A High-Density MIM Capacitor (13 fF/μm^2) Using ALD HfO$_2$ Dielectrics

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***Abstract*—Metal–insulator–metal (MIM) capacitors with a different thickness of HfO$_2$ have been investigated. The results show that both the capacitance density and voltage coefficients of capacitance (VCCs) increase with decreasing the HfO$_2$ thickness. In addition, it is also found that the VCCs decrease logarithmically with increasing the thickness of HfO$_2$. Furthermore, the MIM capacitor with 10-nm HfO$_2$ shows a record high capacitance density of 13 fF/μm^2 and a VCC of 607 ppm/V, which can meet the requirement of the International Technology Roadmap for Semiconductors. It can also provide a low leakage current of 5.95×10^{-8} A/cm^2 at room temperature at 1 V, low tangent values below 0.05, and a small frequency dependence as well. All these indicate that it is very suitable for use in silicon integrated circuit applications.**

***Index Terms*—Frequency dependency, high capacitance density, metal–insulator–metal (MIM) capacitor, thin-film devices, voltage coefficient of capacitance (VCC).**

I. INTRODUCTION

UNTIL recently, the metal–insulator–metal (MIM) capacitors have attracted great attention in silicon integrated circuit (IC) applications because of their high-conductive electrode and low parasitic capacitance [1]–[3]. A high capacitance density is required for a MIM capacitor in order to make the area small, increase the circuit density, and further reduce the cost [4]. Therefore, adoption of high-κ material is a very efficient way to increase the capacitance density [5]. HfO$_2$ is now being researched as a very promising candidate for gate dielectrics in MOSFET applications [6], [7]. Furthermore, a very good-performance HfO$_2$ MIM capacitor with a capacitance density of 3.0 fF/μm^2 has been demonstrated [8]. Further increased capacitance density can be implemented by scaling down the dielectric thickness, which, however, may result in higher voltage coefficients of capacitance (VCCs) [9]. It has been reported that the VCCs were inversely proportional to the square of the dielectric thickness for MIM capacitors with Si$_3$N$_4$ [9]. However, there is no report on the thickness dependence of VCCs for HfO$_2$ MIMs. Thus, the effect of dielectric thickness on capacitor performance needs to be investigated.

In this letter, the effects of different thicknesses of high-κ HfO$_2$ on capacitor performance were investigated for the first time, including capacitance density, frequency dispersion, VCCs, and leakage current. All the HfO$_2$ MIM capacitors are fabricated with a maximum processing temperature of 400 °C, which are compatible with back end of line (BEOL). The structure and fabrication process are described. Device characteristics are measured and discussed.

II. EXPERIMENTS

The MIM capacitors with HfO$_2$ high-κ dielectric films were fabricated on 500-nm SiO$_2$ deposited on silicon substrate. Before high-κ dielectrics deposition, a layer of 100-nm Ta film was deposited on SiO$_2$ as the bottom electrode. Following that, high-κ HfO$_2$ dielectric films were prepared by atomic layer deposition (ALD) at 300 °C. The reactants are HfCl$_4$ and H$_2$O, and the deposition rate is $\sim$0.8 Å per cycle. Then, a layer of Ta was deposited as the top electrode. Following that, a photolithography step and dry etching were conducted to define the MIM capacitors. Finally, annealing was performed at 400 °C with N$_2$/H$_2$ ambient for 30 min. In order to investigate the effect of dielectric thickness, three samples of the MIM capacitors with 10-, 20-, and 30-nm physical thicknesses of HfO$_2$ were fabricated.

The leakage current was measured using an HP4155B semiconductor parameter analyzer, and the capacitance was measured using an HP4284A precision *LCR* meter at frequencies varied from 1 kHz to 1 MHz by applying a small ac (25-mV amplitude) signal.

III. RESULTS AND DISCUSSION

Fig. 1 shows the capacitance density and loss tangent value as a function of frequency for all three HfO$_2$ dielectric MIM capacitors. It can be seen that the capacitance density increases with decreasing the HfO$_2$ thickness, ranging from 5.0 fF/μm^2 of 30-nm HfO$_2$ to 13.0 fF/μm^2 of 10-nm HfO$_2$. It is also observed that the frequency dependency of HfO$_2$ capacitors with thicknesses of 10, 20, and 30 nm are almost the same. On the other hand, no obvious differences in loss tangent values ($1/Q$ factor)

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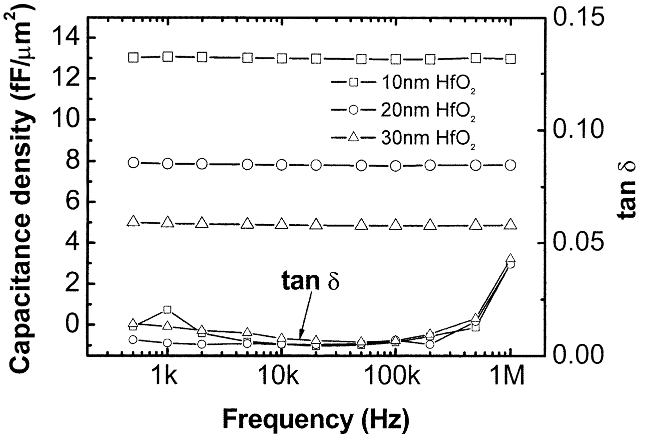


Fig. 1. Capacitance densities and loss tangent values of MIM capacitors with a different HfO_2 thicknesses of 10, 20, and 30 nm as a function of frequency.

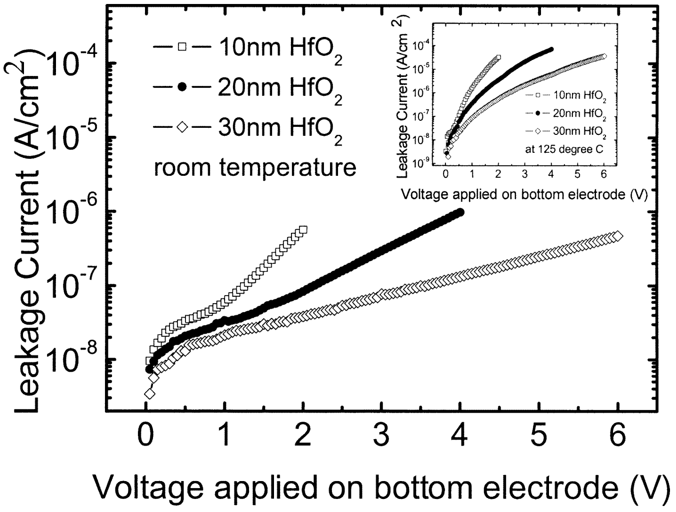


Fig. 2. J–V characteristics of the MIM capacitors with the HfO_2 thicknesses of 10, 20, and 30 nm measured at room temperature and 125 °C.

are observed for any of the samples. All three samples show low-loss tangent values below 0.05 over the entire frequency range from 500 Hz to 1 MHz.

Fig. 2 shows the current density–voltage (J–V) characteristics of HfO_2 MIM capacitance with a different HfO_2 thicknesses of 10, 20, and 30 nm. It is shown that the leakage current decreases with increasing the dielectric thickness of HfO_2. From Fig. 2, the HfO_2 MIM capacitor with 10 nm shows leakage current of 5.95×10^{-8}A/cm^2 (room temperature) and 1.55×10^{-6}A/cm^2 (125 °C) at 1 V. The increased leakage currents of three samples at 125 °C indicate that many traps exist within the films which are possibly due to the low-temperature process. The breakdown voltages of 10-, 20-, and 30-nm HfO_2 MIM capacitors are 2.9, 7.35, and 9.45 V, respectively.

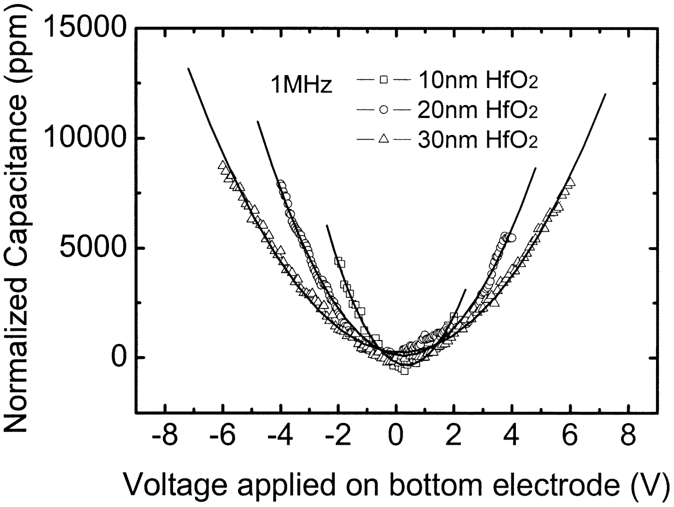


Fig. 3. Normalized capacitance of the MIM capacitors with the HfO_2 thickness of 10, 20, and 30 nm.

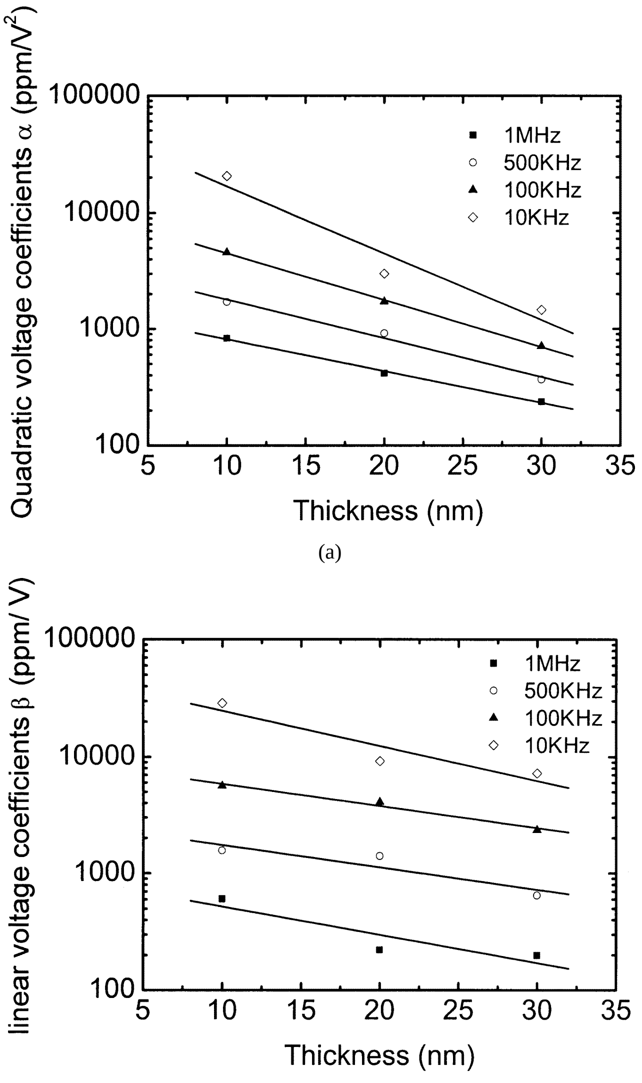
Capacitance voltage linearity is a very important parameter that depends on a number of factors such as material properties of the dielectric film. Fig. 3 shows the normalized capacitance of the MIM capacitor with applied voltage on the bottom electrode at 1 MHz. It is shown that the curve becomes more bent when the HfO_2 thickness of MIM capacitors decreases from 30 to 10 nm, which implies that the capacitance of the HfO_2 MIM capacitors has a stronger voltage dependence with decreasing dielectric thickness.

The voltage dependence of capacitance can be calculated and compared with the VCCs, which can be characterized by

$$C(V) = C_0(\alpha V^2 + \beta V + 1)$$

where C_0 is the zero-biased capacitance at each frequency, and α and β are the quadratic and linear voltage coefficient, respectively. The capacitances are measured at 10 kHz, 100 kHz, 500 kHz, and 1 MHz, respectively. The obtained α and β values are shown in Fig. 4(a) and (b). It can be seen that smaller α and β values are measured at higher frequencies, which can be explained as a result of the slow time constant of traps within the HfO_2 dielectrics. It is also observed that both α and β decrease with increasing dielectric thickness, decreasing from $\sim$831 ppm/V^2 to $\sim$238 ppm/V^2 for α values and from $\sim$607 ppm/V to $\sim$206 ppm/V for β values. As shown in Fig. 4(a) and (b), both α and β decrease logarithmically with increasing thickness of HfO_2.

The quadratic coefficients of capacitance α is mainly driven by the MIM capacitor application in analog circuit, as the linear coefficient of capacitance can be cancelled out by circuit design. The requirement of α value is smaller than 100 ppm/V^2. The linear coefficient of capacitance β is mainly driven by the RF application of the MIM capacitor. According to the ITRS roadmap, the requirements of the MIM capacitor for RF applications are a high capacitance density of 12 fF/μm^2 and a VCC below 1000 ppm/V [4]. The MIM capacitor with the 10-nm HfO_2 shows a high capacitance density of 13 fF/μm^2 and a low VCC of $\sim$607 ppm/V, which can easily meet the requirements of the ITRS roadmap. Also, low dissipation factors below 0.05, a low leakage current of 5.95×10^{-8}A/cm^2 (room temperature) and 1.55×10^{-6}A/cm^2 (125 °C) at 1 V, and a small frequency dependency are also obtained. All these indicate that the 10-nm HfO_2 MIM capacitor is very suitable for use in silicon IC applications.



(a)

(b)

Fig. 4. (a) Quadratic voltage coefficients α of capacitance of HfO_2 MIM capacitors as a function of thickness. (b) Linear voltage coefficients β of capacitance of the HfO_2 MIM capacitors as a function of thickness.

IV. CONCLUSION

MIM capacitors with different thicknesses of HfO_2 have been investigated. The results showed that both the capacitance density and VCCs increase with decreasing the HfO_2 thickness. It was also found that the VCCs decrease logarithmically with increased thickness of HfO_2. Furthermore, the MIM capacitor with 10-nm HfO_2 shows a high capacitance density of 13 fF/μm^2 and a VCC of 607 ppm/V, which can meet the requirement of the ITRS roadmap. It can also provide a low leakage current of 5.95×10^{-8}A/cm^2 (room temperature) and 1.55×10^{-6}A/cm^2 (125 °C) at 1 V, low tangent values below 0.05, and a small frequency dependence. All these indicate that it is very suitable for use in silicon IC applications.

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