EXERCISE: Calculate the on-resistance of an NMOS transistor for $V_{GS} = 2$ V and $V_{GS} = 5$ V if $V_{TN} = 1$ V and $K_n = 250\ \mu A/V^2$.

ANSWERS: 4 kΩ; 1 kΩ

4.2.4 USE OF THE MOSFET AS A VOLTAGE-CONTROLLED RESISTOR

By operating the MOSFET in the triode region, we have a resistor with a value that can be controlled electronically. These resistors in turn may be used as the control element in more complicated electronic circuits. An important aspect of the utility of the MOSFET in this application comes from the fact that the control signal is well isolated from the resistor terminals.

A Voltage-Controlled Attenuator

As one example, the circuit in Fig. 4.8(a), shown conceptually in Fig. 4.8(b), represents a voltage-controlled attenuator in which the voltage transfer through the circuit can be varied electronically. The voltage "gain" is easily found by voltage division to be

$$\frac{v_O}{v_S} = \frac{R_{on}}{R_{on} + R} = \frac{1}{1 + \dfrac{R}{R_{on}}} = \frac{1}{1 + K_n R(V_{GG} - V_{TN})} \tag{4.17}$$

By adjusting the value of V_{GG}, we can change the fraction of the input signal that appears at the output. Suppose $K_n = 500\ \mu A/V^2$, $V_{TN} = 1$ V, $R = 2$ kΩ, and $V_{GG} = 1.5$ V. Then,

$$\frac{v_O}{v_S} = \frac{1}{1 + \left(500\dfrac{\mu A}{V^2}\right)(2000\ \Omega)(1.5 - 1)\ V} = 0.667$$

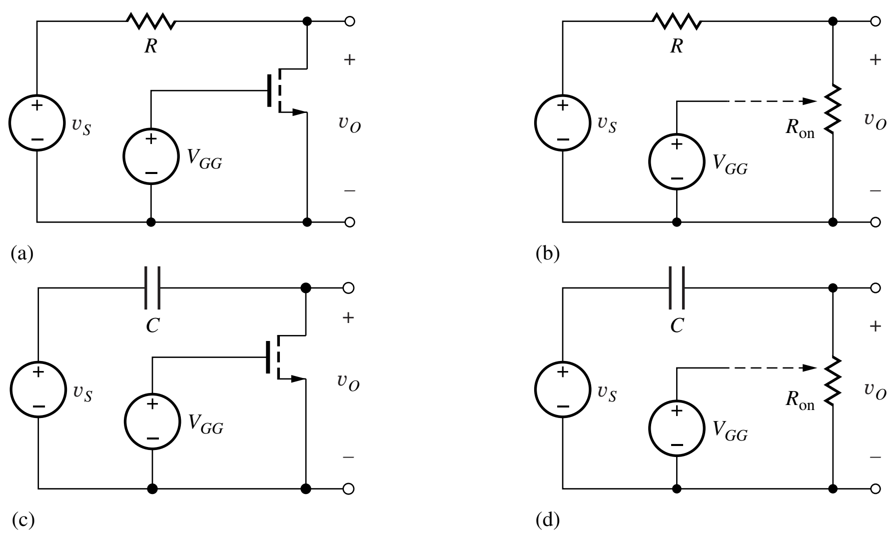

Figure 4.8 (a) Voltage-controlled attenuator circuit, (b) conceptual circuit for the attenuator explicitly indicating the voltage-controlled on-resistance, (c) voltage-controlled high-pass filter, and (d) conceptual circuit for voltage-controlled high-pass filter.

We have a minor semantics problem here. The gain through the network is less than one. This network has a gain of 0.667 or −3.52 dB, or we can say it attenuates the input signal by a factor of 1.5 or +3.52 dB.

In this application, as well as the next one, we desire the transistor to act as a resistor; therefore we must be careful not to violate the conditions required for triode region operation of the device, $v_{DS} \leq v_{GS} - V_{TN}$. In this case, the drain-source voltage equals the output voltage v_O, and the gate-source voltage is the dc bias voltage V_{GG}. Therefore proper operation requires $v_O \leq V_{GG} - V_{TN}$ to ensure that the FET remains in the triode region at all times. For the attenuator calculation here,

$$0.667 v_S \leq (1.5 - 1)\text{ V} \qquad \text{or} \qquad v_S \leq 0.750\text{ V}$$

Exercise: What is the attenuator voltage gain for $V_{GG} = 3$ V? What value of V_{GG} is required to achieve a 6-dB attenuation? A 20-dB attenuation? What are the maximum values of input voltage v_S that correspond to these three conditions?

Answers: 0.333 (−9.54 dB); 2.00 V; 10.0 V; 6.00 V; 2.00 V; 90.0 V

A Voltage-Controlled High-Pass Filter

If we replace R with capacitor C, as in Fig. 4.8(c), we form a voltage controlled high-pass filter with a voltage transfer function given by

$$T(s) = \frac{\mathbf{V}_O(s)}{\mathbf{V}_S(s)} = \frac{s}{s + \omega_o} \qquad \text{where } \omega_o = \frac{1}{R_{\text{on}} C} = \frac{K_n (V_{GS} - V_{TN})}{C} \tag{4.18}$$

The **cutoff frequency** ω_o is set by the location of the pole of the RC network formed by capacitor C and the on-resistance of the FET. Here we see that the cutoff frequency is directly proportional to the gate-source voltage of the NMOS transistor. Let us calculate the cutoff frequency for $K_n = 500\ \mu\text{A/V}^2$, $V_{TN} = 1$ V, and $V_{GG} = 1.5$ V with $C = 0.02\ \mu$F:

$$f_o = \frac{500 \dfrac{\mu\text{A}}{\text{V}^2} (1.5 - 1)\text{ V}}{2\pi (0.02\ \mu\text{F})} = 1.99\text{ kHz}$$

At frequencies well above f_o, the magnitude of $T(s)$ approaches unity. Thus, at those frequencies the full amplitude of the input signal will appear at the output of the high-pass filter. Therefore, to satisfy triode region operation, $v_s \leq (V_{GG} - V_{TN}) = 0.5$ V

Exercise: What is the cutoff frequency for $V_{GG} = 5$ V? What value of V_{GG} is required to achieve a cutoff frequency of 5 kHz? What are the maximum values of input voltage v_S that correspond to these two conditions?

Answers: 15.9 kHz; 2.26 V; 4.00 V; 1.26 V

4.2.5 Saturation of the *i-v* Characteristics

As discussed, Eq. (4.13) is valid as long as the resistive channel region directly connects the source to the drain. However, an unexpected phenomenon occurs in the MOSFET as the drain