High-Density RF MIM Capacitors Using High-\(k\) La\(_2\)O\(_3\) Dielectrics

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The integrity of the metal-insulator-metal (MIM) capacitor with high-\(k\) La\(_2\)O\(_3\) dielectrics formed using a 400°C back-end process was investigated. A very high capacitance per unit area of 9.2 \(\text{pF/\mu m}^2\) was achieved for La\(_2\)O\(_3\) MIM capacitors at 1 MHz, significantly reducing the chip size of radio frequency (rf) circuits. A mathematical derivation, involving measured \(S\) parameters, yielded the small voltage-dependent capacitance \((\Delta C/V) < 100 \text{ ppm at } 1 \text{ GHz}\), indicating that the precision capacitor circuit can be applied in the rf regime. Furthermore, such a high capacitance density can be maintained as the frequency is increased from 10 kHz to 20 GHz with a large \(Q\) factor \(\gg 90\).

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Experimental

MIM capacitors were fabricated using 4 in. p-type Si wafers. A 500 nm layer of isolation-oxide was first deposited on Si wafers to integrate the high-\(k\) capacitors into the VLSI back-end process. The bottom electrode of the MIM capacitor was formed on the isolation-oxide using Pt/Ti bilayer metals. The bottom electrode was also patterned to generate the coplanar transmission line for rf measurements. Then, high-\(k\) La\(_2\)O\(_3\) was formed by depositing La metals on the Pt electrode, oxidizing at 400°C for 45 min, and then annealing for 15 min. The above process meets the lower thermal budget requirement of current VLSI backend integration. La\(_2\)O\(_3\) dielectrics with thicknesses of 22 and 29 nm were formed. Then, Al metal was deposited on the high-\(k\) dielectrics, and patterning to form the top electrode of the MIM capacitor and the coplanar transmission line for rf measurements. The typical area of the MIM capacitor was 50 \(\times\) 50 \(\mu\text{m}^2\). The properties of the La\(_2\)O\(_3\) capacitors were measured using an HP4284A precision inductor-capacitor-resistor (LCR) meter at frequencies from 10 kHz to 1 MHz, and the \(S\) parameters were measured using an HP8510C network analyzer at frequencies from 200 MHz to 20 GHz. Standard de-embedding was performed, and a through transmission line was also de-embedded to reduce the parasitic series inductance to cause resonance.

Results and Discussion

DC leakage current characteristics.—Figure 1 plots the leakage current density vs. voltage \((J-V)\) characteristics of La\(_2\)O\(_3\) MIM capacitors. The leakage current falls rapidly as the thickness of the dielectric increases, because of electron tunneling. The asymmetry of the \(J-V\) characteristic at different polarity bias voltage follows from the different work functions of the top Al and bottom Pt electrodes. The leakage current density of 22 nm La\(_2\)O\(_3\) capacitors at \(\text{1 V}\) is \(<10^{-5}\ \text{A/cm}^2\). The relatively high leakage current is measured in La\(_2\)O\(_3\) because of simple fabrication process. The results obtained for the authors’ previously made AlTaO\(_x\) MIM capacitor were also higher than those for the Ta\(_2\)O\(_5\) grown by advanced atomic-layer chemical-vapor-deposition (ALCVD). However, the capacitance density plotted in Fig. 2 is very high, 9.2 \(\text{pF/\mu m}^2\), so the leakage current density is still sufficiently low to be used in rf circuits. The leakage current density can be further reduced using advanced ALCVD. For a typical, large capacitor of 10 \(\mu\text{F}\) used in rf circuits, leakage currents of under \(10^{-10}\ \text{A}\) were obtained, comparable or even slightly lower than the leakage currents in deep submicrometer MOSFETs. Notably, as VLSI technology continues to be scaled down to the 90 nm node, the operating voltage of the circuit falls only to 1.2 \(\text{V}\). This lower operating voltage and higher operating speed of MOSFETs and circuits are important advantages that reduce the energy-delay product. The lower operating voltage also helps to increase the capacitance density of MIM capacitors without the need for very thick dielectrics.

\(C-V\) characteristics at intermediate frequencies from 10 \(\text{kHz}\) to 1 MHz.—For precision analog circuit applications, MIM capacitors must be effective over a wide range of frequencies. Figure 2 plots the capacitance density \(C\) vs. voltage \((C-V)\) characteristics of La\(_2\)O\(_3\) MIM capacitors. At 1 MHz, high capacitance densities of 9.2 and 6.9 \(\mu\text{F/cm}^2\) are measured for La\(_2\)O\(_3\) capacitors with physical thicknesses of 22 and 29 nm, respectively. The corresponding \(k\) values are 23 for La\(_2\)O\(_3\) dielectrics. \(C-V\) data at 1 MHz are derived from measured \(S\) parameters and equivalent circuit models, considered in a later section.

The capacitance variation, voltage-dependent capacitance \((\Delta C/V)\), is important in precision circuit applications, so \(\Delta C/V\) is determined from the plotted \(C-V\) measurements. Figure 3a and b plot \(\Delta C/V\) for La\(_2\)O\(_3\) MIM capacitors, with physical thicknesses of 22 and 29 nm, respectively. The \(\Delta C/V\) data below 1 MHz are taken from the \(C-V\) plot in Fig. 2, while those above 1 MHz are taken

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from the measured S parameters shown below and from the authors’ previously derived equations.\textsuperscript{14} The asymmetry of the $\Delta C/C$ is caused by the difference between the top Al and bottom Pt electrodes, as in the case of the asymmetry in the $J$-$V$ characteristics, plotted in Fig. 1. Notably, although $\Delta C/C$ is high at 10 KHz, it falls dramatically to a value of $\approx 100$ ppm as the frequency is increased to above 1 GHz. Notably, the $\Delta C/C$ results are better than were obtained for AlTaO\textsubscript{x},\textsuperscript{15} and important for analog circuit matching.

Figure 4 plots $\Delta C/C$ and quadratic voltage coefficient, $\alpha$, against frequency to elucidate further the frequency dependence of $\Delta C/C$ and related $\alpha$. The relationship between $\alpha$ and $\Delta C/C$ is expressed as follows

\[ \Delta C/C = \alpha V^2 + \beta V \]  

The term $\beta$ is the linear voltage coefficient, and is less important than $\alpha$ according to the circuit cancellation method.\textsuperscript{20} Again, $\Delta C/C$ and $\alpha$ fall monotonically as the frequency is increased. Small $\Delta C/C \approx 100$ ppm and $\alpha \approx 130$ ppm/V\textsuperscript{2} are obtained as the frequency is increased into the gigahertz regime, implying that the high-k MIM capacitors can be used in precision circuits at operating frequencies into the gigahertz regime. High-k HfO\textsubscript{2} MIM capacitors also exhibit declining $\Delta C/C$ and $\alpha$ as the frequency rises to 1 MHz;\textsuperscript{20} a possible mechanism for this frequency dependence is the change in the relaxation time in the high-k dielectric, since the carriers inside the high-k dielectric cannot follow the switching signal at very high signal frequencies.\textsuperscript{20} This model also explains the continuous decrease in $\Delta C/C$ and $\alpha$ as the frequency increases into the gigahertz regime. Notably, the current rf circuits presently used in wireless communication are in the gigahertz regime (0.9–1.9 GHz for handset, 2.4 GHz for Bluetooth, 5.2–5.7 GHz for wireless LAN, and 3.1–10.6 GHz for ultrawide band). Hence, $\Delta C/C$ in the gigahertz regime is extremely important in both current and future rf communication.

Weak dependence of capacitance on temperature is also an important factor in circuit application. Figure 5 plots the $\Delta C/C$ of La\textsubscript{2}O\textsubscript{3} MIM capacitors as functions of temperature in both current and future rf communication.
manner consistent with Fig. 3. The $\Delta C/C$ increases with temperature, exhibiting the same trend as other dielectric capacitors published in the literature.\textsuperscript{7}

\textbf{S-parameters and rf analysis from 200 MHz to 20 GHz.—}The maximum frequency at which conventional $C$-$V$ measurements can be made using a precision LCR meter is only 1 MHz; the capacitance $C$ and $\Delta C/C$ at rf frequency must be extracted from measured $S$ parameters. Figure 6a and b plot the measured $S$ parameters of 22 and 29 nm La$_2$O$_3$ MIM capacitors, respectively. Figure 7 shows the equivalent circuit model for MIM capacitors. Figure 2 and 3 also present extracted $C$ and derived $\Delta C/C$ using our previously published equations and measured $S$ parameters at 1 and 10 GHz. The $\Delta C/C$ decreases monotonically by orders of magnitude as the frequency is increased into the gigahertz frequency regime and is sufficiently low to support high-precision circuit applications\textsuperscript{20} in this frequency regime.

Figure 8 plots the La$_2$O$_3$ MIM capacitance densities vs. frequency. The intermediate frequency data are obtained directly from $C$-$V$ measurements. The capacitance values at rf frequencies are extracted from the well-matched measured and modeled $S$ parameters in Fig. 6a and b. La$_2$O$_3$ MIM capacitors exhibit a small drop in capacitance as the frequency is varied from 10 KHz to 20 GHz, indicating the excellence of high-$k$ dielectrics formed at the low temperature of 400°C.

Figure 9 plots the dependence of the $Q$ factor on frequency for high-$k$ La$_2$O$_3$ MIM capacitors, whose parasitic inductance was de-
device integrity of high-density La$_2$O$_3$ dielectric MIM capacitors can greatly reduce the chip size of rf circuits and is useful in precision circuits at high frequencies.

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References


Figure 8. Frequency-dependent capacitance of La$_2$O$_3$ MIM capacitors with two dielectric thicknesses.

Figure 9. Quality factor of La$_2$O$_3$ MIM capacitors as a function of frequency.