TROUBLESHOOTING Analog Circuits

PART 6

Active-component problems yield to painstaking probing

Continuing the previous 5-part series on troubleshooting passive parts, this article from the prolific pen of Bob Pease presents the opening salvo of a 7-part series on troubleshooting active components. Bob begins with the simple stuff: diodes and rectifiers, optically coupled devices, solar cells, and batteries. Subsequent articles will expose the mysteries of more complex active devices.

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Even the simplest active devices harbor the potential for causing baffling troubleshooting problems. Consider the lowly diode. The task of a diode sounds simple: to conduct current when forward biased and to block current when reverse biased while allowing negligible leakage. That task sounds easy, but no diode is perfect, and their imperfections are fascinating.

All diodes start conducting current exponentially at low, microampere levels, and the slope of their I/V curves is given by the equation: $g \approx (38.6\ mS/mA) \times I_F$, where mS = millisiemens = millimhos and I_F = forward current. But as the current levels increase, most diodes tail off to $g = (19\ mS/mA) \times I_F$ and then the conductance per milliampere gets even lower due to ohmic and other nonlinear factors. Therefore, at a large forward current, a diode's forward voltage, V_F, will be considerably larger than predicted by simple theory—and larger than desired. Of course, some rectifiers—depending on their ratings—*can* handle large currents from amperes to kiloamperes; but the V_Fs of all diodes, no matter what their ratings, err from the theoretical at high current levels.

These days, Schottky diodes have smaller V_Fs than ordinary pn diodes. However, even germanium diodes and rectifiers still have their following because their low V_Fs are similar to the Schottky's.

High-speed and ultrahigh-speed (sometimes also called high-efficiency) silicon rectifiers that are designed for switching-regulator and other high-frequency applications are also available. They don't have quite as low V_Fs as Schottky diodes and are not quite as fast, but they are available with high reverse-voltage ratings and thus are useful for certain voltage and power levels and certain circuit topologies that impress large flyback voltages on diodes.

When you reverse bias these various diodes, ah, that is where you start to see wild dissimilarities. For example, the reverse-current specification, I_{REV}, for many types of diodes is 25 nA max at 25°C. When you measure them, many of these devices actually have merely 50 or 100 pA of leakage. But the popular 1N914 and its close cousin, the 1N4148, actually *do* have about 10 or 15 nA of leakage at room temperature because of their gold doping. So although these diodes are inex-

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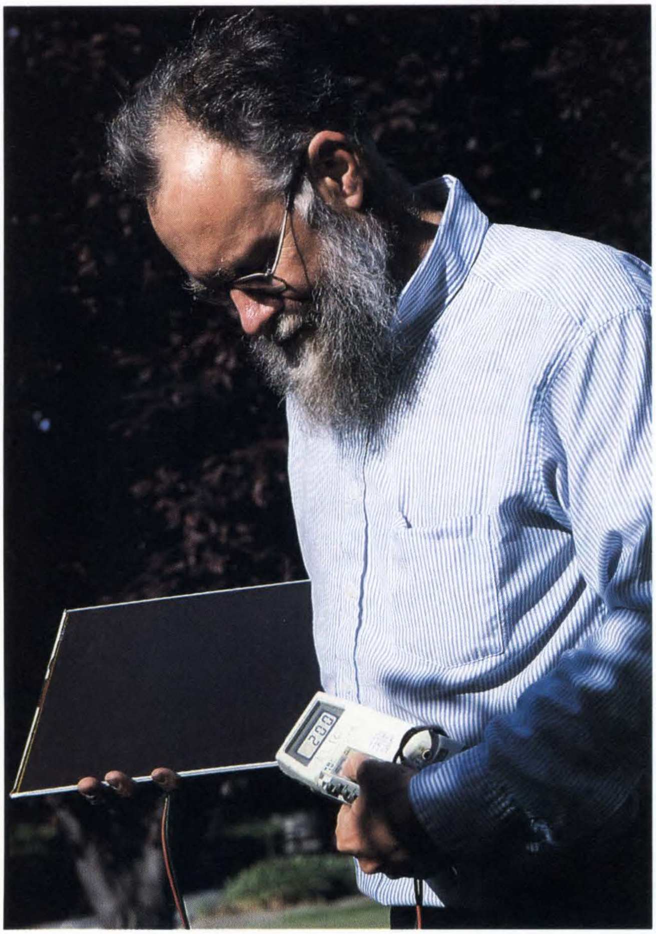


Photographs by Peggi Willis

***With a solar-cell array, you** can make electricity when the sun shines.*

pensive and popular, it's wrong to use them in low-leakage circuits since they're much leakier than other diodes with the same leakage specs.

Why, then, do some low-leakage diodes have the same mediocre 25-nA leakage spec as the 1N914? Diode manufacturers set the test and price at the level most people want to pay because automatic test equipment can test at the 25-nA level—but no lower—without slowing down. If you want a diode characterized and tested for 100 pA, you have to pay extra for the slow-speed testing. Of course, high-conductance diodes such as Schottkys, germaniums, and large rectifiers have much larger reverse leakage currents than do signal diodes.

If you want a very low-leakage diode, use a transistor's collector-base junction instead of a discrete diode (**Ref 1**). You can easily find such "diodes" having less than 1-pA leakage even at 7V or 10 pA at 50V. Although this low leakage is not guaranteed, it's usually quite consistent. However, this diode generally doesn't turn ON or OFF very quickly.

Another source of ultralow-leakage diodes are the 2N4117A and the PN4117A, -18A, and -19A. These devices are JFETS with very small junctions, so leakages well below 0.1 pA are standard—1.0 pA max, guaranteed, for a $0.40 part.

"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 the 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 nsec. 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 nsec before the diode turns ON; this overshoot of 50 to 200 mV is quite surprising (**Fig 1**). Even more astonishing, the V_F overshoot may get worse at low repetition rates but can disappear at high repetition rates (**Fig 1b** through **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 **Figs 1b** and **1c.** Other parts in that batch and other manufacturers' parts had substantially no overshoot.

When I confronted the manufacturers of the faulty diodes, they at first tried to deny any differences but at length admitted that they had changed some diffusions 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 20V/μsec. Therefore, if you want any consistency in, for example, a circuit with pulse detectors, 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.

One "diode" that does turn ON and OFF quickly is a diode-connected transistor. A typical 2N3904's emitter-collector diode can turn ON or OFF in 0.1 nsec with negligible overshoot and less than 1 pA of leakage at 1V, or less than 10 pA at 4V. However, this diode can only withstand 5 or 6V of reverse voltage, and most emitter-base junctions start to break down at 6 or 8V. 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 1 pF.

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

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 (**Fig 2**). I thought nothing more of these diodes until we had the circuit running—the op amp's

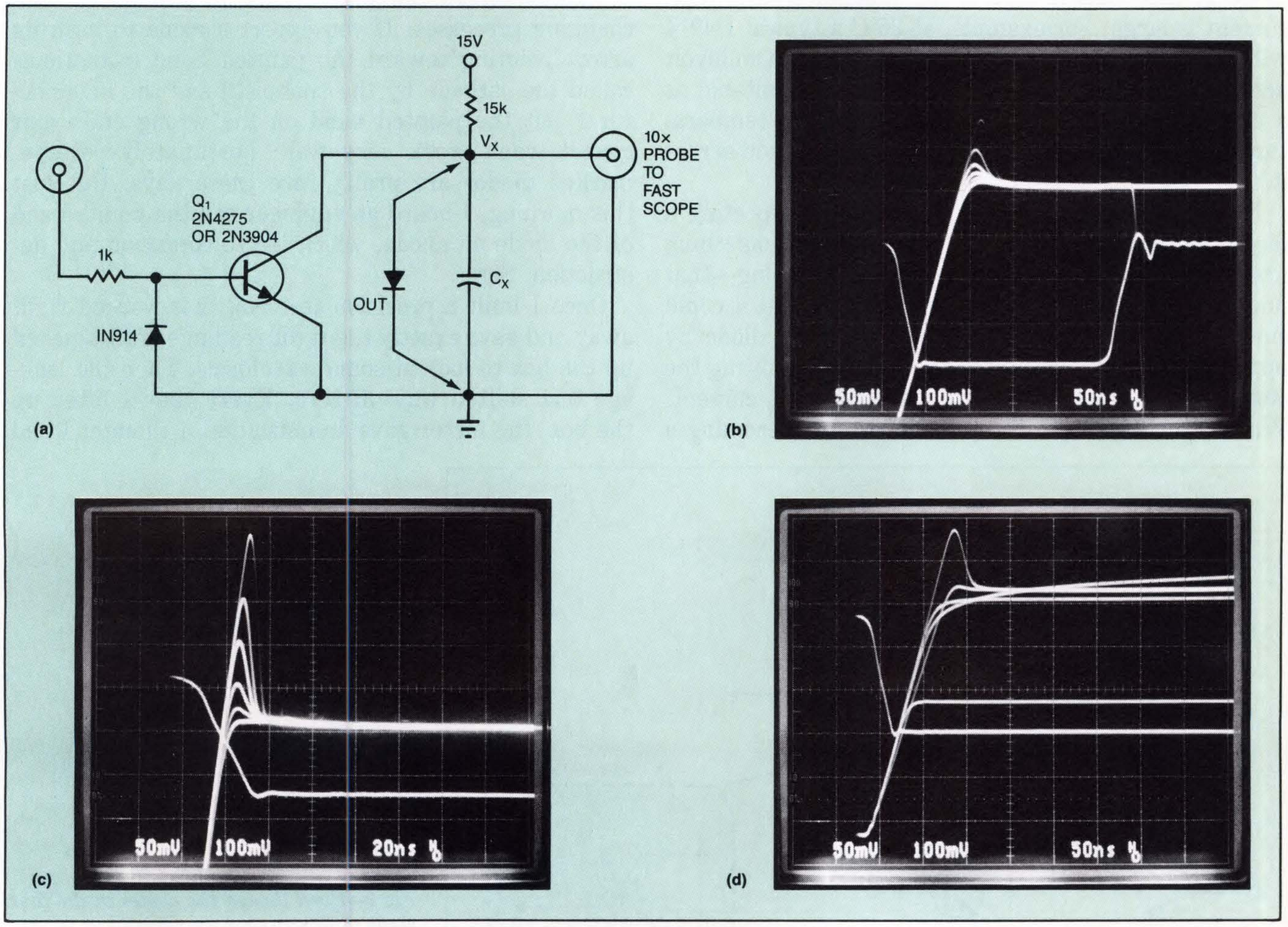


***Fig 1—In this diode-evaluation circuit (a),** transistor Q_1 simply resets V_X to ground periodically. When the transistor turns OFF, V_X rises to about 0.6V until the diode starts conducting. In **b,** when dV_X/dt is 8V/μsec, this 1N4148 overshoots as much as 140 mV at input frequencies below 10 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 $f_{IN} \leq 7$ kHz. In **c,** when dV_X/dt increases to 20V/μsec, 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.*

Always be alert for production changes that may cause problems.

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 5 μA at the high temperature. And—remember that the conductance of a diode at zero voltage is approximately (30 to 40 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 factor of four, even though the diodes may have only been forward or reverse biased by a millivolt. When we substituted collector-base junctions of transistors for the diodes, the gain went back up where it belonged.

You cannot safely assume that the impedance of a diode at zero bias is high if the junction's saturation current is large. For example, at 25°C a typical 1N914 will leak 200 to 400 pA even with only one millivolt across it. Therefore, a 1N914 can prove unsuitable as a clamp or protection diode—even at room temperature—despite having virtually no voltage biased across it.

How can diodes fail? Well, if you were expecting a diode to turn ON and OFF, but it does something unexpected—of the sort I have been mentioning—that unexpected behavior may not be a failure, but it could sure cause *trouble.* Further, you can kill a diode by applying excessive reverse voltage without limiting the current or by feeding it excessive forward current. When a diode fails, it tends to short out, becoming a small blob of muddy silicon rather than an open circuit. I did once see a batch of 1N4148s that acted like thermostats and went open circuit at 85°C, but such cases are rare.

One of the best ways to kill a diode is to ask it to charge up too big a capacitor during circuit turn on. Most rectifiers have maximum ratings for how much current they can pass on a repetitive and on a nonrecurring basis. I've always been favorably impressed by the big Motorola (Phoenix, AZ) books with all the curves of safe areas for forward current as a function of time and repetition rate. These curves aren't easy to figure out at first, but after a while they're fairly handy tools.

Manufacturers can play tricks on you other than changing processes. If you expect a diode to have its arrow pointing toward the painted band (sometimes called the cathode by the snobbish) and the manufacturer put the painted band on the wrong end, your circuit won't work very well. Fortunately reverse-marked diodes are pretty rare these days. But just this morning, I heard an engineer call the pointed end of the diode an anode, which led to confusion and destruction. Sigh . . .

Once I built a precision test box that worked right away and gave exactly the right readings until I picked up the box to look at some waveforms. Then the leakage test shifted way off zero. Every time I lifted up the box, the meter gave an indication; I thought I had

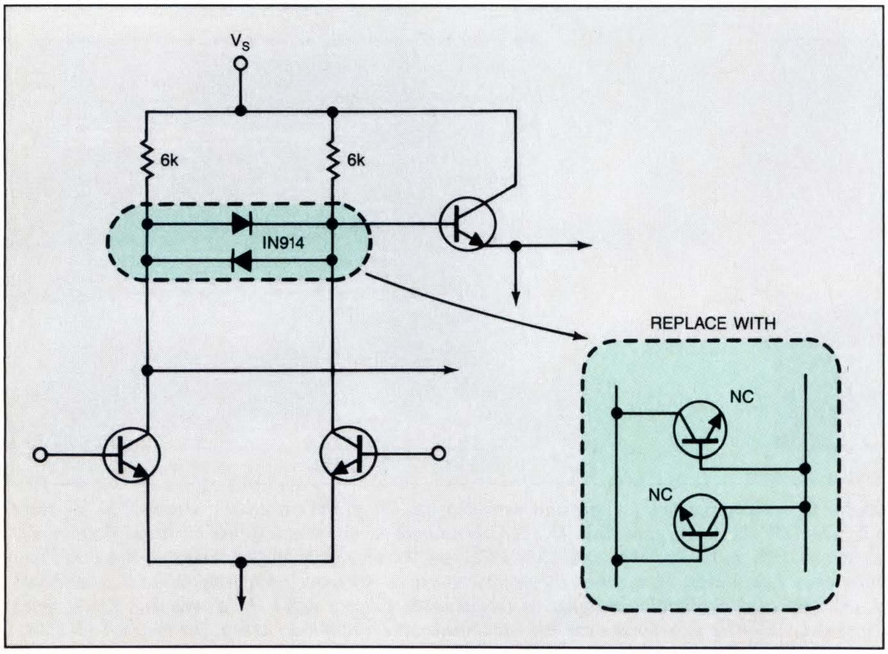


Fig 2—Even though the diodes in the first stage *of this op amp are forward or reverse biased by only a millivolt, the impedance of these diodes is much lower than the output impedance of the first stage or the input impedance of the second stage at high temperatures. Thus, the op amp's gain drops disastrously.*

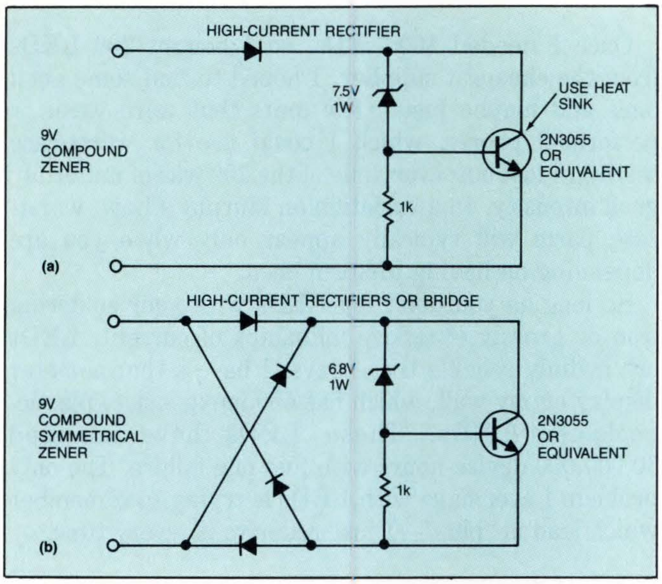


Fig 3—The power rating of this compound Zener (a) *is that of the power transistor. The second compound Zener,* ***(b),*** *is almost the same as* ***a*** *but acts as a symmetrical, matched, double-ended compound Zener.*

designed an altimeter. After some study, I localized the problem to an FD300, whose body is a clear glass DO-35 package covered with black paint. This particular diode's paint had been scratched a little bit, so when I picked up the test box, the light shone under the fixture and onto the diode. Most of these diodes didn't exhibit this behavior; the paint wasn't scratched on most of them.

To minimize such problems, I recommend the following strategies:

- Have each manufacturer's components specifically qualified for critical applications. This is usually a full-time job for a components engineer, with help and advice from the design engineer and consultation with manufacturing engineers.
- Establish a good relationship with each manufacturer.
- Require that manufacturers notify you when, or preferably before, they make changes in their products.
- Keep an alternate source qualified and running in production whenever possible.

My boss may gripe if I say this too loudly, but it is well known that having two good sources is better than having one. The argument that "One source is better than two" falls hollow on my ears. Two may be better than seven or eight, but one is *not* better than two.

Just about all diodes will break down if you apply too much reverse voltage, but Zener diodes are *designed* to break down in a predictable and well-behaved way. The most common way to have problems with a Zener is to starve it. If you pass too little current through a Zener, it may get too noisy. Many Zeners have a clean and crisp knee at a small reverse-bias current, but this sharp knee is not guaranteed below the rated knee current.

Some Zeners won't perform well no matter how carefully you apply them. In contrast to high-voltage Zeners, low-voltage (3.3 to 4.7V) Zeners are poor performers and have poor noise and impedance specs and bad temperature coefficients—even if you feed them a lot of current to get above the knee, which is very soft. This is because "Zeners" at voltages above 6V are really avalanche-mode devices and employ a mechanism quite different from and superior to the low-voltage ones, which are real Zener diodes. At low-voltage levels, band-gap references, such as LM336s and LM385s, are popular because their performance is good compared with low-voltage Zeners.

Zener references with low temperature coefficients, such as the 1N825, are only guaranteed to have low temperature coefficients when operated at their rated current, such as 7.5 mA. If you adjust the bias current up or down, you can sometimes tweak the temperature coefficient, but some Zeners aren't happy if operated off bias. Also, don't test your 1N825 to see what its "forward-conduction voltage" is because in the "forward" direction, the device's temperature-compensating diode may break down at 70 or 80V. This breakdown damages the device's junction, degrades the device's performance and stability, and increases its noise.

And before you subject a Zener to a surge of current, check its derating curves for current vs time, which are similar to the rectifiers' curves mentioned earlier. These curves will tell you that you can't bang an ampere into a 10V, 1W Zener for very long.

If you do need a Zener to conduct a surge of current, check out the specially designed surge-rated Zener devices—also called transient-voltage suppressors—from General Semiconductor Industries Inc (Tempe, AZ). You'll find that their 1W devices, such as the 1N5629 through 1N5665A, can handle a surge of current better than most 10 or 50W Zeners. If you need a *really* high-current Zener, a power transistor can help out **(Fig 3)**.

As mentioned earlier, a diode tends to fail by becom-

If you want a really low-leakage diode, use a transistor's collector-base junction instead of a discrete diode.

ing a short circuit when overpowered, and Zeners cannot absorb as much power as you would expect from short pulses. How dreadful; but, can IC designers serendipitously take advantage of this situation? Yes!

The V_{OS} of an op amp usually depends on the ratio of its first-stage load resistors. IC designers can connect several Zeners across various small fractions of the load resistor. When they measure the V_{OS}, they can decide which Zener to short out—or zap—with a 5-msec, 0.3-to-1.8A pulse. The Zener quickly turns into a low-impedance ($\sim 1\Omega$) short, part of the resistive network shorts out, and the V_{OS} improves.

In its LM108, National Semiconductor (Santa Clara, CA) first used Zener zapping, although Precision Monolithics (Santa Clara, CA) *talked* about Zener zapping first and used it extensively later on. Although Zener zapping is a useful technique, you have to be sure that nobody discharges a large electrostatic charge into any of the pins that are connected to the Zener zaps. If you like to Zap Zeners for fun and profit, they really do make a cute lightning flash in the dark when you zap them. Otherwise, be careful *not* to zap them.

These Zener zaps are also becoming popular in digital ICs under the name of "vertical fuses" or "antifuses." If an IC designer uses platinum silicide instead of aluminum metallization for internal connections, the diode resists zapping.

Once I needed 100 LEDs, so I bought 200 LEDs from the cheapest supplier. I hoped to find some good ones and maybe just a few units that were weak or performed poorly, which I could use for worst-case testing. I lost out; every one of the 200 was of uniformly good intensity. In a variation on Murphy's Law, worst-case parts will typically appear only when you are depending on having uniform ones.

So long as you don't fry LEDs with your soldering iron or grossly excessive milliamps of current, LEDs are awfully reliable these days. I have a thermometer display on my wall, which has 650 inexpensive, plastic-packaged LEDs. These LEDs have amassed 30,000,000 device-hours with just one failure. The only problem I ever have with LEDs is trying to remember which lead is "plus"—I just rederive it, every time.

Optoisolators

An optoisolator usually consists of an LED and a sensitive phototransistor to detect the LED's radiation. In the course of working with the cheaper 4N28s, I've found it necessary to add circuitry to achieve moderate speeds. For example, if you tailor the biases per **Fig 4,** you can usually get a 4N28's response up toward 50 kHz; otherwise the devices can't make even 4 kHz reliably. The trick is decreasing the phototransistor's turn-off time by using a resistor from pin 4 to pin 6.

I've evaluated many different makes and lots of

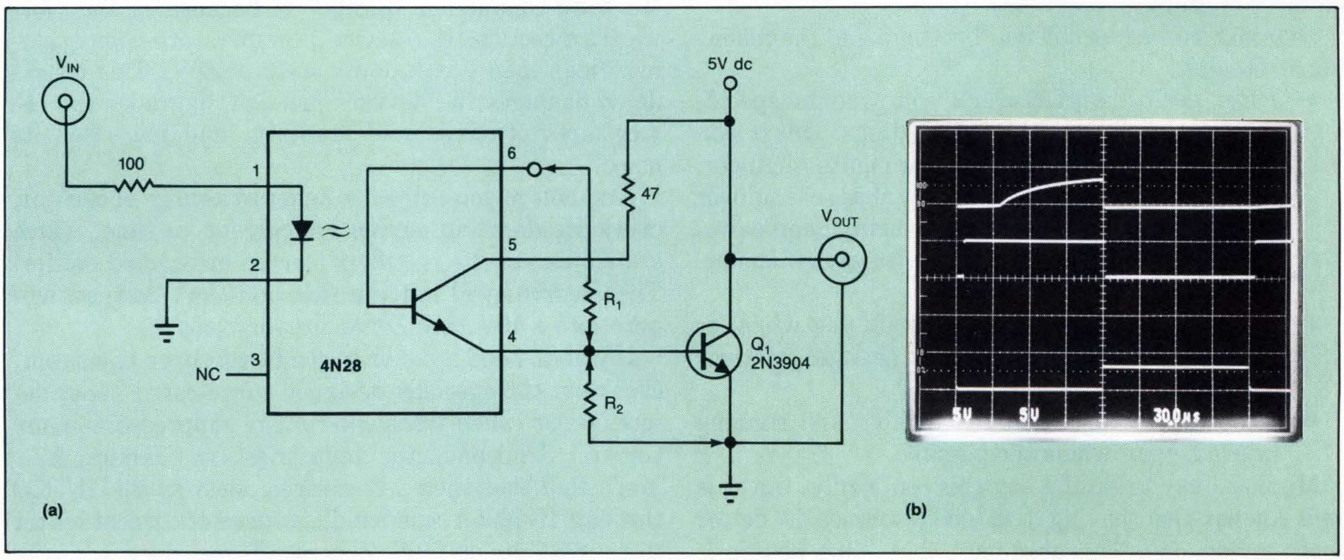
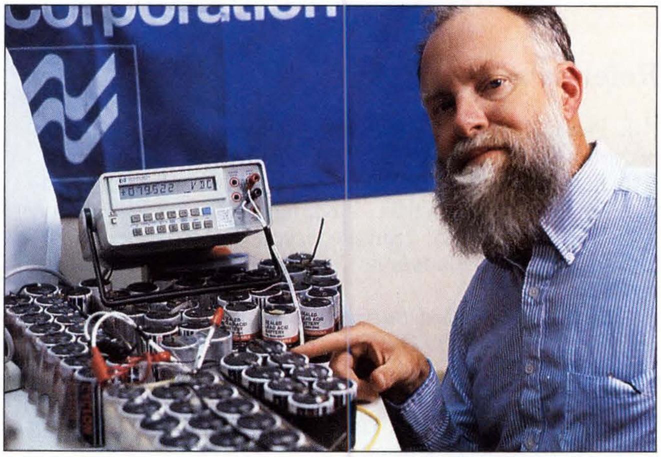


***Fig 4—Adding R_1 and R_2 to the** inexpensive 4N28 optoisolator lets it handle faster signals with less delay—5 μsec vs 60 μsec. The scope photo's bottom trace is an input waveform, the top trace is the circuit's output without R_1 and R_2, and the center trace is the output with R_1=2 MΩ and R_2=1 kΩ.*



Maintaining a healthy battery *involves careful attention to charging, discharging, and temperature.*

4N28s and have found widely divergent responses. For example, the overall current gain at 8 mA can vary from 15 to 104%, even though the spec is simply 10% min. Further, the transfer efficiency from the LED to the photodiode varies over a range wider than 10:1, and the β of the transistor varies from 300 to 3000. Consequently, the transistor's speed of response, which is of course related to β and $f_{-3\ dB}$, would vary over a 10:1 range.

If your circuit doesn't allow for gains and frequency responses that vary so wildly and widely, expect trouble. For example, two circuits, one an optoisolated switching regulator **(Ref 2)** and the other a detector for 4- to 20-mA currents **(Ref 3)**, have enough degeneration so that any 4N28 you can buy will work. I used to have a group of several "worst-case" 4N28s from various manufacturers that I would try out in prototypes and problem circuits. Unfortunately, I don't have the marginal devices anymore, but they were pretty useful.

Also, the data sheets for optoelectronic components often don't have a clear V_F curve or list any typical values; the sheets list only the worst-case values. Therefore, you may not realize that the V_F of an LED in an optoisolator is a couple hundred millivolts smaller than that of discrete red or infrared LEDs. Conversely, the V_F of high-intensity, or high-efficiency, red LEDs tends to be 150 mV larger than that of ordinary red LEDs. And the V_F of DEADs (a DEAD is a Darkness Emitting Arsenide Diode; that is, a defunct LED) is not even defined.

Once I was troubleshooting some interruptor modules. In these modules, a gap separated an infrared LED and a phototransistor. An interruptor—say a gear tooth—in the gap can thus block the light. I tested one module with a piece of paper and nothing happened—the transistor stayed ON. What was that again? It turned out that the paper could diffuse the infrared light but not completely attenuate it. A thin sheet of cardboard or two sheets of paper would indeed block the light.

Solar cells

Extraneous, unwanted light impinging on the pn junction of a semiconductor is only one of many tricky problems you can encounter when you try to design and operate precision amplifiers—especially high-impedance amplifiers. Just like a diode's pn junction, a transistor's collector-base junction makes a good photodiode, but a transistor's plastic or epoxy normally does a very good job of blocking out the light.

When light falls onto the pn junction of any diode, the light's energy is converted to electricity and the diode forward biases itself. If you connect a load across the diode's terminals, you can draw useful amounts of voltage and current from it. For example, you could stack a large number of large-area diodes in series and use them for recharging a battery. The most unreliable part of this system is the battery. Even if you never abuse them, batteries don't like to be discharged a large number of cycles, and your battery will eventually refuse to take a charge.

So much for the charms of solar energy. It's much better to use a solar-powered night-light. Remember that one? A solar-powered night-light doesn't need a battery; it simply needs a 12,000-mile extension cord. To be serious, the most critical problem with solar cells is their packaging; most semiconductors don't have to sit out in the sun and the rain as solar cells do. And it's hard to make a reliable package when low cost is—as it is for solar cells—a major requirement.

In addition to packaging, another major trouble area with solar cells is their temperature coefficients. Just like every other diode, the V_F of a solar cell tends to *decrease* at 2 mV/°C of temperature rise. Therefore, as more and more sunlight shines on the solar cell, it puts out more and more current, but its voltage could eventually drop below the battery's voltage whereupon charging stops. Using a reflector to get even more light onto the cell contributes to this temperature-coefficient problem. Cooling would help, but the attendant compli-

A diode tends to short out when overpowered, and Zeners cannot absorb as much power from short pulses as you would expect.

cations rapidly overpower the original advantage of solar cells' simplicity.

Lastly, I want to say a few things about batteries. The only thing that batteries have in common with diodes is that they are both 2-terminal devices. Batteries are complicated electrochemical systems, and large books have been written about the characteristics of each type **(Refs** 4 through **9).** I couldn't possibly give batteries a full and fair treatment here, but I will outline the basics of troubleshooting them.

First, always refer to the manufacturer's data sheet for advice on which loads will yield optimal battery life. When you recharge a nickel-cadmium battery, charge it with a constant current, not constant voltage. And be sure that the poor little thing doesn't heat up after it is nearly fully charged. If you're subjecting your battery to deep-discharge cycles, refer to the data sheet or the manufacturer's specifications and usage manual for advice. Some authorities recommend that you do an occasional deep discharge, all the way to zero; others say that when you do a deep discharge, some cells in the battery discharge before the others and then get reversed, which is not good for them. I cannot tell you who's correct.

Sometimes a NiCd cell will short out. If this happens during a state of low charge, the cell may stay shorted until you zap it with a brief burst of high current. I find that discharging a 470-μF capacitor charged to 12V into a battery does a good job of opening up a shorted cell.

When you recharge a lead-acid battery, charge it to a float voltage of 2.33V per cell. At elevated temperatures, you should decrease this float voltage by about 6 mV/°C; again, refer to the manufacturer's recommendations. When a lead-acid battery is deeply discharged (below 1.8V per cell), it should be recharged right away or its longevity will suffer due to sulfation.

Be careful when you draw excessive current from a lead-acid battery; the good strong ones can overheat or explode. Also be careful when charging them; beware of the accumulation of hydrogen or other gases that are potentially dangerous or explosive.

And, please dispose of all dead batteries in an environmentally sound way. Call your local solid-waste-disposal agency for their advice on when and where to dispose of batteries. Perhaps some can be recycled. **EDN**

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Author's Biography

For information about Bob Pease, see the box, "Who is Bob Pease, anyway?" in the January 5, 1989, edition of EDN.

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