetime remains a serious problem for CNT-based ion gauges, although some modification could be made to improve the emission stability and the lifetime.[3] The emitted current is not stable beyond 1 Torr for HfC-coated carbon nanotube based ion gauges, possibly due to local heating and nanotip reaction with oxygen. Hence, the problem of realizing a stable electron source operable over a wide operating dynamic range of pressure and temperature is unsolved.

Radioactive isotope ^{63}Ni thin film emitter has been used as fuel for low power batteries[4–6] and nanolithography sources,[7,8] because of its 100 year long half-life, suitable beta electron energy range (E_{av}=14.9 keV, E_{max}=67 keV), and safe radiation applications.[9] The low-energy beta electrons from the ^{63}Ni source can be shielded by thin layers (~25 μm) of most materials and cannot penetrate the dead skin of human beings.[10] The beta emitter has high stability, since the beta emission is independent of pressure or temperature. This stable beta emitter with long life is an attractive candidate for cold cathode ionization gauge application.

Here, we use a radioisotope ^{63}Ni thin film source as the cold cathode to realize a radioisotope-powered ion gauge (RPIG), which eliminates the high voltage requirement but also realizes long lifetime, high electron emission stability, and high linear sensitivity range from high vacuum (down to 10^{-6} Torr) to low vacuum or even up to a high pressure range (10^{3} Torr).

II. EXPERIMENT

Instead of the standard triode structure for conventional cold cathode ionization gauges, the RPIG uses the capacitive structure, as shown in Fig. 1, since the high voltage for electron emission is no longer needed. The radioactive ^{63}Ni thin film was deposited by the electroless nickel plating technique. The thin film source (1×2 cm^2 in size) has ~3.0 mCi beta decay activity. The stainless steel metal plate is located at a distance of 1 mm from the ^{63}Ni. The stainless steel plate was baked in air at 400 °C for 48 h to minimize its outgassing in high vacuum.

Based on a Monte Carlo calculation,[11,12] the high-energy beta electrons with an average energy of 14.9 keV, emitted from the ^{63}Ni thin film source, can travel around 4 cm distance in air under atmosphere pressure at room temperature. Some of these primary high energy electrons will penetrate deeply into the stainless steel metal plate, while the rest will be backscattered. These backscattered electrons may still have high energy and they can possibly be scattered back and forth between the ^{63}Ni thin film and stainless steel plate capacitive structure, for hundreds of times, before they are absorbed. These backscattered electrons and the primary beta

[a)]Author to whom correspondence should be addressed; electronic mail: lal@ece.cornell.edu

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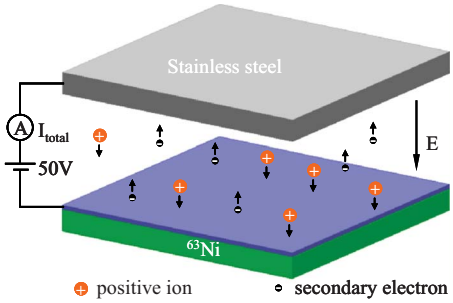

FIG. 1. (Color online) Schematic of the experiment setup. The gap between the ^{63}Ni and the stainless steel plate is 1 mm. The size of the ^{63}Ni thin film source is 1×2 cm^2.

electrons from ^{63}Ni thin film will lead to many gas ionization events, producing a substantial flux of positively charged ions, and related amount of secondary electrons. The density of these positive ions and secondary electrons is proportional to the gas molecule number volume density, which is proportional to pressure.

The ^{63}Ni thin film was grounded and a 50 V constant dc bias was applied on the stainless steel plate. The positive ions and the gas secondary electrons will be collected by the ^{63}Ni thin film and stainless steel plate, respectively (Fig. 1). A Keithley 4200, which has a high current resolution down to 1 fA, was used for the dc voltage supply and the total current measurement. The total current I_{total} includes both the basic current, defined as I_0, due to primary electrons and backscattered electrons, and the ionization current, defined as $I_{ionization}$ due to the positive ions and the secondary electrons,

$$I_{ionization} = I_{total} - I_0. \tag{1}$$

The measured I_{total} versus pressure curve is shown in the logarithmic plot in Fig. 2(a), with pressure ranging from 10^{-6} up to 10^3 Torr ($\sim$1.4 atm). The pressure was measured using commercially available Pfeiffer compact full range gauge with sensitivity down to 10^{-8} Torr as the standard. In the high vacuum region with pressure ranging from 10^{-6} to 10^{-4} Torr, we could see that I_{total} is linearly proportional to the pressure in the double linear plots shown in Fig. 2(b). In this high vacuum region, the ionization current $I_{ionization}$ is much smaller than the current I_0, since there is a small of amount of ionizations due to a very small number density of gas molecules. The I_0 current could be considered to be a constant value in this high vacuum region, since the ionization is small and will give an insignificant effect on the backscattered electrons. Therefore, an extrapolated I_0 value of 20.52 pA can be obtained by extrapolating the linear experimental data to the ideal real vacuum with zero pressure [Fig. 2(b)]. The ionization current $I_{ionization}$ can be obtained by reducing I_0 from the total current I_{total}, as shown in Eq. (1). The double logarithmic plot of $I_{ionization}$ versus pressure curve [Fig. 2(c)] shows good linearity, from high vacuum down to 10^{-6} Torr to high pressure 10^3 Torr. Some nonlinear features in the curve could be due to the nonlinearity of the Pfeiffer gauge.

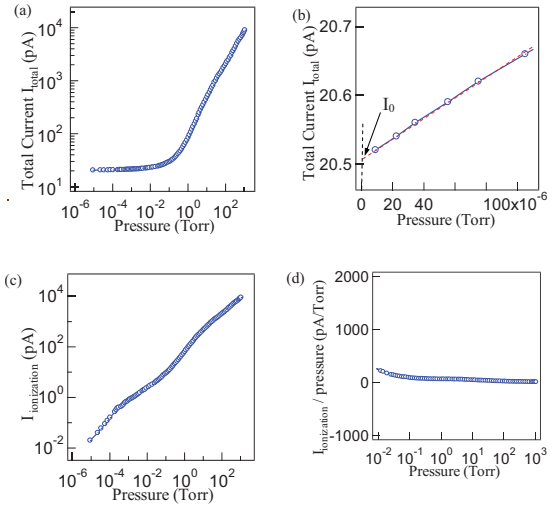

FIG. 2. (Color online) (a) Logarithmic plot of the measured total current I_{total} vs pressure curve of the device, with pressure ranging from 8.9×10^{-6} up to 1.6×10^3 Torr ($\sim$1.4 atm), at room temperature. (b) Linear plot curve of total current I_{total} vs pressure for the high vacuum region. The total current is almost linear with pressure. We extrapolate the curve to the ideal absolute vacuum case (zero pressure) and get a constant current value I_0. (c) Logarithmic plot of the measured ionization current $I_{ionization}$ vs pressure curve. Here, we define ionization current by $I_{ionization}=I_{total}-I_0$. (d) Linear logarithmic plot of the measured ionization current $I_{ionization}$/pressure vs pressure curve.

The relation between ionization current $I_{ionization}$ and the pressure could be expressed as

$$\log(I_{ionization}) = S\log(P) + a_0\log(I_0), \tag{2}$$

where S is defined as the sensitivity of the ion gauge here, which is a constant value; a_0 is also a fitting constant value. From the experimental data plot in Fig. 3(c), the S value was calculated to be $S=0.672$. For the gas ionization process, the ionization cross section is inversely proportional to the energy of the incident electrons, when the energy of the incident electrons is greater than 100 eV. Lower energy incident electrons have a higher probability to ionize a gas molecule. In our case, since our primary electrons are high energy electrons with an average energy of 14.9 keV, most of the ionizations should come from the low energy backscattered electrons, which are produced by the primary electrons bouncing back and forth between these two plates. Therefore, the relation between $I_{ionization}$ and pressure is different from that in conventional ion gauge or that in CNT-based ion gauge.[3]

Moreover, RPIG could be sensitive to higher pressures greater than 1 atm. By pressurizing the chamber, a pressure of 10^3 Torr ($\sim$1.4 atm) could be reached [Fig. 2(a)]. At higher pressures self-absorption of the primary electrons in the gas leads to lower sensitivity. Based on our Monte Carlo simulation, high energy electrons with an average energy of 14.9 keV could penetrate 4 cm in air under atmosphere at room temperature. Even under pressures up to 10^5 Torr ($\sim$100 atm) at room temperature, these high energy electrons could penetrate 500 μm distance. Therefore, by changing

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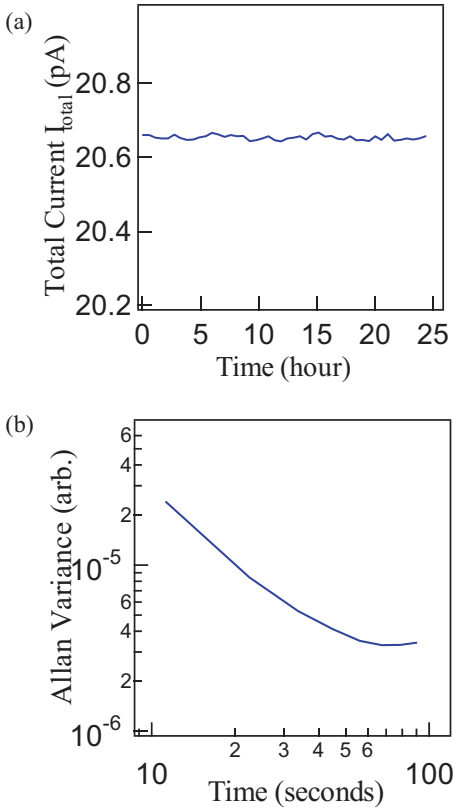

FIG. 3. (Color online) Source current stability characterization. (a) Total current I_{total} vs time measurement under constant high vacuum pressure (8.9×10^{-6} Torr) at room temperature. (b) Measured *Allan Variance* versus averaging time for the source emission current, under constant high vacuum pressure (8.9×10^{-6} Torr) at room temperature.

the plate gap down to below 500 μm, RPIG is able to be used for high pressure gauges up to 10^5 Torr theoretically.

Figure 3(a) shows the I_{total} versus time curve of our RPIG under constant high pressure (8.9×10^{-6} Torr) at room temperature. The curve fluctuation is extremely small over 25 h, with 20.65 pA mean current value and 0.61% standard deviation, indicating the high stability of the emitted current from the source beta emission. This is because the natural basic beta emission is independent of the pressure or the temperature. The Allan variance, which is defined as one-half of the time average of the squares of the differences between successive readings over the sampling period, has proved useful to estimate the stability due to noise processes. Here, the measured *Allan variance* versus averaging time for the source emission current is shown in Fig. 3(b). The small Allan variance value, less than 10^{-4} at average time 10 s, further shows the high stability of the source emission current.

III. CONCLUSION

The RPIG sensitivity can potentially be a function of time owing to the exponentially decaying nature of radioisotope decay. However, this effect can be minimized by choosing radioisotopes with very long half-lives. ^{63}Ni has a 100.1 year half-life, and this leads to a change in pressure sensitivity of 1% every year, which can be calibrated using an external clock, if needed. The RPIG and the calibration method can be used to realize a high dynamic range vacuum ion gauge that potentially only consumes a very small amount of power, which is required to measure the emitted current. The scaling of the RPIG to smaller lateral dimensions would lead to even smaller use of space in small microsystems, at the cost of lower sensitivity as the total flux is reduced. This reduction in sensitivity could be compensated by the use of higher activity radioisotopes such as tritium (^{3}H) or promethium (^{147}Pm).

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