PVD HfO_2 for High-Precision MIM Capacitor Applications

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***Abstract*—Metal–insulator–metal (MIM) capacitors are fabricated using sputtered HfO_2 with Ta and TaN for top and bottom electrodes, respectively. High-capacitance densities from 4.7 to 8.1 $fF/\mu m^2$ have been achieved while maintaining the leakage current densities around 1×10^{-8} A/cm^2 within the normal circuit bias conditions. A guideline for the insulator thickness and its dielectric constant has been obtained by analyzing the tradeoff between the linearity coefficient and the capacitance density.**

***Index Terms*—Capacitance density, HfO_2, metal–insulator–metal (MIM) capacitor, sputter, voltage coefficient of capacitor (VCC).**

I. INTRODUCTION

MOST of the high-precision metal–insulator–metal (MIM) capacitors, one of the key passive components in RF/mixed signal circuit devices [1]–[7], currently use PECVD SiO_2 or Si_3N_4 dielectrics with capacitance density of around 1 $fF/\mu m^2$ [3], [7]. Recently, there has been great interest in replacing those conventional dielectrics with higher dielectric constant materials such as Al_2O_3, Ta_2O_5, TiO_2, HfO_2, etc. [9]–[12] to increase capacitance density while maintaining low-leakage current. It has been reported that HfO_2 is one of the promising materials for the MIM capacitor, showing good performances such as high capacitance density, low-leakage current, and small VCC and TCC [12]. However, the deposition method, pulsed laser deposition (PLD), used in the literature is not a practical technique for mass production. More recently, it has been demonstrated that the $(HfO_2)_{I-x}(Al_2O_3)_x$ MIM capacitor prepared by atomic layer deposition (ALD) provides a high capacitance density of 3.5 $fF/\mu m^2$ and low VCC value ($\sim$ 140 ppm/V^2) [13]. However, since the dielectric thickness range for an analog MIM capacitor is much thicker than the gate dielectric and DRAM capacitor applications, the ALD process has a low throughput problem when it is used for analog MIM capacitor application. In this paper, the feasibility of sputtered HfO_2 MIM capacitors for future RF/mixed signal circuit applications is investigated. Results on capacitance density and leakage are compared with recent publications and the ITRS requirement. In addition, the relationship between the linearity coefficient, VCC, and capacitance density has also been studied.

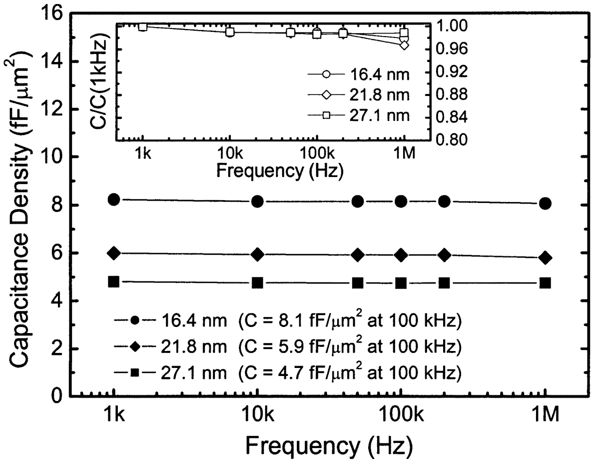

Fig. 1. Capacitance densities of MIM capacitors using three different HfO_2 thicknesses. Densities from 4.7 up to 8.1 $fF/\mu m^2$ have been achieved. Inset shows percentile changes in capacitances with respect to the values at 1 kHz. Dispersions range from 1.2% to 3.2%.

II. EXPERIMENTS

$Ta/HfO_2/TaN$ multilayer MIM capacitor structures were fabricated on a thick field oxide layer. After TaN bottom electrode deposition, HfO_2 was reactively deposited at room temperature in a magnetron sputtering system flowing a gas mixture of O_2 (2 sccm) and Ar (23 sccm). The pressure was maintained at 3 mtorr and a dc power of 200 W was employed. Samples with three different HfO_2 thicknesses, 16.4, 21.8, and 27.1 nm measured by TEM, were prepared. From the TEM analysis and capacitance value, the extracted effective dielectric constant k of the sputtered HfO_2 is 15. The films were annealed at 420 °C in a forming gas ambient (H_2/N_2) before Ta deposition for the top electrode. The area and the perimeter of the MIM capacitors are 168 100 μm^2 and 2576 μm, respectively.

III. RESULTS AND DISCUSSIONS

A. Capacitance Density and Leakage Currents

Capacitance densities of the sputtered HfO_2 MIM capacitors are shown in Fig. 1 as a function of measured frequency. High densities, ranging from 4.7 to 8.1 $fF/\mu m^2$, have been obtained

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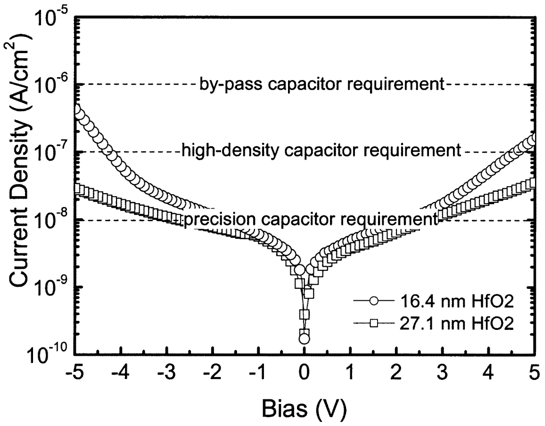


Fig. 2. Leakage currents for 16.4- and 27.1-nm-thick HfO_2 MIM capacitors, which are low enough for most RF and analog applications. Requirements for specific applications are indicated with dashed lines.

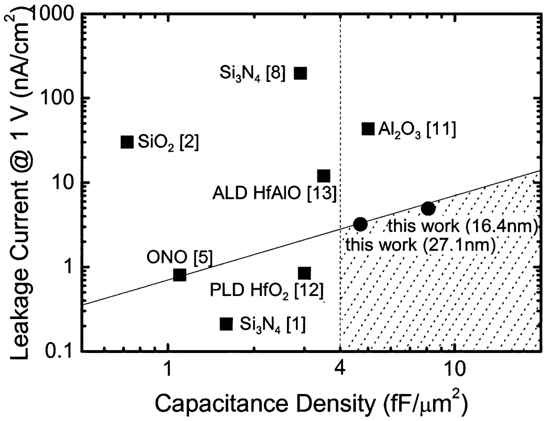


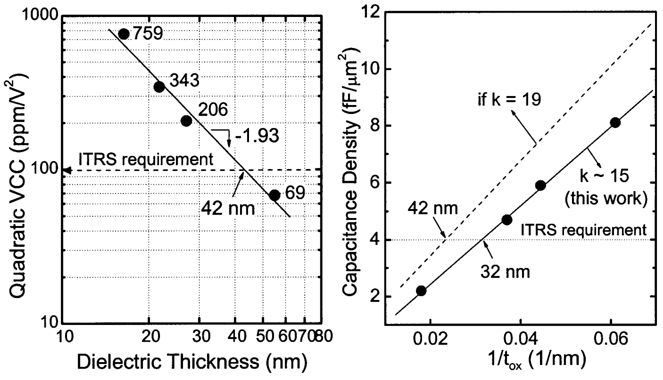
Fig. 3. Performance comparison with results in recent publication. Hatched area is where both the capacitance and the leakage current densities meet the ITRS requirement.

from the capacitors using three different HfO_2 thicknesses. The capacitance obtained is around 5∼8 times higher than current SiO_2 or Si_3N_4-based MIM capacitors [3], [7]. The capacitance values remained nearly unchanged throughout the measured frequency up to 1 MHz. The percentile variations with respect to the value at 1 kHz are shown in the inset of Fig. 1. The variations are 3.2%, 2.1%, and 1.2% for 21.8-, 16.4-, and 27.1-nm-thick HfO_2 samples, respectively. These values are comparable or smaller than those of ALD HfO_2 and Al_2O_3 MIM capacitors [13]. Fig. 2 shows the leakage current densities of 16.4- and 27.1-nm-thick HfO_2 MIM capacitors. Desired device requirements for on-chip capacitors for RF and mixed-signal applications are indicated with dashed lines in the figure for easy assessment. The leakage current densities are fairly low within the normal bias range from -3 to $+3$ V meeting ITRS requirements.

The performances of the 16.4- and 27.1-nm-thick HfO_2 MIM capacitors are compared with published results and ITRS requirements on both capacitance density and leakage current density in Fig. 3. The dashed line indicates the capacitance density requirement. According to the latest ITRS, a capacitor density of 4 $\mathrm{fF}/\mu\mathrm{m}^2$ or higher is required for precision analog capacitors from year 2005 to 2007 [14]. As for the leakage current, 7 $\mathrm{fA}/[\mathrm{pF} \bullet \mathrm{V}]$ or lower is required, which corresponds to the area below the solid line in Fig. 3. The hatched area in the figure is where both the capacitance and the leakage current densities meet the ITRS requirements. From this figure, one can see that our PVD HfO_2 MIM capacitors data lie within that boundary, meeting ITRS requirements for analog capacitor applications up to year 2007. Although Al_2O_3 MIM capacitor [11] also exhibits sufficiently high capacitance density, it suffers from severe leakage current.

B. Linearity Coefficients and Capacitance Density

The relationship between the linearity coefficient of a capacitor and its density was investigated and shown in Fig. 4(a) and (b). The quadratic VCC, α, of the capacitors with three different HfO_2 thicknesses are plotted in Fig. 4(a). The α and linear VCC, β, are usually extracted from the polynomial curve fitting on the CV plots which is expressed as $\Delta\mathrm{C}/\mathrm{Co} = \alpha\mathrm{V}^2 + \beta\mathrm{V}$.



(a) (b)

Fig. 4. (a) Quadratic VCC, α, versus HfO_2 thickness. HfO_2 thicker than 42 nm is required to meet the requirement of 100 $\mathrm{ppm}/\mathrm{V}^2$. (b) Capacitance density versus the reciprocal of dielectric thickness. HfO_2 film thinner than 32 nm is required if $k = 15$ is to meet the requirement of 4 $\mathrm{fF}/\mu\mathrm{m}^2$, while the film thinner than 42 nm is required if $k = 19$.

The quadratic term α indicates the variance of the capacitance on the applied bias, while the linear term β shows the balance of the capacitance. While the capacitors with capacitance densities higher than 4 $\mathrm{fF}/\mu\mathrm{m}^2$ are of interest, an additional capacitor using thick HfO_2 was also fabricated in order to provide more reliable projections in Fig. 4(a) and (b). The α values as a function of HfO_2 thickness exhibit a gradient of -1.93 in log–log scale. This result is consistent with that of the Ta_2O_5 MIM capacitor, which was once reported to be inversely proportional to the square of the dielectric thickness [9]. From the plot in Fig. 4(a), we can see that, in order to meet ITRS 2007 requirement of $\mathrm{VCC} - 100\ \mathrm{ppm}/\mathrm{V}^2$ for the precision analog capacitor [14], the HfO_2 film must be thicker than 42 nm. Meanwhile, when capacitance densities are plotted against the reciprocal of dielectric thickness as shown in Fig. 4(b), we can see that the extrapolation of the line crosses 4 $\mathrm{fF}/\mu\mathrm{m}^2$ at 32 nm on the x axis. This indicates that HfO_2 must remain thinner than 32 nm in order to meet density requirement for precision capacitor. The dashed line in Fig. 4(b) is from calculations assuming that the k value is 19. The result of $k = 19$ crosses 4 $\mathrm{fF}/\mu\mathrm{m}^2$ at 42 nm. From the TEM analysis and capacitance value, the effective dielectric constant k of our PVD HfO_2 is found to be 15. A slight improvement on PVD HfO_2 film quality to increase the effective dielectric constant or the leakage current density will satisfy both linearity and capacitance density requirements. Further improvement of our PVD HfO_2 film quality by optimizing the process conditions is underway.

IV. CONCLUSION

High-performance MIM capacitors have been fabricated using sputtered HfO_2. The capacitance densities and the leakage current characteristics satisfy the ITRS requirements for analog capacitor up to year 2007, indicating that the sputtered HfO_2 is a very promising candidate for precision MIM capacitors. In addition, a preliminary guideline for the insulator thickness and its dielectric constant has been obtained from the tradeoff between the linearity coefficients and the capacitance density.

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