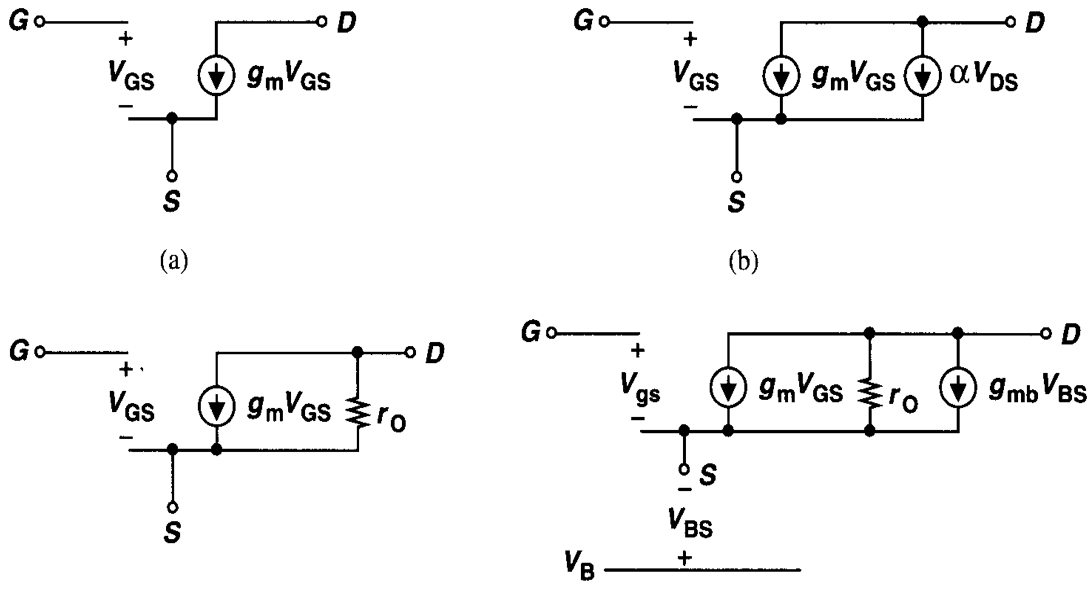

Figure 2.36 (a) Basic MOS small-signal model, (b) channel-length modulation represented by a dependent current source, (c) channel-length modulation represented by a resistor, (d) body effect represented by a dependent current source.

a linear resistor [Fig. 2.36(c)]. Tied between D and S, the resistor is given by

$$r_O = \frac{\partial V_{DS}}{\partial I_D} \tag{2.35}$$

$$= \frac{1}{\partial I_D / \partial V_{DS}}. \tag{2.36}$$

$$= \frac{1}{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2 \cdot \lambda} \tag{2.37}$$

$$\approx \frac{1}{\lambda I_D}. \tag{2.38}$$

As seen throughout this book, the output resistance, r_O, impacts the performance of many analog circuits. For example, r_O limits the maximum voltage gain of most amplifiers.

Now recall that the bulk potential influences the threshold voltage and hence the gate-source overdrive. As demonstrated in Example 2.3, with all other terminals held at a constant voltage, the drain current is a function of the bulk voltage. That is, the bulk behaves as a second gate. Modeling this dependence by a current source connected between D and S [Fig. 2.36(d)], we write the value as $g_{mb}V_{bs}$, where $g_{mb} = \partial I_D / \partial V_{BS}$. In the saturation region, g_{mb} can be expressed as:

$$g_{mb} = \frac{\partial I_D}{\partial V_{BS}} \tag{2.39}$$

$$= \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH})\left(-\frac{\partial V_{TH}}{\partial V_{BS}}\right). \tag{2.40}$$

We also have

$$\frac{\partial V_{TH}}{\partial V_{BS}} = -\frac{\partial V_{TH}}{\partial V_{SB}} \tag{2.41}$$

$$= -\frac{\gamma}{2}(2\Phi_F + V_{SB})^{-1/2}. \tag{2.42}$$

Thus,

$$g_{mb} = g_m \frac{\gamma}{2\sqrt{2\Phi_F + V_{SB}}} \tag{2.43}$$

$$= \eta g_m, \tag{2.44}$$

where $\eta = g_{mb}/g_m$. As expected, g_{mb} is proportional to γ. Equation (2.43) also suggests that incremental body effect becomes less pronounced as V_{SB} increases. Note that $g_m V_{GS}$ and $g_{mb} V_{BS}$ have the same polarity, i.e., raising the gate voltage has the same effect as raising the bulk potential.

The model in Fig. 2.36(d) is adequate for most low-frequency small-signal analyses. In reality, each terminal of a MOSFET exhibits a finite ohmic resistance resulting from the resistivity of the material (and the contacts), but proper layout can minimize such resistances. For example, consider the two structures of Fig. 2.32, repeated in Fig. 2.37 along with the gate distributed resistance. We note that folding reduces the gate resistance by a factor of four.

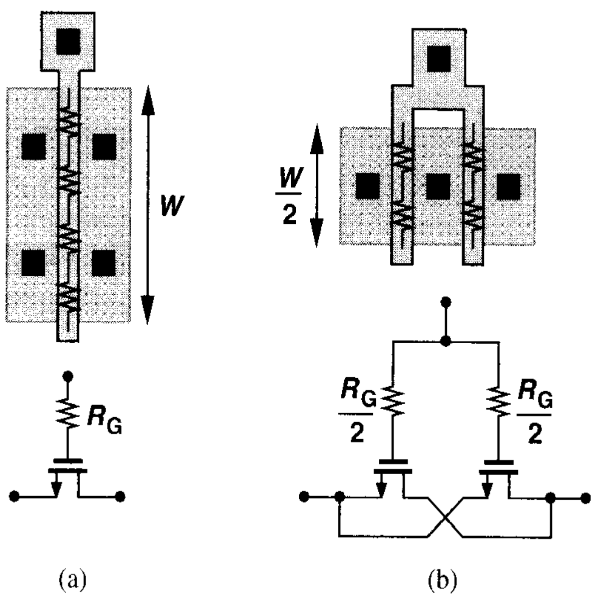

Figure 2.37 Reduction of gate resistance by folding.

Shown in Fig. 2.38, the complete small-signal model includes the device capacitances as well. The value of each capacitance is calculated according to the equations derived in Section 2.4.2. The reader may wonder how a complex circuit is analyzed intuitively if each transistor must be replaced by the model of Fig. 2.38. The first step is to determine