# Design of Analog CMOS Integrated Circuits



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### DESIGN OF ANALOG CMOS INTEGRATED CIRCUITS

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### Sec. 3.5 Cascode Stage





The output impedance is simply equal to

$$R_{out} = \{ [1 + (g_m + g_{mb})r_O]R_P + r_O \} \| R_D.$$
(3.116)

#### 3.5 Cascode Stage

As mentioned in Example 3.10 the input signal of a common-gate stage may be a current. We also know that a transistor in a common-source arrangement converts a voltage signal to a current signal. The cascade of a CS stage and a CG stage is called a "cascode"<sup>1</sup> topology, providing many useful properties. Fig. 3.50 shows the basic configuration:  $M_1$  generates a small-signal drain current proportional to  $V_{in}$  and  $M_2$  simply routes the current to  $R_D$ .



Figure 3.50 Cascode stage.

We call  $M_1$  the input device and  $M_2$  the cascode device. Note that in this example,  $M_1$  and  $M_2$  carry equal currents. As we describe the attributes of the circuit in this section, many advantages of the cascode topology over a simple common-source stage become evident.

First, let us study the bias conditions of the cascode. For  $M_1$  to operate in saturation,  $V_X \ge V_{in} - V_{TH1}$ . If  $M_1$  and  $M_2$  are both in saturation, then  $V_X$  is determined primarily by

(3.114)

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(3.115)

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<sup>&</sup>lt;sup>1</sup>The term *cascode* is believed to be the acronym for "cascaded triodes," possibly invented in vacuum tube days.

 $V_b: V_X = V_b - V_{GS2}$ . Thus,  $V_b - V_{GS2} \ge V_{in} - V_{TH1}$  and hence  $V_b > V_{in} + V_{GS2} - V_{TH1}$ (Fig. 3.51). For  $M_2$  to be saturated,  $V_{out} \ge V_b - V_{TH2}$ , that is,  $V_{out} \ge V_{in} - V_{TH1} + V_{GS2} - V_{TH2}$ 





 $V_{TH2}$  if  $V_b$  is chosen to place  $M_1$  at the edge of saturation. Consequently, the minimum output level for which both transistors operate in saturation is equal to the overdrive voltage of  $M_1$  plus that of  $M_2$ . In other words, addition of  $M_2$  to the circuit reduces the output voltage swing by at least the overdrive voltage of  $M_2$ . We also say  $M_2$  is "stacked" on top of  $M_1$ .

We now analyze the large-signal behavior of the cascode stage shown in Fig. 3.50 as  $V_{in}$  goes from zero to  $V_{DD}$ . For  $V_{in} \leq V_{TH1}$ ,  $M_1$  and  $M_2$  are off,  $V_{out} = V_{DD}$ , and  $V_X \approx V_b - V_{TH2}$  (if subthreshold conduction is neglected) (Fig. 3.52). As  $V_{in}$  exceeds  $V_{TH1}$ ,  $M_1$  begins to draw current, and  $V_{out}$  drops. Since  $I_{D2}$  increases,  $V_{GS2}$  must increase



**Figure 3.52** Input-output characteristic of a cascode stage.

as well, causing  $V_X$  to fall. As  $V_{in}$  assumes sufficiently large values, two effects occur: (1)  $V_X$  drops below  $V_{in}$  by  $V_{TH1}$ , forcing  $M_1$  into the triode region; (2)  $V_{out}$  drops below  $V_b$  by  $V_{TH2}$ , driving  $M_2$  into the triode region. Depending on the device dimensions and the values of  $R_D$  and  $V_b$ , one effect may occur before the other. For example, if  $V_b$  is relatively low,  $M_1$  may enter the triode region first. Note that if  $M_2$  goes into deep triode region,  $V_X$  and  $V_{out}$  become nearly equal.

Let us now consider the small-signal characteristics of a cascode stage, assuming both transistors operate in saturation. If  $\lambda = 0$ , the voltage gain is equal to that of a common-source stage because the drain current produced by the input device must flow through the cascode device. Illustrated in the equivalent circuit of Fig. 3.53, this result is independent of the transconductance and body effect of  $M_2$ .

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 $V_{GS2} - V_{TH1}$  $_{H1} + V_{GS2} - V_{TH1}$ 

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Fig. 3.50 as  $= V_{DD}$ , and s  $V_{in}$  exceeds must increase

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#### Example 3.14

Calculate the voltage gain of the circuit shown in Fig. 3.54 if  $\lambda = 0$ .



#### Solution

The small-signal drain current of  $M_1$ ,  $g_{m1}V_{in}$ , is divided between  $R_P$  and the impedance seen looking into the source of  $M_2$ ,  $1/(g_{m2} + g_{mb2})$ . Thus, the current flowing through  $M_2$  is

$$I_{D2} = g_{m1} V_{in} \frac{(g_{m2} + g_{mb2}) R_P}{1 + (g_{m2} + g_{mb2}) R_P}.$$
(3.117)

The voltage gain is therefore given by

$$A_{\nu} = -\frac{g_{m1}(g_{m2} + g_{mb2})R_P R_D}{1 + (g_{m2} + g_{mb2})R_P}.$$
(3.118)

An important property of the cascode structure is its high output impedance. As illustrated in Fig. 3.55, for calculation of  $R_{out}$ , the circuit can be viewed as a common-source stage with a degeneration resistor equal to  $r_{01}$ . Thus, from (3.60),

$$R_{out} = [1 + (g_{m2} + g_{mb2})r_{O2}]r_{O1} + r_{O2}, \qquad (3.119)$$

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