Desirable characteristics of LV current mirrors

- low AC input resistance (**r_{in}**)
- small DC voltage drop at the input node (**V_{IN}**)
- high output resistance (**r_{out}**)
- low output compliance voltage (**V_{OUTmin}**)
- good frequency response (*for high frequency applications*)
- a linear (*usualy constant and accurate*) current transfer ratio

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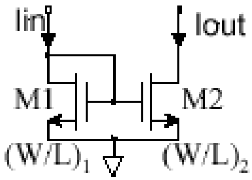
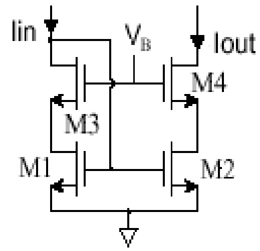


The **basic current mirror** is a good choice for low voltage operation (low **r_{in}** , low **V_{IN}** and low **V_{OUTmin}**) but **r_{out}** and accuracy are poor.

$$V_{IN} = V_{GS1} = \sqrt{2\, I_{IN}/\beta_1} + V_{TH} \qquad (\ \beta = (W/L)\mu C_{ox}\text{'})$$

$$r_{in} = 1/g_{m1} = [\beta_1(V_{GS1}-V_{TH})]^{-1} = [\sqrt{2\beta_1 I_{IN}}\,]^{-1}\ ,\quad r_{out} = (\lambda I_{OUT})^{-1}$$

$$V_{OUTmin} = V_{DSsat2} = V_{GS2} - V_{TH} = \sqrt{2\, I_{OUT}/\beta_2}$$



The **low-voltage cascode current mirror** is a good alternative to the basic current mirror.
☺ The output resistance and tracking accuracy are much better.
☹ **V_{OUTmin}** is worse and additional biasing (**V_B** ; sometimes an *automatic biasing*) is required. Consumed area may sometimes be a drawback (Also, additional care is required in design so as to keep **M3** in saturation).

$r_{out} = g_{m4}\, r_{O4}\, r_{O2}$ (*body effect ignored*) , $r_{in} = 1/g_{m1} = [\beta_1(V_{GS1}-V_{TH})]^{-1}$

$V_{IN} = V_{GS1}$, $V_{OUTmin} = V_{DSsat4} + V_{DS2} = V_{DSsat4} + V_B - V_{GS4} = \mathbf{V_B - V_{TH}}$

$V_{OUTmin,\mathbf{best}} = V_{DSsat2} + V_{DSsat4}$ (*achieved if " **$V_B = V_{GS4} + V_{DSsat2}$**" is satisfied*)

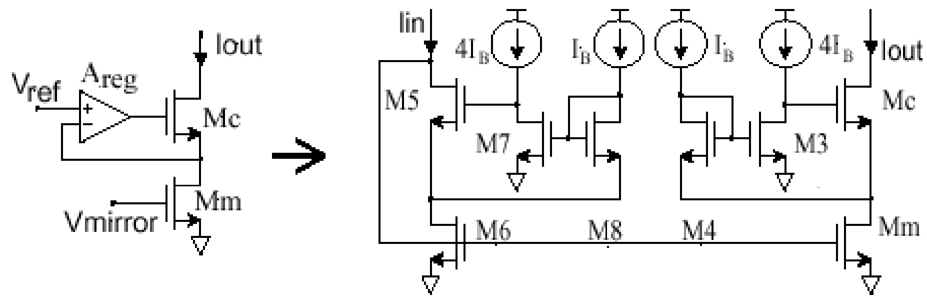
It is also worth mentioning that frequency behavior will be better *wrt* the basic current mirror since the input node capacitor is less (*the feedback capacitance **C_{GD2}** is no longer multiplied by a large gain to contribute to* **C_{in}**).

It is not possible to improve all performance characteristics at the same time, without sacrificing the speed, power and area consumption.

The reported improvements are usually focused on **one or two** of the following items.

- increasing the output resistance
- lowering the output compliance
- lowering the DC input voltage drop
- increasing the tracking accuracy (*actually, this one is usually aimed to be as good as possible !*)

The **regulated cascode** stage (*see the figure on the next page*) can supply a much larger output resistance (**$r_{out} = A_{reg} g_{m4} r_{O4} r_{O2}$**) than the classical cascode stages. A current mirror implementation suitable for low voltage operation is also supplied here.



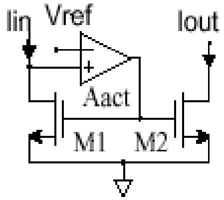
The diode connected MOSFET supplies a DC voltage shift to set **V_{DSm}** close to (*but above*) **$V_{DSsat,m}$**. Assuming $\beta_3 = \beta_{diode} = \beta$,

$V_{DSm} = V_{GS3} - V_{GS,diode} = (2\text{x}4I_B/\beta_3)^{½} - (2\text{x}I_B/\beta_{diode})^{½} = (2\text{x}I_B/\beta)^{½} = \mathbf{V_{DSsat3}}$

I_B , β_3 and β_{diode} must be chosen such that **$V_{Dssat3} > V_{DSsat,m}$** condition is fulfilled for the largest possible I_{OUT} level.

Without the level shifter, **V_{DSm}** would be equal to **V_{GS3}** and this would create a large **V_{OUTmin}** , limiting the output swing severely.

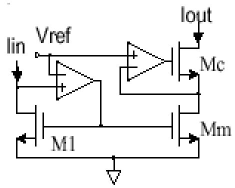
It is possible to keep the DC voltage drop $\mathbf{V_{IN}}$ less than a V_{GS} (**i.e.** *less than* $\boldsymbol{V_{TH}}$). The **active-input current mirror** is a good *conceptual* example.



The opamp and **M1** build an active feedback system to keep the input voltage $\mathbf{V_{IN}}$ fixed at $\mathbf{V_{ref}}$. This voltage can be set close **zero**, *provided that* $V_{ref}>V_{DSsat1}$ *and the opamp common-mode range can go down to the **GND** level.*

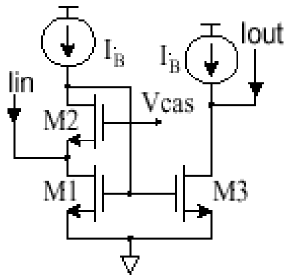
Also, thanks to the feedback, the input resistance r_{in} is also lower *wrt* other current mirrors: $\mathbf{r_{in} = 1/(A_{act}\, g_{m1})}$

☹ Because the feedback is active, extra stability precautions are usually required (*along the feedback loop, the opamp is followed by **another** amplifier stage formed by M1, bringing additional gain and another dominant pole*).



So as to improve $\mathbf{r_{out}}$ and accuracy, the *regulated cascode* scheme can be utilized here as well. ("$V_{ref}>V_{DSsatm}$" must be achieved to keep M_m in sat.)

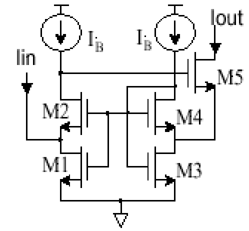
We can use other techniques to set V_{IN} to value less than a V_{GS}. An example is given on the right.



This is a real class-A current mirror. With a sufficiently large I_B, it can handle *negative* input currents as well.

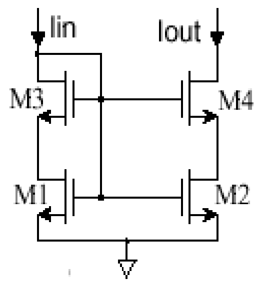
The bias voltage V_{cas} can be adjusted such that, "$V_{IN}>V_{DSsat1}$" is satisfied for all I_{IN} values.

! ! ! The tracking accuracy and r_{out} will not be at sufficient levels unless some additional precautions are taken.



M1 and M2 could have been connected in a "***self cascode***" structure as well. Then, the need for a biasing would fade away (*However, keeping M1 in saturation would be very difficult*). The feedback supplied by M5 on the right improves r_{out} and the tracking accuracy, even when M1 and M3 operate in triode region.

The **self cascode current mirror** is worth discussing on. It has a simple structure but keeping M1 and M2 in saturation is not easy.

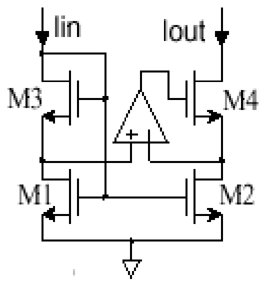


$V_{DS1}=V_{GS1}-V_{GS3}$ (*less than* $V_{GS1}-V_{TH}$)

Keeping $W_3 >> W_1$ (and $W_4 >> W_2$) helps a bit but body effect on M3 spoils this help.

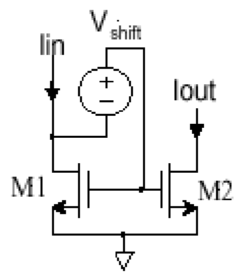
Nevertheless, *"It'll find a way"*. ☺

The same structure can be modified to obtain a *regulated* self cascode current mirror as shown on the right. This structure will work properly even when M1 and M2 are in triode region (*thanks to the opamp*).



! ! ! *The opamp must be able to operate for low common mode input voltages.*

Actually, most of the *V_{IN}-reducing techniques* employ a DC level shifter (*usually with a unity AC gain*) to *virtually* form the diode connection (*The active-input current mirror structure is different; it supplies a large gain along the diode connection for both AC and DC*).



Choosing $V_{shift}=V_{TH}$ (*or a bit smaller*) helps keeping V_{IN} as low as possible while guaranteeing saturation for M1.

An alternative for such a level shifting could be a simple differential pair in *buffer* connection, as shown on the right. $V_{shift}=|V_{GS3}|-|V_{GS4}|$