A look on characterization of semiconductor devices

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Motivation + Goal

› How do we need to characterize devices to describe them fully and hence, (at best) be able to simulate them correctly?
  - I do not want to talk about modeling here
  - i.e. whether we can match the characterization data with a compact model is not relevant for this question

⇒ What kind of analyses do we need to fully describe device behavior?
  - TRAN+DC+AC+HB+XXX?!
How to crack a nut?

› The hammer

› The nutcracker

› As a generic tool, I'd guess the hammer wins, but in this example...

› If you have the choice, you would use the nutcracker, right?
  – I'll use this reference later during the presentation
The whole world runs in transient

- Keep in mind that every signal $V_{\text{sig}}(t)$ in the real world runs in transient
  - Strictly speaking, there is no DC, AC, ...
  - All other analyses are (e.g. mathematical) ways to describe what is going on in transient

- Example: Sine wave $V_{\text{sin}} = V_0 \cdot \sin(t \cdot f_0 \cdot (2 \cdot \pi))$

![Graph of a sine wave](image)

- The sine wave can be broken down to two numbers $(V_0, f_0)$
- .FOUR is the nutcracker for sine waves
Let us break down the transient world

- \( V_{\text{sig}}(t) = \text{const} \) (for \( t > t_{\text{settle}} \))
  - Well, this is obviously a .DC/(.OP)
  - Somehow, this is what is done when a RAMP is used for finding a DC solution using a transient

- \( V_{\text{sig}}(t) = \text{const} + V_0 \sin(t \cdot f_0 \cdot (2 \pi)) \) (for \( t > t_{\text{settle}} \) and sufficiently small \( V_0 \))
  - .DC/(.OP) + .AC
  - All capacitors + inductors (and whatever weird charge/flux controlled elements you have within compact models) simplify to frequency dependent resistors/capacitors/inductors (and as our frequency is const, ...)
  \[ \Rightarrow \text{We are somehow back to running another .DC on top of our original .DC} \]

- I can recommend the lecture notes from Prof. W. Schwarz (F. Kurz wrote it down)
  - R.I.P.
  - http://fkurz.net/et/
Let us break down the transient world

› Arbitrary $V_{\text{sig}}(t)$
  – Well, this might not be easy ...

› Without dynamic contributions
  – Then all voltages/currents in the circuit will instantly follow the stimulus
  – ... and we essentially have a single .DC analysis for each timepoint

› With dynamic contributions
  – From one timepoint to the next
    – ... for capacitors

\[
I_C^{n+1} = \frac{C}{h^n} V_C^{n+1} - \frac{C}{h^n} V_C^n = \omega C \Delta V
\]

(Backward Euler)

– ... for inductors

\[
V_L^{n+1} = \frac{L}{h^n} I_L^{n+1} - \frac{L}{h^n} I_L^n = \omega L \Delta I
\]

[1]: QUCS technical papers
    Stefan Jahn, et al., 2007
Let us break down the transient world

- Arbitrary $V_{\text{sig}}(t)$
  - It seems that with dynamic components, a transient gets additional contributions that can also be described by an .AC

- Another way to phrase it
  - A .DC bias describes how a bias behaves
  - An .AC tells us how the device can exit the current bias and enter a new one
A transient example

› Simple diode
  - Consisting of a diode equation (for a static contribution)
    - \( I_{dio} = I_s \left[ \exp \left( \frac{V_j}{V_{th}} \right) - 1 \right] \)
    - ... and junction capacitance (for a dynamic contribution)

› Apply a voltage pulse to the diode
  - Note that we will apply a negative pulse over the diode

⇒ We bias the diode in forward at first and the first pulse will turn it off
Let us run a true .TRAN simulation first

› The example
  – $V_0 = 0.9\,\text{V}$, $V_1 = -1\,\text{V}$
  – $t_1 - t_0 = 10\,\text{ns}$
  – $t_2 - t_1 = 5\,\text{ns}$

› The result is rather simple 😊
  – Let us interpret it a bit ...
Let us describe the transient simulation with DC+AC

› Discretize the voltage pulse in e.g. 250ps wide steps

1. Run a DC at the current timepoint
   - At the initial timepoint (t=0) we assume no dynamic contributions

2. Run an AC at \( \omega = 1/250\text{ps} = 4\text{GHz} \) at the current DC bias
   - Determine the effective resistance of all dynamic elements
   - e.g. \( R_{eff} = 1/(\omega C) \)

3. Replace all dynamic elements by a surrogate circuit
   - For a capacitor: effective resistance in series with voltage source (\( V^n_C \))

4. Go back to 1 and repeat for the next timepoint

\[
I_{C}^{n+1} = \left( \frac{C}{h^n} \right) V_{C}^{n+1} - \left( \frac{C}{h^n} \right) V_{C}^n = \omega C \Delta V
\]
Let us describe the transient simulation with DC+AC

› Result
- Lines correspond to a true .TRAN simulation
- Markers correspond to the .DC/.AC approach

⇒ We have a match 😊
Conclusion

1. The inverse transient time step may be considered as an effective frequency
2. .DC and .AC seem to be sufficient to describe transient behavior

› Are there limitations?

› Do we need .HB or other RF analyses?
  – At least for characterization normally we do not
    – Why? Nonlinearities come from bias dependence of conductances/capacitances (which we have determined from .AC at different bias)
    – Well, you may enter a different static bias, which you do not reach with normal DC
      – And you also stress your device differently (as it is a dynamic stress)

3. If you characterize a device in all bias points with .DC and .AC at all frequencies you collected all data to fully describe it

› Do not get me wrong
  – I am not saying that other analyses are useless
  – Analyses need to be chosen according to application for true verification
    – Do not use DC+AC to check a transient FoM (=figure of merit). Use the nutcracker!
How characterization is done in practice?

- I hope everybody does DC and AC ...
Part of your life. Part of tomorrow.