Capacitance Analysis of Highly Leaky Al$_2$O$_3$ MIM Capacitors Using Time Domain Reflectometry

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Abstract—Characterization of metal-insulator-metal (MIM) capacitors with a scaled dielectric is a challenge using conventional capacitance–voltage (C–V) measurements due to a high leakage current. In this letter, a method to analyze MIM capacitance that is more immune to the leakage current problem has been successfully demonstrated using time domain reflectometry (TDR). The TDR method can be applied to Al$_2$O$_3$ MIM capacitors with a capacitance density up to \(\sim\)11.1 fF/\(\mu\)m$^2$, for which an impedance analyzer has failed to measure capacitance at 1 MHz. Differences in the voltage coefficient of capacitance and dielectric constant (\(k\)) were also investigated.

Index Terms—Capacitance, metal–insulator–metal (MIM) capacitor, time domain reflectometry (TDR), voltage coefficient.

I. INTRODUCTION

Metal-insulator-metal (MIM) capacitors have been widely used for digital, analog, mixed signal, and RF circuits [1], [2]. For device scaling, their capacitance and accuracy of this method have not yet been explored. Consequently, TDR may be an appropriate method for studying leaky MIM capacitors; however, the actual measurement limit and accuracy of this method have not yet been explored.

In this letter, capacitance characteristics measured using the TDR method and an impedance analyzer were compared while scaling down the electrical thickness of Al$_2$O$_3$ MIM capacitors to determine the limits of the two methods.

II. EXPERIMENTAL PROCEDURE

The MIM capacitors with an Al$_2$O$_3$ dielectric layer were fabricated on Si wafers covered with 300-nm SiO$_2$. First, a 50-nm Pt bottom electrode was deposited by e-beam evaporator. Then, Al$_2$O$_3$ dielectric films of various thicknesses controlled by atomic layer deposition (ALD) cycles from 40 to 80 were prepared at 250 °C, followed by a postdeposition anneal in O$_2$ ambient for 1 min at 400 °C. A circular 50-nm Pt top electrode (area = 30 000 \(\mu\)m$^2$) was e-beam evaporated using a shadow mask. The thicknesses of the dielectric layer were confirmed using a transmission electron microscope (TEM).

The capacitance–voltage (C–V) characteristics of the MIM capacitors were characterized using a HP4294A precision LCR meter (at 1 MHz) and a TDR method (Lecroy Wave Expert 100 H), respectively. For TDR, the capacitance values can be extracted using the following equation [7]:

\[
C = \frac{1}{2Z_{0}V_{\text{step}}} \int_{0}^{\infty} [V_{\text{open}}(t) - V_{\text{TDR}}(t)] \, dt
\]

where \(V_{\text{open}}(t)\) is the reflected waveform from the open circuit, \(V_{\text{TDR}}(t)\) is the reflected waveform from the capacitor, \(Z_{0}\) is the impedance of the transmission line (typically, 50 \(\Omega\)), and \(V_{\text{step}}\) is the height of the step function pulse. Finally, the current-density–voltage (\(J–V\)) curves were analyzed using a semiconductor parameter analyzer (Keithley, 4200-SCS).
high leakage current measured properly using an impedance analyzer due to the signal contains the impedance information about the DUT. A TDR scope. Thus, both outgoing and reflected pulses are monitored in the DUT, the step function pulse is reflected back to the TDR scope. Therefore, the impedance of the cable and bias tee, the parasitic pulse reflection can be suppressed. Because of the impedance change in the DUT, the step function pulse is reflected back to the TDR scope. Thus, both outgoing and reflected pulses are monitored by the TDR scope as a function of time. The reflected signal contains the impedance information about the DUT. A detailed theoretical approach to extract the capacitance from the reflected signal can be found in [6].

Typical TDR signals from Al₂O₃ MIM capacitors are shown in Fig. 1(b). Clear capacitor charging curves were obtained with various dielectric thicknesses such as ALD 40, 60, 70, and 80 cycles. As the Al₂O₃ dielectric becomes thinner, the areas surrounded by the open signal increase because the area enclosed by the open signal represents the total stored charge [7]. The reflected signals from ALD 60-, 70-, and 80-cycle devices merge with the open waveform (black solid line) at a long time, but the reflected voltage of the ALD 40-cycle device reaches a level far below that of the open signal. The difference in the saturation voltage is due to the voltage drop from the series resistance, representing the influence of leakage current [7]. Thus, the impact of the leakage current can be easily factored out in the TDR method.

Fig. 2(a) and (b) show the C–V characteristics of Al₂O₃ MIM capacitors of various dielectric thicknesses. The capacitance increases as the Al₂O₃ becomes thinner, ranging from 7.2 to 11.1 fF/μm². The capacitance of devices with an equivalent oxide thickness (EOT) = 2 nm (ALD 40 cycle) could not be measured properly using an impedance analyzer due to the high leakage current [3.3 A/cm² at 1 V as shown in the inset of Fig. 2(c)]. The effect of the high leakage current was also manifested in the dissipation factors. Fig. 2(c) shows the dissipation factors for Al₂O₃ MIM capacitors, which were below 0.1 for the capacitors with ALD 60, 70, and 80 cycles, i.e., the capacitance values measured by the impedance analyzer are reliable [8]. However, a dissipation factor over one was observed in the device with ALD 40 cycles, as expected from the failed capacitance measurement.

On the other hand, the TDR method successfully obtained a reasonable capacitance value even in devices with ALD 40 cycles, as shown in Fig. 2(b), indicating that the TDR method is more immune to the leakage current problem. The accuracy of the TDR method was measured separately using ceramic capacitors. The capacitance values measured by TDR matched those of the impedance analyzer down to 1 pF within ~2%. (Data are not shown.)

The EOT versus Al₂O₃ thickness measured by TEM [in Fig. 3(b)] is shown in Fig. 3(a). The physical thickness of the dielectric layers shows a reasonably linear relationship with the EOT value, ranging from 2 to 3.1 nm. The values obtained by two different C–V measurement methods were similar except for the thinnest EOT case for which only the TDR method could provide EOT values. The dielectric constant (k) obtained from the slope of EOT versus physical thickness was around six to seven, which is slightly lower than that in the previously reported literature because the process had not been optimized [9].

Voltage linearity is an important parameter crucial to determining the performance of MIM capacitors [10]. Voltage coefficients can be extracted using the following equation:

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

where \( C_0 \) is the capacitance at zero bias, \( \alpha \) and \( \beta \) indicate the quadratic and linear voltage coefficients of capacitance (VCCs), respectively [11], where \( \alpha \) should be smaller to ensure a linear response of C–V characteristics.

Table I shows the VCCs extracted from both the impedance analyzer and TDR method. As the thickness of Al₂O₃ becomes thinner, the quadratic VCC gradually increases with both measurement methods. The degradation of VCC \( \alpha \) is due to the increase in leakage current at a higher bias. Interestingly, the \( \alpha \) value obtained from the TDR method was lower and showed a more gradual increase than those obtained from the impedance analyzer. Given that only the TDR method yielded a reasonable capacitance value at a high leakage current, the \( \alpha \) value from TDR may be more accurate. Even though this


<table>
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<tr>
<th>Impedance analyzer</th>
<th>TDR-C-V</th>
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<tr>
<td></td>
<td>α (ppmV²)</td>
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<tr>
<td>ALD 80 cycles</td>
<td>3240</td>
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<tr>
<td>ALD 70 cycles</td>
<td>4530</td>
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<tr>
<td>ALD 60 cycles</td>
<td>6300</td>
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<tr>
<td>ALD 40 cycles</td>
<td>4990</td>
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The conclusion needs more careful examination using other high-k dielectrics with $a \pm \alpha$ value, the TDR method is clearly a feasible option for MIM studies, which deserves more attention. In addition, another attractive benefit of the TDR method is that it can be applied to simple capacitor structures with a ground-signal-type contact pad. Network analyzer can be used to measure a leaky dielectric at very high frequency up to tens of gigahertz, but it requires elaborated test structures for open/short compensation measurements. Thus, TDR can be a promising test method suitable for an in-line measurement of extremely thin MIM dielectrics.

IV. CONCLUSION

TDR has been successfully applied to the characterization of Al₂O₃ MIM capacitors with a wide range of dielectric thicknesses, using a very simple MIM test structure. The validity of the TDR method was confirmed up to a capacitance density of $\sim$11.1 fF/um² and a leakage current density above 33 A/cm², where an impedance analyzer failed to yield reasonable data. We have shown that TDR is a promising method to guide the study of MIM dielectrics because it demonstrates more reasonable quadratic voltage coefficient values than an impedance analyzer even under very high leakage current conditions.

REFERENCES