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Sensing absolute air pressure using micro corona discharge

Beelee Chua [a,*], Ahjeong Son [b,1]

[a] School of Electrical Engineering Korea University Anam-dong, Seongbuk-gu, Seoul 136-713 Republic of Korea
[b] College of Engineering Environmental Science and Engineering Ewha Womans University 52 Ewhayeodae-gil, Seodaemun-gu, Seoul 120-750 Republic of Korea

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ABSTRACT

We demonstrated the sensing of absolute air pressure using micro corona discharge. Pin-to-plane electrode configuration with an electrode gap of ~1.2 mm was used. The length and height of the plane were 3 mm and 1 mm, respectively. The electrodes were fabricated using a copper electroplating process and subsequently enclosed in a channel. The inception voltage was ~1400 V. Analytical plot of corona current versus absolute air pressure showed that corona current decreased with the increase of absolute air pressure. In the experiment, applied voltages from 2500 to 3500 V and absolute air pressure from 101.3 to 173.7 kPa were used. The experimental corona current ranged from ~2 to ~10 μA. It was observed to decrease with increased absolute air pressure and therefore in agreement with the analytical trend. At a given applied voltage, the upper limit of the pressure measurement range was determined by the extinguishment of the corona discharge. On the other hand, the lower limit was determined by the transition of the corona discharge into streamers. The pressure measurement range could be extended by adjusting the applied voltage accordingly. Limitations of this approach include dependence on gas composition and generation of ionized species.

1. Introduction

Instruments for air pressure measurement was first thought to be invented in as early as the 1600s by E. Torricelli in the form of a liquid based barometer. In 1843, French engineer L. Vidi finally invented and successfully commercialized his aneroid barometer for weather forecasting [1]. It consisted of a deformable chamber sealed at low pressure and an increase in pressure resulted in its deformation. The deformation was amplified mechanically and displayed. Since then two other classes of pressure sensing instruments have gained prominence for ultra-low pressure applications (<10^{-3} Torr or 1.3×10^{-4} kPa). They are Pirani vacuum gages [2,3] and hot/cold cathode ionization gages [4,5]. The Pirani vacuum gage was invented by Marcello Pirani in 1906 and it utilized the rate of heat loss from a heated wire to deduce the corresponding pressure. Ionization gages rely on electrons emitted by its hot cathode to collide with the gas molecules and results in further ionization. In this way, a change in the gas pressure can be detected by a corresponding change in the ion current. More recently, laser induced thermal grating spectroscopy was used to perform non-invasive measurement of gas pressure and temperature [6].

The most notable pressure sensing instrument is probably the diaphragm based pressure sensor. It was invented independently by E. E. Simmons [7] and A. C. Ruge in 1938. The pressure deforms the diaphragm and the deformation is registered by the strain gages bonded to the diaphragm's surface. The advent of silicon micromachining and the leverage of silicon as both mechanical and electronic materials eventually led to the first silicon diaphragm based pressure sensor by O. N. Tufte et al. in 1962 [8]. Since then, the development of silicon diaphragm based pressure sensors have progressed steadily over the decades [9–24] and they are used for numerous applications such as biomedical devices and consumer electronics [25–32]. Today, high performance and low cost silicon diaphragm based pressure sensors with integrated readout integrated circuits are readily available as commercial off-the-shelf components. They cater to various pressure ranges between 10 and 1.5×10^5 kPa.

The key advantage of using a diaphragm in pressure sensing is that its mechanical deformation can be detected via a variety of methods such as capacitive [18], piezoelectric [30,31], piezoresistive [26] and optical transduction [19,20]. The mechanical deformation can also be detected via the resonant frequency shift of resonating elements mounted or fabricated on the diaphragm's surface [21,22]. A diaphragm based pressure sensor is also able

* Corresponding author. Tel.: +82 2 3290 4639/fax: +82 1041962689.
E-mail addresses: chuabeelee@gmail.com, bchua@korea.ac.kr (B. Chua), ahjeong.son@gmail.com (A. Son).
1 Tel.: +82 2 3277 3339.

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to work with both gases and liquids and is largely insensitive to the gas or liquid composition. By varying the size and thickness of the diaphragm, the pressure sensor can be designed for a wide range of pressures. As far as pressure sensors are concerned, the diaphragm based designs appeared to have fulfilled the needs of most applications.

However the use of diaphragm in pressure sensors has its limitations. Firstly, the operating pressure range of a diaphragm-based pressure sensor is inversely related to its sensitivity. In other words, a thicker diaphragm operates over a wider pressure range but is less sensitive to pressure changes. Secondly, a diaphragm-based pressure sensor is unlikely to recover from a pressure spike that significantly exceeds its maximum operating pressure. This is due to possible permanent deformation or fracture of the diaphragm. Finally a hermetically sealed vacuum reference is required for the diaphragm-based pressure sensor to measure absolute pressure. Therefore it may be beneficial to have a pressure sensing mechanism that operates in similar pressure range without the mechanical constraints and liability of using a diaphragm.

A notable device by S. Wright and Y. B. Gianchandani [33] was able to measure absolute pressures between 30 and 200 Torr ($\sim$ 4 to 27 kPa) without using a diaphragm. Instead it employed DC plasma as its pressure transduction element. A change in pressure results in a corresponding change in its plasma current. The key advantage of the DC plasma pressure sensor is that there is no mechanical component and therefore tolerant to pressure spikes. However DC plasma is a full electrical discharge where the avalanche head extends from one electrode to the other. Operation in higher pressures may result in extensive heating and sputtering of the electrodes. This is likely to limit its operating pressure range.

In this paper, we investigated the feasibility of using micro corona discharge as a transduction element for absolute air pressure sensing. Corona discharge is a partial electrical discharge and has a significantly smaller discharge current as compared to DC plasma. Therefore it should have the advantage of the DC plasma pressure sensor with reduced risk of heating and sputtering of electrodes at higher pressures. Micro corona discharge devices have been investigated previously for various applications such as air particle monitoring, air particle filtration and ozone generation [34–38]. By using pin-to-plane micro corona discharge configuration, we demonstrated the use of micro corona discharge for the measurement of absolute air pressure from 101.3 to 173.7 kPa by monitoring the corona current. In addition, we also showed that the response of the corona current to absolute air pressure change can be tuned by adjusting the applied voltage.

2. Design and principle of operation

2.1. Design of Micro Corona Discharge Device (MCDD) for absolute air pressure sensing

In order to evaluate the micro corona discharge as a pressure transduction element, a micro corona discharge device (hereinafter referred to as MCDD) was fabricated for the experiment. As shown in Fig. 1, the MCDD consisted of a pair of pin-to-plane electrodes enclosed within a channel. The pin serves as the discharge cathode and the plane serves as the anode. This generates an asymmetrical electric field between the electrodes for a given applied voltage. The electric field strength is at its maximum near the surface of the discharge cathode.

At a sufficiently high applied voltage, the inception of a corona discharge occurs. Townsend avalanche is formed and is confined to the proximity of the discharge cathode (also known as the ionization region). It does not extend toward the anode (unlike a full electrical discharge). This is because as the electric field strength decreases away from the discharge cathode. In other words, the electrons do not possess sufficient energy to perform further impact ionization as they move away from the discharge cathode. Instead they form an electron cloud and drifts toward the anode (also known as the drift region). This results in the relatively low discharge current as compared to a full electrical discharge.

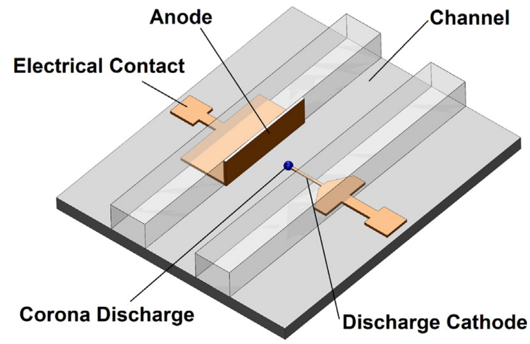

Fig. 1. Schematic of the micro corona discharge device (the channel cover is not shown).

Like any other electrical gas discharges, corona discharge is highly sensitive to pressure changes. As the air pressure increases, the mean free path between air molecules decreases. This reduces the acceleration distance of the electrons between collisions. In other words, the electrons gain less energy between collisions and effectively reduce the amount of ionization as shown in Fig. 2. This means a reduction in the amount of ionization and hence a smaller corona current for the same applied voltage. In other words, the corona current decreases as absolute air pressure increases.

The electrodes were fabricated via a single mask copper electroplating process that was previously developed by Chua et al. [37]. A brief description of the fabrication process is as follows: A thin titanium adhesion layer and copper seed layer was deposited on a glass substrate sequentially via e-beam evaporation. Using

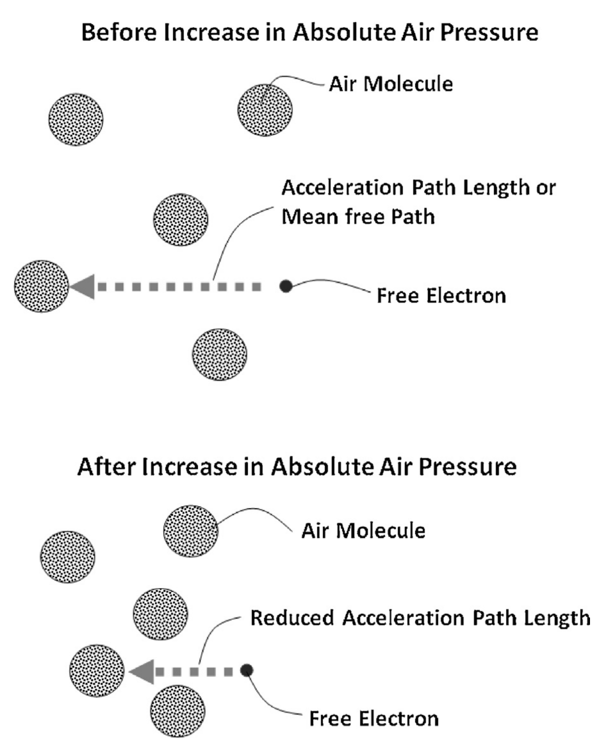

Fig. 2. Schematic showing electrons gaining less energy between collisions due to increase in absolute air pressure.