Recent Improvements in Deep Silicon Etching

J. F. Donohue, J. W. Lee, and J. Sasserath

Plasma Therm Inc.
St. Petersburg, Fl 33716 USA

Abstract:

Much of today's deep silicon etching is accomplished by means of the Bosch Process. This is a cyclic process employing alternating etch and deposition chemistries. To achieve high overall etch rate, the ratio of dep to etch time has to be minimized while the individual dep and etch rates maximized without degrading the properties of the etch, i.e. profile, selectivity, and lag. The focus of this paper is on etch cycle improvement through a pressure, gas flow, and power trend analysis. All work was accomplished with an Inductively Coupled Plasma (ICP) source utilizing sulfahexafluoride (SF_6) as the etchant gas. The dissociation of SF_6 into free fluorine radicals is shown to be one of the keys in delivering high rates.

Data:

1.0 - Introduction

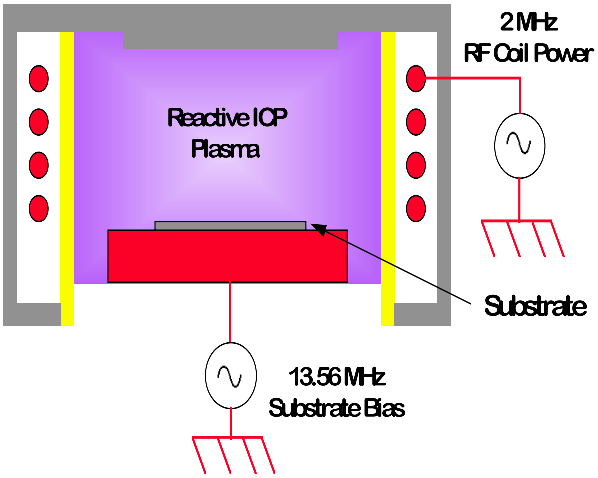

Figure 1 Schematic of ICP reactor

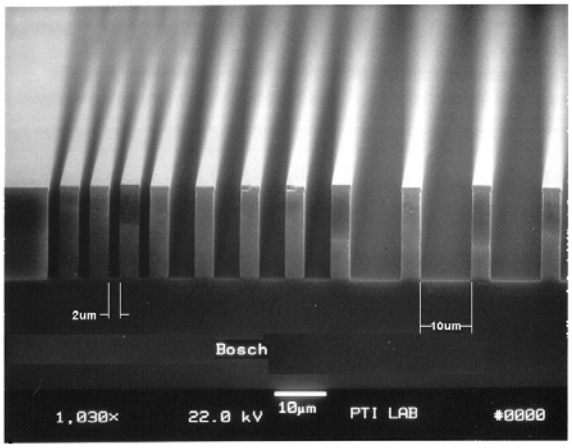

Figure 2 SEM micrograph of Bosch etched trenches from 2 to 10um in width.

The Micro-Electro-Mechanical Systems (MEMS) arena is a rapidly expanding field. Many applications exist [(1-3)], the majority requiring deep silicon trench etching.[(4-8)] The Bosch process is one etch that has been successfully used for deep trench etching. In particular, with an Inductively Coupled Plasma (ICP) reactor. The reactor geometry is shown in Figure 1. Silicon trenches can range from several hundred microns in width to a few microns with aspect ratios as high as 30:1. Figure 2 shows a series of trenches from 10um down to 2um etched with the Bosch process. The process is centered around an alternating chemistry utilizing both etch and deposition steps. The etch phase is basically an isotropic process that yields high rates in silicon utilizing fluorine based chemistries. Owing to the fact that it is isotropic in nature, the sidewalls of a trench need to be protected to maintain anisotropy of the overall trench etch. This protection is the purpose of the deposition portion of the Bosch process. A good balance between the time spent in the etch and dep phases is prudent to achieve high rates and good profiles of trenches. Figure 3 shows a close-up of an etched trench. Note the scallops formed by the isotropic etch portion. If the etch time is too long, these scallops will widen and degradation from a vertical profile will result. For faster rates, it is obviously beneficial to spend as much time etching and as little time depositing. However, there is a limit before the profile degrades. Too much deposition will lead towards a trench narrowing as the etch proceeds, and too little, a widening.

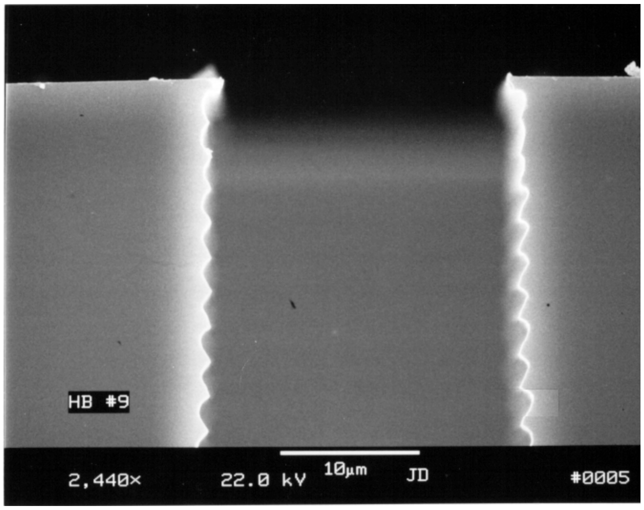

Figure 3 SEM photo depicting the scalloping formed during the isotropic etch portion of the Bosch process.

This paper will not delve into the ratio of times for deposition and etch, but rather concentrate on increasing the actual rate of the etch step to make up for time lost during deposition.

2.0 - Theoretical

Much of the Bosch process is done under little or no RF bias so as to make the process purely isotropic in nature. One of the advantages of this is dramatic improvements in selectivity to photoresist during the etch. Selectivities as high as 150:1 have been reported. With little or no RF electrode power, the induced DC bias is fairly small so as to minimize ion bombardment of the resist during the etch.

On account of this, the role of ions during the etch phase is minimal. Consequently, the importance of neutrals, specifically free fluorine radicals, and their arrival to the wafer surface is of extreme importance for etching. We don't want to completely ignore the role of ions, because they are important in removing any remaining deposition on horizontal surfaces prior to etching, but for overall etch performance, the neutrals are the key. Knowing this, we now proceed to estimate very simply, through a mass balance relation, the important terms in raising the etch rate. Mass balance simply accounts for the number of gas molecules entering and leaving a reaction chamber. Specifically, consider an SF_6 molecule entering our ICP chamber and keep track of how many free fluorines are dissociated from this molecule. In reality, there are many combinations of radicals, each with their own generation rate and reaction rate at the wafer surface, but for our analysis we will concentrate on single fluorine atom dissociation from SF_6.

To determine the overall efficiency of an etch, both with regards to process and hardware, we now define a new efficiency term as follows. For 100% single fluorine dissociation, each SF_6 molecule entering the chamber would yield six fluorine atoms. If all six of these fluorine atoms arrived at the silicon wafer surface, i.e. none were lost in recombination before reaching the wafer, and all six reacted once there, this would represent 100% efficiency in terms of the combined dissociation and reaction rates. A comparison of this figure to actual measured values would then provide a baseline for tool efficiency in terms of both process and hardware.

The removal of Si from the wafer surface will most likely be of the form SiF_4. Consequently, only four fluorine atoms are required to etch the silicon. In other words, for 100% efficiency in dissociation and reaction, 3 molecules of silicon will be removed for every 2 molecules of SF_6 entering the chamber.

From the SF_6 gas flow rate into the reaction chamber, we can determine the number of fluorine atoms entering per minute. From silicon etch rate measurements, we can determine the number of Si atoms leaving per minute. For simplicity, there will be 4 fluorine atoms leaving for every Si atom. A ratio of these two rates, number of fluorine atoms used to the number of fluorine atoms entering times 3/2 will give us a simple efficiency ratio. To clarify further, 2 moles of SF_6 entering the chamber will lead to a 100% overall efficiency if 3 moles of Si are removed. This is the reason for the 3/2 factor.

3.0 - Experimental

All experiments were performed on a Plasma Therm 770 SLR tool. The tool is equipped with a loadlock for easy wafer handling in and out of the reaction chamber. For the experiments mentioned here, all wafers were 4-inch blanket silicon. This tool also packages an Inductively Coupled High Density Plasma Source operated at 2MHz. Independent ion energy control is possible through an RF bias applied to the substrate electrode at 13.56 MHz. For our experiments, the lower electrode was not biased. Only the ICP was operated to utilize the tool in a pure downstream or isotropic mode. The intent was to look at etch rate as a function of neutral flux as outlined in the Introduction of this paper. The 4-inch wafer had a small dot of photoresist in the center as a mask, so that a step height measurement could be made after etches. All etches were performed for 10 minutes. The SF6 flow ranged from as low as 50 sccm to as high as 500. Power ranged from 1200 W to 3000. Pressure ranged from 15 to 50mT.

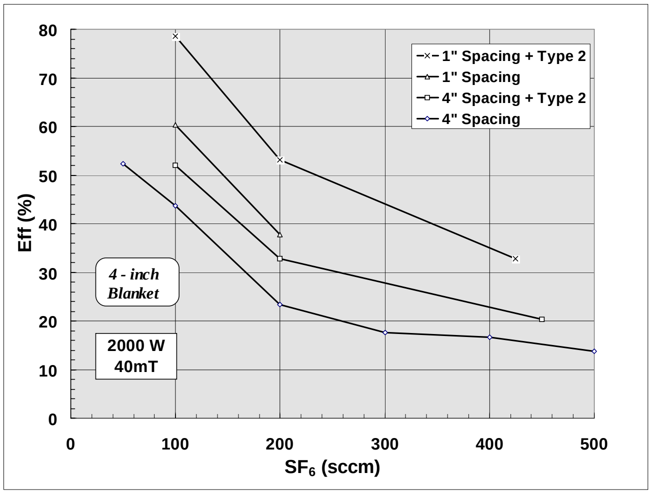

Figure 4 Tool Efficiency as a function of SF6 flow for 2000W ICP power and 40mT chamber pressure.

For a fixed chamber pressure of 40mT and ICP power of 2000W, figure 4 depicts the newly defined efficiency ratio in percentage as a function of SF_6 flow. Clearly, the higher the SF_6 flow, the less the efficiency. One explanation is in terms of the effectiveness of 2000W in dissociating the SF_6 molecule. As more gas is introduced into the chamber, dissociation becomes power limited, i.e. more power needed for higher flows. This is not to say that the actual etch rate drops, but rather our utilization of the available flow falls off. Note the set of curves shown. The curves are representative of two reactor geometry changes. One being the wafer to source spacing and the other a proprietary geometry change to the reactor noted as Type 2. Two spacings were run, 1-inch and 4-inches. The closer the wafer to the source, the better the efficiency. Also, irrespective of wafer to source distance, the type 2 configuration showed better efficiencies.

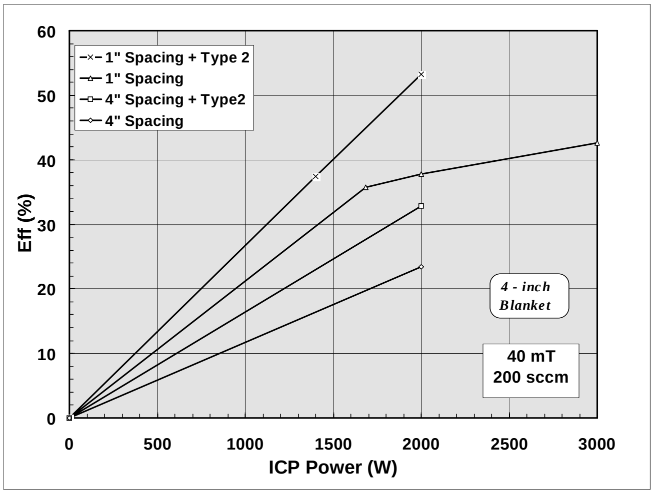

Figure 5 Tool Efficiency as a function of ICP power.

For a fixed pressure of 40mT and 200 sccm SF_6 flow, figure 5 depicts the efficiency ratio as a function of ICP power. Clearly, higher powers improve the overall efficiency. For the same gas flow, more power will dissociate more fluorine. There will be a leveling at the point where there is no more left to dissociate. This level has not been reached in the graphs, but there does appear to be some slight leveling. Also, the efficiencies are higher on any power curve if the source to wafer spacing is smaller and if we operate with a Type 2 configuration.

Figure 6 was run with a fixed power of 2000W and a fixed flow of 200sccm. The pressure was varied from 15 to 50mT. The 4-inch spacing showed a

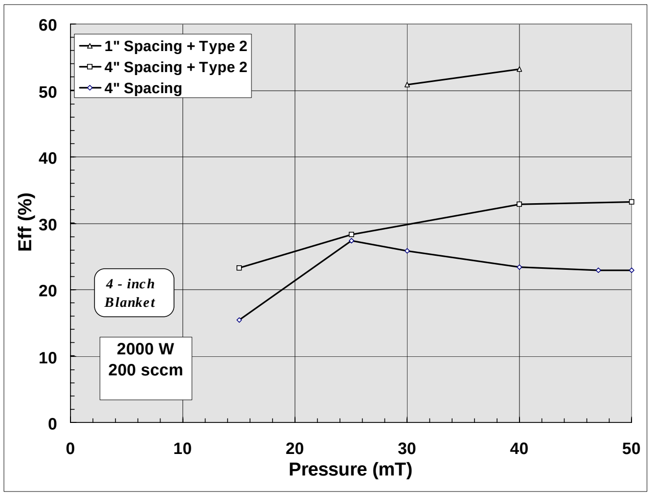

Figure 6 Tool Efficiency as a function of chamber pressure for 200 sccm of SF6 and 2000W ICP power.

peak in efficiency at 25mT and then leveled off with further increases in pressure. As before, the smaller spacing at 1-inch with the Type 2 configuration gave the best efficiency, but no peak was seen. However, there is a leveling.

Conclusions:

We have demonstrated the effects of power, pressure, and flow and their associated role in the isotropic etching of silicon. To make enhancements in the rate of silicon removal is an important goal in improving the Bosch process for deep trench etching, especially when throughput becomes a driving factor. One of the methods that can be utilized to check the effectiveness of a tool is its efficiency in removing silicon for a given gas input. Since the silicon etch rate removal depends upon both process and hardware, our newly defined efficiency ratio has proven useful in deciding the operation of a tool or set of tools for comparison purposes. We have quantified this efficiency in for SF_6 and its relation to silicon etch rate. Utilizing the new efficiency term has enabled us to enhance our system's etch rate and implement a new hardware design to achieve our goal. This newly defined efficiency is general enough to be applied to other chemistries and applications.

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Acknowledgments:

We would like to acknowledge the efforts of many people at Plasma-Therm Inc. for making this project a success, especially Lee Heckerd and Ralph McAffee for their continual support.