Statistical Study on Effect of Reactive Ion Etch Towards the Surface Morphology of Aluminum Pad

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Abstract. Reactive Ion Etching (RIE) is a major process in the fabrication of semiconductor devices for transferring patterns from masks to semiconductor substrates. Design Of Experiment(DOE) has been used to study the effect of Reactive Ion Etch(RIE) towards surface morphology of aluminum bond pad. Important RIE factors involved in this experimental study are ratio of Tetrafluoromethane (CF_4) and Argon gas flow, BIAS, and ICP power. Different combinations of these factors produces different results of surface morphologies which was obtained using Atomic Force Microscopic(AFM). Produced results shows that RMS is an important factor in surface characterization study and DOE offers a better way to optimize the desired outcome.

Introduction

Reactive Ion Etching(RIE), is a type of dry etching process which is assisted by plasma. Plasma is an ionized gas with equal number of positive and negative charges. It involves three types of collision which is ionization(generates and sustains the plasma), excitation(causes plasma glow) and disassociation(creates free radicals)[1]. These collisions will generate chemically reactive species and react with the materials being etched to form volatile by-products. This pre-treatment method uses only efficient resources and apparently improves the manufacturability, reliability and yield for advanced semiconductor packages. The removal of the acquired amount of material from substrates will contribute to the improvement of the surface uniformity and indirectly towards device reliability[2].

The ability to predict the influence of the process parameters of RIE is crucial in terms of machine performance as they may have a serious impact on product quality as well as on the probability of machine failure[3]. Plasma treatment is used for a wide range of process steps and surface preparation to enhance the adhesion, preplate resist wettability, descumming (removal of resist or polymer residues in vias or openings), resist strip, metal etch, rework and the likes. The advantage of dry etching compared to wet etching is the clean nature of the process. There is no residual ions are left on the surface. Furthermore, the process control is excellent because the etching process is started and stopped by switching power. In general, the material consumption is low compared to wet etching process. The total etching process is controlled by the absorption of the etchant on the surface, the reaction rate at the surface and desorption of the products [4].

However, plasma etching is extremely sensitive to many variables, making etch result inconsistent and irreproducible. Therefore, important plasma parameters and their influences are studied vastly and methods to produce desired results consistently are researched [5]. This is the base of this study where controlling the RIE process with a balance set of parameters is important to produce a desired surface morphology of aluminum bond pad. RIE enables the achievement of profile control due to the synergetic combination of physical sputtering with chemical activity of reactive species with high etch rate and high selectivity. It is known that RIE or dry etching process using energetic ion bombardment will affect the silicon surface in several ways[6]. Therefore, to fulfill the requirement of this study Design Of Experiment(DOE), a method which provides a various forms of statistical study is chosen.

As significance, designing an appropriate plan for various fields has been justified by the successful results produced following the completion of the project. Relating to this matter, the concept of experiment design is to use an organized layout to find explanations for the mysteries involving mainly in the manufacturing field. In recent years, "Design of Experiment (DOE)" has been a well-liked 'tool' to investigate systems or processes which maximizes information gain with minimum resource usage. It is a systematic and powerful technique to discover which set of process variables are important, how they interact and which are the best settings suitable for these variable in order to optimize the whole process performance [7]. There are many industries all over the world which have reported success after using DOE to improve product and process reliability, improving process performance, reducing process variability etc. over the last 15 years [8-11].

An experimental plan is developed to gather information/data to find answer for issues regarding ways to improve the quality of certain combination or to find which factor should be controlled to have a robust process. DOE can be applied to almost any problem in any field of investigation. The gained result can be an improvement or an optimization depending on the investigated issue.

Many previous research studies had been done using the method used in this study. As an example in the study of optimization on base-catalyzed sunflower oil ethanolysis[12], in the investigation study of cutting parameters effects on surface roughness in lathe boring operation[13], in the analysis for dye-sensitized hydrogen generation from water[14] and in the study of finite element analysis for grinding of wire-sawn silicon wafers[15]. These previous study shows that this experimental design method can be used in various fields proving the capability of this method. Engineers can benefit from the application of DOE if the problem's discipline involves engineering, development or trouble-shooting. This is the reason why usage of experimental designs and statistic increases the effectiveness of the research experiment. Generally, these are the motive behind the use of DOE in this study which provides a better investigation throughout the study.

Methodology

Initially, a suitable type of DOE is chosen for the experiment. The number of factors and factor's levels used in this experiment will determine the type. In this study there are 4 factors and 2 levels. Therefore, the 2^4 Full Factorial type of DOE is used. Basically, factor is a process variable which can be varied during the experimentation whereas level is the operational setting of a factor. The 4 factors involved in this experiment are quantity of Tetrafluoromethane(CF4), Argon, ICP power and BIAS power. The values that had been used for DOE in RIE are as in the Table 1.

TABLE 1
Maximum and minimum(2 level) value for parameters

Factors(unit)	Level -1(Min)	Level 1(Max)
CF4 (sccm)	20	50
Argon (sccm)	30	80
ICP (watt)	500	1000
Bias (watt)	100	300

Next, the samples are prepared starting by dicing the wafer to the number of sample required. The wafer is diced into samples sizing averagely 3.0 mm X 1.0 mm. In this DOE, 16 samples are needed. The samples are then cleaned with Piranha solution for 1 minute. Piranha solution which is made from mixture of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) is used to clean organic residues off substrates. After cleaned, the deposition of aluminum layer takes place where 3 layers of aluminum are deposited using Physical Vapour Deposition (PVD). PVD is chosen to deposit the aluminum layer because it has higher quality, purer deposited film, higher conductivity and easy to deposit alloys. After the deposition procedure, Atomic Force Microscopic (AFM) is used to capture 3D images of the surface. Surface roughness value for each sample is recorded.

The quantitative measurements derived from AFM images are only as good as the quality of the measurements. For example, if the images have errors due to poor scanner quality or dull probes, the analysis will reflect these problems. In the non-contact mode (of distances greater than 10Å between the tip and the sample surface), Van der Waals, electrostatic, magnetic or capillary forces produce images of topography, whereas in the contact mode, ionic repulsion forces take the leading role. After the samples had gone through AFM, Acetone solution is used to clean the samples from any dust or contaminations that are formed during the prior procedures. Next, all the samples will be etched using RIE. RIE is used to remove the material that we wish to remove from the sample surface, which is aluminum in this experiment. Next all the samples which had been treated with RIE are characterized using AFM. The images are captured and surface roughness values are recorded. Finally the recorded results are compared and analyzed. The methodology overview showed in Fig.1 shows the overall process steps of the experimental study.

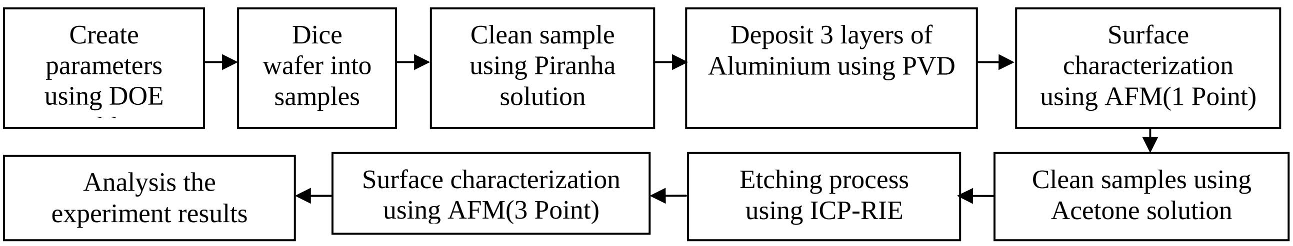

Fig. 1.Methodology overview

Experimental Design

As mentioned, DOE had been utilized in this experimental study because it provides a systematic design with maximum information gain and minimum usage of resource. Below is shown the possible combinations of the parameters that can be produced in this experiment using the 2^4 Full Factorial design. First table shows the combination using the 2 levels used in this experiment and the second table shows the real parameter values that are combined throughout this design. These tables provide a better view on the whole experimental design used.

TABLE 2
Design of Experiment- 24 Full Factorial

Experiment	Parameters			
	CF4 (sccm)	Argon (sccm)	ICP (watt)	Bias (watt)
1	1	1	1	1
2	1	1	1	-1
3	1	1	-1	-1
4	1	-1	-1	-1
5	-1	-1	-1	-1
6	1	1	-1	1
7	1	-1	-1	1
8	-1	-1	-1	1
9	1	-1	1	1
10	-1	-1	1	1
11	-1	1	1	1
12	-1	-1	1	-1
13	-1	1	1	-1
14	1	-1	1	-1
15	-1	1	-1	1
16	1	1	-1	1

TABLE 3
16 combination of RIE parameters

Experiment	Parameters			
	CF4 (sccm)	Argon (sccm)	ICP (watt)	Bias (watt)
1	50	80	1000	300
2	50	80	1000	100
3	50	80	500	100
4	50	30	500	100
5	20	30	500	100
6	50	80	500	100
7	50	30	500	300
8	20	30	500	300
9	50	30	1000	300
10	20	30	1000	300
11	20	80	1000	300
12	20	30	1000	100

13	20	80	1000	100
14	50	30	1000	100
15	20	80	500	300
16	50	80	500	300

Results and Discussions

The AFM results obtained before and after RIE treatment are in 3 different terminologies of surface roughness which are Surface Roughness (RA), Peak Vs Valley (P-V) and Surface Root-Mean-Square Roughness (RMS). Definitions on the terminologies are given in Table 2 below. Each type of surface roughness result has its own advantages and disadvantages towards the product of the process. AFM is used to characterize the surface roughness because it has a better spatial resolution therefore produces results that are more accurate compared to other roughness measuring machines.

Table 4
Definitions on the terminologies

Parameter	Definition
Surface Roughness (RA)	Arithmetic mean of the surface roughness profile from the center line within the measuring length
Peak Vs Valley (P-V)	Vertical distance between the highest and lowest points within the overall measuring length
Surface Root-Mean-Square Roughness (RMS)	Root mean square value of the surface roughness profile from the center line within the measuring length

The results produced from the DOE are presented in the graph plotted below. The surface roughness results are obtained from AFM. As in the graph, the highest value for the RA before RIE treatment is given by sample 1 with 159 nm and the second is sample 6 with the value of 139 nm. The lowest value is given by sample 7 with 0.5 nm. Whereas, after the samples are treated with RIE shows a more balance value of RA throughout all the 16 samples. The highest value for RA is 65 nm by sample 9 and the lowest is 8.3 nm by sample 4. So, after RIE the surface is smoother because the RA values will determine the mean roughness of the surface. In this case, wrinkles are produced on the surface of the samples.

The values of P-V, which means the vertical distance between the highest and lowest point does gives a picture of the surface produced. If the value of P-V is high, it shows that there spikes on the surface. Higher the vertical distance, higher the spike on the surface. Before the samples are treated with RIE, the highest values of P-V are given by sample 1 and 6 with 914 and 837 nm. But after RIE the values of P-V has been reduced. The highest value obtained is from sample 16 with 718nm. This shows RIE treatment does affect the surface of aluminum surface. By reducing the value of P-V, amount of spikes produced will be reduced.

Next is the focused part of this study, the RMS value for samples before and after RIE treatment. RMS is the standard deviation of the height distribution of the sample. Before RIE treatment the RMS value is between fluctuates from 2.1nm which is the lowest and 193nm which the highest value produced. After the RIE treatment value of RMS values for all the samples shows improved consistency. It is between 8.3nm and 65nm. The overall RMS value obtained shows consistency after the pad is treated with RIE.

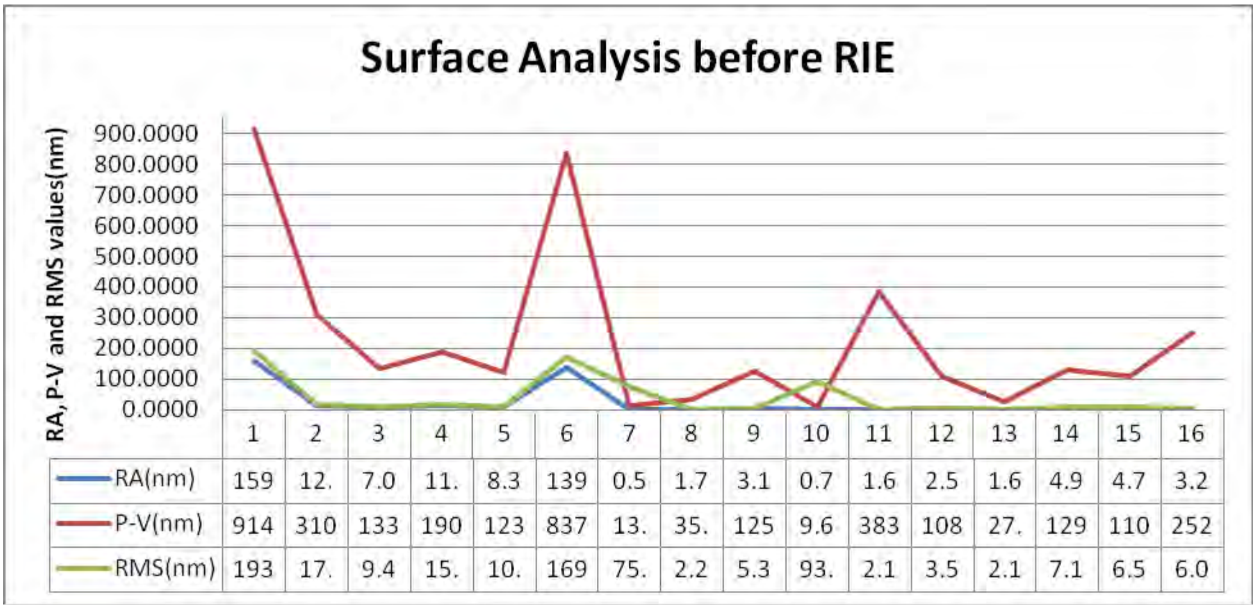

Fig 2.Surface Analysis for 16 Experiments before RIE Process

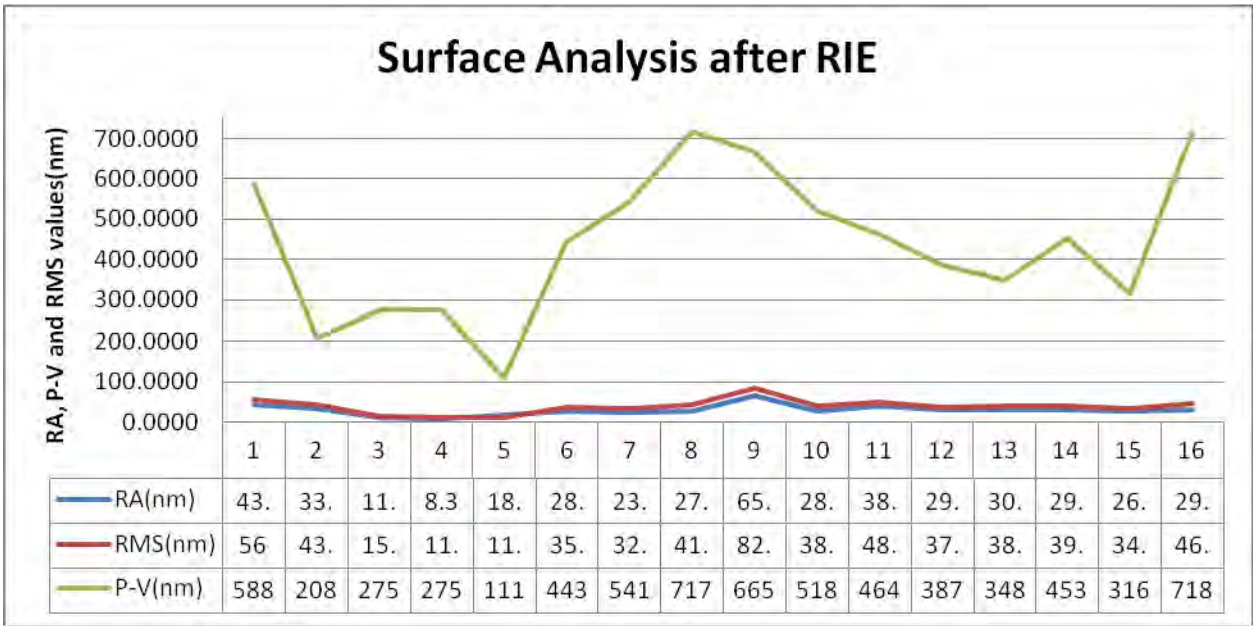

Fig 3.Surface Analysis for 16 Experiments after RIE Process

There are advantages and disadvantages of the surface morphologies produced depending on the material and the application of the product. As example, in the fabrication process of OLED the electrical instability has a close relationship with P-V rather than RA and RMS values of ITO electrodes[16]. In this case, high P-V which indicates spikes on the surface is involved in the electrical instability of the product whereas the other surface roughness values are not considered.

In another experimental study, it is found that approximately linear relationship is deduced between the values of RA, RMS and P-V and the flux. This results proposed that flux can be manipulated by controlling the unevenness of the skin layer surface structures[17]. This correlation shows that the increase in all 3 values also does gives a desired results depending on the application of the product.

But, in this experimental study, the material etched is the aluminum. Materials etched are usually one of the comprising layer of a device. Etching of aluminum should be productive for the next procedures in semiconductor industry. The purpose of etching is to optically enhance microstructural features such as grain size and phase features. Etching selectively alters these microstructural features based on composition, stress, or crystal structure. To provide the features required, gained data should be an overall view of the surface morphology.

This is provided by the RMS value which is closely related to standard deviation where it describes the spread of the height distribution of the sample. Various studies have been done using RMS value as the important factor to determine the roughness profile. Some of the studies done using RMS value as an important contributing factor are in the study of nanolaminates fabrication[18], wet etching characterization[19], study of porous glass surface[20], and in the study of surface roughness reduction of silicon chip[21]. Advantage of standard deviation is its simplicity besides providing statistical significance[22]. Graph plotted below compares the RMS results obtained from AFM for samples before RIE treatment and after. The comparison shows visible contrast in terms of the RMS values throughout the samples.

Before RIE treatment, results of the samples show a vast variation of RMS values. High RMS values show that the value deviates far from the mean while low values shows that the roughness value is close with the mean. Comparison also shows that after RIE treatment the RMS values has decreased and more consistent throughout all the samples. This justifies that RMS results are valuable in the study of surface characterization

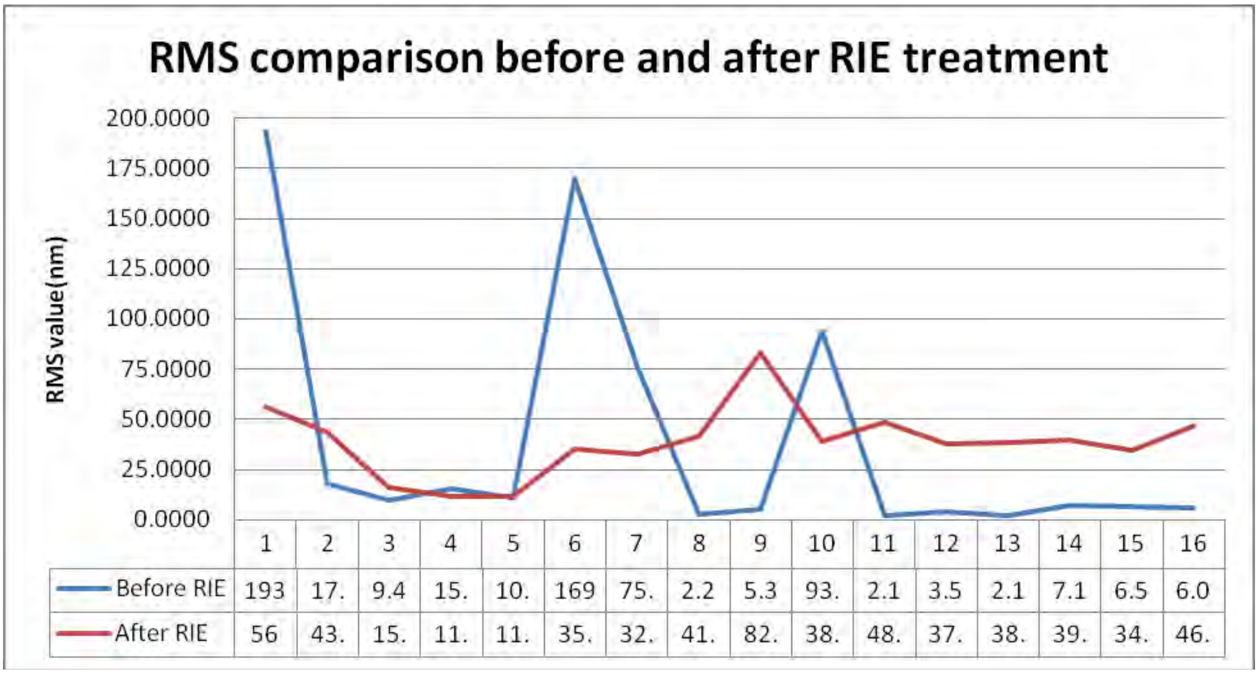

Fig 4.RMS values for Aluminum pad before and after RIE treatment

Advantages of RMS contributing to this study are, it makes use of all data to calculate the spread of data from average which makes it a more accurate measure. Secondly, standard deviation measures the spread of data from the mean. Standard deviation gives weightage to the positive and negative deviation of the data from the mean too. Hence, standard deviation(RMS) is a more precise measure of spread of data as compared to the rudimentary range measure of the spread of data. Therefore, the value of RMS is important to get the desired results of RIE etching in this experimental study.

Conclusion

The study on the effect of RIE towards the surface morphology of aluminum bond pad is done using Design of Experiment. This study involves different combination of RIE parameters and the effect on the aluminum pad surface. The parameters are varied with 2 different levels which are high level(+1) and low level(-1). The variation of the parameter levels and combination which produce 16 sets of experiment with each set gives different combination of parameters. The 16 sets of experiments produced 16 results which consist of surface roughness values provided by AFM. The results produced shows that aluminum pad surface is affected by RIE. Different combination of parameters produces different values of surface roughness. This is shown by the graphs plotted for the samples before RIE treatment and after RIE treatment. Atomic Force Microscopy(AFM) is used instead of many other roughness machines available because AFM has a better spatial resolution therefore it is more accurate.

RIE does affect the surface in terms of the surface generally produced. Finally, the most important results from this experimental study are the RMS value which provides us with the general structure of the surface profile. It shows the deviation of the height from the mean value which provides the overall roughness of the samples. The value of RMS which is closely related to standard deviation shows that the RIE etching serves the purpose of etching the aluminum pad and also gives a better profile of surface for semiconductor device fabrication.

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