Effects of Radio Frequency Power and Sulfur Hexafluoride Flowrate on Etch Rate of Silicon Dioxide

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1. INTRODUCTION

Dry etching methods are commonplace in the semiconductor industry, specifically in the most critical step – etching trenches for FINFET structures [1]. Additionally, as feature sizes in general shrink, the control over etching rates is increasingly more important. These lower etch rates require lower pressures and radiofrequency (Rf) power but result in instabilities [10]. Controlling the etch rate based on the input parameters of Rf power, gas flowrate, and pressure are pivotal in reducing feature sizes alongside lithographic and deposition advances.

Dry etching is mainly used for its anisotropic profiles compared to the typical isotropic profiles of wet etching methods. The straight walled slopes of an anisotropic profile are more consistent and will not etch inward to deplete the structure that is being made. To achieve these straight walls, non-reactive gasses are used with a biased target. This allows vertical physical etching of the inert plasma and prevents isotropic etching. These processes are examined for their etch rates, etch profiles, selectivity, and homogeneity of the surface.

SF_6 is mainly used in respiratory physiology [4]. For the semiconductor industry, it is a source of fluoride ions for dry etching. SF_6 etches by generation of fluoride ions that chemically bond to the target and evaporate as a gas [3]. This process does not require bias but will give isotropic profiles since there is no selectivity of the fluoride ion between any of the available reaction sites exposed. Isotropic etching is useful to undercut deposited layers, namely for dopant diffusion surface area and easier lift off when depositing another layer.

Reactive Ion Etching (RIE) is mostly used in semiconductor manufacturing, but it is also used in medical, dental, and filtering industries to create medical devices, braces, and porous films [5]. A RIE system consist of a vacuum chamber, a radio frequency (Rf) generator, and flow controls for an ionizable gas. The system is ran using high vacuum to prevent excess recombination of ions. The Rf frequency is used to excite electrons to form free ions and radicals.

Sulfur Hexafluoride, SF_6, etches Silicon and Silicon Oxide in similar manners. The fluorine atoms are radicalized off its parent molecule from the Rf power where they then attach to the silicon target. Once four fluorine atoms have bonded to one silicon, they have formed silicon tetrafluoride gas which will sublime off the silicon crystal structure. In the case of silicon dioxide, an O_2 molecule is produced as well. The sulfide ions remain in the gas/plasma phase where fluoride ions can be excited off the parent molecules again [2,3]. As more SF_6 ionizes and becomes SF_n^+, neutral SF_6 is introduced to prevent depletion of the plasma.

2. ABSTRACT

As feature sizes in the semiconductor industry continue to shrink, the precision of lithographic, deposition, and etching methods must increase; namely, the etching of trenches for FinFETs. The main parameters to control etch rate in a Reactive Ion Etch system are pressure, forward power, and gas flowrate. This study found that for low forward powers (0-200W), increasing flowrate of SF_6 gave smaller etch rates of silicon dioxide as ions are displaced/recombine from the excess flow of neutral molecules. This effect was more severe at 120W forward power than 50W forward power as the concentration of ions at 120W is higher than that of 50W. When flowrate was maintained (50.7 and 40.59 SCCM SF_6), increasing power linearly returned higher etch rate. This raising of power yielded raises in concentration of ions in the system. These ions (specifically fluoride ions) are what chemically bond to the silicon of the silicon dioxide to form silicon tetrafluoride gas. The continual increase of power did not reach a limit where the concentration of ions was no longer changing, and the system required neutral molecules to continue to etch at higher rates.

3. EXPERIMENTATION

The test system is composed of a Plasma Sciences RIE-200W Reactive Ion Etcher connected to a mass flow controller, mechanical pump, and turbomolecular pump. The mass flow controllers are mks MASS-FLOW controllers ranging from 0 to 200 SCCM N_2 with control range from 2% to 100%. Between 10 to 5000 SCCM, this controller is accurate to +/- 1% of full scale [6]. The display ranges from 0 to 1 as a fraction of 200 SCCM N_2 (.5 setting yields a flowrate of 100 SCCM N_2). This flowmeter uses two thermocouples to measure temperature across a fixed generation region. Since this is calibrated for N_2, the flowrates displayed are not accurate for any other gas. The equations used by these controllers, $T2-T1=C_p*Q$, can be altered to convert the flowrate read out to the actual flowrate of SF_6 as SCCM SF_6 [12]. The C_p of SF_6 is 0.66411 kJ/kg*k [13]. C_p of N_2 is 1.309 kJ/kg*k. Using this ratio of C_ps, the SCCM N_2 reading can be multiplied by the ratio 0.66411/1.309 to give the actual flowrate in SCCM SF_6. For example, 100 SCCM N_2 read out for this system is truly 50.7 SCCM SF_6 and 80 SCCM N_2 is truly 40.587 SCCM SF_6. This is valid because SCCM is ideal gas based on the number of atoms flowing through, and the only conversion necessary is the C_p that is specific to which atom is flowing [15].

The pumps used are a Varian 969-9001S010 turbomolecular pump and an Edwards E2M18 mechanical pump. The turbomolecular pump is rated to 8E-10 torr [8], while the mechanical is rated to 7.4E-4 torr [7]. The pressure gauge of our system is inaccurate below the scale of millitorr, however it does change readout with different flowrates while the turbomolecular pump is running. To be specific, an increase in flowrate of SF_6 or Argon display a higher pressure. It will be assumed that this change in readout can suggest changes in pressure – even though the exact reading is not precise.

The procedures are as follows. Five p-type two-inch silicon wafers were oxidized using the dry growth method in a tube furnace to reach excess silicon dioxide thicknesses. The furnace was operated at 1000^{o}C and oxygen was flowed at 1 L/min. The resultant silicon dioxide coated wafers were quartered. Each quarter was measured for a ten point average of silicon dioxide thickness using a Filmetrics device.

To begin etching, one quarter is loaded into the center of the RIE. The mechanical pump is run until 3 torr, where the turbomolecular pump is then engaged. After it has reached a stable pressure (approximately 20 mTorr), Argon flow is enabled at 80 SCCM N_2 for 1 minute. Then, SF_6 is flowed at the desired flowrate for 1 minute. At this point, the Rf power is turned on and dialed to the set point. Once the set point is approximately reached, the etch is timed for 45 seconds. At this time, the Rf power is shut off and the system is pumped down. The quarter is then measured again with Filmetrics for a ten point average. The next trial of the same quarter uses the previously measured average as the new average. As the silicon dioxide layers decrease, the excess edge etching becomes apparent in the color of the quarter

(isotropic etching will edge from the sides of the quarter as well as the top face). To minimize this issue, trials etched lower than 100 nm were less frequently conducted.

The set points tested were; 80 and 100 SCCM N_2 of SF_6 at the estimated forward powers of 160, 150, 120, 80, 60, 40, and 20 watts, 80 SCCM N_2 of SF_6 at 200 watts, 200 and 70,72,74…-100 SCCM N_2 of SF_6 at 50 watts, and 66, 68, 70-98 SCCM N_2 of SF_6 at 120 watts. The goals were to analyze effect of same flowrate with different powers, and same powers over many flowrates to identify each trend. The 1/50, and .4/200 [SCCM N_2 of SF_6/watt] trials were to see the extremes of each parameter. The plasma was totally unstable at 100 SCCM N_2 for 120 watts, and the same was true for 50 watts from 66-68 SCCM N_2. The set points are listed in SCCM N_2 since that is how the set point is input to the controller and is most precise to remain in these units.

Large variation occurs in trials due to the manual tuning of the Rf power. Due to sensitivity in vibrations of the gas particles, the scaling of the Rf wave amplitudes can go out of phase of its reflected wave; thus, the plasma is lost. When this occurs, the Rf power must be dialed back and brought up more slowly. Every time this occurs and there is even a dim plasma phase, etching is being conducted. There is no way to mitigate this issue apart from measuring its variable effects and individual ability to scale the Rf power in a controlled manner. Additionally, the rate at which it can be scaled is different depending on the flowrate of SF_6 as new particles are introduced at different rates and must be brought into phase. An Rf power generator and controller that can change its frequency can overcome this issue better than a fixed frequency generator [9].

These phase differences and impedance are what is read by the system controller. The forward power is the wattage of the wave being sent into the system. When this forward wave is completely absorbed, the reflected power is non-existent as no power is left to reflect along the path of the forward wave. This equates to a high impedance that would be sufficient of the system to absorb the set forward power. The systems controller reads the impedance of the system through the forward and reflected power. It is generating an Rf wave at a set power. This power is the sum of the forward and reflected power (thus the difference of reflected from forward power is the energy absorbed by the plasma) [11].

Typically, the reflected power is not zero for lower forward powers. When it is non-zero, a standing wave is created through the system. The power not absorbed returns along the reflected power wave resulting in a net standing wave. Our system aims to increase its power generation not only to the set point, but such that its change in set point does not contradict the phase of the reflected wave – causing complete disturbance and plasma loss [9,10,11]. With advance RIE equipment, it can stably increase its power and maintain the forward power by itself. The coupling of the Plasma Sciences 200W RIE's manual forward power with reflected tuning yields an unstable system of high error.

4. RESULTS

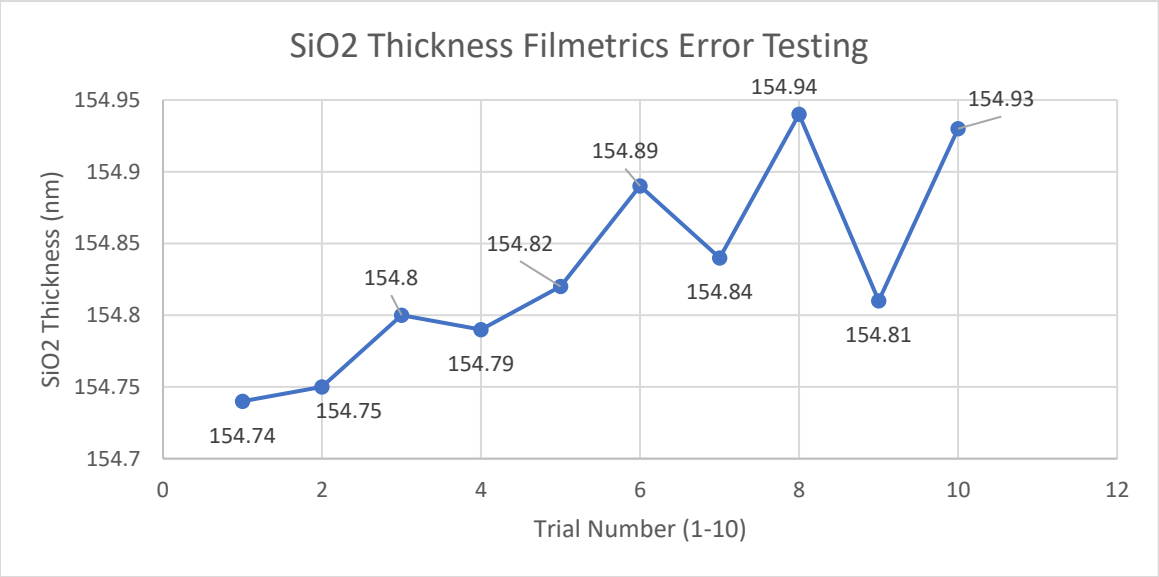

Figure 1: Error analysis of ten repeat measurements of the same point of SiO2 on Si using the Filmetrics device.

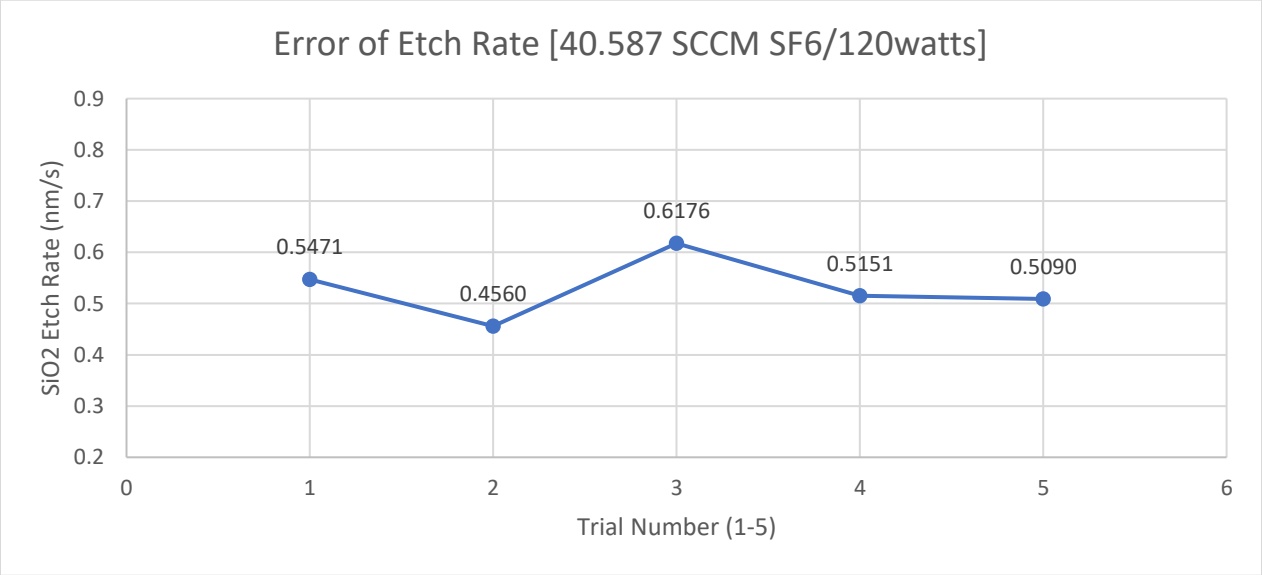

Figure 2: Error analysis of five trials of the 40.587 SCCM SF6 and 120 watts forward power.

Preliminarily, the variability and error in our system must be measured. This was done for the error of the Filmetrics device, and error of repeated etches of the same conditions. The standard error for the Filmetrics resulted in ± 0.0213 nm and .014% error. The standard error for repeated etches yielded ± 0.02655 nm/s and 5.019% error. Due to the high error of the RIE, specific trends and anomalies can only be estimated as general trends.

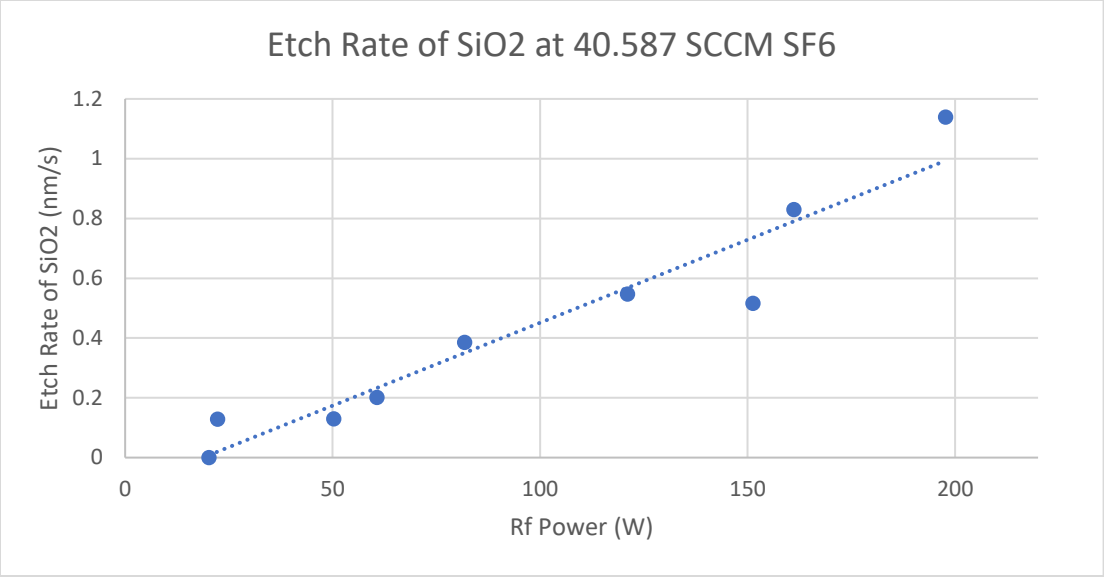

Figure 3: Etch Rate of SiO2 for 40.587 SCCM SF6 with increasing Rf forward power set points.

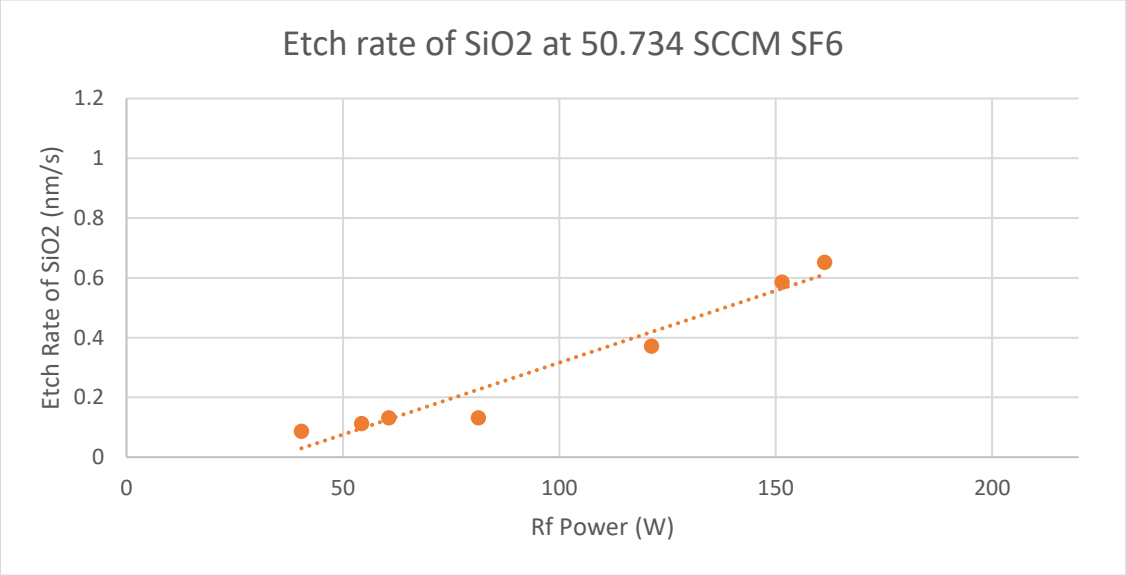

Figure 4: Etch Rate of SiO2 for 50.734 SCCM SF6 with increasing Rf forward power set points.

From figures 3 and 4, constant flowrates with increasing power seemed to yield increasing flowrates. Some values lie below the trendline – this can be attributed to error or to an unstable frequency of the plasma. Since both showed the same trend, it is logical that with increasing power and constant flowrate the etch rate will increase for this range of powers and set flowrate.

With the same regeneration of the plasma, it is reasonable that ever increasing power will always return higher etch rate. This is not true. The larger forward power ionizes the gas more quickly, yet at some limit the gas will be completely ionized, bonds to silicon, and no longer becomes ionizable. The etch rate then becomes dependent on the rate of ion replenishment. Due to limitations in equipment, the scope of this experiment is too small to see this trend. This limitation being a 200W ceiling of power. At no point is our plasma depleting faster than it is replenished. The inverse of this trend, excess gas flow, is visible however and is seen in figures 5 and 6.

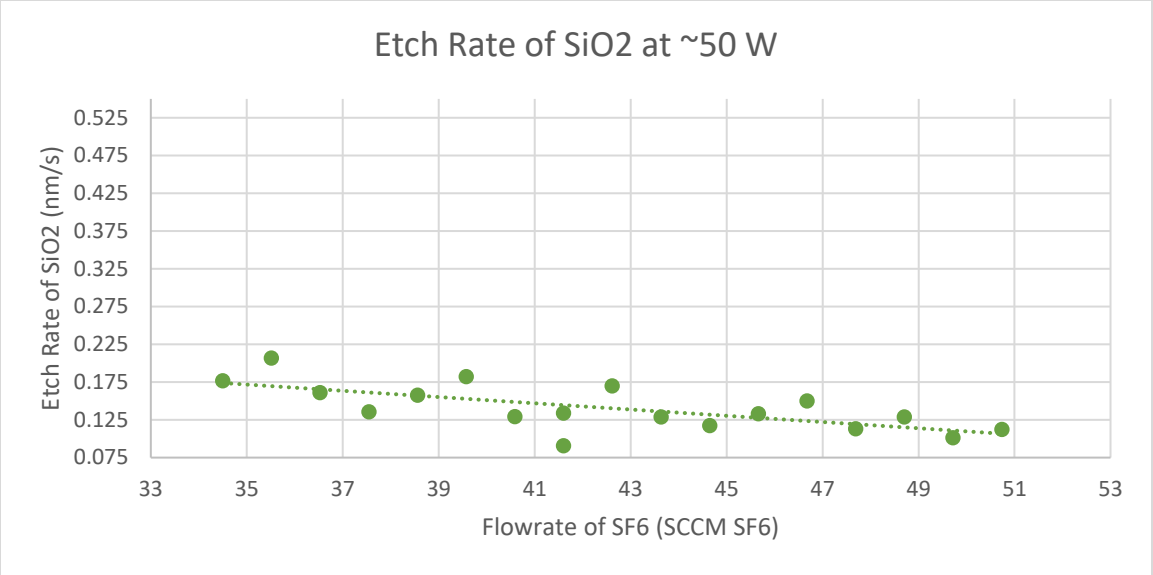

Figure 5: Etch Rate of SiO2 for 50W Rf forward power at increasing flowrate of SF6.

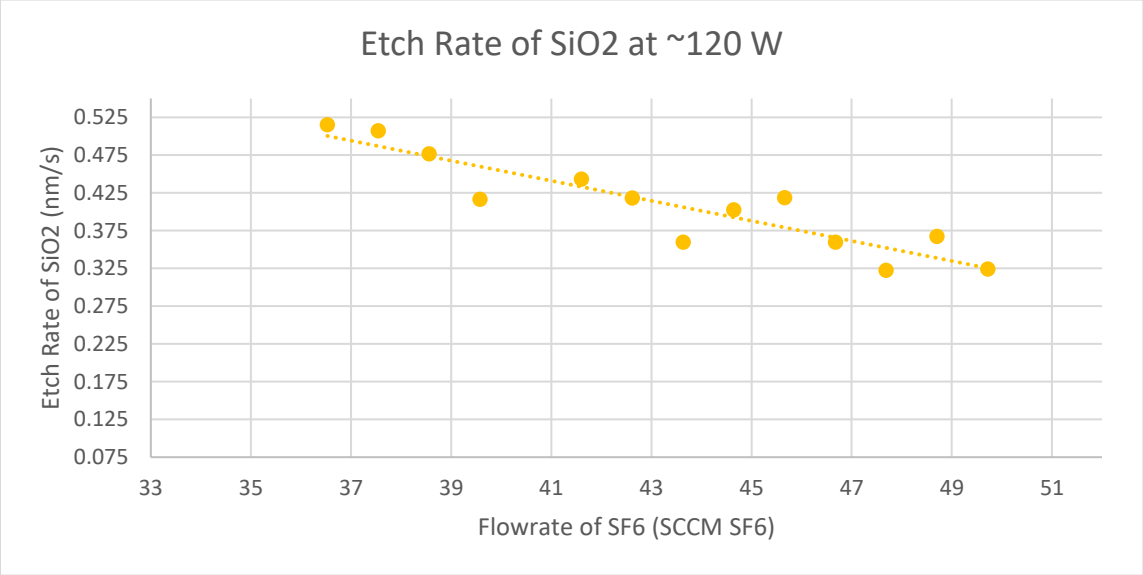

Figure 6: Etch Rate of SiO2 for 120W Rf forward power at increasing flowrate of SF6.

Figures 5 and 6 show the plots of constant power and variable flowrate. Increasing flowrate trended with a decrease in etch rate. This contradicts the idea of replenishing the systems ions. However, the meaning behind this trend is that as ions are forming, the excess gas flow absorbs the free electrons that are being broken off to form ions. This overall reduces the number of ions available to bond to silicon on the target. The recombination region, where new molecules absorb and replace ions rather than replenish, is used to describe this phenomenon.

Furthermore, the trend is more severe at higher powers. At 50W, the trend is ever slightly decreasing. Although the trend is incredibly weak, the trend is proven at 120W and can be extrapolated to justify the trend at 50W. The trendline of 120W shows a steep decrease in etch rate for small changes in flowrate. For 50W, the trendline shows gradual decrease in etch rate for the same changes. In the 120W system, there is a larger concentration of ions as compared to the 50W system. Each increase in flowrate

absorbs more ions for the 120W than for the 50W. It can then be concluded that for higher powers, the same change in flowrate will yield a larger change in etch rate when the system is in the recombination region.

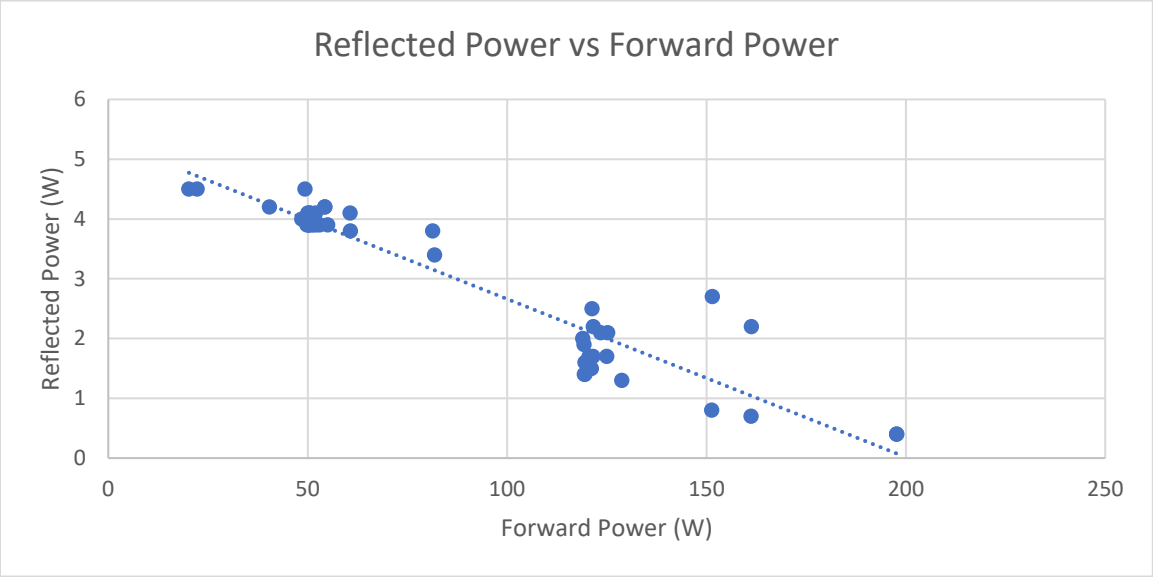

Figure 7: Reflected power decreases as forward power increases.

Figure 7 shows all forward powers and their corresponding reflected powers for all flowrates. Increasing forward power gave lower reflected power. Floettmann et. al describe this trend theoretically to find methods of decreasing reflected power [16]. In summary, controllers iterate each step increase of the total signal amplitude to reach the set point forward power while minimizing the reflected power amplitude. Through all their experimentation, the reflected wave was decreased towards zero as forward power increased to a high set point.

The etch rate for the 200 SCCM N_2 of SF_6/50W trial was 0.0846 nm/s and the 80 SCCM N_2 of SF_6/120W returned 1.138 nm/s. Continuing off of the trends discussed earlier, the maximum power setting of the 200 SCCM N_2 of SF_6 and 80 SCCM N_2 of SF_6 showed that the continually increasing power still gave higher etch rates while continuation of increasing flow continued to decrease etch rate. This proves that the operating parameters for this device are within the recombination/dilution region and increasing ion concentration region.

5. CONCLUSIONS

Findings indicate that between 0 and 200W forward power, and 68 to 100 SCCM N_2 of SF_6 (34.5-50.734 SCCM SF_6), increasing power at constant flowrate will give faster etch rates. This effect is due to an increase in concentration of ions in the system. A linear increase was observed for the measured regime; though this should level off at excess power where the concentration of ions is no longer changing.

When power is held constant and flowrate is increased, the etch rate of SiO_2 decreases. The concentration of ions in the system that chemically bond to the Si to create silicon tetrafluoride and O_2 will decrease. When the power is maintained, the increase in flow displaces ions and recombines charges thus reducing the overall concentration of ions available to etch. When the forward power is higher, this effect is emphasized as the initial concentration of ions is higher at higher powers. Thus, more ions will be displaced/recombined for the same increase of flow rate.

6. REFERENCES

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