

IN3170 V24 - Lab 3

Andreas Engøy, Simen Norrud, Erik Røset & Daniel Tran

May 2024

1 Task 1

1.1 Equipment

Component	Model	Quantity
Resistor	120kΩ	1
Capacitor	390pF	3
Hex inverter	IC CD4007UBE	2
Oscilloscope	HP54622	1
Waveform generator	HP33120	1
Voltage source	HPE3631	1

Table 1: List of components used in task 1.

1.2 Objective

The objective of this task is to build two similar current source circuits, one with a CG current conveyor and one without, and observe the voltage discharge of the capacitor when the clock signal of the pFET transistors M2 goes low.

1.3 Theory

1.4 A "bad" current source

Using the IC CD4007UBE we connected pin 14 to our V_{DD} of 5V so as to give voltage to the Q1 pFET and the bulk of the pFETs.

The voltage on C would be a constant voltage, as the current source would be able to supply a constant current to the capacitor. The voltage on the capacitor would then be given by the formula $V = \frac{Q}{C}$, where Q is the charge on the capacitor and C is the capacitance of the capacitor. The charge on the capacitor is given by $Q = I \cdot t$, where I is the current and t is the time. As the current is constant, the charge on the capacitor will be linear with time, and the voltage on the capacitor will be linear with time.

As the 100kΩ resistor was not available at the lab we used a 120kΩ instead. As per lab instructions we calculated the current through the resistor at 1V to be

$$I = \frac{V}{R} = \frac{1V}{120k\Omega} = 8.33\mu A \quad (1)$$

To get the discharge curve we used the $I = \frac{V}{dt}C$ relation to get the time it would take for the voltage to drop to 0V, which would be the time it takes for the capacitor to discharge through the resistor.

$$I = \frac{V}{dt}C \Rightarrow dt = \frac{V}{I}C = \frac{5V}{8.33\mu A} \cdot 3 * 0.39nF = 0.702ms \quad (2)$$

As seen in ?? the actual discharge curve is not linear, but rather exponential as per a capacitors normal discharge characteristics. This is due to the fact that M2's gate voltage is 0V when the clocked signal is low which gives a $|V_{GS}||V_{TH}|$, moving the pFET from saturation to cutoff. With no voltage at the gate, the pFET will not conduct any current, and the capacitor will discharge through the resistor. The voltage on the capacitor will then be given by $V = V_{DD} \cdot e^{-\frac{t}{RC}}$, where R is the resistance and C is the capacitance of the capacitor.

In stark contrast to the previous circuit, the circuit in ?? follows the theoretical curve down to what we observe to be around 1.2V when we apply 3V on the gate of M1. This is because of the relations I_D and V_{DS} in saturation and triode region. We have that:

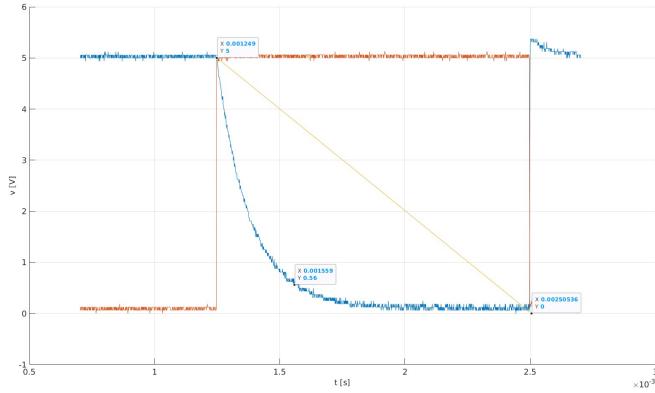


Figure 1: Plot of the circuit in figure 1 a) in the lab manual with the ideal discharge curve in yellow.

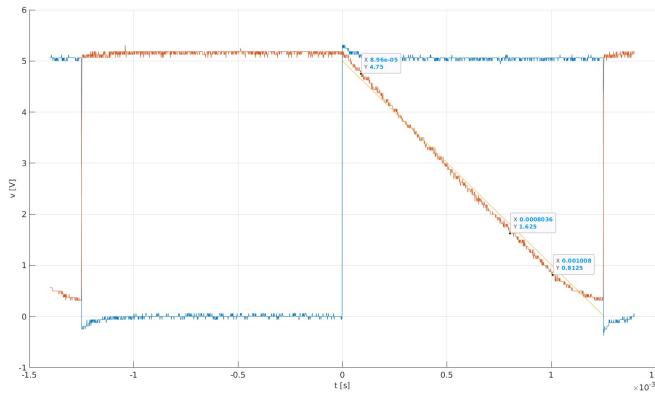


Figure 2: Plot of the circuit in figure 1 b) in the lab manual with the ideal discharge curve in yellow.

$$I_D = \frac{1}{2} \cdot \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot (V_{GS} - V_{TH})^2 (1 - \lambda \cdot V_{DS}) \quad (3)$$

for the saturation region, aka when $V_{DS} \geq V_{GS} - V_{TH}$, and $V_{GS} \geq V_{TH}$. For the triode region, aka when $V_{DS} < V_{GS} - V_{TH}$, and $V_{GS} \geq V_{TH}$, we have that:

$$I_D = \mu_n \cdot C_{ox} \cdot \frac{W}{L} \cdot (V_{GS} - V_{TH} - \frac{V_{DS}}{2}) \cdot V_{DS} \quad (4)$$

From the equations above we can observe

2 Task 2

Objective

The objective of this task is to design a current source using a FET in saturation. By simulating the circuit in Cadence one can plot the I_D vs V_{DS} curve and calculate the output resistance r_{ds} of the current source. Further, changing the design parameter $\frac{W}{L}$ of the FET, or adding a voltage cascode to the circuit is carried out to improve the current source capability.

Theory

In an ideal current source, the output current is independent of the voltage across the terminals. I.e. the current source maintains the same current throughout the circuit, despite changes to V_{DS} .

A Field-Effect Transistor (FET) operating in the saturation region exhibits the same characteristics as an ideal current source. This can be seen from the I_D vs V_{DS} curve in the saturation region, where the current is almost constant. This is because when V_{DS} approaches the saturation region it becomes high enough that it maxes out the number of charge carriers that can contribute to current flow, making the gate voltage the primary factor to the current flow.

In the plot, the curve will flatten out in this region. In a practical FET, the curve will not be completely flat (indicating that the current is not completely constant), but it will give a good approximation of an ideal current source.

Designing a current source

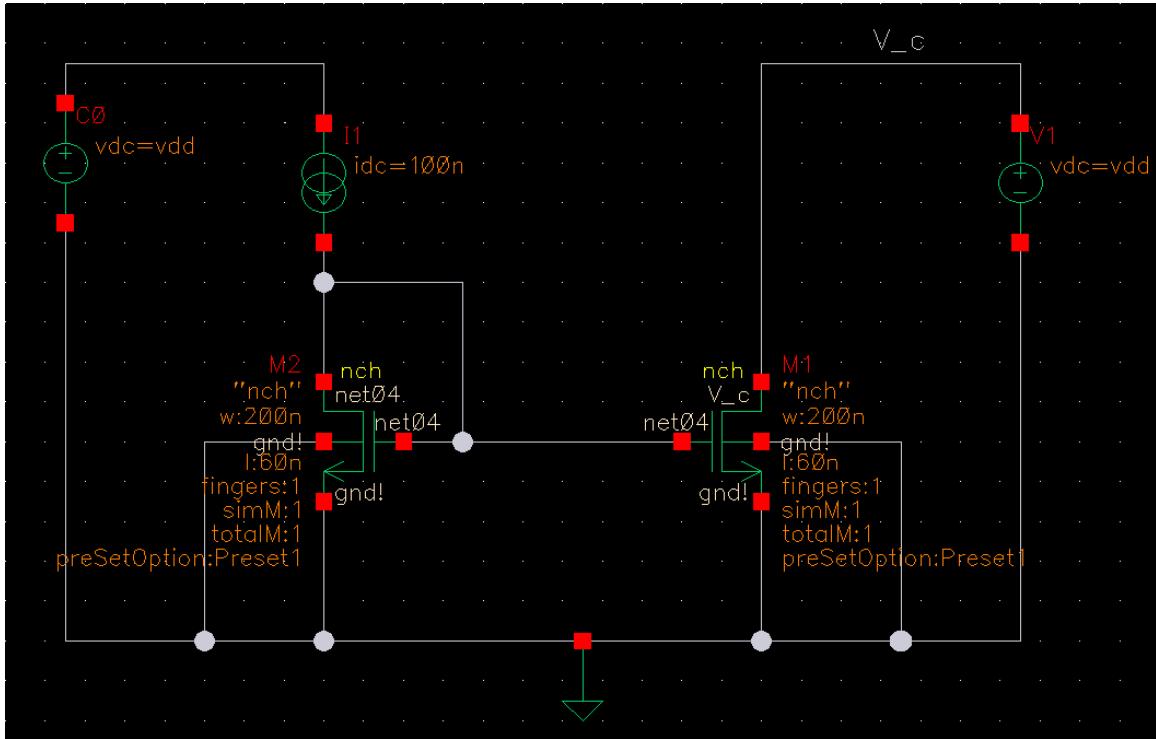


Figure 3: Screencapture of the circuit in figure 1 c) from the lab manual simulated in Cadence.

This design differs a bit from figure 1 d) in the lab manual, following the suggested method of the manual. The bias current is implemented as a current mirror, consisting of M_2 and I_1 , which sets the current that flows through M_1 . Instead of a capacitor in parallel to M_1 , and a clock signal to M_2 , a DC voltage source is used to sweep the voltage V_C in a range simulating the V_{DS} of M_1 .

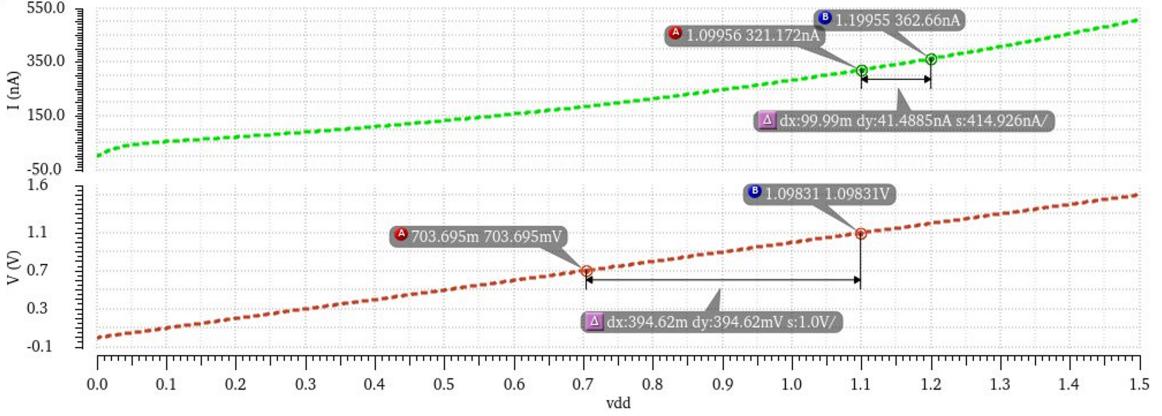


Figure 4: Screencapture of the DC sweep of the circuit in figure 1.

ΔI_D is calculated as the difference between two points on the *most linear* part of the curve. In figure ??, this is chosen to be a segment at the end of the curve. The DC sweep simulation is set to sweep from 0 V to 1.5 V. The lab manual specifies to use only up to 1.2 V, hence the last point is chosen to be close up to 1.2 V.

$$\Delta I_D = 414.926 \text{ nA} \quad (5)$$

The same method is used to calculate ΔV_{DS} , however as V_C is the sweep parameter, the voltage rises linearly. The difference between two points on this line will be the same wherever. In figure ??, the points are chosen arbitrarily.

$$\Delta V_{DS} = 1 \text{ V} \quad (6)$$

r_{ds} can then simply be calculated using Ohm's Law:

$$r_{ds} = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{1 \text{ V}}{414.926 \text{ nA}} = 2.4007 \text{ M}\Omega \quad (7)$$

The next task is to tinker with the design parameter $\frac{W}{L}$ of $M1$ in order to improve the current source capability. Even in saturation, real FETs exhibit channel-length modulation, which is a phenomenon where the effective channel length shortens as V_{DS} increases, leading to a non-ideal increase in current. By increasing the channel length L of the transistor, the channel-length modulation is reduced, and the current source capability is improved. In this report the channel length was increased to $L = 1 \mu\text{m}$. This is an exaggeration of what a normal channel length would be, but will highlight the difference more. A DC sweep is then performed again, resulting in the following plot:

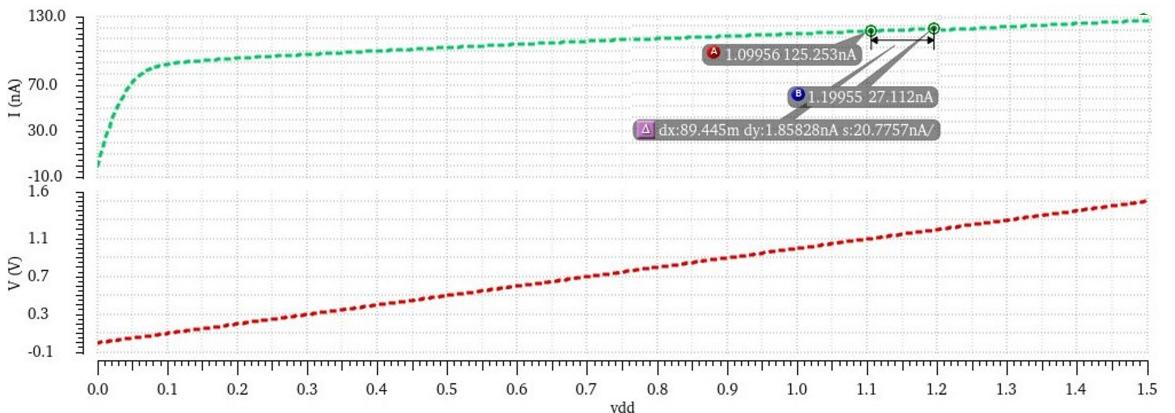


Figure 5: Screencapture of the DC sweep of the circuit in figure 1 with $L = 1 \mu\text{m}$ for $M1$ and $M2$.

For the circuit in figure ??, the same method is used to calculate ΔI_D and ΔV_{DS} as for the previous circuit. r_{ds} is then:

$$r_{ds} = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{1 \text{ V}}{20.7757 \text{ nA}} = 4.8133 \text{ M}\Omega \quad (8)$$

In a ideal current source, the output resistance (or V_{ds}) is infinite. The new r_{ds} is higher than the previous, which indicates a better approximation of an ideal current source.

Implementing a voltage cascode

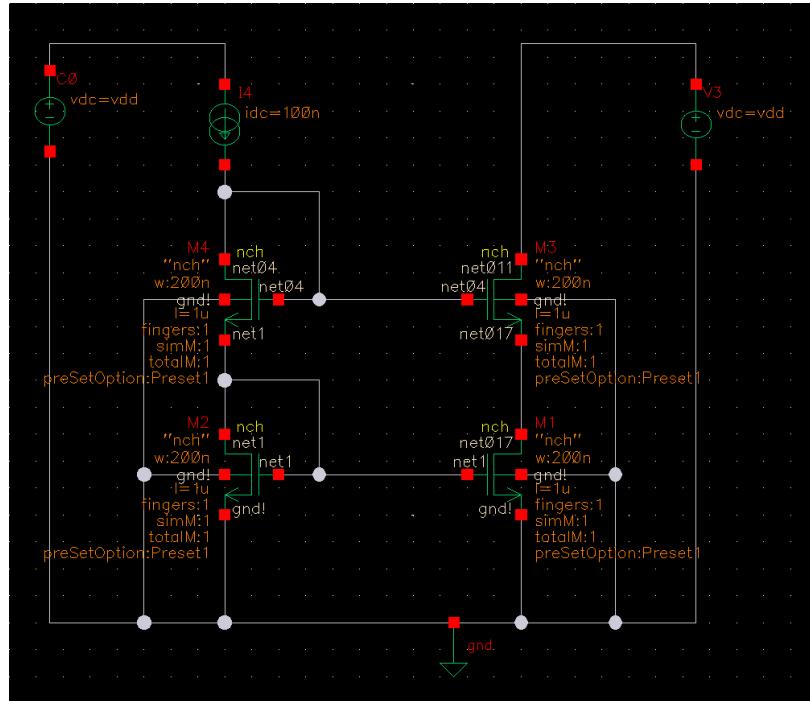


Figure 6: Screencapture of the circuit in figure 1 d) from the lab manual simulated in Cadence.

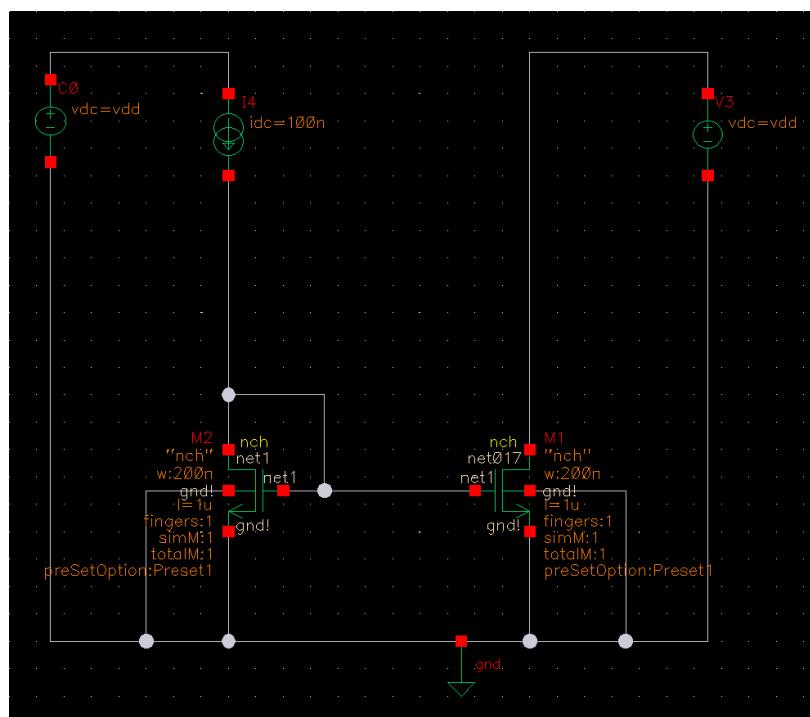


Figure 7: Screencapture of the circuit in figure 1 d) from the lab manual without the voltage cascode.

In similar fashion as the previous circuits, a DC sweep is performed for the circuit in figure ?? and ??:

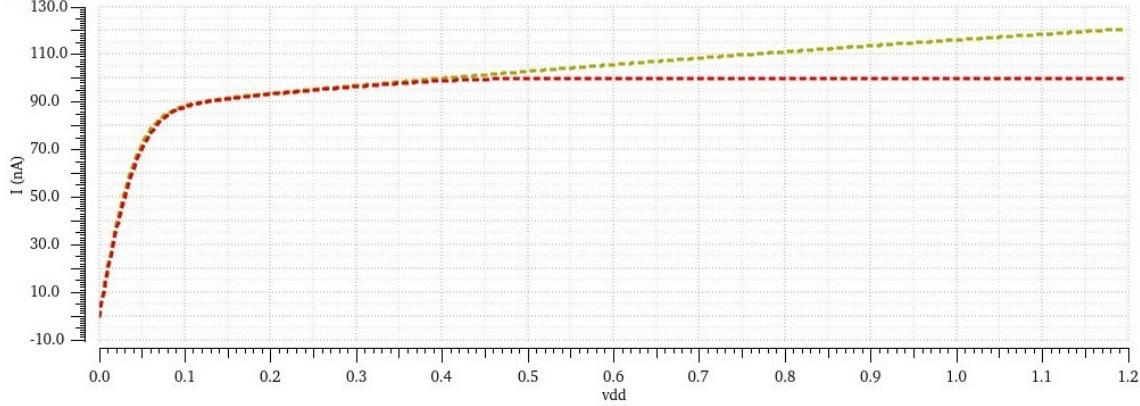


Figure 8: Screencapture of the DC sweep of both circuits in figure 1 d).

In figure ??, the red curve is the simulated I_D vs V_C for the circuit in figure ???. The yellow curve is equivalent curve for the circuit in figure ?? plotted alongside for comparison.

Initially one can observe the two curves start off nearly identical. As V_C increases, the current in both circuits begins with a sharp rise but starts to flatten as the transistors approach the saturation region. The cascode configuration, however, shows a distinct change in behavior around 0.4 V where the current flattens out even more. This enhanced flattening is due to the cascode transistor M_3 , which further restricts the increase in current by also entering saturation and increasing the circuit's output impedance.

Some trade-offs associated with using a cascode configuration include a reduced voltage headroom. That is, the circuit requires a minimum voltage drop across each transistor to ensure that both are operating in saturation. Essentially, the drain-source voltage V_{DS} of the cascode transistor M_3 must be sufficiently high for it to remain in saturation. A cascode circuit also adds complexity to the system that might be unnecessary. If the applied voltage range is small, there will be no benefit to using a cascode configuration, as the cascode transistor will not enter saturation.