PROC. INTERNAT. CONF. SCI. ENGIN.
Volume 4, February 2021
Page 146-149
ISSN 1504607797
E-ISSN 1505707533

Effect of Gas Pressure and Electrode Distance on Self-Bias Voltage in Sputtering System for Thin Films

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Abstract. The production of thin films using the sputtering preparation method is closely related to plasma. The deposition process involves several factors including self-bias voltage, sputter gas pressure, the distance between electrodes, and how to clean the substrate. This study will discuss the effect of variations in gas pressure and electrode distance on the resulting self-bias voltage. The method used is an RF sputtering system equipped with sensors for self-biased pressure and voltage readings. The results show that there is a corelations between pressure and electrode distance with self-biased voltage. Argon gas pressure variations are carried out in the range 4.5 – 8 x 10^{-2} mbar with variations for each increase in argon gas pressure of 0.5 x 10^{-2} mbar. The graph plot results show a logarithmic inversely proportional relationship, that is, when the pressure of argon gas is increased, there will be a decrease in self-bias voltage. The variation of the electrode spacing is carried out in the range 2 – 5 x 10^{-2} meters with a variation of each increase in the electrode distance of 1 x 10^{-2} meters. The corelations between the distance of electrodes and the self-biased voltage is logarithmic. When the electrode distance is increased there will be an increase in the value of the self-bias voltage.

Keywords: Electrode distance, gas pressure, self-bias voltage, sputtering, thin film

Running Title: Effect of Gas Pressure and Electrode Distance

INTRODUCTION

The study of electrical discharges in gases started the plasma physics in the early 1920. Since then this discipline has been developed mainly in the study of atomic physics and nuclear physics. The biggest study of plasma in the nuclear realm is the tokamak plasma in pursuing a fusion reaction to produce energy. Besides that, non-nuclear studies related to plasma are also developing very rapidly (Nur, 2011).

Plasma is the fourth phase after solid, liquid, and gas. The concept of plasma was first started by Langmuir and Tonks in 1928. They defined plasma as a gas ionized in an electrical charge. Plasma has a very significant region for electron collisions to occur. Plasma can appear in the high temperature or energy of a gas to allow the gas atoms to ionize. The size of the energy distribution can be indicated by temperature, while momentum is indicated by the pressure of the gas. The distribution that applies is Maxwell-Boltzman using the ideal gas assumption (Syl, 2008).

Plasma plays a very important role in the formation of thin films through the Sputtering method. Sputtering was first observed in a gas discharge tube by Grove in 1852. Grove found that the cathode surface of the discharge tube was interrupted by ions in the discharge gas, and the cathode material deposited on the inner wall of the discharge tube. Sputtering can be defined as the process of shooting high-energy particles to a target particles so then it get high enough energy to escape from the target surface. The particles that are sprinkled from the target surface which are scattered in all directions, then are focused on the substrate to form a thin layer (Siswanto, et al., 2004).

Preparation of thin layers using the sputtering method are DC sputtering and RF sputtering. The difference between the two lies in the voltage generator used as an energy source for the deposition process. DC sputtering uses a generator with direct voltage, while RF sputtering uses a Radio Frequency generator which is around 13.56 MHz (Atmono, et al., 2000).

The RF sputtering method are more effective in thin films preparation than the DC sputtering method. The voltage required in the RF sputtering technique is smaller than using DC sputtering. The generator in RF sputtering works at a radio frequency of 13.56 MHz and cannot be separated from the oscillator system. The oscillator is an electronic circuit to generate electrical vibrations. The frequency regulator contained in the circuit consists of an inductor and capacitor(Siswanto, et al., 2004).

RF sputtering use to make thin films is greatly influenced by certain factors. These factors include generator power, self-bias voltage, the distance between electrodes, gas pressure, and substrate cleaning. This article will discuss the effect of distance between electrodes and gas pressure on the size of the self-bias voltage.

MATERIALS AND METHODS

This study uses a set of RF sputtering, water for cooling, copper (Cu) cathodes, and the gas used is argon gas. The initial stage carried out is the preparation stage, namely by connecting devices to an electric socket. Proceed with the vacuum of the plasma chamber for approximately 10 minutes until the pressure in the chamber is 3 x 10^{-2} mbar. The next stage is water draining to cool the RF Sputtering system.

The stage after preparation is the plasma ignition process. Plasma ignition start by setting the RF generator to provide the power of 20 watts and a voltage of 200 volts (Al-Ghamidi, et al., 2016). This setting aims to make the plasma ignition easier. The next step is flowing argon gas into the plasma chamber, for the initial pressure of argon gas is 3 x 10^{-2} mbar to match the pressure of the plasma chamber that was previously vacuumed. The ignition stage starts by pressing the on the button on the RF generator, the presence of plasma can be seen when the plasma chamber looks purple.

Variation in gas pressure starts by adjusting the inclusion of argon gas in stages in the range 4.5 – 8 x 10^{-2} mbar. The argon pressure entering the plasma chamber is varied by turning the valve where the argon gas enters the plasma chamber. The size of the incoming argon gas can be seen through a vacuum display which is detected by the Pirani sensor. The same procedure applies to variations in the electrode distance anode and cathode. The anode is a place to place the substrate (glass) then the cathode in the sputter targets. Variation of the distance can be done by giving a distance between the anode and the substrate on a scale of 2 – 5 x 10^{-2} m.

RESULT AND DISCUSSION

The Effect of Argon Pressure Variation on Self-Bias Voltage

The pressure is a unit in physics which expresses the force of area unity, usually symbolized by P. Pressure is closely related to volume and temperature when it is related to fluids. The higher the pressure in a place with the same volume, the higher the temperature in that area. Argon gas pressure in the RF sputtering system as sputter gas is one of the parameters that affect the thin film preparation. The pressure of argon gas flowed into the plasma chamber can be seen through the vacuum display from the reading of the Pirani sensor. Argon gas pressure shows how much momentum is generated due to the collision of argon gas particles with the container or plasma chamber.

The plasma chamber is where the plasma is seen as an ideal gas and follows the Maxwell-Boltzmann law. This is because plasma is low pressure and very high temperature. The density is around 10^3 /cm^3, while the average kinetic energy of 3/2 kT. It is much greater than the interaction force between particles, so the interaction force is negligible. Therefore, the pressure of argon flowing into the plasma chamber greatly affects the self-bias voltage generated during the plasma ignition (Atmono, et al., 1999).

The greater the argon pressure, the shorter the free path average value of the argon gas particles. The average free path is the distance between collisions, when the collision frequency increases, the temperature of the gas particles and electrons will increase (Sze, 2010). The corellation between the increase in argon pressure and the decrease in self-bias stress can be stated in the mathematical equation of the natural logarithm as follow:

$$U_{sb} = - [\, U_{hf} - \frac{kT_e}{2e} \ln(2{,}3\ \frac{M_e}{M_i})\,]$$

Where,
U_{sb} : self-biased voltage
U_{hf} : RF generator voltage
M_e : mass of electrons
M_i : mass of the argon gas particles.

This equation shows that increasing the pressure causing the temperature to rise, it will result in a decrease in self-bias voltage (Oechner, 1975).

Variation in argon pressure easily can be done, namely by turning the valve from the argon gas flow and measuring the size as in Figure 1 below.

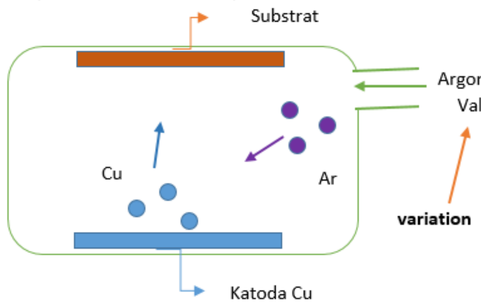

Figure 1. Variation argon gas valve.

Variation in argon gas pressure affects the resulting self-bias voltage. The results of these variations can be seen in Figure 2 below.

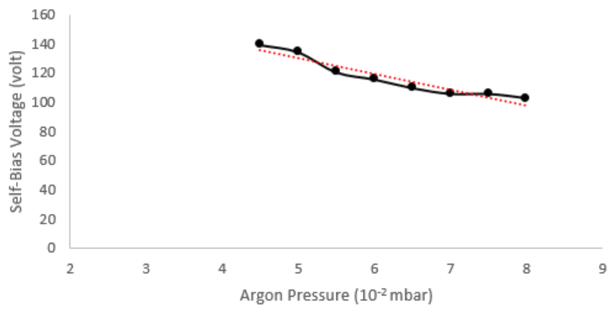

Figure 2. Graph of Argon Pressure Vs Self-Bias Voltage

This research has done by variying the pressure of argon gas in the range of 4.5 - 8 x 10^{-2} mbar by increasing of 0.5 x 10^{-2} mbar. The graph uses a reference function of the natural logarithm (ln), where the property of the function is the inverse of the exponential. The black line in figure 2 is the experimental value of the the self-bias voltage versus argon pressure while the dot line in red is a mathematical calculation of the natural logarithmic function.

The results showed that when the pressure of argon gas increased, will decrease the self-bias voltage. A slight difference between the graph of the experimental results and the calculations, due to the instability of the argon gas valve. During the experiment, argon pressure fluctuated in the plasma chamber. Also, in self-bias voltage measurements, fluctuations sometimes occur, when the power passes through the matching box to reach zero reflection power, meaning that nothing power returns to the RF generator system or the matching box. There is a complex process that occurs in an RF generator system involving many components and parameters (Atmono, et al., 1999).

The results of this study indicate that the argon pressure could influence on self-bias stress. The relationship between the two is inversely proportional when the pressure of argon gas increase self-bias voltage will decrease as a result of an increase in temperature in the plasma chamber. The effect that occurs when making a thin layer is that when the pressure of argon gas increases, the resistance of the thin layer that deposited increases (Yunanto, et al., 2002).

The Influence of Electrode Distance Variation on Self-Bias Voltage

The electrodes in the RF sputtering system are inside the chamber, where the cathode is the negative pole then the anode is the positive pole. The cathode is inside the chamber, more precisely at the bottom of the chamber and the anode is inside with a lever that can be rotated or varied in the distance. In the sputtering process, the anode is a place to attach the glass substrate and a cathode is a place for the interaction of the target material connected to the RF generator. The variation electrode distance is carried out as illustrated in Figure 3 below.

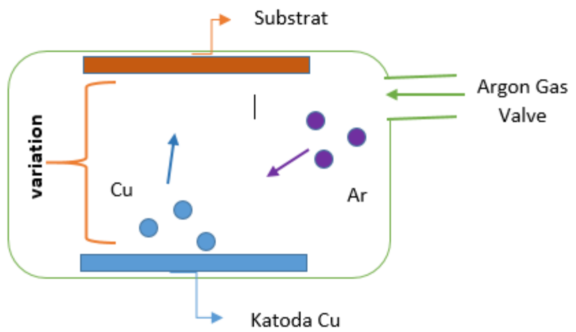

Figure 3. Variation electrode distance.

Experiment of the distance variation in this research was carried out at a constant argon pressure at 3 x 10^{-2} mbar and a fixed power of 50 watts using a Cu target cathode. These pressures and forces were chosen because of the character of the Cu target which can be deposited on the glass substrate over a certain pressure and power range. The variation of the distance in this study is on the centimeter scale, which is between 2 - 5 x 10^{-2} meters. The results obtained are plotted in Figure 4.

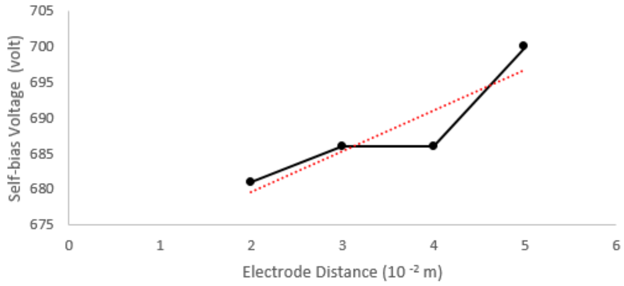

Figure 4. Graph of Electrode Distance Vs Self-Bias Voltage

The results show that there is an increase in the self-bias voltage when the distance between the electrodes also increases. This is because the greater the distance between the electrodes, the more coverage of the argon gas to ionize to become plasma so that the direct self-bias voltage is greater. At an electrode distance of 4 x 10^{-2} meters, the measured self-bias voltage is equal to the voltage at a distance of 3 x 10^{-2} meters, which is 686 volts.

The variation of the electrode spacing is closely related to Paschen's law of Townsend discharge. Paschen's law is a voltage equation between two electrodes with a function of pressure and distance between the electrodes. Paschen studied the stresses of different types of gases between parallel metal plates as a function of pressure and variation in distance (Dermawan, Sujitno, & Artika, 2018).

$$U_d = B\frac{ps}{\ln(\frac{A}{k}ps)}$$

Where,
U_d : self-biased voltage
P : pressure
s : electrode distance
A = 1.355 bar L^2 / mol^2
B = 0.032 x 10^5 bar L / mol
k = 1.38 x10^{23}.

In the experimental results, the electrode distance is 4 x 10^{-2} meters. Self-bias voltage does not change or is constant with the previous distance, while the graph of the calculation results shows that in each variation there is a change in self-bias voltage. The difference between the calculation results and the experiment is due to several factors, including the fluctuation of the self-bias voltage measurement, the RF sputtering anomaly, and the flow instability of the sputter gas, namely argon gas.

The results of research data regarding the variation in the distance between the electrodes on the self-bias voltage show that there is an effect and correlation. The graph that is formed is a graph that goes up from left to right. The relationship between the distance between the electrodes and the self-biased voltage is logarithmic. When the electrode distance is increased, there will be an increase in the value of the self-bias voltage due to the size of the argon gas coverage by the two electrodes.

CONCLUSION

Research on the effect of variations in argon gas pressure and electrode distance was successfully carried out. The variation in gas pressure is carried out in the range 4.5 - 8 x 10^{-2} mbar with a variation of each increase in argon gas pressure of 0.5 x 10^{-2} mbar. The graph plot results show that when the pressure of argon gas increased, there will be a decrease in self-bias voltage. The variation of the electrode spacing is carried out in the range 2 - 5 x 10^{-2} meters with a variation of each increase in the electrode distance of 1 x 10^{-2} meters. The relationship between the distance between the electrodes and the self-biasing voltage is logarithmic. When the electrode distance is increased, the self-bias voltage value increases.

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