Development and Characterization of a 600 Å PECVD Si_3N_4 High-Density MIM Capacitor for InGaP/GaAs HBT Applications

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Abstract

We have developed and characterized an ultra-thin 600 Å silicon nitride high-density MIM capacitor for InGaP/GaAs HBT applications. This thin silicon nitride film was deposited using PECVD method at 300ºC, and has a capacitance density of 0.93 fF/μm^2 with a high breakdown field of >10 MV/cm. The film has low wet-etch rate and passes standard high humidity and high temperature pressure cooker tests. This Si_3N_4 MIM capacitor was demonstrated to have excellent TDDB lifetime, as well as good ESD characteristics. Physical and optical characterization, including X-SEM, AFM, and FTIR, show that the film has good conformality, low surface roughness, and does not degrade and absorb water. Furthermore, the film is manufacturable with good process control characteristics, including film thickness, refractive index, uniformity, stress, and with low particle density.

INTRODUCTION

Due to the increasing demand for capacity and revenue, die size in wafer manufacturing must be reduced. One way to reduce die size is to increase the capacitance density and reducing the area of the metal-insulator-metal (MIM) capacitor, which is a key passive component in GaAs-based HBT technologies. Excluding bondpad area and scribe-streets, MIM capacitors could consume up to 35% of the die area in many HBT circuit designs. Increased capacitance density in these designs allows capacitor size reductions, which results in die size reduction. The most common dielectric material used as the insulator of MIM capacitors in the industry is silicon nitride (Si_3N_4), due to its compatibility with GaAs processing and good electrical characteristics, including relatively high dielectric constant and breakdown field [1-4]. Typical thickness for the MIM silicon nitride capacitor in GaAs processing is 1500 Å or thicker.

There are several methods of increasing the capacitance density of capacitors: (1) optimize the current Si_3N_4 film, (2) reduce the thickness of the Si_3N_4 insulator, (3) replace the Si_3N_4 with a material that has a higher dielectric constant, e.g. Ta_2O_5, and (4) develop a stacked capacitor, connected in parallel. The first two methods are by far the easiest, simplest, and least expensive to perform. Since the same process tools and equipment can be used, less time and resources are needed for process development, integration, and characterization. However, it is critical that the higher capacitance density be obtained without any degradation to other electrical and physical characteristics. Additionally, many items, including the manufacturability and reliability of this film need to be investigated and characterized before the film can be used in volume production.

In this study, we have developed and characterized an ultra-thin 600 Å silicon nitride high-density MIM capacitor for InGaP/GaAs HBT applications and compared the characteristics to those of a previously developed 1000 Å film deposited at different conditions. Electrical characterization was performed by studying the capacitance, breakdown field, and I-V characteristics of the film. Reliability studies were performed by investigating the time-dependent dielectric breakdown (TDDB) and electrostatic discharge (ESD) characteristics of the film. Additionally, physical and optical characterization, including deposition rate, refractive index, stress, and wet-etch rate studies were performed. Analysis was performed using Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) to study the film conformality and surface roughness, Fourier Transform infrared (FTIR) spectroscopy to study the stability of and the chemical bondings in the film. Furthermore, the manufacturability, robustness, and reliability of the film and process was studied, in addition to performing standard high humidity and high temperature pressure cooker /autoclave test.

EXPERIMENTAL

The plasma-enhanced CVD (PECVD) Si_3N_4 film was deposited at 300ºC on a Novellus C-1 multi-station sequential deposition system. The gases used are SiH_4, NH_3, and N_2. Optimization was performed by varying the gas flows and pressure. In this study, both full-up and shortloop wafers were used, where the latter only have Metal 1 and Metal 2 as the conductor layers. Various capacitor structure sizes, ranging from an area of 250 μm^2 to 5,000,000 μm^2, were used in this study. The small area capacitors are used to characterize intrinsic breakdown (non-defect related), while the larger area capacitors are used to evaluate extrinsic defects.

Both the thickness and refractive index were measured using a Rudolph FE-VII ellipsometer, while the stress was obtained using a Frontier FSM 8800 system. The particle count was performed using a Tencor Surfscan 6420, measuring 0.5 μm particles and larger. FTIR analysis was performed using a Nicolet Magan 550 at 4 cm^{-1} resolution and 100 scans. The AFM analysis was performed using NanoScope III Dimension 5000 with an accuracy better than 2% with NanoProbe silicon tips. The wafers used for FTIR analysis are bare GaAs test wafers deposited with the 6000 Å Si_3N_4 films, while those used for AFM analysis are patterned wafers. Wet-etch rate was obtained by etching wafers deposited with the silicon nitride films in a wet bench with 10:1 BOE solution.

Current-Voltage (I-V) measurements were performed on both manual probe station and automated parametric tester. Both ramped and constant voltage measurements were performed. The ramped voltage method, in which the test was performed while monitoring the current until breakdown occurs, allows for rapid characterization of extrinsic defects. The constant voltage method, in which the capacitor is stressed at a constant voltage until breakdown occurs, allows characterization of failures due to wear-out, including time-dependent dielectric breakdown (TDDB) lifetime reliability characterization [5]. The stress was performed both at room temperature and at 125ºC at different constant voltages, near the film breakdown voltage, while the time-to-breakdown was recorded.

Electrostatic discharge (ESD) test was also performed as another method to evaluate the reliability of the film [6]. The test was performed using an Oryx 5000 ESD test system and was based on both the Human Body Model and Machine Model events. A voltage was applied to packaged structures comprising capacitors of various sizes, and with or without ESD protection circuit, until breakdown occurs. This protection circuit consists of 10 diodes stacked in a positive path stack, parallel with 2 diodes in the negative path. Both positive and negative polarity tests were performed.

Standard pressure cooker/autoclave test was performed in an oven, in which completed, patterned wafers were subjected to an environment of 100% relative humidity at > 1 atm and > 120ºC for > 15 hours. Visual observation and electrical characterization were performed before and after the test in order to study whether any degradation occurs, including moisture penetration into the film.

RESULTS AND DISCUSSION

A. *Film and Process Characteristics*

Table I shows some selected process and film properties of the newly developed 600 Å PECVD silicon nitride, which has been optimized for use as a MIM capacitor film, and compared to those of a 1000 Å PECVD silicon nitride film developed for a previous generation MIM capacitor and deposited at different conditions. As can be seen, both the deposition rate and the refractive index of the 600 Å film is lower than the 1000 Å film. The stress of both films are compressive, and the wet-etch rate are both relatively low for a PECVD Si_3N_4 film, indicating the superior quality of the films [7,8].

TABLE I.
Selected process and film properties of the 600 Å and 1000 Å Si_3N_4 films.

Parameter	600 Å Si_3N_4	1000 Å Si_3N_4
Deposition Rate (Å/s)	8.8	9.3
Refractive Index	1.875	1.932
Stress (dyn/cm^2)	-2.20 E 9	-2.85 E 9
Wet-Etch Rate (Å/s)	13.3	11.5

B. *AFM/SEM Analysis*

Figure 1 (a) and (b) shows the AFM and cross-section SEM images of the 600 Å Si_3N_4 film. The AFM image shows the surface after the deposition of the film on the Metal 1, while the X-SEM image shows the film being sandwiched by Metal 1 and Metal 2. As shown, the silicon nitride film is quite conformal and has excellent step coverage over the rough Metal 1 surface, and in fact, reduces this metal surface roughness. The good conformality is critical in order to reduce increased electric field and fringe capacitance due to the sharp features and non-uniformity of the underlying metal surface. Table 2 lists the surface roughness values obtained from AFM analysis, and confirms the reduced roughness of the underlying surface after the Si_3N_4 deposition.

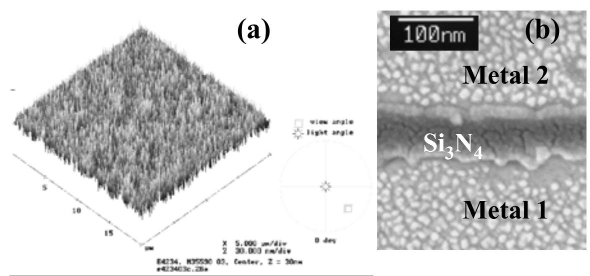

FIGURE 1. Images obtained using (a) AFM and (b) X-SEM, showing the 600 Å Si_3N_4 on Metal 1 and between Metal 1 and Metal 2.

TABLE II.
Surface roughness analysis before and after the 600 Å Si_3N_4 deposition on Metal 1.

Surface Roughness	Metal 1 Only	Metal 1 with Si_3N_4
R_{ms} (Å)	33.3	26.3
R_a (Å)	30.9	24.3

C. *FTIR Analysis*

Figure 2 shows the FTIR spectra of the silicon nitride film deposited on the GaAs wafer before and after pressure cooker test. As can be seen, there is minimal or no change to the spectra, including to the Si-H absorbance peak at 2180 cm^{-1} and the N-H bond at 3340 cm^{-1}. Additionally, no peaks related to SiO-H in the 3200-3400 cm^{-1} range can be observed in both spectra, indicating that there is no moisture in the film. These results suggest that no degradation of the film and no absorption of moisture occurs during the pressure cooker test.

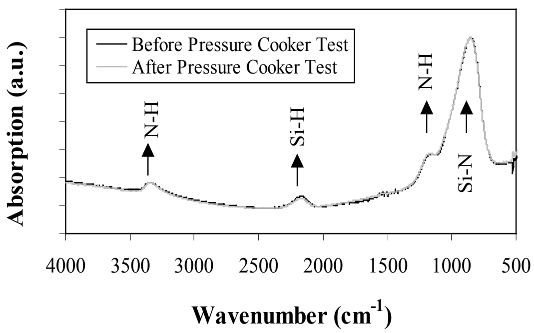

FIGURE 2. FTIR spectra of silicon nitride before and after pressure cooker test, with no degradation or moisture absorption observed.

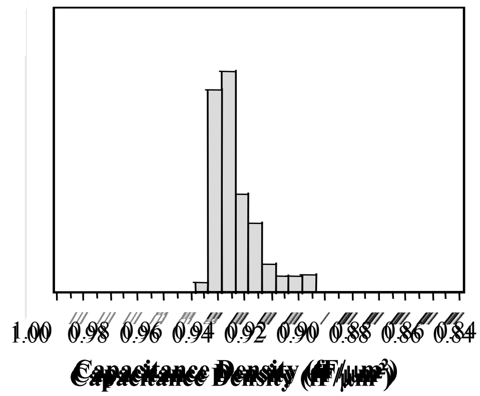

FIGURE 4. Typical capacitance density distribution of a wafer deposited with 600 Å MIM silicon nitride, obtained with 3 mm edge exclusion.

D. Capacitance and Breakdown Voltage Studies

The typical current-voltage (I-V) characteristics of the MIM capacitor with 600 Å silicon nitride film before and after pressure cooker test are shown in Figure 3. As shown, there is no significant degradation of the film with the test. Table III lists the good breakdown and capacitance characteristics of this 600 Å Si_3N_4 film, compared to those of the previously developed 1000 Å film. Figure 4 shows the typical capacitance density distribution for a wafer deposited with the 600 Å silicon nitride film as MIM capacitor dielectric, with > 800 MIM structures measured on the wafer with 3 mm edge exclusion.

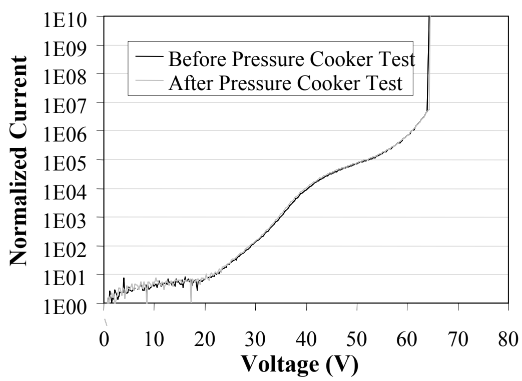

FIGURE 3. The I-V curve of MIM capacitor with 600 Å silicon nitride (a) before and (b) after pressure cooker test, with no degradation detected.

TABLE III.
Electrical characteristics of the 600 Å silicon nitride film, compared with those of the 1000 Å previously developed film.

Parameter	600 Å Si_3N_4	1000 Å Si_3N_4
Capacitance Density (fF/μm^2)	0.93	0.565
Breakdown Voltage (V)	65	100
Breakdown Field (MV/cm)	10.8	10.0

E. TDDB Lifetime Studies

The TDDB characteristics of the 600 Å silicon nitride film was studied in order to evaluate the reliability of capacitors utilizing the film as capacitor dielectric material [1,5,9]. Figure 5 shows the plot of the TDDB lifetime of the 600 Å film compared to that of the 1000 Å film as a function of stress operating voltage. As demonstrated, the extrapolated TDDB lifetime of both films well exceeds 20 years at 20 V operation at 125ºC. Additionally, the lifetime projection of the 600 Å film will actually cross-over that of and therefore will have a longer lifetime than the 1000 Å film at voltage of < 18 V, indicating the superior quality of the 600 Å film. Figure 6 shows the failure distribution log-normal plot of the film with the 0.1% and 50% cumulative failure times stressed at 60 V and 125ºC, being 0.28 s and 15 s, respectively. Based on these results, the projected 0.1% and 50% cumulative failure times for 20 V operation at 125ºC are 79,000 and 400,000 h, respectively.

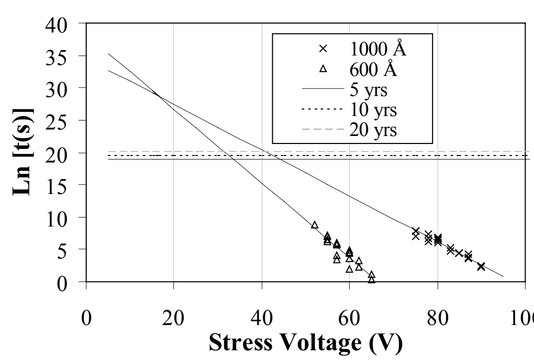

FIGURE 5. The TDDB lifetime characteristics of the 600 Å and 1000 Å Si_3N_4 films obtained at 125ºC.

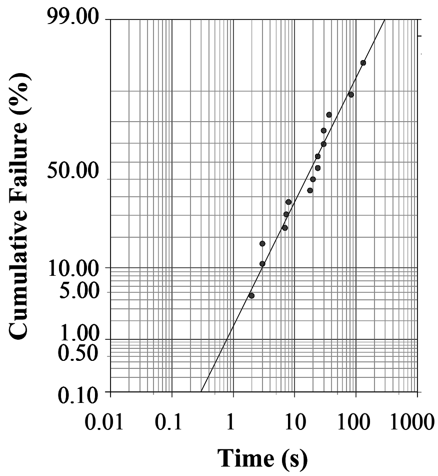

FIGURE 6. The failure distribution log-normal plot of the 600 Å Si_3N_4 film stressed at 60 V and 125° C.

F. ESD Studies

Electrostatic discharge (ESD) has been known to be one of the major causes of yield and reliability failures in IC manufacturing [6]. In this study, the ESD characteristics of MIM capacitors with and without protection circuit in the test structures have been investigated using both Human Body Model (HBM) and Machine Model (MM) events. Table IV shows that the capacitors protected with the diodes pass the standard, generally accepted ESD voltage criteria for devices of $\geq$ 2000 V for Human Body Model and of $\geq$ 200 V for Machine Model events [10,11]. Furthermore, the unprotected capacitors have lower ESD voltage threshold. However, this is not critical, as the capacitors that are used without protection are usually placed within the main circuit itself, in which the GaAs transistor, with breakdown voltage of < 20 V would fail first. As expected, the ESD voltage of the unprotected capacitors show some dependence on the capacitor area, where the ESD voltage increases with increasing capacitor area.

TABLE IV.
The ESD test results using Human Body Model- and Machine Model-based events of capacitors.

Capacitor Area (μm^2)	ESD Voltage (V) Human Body Model		ESD Voltage (V) Machine Model	
	With Protection Circuit	With no Protection Circuit	With Protection Circuit	With no Protection Circuit
50,000	$\geq$ 2000	$\geq$ 800	$\geq$ 250	N/A
5000	$\geq$ 2000	$\geq$ 800	$\geq$ 250	$\geq$ 125
1000	$\geq$ 2000	$\geq$ 800	$\geq$ 250	$\geq$ 125
250	$\geq$ 2000	$\geq$ 800	$\geq$ 250	$\geq$ 100

G. Manufacturability and Robustness

Long term data collection was performed in order to evaluate the manufacturability and robustness of the process. The data, which were collected from 19 runs taken over a 2-month period, show good process control characteristics, even when standard and non-standard maintenance to the tool was still performed, with no changes to the process made in this time period. The data that were collected include the thickness, refractive index, stress, and particle count, and are summarized in Table V. The thickness and refractive index data were measured using 50 pts, with 3 mm edge exclusion. The thickness and refractive index minimum and maximum values are obtained from all the data points. The % uniformity was obtained by using the difference of these maximum and minimum values divided by 2 times the average.

TABLE V.
The results obtained from performing long-term data collection, consisting of 19 runs over a 2-month period.

Parameter	Avg.	Min.	Max.	% Unif.
Thickness (Å)	614	583	633	4.86
Refractive Index	1.875	1.869	1.889	0.29
Stress (xE9 dyn/cm^2)	-2.2	-1.3	-3.1	N/A
Particle Adders ($\geq$0.5μm)	8.1	0	21	N/A

CONCLUSIONS

An ultra-thin 600 Å PECVD silicon nitride high-density MIM capacitor for InGaP/GaAs HBT applications was developed and characterized. The film has a capacitance density of 0.93 fF/μm^2 and a high breakdown field of > 10 MV/cm, and was shown to have good physical characteristics and passes standard pressure cooker test. The film has excellent TDDB lifetime, as well as good ESD characteristics. Additionally, the film is manufacturable with good process control characteristics, including film thickness, refractive index, uniformity, stress, and with low particle density.

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