Comparison of Multilayer Dielectric Thin Films for Future Metal–Insulator–Metal Capacitors: \(\text{Al}_2\text{O}_3/\text{HfO}_2/\text{Al}_2\text{O}_3 \text{ versus SiO}_2/\text{HfO}_2/\text{SiO}_2\)

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Received February 10, 2011; accepted July 27, 2011; published online October 20, 2011

In this paper, we electrically characterized MIM capacitors with SHS and AHA sandwiched dielectrics and evaluated their dielectric reliability. We also carried out a comparative study of the AHA structure, which is considered to be one of the dielectric structures of future MIM capacitors. Although the electrical oxide thickness (EOT) of the AHA structure is much greater than that of the SHS structure, the comparative study is necessary because dielectric constant of the AHA structure is much greater than that of the SHS structure, which implies the possible adoption of an AHA structure for future AMS/RF circuit applications.

1. Introduction

Metal–insulator–metal (MIM) capacitors have been widely used as one of the key passive devices for radio frequency (RF) and analog mixed signal (AMS) integrated circuit (IC) applications. On-chip integrated capacitors with higher capacitance density have been required to increase functionality along with the scaling down of the capacitor area.¹ Conventional MIM capacitors with \(\text{SiO}_2\) (~3.9) and \(\text{Si}_3\text{N}_4\) (~7) have been used as insulator materials since they have stable dielectric characteristics, a good matching property, and low deposition temperature (400 °C), and can be easily integrated.² Even conventional MIM capacitors can indicate low voltage linearity, low temperature coefficients, and high quality for AMS/RF application, their use has been limited due to their low dielectric constant, high leakage current density with scaling down, and necessity for high capacitance density for high performance.³⁻⁵ To obtain a low leakage current and high capacitance density, a high-\(k\) (HK) dielectric for MIM capacitors has been proposed to replace conventional \(\text{SiO}_2\) and \(\text{Si}_3\text{N}_4\). Several HK dielectrics such as \(\text{HfO}_2\) (~25), \(\text{Al}_2\text{O}_3\) (~9), and \(\text{ZrO}_2\) (~20) have been investigated in order to achieve high capacitance density and to reduce the cell area.³⁻⁵ Among the various HK dielectric candidates, \(\text{HfO}_2\) has been investigated as a promising material in MIM capacitors due to its high dielectric constant, excellent thermal stability, and wide band gap.⁶ However, MIM capacitors with a single HK dielectric can exhibit high leakage current due to the low band offset and unstable interactions between metal and the HK dielectric. Hence, it is necessary to reduce the leakage current induced by a single HK dielectric by adding \(\text{SiO}_2\) or \(\text{Al}_2\text{O}_3\) as a sandwich structure to the \(\text{HfO}_2\) layer, which is called \(\text{Al}_2\text{O}_3/\text{HfO}_2/\text{Al}_2\text{O}_3\) (AHA) or \(\text{SiO}_2/\text{HfO}_2/\text{SiO}_2\) (SHS).⁷⁻⁹ As a sandwich structure in the \(\text{HfO}_2\) layer, ultrathin \(\text{Al}_2\text{O}_3\) or \(\text{SiO}_2\) improves interface quality and leakage current between the metal and the insulator because it increases the barrier height; however, there have been few reports on the concurrent investigation of electrical performance and reliability.

2. Experiments

MIM capacitors were fabricated on 8-in. p-type silicon substrates. First, the bottom electrode was formed on a 500-nm-thick \(\text{SiO}_2\) layer. \(\text{SHS}\) (3 nm/4 nm/3 nm) and \(\text{AHA}\) (2 nm/11 nm/2 nm) stacked layers were then sequentially deposited using the atomic layer deposition (ALD) method at 300 °C. Finally, the top electrode was formed on the dielectric layers.

Capacitance–voltage (\(C–V\)) characteristics were measured using an HP4284A precision inductance capacitance resistance (LCR) meter (HP4284A) at frequencies from 1 kHz to 1 MHz. Before \(C–V\) measurement, open/short calibration was performed to remove the parasitic series resistance and capacitance. Leakage current and reliability characteristics were measured using an Agilent 4156C semiconductor parameter analyzer, which was connected to a probe station with a temperature-controlled heating plate.

3. Results and Discussion

Figure 1 shows the capacitance density and dissipation factor as a function of frequency for the sandwiched MIM capacitors. Capacitance density remained around 5.1 IF/µm² (SHS) and 8.0 IF/µm² (AHA) at a frequency range from 1 kHz to 1 MHz. In addition, a low dissipation factor below 0.05 was also observed over the entire frequency range, which is low enough for RF application.¹⁰ Although the
physical thickness of the AHA structure is thicker than that of the SHS structure by about 50%, the capacitance density of the AHA structure is greater than that of the SHS structure by about 60%. It suggests that AHA structure is desirable for next-generation MIM capacitor.

The voltage coefficient of capacitance (VCC) is one of the key parameters for a MIM capacitor in AMS/RF applications. The normalized capacitance of MIM capacitors can be obtained by fitting the measured data with the second-order polynomial equation (1):

$$
C(V) = C_0(\alpha V^2 + \beta V + 1) \Rightarrow \frac{C(V) - C_0}{C_0} \times 10^6
$$

$$
= \frac{\Delta C}{C_0} \times 10^6
$$

$$
= [\alpha V^2 + \beta V] \text{ ppm}, \quad (1)
$$

where $C_0$ is the zero-biased capacitance, $\alpha$ and $\beta$ are the quadratic and linear VCC, respectively, and $V$ is the applied voltage. Because $\beta$ can be canceled out by the circuit design, the value of $\alpha$, which is one of the main focuses of this paper, was extracted from the $\Delta C/C_0$ versus voltage, as shown in Fig. 2. The extracted value of $\alpha$ of the sandwich SHS and AHA MIM capacitors were 31.90 and 694.1 ppm/V$^2$, respectively. Therefore, care should be taken in the AHA structure to decrease $\alpha$ for AMS application. The extracted $\alpha$ had a strong dependence on frequency, as shown in Fig. 3, which is undesirable but is a common property of MIM capacitors with HK dielectrics. It can be seen that logarithmic $\alpha$ decreases linearly with a logarithmic increase in frequency. The SHS structure shows more stable $\alpha$ values at a greater frequency range than the AHA structure due to the non-dispersive characteristic of the SiO$_2$ layer. The charge mobility becomes smaller with increasing frequency as well, which leads to higher relaxation time and a smaller capacitance variation. The frequency dependency of $\alpha$ can be explained as the change of relaxation time with different carrier mobilities in HK dielectrics.

To strictly evaluate the electrical properties of the capacitors (AHA versus SHS), the breakdown electric field under positive and negative voltage are compared in Fig. 4. The leakage currents of the SHS and AHA dielectrics at 1 MV/cm were $1.3 \times 10^{-8}$ and $9.2 \times 10^{-8}$ A/cm$^2$, respectively. Although the SHS MIM capacitor exhibits a smaller leakage current than AHA at the low electric field region, the AHA structure shows a greater breakdown electric field and lower leakage current in the higher electric field region, because HfO$_2$ dominates the leakage current of both MIM structures and the AHA structure has a greater physical thickness HfO$_2$ than the SHS structure.
projected electric field for a 10-year lifetime at 125°C is 1.53 MV/cm (SHS) and 1.61 MV/cm (AHA) as shown in Fig. 6. In addition, the breakdown electric field of the SHS and AHA MIM capacitors is 3.03 MV/cm (SHS) and 3.38 MV/cm (AHA), which seems to be in good agreement with the recently reported breakdown field of HK dielectrics. The 10-year life time and breakdown strength are almost identical, which implies that HfO₂ dominates the TDDM degradation of the two MIM capacitors. In addition, the activation energy was derived from the Arrhenius plot. The extracted activation energy was estimated to be 1.14 eV for the SHS and 1.10 eV for the AHA MIM capacitors, as shown in Fig. 7. Therefore, it is believed that same mechanism dominates the TDDM of the two structures because the activation energy of these structures is almost the same.

4. Conclusions
The electrical performance and reliability characteristics of multilayered MIM capacitors with AHA and SHS were characterized and compared. Although the physical thickness of the AHA structure is greater than that of SHS structure, the AHA structure exhibits greater capacitance density which is desirable for next-generation MIM capacitors. The variation of quadratic VCC under CVS gradually decreased, which may be attributed to the phenomenon of charge trapping due to the generation of new dipoles in the HK dielectrics. It is shown that variation of quadratic VCC of SHS structure is smaller than that of AHA MIM capacitor. It is shown that the TDDM degradation of the two structures is dominated by the same mechanism as the extracted activation energy of the two structures is similar.

Acknowledgments
This work was partly supported by the IT R&D program of MKE/KEIT (10030838, Development of Oxide Trench Etcher beyond 25 nm). This research was also financially supported by the Ministry of Knowledge Economy (MKE) and Korea Institute for Advancement in Technology (KIAT) through the Workforce Development Program in Strategic Technology.

Figure 5 shows the relative variation of quadratic VCC, α/α₀ under constant voltage stress (CVS). There is little difference in α/α₀ between the two MIM structures. The change of capacitance as a function of stress time becomes saturated as stress time increases, as shown in the inset for both structures. In fact, the increase in capacitance is correlated with the increase of the dipole effect in the dielectric due to the charge trapping behavior. In addition, the trapped charges can result in a decrease in the carrier mobility in the HK dielectrics due to electrostatic scattering, which can lead to a smaller α, because the dielectric constant and carrier mobility become smaller under CVS. Therefore, the trapped charges of the HfO₂ layer result in decreased carrier mobility which can be attributed to a smaller α and higher capacitance, according to the free-carrier injection model.

Regarding the stability of MIM capacitors with HK dielectrics, it is necessary to clarify the long-term voltage stress effect. The time dependent dielectric breakdown (TDDBM) reliability of the SHS and AHA MIM capacitors is evaluated under different CVS conditions at 125°C. The dielectric constant and carrier mobility become smaller under CVS. This is because the dielectric constant and carrier mobility become smaller under CVS. It is shown that the TDDBM degradation of the two structures is dominated by the same mechanism as the extracted activation energy of the two structures is similar.

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