A

Analysis of a Distributed Model for a MOS Capacitor

In this section, we will analyze the distributed model for the MOS capacitor, shown in Fig. A.1. The analysis here is modeled after [71].

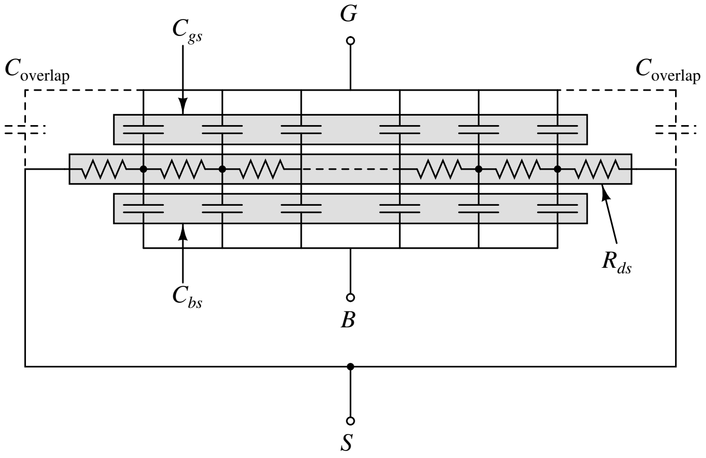

Fig. A.1: Distributed model for a MOS capacitor.

Of particular interest in this analysis, is the gate-source transadmittance, $\overline{Y_{gs}(jw)}$, which is defined as:

$$\overline{Y_{gs}} = \frac{\overline{I_g}}{\overline{V_s}}\bigg|_{\overline{V_g},\overline{V_b}=0} \tag{A.1}$$

$\overline{I_g}$, $\overline{V_s}$ are shown in Fig. A.2. To evaluate $\overline{Y_{gs}}$, we can perform a thought experiment as shown in Fig. A.2. $\overline{I} = \overline{I_g} + \overline{I_b}$ is measured with an ammeter, when a signal $\overline{V_s}$ is applied at the drain-source. It can be seen that

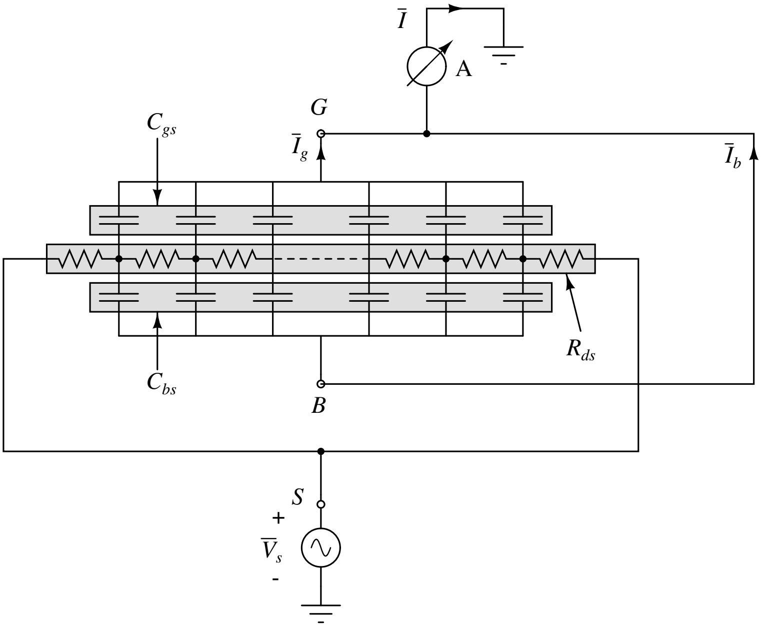

Fig. A.2: Thought experiment to measure $\overline{Y_{gs}}$.

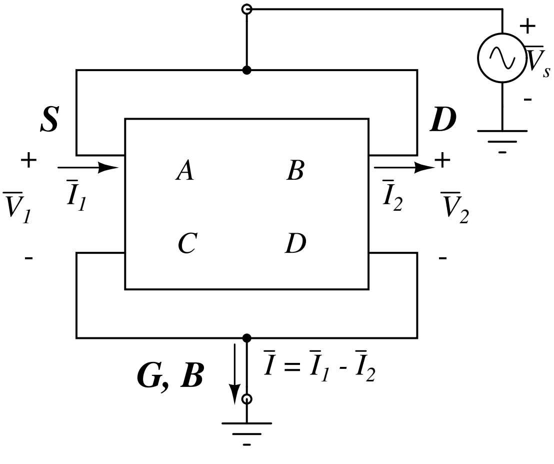

Fig. A.3: Replacing the MOS capacitor with its lumped transmission parameters.

$$\overline{I_g} = \frac{C_{gs}}{C_{gs} + C_{bs}} \overline{I} \tag{A.2}$$

The MOS capacitor in Fig. A.2 can be replaced with a circuit that has the same lumped transmission parameters as shown in Fig. A.3 with the correspondence in the terminals as shown. Then, $\overline{Y_{gs}}$ can be represented in terms of the lumped transmission parameters in the following manner:

From the transmission matrix, we get:

$$\overline{V_2} = A\overline{V_1} + B\overline{I_1} \tag{A.3}$$

$$\overline{I_2} = C\overline{V_1} + D\overline{I_1} \tag{A.4}$$

Applying Kirchoff's equations to the circuit, we get:

$$\overline{V_s} = \overline{V_1} = \overline{V_2} \tag{A.5}$$

$$\overline{I} = \overline{I_1} - \overline{I_2} \tag{A.6}$$

From (A.3), (A.4) and (A.5), (A.6), we can deduce:

$$\overline{I}/\overline{V_s} = \frac{(1-A)(1-D)}{B} - C \tag{A.7}$$

$\overline{Y_{gs}}$ can be obtained from (A.1), (A.2) and (A.7).

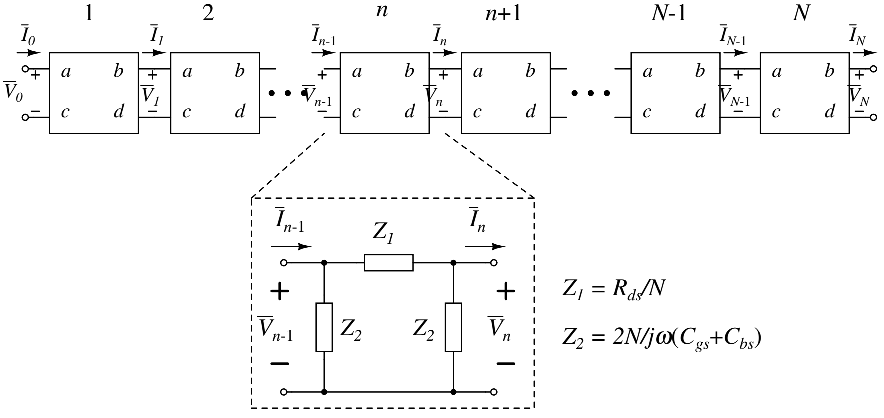

Fig. A.4: Expanding the distributed network into a cascade of N sections, $N \to \infty$.

The lumped transmission network in Fig. A.3 can be broken up into a cascade of N sections, where $N \to \infty$. This is shown in Fig. A.4. In each section, Z_1 and Z_2 are given by:

$$Z_1 = R_{ds}/N \tag{A.8}$$

$$Z_2 = 2N/j\omega(C_{gs} + C_{bs}) \tag{A.9}$$

For the n^{th} section,

$$\begin{bmatrix} \overline{V_{n+1}} \\ I_{n+1} \end{bmatrix} = \begin{bmatrix} 1+\frac{Z_1}{Z_2} & -Z_1 \\ -\frac{Z_1+2Z_2}{Z_2^2} & 1+\frac{Z_1}{Z_2} \end{bmatrix} \begin{bmatrix} \overline{V_n} \\ I_n \end{bmatrix} = [M] \begin{bmatrix} \overline{V_n} \\ I_n \end{bmatrix}$$

And for the complete network,

$$\begin{bmatrix} \overline{V_N} \\ I_N \end{bmatrix} = [M]^N \begin{bmatrix} \overline{V_0} \\ I_0 \end{bmatrix}$$

Note that $[M]^N$ is the transmission matrix for the entire network. Now let us identify the eigenvalues of the matrix $[M]$. If λ is an eigenvalue, then:

$$\det |[M] - \lambda[I]| \equiv 0$$

or,

$$\lambda^2 - 2\lambda(1 + Z_1/Z_2) + 1 = 0 \tag{A.10}$$

(A.10) is the characteristic equation of the matrix $[M]$. If λ_1 and λ_2 are two solutions to this characteristic equation, and hence eigenvalues of $[M]$, then:

$$\lambda_1\lambda_2 = 1 \tag{A.11}$$

$$\lambda_1 + \lambda_2 = 2(1 + Z_1/Z_2) \tag{A.12}$$

So, to satisfy (A.11),

$$\text{if } \lambda_1 = e^{\tau} \text{ and } \lambda_2 = e^{-\tau}$$

then to satisfy (A.12),

$$\cosh\tau = (1 + Z_1/Z_2) \tag{A.13}$$

Now we can simplify the definition of $[M]$ using (A.13):

$$[M] = \begin{bmatrix} \cosh\tau & -Z_1 \\ -\frac{\sinh^2\tau}{Z_1} & \cosh\tau \end{bmatrix} \tag{A.14}$$

From the Cayley-Hamilton theorem,

$$[M]^N = C_0[I] + C_1[M] \tag{A.15}$$

where C_0 and C_1 are constants, and

$$\lambda^N = C_0 + C_1\lambda \tag{A.16}$$

Inserting the specific eigenvalues in (A.16),

$$(e^{\tau})^N = C_0 + C_1 e^{\tau} \tag{A.17}$$

$$(e^{-\tau})^N = C_0 + C_1 e^{-\tau} \tag{A.18}$$

From (A.17) and (A.18),

$$C_1 = \frac{\sinh N\tau}{\sinh \tau} \tag{A.19}$$

$$C_0 = - \frac{\sinh(N-1)\tau}{\sinh \tau} \tag{A.20}$$

From (A.15), (A.14) and (A.19), (A.20), we get:

$$[M]^N = \begin{bmatrix} \cosh(N\tau) & -Z_1 \frac{\sinh(N\tau)}{\sinh \tau} \\ -\frac{\sinh(N\tau)\sinh\tau}{Z_1} & \cosh(N\tau) \end{bmatrix} \tag{A.21}$$

This gives us the transmission matrix for the complete network. In the limit where $N \to \infty$, (A.21) will be the transmission matrix for the distributed-RC network that we started with, as shown in Fig. A.3.

Now from (A.7) and (A.21), we obtain:

$$\overline{I}/\overline{V_s} = -\frac{[1-\cosh(N\tau)]^2 \sinh\tau}{Z_1 \sinh(N\tau)} + \frac{\sinh\tau \sinh(N\tau)}{Z_1}$$

Simplifying further and using (A.8) and (A.9), we can deduce:

$$\overline{I}/\overline{V_s} = -\frac{2N}{R_{ds}} \cdot \frac{\sinh\tau}{\sinh(N\tau)} \cdot [1-\cosh(N\tau)] \tag{A.22}$$

where τ is given by (A.13), (A.8) and (A.9) as:

$$\tau = \cosh^{-1}\left[1 + \frac{j\omega R_{ds}(C_{gs}+C_{bs})}{2N^2}\right] \tag{A.23}$$

As a sanity check, when $N = 1$, the network reduces to a simple lumped network, with the channel resistance, R_{ds}, shorted out. As a result, we expect the expressions (A.22), (A.13) to give us a purely capacitive result, i.e, $j\omega(C_{gs} + C_{bs})$.

From (A.23), in the limit when $N \to \infty$,

$$\lim_{N\to\infty} \tau = 0$$

From the definition of τ in (A.23),

$$N^2 \sinh^2(\tau/2) = j\omega R_{ds}(C_{gs}+C_{bs})/4$$

In the limit, as $N \to \infty$ and $\tau \to 0$,

$$\lim_{\substack{N\to\infty \\ \tau\to 0}} N^2 \sinh^2(\tau/2) = j\omega R_{ds}(C_{gs}+C_{bs})/4$$

Simplifying further, we obtain:

$$\lim_{\substack{N\to\infty \\ \tau\to 0}} N\tau = \sqrt{j\omega R_{ds}(C_{gs}+C_{bs})} = \alpha \tag{A.24}$$

From (A.22), in the limit where $N \longrightarrow \infty$ and also $\tau \longrightarrow 0$:

$$\lim_{N \to \infty} \overline{I}/\overline{V_s} = \frac{2\alpha}{R_{ds}\sinh\alpha}(\cosh\alpha - 1) = \frac{\alpha^2}{R_{ds}} \cdot \frac{\tanh\alpha/2}{\alpha/2} \tag{A.25}$$

This is rewritten, with the help of (A.24) to give:

$$\lim_{N \to \infty} \overline{I}/\overline{V_s} = j\omega(C_{gs} + C_{bs}) \cdot \frac{\tanh\alpha/2}{\alpha/2}$$

where α is given by (A.24).

Using (A.1) and (A.2), we can finally arrive at the desired expression for $\overline{Y_{gs}}$ as:

$$\overline{Y_{gs}} = j\omega C_{gs} \cdot \frac{\tanh\alpha/2}{\alpha/2} \tag{A.26}$$

where α is given by (A.24). As a second sanity check, when $\alpha \longrightarrow 0$, (A.26) gives $j\omega C_{gs}$, which is expected.

For cases where N does not tend to ∞, but is a large integer, note that $N\tau = \alpha$, as defined, as long as $\tau \longrightarrow 0$. This means that the expression in (A.26) is approximately valid as long as N is large enough such that $\tau \longrightarrow 0$. Looking at (A.13), this is true as long as:

$$\omega R_{ds}(C_{gs} + C_{bs}) << 2N^2 \tag{A.27}$$

(A.27) can be used to determine the minimum number of discrete sections that will be required to perform a reasonably accurate simulation of this distributed network.

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Index