Abstract—High frequency characterizations and simulations of 3D damascene Metal-Insulator-Metal (MIM) capacitors are presented. We focused on the impact of the design on the performance of integrated capacitors. Results showed that properties of MIM capacitor get improved with specific design recommendations on electrodes shape.

I. INTRODUCTION

The Metal-Insulator-Metal (MIM) capacitor is a key passive component in Radio Frequency (RF) and analog integrated circuits. MIM capacitors have attracted great attention because of their high performance, excellent voltage linearity and good reliability. The main challenge in the development of new MIM capacitors is the increase of capacitance density while keeping good RF properties, in order to obtain smaller size leading to higher circuit densities, and cheaper fabrication. To improve the capacitance density, three solutions are possible, increasing either the developed area between electrodes or the dielectric k-value [1]. Another choice is to reduce the dielectric thickness but this solution increases the undesired leakage current.

In this paper, we were more particularly interested by the increase of area and its impact on RF performance, as quality factor and cut-off frequency. By modifying the MIM capacitor architecture and design, from a 2D to a 3D architecture [2], the density can be increased from 2 fF/µm² to 5 fF/µm² respectively [3] while keeping the same dielectric, Si₃N₄, which k-value is equal to 7.

A method has been developed to determine MIM capacitors performance on a broad frequency band. All inductive and resistive parasitic effects resulting from architecture, design and material characteristics were taken into account to extract an equivalent electrical circuit of the capacitor.

Architecture of 3D damascene is described in a first part. Next the de-embedding technique for the HF measurement of MIM capacitor is presented. Measurement and simulation are compared and results validate QUEST Silvaco as a reliable HF modeling tool for MIM capacitor. Finally, studies concerning the capacitance value according to capacitor geometry are discussed. Thus, design rules will be defined to increase MIM capacitors RF performances.

II. MIM CAPACITORS DESCRIPTION

A 3D damascene architecture is used to integrate MIM capacitors in the upper copper interconnect levels of integrated circuit (Fig. 1). All MIM capacitors are integrated...
between M5 and M6 levels. Once a cavity is etched in the V5 level, the bottom electrode, a 30 nm thick SiN film, and the top electrode are successively deposited into the cavity, followed by standard Cu metallization to fill the cavity. Next, a polishing step ensures the definition of MIM capacitors and removal of materials in excess. Finally, upper interconnect integration is completed with V5 and M6 standard realization, and final passivation.

Fig. 2 illustrates a typical top view of MIM capacitor. MIM is designed using a comb shape and geometrical parameters of interest are: the spacing S between fingers, the finger width W, the finger length L and the number N of fingers. Seven structures have been selected for this study which designs are represented in the table I. The surface is calculated as the area occupied by the structure, given by: \( L \times N (W+S) \).

<table>
<thead>
<tr>
<th>Structures</th>
<th>Combs Numbers</th>
<th>Comb length (µm)</th>
<th>Surface (µm²)</th>
<th>Theoretical capacity value (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 )</td>
<td>5</td>
<td>146</td>
<td>467</td>
<td>2.25</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>10</td>
<td>73</td>
<td>492</td>
<td>2.25</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>15</td>
<td>49</td>
<td>503</td>
<td>2.25</td>
</tr>
<tr>
<td>( C_4 )</td>
<td>15</td>
<td>97</td>
<td>996</td>
<td>4.5</td>
</tr>
<tr>
<td>( C_5 )</td>
<td>15</td>
<td>146</td>
<td>1489</td>
<td>6.75</td>
</tr>
<tr>
<td>( C_6 )</td>
<td>15</td>
<td>194</td>
<td>1983</td>
<td>9</td>
</tr>
<tr>
<td>( C_7 )</td>
<td>10</td>
<td>146</td>
<td>978</td>
<td>4.5</td>
</tr>
</tbody>
</table>

### III. RF MEASUREMENT PROCEDURE

Capacitor access lines are connected to RF pads in order to contact measurement probes. Impedance of MIM Capacitor is extracted using an ANRITSU 37397C Vector Network Analyzer (VNA) and a prober. First an on-wafer OSTL (Open Short Thru Load) calibration is achieved. Next a deembedding technique is used, which main steps are summarized below.

After calibration, a pad is measured in order to determine its impedance, noted \( Z_{pad} \), by using the following formula:

\[
S_{11} = \frac{Z_{pad} - 50}{Z_{pad} + 50}
\]

(1)

The ABCD matrix of the pad can be deduced using:

\[
[ABCD]_{pad} = \begin{bmatrix} 1 & 0 \\ 1/Z_{pad} & 1 \end{bmatrix}
\]

(2)

In a second time, a section of MIM access transmission line is also measured on the wafer. From measurements, one can establish the ABCD matrix of the device “pad + line + pad”, noted by the following equation:

\[
[ABCD]_{measurement} = [ABCD]_{pad} \cdot [ABCD]_{line} \cdot [ABCD]_{pad}
\]

(3)

According to the formula (3), the ABCD matrix from the line can be deduced. Then, by identification with the formula (4), the propagation coefficient of the line and its characteristic impedance can be determined.

\[
[ABCD]_{line} = \begin{bmatrix} \cosh (\gamma l) & \frac{Z_{line} \sinh (\gamma l)}{Z_{line}} \\ \sinh (\gamma l) & \cosh (\gamma l) \end{bmatrix}
\]

(4)
From the previous elements obtained and according to the capacitor measurement, the characteristics elements of the investigated MIM capacitor can be determined. From measurements, one can establish the ABCD matrix of the device “pad + line + capacitor + line + pad”, noted by the equation (5) and the ABCD matrix of the capacitor can be deduced.

\[[ABCD]_{\text{source}} = [ABCD]_{\text{pad}} [ABCD]_{\text{line}} [ABCD]_{\text{capacitor}} [ABCD]_{\text{line}}^{-1} [ABCD]_{\text{pad}}^{-1} \]  

For a better understanding of MIM capacitors in a high frequency regime, an equivalent circuit model is established and presented in Fig. 3. The C element corresponds to the capacitor basic model, whereas additional series Rs and Ls represent the parasitic resistance and inductance due to the specific MIM capacitor design. Finally the shunt resistance, Rp, describes the dielectric losses [3]-[4]. Rp is considered as infinite because dielectric losses of Si3N4 are negligible.

These various elements can be identified by establishing the agreement between capacitance ABCD matrix and the following equation:

\[[ABCD]_{\text{capacitor}} = \begin{bmatrix} 1 & R_s + j \left( \frac{L_s \omega - \frac{1}{C \omega}}{1} \right) \\ 0 & 1 \end{bmatrix} \]  

**IV. SIMULATION - MEASUREMENT COMPARISON**

In order to forecast the behavior of MIM capacitors in the high frequency range, results of QUEST electromagnetic 3D simulator were compared with measurements [5]. Comparison between modeled and measured scattering parameters of the C3 MIM capacitor is plotted on figure 4.

A good agreement is observed between electromagnetic 3D simulation results and measurements for C3 MIM capacitor structure in the high frequency domain. Such a 3D electromagnetic simulator is a good tool to understand phenomenon caused by each specific MIM capacitor design or material choices and to predict their impacts on RF performance.

**V. RESULTS AND DISCUSSION**

**A. Evaluation of different geometries with same capacitance**

In this first study, C1, C2 and C3 capacitors characterized by identical surface and capacitance (table I) are considered. Experimental measurements showed that these three capacitances present the same value, equal to 2.16 pF (table II).

According to figure 5, which represents the imaginary part of the impedance, one can observe that in high frequency, there is a difference between these three capacitors, related to the parasitic inductance. According to tables I and II, the parasitic inductance increases when the number of combs decreases.

<table>
<thead>
<tr>
<th>Structures</th>
<th>C (pF)</th>
<th>Rs (Ω)</th>
<th>L (pH)</th>
<th>Density (fF/µm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>2.16</td>
<td>0.91</td>
<td>2</td>
<td>4.6</td>
</tr>
<tr>
<td>C2</td>
<td>2.16</td>
<td>0.37</td>
<td>1.5</td>
<td>4.4</td>
</tr>
<tr>
<td>C3</td>
<td>2.16</td>
<td>0.24</td>
<td>0.5</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Table II. Extracted element values of MIM capacitors.
This result indicates that a compromise between the number of combs and their lengths should be found to maintain an identical value of capacity.

According to these observations, it seems that more the combs are long, more the parasitic inductance is high, leading to lower cut-off frequency.

By considering the real part of the impedance, we may deduce the series resistance, $R_s$, which remains constant in the frequency band of 2 to 40 GHz. According to figure 6, the resistance values vary from 0.24 to 0.91. On the other hand, the parasitic resistance decreases when the combs numbers is increased (Fig. 6). We can explain these results by the following hypothesis. Each comb presents an elementary resistance. At the same time the parasitic resistance, $R_s$, of the capacitor is equal to the parallel elementary resistance of each comb. Thus if the capacity presents more combs, its parasitic resistance is lower.

From this study, one can also deduce the quality factor of these capacitors by the following equation:

$$Q = \frac{f_0}{f_1}$$

For a quality factor equal to 100, the frequency bandwidth is respectively 0.75 GHz, 1.8 GHz and 3.3 GHz for $C_1$, $C_2$ and $C_3$ MIM capacitors. These results show an increasing band frequency in a ratio 4 between $C_1$ and $C_3$ capacitors. So optimization of design allows increasing electrical performance of MIM capacitors.

To conclude, this study showed the interest of having a high number of short combs, in order to decrease both the parasitic resistance and inductance.

### B. Influence of the comb length

In this section, the considered capacitors are $C_3$, $C_4$, $C_5$ and $C_6$. These components have an identical comb number, equal to 15, while the combs length increases with capacitance.

Results (table III) show that when the combs length increases, resistance and inductance values are also increased.

Concerning the resistance, these results may be explained by the fact that more the combs length is increased, more their resistance is also increased.

According to tables I and III, the parasitic inductance increases when the combs length increases. This can be explained by the mutual coupling between combs.

<table>
<thead>
<tr>
<th>Structures</th>
<th>C (pF)</th>
<th>Rs (Ω)</th>
<th>L (pH)</th>
<th>Density (fF/µm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_3$</td>
<td>2.16</td>
<td>0.24</td>
<td>0.5</td>
<td>4.3</td>
</tr>
<tr>
<td>$C_4$</td>
<td>4.39</td>
<td>0.33</td>
<td>1.3</td>
<td>4.4</td>
</tr>
<tr>
<td>$C_5$</td>
<td>6.6</td>
<td>0.41</td>
<td>2</td>
<td>4.4</td>
</tr>
<tr>
<td>$C_6$</td>
<td>8.92</td>
<td>0.46</td>
<td>2.2</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table III. Extracted element values of MIM capacitors.

<table>
<thead>
<tr>
<th>Structures</th>
<th>C (pF)</th>
<th>Rs (Ω)</th>
<th>L (pH)</th>
<th>Density (fF/µm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>2.16</td>
<td>0.91</td>
<td>2</td>
<td>4.6</td>
</tr>
<tr>
<td>$C_2$</td>
<td>6.6</td>
<td>0.41</td>
<td>2</td>
<td>4.4</td>
</tr>
<tr>
<td>$C_3$</td>
<td>4.38</td>
<td>0.53</td>
<td>2</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table IV. Extracted element values of MIM capacitors.
More the combs length is high, more the interaction is highlighted.

To illustrate hypothesis, the C\textsubscript{6} capacitor which is equal to 9 pF and presents the longest combs is considered. According to the measurements, the parasitic resistance and inductance of this capacitor are the highest.

In addition, quality factor is higher when the capacitors present shorter combs.

As a conclusion, it seems to be necessary to minimize the combs length in order to reduce the parasitic resistance and inductance.

**C. Influence of the number of comb**

In the last section, the combs lengths are identical and equal to 146 µm and only their number varies. Capacities C\textsubscript{1}, C\textsubscript{5} and C\textsubscript{7} are considered.

According to tables I and IV, the parasitic resistance decreases when the combs number increases. This conclusion checks and corroborates the results obtained by previous studies.

The parasitic inductance is equal to 2 pH for the three capacitors. This result shows that the inductance value depends only on the combs length and not on their number.

**VI. CONCLUSION**

3D MIM damascene capacitors with high capacitance densities were successfully integrated and characterized over a wide band of frequencies. Their properties were determined at high frequencies using an OSTL calibration and a deembedding technique. Experimental results were compared to 3D electromagnetic simulations (QUEST), demonstrating the good agreement between simulation and measurement results and the potentiality of such electromagnetic software to predict the impact of technological and design choices on RF performance.

Experimental results show the possibility to determine an improved geometry for 3D MIM damascene capacitors. According to these results, capacitors should present many short combs leading to low parasitic elements and better RF performance. This very high capacitance density (4.5 fF/µm\textsuperscript{2}) with good MIM capacitor characteristics can significantly reduce the chip size of integrated circuits.

**REFERENCES**


