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Optimization of Reactive Ion Etching (RIE) Process Using SF_6 and CHF_3 Gases

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Abstract: Reactive ion etching (RIE) is a technology of etching that is used in microfabrication and one of the methods of dry etching and has different characteristics compared to wet etching. The chemical process of the reactive plasma from the RIE is used to remove materials deposited on the wafer. The RIE etcher has several variable factors such as RF power, pressure, gas flow rate, and etching time that correspond to output parameters of its etching depth and its etching rate. There are many numbers of experiments needed to be run to find the optimum setting of RIE to establish the ideal conditions for the output etching rate. In this study, Si and SiO_2 wafers are used to etch using the process gas of SF_6 and CHF_3 that feed to the RIE system. The etching depth and etching rate were investigated by using Dektak XT Bruker Surface Profiler and also to characterize the surface roughness of etched Si and SiO_2 by using 3D mapping mode. The result shows the effect between varied RF power, time and flow rate on the etching depth and rate so the optimum parameters can be selected.

Keywords: Reactive Ion Etching, RIE, Plasma Etching, Silicon, Silicon Dioxide

1. Introduction

In the world of integrated circuits (IC) is playing a major role in our modern daily life, the performance of IC needs to be followed along with the growth of its technology. This powerful capability IC is made from a good quality microelectronic process technology. It is a complex process consisting of more than 800 processes and materially of them involve reactions at the surface that particularly impact the device yield and its performance [1]. This includes the process technology of reactive ion etching. Reactive ion etching (RIE) is one of the etching technologies that has been used in microfabrication. It removes material placed on wafers using chemically reactive plasma. The high-energy ions from the plasma will strike the wafer surface and react with it. It is a high-resolution etching mechanism that uses reactive gas discharges. It is a process that can be controlled to process a wide

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variety of materials including semiconductors, dielectrics and some metals [2]. Nevertheless, RIE had some issues which had a conflict between the etching rate and its anisotropic profile.

This paper aims to optimize the usage of process gases involving Sulfur Hexafluoride (SF_6) and Trifluoromethane (CHF_3) as the gas feed to the plasma reaction process in the RIE machine. Both types of gases will be implemented in the study to be monitored and figured out their configuration so that they can be optimized and eventually grant out a good result of the etching rate by using the RIE machine in the laboratory.

2. Materials and Methods

2.1 Materials

This section will describe each step that will be implemented in the project. In this research, the types of equipment used to carry out this experiment to achieve the objectives are as follows.

- SNTEK Asher, RIE System
- Dektak XT Bruker Surface Profiler

2.2 Methods

The method that will be used to etch the Si and SiO_2 samples is by using SNTEK Asher, RIE System. It uses chemically reactive plasma to remove material deposited on wafers. High-energy ions from the plasma attack the wafer surface and react with it. The specification of the system can fit in substrate size up to 6 inches, with a max temperature of 700°C, RF power supply up to 600 W with a frequency of 13.56 MHz. The gas flow system specification with a flow control range of 0 to 100 sccm using process gases such as Argon, O_2, SF_6, CF_4 and CHF_3 and the ultimate pressure below 1 x 10^{-6} Torr within 10 minutes. In this research, the process gases that will be used to etch silicon wafers are SF_6 and CHF_3 with various parameters of RF power, time and flow rate.

The samples are then analyzed using Dektak XT Bruker Surface Profiler to determine their etching depth and also to characterize the surface roughness of Si and SiO_2. The Dektak XT surface profiler is an advanced thin and thick film step height measurement tool. Besides that, the Dektak XT system measures roughness in the nanometer range. The system also can produce three-dimensional measurements and analyses when equipped with the 3D mapping option.

2.3 Sample Preparation

For the experiment, Si and SiO_2 wafers with the silicon orientation of (100) that have been cut into 2x2-cm sizes while using a Kapton tape as the masking. The samples were then etched in a SNTEK Asher, RIE System with different parameters used. The full processes are shown in Figure 1 and Figure 2.

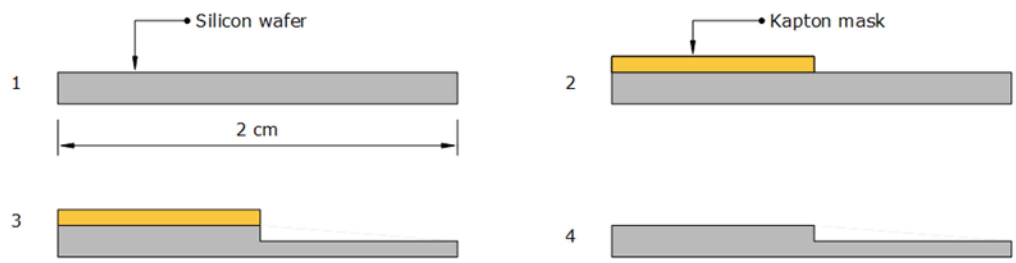

Figure 1: Process steps; (1) bare silicon wafer, (2) Kapton tape as mask, (3) RIE etch, (4) Kapton tape is removed to measure etch depth

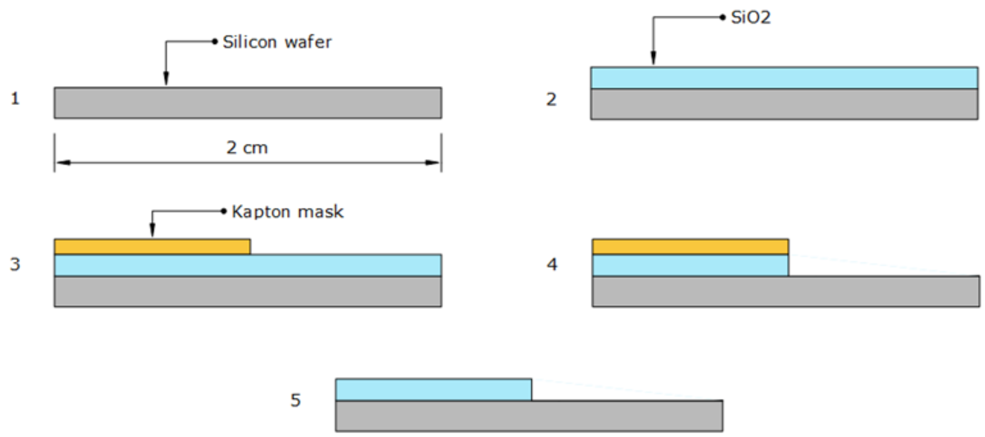

Figure 2: Process steps; (1) bare silicon wafer, (2) SiO_2 oxidation growth, (3) Kapton tape as a mask, (4) RIE etch, (5) Kapton mask is removed to measure etch depth

2.4 Chemical Reaction

The chemical reaction between two chemical substances SF_6 and silicon is the reason the etching process is successful. With the help of a high vacuum chamber surrounding and plasma, meanwhile SF_6 as the feeding gas targeting exposed silicon, a surface reaction happens [3].

$$SF_6 + e \rightarrow SF_4 + 2F + e \qquad Eq.1$$

$$Si\ (solid) + 4F\ \rightarrow\ SiF_4 \qquad Eq.2$$

SF_6 dissociates in plasma to form SF_4 or SF_2 and atomic fluorine that reacts with silicon. Both SF_4 and the etching reaction product, SiF_4, exist as gases that are evacuated from the chamber. SF_4 is so stable that fluorine atoms cannot recombine with it. Therefore, a large amount of atomic fluorine can be produced and participates in the etching reaction.

Next, a chemical reaction is happened in the high vacuum chamber between solid silicon and CHF_3 gases to realize the etching process [4].

$$CHF_3 + e\ \rightarrow CHF + 2F + e \qquad Eq.3$$

$$SiO_2 + CHF_3\ \rightarrow CO_2 + SiF_3 +\ H_2 \qquad Eq.4$$

CHF_3 dissociates in plasma to form 2F atomic fluorine that reacts with silicon dioxide. The etching reaction product, SiF_3, exists as gases that are evacuated from the chamber. With the help of a large amount of atomic fluorine that can be produced, those will perform in the etching reaction.

3. Results and Discussion

The results and discussion section presents data and analysis of the study. The result from each variation of parameters of RIE etching on the Si and SiO_2 was obtained from Dektak XT Bruker Surface Profiler to identify the etching depth and etching rate and also to determine their surface roughness.

3.1 RF Power Variations

A set of the parameter has been selected in the different RF power configurations shown in Table 1 and Table 2. The experiment is conducted in four runs with the varied RF power starting with 25W, 50W, 75W and 100W with an increase of 25W each. The time chosen is a constant of 10 minutes with the flow rate of process gases SF_6, CHF_3 and argon with the gas ratio of 1:1 of 5 sccm constants. The base pressure in the RIE system shown is 60 mTorr and 53 mTorr respectively.

Table 1: The parameter of different RF power in Si etch depth and etch rate

Time (min)	SF_6 (sccm)	Ar (sccm)	Pressure (mTorr)	RF (W)	Depth (µm)	Rate (µm/min)
10	5	5	60	25	3.60	0.36
10	5	5	60	50	5.56	0.57
10	5	5	60	75	6.49	0.65
10	5	5	60	100	7.72	0.77

Table 2: The parameter of different RF power in SiO_2 etch depth and etch rate

Time (min)	CHF_3 (sccm)	Ar (sccm)	Pressure (mTorr)	RF (W)	Depth (µm)	Rate (µm/min)
10	5	5	53	25	0.30	0.03
10	5	5	53	50	0.37	0.04
10	5	5	53	75	0.58	0.06
10	5	5	53	100	0.65	0.07

The etch depth is analyzed by Dektak XT Bruker Surface Profiler. The etch depth of Si is the deepest at 7.72 µm and its etch rate peaked at 0.77. Meanwhile, the etch depth of the SiO_2 is the deepest at 0.65 µm and its etch rate peaked at 0.07. This result confirms greater RF power gave a higher etching rate. The etching rate increasing following the increasing of the RF power 25W, 50W, 75W and 100W with 0.36, 0.57, 0.65, 0.77 for Si and 0.03, 0.04, 0.06, 0.07 for SiO_2 respectively. Figure 3 and Figure 4 shows the double Y graph of RF power vs etch depth and etch rate for both Si and SiO_2. The result shown is linear.

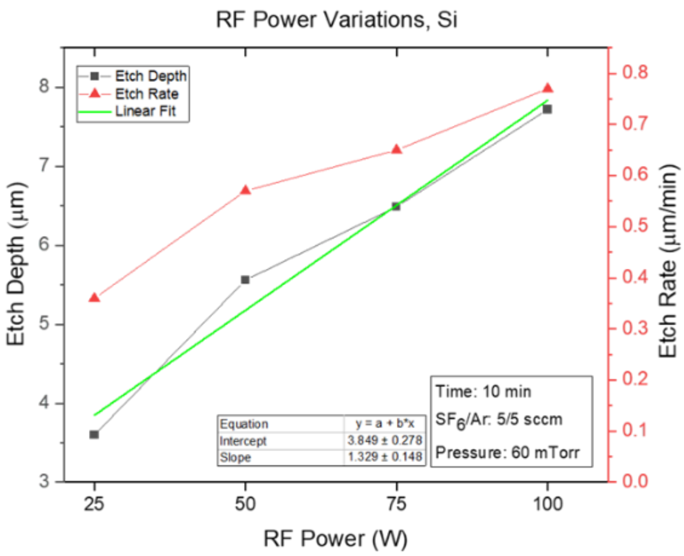

Figure 3: Influence of RF power on Si etch depth and rate

Furthermore, the characterization is done by using the 3D mapping which is another method of measurement in the Dektak XT Bruker Surface Profiler. The result shown in Figure 5 shows the different surface roughness of Si affected varied RF power. Based on the observation at 25W, the Si surface presents rough and low etch depth. At 50W, the surface is slightly better than the 25W. The smooth surface roughness starts to show between 75W and 100W. Both present a good fit but 100W is chosen because it has a smooth surface with a higher etching rate. From the observation of 100W, there is a spike on the surface that has been etched probably because there is dust on the sample when the measurement of 3D mapping has occurred. In addition, the 3D mapping of the Si sample showed the anisotropic slope because of (100) Silicon wafer orientation. RF power of 100W is later to be constant for the other two variations of time and flow rate. The smooth Si surface is preferred as it is important for electrical and capacitance capabilities [5]-[6].

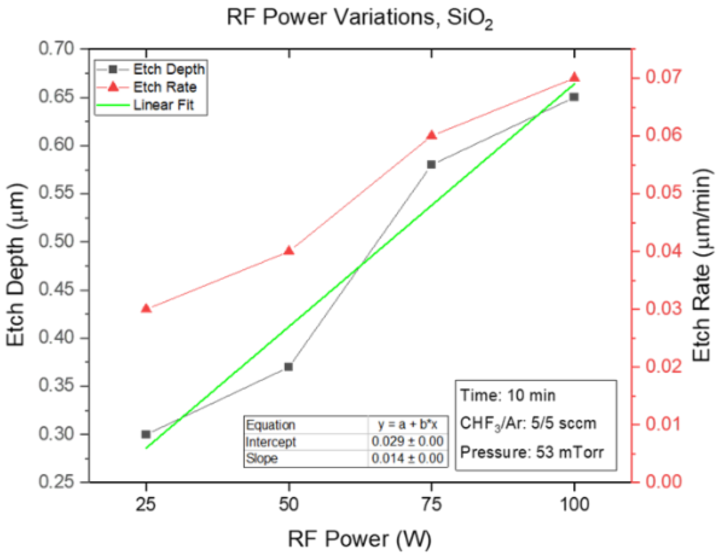

Figure 4: Influence of RF power on SiO_2 etch depth and rate

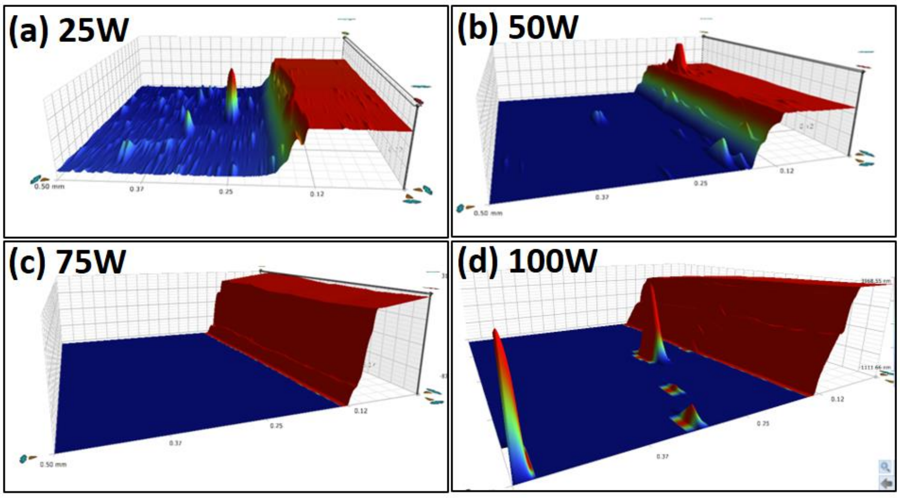

Figure 5: Characterization of surface roughness in Si between different RF power

Next for the characterization of SiO_2, the result shown in Figure 6 shows the different surface roughness of Si affected by varied RF power. Based on the observation at 25W, the lower etch slope and the SiO_2 surface present are not smooth. At 50W, the surface is rougher than the 25W but the etch depth is a bit deep. The smooth surface roughness starts to show between 75W and 100W with deeper etch depth. From the observation, it is hard to characterize the SiO_2 because of the non-uniform oxidation growth on the Si substrate. Regardless of its not uniformity of oxide layer, 100W is still the best to be the constant parameter as it is shown a great slope, deeper etching depth and higher etching rate better than 75W.

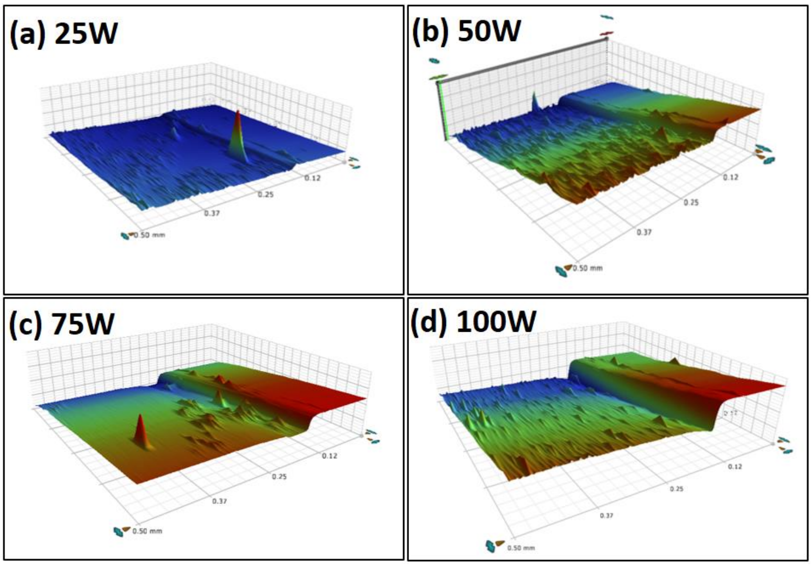

Figure 6: Characterization of surface roughness in SiO_2 between different RF power

3.2 Flow Rate Variations

As RF power of 100W is being the constant parameter, a set of parameters has been selected in the different flow rate configurations as shown in Table 3 and Table 4. The experiment is conducted to study the influence on etching rate when the varied flow rate of etching starting with 5, 10, 15 and 20 sccm with the increase of 5 sccm each and using a 1:1 ratio increasing in flow rate of SF_6, CHF_3 and argon gases respectively. The base pressure in the RIE system is also increasing along with its flow rate with 60, 78, 96 and 112 mTorr for Si and 53, 78, 97 and 112 mTorr proportionally for SiO_2 and with the constant time of 10 minutes etching each experiment run.

Table 3: The parameter of different flow rates in Si etch depth and etch rate

Time (min)	SF_6 (sccm)	Ar (sccm)	Pressure (mTorr)	RF (W)	Depth (µm)	Rate (µm/min)
10	5	5	60	100	7.72	0.77
10	10	10	78	100	13.74	1.37
10	15	15	96	100	21.54	2.15
10	20	20	112	100	27.46	2.75

Table 4: The parameter of different flow rates in SiO_2 etch depth and etch rate

Time (min)	CHF_3 (sccm)	Ar (sccm)	Pressure (mTorr)	RF (W)	Depth (µm)	Rate (µm/min)
10	5	5	53	100	0.65	0.07
10	10	10	78	100	0.84	0.08
10	15	15	97	100	0.92	0.09
10	20	20	112	100	1.05	0.10

The influence of flow rate gives an impact on the etching rate. A high etching rate value of 2.75 is obtained at 20 sccm of gas flow rate with the etching depth of 27.46 µm for Si. Meanwhile, a higher etching rate value than all other parameters is 0.10 is obtained at 20 sccm of gas flow rate with the etching depth of 1.05 µm for SiO_2 samples. Figure 7 and Figure 8 shows the double Y graph of flow rate vs etch depth and etch rate. Both results shown is linear. The etch rate of Si obtained is the highest compared to the other two varied parameters of RF power and etching time.

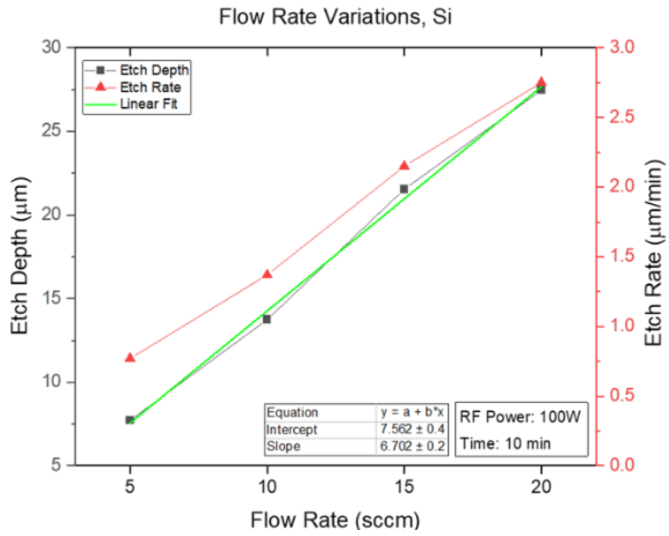

Figure 7: Influence of flow rate on Si etch depth and rate

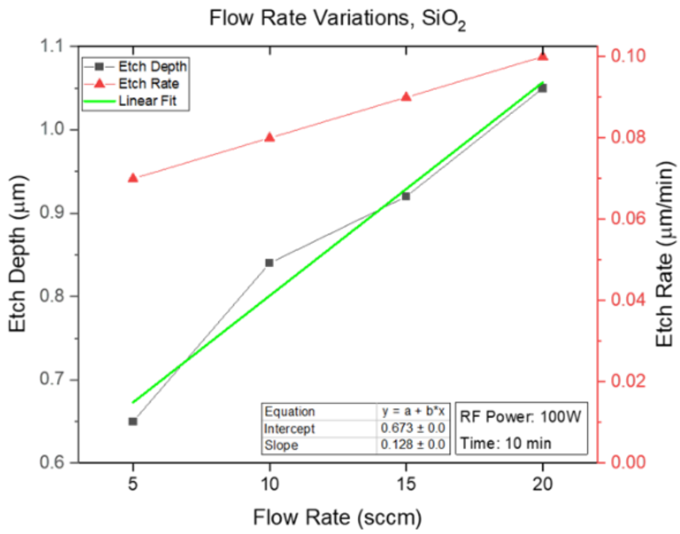

Figure 8: Influence of flow rate on SiO_2 etch depth and rate

3.3 Time Variations

Still, the RF power of 100W is the constant parameter, a set of parameters has been selected in the different time configurations shown in Table 5 and Table 6. The experiment is conducted to study the effect in etching rate when the varied time of etching starting with 5, 10, 15 and 20 minutes with the increasing of 5 minutes each. The flow rate of process gases SF_6, CHF_3 and argon with the gas ratio of 1:1 of 5 sccm constants. The base pressure in the RIE system shown is 60 mTorr for Si and 53 mTorr for SiO_2.

The etch depth is the deepest at 18.77 µm and its etch rate peaked at 0.97 at 20 minutes of etching time for the Si. A high etching rate is obtained at 20 minutes of etching time than 5 minutes with etch rate of 0.89, 10 minutes with etch rate of 0.77 and 15 minutes with the etch rate of 0.91. Meanwhile for the SiO_2, the etch depth is increasing from 0.43, 0.65, 0.93 and 1.32 µm and etch rate peaked at both 10 and 20 minutes of etching time but decreasing for the etch rate from 0.09 to 0.07 and the lowest at 0.06 but increasing again at 0.07. It is different than time varied in etching Si where its higher etched rate is at the longest time to etch meanwhile for the SiO_2, the higher etch rate is obtained at the fastest time to etch which is at 5 minutes mark. The graph plotted is shown in the Figure 9 and Figure 10 showing graph of etching time vs etch depth. The result shown is linear in etch depth for both Si and SiO_2.

Table 5: The parameter of different etching time in Si etch depth and etch rate

Time (min)	SF_6 (sccm)	Ar (sccm)	Pressure (mTorr)	RF (W)	Depth (µm)	Rate (µm/min)
5	5	5	60	100	4.46	0.89
10	5	5	60	100	7.72	0.77
15	5	5	60	100	13.58	0.91
20	5	5	60	100	18.77	0.94

Table 6: The parameter of different etching time in SiO_2 etch depth and etch rate

Time (min)	CHF_3 (sccm)	Ar (sccm)	Pressure (mTorr)	RF (W)	Depth (µm)	Rate (µm/min)
5	5	5	53	100	0.43	0.09
10	5	5	53	100	0.65	0.07
15	5	5	53	100	0.93	0.06
20	5	5	53	100	1.32	0.07

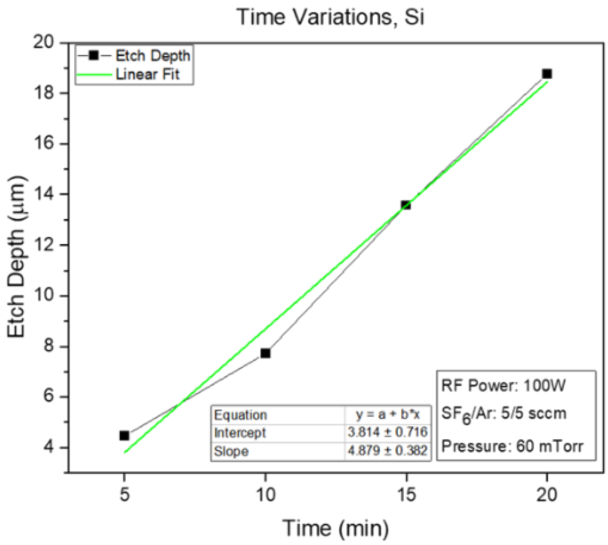

Figure 9: Influence of time on Si etch depth

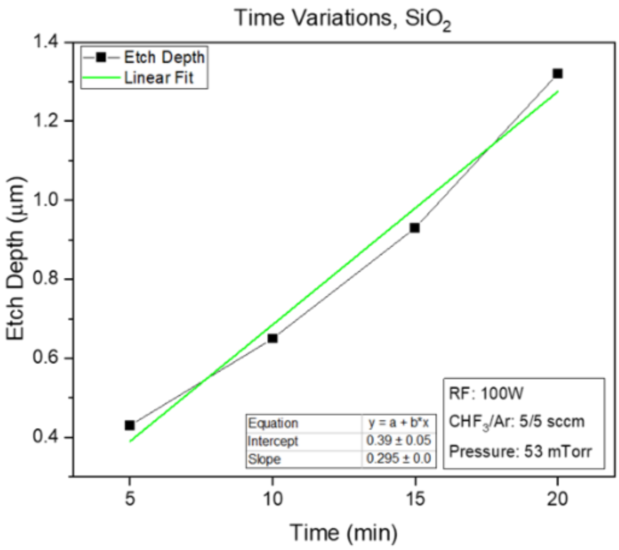

Figure 10: Influence of time on SiO_2 etch depth

4. Conclusion

The etching rate of Si and SiO2 had been studied to optimize the parameters for the dry etching process of RIE. This study objective is achieved. The etch depth and surface roughness of Si and SiO2 are analyzed by using Dektak XT Bruker Surface Profiler to prove the effect of a few sets of parameters on the etch rate. Higher RF power gave smooth surface roughness. Furthermore, the etching rate and etch depth are increasing when the parameters of RF and flow rate are also increasing for both the silicon and silicon dioxide samples. These results matched the theory. Meanwhile, the etch rate of time variations is not linear because different time is applied but the etch depth is still followed by the theory.

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