LOAD LINES

APPENDIX F

The graphic method of "load lines" usually makes an early appearance in electronics textbooks. We have avoided it because, well, it just isn't useful in transistor design the way it was in vacuum-tube circuit design. However, it is of use in dealing with some nonlinear devices (tunnel diodes, for example), and in any case it is a useful conceptual tool.

F.1 An example

Let's start with an example. Suppose you want to know the voltage across the diode in Figure F.1. Assume that you know the voltage-versus-current (V–I) curve of the particular diode (of course, it would have a manufacturing "spread," as well as a dependence on ambient temperature); it might look something like the curve drawn. How would you figure out the quiescent[1] point?

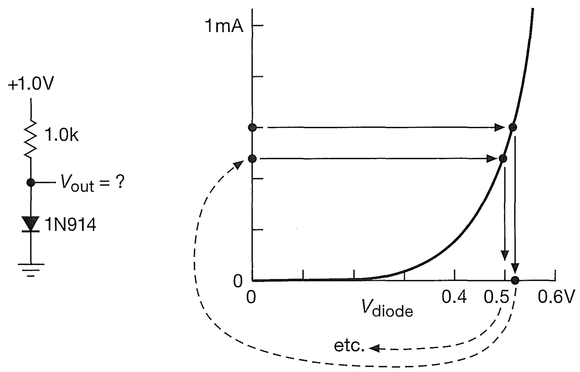

Figure F.1. Finding the operating point by iteration.

One method might be to guess a rough value of current, say 0.6 mA, then use the curve to get the drop across the resistor, from which you get a new guess for the current (in this case, 0.48 mA). This iterative method is suggested in Figure F.1. After a few iterations, this method will get you an answer, but it leaves a lot to be desired.

[1] The quiescent point, also known as the *operating point*, describes the various dc voltages and currents in a circuit with no ac signals applied.

The method of load lines gets you the answer to this sort of problem immediately. Imagine *any* device connected in place of the diode; the 1.0k resistor is still the load. Now plot, on a V–I graph, the curve of resistor current versus device voltage. This turns out to be easy: at zero volts the current is just V_+/R (full drop across the resistor); at V_+ volts the current is zero; points in between fall on a straight line between the two. Now, on the same graph, plot the V–I curve of the device. The operating point lies on both curves, i.e., at the intersection, as shown in Figure F.2.

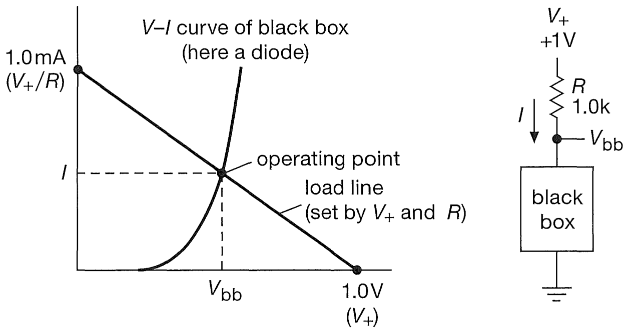

Figure F.2. A "load line" lets you find the operating point directly.

F.2 Three-terminal devices

Load lines can be used with a three-terminal device (tube or transistor, for example) by plotting a family of curves for the device. Figure F.3 shows what such a thing would look like for a depletion-mode field-effect transistor (FET), with the curve family parameterized by the gate-source voltage. You can read off the output for a given input by sliding along the load line between appropriate curves corresponding to the input you've got, then projecting onto the voltage axis. In this example we've done this, showing the drain voltage (output) for a gate swing (input) between ground and −2 V.

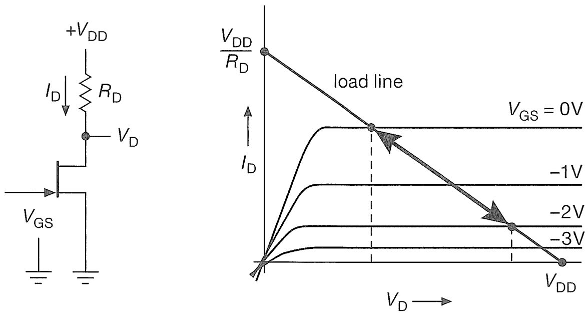

Figure F.3. Load-line solution for a three-terminal device.

As nice as this method seems, it has quite limited use for transistor or FET design, for a couple of reasons. For one thing, the curves published for semiconductor devices are "typical," with manufacturing spread that can be as large as a factor of five. Imagine what would happen to those nice load-line solutions if all the curves shrank to one-fourth their height! Another reason is that for an inherently logarithmic device like a diode junction, a linear load-line graph can be used to give accurate results over only a narrow region. Finally, the nongraphic methods we've used in this book are entirely adequate for handling solid-state design. In particular, these methods emphasize the parameters you can count on (r_e, I_C versus V_{BE} and T, etc.), rather than the ones that are highly variable (β, V_{th}, etc.). If anything, the use of load lines on published curves for transistors only gives you a false sense of security, since the device spread isn't also shown.

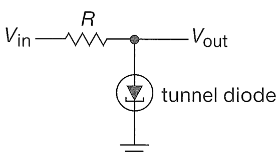

Figure F.4. The tunnel diode: a two-terminal nonlinear device with a region of negative resistance (see Figure F.5).

F.3 Nonlinear devices

Load lines turn out to be useful in understanding the circuit behavior of highly nonlinear devices. The example of tunnel diodes illustrates a couple of interesting points. Let's analyze the circuit in Figure F.4. Note that in this case, V_{in} takes the place of the supply voltage in the previous examples. So a signal swing will generate a family of parallel load lines intersecting with a single device V–I curve (Figure F.5). The values shown are for a 100 Ω load resistor. As can be seen, the output varies most rapidly as the input swing takes the load line across the negative-resistance portion of the tunnel-diode curve. By reading off values of V_{out} (projection on the x axis) for various values of V_{in} (individual load lines), you get the "transfer" characteristics shown. This particular circuit has some voltage gain for input voltages near 0.2 V.

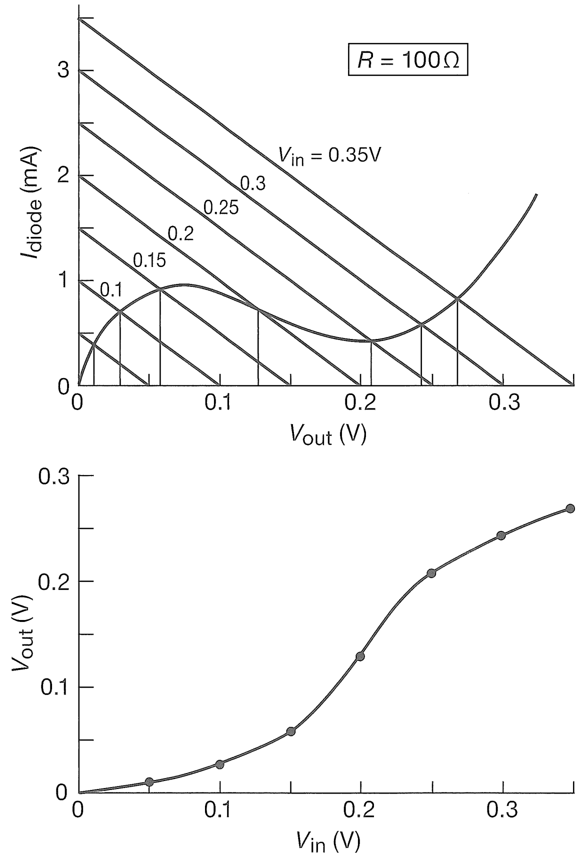

Figure F.5. Load lines and transfer characteristic for the tunnel-diode circuit.

An interesting thing happens if the load lines become flatter than the middle section of the diode curve. That happens when the load resistance exceeds the magnitude of the diode's negative resistance. It is then possible to have *two* intersection points, as in Figure F.6. A rising input signal carries the load lines up until the intersection point has nowhere to go and has to jump across to a higher V_{out} value. On returning, the load lines similarly carry the

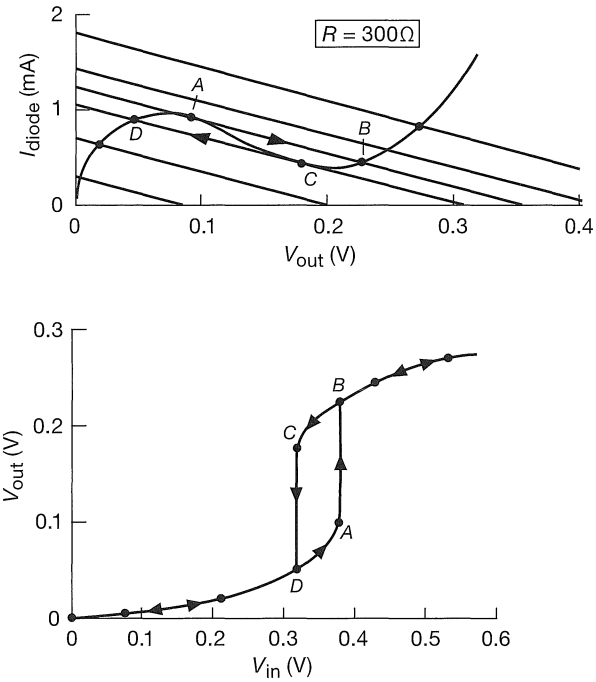

Figure F.6. Having $|R_{load}| > |R_{neg}|$ produces hysteretic switching behavior in the tunnel-diode circuit.

intersection point down until it must again jump back. The overall transfer characteristic has *hysteresis*, as shown. Tunnel diodes have been used in this manner as fast-switching devices (triggers).