Optimized PECVD Chamber Clean for Improved Film Deposition Capability

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Abstract

Optimization of the PECVD in-situ SF_6/N_2O chamber clean process was performed to improve the silicon nitride deposition uniformity and chamber uptime. In the designed experiment, etch rate, wafer-to-wafer non-uniformity, and within-wafer non-uniformity were modeled with respect to SF_6 and N_2O flow rates and chamber pressure. Optimizing the chamber clean process etch rate and non-uniformity has resulted in a greater than 50% improvement in deposition capability (CpK) and has also eliminated the non-scheduled chamber wet clean events that were necessary due to poor deposition uniformity.

Using SIMS analysis, we studied the fluorine concentrations that are found in the bulk silicon nitride films as a result of the in-situ SF_6/N_2O chamber clean. Significantly higher levels of fluorine are found in the film immediately following a chamber clean. Including a chamber passivation layer following the clean is standard practice to encapsulate residual fluorine although it was determined that very thick layers were required to significantly reduce the fluorine concentrations. Adding a fluorine removal step to the chamber clean process was found to further reduce fluorine levels in the silicon nitride film.

INTRODUCTION

Plasma enhanced chemical vapor deposition (PECVD) silicon nitride (SiN_x) films are used extensively in the fabrication of integrated circuits as interlayer dielectrics and final passivation layers. Additionally, SiN_x interlayer dielectrics are often used for metal-insulator-metal (MIM) capacitors in circuit design. PECVD SiN_x film thickness process control is essential to achieve both precision and accuracy of capacitance density as it is inversely proportional to film thickness.

PECVD wafer processing results in coating thin films on both the substrate and chamber hardware. The accumulation of the SiN_x film on the chamber hardware must be removed at some interval to prevent film flaking from the hardware and particle generation on the production wafers. Typically, a fluorine based chemistry is introduced into the chamber to plasma etch the accumulated film from the hardware. The chamber clean process under investigation uses an SF_6/N_2O process gas mixture. The N_2O is added to the gas mixture as an oxygen source to bond with the free sulfur. We have found that the selection of process parameters greatly influences the chamber clean etch uniformity and resulting SiN_x deposition capability. Others have also shown that the chamber clean process plays a significant role in determining the deposition capabilities and the chamber uptime [1]. The motivation behind this work was to increase the deposition capability of the PECVD equipment and reduce downtime due to unscheduled chamber wet clean events through optimization of the SF_6/N_2O chamber clean process.

EXPERIMENT

SiN_x films were deposited on 150 mm silicon substrates using the Plasma-Therm LLC PECVD system. The PECVD system is a commercially available platform using the conventional parallel plate design and 13.56 MHz RF power source. The process gases for the SiN_x deposition consist of a mixture of SiH_4, NH_3, and N_2. Post deposition SiN_x film characterization consisted of thickness, non-uniformity, deposition rate, refractive index, particle count, capacitance density, and secondary ion mass spectrometry (SIMS) analysis.

To characterize the chamber clean etch rate and non-uniformity, SiN_x films were processed in the PECVD system using the chamber clean process parameters. All design of experiment (DOE) trials were performed following the same chamber clean and passivation routine to insure the same conditions for each DOE trial. Pre and post SiN_x thickness measurements were taken using a Nanospec 8000X metrology system to determine the etch rate and etch non-uniformity. Non-uniformity is defined as the range divided by twice the mean expressed as a percentage. Refractive index measurements were taken with a Rudolph Research AutoEL Ellipsometer and particle count measurements were taken with a Tencor Surfscan 6220.

The chamber clean optimization experiment was conducted on gas flow and pressure while holding the RF power and temperature constant. The DOE was designed using a range of SF_6 and N_2O flow rates from 100 sccm to 600 sccm, and chamber pressure from 200 mTorr to 600 mTorr.

EFFECT OF PROCESS PARAMETERS ON CHAMBER CLEAN ETCH RATE AND NON-UNIFORMITY

Figure 1 shows the chamber clean SiN_x etch rate and etch non-uniformity results modeled with respect to pressure, SF_6 flow rate, and N_2O flow rate using JMP statistical software. A two level full factorial design on three variables was

executed and modeled using the standard least squares method. Each variable had an Actual by Predicted Plot RSquare value greater than 0.90 indicating good prediction by the model. The dashed lines indicate the confidence intervals of the model. Within the process space investigated, both the within-wafer and wafer-to-wafer etch non-uniformity increased linearly with an increase in pressure. Pressure was found to have the greatest leverage on non-uniformity with lower pressure giving the lowest non-uniformity results. SF_6 flow rate was also found to be a significant variable with respect to etch non-uniformity with higher SF_6 flow rate giving the lowest non-uniformity results. Less than 2 % non-uniformity for both within-wafer and wafer-to-wafer was predicted by the model and achieved using the low pressure and high SF_6 flow rate process space. Furthermore, the SF_6 flow rate was found to have the most leverage on etch rate with higher SF_6 flow rate resulting in higher etch rate. The N_2O flow rate was found to have the least leverage in the uniformity model.

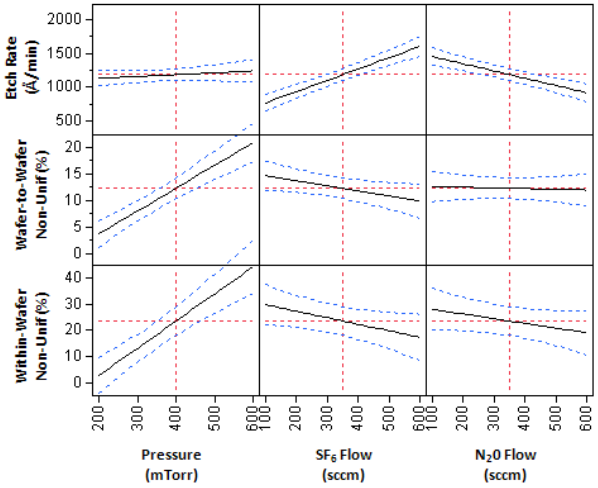

Figure 1. Chamber clean etch rate and non-uniformity results modeled with respect to pressure, SF_6 flow rate, and N_2O flow rate.

The high pressure and low flow rate process produced wafer-to-wafer etch non-uniformity greater than 40 %. This poor etch uniformity is most likely a result of the loading effect. A loading effect occurs when the supply of incoming gas reactants is the limiting factor in etch rate. As the etch rate becomes dependent upon the chamber loading, the etch uniformity will suffer. As discussed in more detail elsewhere, small changes in flow rate or gas distribution uniformity can lead to poor etch uniformity in this process regime [2].

The DOE model predicts a process "sweet spot" consisting of low pressure and high SF_6 flow rate to minimize both within-wafer and wafer-to-wafer non-uniformity. Figure 2 shows the contour plot of Pressure vs. SF_6 flow rate while holding the N_2O flow constant at 350 sccm. The non-shaded area of the plot illustrates the desired process space consisting of non-uniformity less than 5 % and etch rate greater than 1200 Å/min.

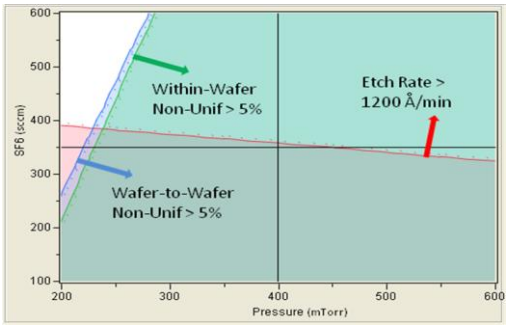

Figure 2. Chamber clean etch rate and uniformity results modeled with respect to pressure and SF_6 flow rate. The N_2O flow rate is held constant at 350 sccm.

DETERMINING THE CHAMBER CLEAN FREQUENCY

The time between cleans, or clean frequency, was determined by investigating the SiN_x film deposition properties over an extended period of processing. The deposition rate, non-uniformity, refractive index, and particle count was measured at set intervals up to approximately 30 µm of SiN_x accumulation on the chamber hardware. Figure 3 shows the resulting non-uniformity and refractive index results. The refractive index was found to be very stable at all chamber thickness conditions with an average refractive index of 1.977 and standard deviation of 0.002. Both the within-wafer and wafer-to-wafer non-uniformity were found to decrease slightly with the accumulation of SiN_x on the chamber hardware with a reduction of approximately 0.5 % each across the chamber thickness study. A slight increase of 1 % in deposition rate was observed across the experimental thickness range as shown in Figure 4.

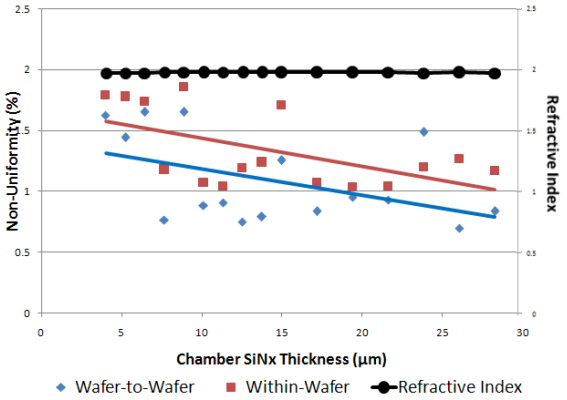

Figure 3. Refractive index and non-uniformity vs. chamber SiN_x thickness.

The process failure mechanism was found to be SiN_x cracking from the showerhead resulting in particle generation that started at approximately 12 µm of SiN_x film accumulation as shown in Figure 5. Although less than 10 added particles were found on each wafer up to the maximum chamber thickness, they were found to be very large (>100 µm) and would result in device failures.

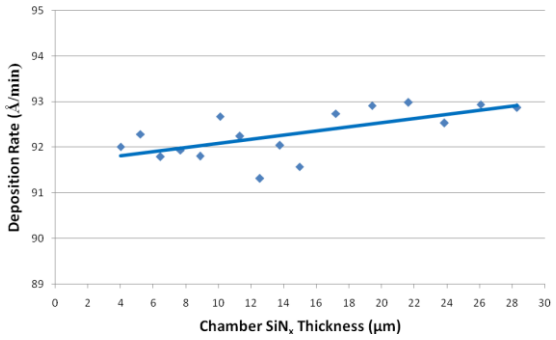

Figure 4. SiN_x deposition rate vs. chamber SiN_x thickness.

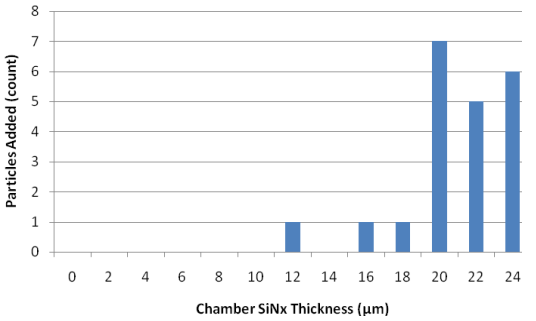

Figure 5. Particles added vs. chamber SiN_x thickness.

IMPROVED FILM DEPOSITION CAPABILITY AND UPTIME RESULTING FROM THE OPTIMIZED CHAMBER CLEAN

The SiN_x film deposition uniformity improvements were directly translated into a significant decrease in capacitance density variation. Figure 6 shows the CpK results during the implementation period for two device capacitors. Greater than 50 % improvement in CpK was realized following the full implementation across 20 PECVD platforms. The gradual increase in CpK is due to releasing the new clean process slowly across the manufacturing line to minimize risk associated with the process change.

A reduction in tool down time has also been realized with the chamber clean process change. Previously, the PECVD chambers would run until the non-uniformity reached the specification limits. The out of specification event would result in unscheduled tool down time and would require maintenance personnel to remove the shower head for chemical cleaning. Following implementation of the optimized clean we have eliminated the chamber wet clean events that were driven by poor deposition non-uniformity as shown in Figure 7.

The results of this study clearly show that cleaning the chamber with a poor uniformity etch process will result in degradation of film deposition uniformity over time. The mechanism is most likely due to an uneven accumulation of dielectric material across the showerhead. As verified elsewhere [3], a dielectric layer on the showerhead increases the impedance between the matching unit and the plasma and results in a decrease in plasma density. Variations in plasma density across the showerhead will result in deposition non-uniformities.

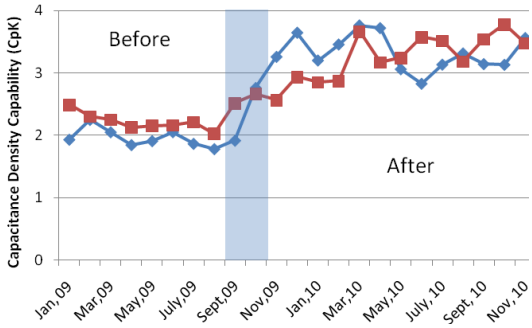

Figure 6. Capacitance density capability before and after the implementation of the optimized chamber clean. Shaded region shows implementation period.

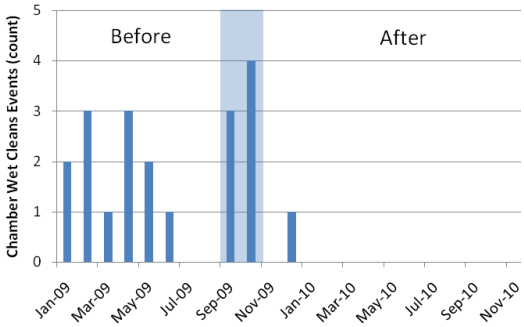

Figure 7. Chamber wet clean events per month before and following the implementation of the optimized SF_6/N_2O clean. Shaded region shows implementation period.

FLUORINE LEVELS IN THE SIN_x FILM RESULTING FROM THE CHAMBER CLEAN

SIMS analysis was performed on the SiN_x films to understand the role of the SF_6/N_2O chamber clean with respect to fluorine level incorporation into the film during deposition. It was determined that a significant increase in fluorine is present in the SiN_x film immediately following a chamber clean. Trials 1 and 2 in Figure 8 compare the fluorine levels in the SiN_x films immediately before and after the chamber clean process and shows approximately 100 % increase in fluorine concentration for films processed immediately following the clean. Further trials were performed to try and reduce the fluorine levels in the SiN_x following a chamber clean. Trial 3 consisted of reducing the clean over-etch time and increasing the number of pump purge cycles. No reduction in SiN_x fluorine concentration was found. Trial 4 included a post clean SiH_4 plasma step followed by a NH_3/N_2 plasma step to try and scavenge the fluorine from the chamber through chemical reactions to produce gas products such as SiF_x and HF. This revised clean was found to lower the fluorine concentration to levels consistent with the before clean concentration although future work is necessary to understand the mechanism and

separate the effects of the SiH_4 and NH_3/N_2 plasmas. Furthermore, Trial 5 tested the passivation approach by following the clean process with a 25 µm post clean passivation step. This technique also resulted in a significant drop in the fluorine levels found in the SiN_x film.

To further understand the leverage of the post clean passivation approach, a series of passivation thicknesses was performed ranging from 0.2 µm to 4 µm. As shown in Figure 9, a reduction in the SiN_x fluorine concentration was realized with increasing passivation thickness although 4 µm was required to lower the fluorine concentration to levels consistent with the before clean condition. Although successful, the passivation approach is not a production worthy solution to reduce fluorine levels in the chamber.

Furthermore, the accumulation of fluorine in the SiN_x films appears to track with RF hours on the tool. A tool with long RF hours shows significantly more fluorine than a tool with short RF hours as shown in Figure 10. The RF timer is reset following the annual preventative maintenance which includes a complete wet clean of the entire chamber hardware. It appears that there is a continuous accumulation of fluorine in the chamber over time.

Future work will concentrate on reducing the fluorine levels in the PECVD chamber with the use of a post clean plasma step as we have shown success with this approach. We have also demonstrated that the SIMS technique is an excellent metrology approach to understanding the fluorine levels in the PECVD chamber.

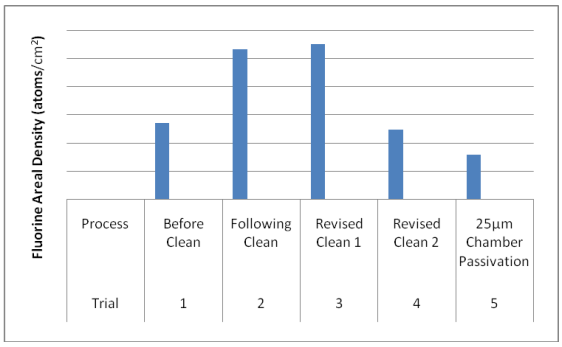

Figure 8. Fluorine concentrations in SiN_x film Trials 1 – 5.

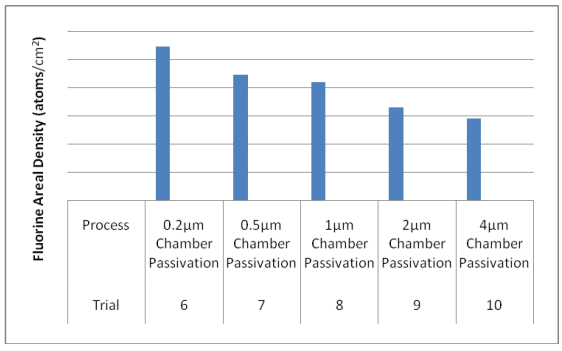

Figure 9. Fluorine concentrations in post chamber clean SiN_x films with respect to post chamber clean passivation thickness.

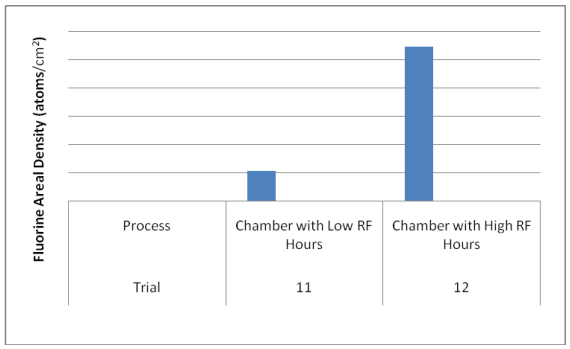

Figure 10. Fluorine concentrations in post chamber clean SiN_x films with respect to chamber RF hours.

CONCLUSIONS

Optimization of the PECVD in-situ SF_6/N_2O chamber clean process was performed and has resulted in a greater than 50% improvement in deposition capability (CpK). The optimized clean has also resulted in the elimination of the non-scheduled chamber wet clean events that were necessary due to poor deposition uniformity.

We have shown by SIMS analysis that the SiN_x films processed immediately following the chamber clean process have elevated concentrations of fluorine. Adding a fluorine scavenging step at the end of the chamber clean process was found to reduce fluorine levels in the PECVD chamber and will be the focus of future chamber clean process development.

ACKNOWLEDGEMENTS

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REFERENCES

[1] B.C. Smith and A. Young, *Optimizing Chamber Cleans for Better Film Deposition Performance*, Journal of The Electrochemical Society, 148 (11) C721-C725, 2001.

[2] M.J. Madou, *Fundamentals of Microfabrication: The Science of Miniaturization*, 2nd Ed. CRC Press, 2002.

[3] A. Zhao et. Al., *Improvement of Film Uniformity Stability of PECVD Silicon Nitride Deposition Process by Addition of Fluorine Removal to the Plasma Clean Sequence*, IEEE/SEMI Advanced Semiconductor Manufacturing Conference 2005.

ACRONYMS

PECVD: plasma enhanced chemical vapor deposition
MIM: metal-insulator-metal
SiN_x: silicon nitride
DOE: design of experiment
SIMS: secondary ion mass spectrometry