Lecture 16, Nov 1, 2023

MOSFET Real-World Issues

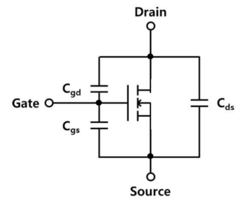

Figure 1: Model of parasitic capacitance in a MOSFET.

- In real life the construction of the MOSFET introduces a parasitic capacitance from gate to source (there are also gate-to-drain, drain-to-source parasitic capacitances but these are small)
  - Typically $C_{GS} \sim 5\,\text{pF} - 50\,\text{nF}$
  - This introduces a time limit for switching since we need to charge the capacitor
  - This can also draw large transient currents when V_{GS} changes rapidly, so we will need a driver IC or series gate resistors to mitigate this issue

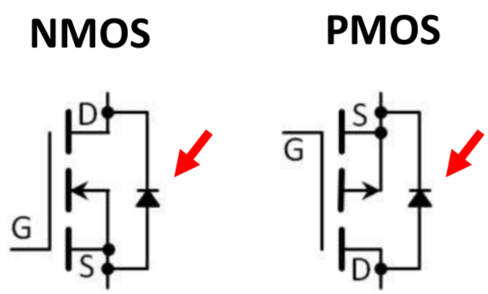

Figure 2: MOSFET body diode.

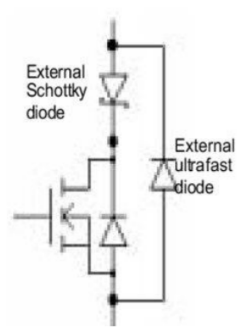

Figure 3: Fixing the MOSFET body diode.

- The construction creates 2 unintended PN junctions between the body and source/drain, which acts as a diode
  - Since we short body to source, one of these will be shorted out; however, the body-drain diode (known as the *body diode*) will now exist between the source and drain
  - If the drain-to-source voltage is too large, this diode will enter reverse breakdown and cause issues; this limits the max allowable V_{DS} in all modes
  - This diode can also make the MOSFET conduct even when it is in cut-off; this happens when $I_D < 0$

- Sometimes we want a diode in this location (e.g. motor driver) but this is a really bad diode
- Generally we place external diodes with better specifications to fix the problem

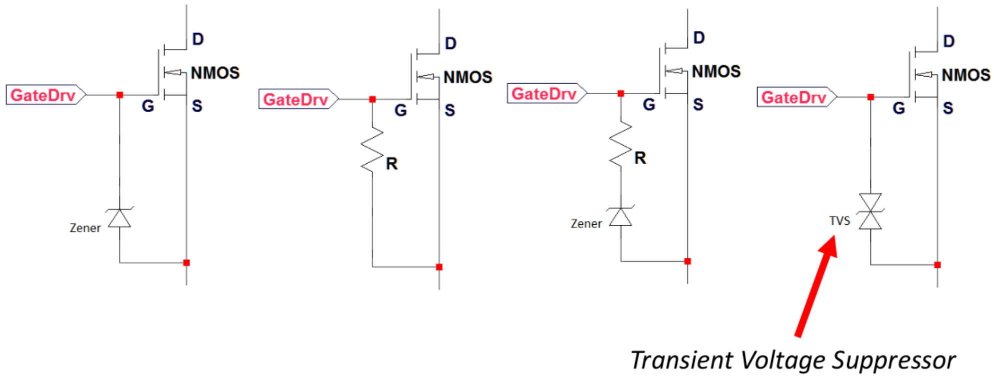

Figure 4: MOSFET ESD protection.

- The thin oxide layer under the gate is very easy to damage; typically V_{GS} is limited to $\pm 10\,\mathrm{V}$ or $\pm 20\,\mathrm{V}$
  - This means static discharge can easily damage the oxide layer
  - Most modern ICs and devices with MOSFETs now have additional ESD protection for this reason

Design Examples

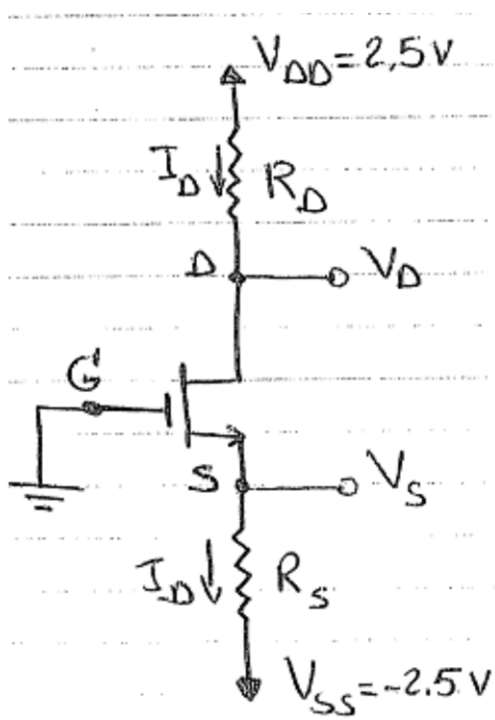

Figure 5: Example circuit.

- Example: design the circuit above for a drain current of $1\,\mathrm{mA}$ and a drain voltage of $0\,\mathrm{V}$; the transistor has $V_T = 1\,\mathrm{V}$, $k'_n = 60\,\mathrm{\mu A/V^2}, L = 3\,\mathrm{\mu m}, W = 100\,\mathrm{\mu m}$
  - We assume that gate current is 0 at DC, so current into the drain must be the same as current out of the source

    * Therefore generally we use drain current, source current, and drain-to-source current interchangeably
  - Note we always use uppercase subscripts for DC and lowercase subscripts for small signals
  - We usually start at the drain-to-source path
  - Since the voltage at V_D is 0, we know the voltage and current across the resistor R_D immediately
    * $R_D = \dfrac{V_{DD} - V_D}{R_D} = 2.5\,\mathrm{k\Omega}$
  - Now we need to relate V_S to V_D by determining the mode of operation for the MOSFET
    * We will assume one of the conduction modes (since we have a nonzero drain current, it cannot be in cut-off mode)
    * Recall that for saturation, $V_{DS} > V_{GS} - V_T \implies V_D - V_S \geq V_G - V_S - V_T \implies V_D \geq V_G - V_T \implies V_D - V_G > V_T \implies V_{GD} < V_T$
      - This is satisfied in our example
    * Note that in general, we won't always be able to determine the MOSFET's mode of operation directly like this
    * However in general in saturation mode, we typically expect drain to source currents on the order of milliamps or drain/source resistances on the order of kilohms
  - In saturation current is a direct function of V_{GS} so we can find V_{GS} using the MOSFET parameters and find V_S given V_G
    * This will yield us two values $0\,\mathrm{V}$ or $2\,\mathrm{V}$, but we can eliminate one since we require $V_{GS} > V_T$
    * At this point we can check our assumption of saturation mode
  - This gives us $V_S = V_G - V_{GS} = -2\,\mathrm{V}$
  - Now we can solve for $R_S = \dfrac{V_S - V_{SS}}{I_D} = 500\,\Omega$
    * Typically in many designs the source resistance is the smaller of the two

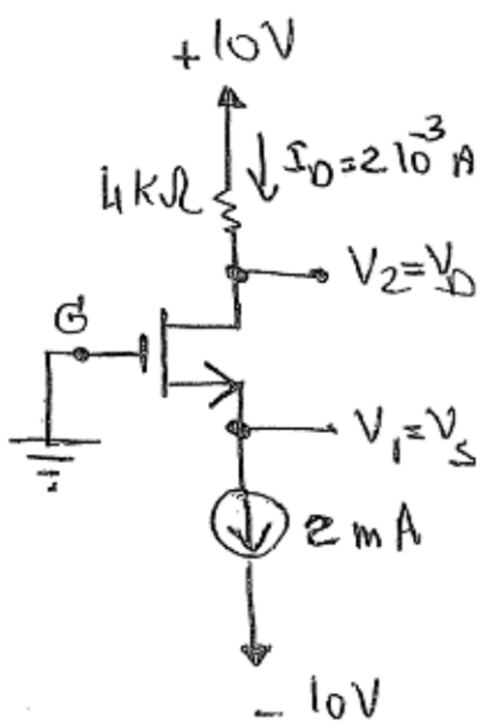

Figure 6: Example circuit.

- Example: find the drain and source voltage of the MOSFET above, and select a resistor to replace the current source with, without changing the source or drain current
  - We expect the MOSFET to be in saturation mode

- We have $V_G = 0\,\text{V}, I_D = 2\,\text{mA}$
- The drain voltage can be calculated by as $V_D = V_{DD} - R_D I_D = 2\,\text{V}$
  * Note when we solve the equation we will get 2 possible values, but one of them will give us cutoff instead of saturation
- $V_{GD} = -2\,\text{V} < V_T$ so we are indeed in saturation mode
- Now use $I_D = \frac{1}{2} k_n \frac{W}{L} (V_{GS} - V_T)^2$, with $I_D = 2\,\text{mA}$ to solve for $V_{GS} = 4\,\text{V}$
  * Again we will get 2 values, but one of them gives us cutoff
- So $V_S = V_G - V_{GS} = 4\,\text{V}$
- We can now solve for an equivalent resistance value that can replace the current source: $I_S = I_D = 2\,\text{mA} = \frac{V_S - V_{SS}}{R_S}$ to get $R_S = 3\,\text{k}\Omega$