Optimization of Low Stress PECVD Silicon Nitride

for GaAs Manufacturing

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Unaxis solutions for plasma-enhanced chemical vapor deposition (PECVD) silicon nitride (SiN_x) are used extensively in the production of GaAs devices. PECVD is compatible with the low temperature constraints required for GaAs device manufacturing. With this technique, high quality SiN_x can be deposited at temperatures less than 400°C. PECVD SiN_x is used in many different GaAs-based devices such as MESFETs, HBTs, and HEMTs. In these devices, PECVD SiN_x is typically used for passivation, encapsulation, and as a capping layer. In addition, the large dielectric constant of SiN_x makes it attractive for use as the intermetallic dielectric in MIM capacitors.

It is well recognized that the stress of the SiN_x layer in GaAs-based device structures can impact the electrical performance and lead to degradation. For GaAs MESFET and HEMT devices, it has been demonstrated not only the magnitude of the stress but also the stress state, compressive or tensile, can affect the performance [1]. Stress-induced failure via microvoid formation in SiN_x MIM capacitors has also been reported [2]. Therefore, the capability of tailoring the magnitude and state of the SiN_x stress required for a specific device structure is very important.

For SiN_x, a common technique to control the stress in a conventional 13.56 MHz parallel plate PECVD reactor is through the addition of low frequency power. At 13.56 MHz, SiN_x films prepared from standard gas mixtures of SiH_4, NH_3, and N_2 are typically tensile in nature. The added low frequency (< 1 MHz) component results in high energy ion bombardment of the growing SiN_x film. This results in a change of the stress state from tensile to compressive [3, 4]. At Unaxis, a He dilution method has been developed as a simpler alternative technique to control the stress of PECVD SiN_x. As illustrated in *Figure 1*, the addition of He to the standard gas mixture of SiH_4, NH_3, and N_2, enables stress control from about 300 MPa, tensile through zero to about –300 MPa, compressive.

Plasma-induced damage during the SiN_x deposition process, resulting in physical and electronic degradation of GaAs devices is a very important issue [5–7]. Without the requirement of a low frequency power source, the possibility of damage is reduced with the He dilution method. The RF power density at 13.56 MHz is very low and typically less than 50 mW/cm^2.

A designed experiment (DOE) was implemented to characterize and optimize a low stress SiN_x process based on the He dilution method on a Unaxis PECVD production platform developed for high volume GaAs manufacturing. To understand the mechanism involved in this technique for stress control, optical spectroscopic analysis of different He/N_2 plasmas in the PECVD reactor has been performed.

Experimental

All the SiN_x films were prepared on 100 mm Si test wafers from gas mixtures of SiH_4, NH_3, N_2, and He on a Unaxis VERSALOCK® PECVD system [8]. This fully automated cassette-to-cassette system is capable of batch handling eight 100 mm GaAs or five 150 mm GaAs wafers. The PECVD reactor is a conventional parallel plate configuration and uses a 13.56 MHz RF power source to generate the plasma. Wafer temperature can be controlled over a range of 100°C to 350°C. To obtain a high yield and minimize system downtime, several features in the PECVD reactor have been implemented to maintain system cleanliness. For example, both the chamber walls and the upper gas distribution electrode of the reactor are heated to minimize particulate formation during the SiN_x deposition process. In addition, an automated plasma etchback sequencer interfaced to an *in-situ* optical emission spectrometer is used to achieve and consistently maintain the reactor in a clean state. Single wafer modules with either manual or automatic loading are also available for situations where batch processing is unnecessary.

For process optimization, a two level full factorial design on three factors was constructed for the DOE. The three factors were NH_3 gas flow rate, $N_2/(N_2+He)$ gas flow ratio, and RF power. All films were deposited at 300°C. The diluted SiH_4 gas flow rate, process pressure, and the combined N_2 and He gas flow rates were held constant during the experiments.

The measured responses were refractive index, deposition rate, thickness non-uniformity, stress, and wet-etch rate. The thickness non-uniformity is defined as the thickness range divided by twice the mean thickness expressed as a percentage. The edge exclusion was 6 mm. A buffered oxide etch (BOE) solution of 7:1 NH_4F : HF was used for the wet-etch rate measurements.

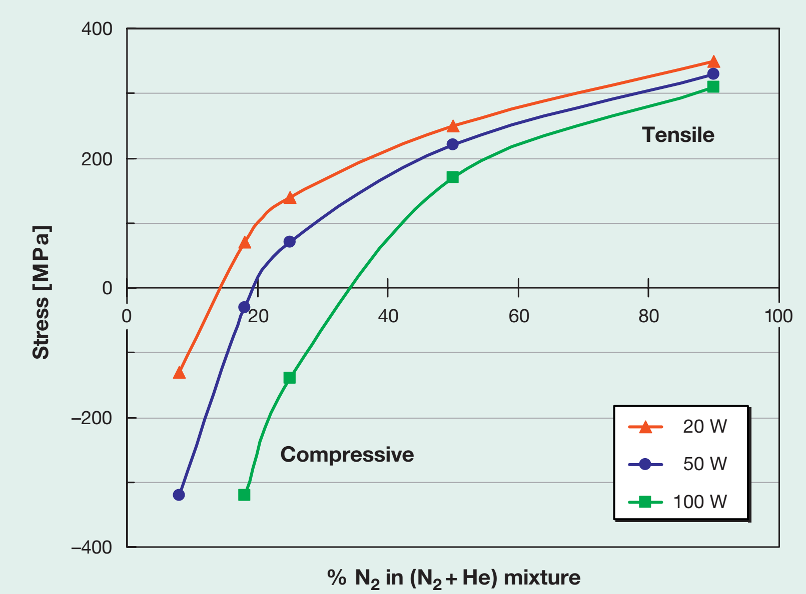

Figure 1: Stress control of PECVD Sin_x by the He dilution method at the different rf power levels indicated

Responses

Factors	Index	Dep rate	Thickness non-uniformity	Stress	Etch rate
↑ NH_3	↓↓	–	–	↑	↑↑
↑ % N_2 / He	↓	↑	↓↓	↑	↑↑
↑ Power	↓	↑↑	↑↑	↓	↓↓

Figure 2: General response trends from DOE

Designed experiment results

In *Figure 2*, the general response trends from the analyzed DOE are summarized. The up and down arrows indicate the directional change in the response resulting from an increase in a process factor, NH_3 gas flow rate, N_2 concentration in He, or RF power. Double and single arrows respectively indicate a strong or weak dependence of a response on a factor over the range investigated. All three factors have a major influence on the SiN_x film stress. The measured film stresses ranged from about 300 MPa, tensile to about 400 MPa, compressive.

Low stress optimization

Figure 3 summarizes the typical customer property requirements for a low stress SiN_x film. *Figure 4* maps out the predicted process space from the DOE for these criteria as a function of NH_3 gas flow rate and N_2/He concentration in the plasma. These results clearly indicate a practical process regime exists to achieve a low-stress silicon nitride film to meet the desired criteria. The deposition rate for the low stress films is greater than 100 Å/min. Faster deposition rates are possible with either higher RF power or more concentrated SiH_4.

Stress control mechanism

Examination of the optical emission spectra of the deposition plasma provides important insight concerning the mechanism responsible for compressive stress by the He dilution method. Shown in *Figure 5* are two 13.56 MHz plasma spectra, pure N_2 and 10% N_2/He. These correspond to deposition conditions associated with tensile and compressive films. Emission lines at 391.4 nm and 427.8 nm are present in the 10% N_2/He plasma and are absent in the pure N_2 plasma. These two lines are assigned to N_2^+ ions and indicate its presence in the 10% N_2/He plasma. As shown in *Figure 5,* these N_2^+ spectral lines are also present in a 380 kHz N_2 plasma without any He dilution. SiN_x films prepared from SiH_4,

Figure 3: Criteria for low-stress SiN_x process optimization.

Film parameter	Range
Stress (MPa)	–100 to +100
Refractive index	2.0 to 2.05
Thickness non-uniformity (%)	< ± 2.5
Wet-etch rate (Å/min)	> 300

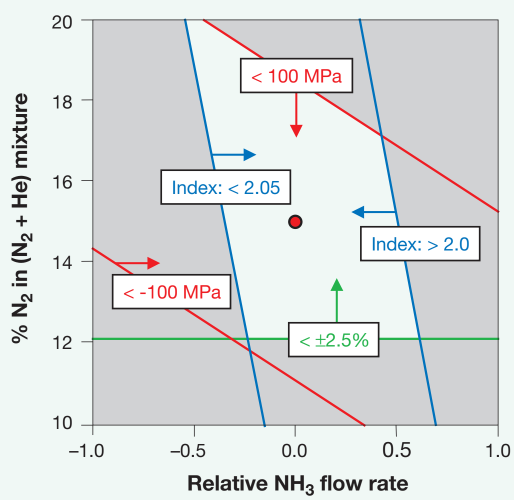

Figure 4: Overlay plot for an optimized low stress SiN_x process. Non-shaded area is the optimized process regime. Point in center denotes center point of the design.

Figure 5: Optical emission spectra for various plasmas. Spectra are displaced vertically for clarity.