Cold S-Parameter Measurements on Vertical PNP Transistors

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Agenda

- Introduction
- Measurement and parameter extraction for $C_{BE}$ and $C_{BC}$
- Measurement and parameter extraction for $C_{BC}$ and $C_{CN}$
- Measurement and parameter extraction for $C_{CN}$ and $C_{NS}$
- Summary
## Intro

### Two way’s for junction capacitance measurement

#### How to measure junction capacitances?

<table>
<thead>
<tr>
<th>C(V)-Measurement</th>
<th>Cold S-Parameter-Measurement</th>
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</thead>
<tbody>
<tr>
<td><strong>Measurement device</strong></td>
<td><strong>Cold s-parameter</strong></td>
</tr>
<tr>
<td>LCR meter</td>
<td>NWA</td>
</tr>
<tr>
<td><strong>Advantage</strong></td>
<td>Only one contact necessary for fwd DC, CV and S-parameter measurements, ensuring consistent data</td>
</tr>
<tr>
<td>Fast measurement</td>
<td>Sufficient accurate, if four probes are used</td>
</tr>
<tr>
<td>Sufficient accurate, if four probes are used</td>
<td></td>
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<tr>
<td><strong>Disadvantage</strong></td>
<td>Additional calibration for cold s-parameter frequencies needed</td>
</tr>
<tr>
<td>Calibration slow (minutes)</td>
<td>Bias tee’s must cover frequency range for both cold and hot s-parameter measurements</td>
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<tr>
<td>Resolution: for small cap’s parallel structures needed</td>
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The term “cold” is used, if a bipolar transistor is operated in non-active mode: all junctions are reverse or zero biased and no transfer currents flow \([1][2]\)

Under these circumstances the small signal equivalent circuit may be reduced to a capacitive PI circuit

Assuming the elements of a PI circuit are pure capacitive, we get the matrix \(Y_{PI, C}\) and may calculate \(C_A, C_B\) and \(C_C\)

\[
Y_{PI, C} = \begin{bmatrix}
  Y_{11} & Y_{12} \\
  Y_{21} & Y_{22}
\end{bmatrix} = \begin{bmatrix}
  Y_A + Y_C & -Y_C \\
  -Y_C & Y_B + Y_C
\end{bmatrix}
\]

\[
Y_{PI, C} = \begin{bmatrix}
  j\omega (C_A + C_C) & -j\omega C_C \\
  -j\omega C_C & j\omega (C_B + C_C)
\end{bmatrix}
\]

\[
C_A(V) = \frac{\text{IMAG}(Y_{11} + Y_{12})}{2\pi * f}
\]
\[
C_B(V) = \frac{\text{IMAG}(Y_{22} + Y_{12})}{2\pi * f}
\]
\[
C_C(V) = 0.5 \frac{\text{IMAG}(Y_{21} + Y_{12})}{2\pi * f}
\]
Contrary to the npn transistor, there are four junction capacitances $C_{BE}$, $C_{BC}$, $C_{CN}$ and $C_{NS}$ to determine for a VPNP.

Whereas for the npn all three capacitances $C_{BE}$, $C_{BC}$ and $C_{CS}$ may be measured and extracted using one test structure, we need TWO test structures for the VPNP.

Test structure 1: NWA-Ports connected to B and C

Test structure 2: NWA-Ports connected to C and N
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VPNP cold s-parameter measurements

Circuit 1: BE and BC capacitance

- BE and BC junctions are reverse biased, $V_C = V_E = V_S = 0$ V
- Sweep $V_B$ is applied to port 1, the maximum value is given by $BV_{BE0}$
- This circuit is preferred for $C_{BE}$ extraction, but not for $C_{BC}$

\[
C_{BE}(V) = \frac{\text{IMAG}(Y_{11} + Y_{12})}{2\Pi \ast f}
\]

\[
C_{BC}(V) = -\frac{1}{2} \frac{\text{IMAG}(Y_{21} + Y_{12})}{2\Pi \ast f}
\]
VPNP cold s-parameter measurements
Circuit 1: BE and BC capacitance

- 1st extraction step delivers $C_{BE}$ and $C_{BC}$ vs. frequency
- A pure capacitive PI circuit will deliver constant curves
- For $C_{BE}$ this is nearly given, for $C_{BC}$ not. Why?

$C_{BE} = f(freq)$, $V_B = \text{Par.}$
Mean value

$C_{BC} = f(freq)$, $V_B = \text{Par.}$
Mean value
VPNP cold s-parameter measurements
Series resistance effect

- A simulation using only a few SGP parameters demonstrates the effect of a series resistance, reducing the extracted capacitance with increasing frequency.
- We found: RB, RC affects $C_{BE}$ & $C_{BC}$, Rsub affects Csub [3].
- Conclusion: To avoid the series resistance effect, the frequency range must be chosen low enough for cold s-parameter measurements.

Cbe=f(f), Vbe=+0.2 ...-2, SGP-simulation with RB=0

Cbe=f(f), Vbe=+0.2 ...-2, SGP-simulation with RB=100
2nd extraction step: using the mean values we may calculate \( C_{BE}(V) \) and \( C_{BC}(V) \)

For the parameter extraction we have two possibilities: optimization of a calculated or of a simulated curve on the measured \( C(V) \) data

Which way is the better one?
VPNP cold s-parameter measurements
Two way’s for model parameter extraction

How to extract the junction capacitance model parameters?

Optimization on a calculated curve using the function PNCApSimu

Optimization on a simulated curve using a compact model e.g. VBIC or HLO

<table>
<thead>
<tr>
<th>Optimization on</th>
<th>calculated data</th>
<th>simulated data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantage</td>
<td>Very fast</td>
<td>Real equations of the compact model are used</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>PNCApSim does not include effect like punch through etc. For more complicated capacitance equations a transform must be written</td>
<td>Only capacitances between Port1 and Port2 may be simulated Capacitances to ground, e.g. the substrate capacitance, may not be simulated</td>
</tr>
</tbody>
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Circuit 2: BC and CN capacitance

- BC and CN junctions are reverse biased, $V_N = V_E = V_S = 0\, V$, sweep $V_C$ is applied to port 2
- This circuit is preferred for $C_{BC}$ extraction, because $BV_{CB0}$ may be applied

\[
C_{BC}(V) = -\frac{1}{2} \frac{\text{IMAG}(Y_{21} + Y_{12})}{2\pi f}
\]

\[
C_{CN}(V) = \frac{\text{IMAG}(Y_{22} + Y_{12})}{2\pi f}
\]
VPNP cold s-parameter measurements
Circuit 2: BC and CN capacitance

- 1st extraction step delivers $C_{CB}$ and $C_{CN}$ vs. frequency
- Effect of series resistances is clearly visible again

**Graphs:**

- $C_{CB} = f(freq), V_{C} = \text{Par.}$
  - Mean value
- $C_{CN} = f(freq), V_{C} = \text{Par.}$
  - Mean value
VPNP cold s-parameter measurements

Circuit 2: BC and CN capacitance

- 2nd extraction step delivers $C_{CB}(V)$ and $C_{CN}(V)$
- For $C_{CB}$ the punch through effect becomes clear visible
- $C_{CB}$ was optimized here using the transform cjc_pt, which uses the HL0 equation set for a capacitance including punch thru effect

$$C_{CB} = f(V_C)$$

$$C_{CN} = f(V_C)$$
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Circuit 3: CN and NS capacitance

- CN and NS junction are reverse biased, $V_B = V_E = V_S = 0 \text{ V}$, sweep $V_N$ is applied to port 1
- This circuit is preferred for $C_{CN}$ extraction (because it may be extracted here from the mean of $Y_{12}$ and $Y_{21}$) and for $C_{NS}$ extraction

\[ C_{CN}(V) = -\frac{1}{2} \frac{\text{IMAG}(Y_{21} + Y_{12})}{2\Pi \cdot f} \]

\[ C_{NS}(V) = \frac{\text{IMAG}(Y_{11} + Y_{21})}{2\Pi \cdot f} \]
VPNP cold s-parameter measurements
Circuit 3: CN and NS capacitance

- 1st extraction step delivers $C_{CN}$ and $C_{NS}$ vs. frequency
- Here only two frequency points have been used to reduce the series resistance effect

$C_{CN} = f(\text{freq}), \quad V_N = \text{Par.}$

Mean value

$C_{NS} = f(\text{freq}), \quad V_N = \text{Par.}$

Mean value

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2nd extraction step delivers $C_{CN}(V)$ and $C_{NS}(V)$
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The four space charge layer capacitances of a VPNP may be extracted using cold s-parameter measurements. Advantage is the possibility to measure the data for fwd DC curves, for $C_{BE}$, $C_{BC}$ and $fT$ consistent using one contact event only. For the capacitances $C_{CN}$ and $C_{NS}$, however, a 2nd test structure and, consequently, a 2nd contact event is necessary. The frequency range for cold s-parameter measurements must be chosen carefully to avoid series resistance effects. For fast transistors, the frequency range for the “standard”-fT-measurements and cold s-parameter measurements my be differ considerably. For this reason the calibration process and the measurement of open and short deembedding structures must be made twice. The measurement routine must be able to handle these two different deembedding steps.
Literature


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