Investigation of De-embedding procedures up to 110GHz

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Outline

● Introduction
● Calibration
● De-embedding steps
  ● OPEN-SHORT
  ● 3 steps
  ● 4 steps
  ● 5 steps
  ● 6 steps
● Two-step de-embedding
● Conclusion
Introduction

● Deembedding importance:
  - For process engineers (technology performance $f_T$, $f_{\text{max}}$)
  - Highly important for compact device modeling
  - S parameter perfectly corrected

● Main issues
  - What is an accurate deembedding technique?
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Calibration

- Takes into account parasitic between VNA and Probe tips
- After calibration the reference planes are at the probe tips

Source: IBM IEEE Spectrum
De-embedding

- Retrieve intrinsic device performance → de-embedding
- How?!!

Reference plane after calibration
Reference plane after de-embedding

Source: IBM IEEE Spectrum
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De-embedding steps

- **Open-Short**
  - *Koolen, Bipolar Circuits and Technology Meeting, Sep. 1991*

- **3 Steps**

- **4 Steps**
De-embedding steps

● 5 Steps
Probes-Short  Pad-Open  Pad-Short  Line  Complete-Short

* F. Pourchon et al, BCTM 08, Invited talk

● 6 Steps
Probes-Short  Pad-Open  Pad-Short  Line  Complete-Short

* C. Raya et al, HICUM Workshop 08
De-embedding Steps

- 5 de-embedding steps

Source: IBM IEEE Spectrum
De-embedded equivalent circuit (1): Probe Short
Results

• Probe short:
  – short circuit for the probes
  – Correct the probe contact resistance

Attention: probe contact problem at Port 1
Manual probing !!!
De-embedded equivalent circuit (2): Pad Open
De-embedded equivalent circuit (2): Pad Open

- Pad capacitance

![Graph showing capacitance vs. frequency for C1 and C2]

- Equivalent circuit (2)

![Diagram of equivalent circuit with components C1PO and C2PO]
De-embedded equivalent circuit (3): Pad Short
De-embedded equivalent circuit (3): Pad Short

- Pad short:
  - short circuit at the edge of the signal pad.
De-embedded equivalent circuit (4): Line scalable
De-embedded equivalent circuit (4): Line scalable

- First: measure and de-embed a long line:
Re-dimensioning the line

\[ T = a + d \quad K = a - d \quad \Delta = K^2 + 4bc \quad \delta = \sqrt{\Delta} \quad \text{si} \ \Delta \geq 0 \quad \text{ou} \quad \delta = i\sqrt{\Delta} \quad \text{si} \ \Delta < 0 \quad n = \frac{L}{L_{\text{line}}}
\]

\[
\begin{bmatrix}
a \\
b \\
c \\
d
\end{bmatrix}
= \frac{1}{\delta}
\begin{bmatrix}
\frac{(\delta+K)(T+\delta)^p + (\delta-K)(T-\delta)^p}{2^{n+1}} \\
\frac{(T+\delta)^p - (T-\delta)^p}{2^n} \\
\frac{(\delta-K)(T+\delta)^p + (\delta+K)(T-\delta)^p}{2^{n+1}}
\end{bmatrix}
\]

\text{Phase (degree)}
\text{Frequency (Hz)}
\text{S12} \quad \text{S21} \quad \text{S12_Shortline} \quad \text{S21_Shortline}
De-embedded equivalent circuit (5): Complete short
De-embedded equivalent circuit (5): Complete short

$Z_B$: Base impedance
$Z_C$: Collector impedance
$Z_E$: Emitter impedance
The three shorts:

- **Probes-Short**
- **Pad-Short**
- **Complete Short**

The graph shows the resistance (Ohm) vs. frequency (Hz) for three different types of shorts: `comple_short`, `probe_short`, and `pad_short`. The x-axis represents the frequency in Hz ranging from 1G to 100G, while the y-axis represents the resistance in Ohm ranging from -0.6 to 1.0.
De-embedded equivalent circuit (6): Capacitances

- 6 de-embedding steps

Specific open could be used only between port 1 & 2 ($C_{PBC}$ capacitance)
De-embedded equivalent circuit (6): Capacitances

**Symmetrical test structures**

\[ C_{BE}(2.B) \parallel C_{BE}(1.B) \]

\[ C_{backend}(1.B) \approx C_{BE}(2.B) - C_{BE}(1.B) \]
Comparison (Open Vs 6 steps):

BiCMOS9MW CBEBC $W_E=0.3\mu m$, $L_E=14.92\mu m$ et $L_E=3.7\mu m$

$V_{BE}=-0.5V$

$f_T$ extracted from measurements @10GHz
Discussion

- Good correction for 6 steps
- Different type of dummies → processing is more complex
- More de-embedding dummies for one DUT
  - Large set of devices end by doubling or tripling the number of dummies → Si area

6 steps very complex → Specified approach, Two steps

![Diagram of R, L circuit with symbols for Probes-Short, Pad-Open, Pad-Short, Line, Complete Short]
Two-Step de-embedding

- Pad Open

\[
\begin{pmatrix}
i_1 \\
i_2
\end{pmatrix} =
\begin{pmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{pmatrix}
\begin{pmatrix}
v_1 \\
v_2
\end{pmatrix}
\]

\[C_1 = \left( \frac{1}{2\pi f} \right) \text{Im}(Y_{11})\]

\[C_2 = \left( \frac{1}{2\pi f} \right) \text{Im}(Y_{22})\]
Two-Step de-embedding

- Complete-Short

\[
\begin{bmatrix}
    v_1 \\
    v_2
\end{bmatrix} =
\begin{bmatrix}
    Z_{11} & Z_{12} \\
    Z_{21} & Z_{22}
\end{bmatrix}
\begin{bmatrix}
    i_1 \\
    i_2
\end{bmatrix}
\]

\[
R_1 = \text{Re}(Z_{11}) - \text{Re}(Z_{12})
\]

\[
R_2 = \text{Re}(Z_{22}) - \text{Re}(Z_{21})
\]

\[
R_3 = \left(\text{Re}(Z_{12}) - \text{Re}(Z_{21})\right)/2
\]
Comparison:

- Validation of the Two-steps method

CBEBC $L_E=5\mu m$, $V_{BE}=0.9V$, $V_{CB}=0V$
Comparison:

- Validation of the Two-steps method

CBEBC \( L_E=5 \mu m, V_{BE}=0.9V, V_{CB}=0V \)
Conclusion

- Different de-embedding methods were presented
- A scalable solution for deembedding is the key
- De-embedding structures use a lot of Si surface
- Pad open and complete short may be sufficient
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Thanks For Your attention