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

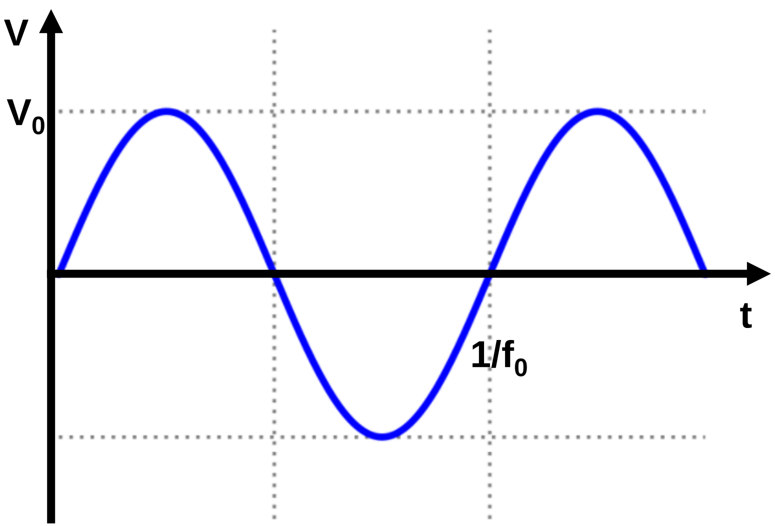
- The nutcracker

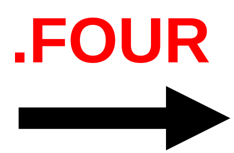
- As a generic tool, I‘d guess the hammer wins, but in this example...
- If you have the choice, you would use the nutcracker, right?
  - I‘ll use this reference later during the presentation

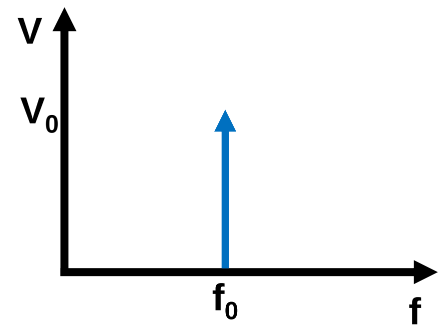
The whole world runs in transient

- Keep in mind that every signal $\mathbf{V_{sig}(t)}$ 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 $V_{sin}=V_0*\sin(t*f_0*(2*\pi))$







- 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_{sig}(t)** = const (for t > t_{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_{sig}(t)** = const + V_0*sin(t*f_0*(2*π)) (for t > t_{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, ...)
  - ⇒ 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 $\mathbf{V_{sig}(t)}$
  - 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

$$I_C^{n+1} = \frac{C}{h^n} V_C^{n+1} - \frac{C}{h^n} V_C^n \quad \text{(backward Euler)}$$

$$\frac{C}{h^n} = \omega C * \Delta V$$

    - ... for inductors

$$V_L^{n+1} = \frac{L}{h^n} I_L^{n+1} - \frac{L}{h^n} I_L^n$$

$$\frac{L}{h^n} = \omega L * \Delta I$$

[1]: QUCS technical papers
Stefan Jahn, et al., 2007

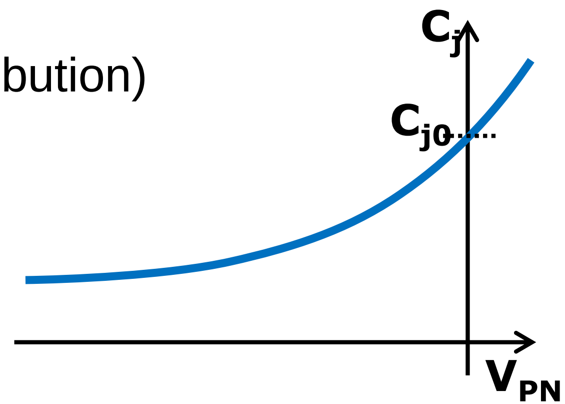
Let us break down the transient world

- Arbitrary $\mathbf{V_{sig}(t)}$
  - 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

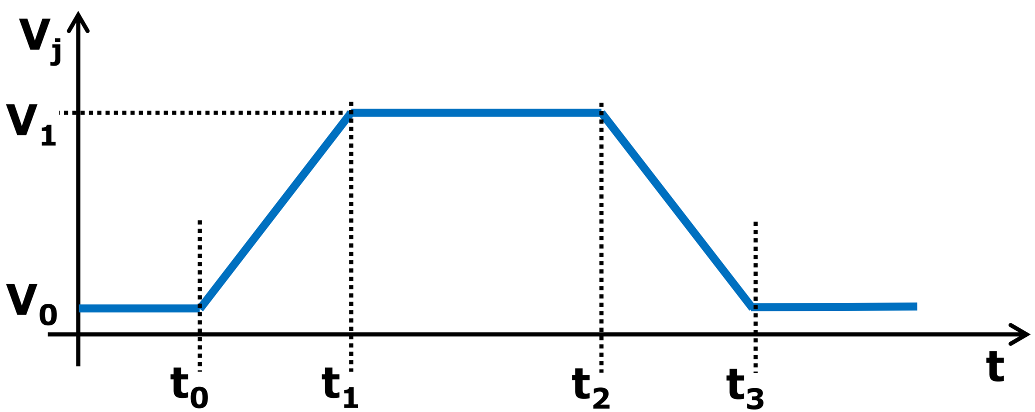
A transient example

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



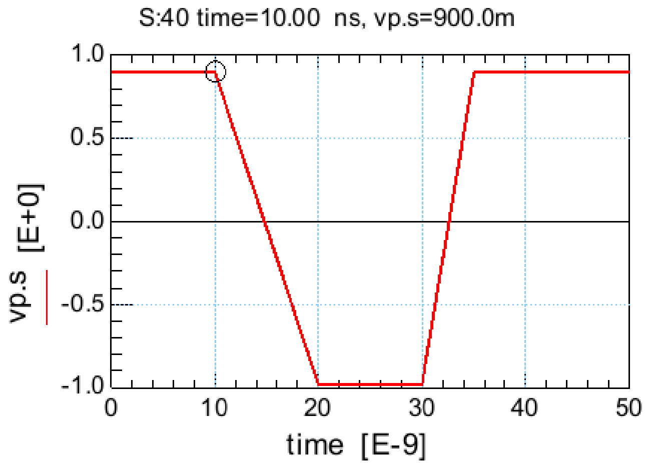
- Apply a voltage pulse to the diode
  - Note that we will apply a negative pulse over the diode

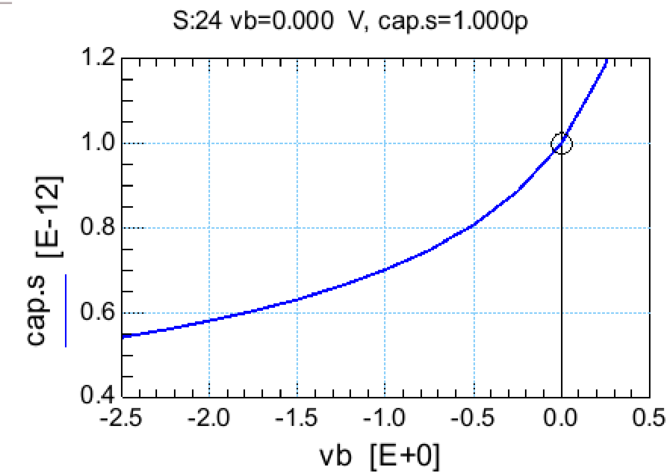
⇒ We bias the diode in forward at first and the first pulse will turn it off



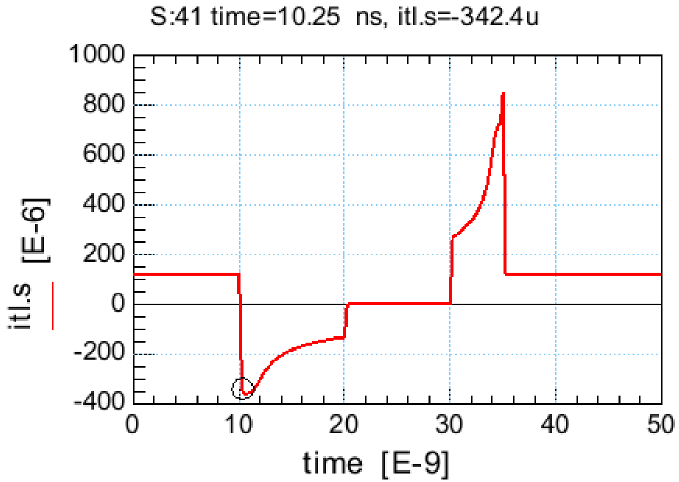
Let us run a true .TRAN simulation first

- The example
  - $V_0 = 0.9V$, $V_1 = -1V$
  - $t_1 - t_0 = 10ns$
  - $t_2 - t_1 = 5ns$





- 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

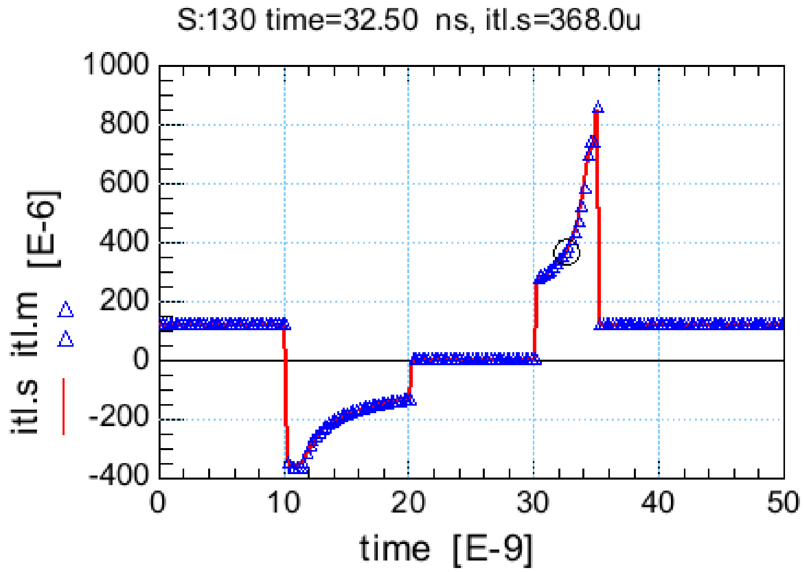
1. Run a DC at the current timepoint
   – At the initial timepoint (t=0) we assume no dynamic contributions
2. Run an AC at $\omega = 1/250ps = 4GHz$ at the current DC bias
   – Determine the effective resistance of all dynamic elements
   – e.g. $R_{eff} = 1/(\omega C)$
3. Replace all dynamic elements by a surrogate circuit
   – For a capacitor: effective resistance in series with voltage source (V_C^n)
4. Go back to 1 and repeat for the next timepoint

$$I_C^{n+1} = \frac{C}{h^n} V_C^{n+1} - \frac{C}{h^n} V_C^n \quad \text{(backward Euler)}$$

$$= \omega C * \Delta V$$

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.