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PRELIMINARY STUDY OF GLOW DISCHARGE PLASMA ON THE STATIC PRESSURE MEASUREMENT

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ABSTRACT

With an aim to break the barrier of MHz level measurement, a new time-resolved plasma pressure sensor based on the direct-current glow discharge is investigated in this paper. The principle of the plasma pressure sensor is initially introduced. The experimental system used to calibrate the correlation between the discharge voltage (U) and air pressure (P) is then presented. The test air pressure is in a wide range from 0.4 to 1.0 atmosphere pressure. The effects of two key parameters of electrode spacing and circuit current on the glow discharge regime of the plasma sensor and the U-P correlation are investigated. A total of four electrode spacing of 50μm，100μm，160μm and 250μm are tested. The plasma sensor is not sensitive to the pressure fluctuation when the spacing is set to be 100 or 160μm. For the spacing of 50μm with the current increasing from 3mA to 5mA, the probe works in the “abnormal” GD regime. The calibrated curves of discharge voltage as a function of air pressure show a definite monotonically decreasing trend. On the contrary, the calibrated curves for the spacing of 250μm with the current increasing from 2mA to 3.5mA, show a monotonically increasing trend. The probe works in the “sub-normal” GD regime. These results demonstrate that maintaining the discharge in the same regime is crucial to guarantee the monotonic relationship between the discharge voltage and the air pressure.

Keywords: Glow discharge, plasma, static pressure, discharge regime, response regularity

1 INTRODUCTION

Robustness, fast-response and high spatial resolution are eternally pursued characteristics of measurement techniques in aerospace and turbomachinery fields. In order to capture more detailed and accurate unsteady flow information, such as flow instability in compressors, transition and turbulence in the high-speed compressible boundary layers, and unsteady flow separation bubbles, the sensors with an ultra-high frequency response of MHz level are desirable. Nowadays, the piezoresistive silicon pressure transducers are widely used for the pressure measurement. Thermally based sensors, such as hot-wire anemometers and surface mounted hot-films, almost monopolize the markets of the mass-flux and turbulence structure measurement. However, the response frequency of piezoresistive silicon pressure sensors and thermally based sensors is limited to less than 500 kHz due to the mass and thermal inertia effects. These sensors could become unstable due to the non-linear response to changes in overheat and cable capacitance [1-5].

The plasma sensors based on the glow discharge (GD) has the potential to break the barrier of MHz level measurement as its response frequency is determined by the carrier frequency theoretically. As the plasma sensor is sensitive to both the pressure and velocity of the incoming flow, it could be designed as mass-flux anemometer or pressure probe. The concept of plasma sensor is believed to be first proposed by Lindvall [6] in 1934. He suggested that an electric discharge could be used in an anemometer application. Encouraged by Dr. Theodor Von Karman, the glow had been investigated to measure the flow mass-flux as an anemometer. Lindvall used the D.C. (direct current) glow discharge to measure the velocity of the turbulent flow behind a cylinder based on the correlation of circuit voltage with air velocity.

In 1949 Mettler [7] succeeded in developing a D.C. glow discharge anemometer. It is also named plasma anemometer because plasma is generated when the glow discharge occurs. This anemometer can be maintained stable in a transverse air stream at pressure near atmospheric throughout the subsonic velocity range (0~25m/s). Keeping the current constant, the direct current voltage across the glow discharge responds quantitatively and in a reproducible manner to velocity changes. The sensitivity of the anemometer depends chiefly upon the spacing between the electrodes. He developed a quantitative theory for the response of the glow discharge to an air-flow. In order to eliminate the asymmetric burning and reduce the sputtering that exsist in the D.C. glow process, Vrebalovich (1954) [8] designed an A.C. driven probe with the carrier frequency of 700 kHz. The typical spacing distance between the two electrodes is 0.003 in. Plasma was formed in the spacing between two electrodes when glow discharge occurs. He performed boundary layer measurements for Mach numbers from 1.3 to 4. The power spectrum analysis of the anemometer voltage fluctuation at several stations indicated that the probe was able to sense signals in frequency above 100 kHz.

Recent progress in developing plasma probes has been made by Matlis and Corke(2006) [9~10]. They used A.C. current, native frequency response in excess of 1MHz, and weakly ionized glow discharge to produce the plasma. Several other experiments were conducted with this configuration to document its static sensitivity and frequency response. The vortex shedding in the wakes of cylinders with a definite frequency was used calibrate the response frequency of the plasma sensor. The results demonstrated that frequency componets up to 200 kHz were directly captured by the plasma sensor. They suggested that an uncompensated frequency response up to the carrier frequency is possible, which for this experiment was as much as 2 MHz. Then, as reported by Vrebalovich, the plasma probe was used to measure the turbulent boundary layer on the floor of a Mach 1.4 test section.

However, according to the aerodynamic theory, local velocity variation will cause pressure change. Therefore, the plasma anemometer responds to velocity and pressure at the same time. Since the fluctuating parameters like pressure and velocity could not be separated in an open airstream, it is not certain which quantity the glow responds to the glow.

Considering these limitations to make use of glow discharge in mass-flux measurements, Matlis [11] modified a thermocouple to a plasma pressure sensor. He placed the plasma element flush to or just below the level of the compressor wall. In this way, it is thought that the plasma would respond primarily to pressure fluctuations while maintaining the same frequency response as that of the mass-flux sensor greater than 1 MHz. The electrode pair is formed by the two conductors, which are spaced roughly 0.15 mm (0.006 inch) apart. As a baseline comparison to a traditional sensor, the plasma sensor output was compared to data previously captured from a fast-response Kulite pressure sensor. This was done for a case in which the compressor was throttled at an intermediate speed from non-stalled operation into transient stall and then back to a non-stalled state. However, the coupling mechanism of the glow discharge plasma and aerodynamic parameters is not clear. The geometry parameters of the plasma sensor like electrode spacing and diameter were determined by trial and error.

Plasma pressure sensor based on the GD theory is to embed the electrodes within the solid wall where the velocity is zero, as shown in Figure 1. We can conclude that the plasma sensor only responds to the pressure.

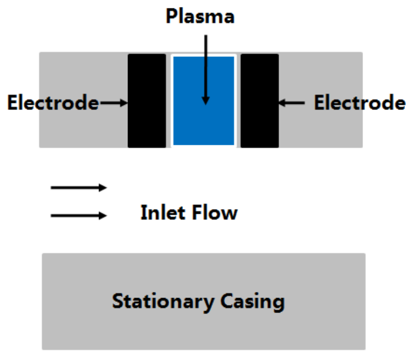


Figure 1. The schematic design for plasma pressure sensor

As a new developing measurement technique, it is necessary to investigate whether the glow discharge has a monotonic response and high sensitivity to the pressure fluctuation before applying to the practical flow field. Based on the gas discharge theory, the monotonic response and pressure sensitivity not only can be affected by the discharge stability and discharge regime, but also bound up with the coupling mechanism between the field pressure fluctuation frequency and the A.C. power supply frequency. Therefore it is necessary to develop both experimental and theoretical research on the glow discharge plasma, with the aim to reveal the generation and evolution of the plasma under different pressure, thus to provide the effective and reliable principle of the sensor design.

As the first step of fundamental research, a calibration procedure is developed in this paper. The platinum electrodes are chosen. It is found that a glow discharge can be maintained and is stable in a static flow field with several clearances throughout the pressure range. By fixing a proper clearance and changing the power supply, a series of typical current–voltage (I–U) characteristics curves between the electrodes can be obtained by varying the static pressure. A qualitative explanation is presented and gives results which agree in form with reported experimental results.

2 INTRODUCTION TO THE GLOW DISCHARGE MEASURING PRINCIPLE

The GD is just one of many forms of gaseous discharges, often called plasma. Figure 1 depicts the characteristic current－voltage relationships that exist for a number of diode-type discharges Of the three major classifications, the townsend discharge, the GD, the GD and the arc discharge, only the GD is expected to operate in plasma pressure sensor, between points D and G in Figure 2. Therefore the measurement and accurate diagnosis of electrical characteristics become the foundation for sensor design.

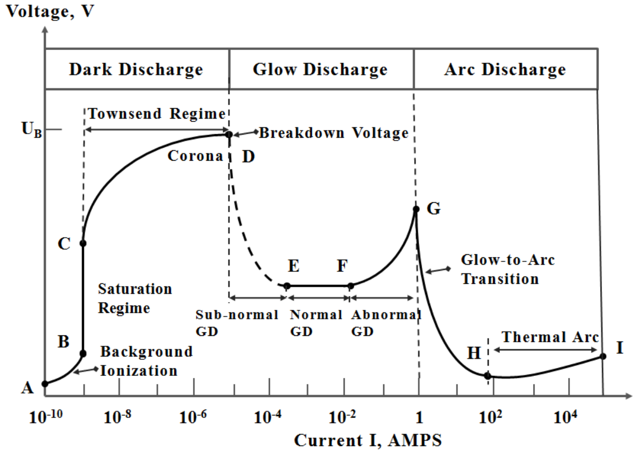


Figure 2. Current–voltage (I-U) characteristics of direct current (D.C.) electrical discharges

The electrical characteristics of a gas discharge can be best understood by beginning with the Townsend discharge regime, in Figure 1 between points C to D. Following the Townsend discharge is a transition region or so-called "sub-normal" GD region, between points D to E, resulting from the increased energy exchange through collisions, wherein the electrical current increases while actually decreasing the required discharge maintenance voltage. This is a basic characteristic of a self-sustained discharge. U_b is the breakdown voltage.

After the transition region, a luminous glow forms between the electrodes and is thus named a 'normal GD', between points E to F. At the onset of the normal GD regime, increases in the current do not change the current density because the cathode surface is only partially covered by the discharge; as such, no increase in voltage is required. As the current is further increased, the discharge glow will eventually cover the entire cathode surface. At this point, any increases in discharge current will result in an increase in current density, requiring an increase in the discharge voltage. Plasmas that display this type of increasing I–U relationship are termed 'abnormal' GD regime, between points F to G. As the discharge current is increased further, the GD will transit to arc discharge regime, between points G to H. [12]

The different regime s indicated on the curve in Figure 2 are not sharply divided and in fact blend on into another in a gradual manner. They are distinguished from each other by corresponding to different physical mechanisms of producing a maintaining electrical discharge. It can be seen that different GD regime correspond different resistance characteristics, which will be the judging criterion for data analysis.

3 EXPERIMENTAL APPARATUS FOR STATIC CALIBRATION

A general picture of the experimental apparatus used will present, followed by a detailed description of the more important features of the apparatus.

3.1 Microscope observation platform

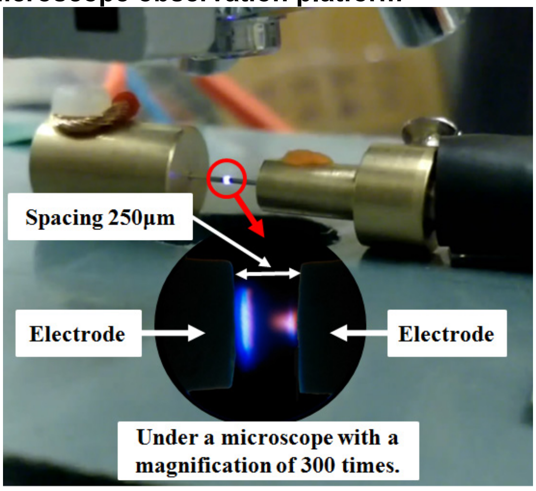


Figure 3. The electrodes with a spacing of 250μm under a microscope.

Circuit current, electrode shape and spacing are the three main parameters of influencing the plasma pressure sensor's sensitivity to pressure. With the aim to measure the electrode spacing accurately, it is necessary to ensure a uniform spacing between the two electrodes each other, and change the electrodes conveniently (including the replacement of electrode material, size, shape, etc), a multiplication microscope was designed and refitted. Two plane parallel platinum electrodes are 0.5 mm in diameter. The electrode spacing is changed by monitoring a micro-calliper. Figure 3 shows the electrodes with a spacing of 250μm under a microscope with a magnification of 300 times.

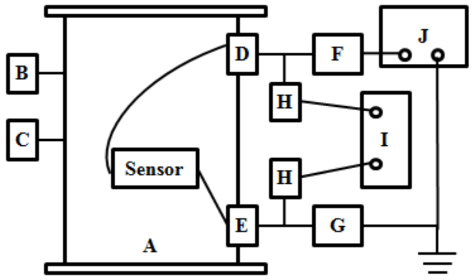
3.2 Experimental system for static calibration

The experimental arrangement is shown schematically in Figure 4. The microscope observation platform with electrodes (sensor) is put in the centre of a chamber (A). When a new experiment begins, the pump (C) pumps the air out. The barometer (B) measures the gas pressure.

The electrical measurement was used to diagnose the discharge. R_t (F) is a current-limited resistance with a value of 100 kΩ~500 kΩ to prevent the electrode overheat. R_t is concatenated between the glow anode and high-voltage contactor (D). The discharge current is measured with a current-monitoring non-inductive resistor R_i (G) of 509Ω concatenated between the glow cathode and ground contactor (E).

A direct voltage from a power source (J) was applied to the electrodes. The output from the plasma sensor was measured by a Tektronix 1000:1 high-voltage high-bandwidth probe (H). A digital storage oscilloscope (I), DPO3012 from Tektronix is used to record the voltage U_{gas} across the electrodes and the voltage U_i across the current sampling resistance. The current of the circuit is calculated by:

$$I = \frac{U_i}{R_i} \qquad (1)$$



A. The gas discharge chamber
B. The barometer
C. The pump
D. The high-voltage contactor
E. The ground contactor
F. The current-limited resistance R_t
G. The current-monitoring resistance R_i
H. The high-voltage probe
I. The digital storage oscilloscope
J. The high-voltage power supply

Figure 4. Schematic diagram for the experimental system

4 STATIC PERFORMANCE OF PLASMA SENSOR

The experimental observations made in connection with this research will present and analyze.

4.1 Effect of pressure on the sensor voltage at a constant current with different electrode spacings

The effect of static pressure on the plasma voltage at constant current under different electrode spacing was investigated. Four typical electrodes spacing as follows 50μm, 100μm, 160μm and 250μm were selected. The constant current was chosen as 3mA. A typical set of calibration curves is shown in Figure 5. Each point was taken under equilibrium conditions.

The calibration curves are easily used to determine pressure fluctuations. These characteristics were intended to be used in the following ways: For example, a spacing and current are chosen such that the glow will be operating in a linear region and high sensitivity. of its calibration curve In order to convert voltage fluctuations to pressure fluctuations, one must multiply the fluctuating voltage, $\triangle U_{gas}$, by the inverse of the slope of the calibration curve, $\triangle P/\triangle U_{gas}$, at the pressure P.

It can be observed that by properly selecting the spacing, several sensitivities are available in particular pressure range. The curve given in Figure 5 for a spacing of 50μm shows a definite monotonically decreasing trend from 0.3atm to 1.0atm, corresponding a voltage change of 35V. However, the curve for a spacing of 250μm shows an opposite monotonically increasing trend, corresponding to a voltage change of 25V. Such linear and high sensitivity behavior was not characteristic of any particular spacing, such as 100μm and 160μm.

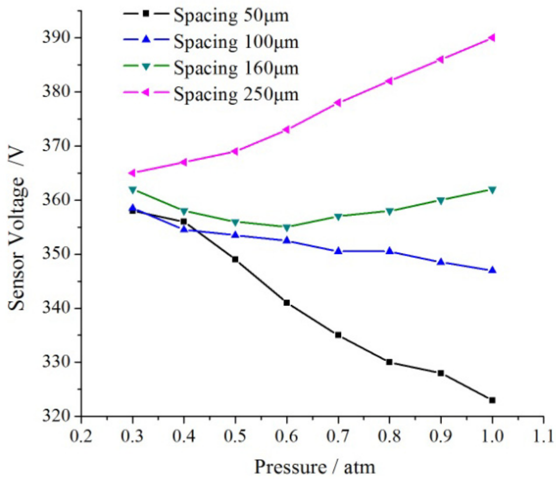


Figure 5. The calibration curves between sensor voltage and pressure at constant current for different electrode spacing

4.2 Effect of pressure on the current–voltage characteristic curves with a spacing of 50μm

From the last chapter we found that different electrode spacing represent different sensitivity and linear trend to particular pressure range. Especially for spacing of 50μm and 250μm, represented high pressure sensitivity but opposite linear trend. With the aim to investigate the physical mechanism behind this phenomenon, these two spacing were selected to investigate further.

Firstly, ensure the fixed electrode spacing uniform and parallel to each other as much as possible to make sure that the discharge could work stable in a certain range. Secondly, switch on the suction pump and draw off the air to a certain pressure like 0.4atm. Thirdly, vary the current every change of 0.5mA by adjusting the voltage regulator and record the discharge voltage. Finally, vary the chamber pressure every change of 0.1atm. Therefore, a set of characteristic current–voltage relationships will be obtained as shown in Figure 6 and Figure 7.

These characteristic I-U relationships were intended to analyze in the following ways:

a) Determine the GD regime at certain current and pressure. Based on the measuring principle introduced in the first chapter, we have learned that different GD regime correspond different resistance characteristics. This will be the judging criterion for the characteristic I-U relationships analysis.
b) Predict the GD regime at high pressure based on the similarity criterion of gas discharge. There are certain similar relations, which hold for the GD. If the pressure P and spacing d are varied such that Pd is constant, then the discharge is similar.

Therefore the mechanism and character of the low pressure GD will aid in the understanding of the high pressure GD.

c) Obtain the calibration curve between pressure and discharge voltage by selecting a constant current.
d) Find the appropriate current range where the glow will be operating in a linear region of its calibration curve.
e) Compare the pressure sensitivity in different current.

Figure 6 shows the effect of pressure on the characteristic I-U relationships for a spacing of 50μm. For characteristic I-U relationships under the pressure from 0.4atm to 0.8atm, the plasma sensor voltage increased with the current increasing. We can conclude that the probe was working in the “abnormal” GD regime.

For characteristic I-U relationships when the pressure varying from 0.9atm to 1.0atm, the plasma sensor voltage decreases with current increasing at the beginning. When the current was larger than 2mA, the sensor voltage increases while the current increasing. Therefore we can draw a conclusion that the sensor was firstly working in the “sub-normal” GD regime, then transited to the “abnormal” GD regime.

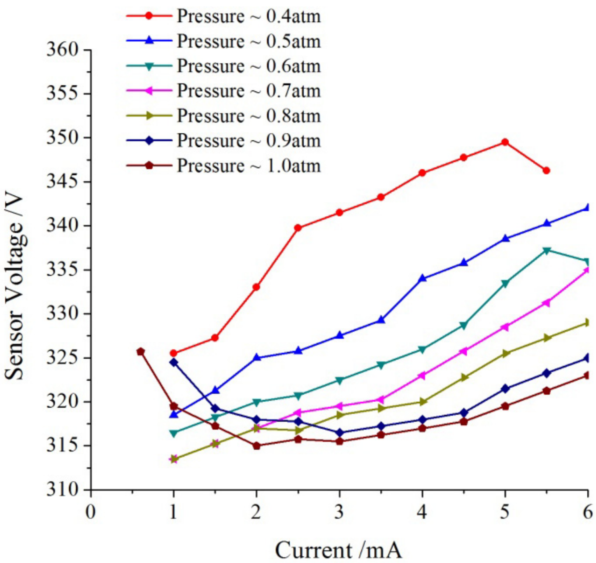


Figure 6. The effect of pressure on the characteristic I-U relationships for a spacing of 50μm

From figure 6, we also discovered when the current is less than 2mA, the response of sensor voltage to pressure variation is not in a monotony trend. In this circumstance, the plasma sensor was working in the “abnormal” GD regime under the pressure from 0.4atm to 0.8atm but “sub-normal” GD regime while the pressure varying from 0.9atm to 1.0atm.

However, when the current is varying from 3mA to 5mA, the response of sensor voltage to pressure variation was in a monotony trend. The discharge voltage decreases with pressure increasing from 0.4atm to 1.0atm. In this circumstance, the sensor is working in the “abnormal” GD regime.

We notice that only when the sensor is always working in the “abnormal” GD regime, can the sensor voltage responding to pressure variation is in a monotonically decreasing trend.

4.3 Effect of pressure on the current–voltage characteristic curves with a spacing of 250μm

Figure 7 shows the effect of pressure on the characteristic I-U relationships for a spacing of 250μm.

For the current–voltage (I-U) characteristics under pressure 0.4atm, the discharge voltage decreases with the current increasing at the beginning, then have no significant changes with current increasing. According to the measuring principle introduced in the first chapter, we can predict that the sensor is working in the “sub-normal” GD regime firstly, then transit to the “normal” GD regime

As for pressure 0.5atm, the discharge voltage decreases while the current increasing first. When current is larger than 3.5mA, the discharge voltage increases while current increasing, however decreases again after a maximum value. We can conclude that the sensor works in the “sub-normal” GD regime firstly, and transit to the “abnormal” GD regime, finally reaches to the “glow-arc transition” regime.

While the pressure varies from 0.6atm to 1.0atm, the discharge voltage decreases while the current increasing at the beginning with current increasing from 1mA to 5.5mA. However, when current is larger than 5.5mA, the discharge voltage decreases rapidly. We can conclude that the sensor works in the “sub-normal” GD regime firstly, and transit to the “normal” GD or “abnormal” GD regime, finally reaches to the “glow-arc transition” regime.

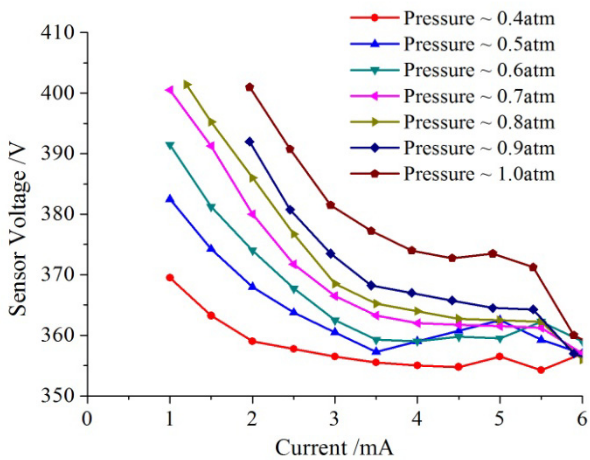


Figure 6. The effect of pressure on the characteristic I-U relationships for a spacing of 250μm

When the current is less than 2mA, the discharge cannot be sustained under pressure 0.9atm and 1.0atm because of the low supply voltage. When the pressure varies from 0.4atm to 0.8atm, the response of sensor voltage to pressure variation is in a monotonically increasing trend.

While the current is between 2mA and 3.5mA, the sensor is working in the “sub-normal” GD regime under pressure 0.4atm to 1.0atm. Meanwhile the response of discharge voltage to pressure variation is also in a monotonically increasing trend.

When the current is larger than 3.5mA, the probe is working in different regimes under different pressure, therefore the response is not in a monotonous trend. Nevertheless, for the pressure from 0.6atm to 1.0atm with current limiting between 4mA and 5.5mA, the sensor voltage still increases with pressure increasing.

From the first chapter, we have discovered that sensor for a spacing of 50μm shows a definite monotonically decreasing trend from 0.4atm to 1.0atm but for a spacing of 250μm represents an opposite monotonically increasing trend. Based on the analysis above, we find out the reason for this phenomenon is that these two different electrode spacing are working in different discharge regimes. Except for the electrode spacing factor, current can also have an influence on the working regime. Only when the sensor is always working in same discharge regime, can the response of sensor voltage to pressure variation be in a monotony trend. As for the electrode spacing of 50μm, when current is varying from 3mA to 5mA, the sensor is working in the "abnormal" GD regime under pressure range from 0.4 to 1.0atm. As for the electrode spacing of 250μm, while current is chosen between 2mA and 3.5mA, the sensor is working in the "sub-normal" GD regime under pressure range from 0.4atm to 1.0atm.

4.4 Pressure sensitivity at different circuit currents for two typical electrode spacings

From the discussed above, we have found that the electrode spacing and circuit current are two main factors which influence the probe discharge regime and the sensitivity to pressure fluctuation. In this chapter, we will investigate the pressure sensitivity by selecting different constant current.

Figure 8 and Figure 9 represent the calibration curves with an electrode spacing of 50μm and 250μm separately. As to the electrode spacing of 50μm, when the current is varying from 3mA to 5mA, the calibrated curves show a definite monotonically decreasing trend from 0.4atm to 1.0atm, corresponding to a voltage change of 30V, 31V, 32Vand 31V respectively. The pressure sensitivity has no significant change. While the calibration curves for a spacing of 250μm show a monotonically increasing trend, while the current was between 2mA and 3.5mA, corresponding to a voltage change of 46V, 34V, 26V and 22V respectively. Therefore, the pressure sensitivity reduces with the current increasing.

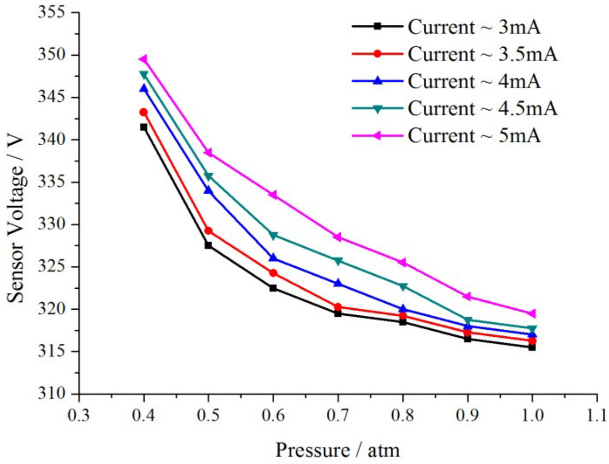


Figure 8. The calibration curves between sensor voltage and pressure at different constant current for the spacing of 50μm

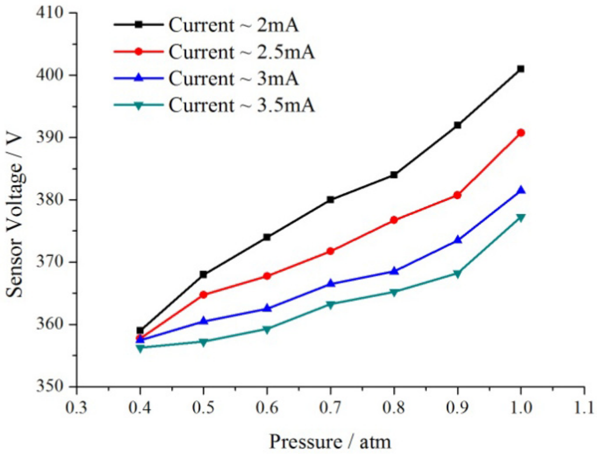


Figure 9. The calibration curves between sensor voltage and pressure at different constant current for the spacing of 250μm

5 CONCLUSIONS

A glow discharge can be maintained stable in a chamber at a standard atmospheric pressure. Maintaining the discharge in same regime is the key to guarantee the monotonic response of voltage to air pressure. The electrode spacing and circuit current are two main factors which influence the probe discharge regime and the sensitivity to pressure fluctuation. Keeping the current constant, the sensor voltage responds quantitatively and in a reproducible manner to pressure changes with a sensitivity depending chiefly upon the electrodes spacing. The main conclusions are summarized as follows:

(1) It can be observed that by properly selecting the spacing, several sensitivities are available in a particular pressure range. For a spacing of 50μm shows a definite monotonically decreasing trend from 0.3atm to 1.0atm, corresponding a voltage change of 35V. However, the curve for a spacing of 250μm shows a monotonically increasing trend, corresponding to a voltage change of 25V. Such linear and high sensitivity behaviour is not the characteristic of any

particular spacing, such as 100μm and 160μm. The reason for this phenomenon is that they are working in different discharge regimes.

(2) Except for the electrode spacing factor, current can also have an influence on the working regime. Only when the sensor is always working in same discharge regime, can the response of sensor voltage to the pressure variation be in a monotony trend.

(3) As for the electrode spacing of 50μm, when current is varying from 3mA to 5mA, the sensor is working in the "abnormal" GD regime under pressure range from 0.4 to 1.0atm. The pressure sensitivity has no significant change with current increasing.

(4) As for the electrode spacing of 250μm, while current is chosen between 2mA and 3.5mA, the sensor is working in the "sub-normal" GD regime under pressure range from 0.4atm to 1.0atm. The pressure sensitivity reduces with the increasing current.

Although the experiment has verified that the GD plasma has high sensitivity to the pressure fluctuation, there are also some shortcomings which made it very difficult to use the glow for practical application. The effects of sputtering and the asymmetric burning properties of the D.C. glow introduced anomalies in the calibration curves. Material sputtered from the cathodes tends to introduce instability which would cause the glow voltage to change markedly during a calibration run. Some of the sputtered material would stick to the anode and form small bumps on it. With no air flow a large bump was formed on the anode and eventually shorted out the discharge. The cathode developed a shiny circular depression in the area where the glow tended to burn.

In order to eliminate the asymmetric burning, reduce the effects of sputtering, and obtain a high time resolution of the plasma sensor, A.C. glow needs to be investigated in the further research. In addition, the plasma sensor is an ideal candidate for mems-scale fabrication techniques, which would provide better spatial resolution, and could be combined in arrays of multiple units for distributed measurements.

NOMENCLATURE

P	Air static pressure
d	Electrode spacing
V	Voltage
I	Circuit current
μm	Micrometer
min	Minute
mA	Milliampere
atm	Atmosphere pressure
GD	Glow discharge
D.C.	Direct current
A.C.	Alternating current

ACKNOWLEDGMENTS

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