Lecture 7

Diode connected MOSFET, current source and current mirror

The themes of this lecture are several basic circuits, such as diode connected MOSFET, current source and current mirror

Diode-Connected MOSFET

Applications

The original application of a diode is a rectifier. In a CMOS technology it is often impractical to use PN diode. Diodes in the forward direction inject minority charge carriers which can lead to problems (latchup). A MOSFET circuit that can replace the diode is shown in Fig 1 on the right. It is called diode connected transistor of MOSFET diode.

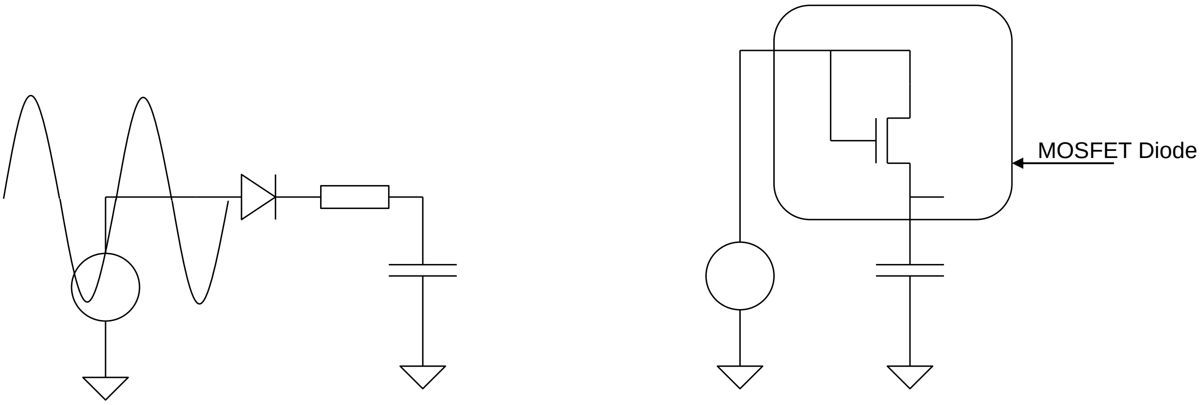

Fig 1: MOSFET diode used as a rectifier

Another application of a MOSFET diode is a replacement for resistor as a component. Resistors are realized in CMOS technology with polysilicon structures. Resistors of > 1MΩ is very large in layout. A MOSFET diode can replace a large resistance if linearity is not particularly important. This is shown in Fig 2.

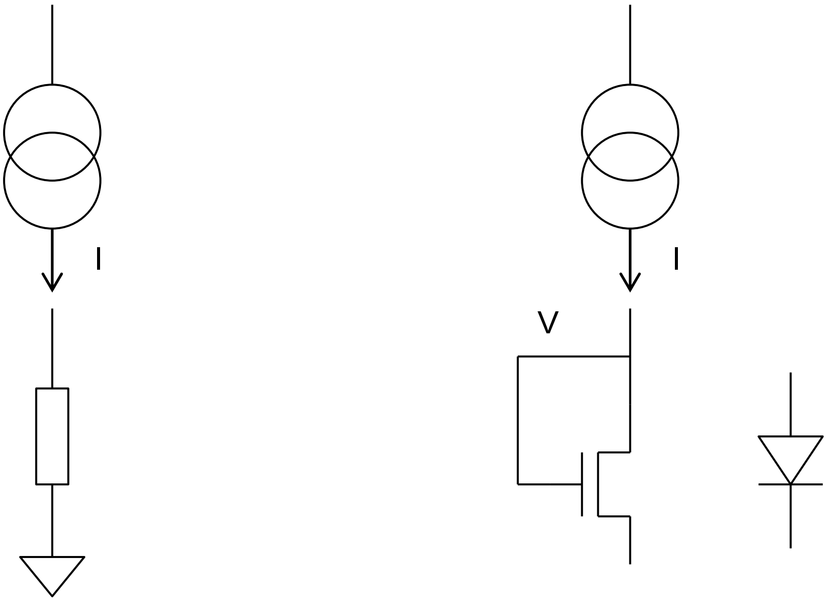

Fig 2: MOSFET diode as replacement for a resistor

Working principle

To understand how a circuit works, it is often helpful to imagine a switching process. We can imagine an input source that is switched on. We can also imagine that every node in the circuit has a capacitance. When a current flows into the capacitance, the potential increases as an integral of the current.

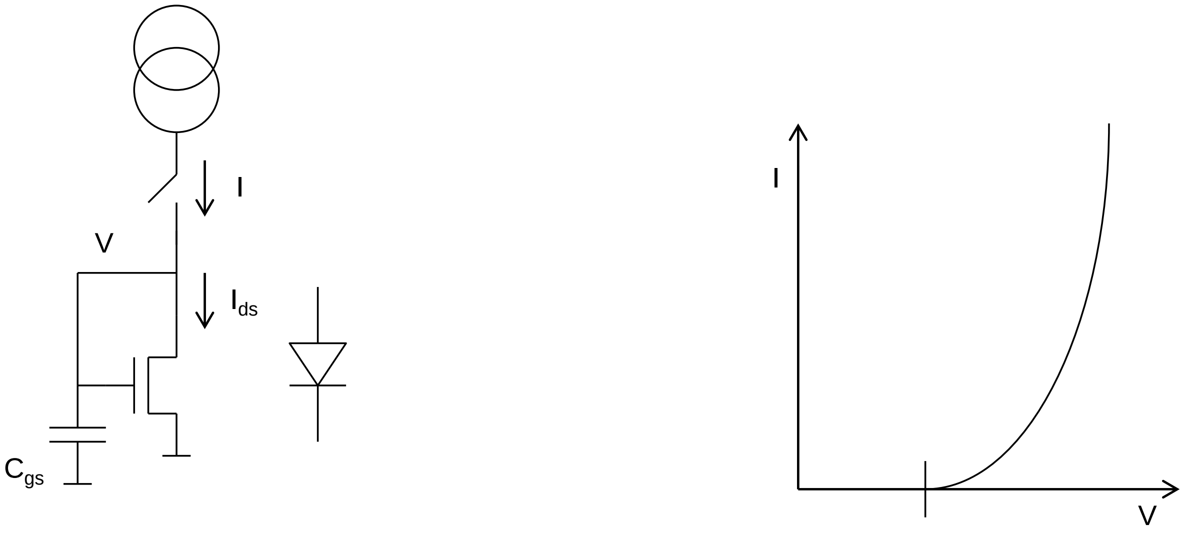

Fig 3: Working procniple

Let us also assume that a signal current source is connected to the MOSFET diode and it is switched on, Fig 3.

If the I_{ds} current is too small to direct the input current (I) into the ground, part of the input current flows into the gate capacity. As consequence V_{gs} rises. This also increases the transistor current ($I_{ds} \sim (V_{gs}-V_{th})^2$) until the I_{ds} current equals the I. From then on, the voltage at the gate doesn't change.

A MOSFET with connected gate and drain is always in saturation, if we assume strong inversion. The condition for saturation $V_{ds} > V_{gs} - V_{th}$ is fulfilled when drain and source are short circuited.

We will assume strong inversion in this lecture and neglect the body effect at the drain.

MOSFET diode has a diode-like characteristic.

$$I = \frac{1}{2}\mu C_{ox}\frac{W}{L}\left(V_{gs} - V_{th}\right)^2$$

Let us breifly consider the application of the MOSFET Diode as resistance

There are two variants of the circuit:

The signal current can be connected to either Drain/Gate or Source, as shown in Fig 4

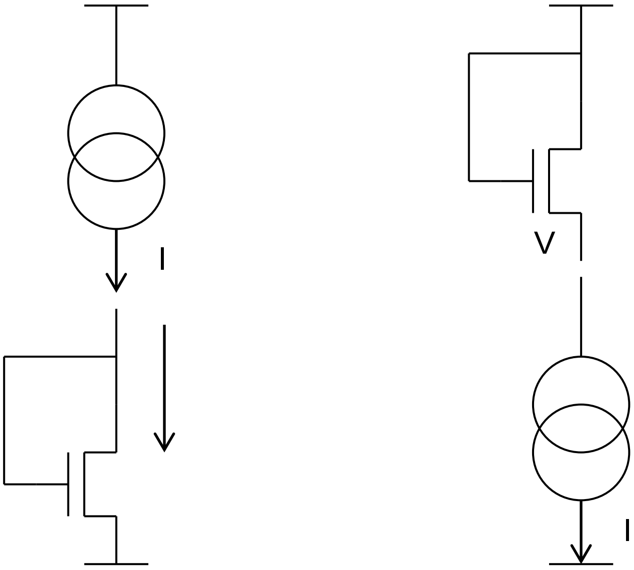

Fig 4: Two implementation of a MOSFET diode

Diode connected MOSFET is a *passive* circuit. Passive means $i_{out} = 0$, if $v_{out} = 0$. i_{out} and v_{out} are the small signals. Passive circuits are described only by an impedance. The small signal circuit of the MOFET diode is shown in Fig 5.

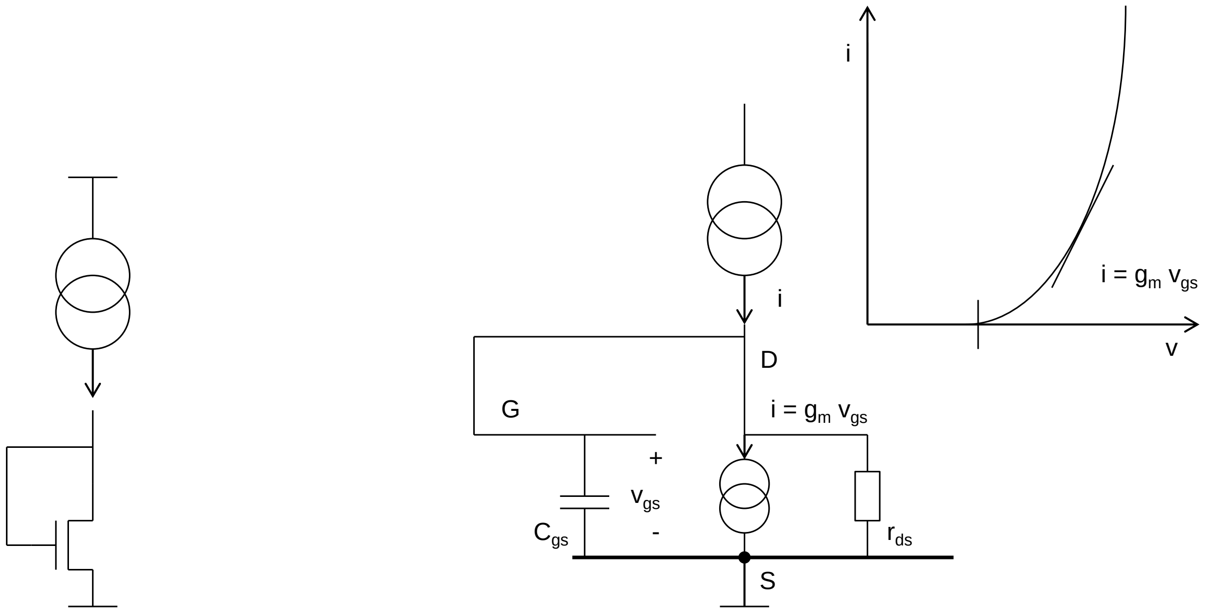

Fig 5: Small signal model of the MOSFET diode

How large is the small signal resistance of the diode connected transistor?

In order to calculate the small signal resistnace, let us imagine an ohmmeter connected to the diode. Suppose the ohmmeter produces a voltage and measures the current to determine the resistance. We consider only changes in voltage and current (small signals). A voltage change dv (small signal voltage dv) produces the small signal v_{gs} voltage of equalt amplitude (v_{gs} = dv) , leading to the small signal current $i_{ds} = g_m \times dv$. This corresponds to a resistance of $1/g_m$. There is also a current through the r_{ds} resistance that models the Early effect. The total resistance is then r_{ds} in parallel with $1/g_m$. Normally we can neglect r_{ds} since it is larger than $1/g_m$. Therefore the small signal resistance of the diode connected transistor is:

$$r_{dio} = \frac{1}{g_m} || r_{ds} \approx \frac{1}{g_m}$$

The small signal capacitance of the diode is C_{gs} (gate-source dynamic capacitance) in parallel with C_{jd} (drain junction dynamic capacitance).

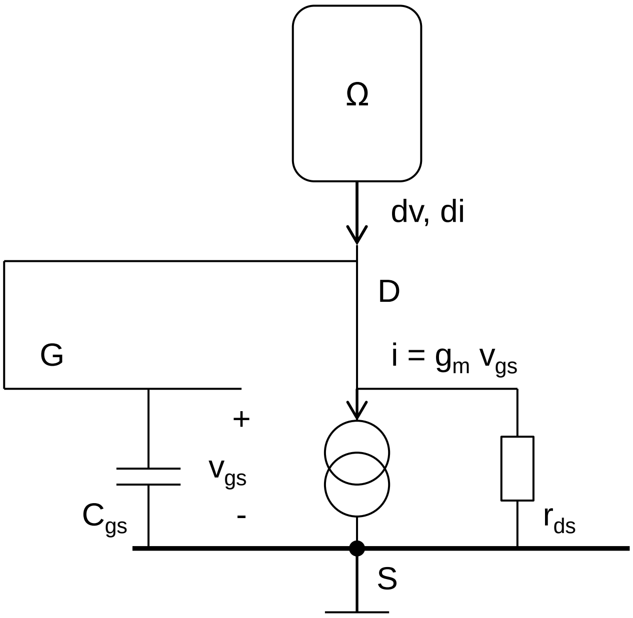

Fig 6: Small signal resistance of the MOFET diode

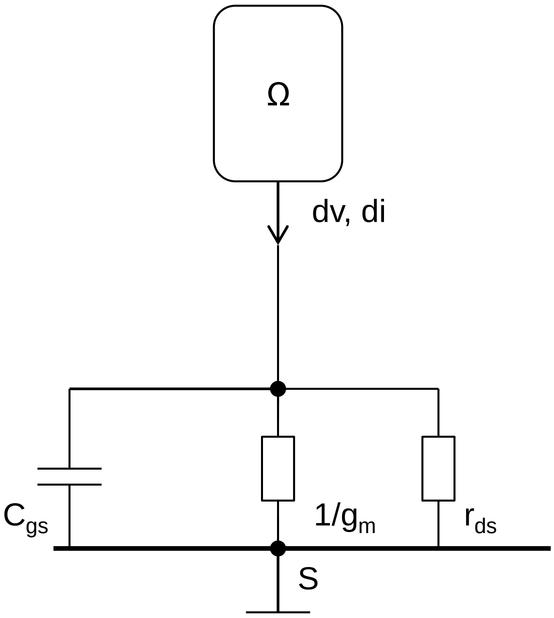

Fig 7: Equivalent circuit of the MOFET diode

Fig 8 shows several variants of the diode connected transistor.

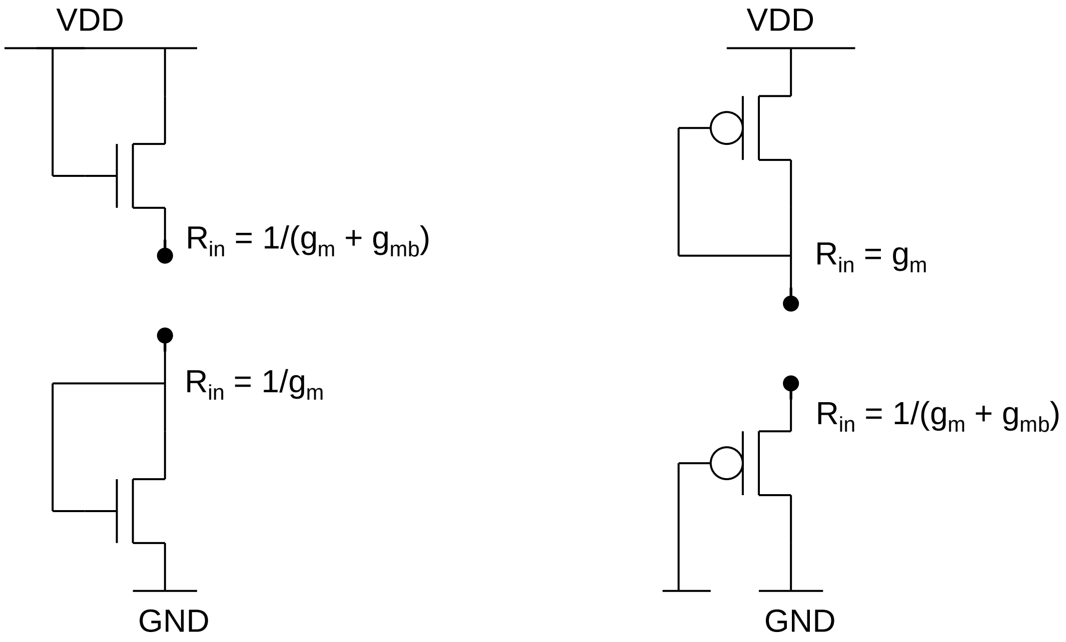

Fig 8: Input resistances of different implementations of the diode connected NMOSFET

The small signal resistances are a bit different, depending whether the body effect plays a role or not. When the input of the diode (the node denoted with a point in Fig 8) is source, the small signal at the input (dv) causes both change in v_{gs} and v_{sb} equal to dv. This leads to a larger i_{ds} then when only v_{gs} is changed as it was in Fig 6. The dynamic resistance for the diodes with input at source is:

$$r_{dio} \approx \frac{1}{g_m + g_{mb}} = \frac{1}{n g_m}$$

Factor n is the slope factor of 1.25.

Current source

Another important circuit is the voltage controlled current source (U-I-converter or transconductor), shown in Fig 9.

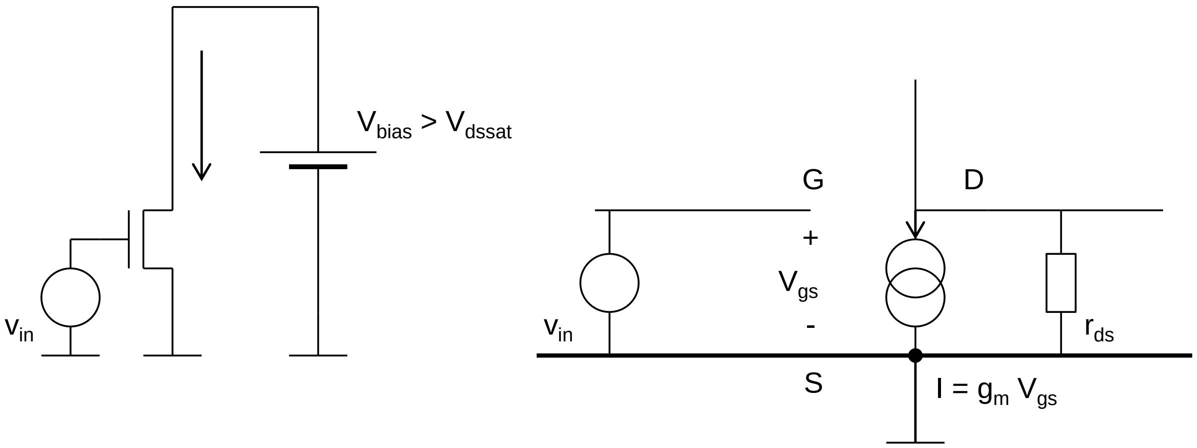

Fig 9: Current source. Small signal model is shown at the right side

The input (small signal) voltage v_{in} is connected to the gate of the transistor. The drain must be connected to a bias voltage to achieve saturation of the transistor. (Condition $V_{ds} > V_{dssat} = V_{gs} - V_{th}$)

The output resistance is r_{ds}. The voltage controlled current source is an active circuit. Active means that for small signals: i_{out} can be different than zero, if $v_{out} = 0$. Active circuits are described by input/output impedance and amplification.

There are two main applications for the current source:

Signal current source, e.g. as a part of a amplifier

Constant (bias) current source

Fig 10: Two applications of the current source

Application 1 (Fig 10): Bias current source or source of a constant current.

We get a constant current source if we connect a constant voltage source between gate and source.

We can implement such current sources both using NMOS and PMOS transistors.

The source of an NMOS based current source is usually connected to ground (GND), as shown in Fig 11, right.

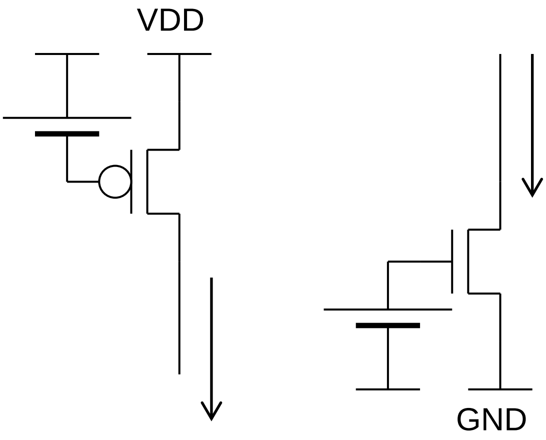

Fig 11: PMOS and NMOS variant of current source

The source of a PMOS based current source is usually connected to positive supply voltage (VDD), as shown in Fig 11, left.

Current mirror

Constant current sources are important components. Application are: bias- or load elements, D/A converters.

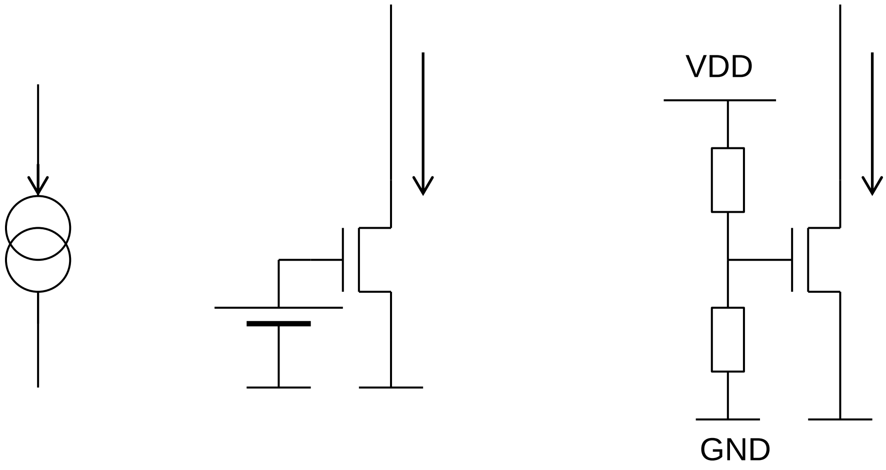

Fig 12: Generation of the input voltage for a current source

The question arises: How to generate appropriate gate source voltage for the current source?

The design goals (objectives) could be that the current should be independent of process variations and supply voltage and it should be temperature stable. (The current should be PVT variation independent.)

The easiest way would be to use a voltage divider, like Fig 12 right shows. Disadvantage: V_{gs} would depend on supply voltage.

Note that, g_m, V_{th}, W, L, μ, C_{ox} are subjects of process- and temperature variations. They vary from chip to chip, from component to component and as a function of temperature. Consequently, even if V_{gs} were constant, the drain current would be temperature dependent as it depends on transistor parameters.

Fig 13 illustrates the temperature dependence of threshold voltage.

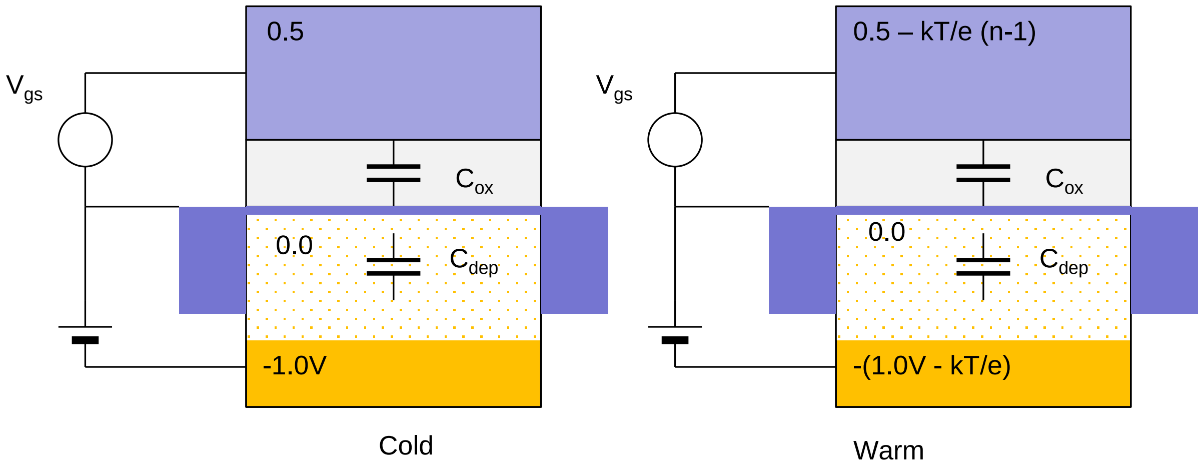

Fig 13: Temperature dependence of the threshold voltage

A better approach would be to build a circuit that produces a temperature-stable reference current. This current can be copied when needed, as illustated in Fig 14 and Fig 15.

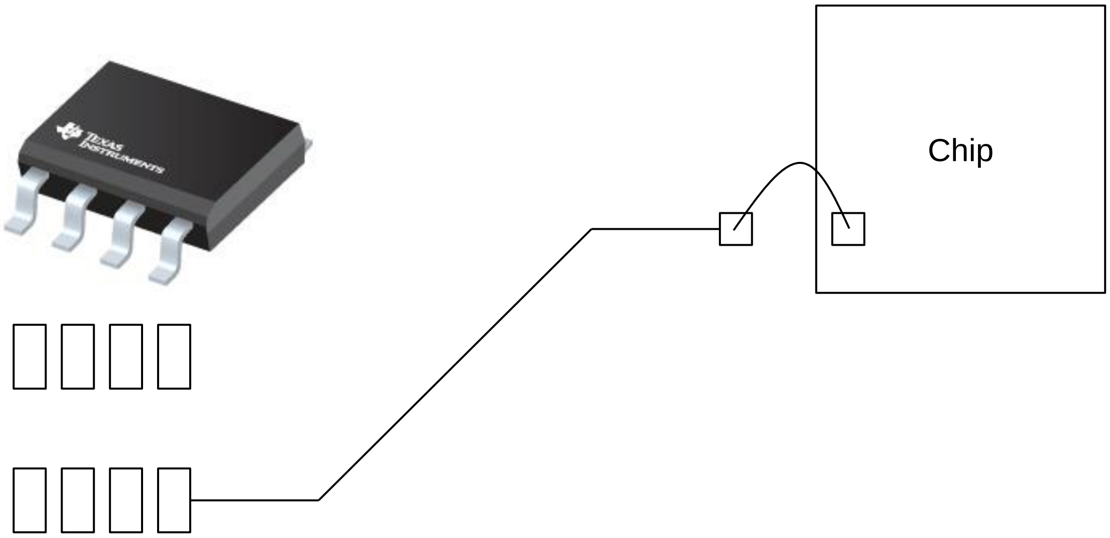

Fig 14: Reference current source

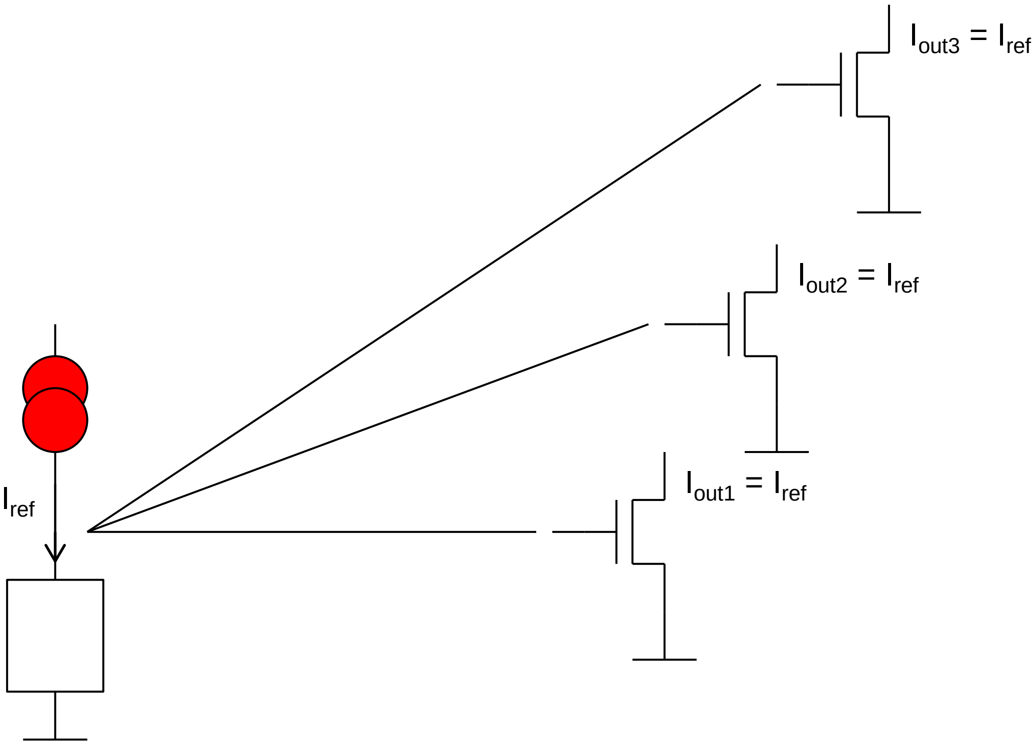

Fig 15: Reference current is copied

Remember that a MOSFET current source generates from V_{gs} voltage a current: It holds generally: $I_{ds} = f(V_{gs})$. Therefore we need a circuit that generates a suitable V_{gs} voltage from the reference current (I_{ref}), so that $I_{ds} = I_{ref}$ Holds. Accordingly: $Vgs = f^{-1}(I_{ref})$. A MOSFET diode has exactly this characteristics. This is illustrated in Fig 16.

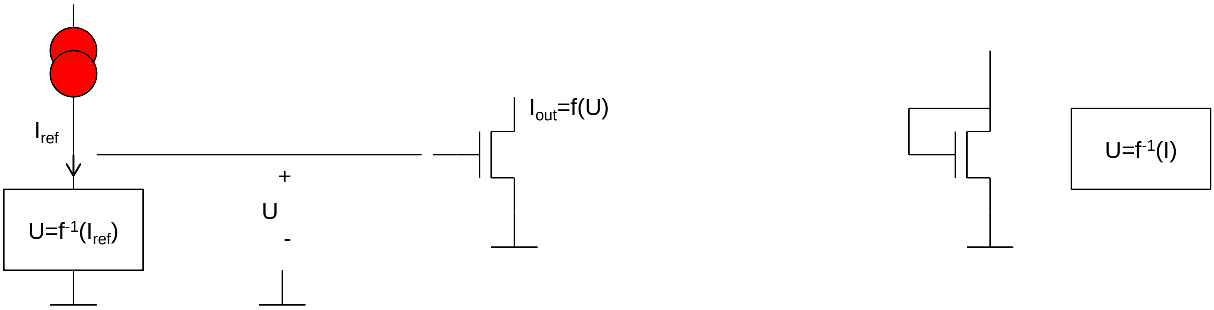

Fig 16: Current mirror uses a MOSET diode to convert input current to voltage

A current mirror is the combination of a MOSFET diode and a current source.

For the diode (transistor Tdio) it holds:

$$I_{in} = \frac{1}{2}\mu C_{ox}\frac{W_{dio}}{L_{dio}}\left(V_{gs} - V_{th}\right)^2$$

For the current source T_{out}:

$$I_{out} = \frac{1}{2}\mu C_{ox}\frac{W_{out}}{L_{out}}\left(V_{gs} - V_{th}\right)^2$$

Therefore:

$$\mathrm{I_{out}} = \frac{\left(\frac{W}{L}\right)_{\mathrm{out}}}{\left(\frac{W}{L}\right)_{\mathrm{dio}}} \mathrm{I_{ref}} \qquad (1)$$

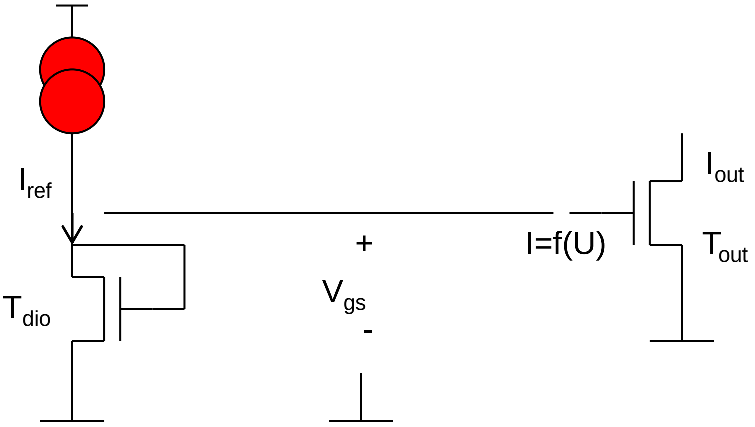

Fig 17: Current mirror

If the transistors have identical dimensions, the currents are the equal. (We are neglecting the drain source resistances)

We denote the ratio of “aspect rations” (W/L) of the current source and the diode with "n".

Therefore

$$\mathrm{I_{out}} = n\, \mathrm{I_{ref}} \quad (2)$$

If we want the factor n to be integer number and accurate, it is good to realize the current source as a parallel connection of several transistors. Let us take as an example, that we want a current amplification of 2. There is here a small problem. When a transistor is designed with W = 1 µm, it has in reality the gate width by a constant dW smaller than the designed value. For example, for dW = 100 nm, the transistor with the designed value W = 1µm has the actual effective width W_{eff} = 0.9µm. This is shown in Fig 18.

Accordingly, a transistor with the designed value W = 2µm, has W_{eff} = 1.9µm. The ratio of effective widths is no longer 2, as shown in Fig 19.

Solution: We use as the current source two transistors with designed W = 1 µm and L = 1 µm in parallel and short circuit their drains, gates and sources, respectively. If the diode transistor has designed W = 1 µm and L = 1, it holds quite accurately $I_{out} = 2 \times I_{in}$. This is illustrated in Fig 20.

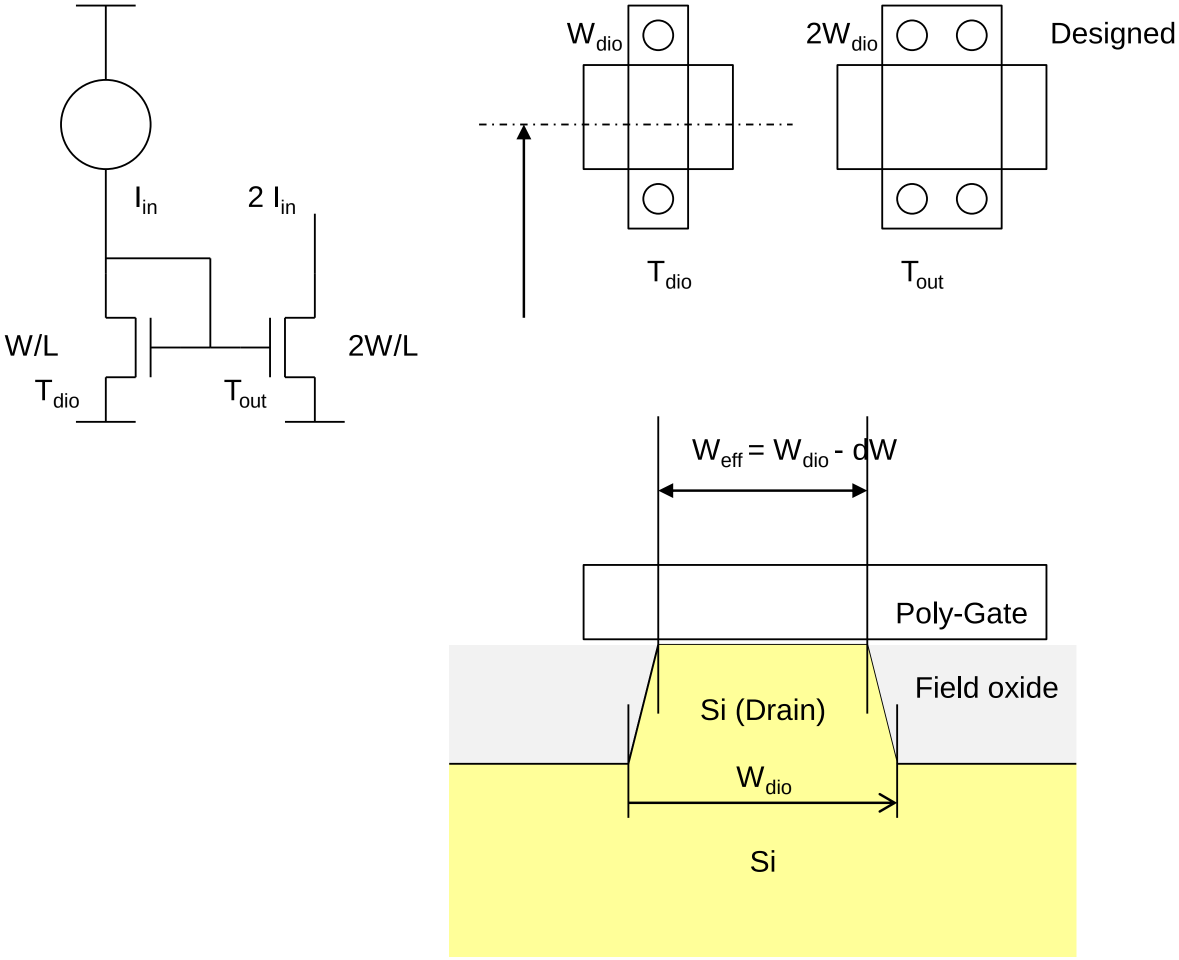

Fig 18: Accuracy of the current mirror with n = 2. Systematic error

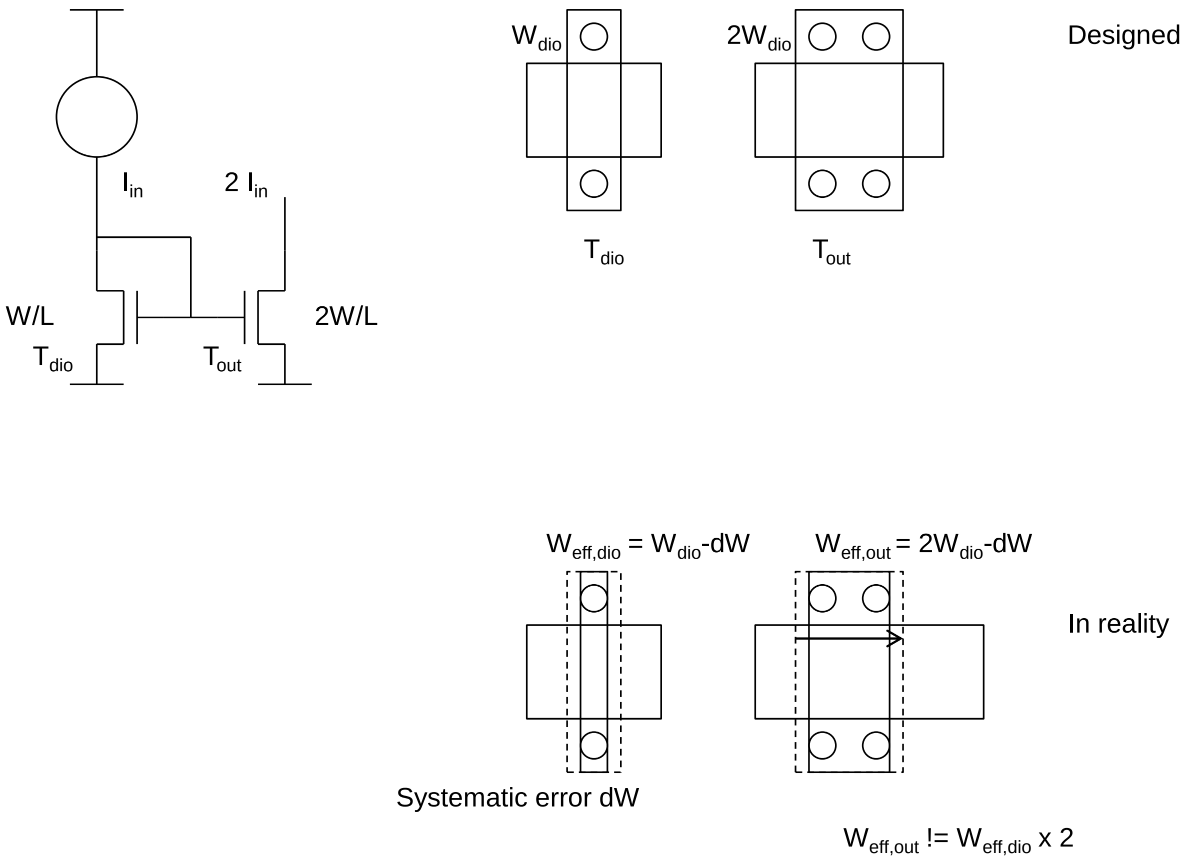

Fig 19: Accuracy of the current mirror with n = 2. T_{out} has double width

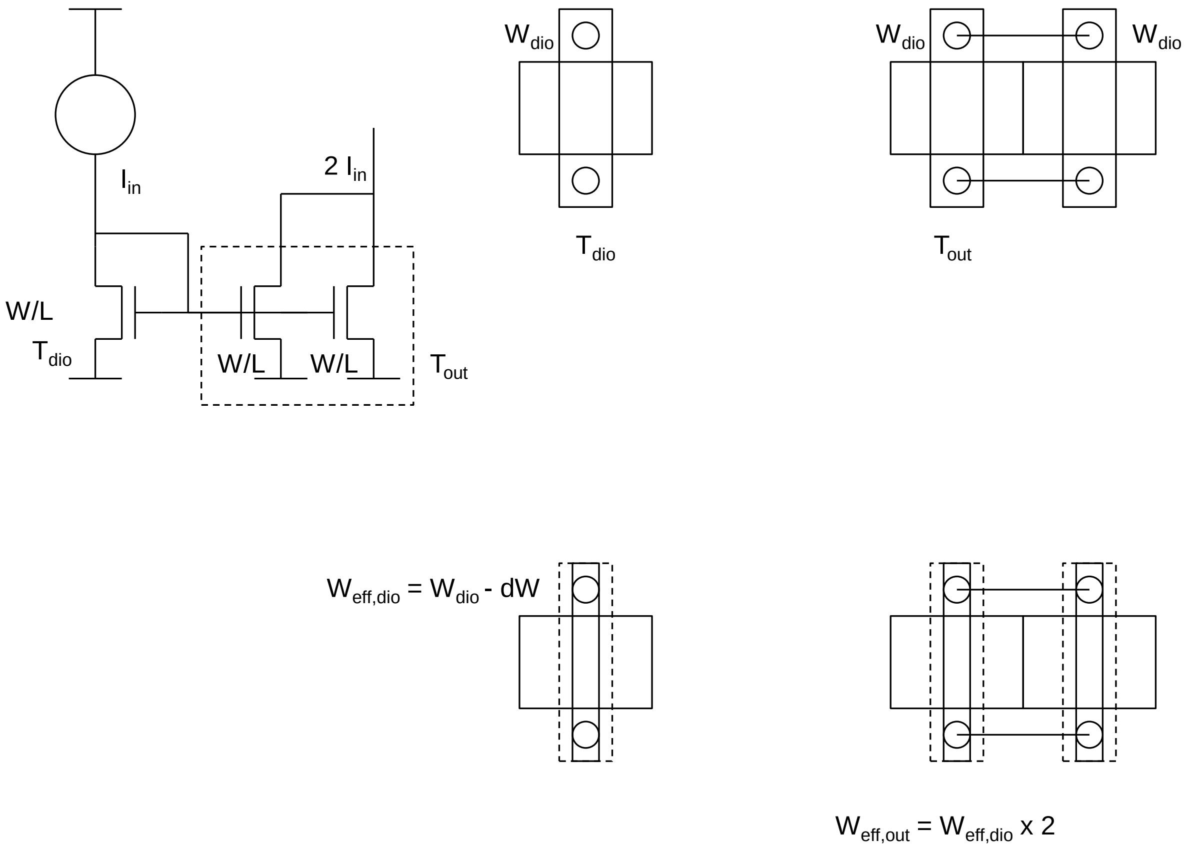

Fig 20: Accuracy of the current mirror with n = 2. T_{out} has two gates

A current mirror is more than a way to distribute the reference curnts. Instead of I_{ref}, we can also use a signal current I_{in}. In that case, we have an active current mirror. It is important that both transistors work in saturation. Otherwise the current multiplication is not described with eq. (1). Diode is always in saturation, the current source T_{out} is in saturation only for large enough V_{ds} voltage: $V_{ds} > V_{dssat}$.

The size ratio of diode to output transistor is often 1:n or n:1. This results is a current amplification or a current division, respectively.

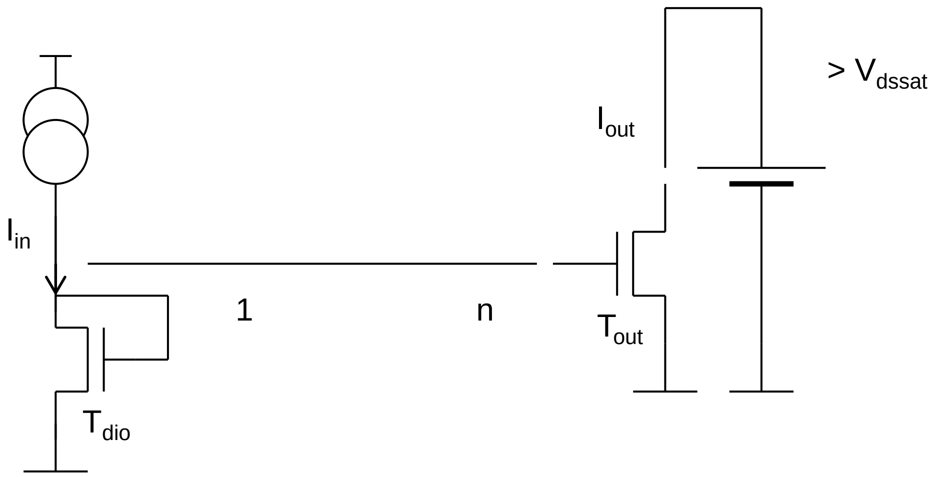

Fig 21: Current mirror as signal current amplifier

The small signal circuit of the current mirror can be obtained when both transistors are replaced with small signal models. Fig 22 - Fig 25 illustrate the approach.

It holds for small signals:

$$\frac{i_{out}(s)}{i_{in}(s)} = \frac{n}{1+(n+1)\frac{C_{gs,dio}}{g_{m,dio}}} \qquad (3)$$

With: $n = g_{m,out}/g_{m,dio}$ and $n = C_{gs,out}/C_{gs,dio}$.

Notice the following:

The current multiplication is equal to n. The current mirror acts as a low pass filter. The time constant is $(n+1)\ C_{gs,dio}/g_{m,dio}$. The circuit is slower when the gain is higher.

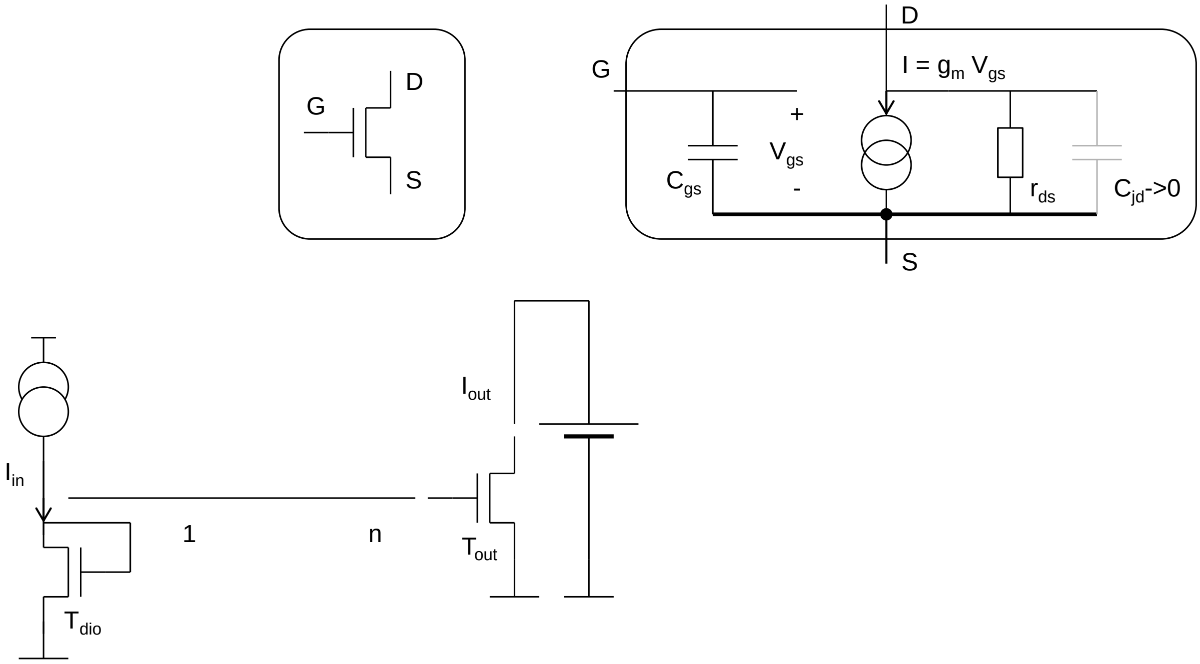

Fig 22: Small signal model of the current mirror (1)

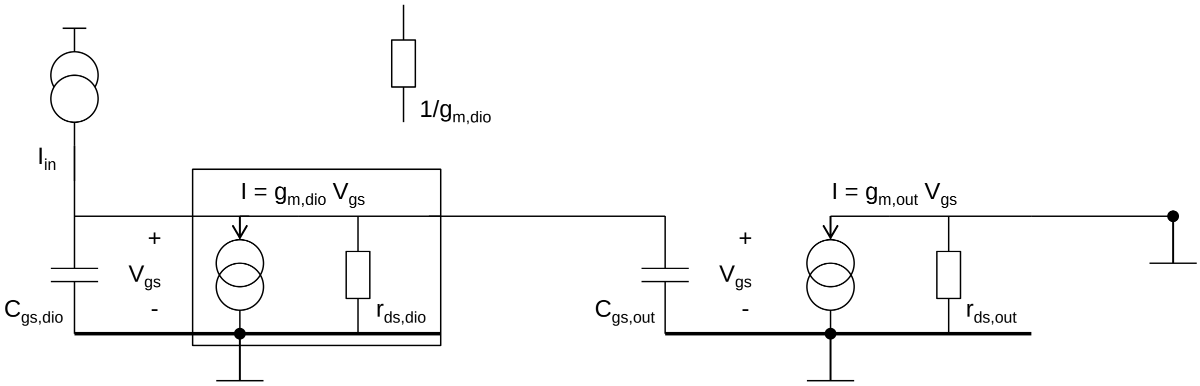

Fig 23: Small signal model of the current mirror (2)

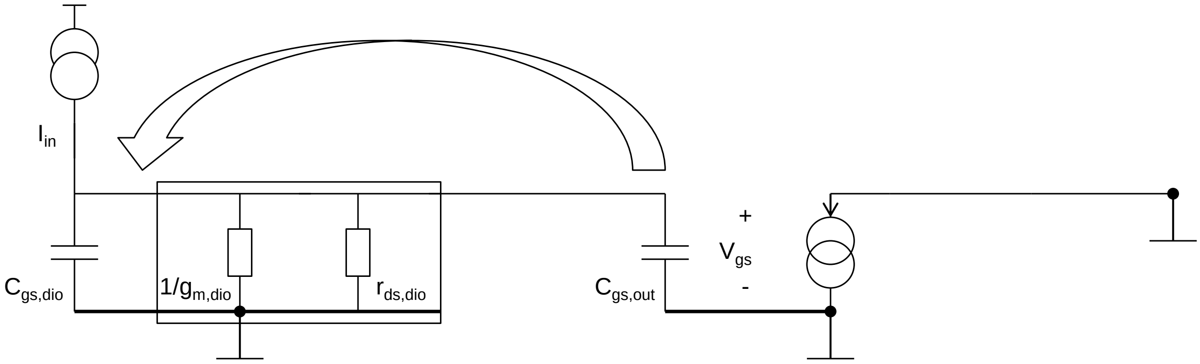

Fig 24: Small signal model of the current mirror (3)

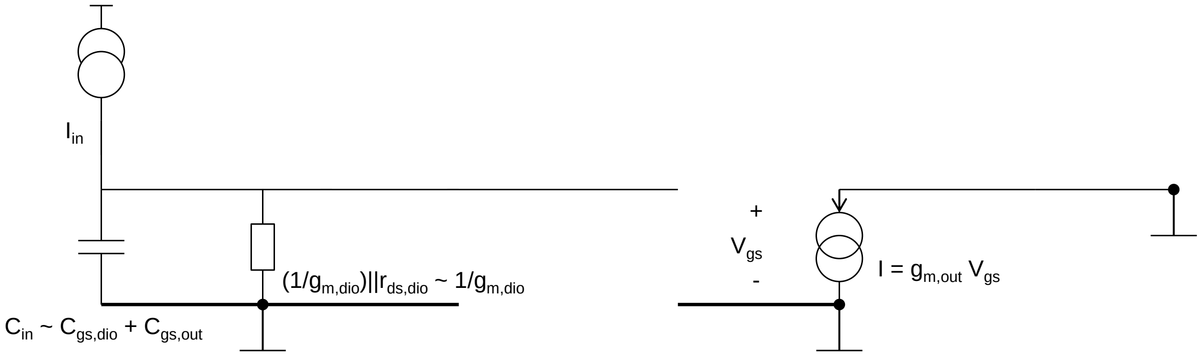

Fig 25: Small signal model of the current mirror (4)

We have shown (1) and (2) that: $n = \frac{\left(\frac{W}{L}\right)_{out}}{\left(\frac{W}{L}\right)_{dio}}$.

The small signal analysis leads to (3) $n = \frac{g_{m,out}}{g_{m,dio}}$.

Are the n-factors equal? Yes, because:

$I = ½ \mu C_{ox} W/L (V_{gs} - V_{th})^2$ and $g_m = dI/dV_{gs} = \mu C_{ox} W/L (V_{gs} - V_{th})$.

Since $V_{gs} – V_{th}$ are equal for T_{dio} and T_{out} , it holds $g_{m,out} / g_{m,dio} = (W/L)_{out} /(W/L)_{dio}$.

One application example for the current mirror:

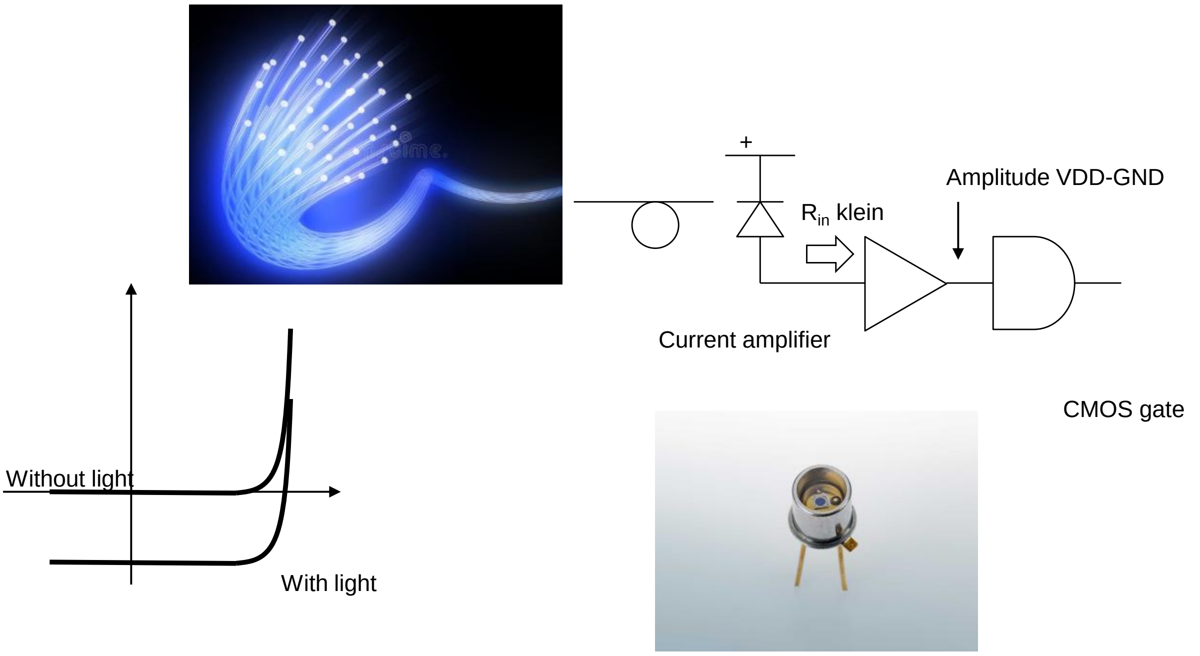

Fig 26: Fast current amplifier based on a current mirror

Current mirrors are fast current amplifiers. An application example for a current mirror as an amplifier shown in Fig 26. A photodiode measures the light and generates the photo current. The current sould be converted into a voltage whose amplitude is large enough so that the digital circuits "understand" the logical 1 or 0.

The important feature of a current amplifier is a small input resistance. Why? If the resistance is large, a large time constant is created at the input and makes the circuit slower.

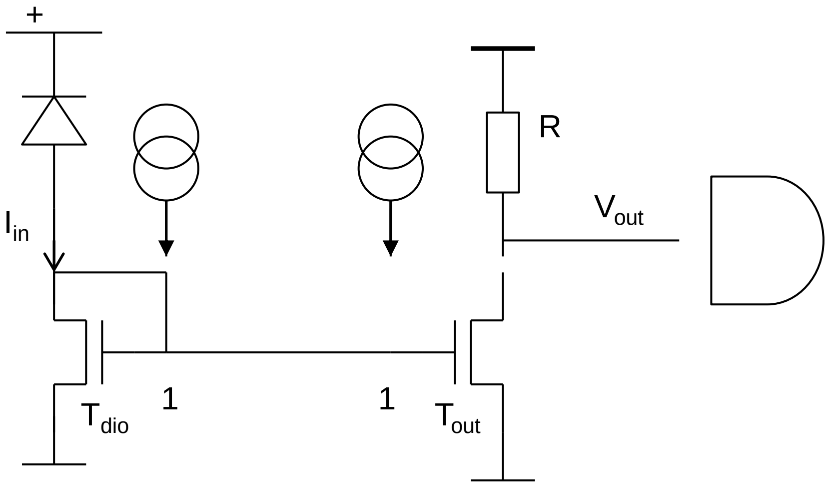

Fig 27: Fast current amplifier based on a current mirror - schematics

Fig 27 shows the schematic diagramm of the current amplifier. The photodiode is placed at the input of the current mirror, the output is connected to the resistance R.

The voltage is generated at at the output. It holds $V_{out} = R \times I_{out}$. The time constant of the circuit is $C_{in}R_{in}$ ($C_{in} = C_{photodiode} + 2 \times C_{gs}$) For fast signal transmission we need $R_{in} \sim 100\ \Omega$ so that the time constant is small and the bandwidth is high.

It holds: $R_{in} = 1/g_{m,dio}$.

It follows that the transconductance $g_{m,dio}$ must be sufficiently high (e.g. 10 mS).

This can be assured using bias current sources (shown in Fig 27), which generate the current flows from VDD to T_{dio} and T_{out}. Only with these bias sources the transistors have large g_m even when the photodiode does not generate dark current.

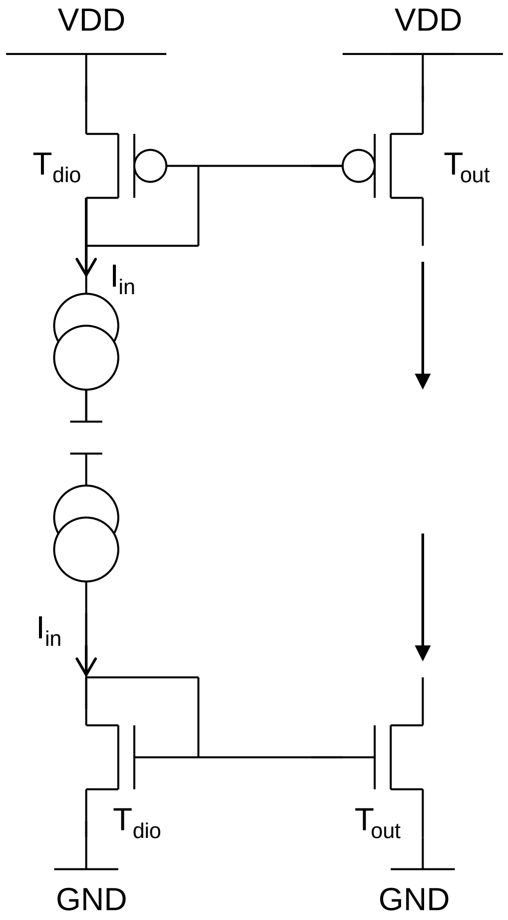

Fig 28: PMOS und NMOS implementation of a current mirror

Fig 28 shows PMOS and NMOS variants of a current mirror. There are following differences.

PMOS current mirror is normally connected to VDD (positive voltage supply). The current flows to GND. NMOS sources are normally connected to GND. The current direction is from "outside to inside".

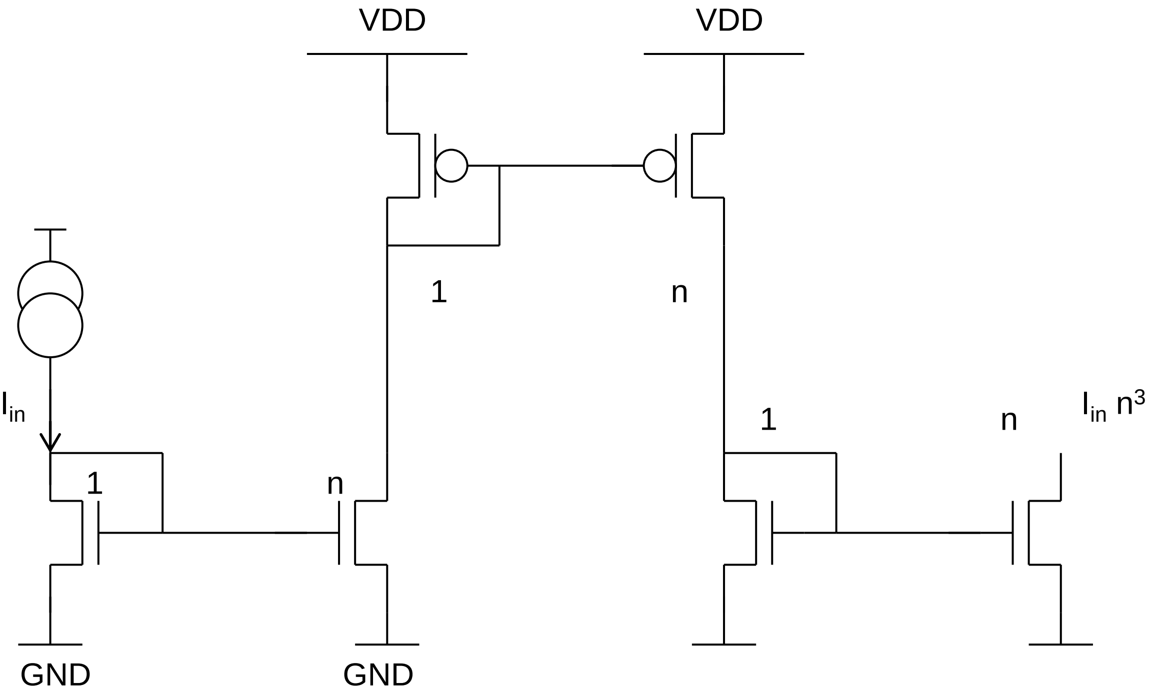

Fig 29: Cascade of current mirrors

Let us bierfly discuss the influence of R_{ds} on the transmission function.

The resistors $R_{ds,dio}/R_{ds,out}$ lead to an error in the current copying and the current multiplication if V_{dsout} is different as V_{dsin}. If the drain-source voltages of T_{dio} and T_{out} transistors are different, I_{in} and I_{out} are not in the same relationship with the W/L-s because parts of the currents flow through R_{ds}. This is shown in Fig 30.

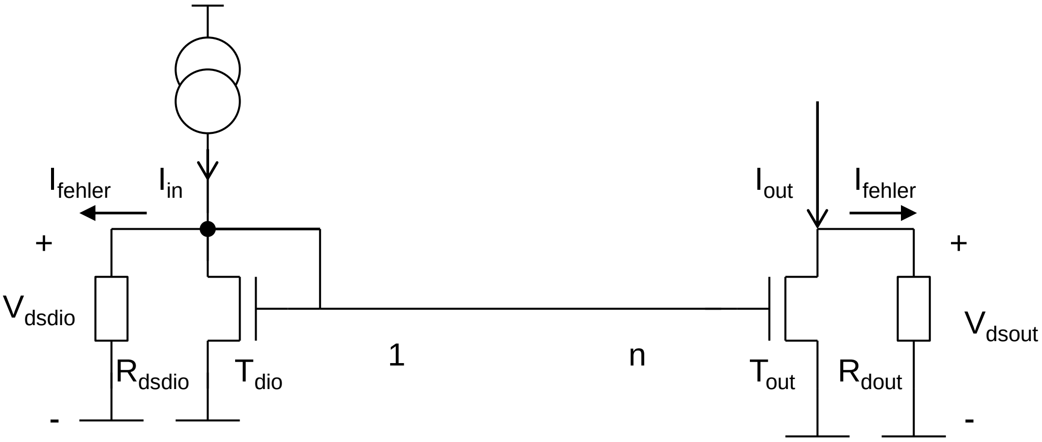

Fig 30: Influence of drain source resistances to the output current

How can we improve a current mirror? Remember that R_{ds} will be higher if the transistors are longer. Long transistors are usually suitable for current mirrors and for current sources.

There is a problem here: if we extend L, V_{gs} and V_{dssat} increase as well. The condition $V_{out} > V_{dssat}$ is more difficult to fulfil and we get a limited range for the output voltage, as shown in Fig 31.

There are trade offs between amplification, speed, linearity (absence of signal-dependent errors) and the possible dynamic range.

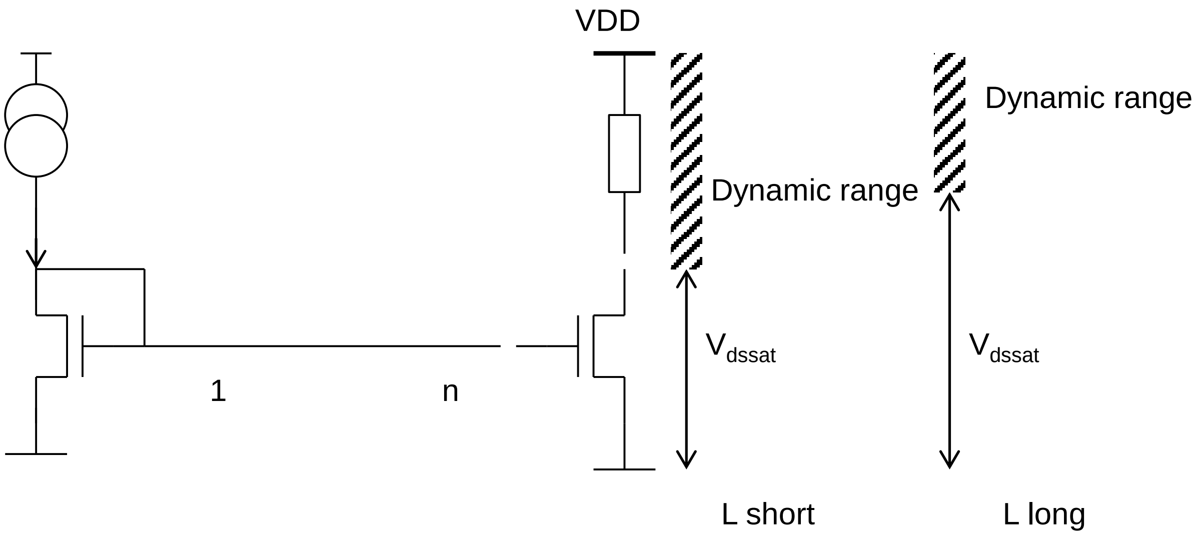

Fig 31: Voltage dynamic range at the output of the current mirror