Statistical Characterization Fabricated Charge-up Damage Sensor

(Invited Paper)

Seiji Samukawa[a]
Institute of Fluid Science, Tohoku University,
2-1-1 katahira, Aoba-ku, Sendai-shi, 980-8577, Japan

Sang Jeen Hong
Department of Electronic Engineering, & Nano Bio Research Center, Myongji University,
Nam-dong, Yongin-si, Gyeonggi-do 449-728, Korea

[a] E-mail : samukawa@ifs.tohoku.ac.jp

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SiO_2 via-hole etching with a high aspect ratio is a key process in fabricating ULSI devices; however, accumulated charge during plasma etching can cause etching stop, micro-loading effects, and charge build-up damage. To alleviate this concern, charge-up damage sensor was fabricated for the ultimate goal of real-time monitoring of accumulated charge. As an effort to reach the ultimate goal, fabricated sensor was used for electrical potential measurements of via holes between two poly-*Si* electrodes and roughly characterized under various plasma conditions using statistical design of experiment (DOE). The successful identification of potential difference under various plasma conditions not only supports the evidence of potential charge-up damage, but also leads the direction of future study.

Keywords : SiO_2 via-hole etching, Charge-up damage sensor, DOE, RSM

1. INTRODUCTION

Moving towards future generation of ultra large scale integrated-circuits (ULSI), etching with a high aspect ratio becomes crucial. Particularly, the etching in dielectric layers is a key process for fabrication of multilayer interconnects. For instance, via etching for dual-damascene process in the structure compatible with 0.18 μm node or less requires high aspect ratio inter-metal dielectric (IMD) etching consisting of intermediate nitride and oxide layers or low-*k* dielectrics. Deep-via etching has become feasible and continuously developed. However, high aspect ratio via-hole etching processes still hold some unresolved difficulties, such as etching stop[1], micro-loading effect[2], and charge-buildup damage[3-5]. One of the main reasons are accumulated charge in via holes. Etching stop or etch rate reduction can be caused by a reduced transport of reactive species in deep and narrow structures, and the microloading effects by a local depletion of reactive species. Thus, it is expected that as the aspect ratio of via holes increases, the influence of charge accumulation will be a significant in next generation ULSI devices.

In SiO_2 etching process using fluorocarbon gas plasmas, it is well known that a fluorocarbon film is deposited on the underlayer surface and sidewall of the via-holes. Thus, the deposited fluorocarbon polymer should exert a great influence on the etching characteristics and charge accumulation[6]. To achieve an optimal high aspect ratio for next-generation device fabrication, it will be very important to monitor and control the amount of charge accumulated in high aspect ratio via-holes of SiO_2 layer. In this paper, to verify the functionality of the fabricated sensor, the charging potential between two electrodes was measured during *Ar* plasma discharge. A set of experiment was performed by a 2^3 full factorial design of experiment (DOE) and response surface methodology (RSM). We have confirmed that the charging potential varied under different plasma conditions, and this result accord with our hypothesis of different degree of charge accumulation. In addition, the proposed charge-up damage sensor is suitable for monitoring charge-up damage in deep via-hole etching process.

2. SENSOR FABRICATION AND MEASUREMENT

Not a long ago, we have experienced bowing of high aspect ratio via hole etching in SiO_2 dielectrics in our previous experiment, and a major reason for the via-hole bowing was converged to the charge accumulation on the sidewall due to fluorocarbon polymer. When SiO_2 film is etched under fluorinated plasma, such as C_4F_8 or C_2F_4, it generates many high molecular weight radicals (C_xF_y radicals) that contribute to the fluorocarbon polymer deposition. Recently, it has been reported that the deposited fluorocarbon on sidewall of via-hole patterns is conductive, and this can cause mitigation of accumulated electric charge[7].

Original intention of developing the charge-up damage sensor is to monitor SiO_2 etching process in real-time with respect to accumulated charge. On a 2” *Si* <100> wafer, 300 *nm* of silicon dioxide layer was thermally deposited. On the top electrode, a great number of 300 *nm* vias in their diameters were formed to perform high aspect ratio (=1:5) via hole etching process. For higher aspect ratio, either/both thinner IMD SiO_2 and/or smaller via size was desired, but this was the critical fabrication capability under the university research environment. However, 1:5 aspect ratio was high enough to performing sidewall conductivity measurement. Figure 1 shows a schematic of the structure of fabricated charge-up sensor.

To verify the performance of the fabricated damage sensors, the charging potential of two polycrystalline silicon electrodes was measured after via-etching is completed. A cross sectional SEM photograph is presented in Fig. 2. In this exercise, a home-made UHF (500 MHz) plasma reactor was employed. This etching system provides the mean electron energy was about 2-3 eV, and the electron density was about 10^{11} cm^{-3}.

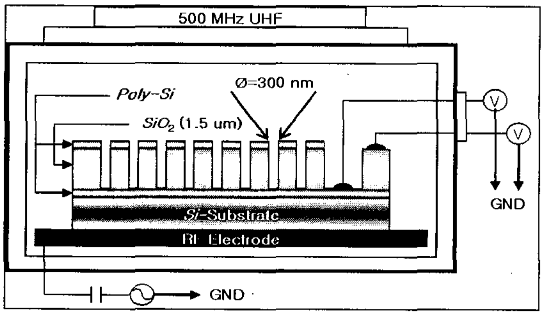


Fig. 1. A schematic of charge-up damage sensor.

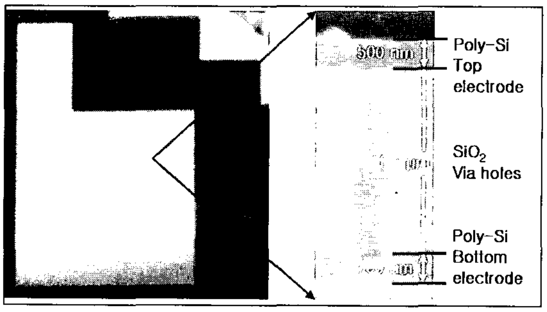


Fig. 2. A cross sectional SEM photo of fabricated sensor with 300 nm via holes.

The charge-up sensor was located on the RF electrode in the plasma reactor (see Fig. 1). While *Ar* plasma was irradiated, DC potential between the top and the bottom electrodes was measured.

3. STATISTICAL ANALYSIS

If a process has more than a very small number of variables whose possible values have a large range, the number of experiments needed for the characterization can be prohibitively large. The traditional method of collecting large quantities of data have been tested is an approach that quickly becomes impossible as the number of factors increases. Statistical experimental design is a systematic and efficient alternative methodology for characterization.

In this study, three input factors with two levels of each were considered. Refer to the Table 1 for the parameters and their ranges.

The response of interest was the potential difference measured between the top electrode and the bottom electrode. 2^3 factorial experiments with a single center point were performed. More input factors with multiple center points were initially considered, but the experiment was tightly limited to only three factors and one response in this study due to the experimental cost. For detailed information of the experiment, refer to the design matrix shown in Table 2.

Utilizing *Minitab*, a commercial statistical analysis tool, screening experiment was performed. RSM was employed to visually clarify the relationship among input factors and the response of interest. Authors admit that augmented experiments were recommended for improving statistical significance of established regression and surface model, but to fabricate another set of sensors would be time consuming and cause unknown variance between two sets of samples. For these reason, further augmentation was ignored.

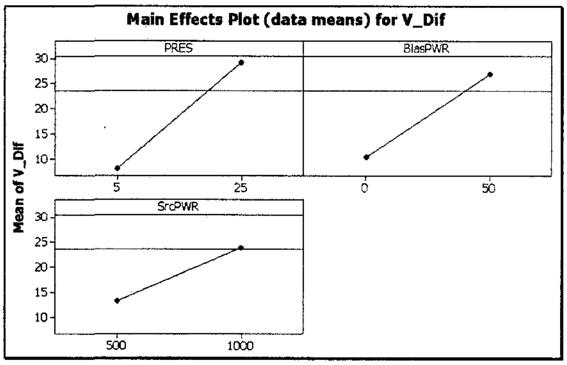
Table 1. Process parameters and their ranges.

Input factor				
Name	Alias	Abbrv.	Range	Unit
Pressure	*A*	PRES	5-25	mTorr
Bias Power	*B*	Bias PWR	1-50	watts
Source Power	*C*	SrcP WR	500-1000	watts

Response		
Name	Alias	Unit
Potential	V_Dif	V

Table 2. Design matrix for screening experiment.

Std order	Run order	PRES	Bias PWR	Src PWR
5	1	5	1.0	1000
7	2	5	50.0	1000
1	3	5	1.0	500
6	4	25	1.0	1000
9	5	15	25.5	750
2	6	25	1.0	500
3	7	5	50.0	500
4	8	25	50.0	500
8	9	25	50.0	1000



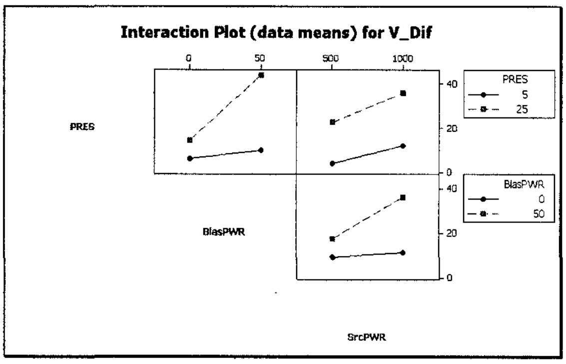


Fig. 3. Factorial plot for the response of interest : (Top is main effect plot and bottom is interaction plot).

A full model was first investigated to check the main effect, 2-way interactions, and any quadratic effect. From the ANOVA table for the response of interest, most of the parameters are not statistically significant, and *AC* interaction turned out to be the most insignificant. Thus, a reduced model was fit excluding the *AB* interaction term. To visually crosscheck this insignificance, main effect plot and interaction plot are provided in Fig. 3. As shown in the figure, main effect of source power is less significant than other main factors and the interactions between pressure and source power is negligible.

The ANOVA table of the reduced model is presented in Table 3. In the reduced model, significant main effects and significant curvature could be found, but 2-way interactions turned out somewhat less significant than main effects. One simple way to determine the statistical significance in the ANOVA is *P*-value in the last column represents the power of the hypothesis testing calculated from *F*-statistics. *P*-value stands for the probability that the hypothesis falls in to false.

Table 3. ANOVA table for the reduced model : (Statistically significant if $P<0.1$).

Source	DF	SS	MS	*F*	*P*
Main effect	3	1688.4	562.8	11.75	0.079
Interactions	2	465.8	232.9	4.86	0.171
Curvature	1	1829.1	1829.1	38.18	0.025
Res. Err	2	95.8	47.9		
Total	8	4079.1			

4. RESULTS AND DISCUSSION

Significant main effect of chamber pressure on the potential difference was observed. Charging potential under higher pressure can be less than others. Considering applied power, the positive relationships are not surprising. No significant interaction was observed between pressure and source power, but other interactions associated with bias power was observed in this data set.

In order to further investigate the relationships of all three parameters visually, RSM was employed. Contour plots presented in Fig. 4 shows the relationship between two input factors and the response while the rest of input factor is held at its mid-range, respectively. In the Fig. 4(a), it was observed that both bias power and source power are positively related with the accumulated charge.

From the Fig. 4(b) and (c), as pressure change, the accumulated charge distribution is somewhat notable. The graph presents very high curvature near the middle range of the pressure. This presents high degree of correlation between process parameters and the responses. Assuming the center point is outlier and removed from the data set, we still can confirm that less accumulated charge at higher pressure. Nevertheless, this phenomenon can be interpreted by mean free path of particles associated with chamber pressure and applied source/bias power. in the chamber.

5. SUMMARY AND FUTURE WORK

In this paper, a sensor fabrication and a measurement of charging potential under *Ar* plasma discharge. An useful method for measuring accumulated charge using the fabricated charge-up damage sensor has described.

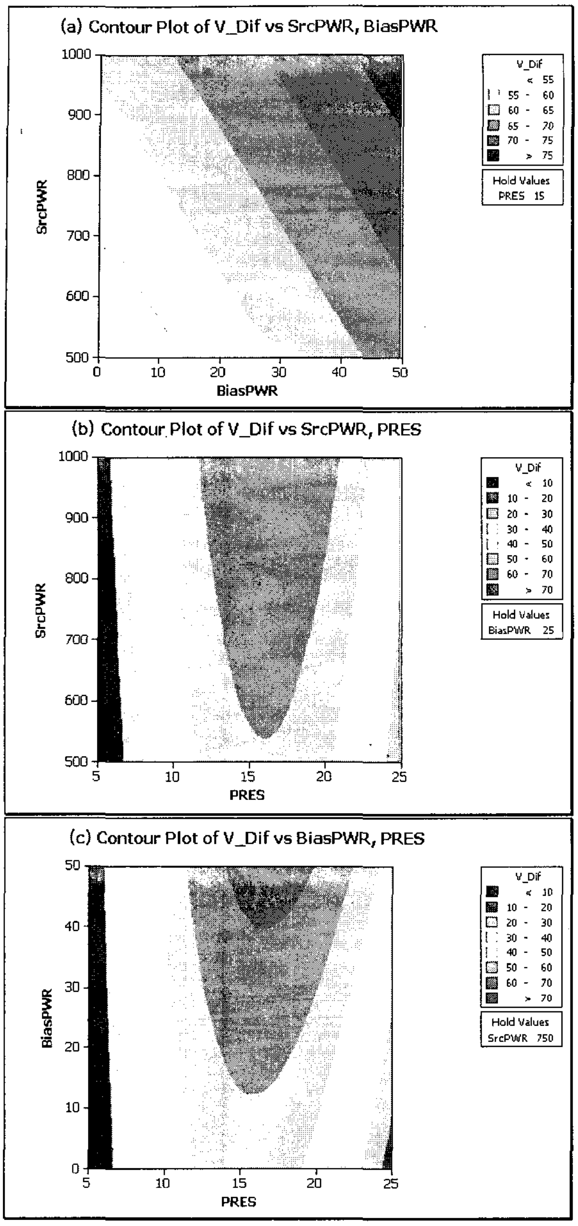


Fig. 4. Response contour plot V_Dif.

To reach the final goal of *in-situ* monitoring of charge accumulation, the fabricated sensor still further need to be scaled and fully characterized for general purpose, but the functionality and efficiency is proven, and roughly characterized under various plasma conditions. Expanded scale of characterization associated with charge-up damage is currently under investigation.

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