SELF-POWERED ION GAUGE AND SELF-POWERED ION PUMP

Yuerui Lu, and Amit Lal

SonicMEMS Laboratory

School of Electrical and Computer Engineering

Cornell University, Ithaca, NY

ABSTRACT

We used a radioisotope ^{63}Ni thin-film source as a cold cathode to realize a Self-Powered Ion Gauge (SPIG), demonstrating the largest sensitivity range among all reported pressure sensors, from high vacuum (10^{-6} Torr) to high pressure (10^3 Torr). We also show that SPIG can be transformed into a Self-Powered Ion Pump (SPIP) due to self-charge generated voltage induced ion-implantation of ionized gas atoms. The combination of SPIG and SPIP provides a near-zero-power solution to measuring and maintaining high vacuum in micro-system packages. The amount of radioactivity is in the micro-Ci to milli-Ci range, which is a commercially viable from both the point of view of safety and cost in a sealed package.

INTRODUCTION

Obtaining high-vacuum in cm-cubic chambers has been an active field of research in MEMS packaging. Several solutions of hermetic packages have been developed [1-3] for inertial sensors and resonators. Recently a number of solutions have used thin-film sealing to achieve partial vacuum [4]. A few efforts, mainly stemming from U-Michigan have demonstrated sustained pressure of a few milli-Torr. Using UHV packaging techniques and use of getters, some solutions have demonstrated micro-Torr pressures, but the lifetime of good vacuum is limited by getter life. As the size of the vacuum package become small, the surface to volume ratio increases. If a pumping mechanism is found based on radioisotope films, then the pumping rate will be proportional to the film area, resulting in more efficient pumping as package become smaller.

Moreover, in order to measure the pressure in a high vacuum package, ionization gauges are widely used, which can be classified into hot and cold cathode gauges, depending on the generation methods of electrons. Conventional hot cathode ionization gauges use thermally generated electrons, causing power for heating. 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. In the case of miniature vacuum systems (1-10cc), power and volume dedicated to an ion-gauge is highly limited, specially for battery powered portable applications.

Radioactive isotopes ^{63}Ni thin film emitter has been used as fuel for low power batteries [5-7], nano-lithography sources [8], because of its 100 years long half-life, suitable beta electron energy range ($E_{av}=14.9\text{keV}$, $E_{max}=67\text{keV}$) and safe radiation applications. The low-energy beta electrons from ^{63}Ni source can be shielded by thin layers ($\sim 25\mu\text{m}$) of most materials, and can not penetrate the dead-cell layer of skin [9]. 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 gauges application.

Here, we used a radioisotope ^{63}Ni thin-film source as a cold cathode to realize a Self-Powered Ion Gauge (SPIG) (Fig.1), demonstrating the largest sensitivity dynamic range among all reported pressure sensors, from high vacuum (10^{-6} Torr) to high pressure (10^3 Torr). Since ^{63}Ni emits electrons with average energy 14.9 keV, this eliminates the high voltage and temperature for field emissions and thermal emission typically required in high vacuum

gauges. ^{63}Ni has 100 years' half-life ensuring SPIG long time operation. The ^{63}Ni source is also highly stable as the radioisotope electron emission is independent of pressure or temperature [10]. We also show that SPIG can be transformed into a Self-Powered Ion Pump (SPIP) due to self-charge generated voltage induced ion-implantation of ionized gas atoms. The combination of SPIG and SPIP provides a near-zero-power solution to measuring and maintaining high vacuum in microsystem packages. The amount of radioactivity is in the microCi to milliCi range, which is a commercially viable from both the point of view of both safety and cost in a sealed package.

SELF-POWERED ION GAUGE (SPIG)

Figure 1: Schematic of Self-Powered Ion Gauge (SPIG). The gap between the ^{63}Ni and the Ti plate is 1mm. The size of the ^{63}Ni thin film source is 1cm X 2cm. We define $I_{total} = I_0 + I_{ion} + I_s$.

In the case of miniature, potentially battery-powered vacuum systems (1-10cc), power and volume dedicated to an ion-gauge is highly limited, and is often the performance limiting component of MEMS portable vacuum instruments. Attempts at realizing miniature ion gauges have utilized nanostructures to amplify emitted electron flux, such as carbon nanotubes (CNTs) ion gauges [11]. But the degradation of the field-emission current leading to short life time remains a serious problem for CNT-based ion-gauges. This damage is possibly due to local heating and nano-tip reaction with oxygen. Hence, the problem of realizing a stable electron source operable over wide operating dynamic range of pressure and temperature is unsolved. Here, we use the stable radioisotope ^{63}Ni thin film source as the cold cathode to realize a SPIG (Fig. 1&2). A capacitor formed of a titanium plate and ^{63}Ni thin film were placed in a package that was placed in a 10cc vacuum chamber, being pumped by a turbo pump and pressure was controlled by a leak-valve. The current across the capacitor consists of the emitted current and ion current due to electron ionization. Figure 3 shows the ability to measure pressure down to 10^{-6} Torr by calibrating the ionization current versus pressure. Pressure measured over several days shows no drift in the current measurement.

Figure 2: Photo of the device set up; the Teflon was chosen as outgassing is minimal.

Based on Monte Carlo calculation, the high-energy beta electrons with average energy of 14.9 keV, emitted from the ^{63}Ni thin film source, can travel 4 cm in air under atmosphere pressure at room temperature. Some of these primary high energy electrons will penetrate deeply into the titanium metal plate, while the rest will be back-scattered. These back-scattered electrons might still have high energy and they are possible to be scattered back and forth between the ^{63}Ni thin film and titanium plate capacitive structure, for hundreds of times, before they are absorbed. These back-scattered electrons and the primary beta electrons from ^{63}Ni thin film, will lead to many gas ionization events, producing 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 50V 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). Keithley 4200, which has a high current resolution down to 1fA, 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 back-scattered electrons, and the ionization current, defined as $I_{\text{ionization}}$ due to the positive ions and the secondary electrons.

$$I_{\text{ionization}} = I_{\text{total}} - I_0 \quad (1)$$

The measured Total current I_{total} vs Pressure curve is shown in a log plot in Figure 3(a), with pressure ranging from 10^{-6} Torr up to 10^3 Torr (~ 1.4 atm). The high pressure was measured using commercially available Pfeiffer compact full range gauge with useful sensitivity range from 10^{-3} Torr down to 10^{-8} Torr as the standard. For high pressure measurement, we used Pirani gauge and membrane-type pressure manometer. In high vacuum region with pressure ranging from 10^{-6} Torr to 10^{-4} Torr, we could see that I_{total} is linearly proportional to the pressure, in the double linear plots $I_{\text{ionization}}$ is much smaller than current I_0 , since there is a small amount of ionizations due to very small number density of gas molecules. The I_0 current could be considered to be a constant value shown in figure 3(a) inset, since the ionization is small and will give an insignificant effect on the back-scattered electrons. Therefore, an extrapolated I_0 value of 20.5pA can be obtained by extrapolating the linear experimental data to the ideal real vacuum with zero Pa pressure (Fig.3(a) inset). The ionization current $I_{\text{ionization}}$ can be

obtained by reducing I_0 from the total current I_{total} , as shown in

Figure 3: (a) Log plot of the measured Total current I_{total} vs Pressure curve of the device, with pressure ranging from 8.9×10^{-6} Torr up to 1.6×10^3 Torr (~ 1.4 atm), at room temperature. Inset shows the linear plot curve of Total current vs Pressure for high vacuum region. The total current is almost linear to the pressure. We extrapolate the curve to the ideal absolute vacuum case (zero Pa pressure) and get a constant current value I_0 . (b) Log plot of the measured ionization current $I_{\text{ionization}}$ vs Pressure. Here, we define ionization current by $I_{\text{ionization}} = I_{\text{total}} - I_0 = I_{\text{ion}} + I_s$

Eq.1. The double log plot of $I_{\text{ionization}}$ vs Pressure curve (Fig.3(b)) shows good linearity, from high vacuum down to 10^{-6} Torr to high pressure 10^3 Torr.

SELF-POWERED ION PUMP (SPIP)

Figure 4: Schematic drawing for Self-Powered Ion Pump (SPIP) set up. When the switch S is open, there will be an electrical field E between the Ti and ^{63}Ni plates, due to the built up voltage (up to 10kV) by the Ti self-charging from ^{63}Ni beta emission. The positive ions, from air gas ionization, will be accelerated and implanted into the Ti plate permanently. This will cause pumping effect. The SPIP is on when S is open, while it is off when S is closed.

To solve the vacuum problem, we develop ion-pumps that use the electron emission from ^{63}Ni directly. If no bias is applied across the SPIG capacitor at low initial vacuum (< 0.01 Torr), voltage as high as 7-10kV can be generated across the capacitor [5]. This high voltage is able to accelerate the ions, created from gas ionization by emitted electrons, to high energy, and implant these ions into the top metal plate permanently. Energies as low as 1keV are needed to implant a few nm into the top plate (Fig.6). This pumping effect makes the capacitor a Self-Powered Ion Pump (SPIP) (Fig. 4).

Figure 5: Experimental demonstration for SPIP. When SPIP is off (S closed), the highest vacuum we could reach is 7.5×10^{-7} Torr, due to the balance of the external pumping with the vacuum system leaking. When SPIP is on (S open), the highest vacuum turns to be 5.0×10^{-7} Torr, due to the new balance of the vacuum system leaking with the external pumping and the pumping from SPIP. As shown in figure 3b, if we turn on and off the SPIP back and fourth, by controlling the switch open and closed, the minimum vacuum point will be switched up and down according. This experimentally demonstrated the SPIP pumping.

SPIP is experimentally demonstrated in Figures 4 and 5. When SPIP is off (S closed), the highest vacuum we could reach is 7.5×10^{-7} Torr, due to the balance of the external pumping with the vacuum system leaking. When SPIP is on (S open), the highest

vacuum turns to be 5.0×10^{-7} Torr, due to the new balance of the vacuum system leaking with the external pumping and the pumping from SPIP. As shown in Figure 5, if we turn SPIP on and off, by controlling the switch to open and closed position, the minimum vacuum level change accordingly. This experimentally demonstrates the SPIP pumping.

Figure 6. Ion implantation depth vs ion energy curve. The ion is oxygen and the target is Ti metal.

SPIP PUMPING SPEED MODEL ANALYSIS

The emitted electrons can undergo many energy transfer interactions with the gas atoms. As the electrons travel across a gap, they undergo ionization reactions with the gas atoms resulting in ion creation. As the initial electron energy is quite high (average $E_{av}=14.9\text{keV}$), the cross-section of ionization is very small. The electrons eventually hit the opposing electrode and the impact can result in secondary electron emission. The secondary electron energy is on the order of a few to hundreds of eV. We believe it is the secondary electrons that lead to a larger amount of ionization of the gas molecules, as the cross-section is higher at lower electron energies. The original emitted electrons build up charge on the collector and also result in positive charge on the emitting plate. This leads to a voltage and electric field buildup in the gap that accelerates away the secondary electrons toward the emitter, if the initial pressure is low enough for voltage to build up. The number of electrons emitted for high-energy electrons is very low, causing the back current due to secondary electrons being less than the emitted current. Our current measurements in vacuum indicate that 20 secondary electrons are emitted from the cathode for every 100 emitted from the anode to the cathode. In addition to the secondary electrons, the ionization due to the emitted and secondary electrons lead to an ionic current that also reduces the current due to the emitted electrons.

The ions are generated by secondary electrons with kinetic energies of approximately 10-300 eV, which can collide with other gas atoms or can impact the cathode sputtering the atoms off the cathode. Atoms that have energy higher than the ionization potential of 100-200 V govern the sputtering process. The ions that collide with the cathode can undergo two actions. First, most of ions will be accelerated by the high build up voltage and be implanted into the

top metal plate permanently. Second, the ions can also sputter the Ti metal plate the sputtered Ti atoms can also remove atoms from the gas due their specific reactivity. The rate at which ions are generated can be approximated by:

$$n_{ion} = \frac{\sigma}{A} N n_{gas} \quad (2)$$

where n_{ion} is the rate of ion generated per cm^3 per second, σ is the cross-section of the incident electron and gas particle impact, A is the total area of the emission, N is the rate of electrons emitted per second from the radioactive thin film, and n_{gas} is the density of gas. The cross-section σ is a strong function of the energy of the electron and is low at high energies beyond a few hundred eV. The secondary electrons produced during the electron impact also contribute to the gas ionization with a similar rate given by Eq.2.

Figure 7: Pumping speed Simulation for SPIP. We assume to use 1cm^3 small volume chamber, which is pre-pumped to initial pressure $P_0 = 1 \times 10^{-6}$ Torr.

$$n_{ion-se}(E) = \frac{\sigma_{se}(E)}{A} N_{se} n_{gas} = \frac{\sigma_{se}}{A} n_{seg}(E) N n_{gas} \quad (3)$$

Here, $\sigma_{se}(E)$ is the cross-section of ionization for electrons with energy E , N_{se} is the total number of secondary electrons generated per second, $n_{seg}(E)$ is the number of secondary electrons generated with incident electrons of energy E , and N is the rate of incident electron generation. We need to integrate over the ^{63}Ni energies and particle densities to get the total ion generation.

The generated ions can also undergo secondary reactions with the gas creating further electrons and ions. Since the secondary ion generation rate is proportional to the initial ion generation, the total generation rate for the ions is proportional to the gas concentration and the incident electron rate. The rate of sputtering of atoms from the Ti plate and the corresponding rate of pumping will also be proportional to this product. The total rate of gas atom removal assuming removal of all ions (assuming no recombination) will therefore be

$$\frac{dn_{gas}(E)}{dt} = -(n_{ion} + G n_{ion}) = -(1 + G)(\sigma + \sigma_{se} n_{seg}(E)) \frac{N}{A} n_{gas} \quad (4)$$

Here G is the number of secondary ion generated.

Once the solution for the gas density is obtained, the expression for the gas pressure can be written as:

$$p = n_{gas} kT \quad (5)$$

where P is the pressure; k is Boltzmann constant and T is temperature,

In the case of externally pump system, outgassing is balanced by the pump. The pressure modulation due to SPIP can be

calculated by Eq. 4, as showed in Figure 7.

CONCLUSION

We have realized a Self-Powered Ion Gauge (SPIG), using radioisotope ^{63}Ni thin-film source as the cold cathode, which has the largest sensitivity range among all reported pressure sensors, from high vacuum (10^{-6} Torr) to high pressure (10^3 Torr). SPIG can also be transformed into a Self-Powered Ion Pump (SPIP) due to self-charge generated voltage induced ion-implantation of ionized gas atoms. The pumping model for our SPIP is analyzed, which matches well with our current available experimental data. Here, the combination of SPIG and SPIP provides a near-zero-power solution to measuring and maintaining high vacuum in micro-system packages.

REFERENCE

- [1]. J. S. Mitchell, and K. Najafi, "A detailed study of yield and reliability for vacuum packages fabricated in a wafer-level Au-Si eutectic bonding process", 6/21-25/2009, TRANSDUCERS, (2009), pp. 841 – 844.
- [2]. S. H. Lee, J. Cho, S.W. Lee, M.F. Zaman, F. Ayazi, and K. Najafi, "A Low-Power Oven-Controlled Vacuum Package Technology for High-Performance MEMS", 01/25-29/2009, MEMS, (2009) pp.753 – 756.
- [3]. C. Junseok, J. M. Giachino, and K. Najafi, "Fabrication and Characterization of a Wafer-Level MEMS Vacuum Package With Vertical Feed throughs", JMEMS, Vol. 17(1), (2008), pp.193-200.
- [4]. R. N. Candler, M. A. Hopcroft, B. Kim; W. T. Park, R. Melamud, M. Agarwal, G. Yama, A. Partridge, M. Lutz, and T.W. Kenny, "Long-Term and Accelerated Life Testing of a Novel Single-Wafer Vacuum Encapsulation for MEMS Resonators", JMEMS, Vol. 15(6), (2006), pp.1446-1456.
- [5]. R. Duggirala, H. Li, and A. Lal, "High efficiency β radioisotope energy conversion using reciprocating electromechanical converters with integrated betavoltaics", Appl. Phys. Lett. 92, (2008), pp.153105.
- [6]. M. V. S. Chandrashekhar, R. Duggirala, M. G. Spencer, and A. Lal, "4H SiC betavoltaic powered temperature transducer" Appl. Phys. Lett. 91, (2007), pp.053511.
- [7]. M. V. S. Chandrashekhar, C. I. Thomas, H. Li, M. G. Spencer, and A. Lal, "Demonstration of a 4H SiC betavoltaic cell", Appl. Phys. Lett., 88, (2006), pp. 033506.
- [8]. Y. R. Lu, N. Yoshimizu, and A. Lal, "Self-powered near field electron lithography", J. Vac. Sci. Technol. B. 27, (2009), pp.2537.
- [9]. H. Cember, "Introduction to Health Physics", Pergamon, New York, (1983).
- [10]. Klapdor, J. Metzinger, and T. Oda, "Beta decay half lives of nuclei far from stability", H. V. Zeitschrift für Physik A Hadrons and Nuclei, (1982), 309, pp.91.
- [11]. Y. C. Yang, L. Qian, J. Tang, L. Liu, and S. S. Fan, "A low-vacuum ionization gauge with HfC-modified carbon nanotube field emitters", Appl. Phys. Lett., (2008), 92, pp.153105.