MIMC Reliability and Electrical Behavior Defined by a Physical Layer Property of the Dielectric

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Metal-Insulator-Metal Capacitor (MIMC) reliability and electrical properties are defined by the TDDB lifetime, breakdown voltage and leakage current. This article demonstrates the correlation between these electrical properties and the physical properties of the dielectric layer. The intrinsic quality of MIMC capacitors can therefore be predicted before complete processing by measuring a physical property of the MIMC dielectric.

Introduction

High-performance mixed-signal and RF circuits built in CMOS or BiCMOS require integrated capacitors with low voltage dependency, high quality factor, good capacitor matching, precision control of capacitor values and low parasitic capacitance, along with high reliability and a low defect density. Conventional high-density capacitors such as poly-substrate (1), poly–poly (2) and metal–poly (3), (4) structures suffer from low voltage independency due to voltage induced depletion effects as well as a large parasitic capacitance due to their proximity to the substrate. The metal–insulator–metal capacitors has thus become a key building block for mixed signal applications as it offers low parasitic capacitance, especially when fabricated on metal 2 or higher, as well as good linearity since the both electrodes are made of metal. Previous studies demonstrated that because of the higher dielectric constant of the PECVD nitride compare to oxide (5), nitride allows a higher capacitance for the same thickness of the dielectric. This makes it the most popular layer used as MIMC dielectric. On top of the performances in terms of capacitance density the MIMC must also meet specifications in terms of breakdown voltage, TDDB lifetime and leakage current. As these parameters strongly depend on the MIMC dielectric, our study focuses on the relation between the reliability and electrical properties of the MIMC and the physical properties of the dielectric film.

Experimental

The electrical requirements for the MIMC processed in AMIS are 1.5 fF/µm\textsuperscript{2} capacitance per area, 3.63 V maximum operating voltage, and less than 100 ppm 1\textsuperscript{st} order voltage coefficient. The capacitor is integrated using the 2\textsuperscript{nd} layer metal as bottom plate, a 475 Å thick PECVD nitride as dielectric and a special top plate metal (Metal 2.5) between the 2\textsuperscript{nd} and 3\textsuperscript{rd} layer metal (6). The PECVD nitride is deposited in a commercially available PECVD chamber.

In our experiments the total gas flow was varied from 100 to 160 sccm, the gas ratio (SiH\textsubscript{4}/NH\textsubscript{3}) from 2.2 to 2.7, the gap spacing from 540 to 700 mils, the RF power from
240 to 300 W and the pressure from 4.15 to 4.85 Torr. The refractive index and thickness were measured with a spectrometric ellipsometer on a 475 Å thick PECVD nitride layer deposited on bare silicon. The nitride layer was assumed to be transparent and modeled by a Cauchy layer fitted to the measured ellipsometric parameters for wavelengths ranging from 400 to 762 nm. The refractive index is given for a wavelength of 632.8 nm. The capacitance, leakage current and breakdown voltage were measured on 810,000 µm² MIMC in order to have a measurable leakage current. The leakage current was given for a bias voltage of 25V and was then expressed as current density in A/µm². The breakdown voltage is defined as the voltage at which the current is above 1 mA. TDDB measurements were performed on 40,000 µm² capacitor. The lifetime for a 100 ppm failing rate for an operating voltage of 3.63 V at 125 °C was extracted using the Frenkel-Poole model, best suited for nitride (7).

Energy dispersive X-ray (EDX) analysis was carried out on the SiN films to obtain elemental composition. A Leo 982 field emission scanning electron microscope (FESEM) equipped with an EDAX CDU Leap detector was used for EDX analysis. In order to minimize the signal from the Si substrate the wafers were coated with 2 µm aluminum prior to SiN PECVD Deposition. The energy of the incident electron beam was fixed at 8 keV. The peaks were identified as follows: N – 0.392 keV, Al – 1.487 keV and Si – 1.74 keV. The high intensity of the aluminum signal (not presented) clearly demonstrates that the SiN film was penetrated completely and that the composition analysis was performed over the entire depth of the nitride layer.

**Result and discussion**

**Electrical result**

In the first experiment the RF power and gap spacing were kept constant while gas ratio and gas flow were varied. Fig. 1 gives the leakage current density for a bias voltage of 25 V and breakdown voltage of the capacitors for the different plasma conditions.

![Figure 1: Leakage current density at 25 V and breakdown voltage in function of SiH4/NH3 gas ratio for 100 sccm (♦) 133 sccm (■) and 160 sccm (▲) gas flows.](image-url)
At low gas flow the leakage current density is in the order of magnitude from the equipment resolution and increases then exponentially with the reactant gas flow. For a total gas flow larger than 133 sccm, increasing the gas ratio increases also the leakage current density, probably by increasing the silicon fraction of the PECVD nitride as the silane proportion in the feed gas increases (8). The breakdown voltage is maximal for a gas flow of 133 sccm and insensitive to the gas ratio for gas flow ranging from 100 sccm to 133 sccm. Increasing the gas flow above the 133 sccm results in a reduction in breakdown voltage. This effect is emphasized when increasing the gas ratio.

In the second experiment, the gas flow and ratio were kept constant while the RF power was varied from 240 W to 300 W and the gap spacing from 540 mils to 700 mils. Fig. 2 plots the leakage current density at 25 V and the Breakdown voltage for various RF power and gap spacing.

The leakage is decreased by increasing the RF power or the gap spacing. At high gap spacing the leakage is below the equipment resolution and the impact of RF power on leakage is not measurable any more. Decreasing the RF power or the gap spacing makes the Breakdown voltage drop. For gap spacing above 637 mils the Breakdown voltage decreases slightly with increasing the RF power over 270 W.

In the third experiment the gas flow, gas ratio, gap spacing and RF power were kept constant while the impact of pressure on the MIMC electrical properties was measured. Fig. 3 plots the leakage current density for a bias voltage of 25 V and the breakdown voltage for pressure varying from 4.15 to 4.85 Torr. A decrease in pressure yields a slight decrease in breakdown voltage while the capacitor leakage increases. At high pressure the leakage is below the resolution of the measurement set-up and the breakdown voltage is not impacted by pressure variation.
Figure 3: Leakage current density at 25 V and breakdown voltage of pressure variation.

The three previous graphs show that the electrical properties of the MIMC, like breakdown voltage and leakage current, are extremely sensitive to the plasma parameters. It is also the case for the reliability properties of the MIMC. The TDDB lifetime of the capacitors was measured for various nitride dielectric obtained by varying the plasma parameters. Fig. 4 gives the lifetime extracted from TDDB measurements. The lifetime shows a very good correlation with breakdown voltage through an exponential relationship.

Figure 4: Lifetime in function of Breakdown voltage

For a Breakdown voltage of 34 V a lifetime of $1.10^8$ years can be expected. Decreasing Breakdown voltage to 30 V decreases the TDDB lifetime with 4 decades. The
knowledge of Breakdown voltage is thus a determining factor to predict the lifetime of the MIMC.

Effect on the Refractive index

Changing the plasma parameters changes the nitride properties as reported by the observation of leakage and MIMC breakdown voltage. However, spectroscopic ellipsometry is also used to monitor these changes of properties by measuring the refractive index. Fig. 5 plots the evolution of refractive index for the various plasma conditions from the previous graphs.

Figure 5: Refractive index in function of gas flow for 2.2 (♦), 2.5 (■), 2.7 (▲) SiH₄/ NH₃ gas ratio and in function of gap spacing for 240 W (+), 270 W (+), 300 W (X) RF power.

The refractive index decreases when decreasing the gas flow or gas ratio at high gas flow. Increasing the gap spacing or the RF power although decreases the refractive index. The impact of pressure on refractive index is shown in Fig. 6. The refractive index decreases linearly when increasing the pressure.
Correlation between electrical and physical properties

We have until now linked the physical, electrical and reliability properties of the nitride to the process parameters. This link is however only qualitative and might change in absolute value from one PECVD reactor to another due to for example to different chamber volumes or shift in gas flow, pressure gauge calibration. Fig. 7 directly links the electrical properties of the nitride to the RI, which is a parameter depending on the material itself.

The leakage is below measurement resolution for refractive index lower than 1.95 and increases then exponentially with refractive index. Breakdown voltage has a maximum at a refractive index of 1.96. The fact that the same change in refractive index induced by an increased gas flow or a decreased gap spacing or power gives the same response in

Figure 6: Refractive index in function of pressure.

Figure 7: Leakage and breakdown voltage versus refractive index for various plasma parameters variation: gas flow – gas ratio (GF GR), gap spacing - RF power (GP RF), gas flow, pressure (P).
electrical properties for both leakage and breakdown voltage, makes thus the refractive index a very good parameter to monitor inline the electrical and reliability properties of the PECVD nitride layer.

To further extend our analysis we performed EDX elemental analysis and correlate them with the refractive index. As shown in Fig. 8, the refractive index increases monotonically with the content in Si. The deviations are attributed to the EDX measurements error (5-10 %).

![Graph](image)

Figure 8: N to Si atomic ratio determined from EDX analysis versus refractive index for PECVD nitride deposited in various plasma conditions. The plain line represents the best-fit linear model.

The refractive index appears to be a very good parameter to monitor the material properties of the nitride layer, as the correlation between refractive index and N/si atomic ratio is valid for any way of varying the refractive index. For example, an increase in gas flow or a decrease in RF power, which presents the same response in terms of refractive index are in fact resulting of an identical change in nitride composition. It is of interest to note that the fit line intercept the point with a refractive index of 2.02 for an atomic ratio N/Si of 1.33, which is the values obtained for stoichiometric nitride. The PECVD nitrides from our study are N-rich nitride.

This last graph gives a physical explanation to the relation between refractive index and leakage. High leakage is induced by a higher silicon content of the nitride film. Reversely, nitrogen rich films are more insulating.

**Conclusion**

The nitride deposition conditions have been varied by different means, RF power, gas flow, gas ratio, gap spacing and pressure. Any variation in process conditions induces a change in physical composition and electrical properties of the nitride. The change in physical composition can be monitored by the measure of the refractive index, nitrogen rich nitride yielding lower refractive index. The change in electrical properties such as breakdown voltage, leakage and TDDB lifetime induced by a change in composition of the layer can therefore be monitored by the measure of the refractive index. The
refractive index is thus a parameter which allows a good monitoring of the intrinsic quality of the PECVD nitride and can detect process drifts in a manufacturing environment immediately and avoiding thus waiting for electrical and reliability measurements. Upper and lower specification limits can thus be fixed on refractive index which will ensure processing of nitride with the desired electrical and reliability properties.

Acknowledgments

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References