Speed Demons

When a diode is carrying current, how long does it take to turn the current off? There's another wide-range phenomenon. Slow diodes can take dozens and hundreds of microseconds to turn off. For example, the collector-base junction of a 2N930 can take 30 μs to recover from 10 mA to less than 1 mA, and even longer to the nanoampere level. This is largely due to the recombination time of the carriers stored in the collector region of the transistor. Other diodes, especially gold-doped ones, turn off *much* faster—down into the nanosecond region. Schottky diodes are even faster, much faster than 1 ns. However, one of my friends pointed out that when you have a Schottky diode that turns off pretty fast, it is still in parallel with a p-n junction that may still turn off slowly at a light current level. If a Schottky turns off from 4 mA in less than 1 ns, there may still be a few microamperes that do not turn off for a microsecond. So if you want to use a Schottky as a precision clamp that will turn off very quickly, as in a settling detector (Ref. 2), don't be surprised if there is a small long "tail."

Switching regulators all have a need for diodes and high-current rectifiers and transistors to turn off quickly. If the rep rate is high and the current large and the diode turns off slowly, it can fail due to overheating. You *don't* want to try a 1N4002 at 20 or 40 kHz, as it will work very badly, if at all. Sometimes if you need a moderate amount of current at high speed, you can use several 1N914s in parallel. I've done that in an emergency, and it seemed to work well, but I can't be sure I can recommend it as the right thing to do for long-term reliability. The right thing is to engineer the right amount of speed for your circuit. High-speed, fast-recovery, and ultrafast diodes are available. The Schottky rectifiers are even faster, but not available at high voltage breakdowns. When you start designing switching regulators at these speeds, you really must know what you are doing. Or at least, wear safety-goggles so you don't get hurt when the circuit blows up.

Turn 'Em Off—Turn 'Em On . . .

"Computer diodes" like the 1N914 are popular because they turn OFF quickly—in just a few nanoseconds—much faster than low-leakage diodes. What isn't well known is that these faster diodes not only turn OFF fast, they usually turn ON fast. For example, when you feed a current of 1.0 mA toward the anode of a 1N914 in parallel with a 40 pF capacitance (20 pF of stray capacitance plus a scope probe or something similar), the 1N914 usually turns ON in less than 1 ns. Thus, the V_F has only a few millivolts of overshoot.

But with some diodes—even 1N914s or 1N4148s from some manufacturers—the forward voltage may continue to ramp up past the expected DC level for 10 to 20 ns before the diode turns ON; this overshoot of 50 to 200 mV is quite surprising (Figure 6.2). Even more astonishing, the V_F overshoot may get worse at low repetition rates but can disappear at high repetition rates (Figure 6.2b–d).

I spent several hours once discovering this particular peculiarity when a frequency-to-voltage converter suddenly developed a puzzling nonlinearity. The trickiest part of the problem with the circuit's diodes was that diodes from an earlier batch had not exhibited any slow-turn-on behavior. Further, some diodes in a batch of 100 from one manufacturer were as bad as the diodes in Figures 6.2b and 6.2c. Other parts in that batch and other manufacturers' parts had substantially no overshoot.

When I confronted the manufacturers of these nasty diodes, they at first tried to deny any differences, but at length they admitted that they had changed some diffu-

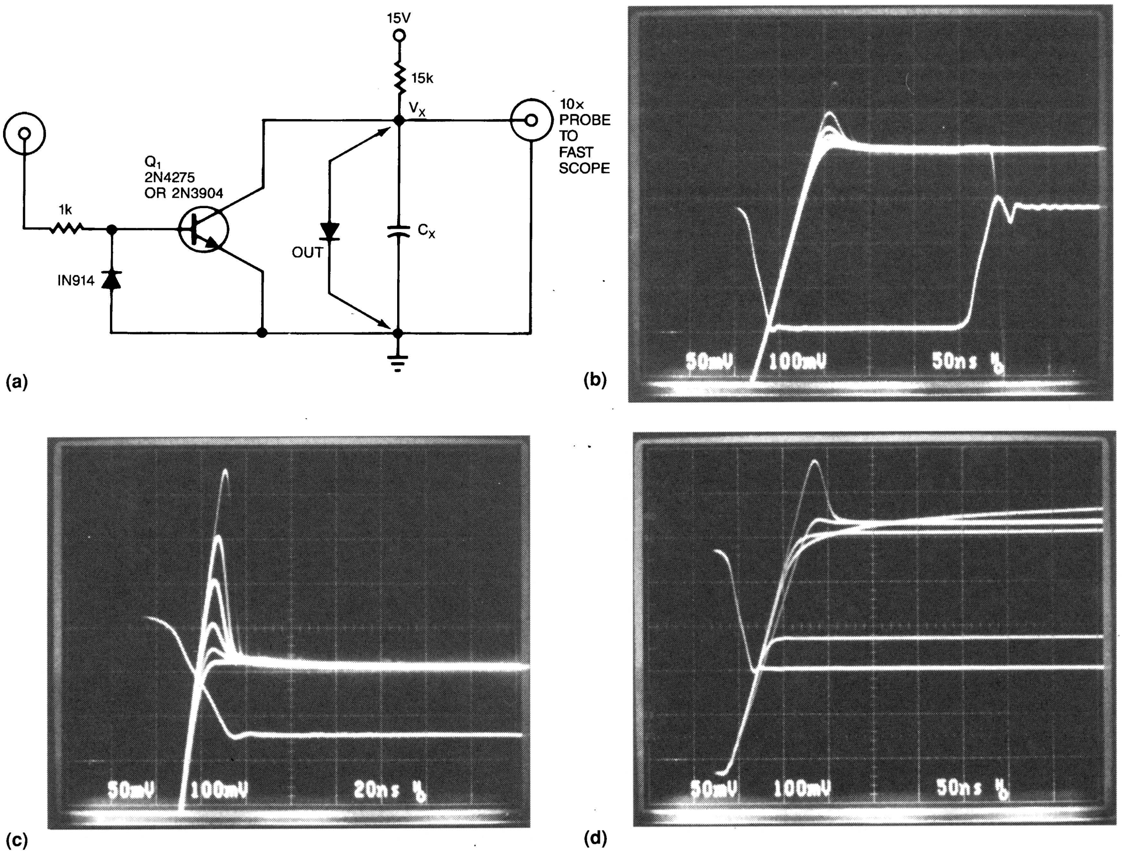

Figure 6.2. In this diode-evaluation circuit (a), transistor Q_1 simply resets V_x to ground periodically. When the transistor turns OFF, V_x rises to about 0.6 V at which point the diode starts conducting. In (b), when dV_x/dt is 8 V/μs, this 1N4148 overshoots as much as 140 mV at input frequencies below 10 kHz before it turns ON. At higher frequencies—120, 240, 480, 960, and 1920 kHz—as the repetition rate increases, the overshoot shrinks and disappears. Maximum overshoot occurs when $f_{in} < 7$ kHz. In (c), when dV_x/dt increases to 20 V/μs, this same 1N4148 overshoots as much as 450 mV at 7 kHz but only 90 mV at 480 kHz and negligible amounts at frequencies above 2 MHz. In (d), various diode types have different turn-on characteristics. The superimposed, 120-kHz waveforms are all invariant with frequency except for the bad 1N4148.

sions to "improve" the product. One man's "improvement" is another man's poison. Thus, you must always be alert for production changes that may cause problems. When manufacturers change the diffusions or the process or the masks, they may think that the changes are minor, but these changes could have a major effect on your circuit.

Many circuits, obviously, require a diode that can turn ON and catch, or clamp, a voltage moving much faster than 20 V/μs. Therefore, if you want any consistency in a circuit with fast pulse detectors (for example), you'll need to qualify and approve only manufacturers whose diodes turn ON consistently. So, as with any other unspecified characteristic, be sure to protect yourself against "bad" parts by first evaluating and testing and then specifying the performance you need. Also if you want to see

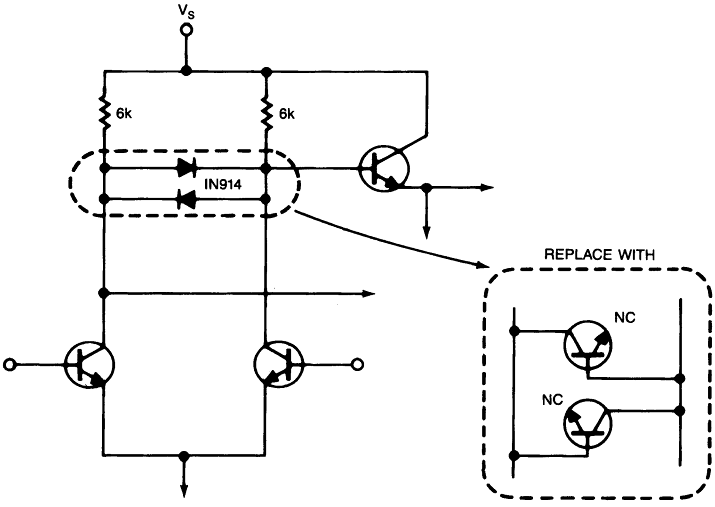

Figure 6.3. Even though the diodes in the first stage of this op amp are forward or reverse biassed by only a millivolt, the impedance of these diodes is much lower than the output impedance of the first stage or the input impedance of the second stage at high temperatures. Thus, the op amp's gain drops disastrously.

fast turn-on of a diode circuit, with low overshoot, you must keep the inductance of the layout small. It only takes a few inches of wire for the circuit's inductance to make even a good fast rectifier look bad, with bad overshoot.

One "diode" that does turn ON and OFF quickly is a diode-connected transistor. A typical 2N3904 emitter diode can turn ON or OFF in 0.1 nsec with negligible overshoot and less than 1 pA of leakage at 1 V, or less than 10 pA at 4 V. (This diode does, of course, have the base tied to the collector.) However, this diode can only withstand 5 or 6 V of reverse voltage, and most emitter-base junctions start to break down at 6 or 8 V. Still, if you can arrange your circuits for just a few volts, these diode-connected transistors make nice, fast, low-leakage diodes. Their capacitance is somewhat more than the 1N914's 1pF.

Other Strange Things That Diodes Can Do to You . . .

If you keep LEDs in the dark, they make an impressive, low-leakage diode because of the high band-gap voltage of their materials. Such LEDs can exhibit less than 0.1 pA of leakage when forward biassed by 100 mV or reverse biassed by 1 V.

Of course, you don't have to reverse-bias a diode a lot to get a leakage problem. One time I was designing a hybrid op amp, and I specified that the diodes be connected in the normal parallel-opposing connection across the input of the second stage to avoid severe overdrive (Figure 6.3). I thought nothing more of these diodes until we had the circuit running—the op amp's voltage gain was falling badly at 125 °C. Why? Because the diodes were 1N914s, and their leakage currents were increasing from 10 nA at room temperature to about 8 μA at the high temperature. And—remember that the conductance of a diode at zero voltage is approximately (20 to 30 mS/mA) × $I_{LEAKAGE}$. That means each of the two diodes really measured only 6 kΩ.

Because the impedance at each input was only 6 kΩ, the op amp's gain fell by a