Report: MOSFET Test Procedures

Lukas Deutz

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This report presents simulation results from the project's test suite using the Gnucap and ngspice circuit simulators. Simulation outputs from both simulators are quantitatively compared for cross-validation. The report covers individual test cases including DC sweeps, AC analysis, transient analysis, and noise analysis for different MOSFET device models using the cmos90 technology defined in the cmos90.params file (L=0.9u W=10u and VNOM=1.2V).

All figures in this report are generated from the raw data included in the `results/reference` directory of this project. The data was produced using the simulator versions Gnucap 2025.12.18 (tag: 20251222-dev) and ngspice 45.2.

Postprocessing

To compare simulation outputs from Gnucap and ngspice, the relative error ε_{rel} as:

$$\varepsilon_{\text{rel}} = \frac{|x_{\text{Gnucap}} - x_{\text{ngspice}}|}{\max(|x_{\text{ngspice}}|, \text{atol})} \tag{1}$$

Here, x denotes an output quantity such as node voltage or through current. The absolute tolerance $\text{atol} = 10^{-10}$ sets a lower bound for the denominator, preventing division by zero when the reference approaches zero.

DC Sweeps

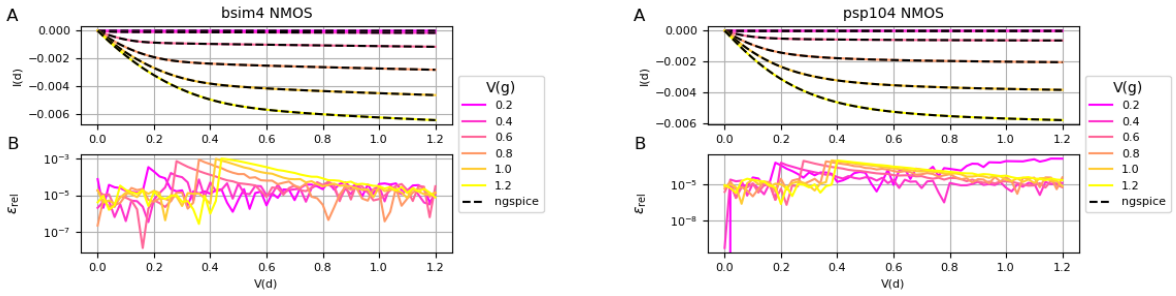

Figure 1: NMOS Id-Vd characteristics for BSIM4 and PSP104 MOSFET models. (A) Drain current I(d) versus drain voltage V(d) for different gate voltages V(g) illustrating the impact of gate bias on NMOS behavior. Colored lines represent Gnucap results, overlaid by ngspice results shown as black dashed lines. (B) Relative error ε_{rel} between Gnucap and ngspice drain currents I(d) over V(d) for different gate voltages.

DC sweeps include single-device NMOS and PMOS I–V characterization across varying gate, drain, and bulk voltages under nominal, low, and high temperature conditions. Id-Vd curves obtained from the test case `id_vd_nmos_1` using the BSIM4 and PSP104 MOSFET models are shown in Figure 1. The simulated

characteristics exhibit the expected linear and saturation regions, with cutoff behavior for gate voltages below threshold.

The relative error ε_{rel} between Gnucap and ngspice remains in the range of 10^{-4} and 10^{-7}, well within numerical tolerances for circuit simulations. Figures for additional DC test cases are included in project's repository. Across device models and test cases, Gnucap and ngspice produce consistent characteristics within numerical tolerance.

AC analysis

AC test cases include small-signal characterization for single-stage MOSFET common-source, common-drain and common-gate amplifiers evaluated at different DC operating points. The small-signal voltage gain $A_v = v_{out}/v_{in}$ of a common source amplifier is examined as a function of frequency for different bias conditions in Figure 2. The results show a bias-dependent flat midband gain followed by a high-frequency roll-off, limiting the amplifier bandwidth.

Across the frequency range the relative error ε_{rel} in voltage gain between Gnucap and ngspice remains on the order of 10^{-5}. Figures for common-drain and common-gate amplifiers are included in the project's repository. Consistent with the DC analysis, Gnucap and ngspice produce matching AC characteristics across device models and test cases within numerical tolerances.

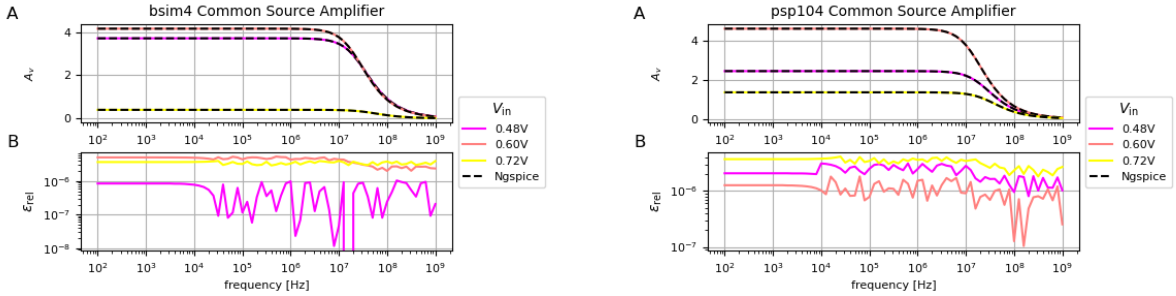

Figure 2: AC analysis of a single-stage common-source MOSFET amplifier with a passive resistor load for BSIM4 and PSP104 MOSFET models. (A) Small-signal voltage gain A_v as a function of the AC input frequency for different gate bias $V_{\text{DC,in}}$ illustrating the impact of operating point on the transfer characteristics. Colored lines represent Gnucap results, overlaid by black dashed lines for ngspice results. (B) Relative error ε_{rel} in voltage gain A_v between Gnucap and ngspice for different $V_{\text{DC,in}}$.

Transient analysis

Transient test cases include basic logic gates — NOT, NAND, NOR, AND, and OR — as well as inverter chains, ring oscillators, and comparators. The transient simulation of a CMOS NAND gate is shown for BSIM4 and PSP104 MOSFET models in Figure 3. The output voltage demonstrates correct logical behavior. The relative error ε_{rel} between Gnucap and ngspice output voltages is in the order of 10^{-2}, which is notably larger than for the DC and AC analysis.

Figure 4 shows the voltage waveform of a five-stage ring oscillator. The output voltage is probed at the first inverter stage. Both Gnucap and ngspice produce similar oscillatory behavior, with a relative error of the order of 10^{-2}.

Overall, transient simulations show good agreement between Gnucap and ngspice. Logical gates exhibit correct logical behavior, with comparable rise times, fall times, and propagation delays in both simulators (TODO). Notably, the relative error for transient cases is larger, which can be attributed to differences in time-step control and numerical integration between the two simulators.

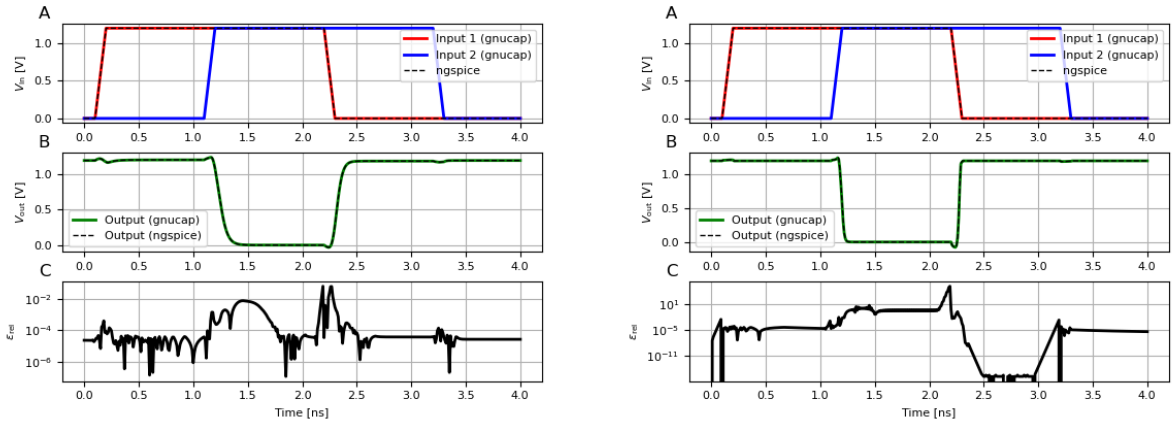

Figure 3: NAND gate transient analysis for BSIM4 and PSP104 MOSFET models. (A) Input voltages in Gnucap, overlaid with black dashed lines for ngspice. (B) Output voltage demonstrating correct NAND logic operation. (C) Relative error ε_{rel} in output voltage between Gnucap and ngspice.

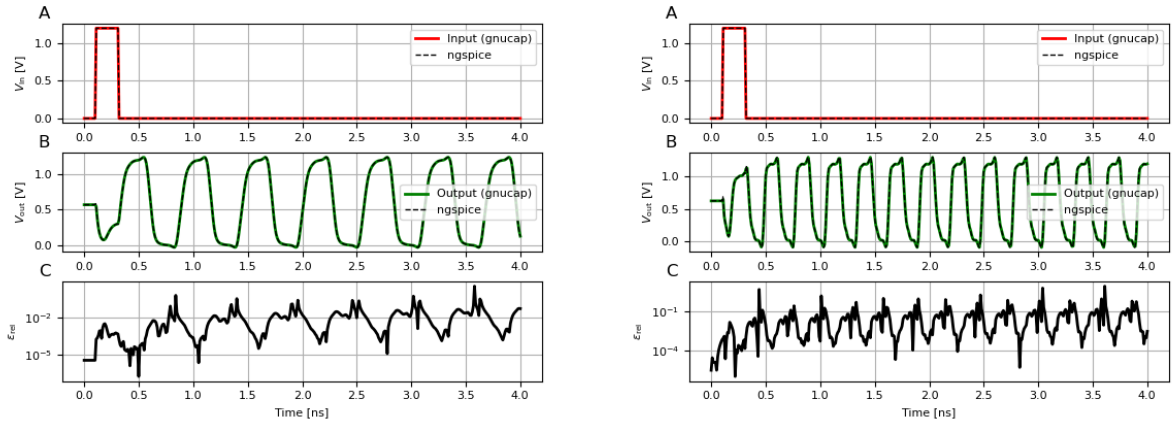

Figure 4: 5-stage ring oscillator transient analysis for BSIM4 and PSP104 MOSFET models. (A) Voltage input trigger in Gnucap, overlaid with black dashed lines for ngspice. (B) Output voltage demonstrating sustained oscillation. (C) Relative error ε_{rel} in output voltage between Gnucap and ngspice.

Noise analysis

Noise test cases analyze the power spectral density (PSD) of the built-in noise models for a given MOSFET device as a function of input frequency. The voltage noise PSD of PSP104 NMOS devices under low, nominal and high temperature conditions is compared in Figure 5. At low frequencies, noise is dominated by 1/f flicker noise, and PSD decreases with increasing frequency. At mid to high frequencies, thermal noise dominates, and PSD becomes approximately flat (white noise plateau). As expected, the noise contribution is generally larger with higher temperatures. Both Gnucap and ngspice produce similar noise PSD, with the relative error ε_{rel} between 10^{-5} and 10^{-7} across the entire frequency range for different temperatures.

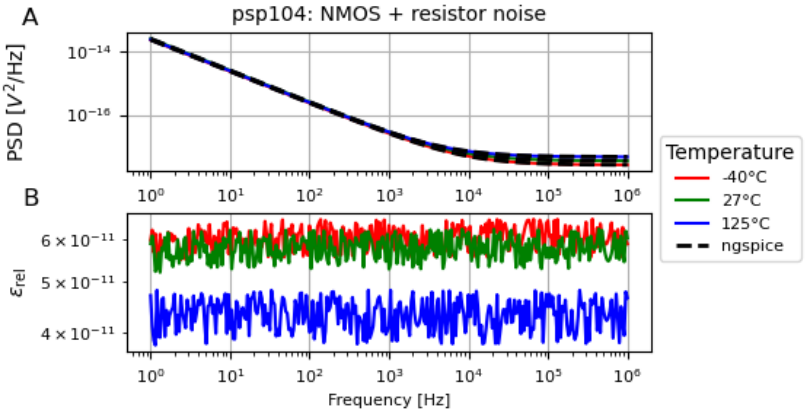

Figure 5: Noise characteristics for PSP104. (A) Power spectral density (PSD) as a function of frequency for different temperatures illustrating thermal and flicker noise contributions. Colored lines represent Gnucap results, overlaid by black dashed lines for ngspice results. (B) Relative error ε_{rel} of the PSD between Gnucap and ngspice over frequency for different temperatures.