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*** Figure 5.2 CMOS: Circuit Design, Layout, and Simulation ***

.control
destroy all
set temp=0
run
set temp=27
run
set temp=100
run
let iref0=-dc1.i(vr)
let iref27=-dc2.i(vr)
let iref100=-dc3.i(vr)
let r0=vr/iref0
let r27=vr/iref27
let r100=vr/iref100
plot r0 r27 r100
.endc

.dc Vr 0.9 1.1 1m
vr vr 0 DC 0

r1 vr 0 rmod L=100 W=5
.model rmod R RSH=500 TNOM=27 TC1=0.0024
.end
```

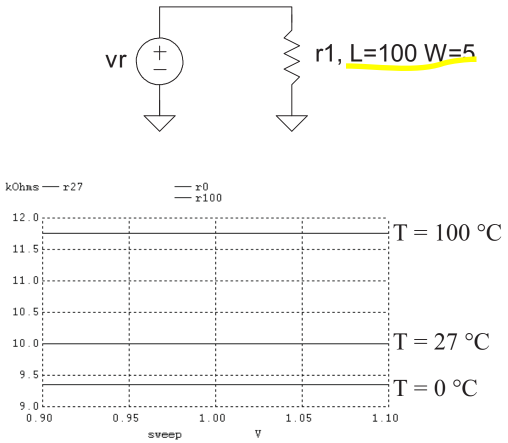

Figure 5.2 Simulating the temperature dependence of an n-well resistor.

$$\mu_{n,p} = \frac{\text{Average velocity of carriers, } cm/s}{\text{Applied electric field, } V/cm} \qquad (5.4)$$

noting mobility's units are $cm^2/V \cdot s$. The resistivity of the material depends on the number of free carriers (electrons/cm^3, n, and holes/cm^3, p) or

$$\rho = \frac{1}{q(\mu_n n + \mu_p p)} \qquad (5.5)$$

where q is the electron charge (see Eqs. [2.2] and [2.3]). This equation is important and shows why we can have a negative or positive resistor temperature coefficient. If the mobilities decrease faster than the carrier concentrations increase, we get a positive temp co. The resistor's value goes up with increasing temperature because the mobility is dropping faster than the carrier concentration is increasing. However, if the increase in carrier concentration with temperature is faster, the resistivity goes down with increasing temperature and we get a negative temp co (the resistor's value goes down with increasing temperature). At room temperature, a positive temperature coefficient is normally observed.

Voltage Coefficient

Another important contributor to a changing resistance is the voltage coefficient of the resistor given by

$$VCR = \frac{1}{R} \cdot \frac{dR}{dV} \qquad (5.6)$$