High Throughput Stress-Controlled Silicon Nitride Deposition For Compound Semiconductor Device Manufacturing

Kenneth. D. Mackenzie, Rohit Khanna, and John Jacob

Plasma-Therm LLC, 10050 16th Street North, St. Petersburg, FL 33716
Email: ken.mackenzie@plasmatherm.com, Tel: (727) 577-4999.

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Abstract

In support of higher throughput requirements for compound semiconductor device manufacturing, new work is reported on the development of higher rate (>1000Å/min) stress-controlled PECVD silicon nitride processes and more efficient high power plasma clean processes. The gain in productivity through implementation of these improved processes is also discussed.

INTRODUCTION

Silicon nitride (SiN_x) is perhaps the most widely used film prepared by plasma-enhanced chemical vapor deposition (PECVD) in III-V and III-N compound semiconductor manufacturing. The excellent electrical, dielectric, and ceramic-like properties of SiN_x prepared by this low temperature (<400°C) technique is responsible for its inclusion in many different areas of both electronic and optoelectronic device manufacture such as GaAs pHEMTS, GaAs HBTs, AlGaAs lasers, and GaN LEDs.

The use of PECVD SiN_x has extended beyond its traditional application as a surface passivation layer. Some newer and now established applications include hermetic encapsulation, electrical isolation, and as a capping layer for thermal annealing. In addition, the large dielectric constant of SiN_x makes it suitable and thus widely used as the dielectric in MIM capacitors in high frequency RF GaAs devices.

As the demands for higher volumes in compound semiconductor device manufacturing increase, higher throughputs and lower cost of ownership are consequently sought from key processing equipment including PECVD reactors. To meet this requirement for PECVD, reduction in overall process time is essential. Illustrated by the example in Figure 1, the process time is divided into 4 main steps: process overhead (gas & pressure stabilization), precoat (reactor passivation following plasma clean), plasma deposition, and plasma clean. Both plasma deposition and plasma clean are the majority contributors to the overall process time. Therefore, any reduction in the process time for these steps will lead to a significant increase in wafer throughput. This is the main goal of the work in this paper which focuses on the development of higher SiN_x film deposition rates and more efficient automated plasma cleaning processes.

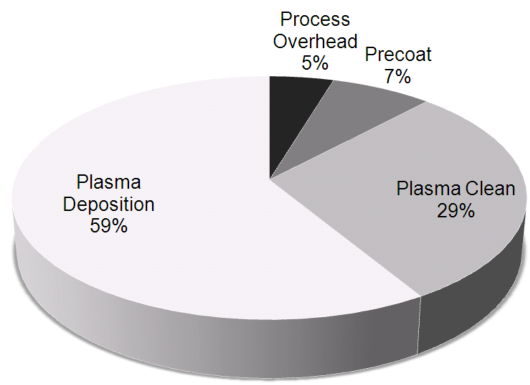

Figure 1. Example of percentage time allocation for a typical process.

In the development of a new higher deposition rate process regime, the preservation of control of film properties such as film stress is also essential. The ability to control the SiN_x film stress magnitude and stress state, tensile or compressive is extremely important both for device reliability and device performance.[1,2] Typical requirements are for SiN_x films with either a low or slightly compressive stress. In a previous paper in this conference series, we reported on the helium dilution technique to control stress of SiN_x in a production batch PECVD reactor. [3] It was shown that through the addition of helium dilution gas to the standard admixture of SiH_4, NH_3, and N_2, the stress of SiN_x can be controlled from tensile through zero to compressive. The physical mechanism involved for stress control and the benefits of this technique compared to the low frequency ion bombardment technique are discussed elsewhere. [3-6]

In this paper, we present new results on further development of the helium dilution technique to extend compressive stress control of SiN_x from the previous 200 Å/min capability into a new higher deposition rate regime in the range of 1200 to 1400 Å/min. Results are also presented on work done to improve the efficiency of the automated plasma clean process. Plasma clean chemistries based on SF_6/N_2O and NF_3 were investigated. With the emphasis on productivity enhancement, the gains in productivity through implementation of the higher rate deposition process and the more efficient plasma cleans are discussed. Some results from wafer marathon runs to study the stability of the higher rate deposition process over time are also presented.

EXPERIMENTAL

All the process development work was conducted on a Plasma-Therm, LLC Versaline™ PECVD parallel-plate production reactor with a high power 13.56 MHz RF excitation source. Pertinent features of this system key to volume manufacturing are the design of the reactor and software process control to achieve repeatable high quality uniform films. As part of the design, the reactor volume is minimized and heated to ensure particulate formation during deposition is kept low. Process control utilizes Plasma-Therm, LLC EndpointWorks™ software for fully automated real-time deposition thickness monitoring and control by optical emission interferometry (OEI), and automated plasma clean control by optical emission spectrometry (OES). [7-9] Real-time thickness control ensures process repeatability and reduces the common issues with "first wafer" effects that can often occur following plasma cleans. Regular plasma clean cycles are important to keep particle counts low and return the reactor to a clean known state. As demonstrated by Hess[10], to consistently achieve good deposition uniformity, it is critical that the plasma clean process adopted is optimized to yield not only a high clean rate but also to uniformly clean the entire reactor.

The higher rate SiN_x work focused on development of both low stress and compressive stress deposition processes. The reactor was configured for single 150 mm Si wafer handling. The SiN_x films were deposited using a plasma chemistry of SiH_4, NH_3, and He at a fixed deposition temperature of 200°C. OEI was used for real-time thickness control to target a deposition thickness of about 1 micron for accurate metrology.

To fully explore the influence of deposition parameters on film properties including film stress, a parametric approach was adopted to investigate primarily their dependence on RF power, SiH_4/NH_3 gas flow ratio, process pressure, and helium dilution ratio. This ratio is defined as He gas flow relative to the combined He and N_2 inert gas flow expressed as a percentage. The total gas flows were held constant. The SiH_4/NH_3 ratio was optimized and then fixed to achieve a stoichiometric film composition at the midpoint of process parameter space. All deposited films were characterized by refractive index, stress, deposition rate, and deposition non-uniformity. The refractive index was measured at 633 nm with a Metricon model 2010 prism coupler. A Nanometrics NanoSpec model 6100 spectroscopic reflectometer was used to map both the deposition thickness and the deposition thickness non-uniformity. The thickness non-uniformity is defined as the thickness range divided by twice the mean thickness expressed as a percentage. The film thickness was measured at 81 sites on each wafer. The edge exclusion was 5mm. The film stress was estimated from Stoney's equation from the measured change in wafer bow following film deposition. For this work, a Tencor model P-2 long scan profilometer and an FSM model 128 stress measurement system were used.

For the experimental work on improving the plasma clean efficiency, two different fluorine-based chemistries, SF_6/N_2O and NF_3 were investigated. RF power was identified as the key parameter for the plasma clean rate. A comparative study of the plasma clean rate as a function of RF power under similar process conditions was conducted for the two different chemistries. Immediately following a SiN_x deposition, the plasma clean process was initiated with the coated wafer deliberately left in the center of the reactor. Using OEI during the plasma clean, the clean rate was determined directly as the SiN_x film on the wafer is removed by plasma etching.

Recognizing that plasma clean rate in the reactor is spatially non-linear with different parts of the reactor cleaning at different rates, visual inspection of the reactor following plasma clean was done to verify the reactor cleanliness. Typically in a PECVD reactor, the RF powered upper electrode cleans first followed next by the lower electrode and then the reactor walls. For automated termination of the plasma clean, the endpoint OES algorithm was optimized based on monitoring the rate of change and subsequent saturation of the main fluorine emission line at a wavelength of 704 nm.

RESULTS AND DISCUSSION

A) High Deposition Rates

From the investigation, high RF power is essential to achieve high deposition rates. Figures 2 to 4 summarize dependence on applied RF power of deposition rate, stress, and refractive index of SiN_x prepared from SiH_4, NH_3, N_2, and He. For this study, the helium dilution ratio and process pressure were fixed at 53% and 1 Torr, respectively.

As shown in Figure 2, the deposition rate increases linearly with increasing RF power up to 1400Å/min at the maximum power applied. From Figure 3, the film stress becomes more compressive with increasing RF power going from about zero at the lowest power to about -300 MPa at the highest power. From Figure 4, it is worthwhile noting that the RF power level does not have a major impact on the refractive index and hence the film composition. Fine adjustment of the refractive index if required can be achieved by changing the NH_3 gas flow rate. Deposition thickness non-uniformity for all films in this study was ±2% or less.

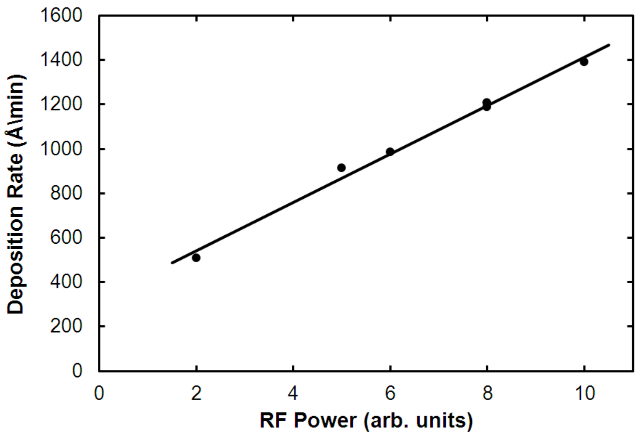

Figure 2. Deposition rate of PECVD SiN_x as a function of RF power prepared from SiH_4, NH_3, N_2, and He plasma chemistry.

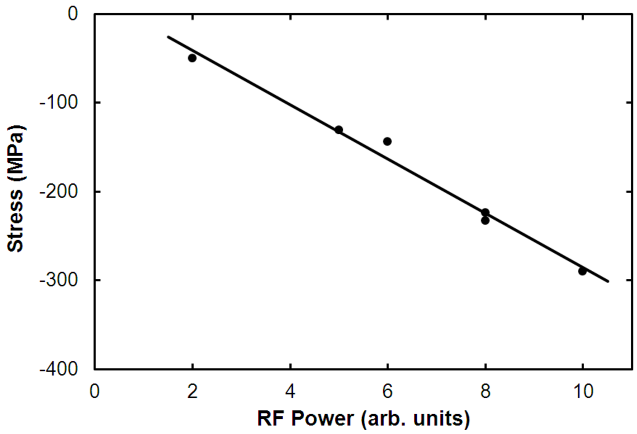

Figure 3. Film stress of PECVD SiN_x *versus* RF power prepared from SiH_4, NH_3, N_2, and He plasma chemistry for series of films shown in Figure 2.

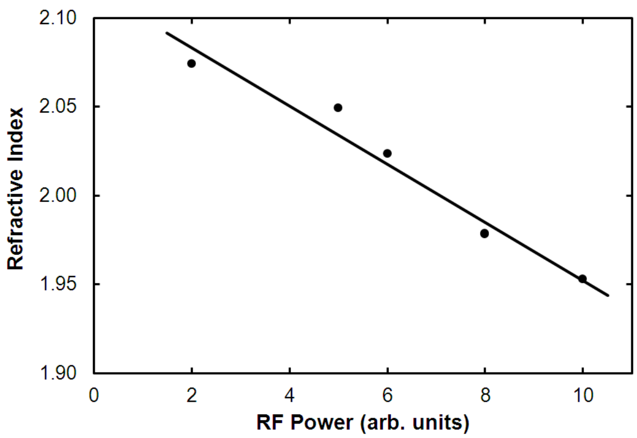

Figure 4. Variation of refractive index of PECVD SiN_x with RF power prepared from SiH_4, NH_3, N_2, and He plasma chemistry for series of films shown in Figure 2.

B) High Deposition Rates: Stress Control by Helium

In the higher deposition rate regime, the effectiveness of helium dilution for stress control was studied. Figure 5 shows for SiN_x deposited at 1200Å/min, the dependence of compressive stress on the helium dilution ratio. RF power and process pressure were fixed. As illustrated by these results, stress control of SiN_x over a wide range from about 0 to -500 MPa, compressive is possible at high deposition rates. Deposition thickness non-uniformity over this range is ±2% or less. Refractive index was within normal limits.

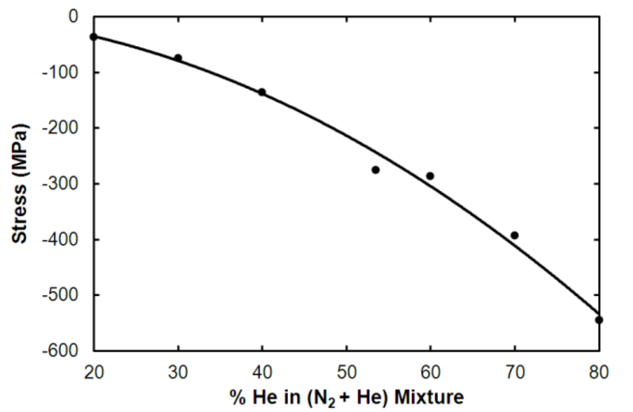

Figure 5. Stress control of high rate PECVD SiN_x by the helium dilution technique.

C) Plasma Clean Efficiency

Figure 6 shows the clean rate as a function of RF power determined from OEI during the clean for the SF_6/N_2O and NF_3 based chemistries. The cleaning efficiency of NF_3 is about a factor of 1.2 to 2 better than SF_6/N_2O dependent on the RF power. For SF_6/N_2O, doubling the RF power from standard plasma clean power to 20 on the normalized RF power scale reduces the clean time by about a factor of 2. At this power level, the overall clean efficiency of the entire reactor with NF_3 based on optimized OES endpoint is about 50% faster compared to SF_6/N_2O.

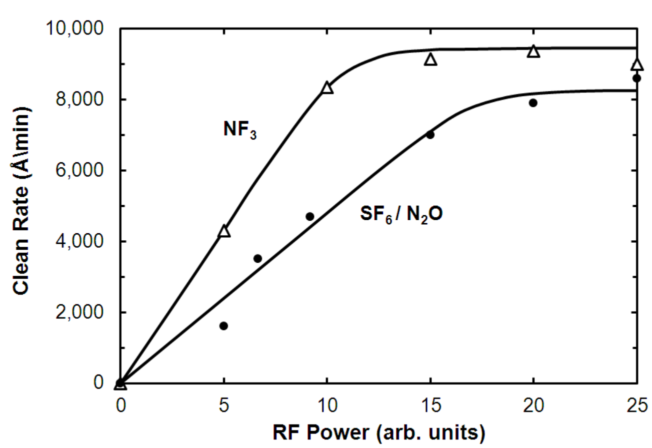

Figure 6. Comparison of plasma clean rates measured *versus* RF power for plasma chemistries of SF_6/N_2O and NF_3. The results are taken from a coated wafer located in the center of the reactor.

D) Marathon Results: Process Stability

The stability of film properties produced by the high rate deposition process was monitored during a 43 wafer run marathon. For this test, a process was setup to target a stress of -300 MPa at a deposition rate of 1400 Å/min. All film properties were stable. Figure 7 shows the statistical process control chart for the film stress. Control is within 3σ statistical limits.

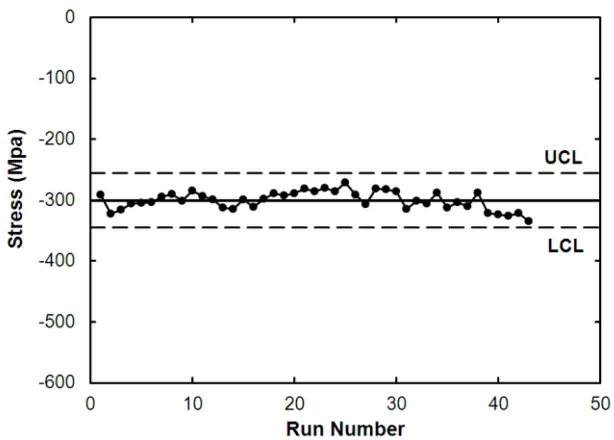

Figure 7. Compressive stress data from 43 wafer marathon runs. UCL and LCL are the respective upper and lower 3σ statistical control limits.

E) Productivity: Wafer Throughput

For production, the benefit of the higher deposition rate and improved plasma clean efficiency is best demonstrated by their effect on wafer throughput. Summarized in Figure 8 is a simulation of the wafer throughput *versus* film thickness for the PECVD reactor interfaced with dual wafer cassette loading stations. In addition to the process time, mechanical overhead time that includes wafer transfer, wafer alignment, pump and vent are included in the throughput calculation. A plasma clean after every 4 microns of accumulated deposition is assumed.

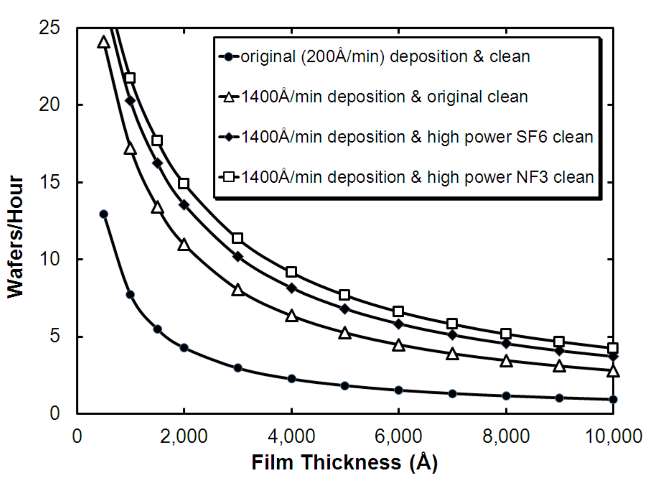

Figure 8. Calculated wafer throughputs *versus* film thickness for a cassette handler system.

From these results, the higher rate deposition followed by the higher power clean processes has the greatest effect on wafer throughput.

CONCLUSIONS

1. The use of helium dilution technique for stress control can be extended to higher deposition rates (1400Å/min).
2. Implementation of the achieved process improvements summarized in Table I lead to a significant enhancement in wafer throughput.
3. Dependent on film thickness, throughput is improved up to a factor of 5.

TABLE I
SUMMARY OF KEY PROCESS IMPROVEMENTS

Item	Improvement
SiN_x Deposition Rate	7x (200 to 1400Å/min)
Reactor Plasma Clean Efficiency (SF_6/N_2O)	~ 2x (higher power)
Reactor Plasma Clean Efficiency (NF_3)	~ 3x (higher power)

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ACRONYMS

PECVD: plasma enhanced chemical vapor deposition
SiN_x: silicon nitride
HBT: Heterojunction Bipolar Transistor
pHEMT: pseudomorphic High Electron Mobility Transistor
MIM: Metal-Insulator-Metal
OEI: Optical Emission Interferometry
OES: Optical Emission Spectroscopy