Electrical Properties of High-k MIM Interlevel Capacitors
Prepared for RF-CMOS Device Applications

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1. Introduction
Rapid growth in personal wireless communications gave significant importance on the accompanying high-frequency device technologies. For these devices, it is of great importance to fabricate high quality passive elements with low parasitic components, to ensure the high frequency operation. For this purpose, a metal/insulator/metal (MIM) capacitor prepared at an upper interlevel layer has been developed and investigated [1].

With a conventional SiO₂ or SiN dielectric of low capacitance density, the MIM capacitors still occupy large area that makes difficult to further increase circuit density and reduce the cost. To overcome this deficiency, it is considered to be promising to apply high-k material, like SrTiO₃ (ST) or (Ba, Sr)TiO₃ (BST) [2, 3] as a dielectric. However, there are few reports on the high-k MIM capacitors prepared with the process temperature below 400°C, that is the maximum allowable temperature of the metallization process.

In this paper, we fabricated high-k MIM interlevel capacitors using ST or BST dielectric prepared by process conditions below 400°C, and investigated the basic and RF electrical properties of the capacitors, focusing on differences in the dielectric property between ST and BST films.

2. Experiment
Fig. 1 shows a schematic and cross-sectional SEM images of the MIM capacitor. A 200-μm-thick Pt bottom electrode, with a 50-μm-thick TiN underlayer, was deposited on silicon substrate with 800-μm-thick SiO₂. Then, ST or BST film was deposited by RF magnetron sputtering at 300°C, 0.1-0.2 Pa with Ar/N₂/O gas, followed by a 60-μm-thick top Pt electrode deposition. Table I shows deposition conditions of the ST and BST films. The film thickness was set to be 70 nm, which gave good insulating property. Dry etching was done by RIE with O₂/Cl₂ gas. Post annealing was also done several times below 400°C to remove etching damages. Then a 400-μm-thick SiO₂ was deposited by plasma CVD with a thin adhesive layer. Finally aluminum interconnects to the top and bottom electrodes were fabricated with a TiN barrier metal layer via ~2 μm through-holes. Various capacitors of a wide variety of sizes and shapes were fabricated and measured by HP4155A, HP4194A for basic electrical properties and an HP8150C network analyzer for RF properties, respectively.

3. Results and Discussions
Figs. 2 and 3 show the relationship between capacitance or capacitance-density and the top electrode size, measured at 100 kHz, respectively. Dielectric constant and the capacitance density at zero-bias voltage were found to be k~70, ~9 fF/μm² for ST (almost flat for the capacitors from 25 μm² to 6400 μm² in size). The ST film consisted of fine polycrystalline grains and the dielectric constant was smaller than those of high temperature-grown films (k~200) [2, 3]; nevertheless, the capacitance density was very high compared with those of the conventional SiO₂ capacitor (~1 fF/μm²) in contrast. BST showed even higher dielectric constant (k~140) and capacitance density ~19 fF/μm², which decreased with increasing the top electrode size. Fig. 4 shows the capacitance-voltage relationship for 20x20-μm² size capacitor, revealing BST had relatively large voltage coefficient of ~7 %/V at 3V, while ST had ~3 %/V. Fig. 5 is leakage current density-voltage curve of the capacitors showing that BST had a larger leakage than ST. From the data in the Figs. 4 and 5, leakage/capacitance values were found to be still under 1 fA/fF at 3V for both films.

From these results, it is concluded that both ST and BST films have high dielectric constant, capacitance density and low leakage despite the low process temperature below 400°C. However BST has a disadvantage of large voltage coefficient, in addition, the non-linearity in capacitance as a function of the size (possibly due to stress-induced effect [4]). Hence, ST is considered to be more appropriate for circuit design with good capacitance density and moderate voltage coefficient.

RF properties of the MIM capacitors were evaluated by measuring S-parameters of the 1-port type test pattern (as shown in Fig. 6) from 0.1 to 15 GHz. The S-parameters of a dummy pattern without a capacitor cell were also measured to calculate the intrinsic S-parameters. Fig. 7 shows the lumped equivalent circuit model for the present MIM capacitors and a formula for the complex impedance (Z) of the circuit, where an intrinsic capacitance (C₀), a series resistance (Rₛ) and an inductance (Lₛ) were considered. Fig. 8 is the RF response of the MIM capacitors with a square top electrode of 5x5 μm². The imaginary part (-1/αm[Z]) of the impedance showed only a slight decrease, revealing both the ST and BST maintain their dielectric properties up to GHz range. (The increase at ~10 GHz for BST was caused by resonance effect of the circuit.) Table II shows the fitted parameters of the lumped equivalent elements for 15x15 μm² cell capacitors, revealing that, by using ST or BST, it is possible to fabricate the MIM capacitors of practical capacitance (~5 pF) in the small size with very low Rs (~1.3 Ω) and Lₛ (~0.05 nH), applicable to GHz range operations.

4. Conclusions
We have successfully fabricated high-k MIM interlevel capacitors using SrTiO₃ or (Ba, Sr)TiO₃ by conventional processes below 400°C, with high capacitance densities of ~9 fF/μm² for ST, and ~19 fF/μm² for BST. ST is considered to be more suitable than BST for the smaller voltage coefficient and good linearity in the capacitance-size relationship. The measurements of the RF properties using 1-port type test patterns have revealed that the high-k MIM capacitors maintain their capacitance up to ~10 GHz, with low serial resistance and inductance. The high-k MIM interlevel capacitor technology is promising for future RF-CMOS device applications.

Acknowledgments
The authors would like to thank Mr. H. Matsuda for kind support in RF measurements.

References
Table I Deposition conditions for ST and BST films.

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<tr>
<td>Substrate temperature</td>
<td>300°C</td>
<td></td>
</tr>
<tr>
<td>Method</td>
<td>RF magnetron sputtering</td>
<td></td>
</tr>
<tr>
<td>RF-power</td>
<td>850 W</td>
<td></td>
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<tr>
<td>Gas</td>
<td>Ar/N₂O (4:1)</td>
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<tr>
<td>Pressure</td>
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<tr>
<td>Deposition time</td>
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<tr>
<td>Film thickness</td>
<td>70 nm</td>
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Fig. 1 Cross-sectional structure of MIM capacitor.

![Cross-sectional structure of MIM capacitor](image)

Fig. 2 Capacitance-Size relationship.

![Capacitance-Size relationship](image)

Fig. 3 Capacitance density-Size relationship.

![Capacitance density-Size relationship](image)

Fig. 4 Capacitance density-Voltage relationship. (20x20-μm² cell)

![Capacitance density-Voltage relationship](image)

Fig. 5 Leakage-Voltage characteristics of the MIM capacitors (100 integrated cells of 20x20-μm² in size.)

![Leakage-Voltage characteristics](image)

Fig. 6 Optical micrograph and schematic of 1-port type test pattern.

![Optical micrograph and schematic](image)

Fig. 7 Lumped equivalent circuit of the MIM capacitor used for parameter fitting.

![Lumped equivalent circuit](image)

Table II Fitted parameters of MIM 15x15 μm² size capacitors from S-parameters measured at 0.1 - 15 GHz.

<table>
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<tr>
<th>Values</th>
<th>ST</th>
<th>BST</th>
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<tr>
<td>Cs</td>
<td>1.8 pF</td>
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<td>Rs</td>
<td>1.3 Ω</td>
<td>1.2 Ω</td>
</tr>
<tr>
<td>Ls</td>
<td>0.05 nH</td>
<td>0.05 nH</td>
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Fig. 8 RF response of square-type MIM capacitors. Both ST and BST films maintain their dielectric property up to GHz range.

![RF response of square-type MIM capacitors](image)