Lanthanoid Metal Oxide MIM Capacitors for Precision Analog Circuits: Material Screening, Process Development, and Characterization

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I. Introduction
Metal-insulator-metal (MIM) capacitors occupy substantial areas in integrated circuits for radio-frequency (RF) and analog/mixed-signal applications. Increasing the capacitance density enables smaller die sizes. A high capacitance density should be achieved without compromising the voltage coefficient of capacitance (VCC) and leakage current. High-κ dielectrics have been investigated to replace the conventional SiO2 and SiON in MIM capacitors [1]-[2]. High-κ (κ>20) lanthanoid metal oxides have attracted much attention [3]. However, a systematic study of lanthanoid metal oxides for the application in RF and analog/mixed-signal MIM capacitors has not been performed except for La2O3 [4]. In this paper, we report the first investigation of a series of oxides of lanthanoid elements (La, Gd, Tb, Dy, Er, and Yb) for MIM capacitor applications. Er2O3 was found to be very promising. We further discuss the optimization and electrical characterization of MIM capacitors with Er2O3 dielectric.

II. Experiments
MIM capacitors were fabricated on Si wafers covered with 400 nm thick SiO2. A 200 nm thick TaN bottom electrode layer was sputter-deposited. Lanthanoid dielectrics (La2O3, Gd2O3, Dy2O3, Er2O3, and Yb2O3) were reactively sputtered from metal targets in Ar/O2 ambient with various Ar/O2 ratios, while the total gas flow was fixed at 30 sccm. Post deposition annealing (PDA) was performed in 3 different ambient: (1) 100% N2 with no O2, (2) trace O2, or (3) 95% N2 mixed with 5% O2. For the process with "trace O2", the N2 gas flow contained 5% O2 before temperature ramp-up, but there was no O2 flow afterwards. Finally, a 150 nm thick TaN top electrode layer was formed by sputtering and patterning using dry etching. The MIM device structure and process flow are shown in Fig. 1.

III. Results and discussions
(a) Material Screening
Table I lists the lanthanoid oxides investigated. All these oxides have energy gaps close to or larger than 5 eV, except Tb2O3. Fig. 2 compares the quadratic VCC κ of MIM capacitors with 6 different dielectrics. Data presented in Fig. 2 are the best ones for each oxide obtained from a first round of process optimization (Section II). The black line represents the highest capacitance density for a given κ and is contributed by data points from Er2O3. MIM capacitors with Er2O3 dielectric have lowest α (positive) for a given capacitance density. Fig. 3 compares the leakage current density J at ±3.3 V for all 6 materials. Er2O3 dielectric gives the lowest leakage current (black line) for a given capacitance density. Er2O3 outperforms all other 5 candidates in both quadratic VCC and leakage current; it is also better than other high-κ materials reported in literature, which will be discussed later.

(b) Process Development of Er2O3 MIM capacitors
To optimize the performance of Er2O3 MIM capacitors, we varied the ambient oxygen concentration during deposition and PDA. Fig. 4 shows the capacitance obtained at the different process conditions. For the 12 nm split, the capacitance density drops significantly with increased O2 in PDA process; this is due to the oxidation of bottom TaN electrode. However, there is no significant capacitance change for 24 nm and 36 nm splits. Fig. 5 demonstrates typical C-V curves of MIM capacitors with 12 nm Er2O3 split, the capacitance density drops significantly with increased O2 in PDA process; this is due to the oxidation of bottom TaN electrode. However, there is no significant capacitance change for 24 nm, 24 nm, and 36 nm Er2O3 MIM capacitors, respectively. The τtangent increases from ~10 -4 at 1 kHz to ~10 -2 at 200 kHz for all samples. The frequency dispersion of α and β are shown in Fig. 9 and Fig. 10. Another unique characteristic of Er2O3 MIM capacitors is the temperature dependence of capacitance. Fig. 11 shows the temperature dependence of capacitance (TCC). The smaller TCC for 12 nm sample might be due to the interfacial layer caused by the oxidation of bottom electrode. Literature data on high-κ MIM capacitors are summarized and compared in Table II. In comparison with the data in literature, MIM capacitors with Er2O3 dielectric show high capacitance density, low leakage current, and small TCC, suggesting its potential use in future RF and analog/mixed signal IC applications.

IV. Conclusion
We systematically studied 6 lanthanoid oxides as dielectrics in MIM capacitors for RF and analog/mixed-signal circuits. Among those oxides, Er2O3 outperforms others in quadratic VCC and leakage current. With process optimization, Er2O3 MIM capacitors achieve high capacitance densities ranging from 5.8 to 18.4 fF/μm2, low VCC and TCC values, and low leakage current at around 1×10 -8 A/cm2.

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References
Our results: Er$_2$O$_3$ (36 nm)

Table II. Comparison of DC performance of reported binary high-K MIM capacitors

<table>
<thead>
<tr>
<th>Dielectrics</th>
<th>Cap. Density (fF/μm$^2$)</th>
<th>$J_{sat}$ @ 1 V (A/cm$^2$)</th>
<th>$J_{sat}$ @ 3.3 V (A/cm$^2$)</th>
<th>α @ 100kHz (ppm/V$^2$)</th>
<th>β @ 100kHz (ppm/V)</th>
<th>TCC</th>
</tr>
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<tr>
<td>SiO$_2$/SiN$_x$ MIM</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>High-k MIM</td>
<td>Ta$_2$O$_5$ [12]</td>
<td>4</td>
<td>N/A</td>
<td>6E-5-9</td>
<td>9.9</td>
<td>N/A</td>
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<td></td>
<td>Al$_2$O$_3$ [13]</td>
<td>5.2</td>
<td>4.3E-8</td>
<td>N/A</td>
<td>2051</td>
<td>1888</td>
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<td>ALD HfO$_2$ [14]</td>
<td>8</td>
<td>–4E-8</td>
<td>–6E-7</td>
<td>–1800</td>
<td>–4000</td>
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<td>PVD HfO$_2$ [15]</td>
<td>13.7</td>
<td>N/A</td>
<td>4E-4@125°C</td>
<td>4631</td>
<td>–4843</td>
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<tr>
<td>Our results</td>
<td>Er$_2$O$_3$ (36 nm)</td>
<td>3.8</td>
<td>3.5E-9</td>
<td>6E-4-9</td>
<td>240</td>
<td>–430</td>
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<td>Er$_2$O$_3$ (24 nm)</td>
<td>8.9</td>
<td>5.5E-9</td>
<td>–1.4E-8</td>
<td>580</td>
<td>–620</td>
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<td></td>
<td>Er$_2$O$_3$ (12 nm)</td>
<td>18.4</td>
<td>1.3E-8</td>
<td>–4.9E-7</td>
<td>2000</td>
<td>–560</td>
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