TROUBLESHOOTING Analog Circuits

PART 7

Rely on semiconductor basics to identify transistor problems

Although transistors—both bipolars and MOSFETs—are immune to many problems, you can still have transistor troubles. Robust design methods and proper assumptions regarding their performance characteristics will steer you past the shoals of transistor disasters. After taking on 2-terminal devices in part 6, Bob covers these 3-terminal devices. Future parts will cover analog ICs.

Robert A Pease, *National Semiconductor Corp*

Transistors are wonderful—they're so powerful and versatile. With a handful of transistors, you can build almost any kind of high-performance circuit: a fast op amp, a video buffer, or a unique logic circuit.

On the other hand, transistors are uniquely adept at causing trouble. For example, a simple amplifier probably won't survive if you short the input to the power supplies or the output to ground. Fortunately, most op amps include forgiving features, so that they can survive these conditions. When the μA741 and the LM101 op amps were designed, they included extra transistors to ensure that their inputs and outputs would survive such abuse. But an individual transistor is vulnerable to damage by excessive forward or reverse current at its input, and almost every transistor is capable of melting. So it's up to us, the engineers, to design transistor circuits so that the transistors do not blow up, and we must troubleshoot these circuits when and if they do.

A simple and sometimes not so obvious problem is installing a transistor incorrectly. Because transistors have three terminals, the possibility of a wrong connection is considerably greater than with a mere diode. Small-signal transistors are often installed so close to a printed-circuit board that you can't see if the leads are crossed or shorted to a transistor's can or to a pc trace. In fact, I recall some boards in which the leads were often crossed and about every tenth transistor was the wrong gender—pnp where an npn should have been, or vice versa. I've thought about it a lot, and I can't think of any circuits that work equally well when you install a transistor of the opposite sex. So, mind your Ps and Qs, your Ps and Ns, and your 2N3904s and 2N3906s.

In addition to installing a transistor correctly, you must design with it correctly. First of all, transistors require input protection. Most transistors can withstand dozens of milliamperes of forward base current but will die if you apply only a few volts. One of my pet peeves has to do with adding protective components. MIL-HDBK-217 has always said that a circuit's reliability decreases when components are added. Yet when you add resistors or transistors to protect an

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amplifier's input or output, the circuit's reliability actually improves. It just goes to show that you can't believe everything you read in a military specification. For a specific criticism of the notion of computing reliability per MIL-HDBK-217, see **Ref 1.**

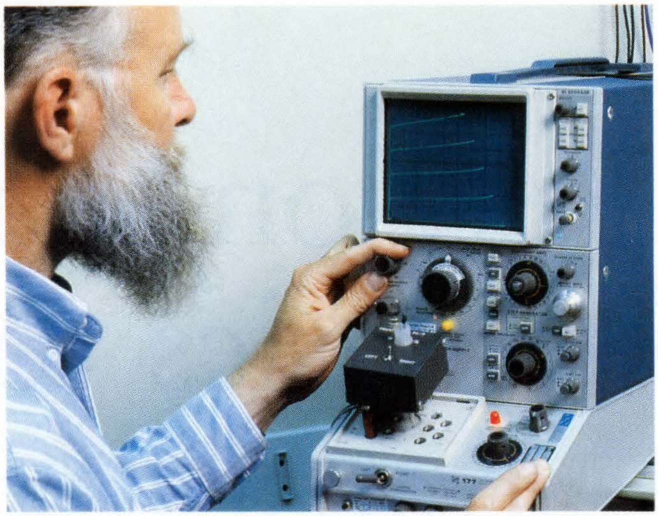
Similarly, if you pump current out of the base of a transistor, the base-emitter junction will break down. This reverse current—even if it's as low as nanoamperes or very brief in duration—tends to degrade the beta of the transistor, at least on a temporary basis. So in cases where accuracy is important, find a way to avoid reverse biasing the inputs.

Transistors are also susceptible to ESD. If you walk across a rug on a dry day, charge yourself up to a few thousand volts, and then touch your finger to an npn's base, it will probably survive because a forward-biased junction can survive a pulse of a few amperes for a small part of a microsecond. But, if you pull up the emitter of a grounded-base stage, you risk reverse-biasing the base-emitter junction. This reverse bias can cause significant damage to the base-emitter junction and might even destroy a small transistor.

When designing an IC, smart designers add clamp diodes, so that any pin can survive a minimum of ±2000V of ESD. Many IC pins can typically survive two or three times this amount. These ESD-survival design goals are based on the human-body model, in which the impedance equals 100 pF in series with 1500Ω. In discrete transistors, whose junctions are considerably larger than the small geometries found in ICs, ESD damage may not be as severe. But in some cases, ESD damage can still happen. Delicate RF transistors such as 2N918s, 2N4275s, and 2N2369s sometimes blow up "when you just look at 'em" because their junctions are so small.

Other transistor-related problems arise when engineers make design assumptions. Every beginner learns that the V_{be} of a transistor decreases by about 2 mV per degree Celsius and increases by about 60 mV per decade of current. Don't forget about the side effects of these rules, or misapply them at extreme temperatures. Don't make sloppy assumptions about V_{be}s. For instance, it's not fair to ask a pair of transistors to have well-matched V_{be}s if they're located more than 0.1 in. apart and there are heat sources, power sources, cold drafts, or hot breezes in the neighborhood. Matched pairs of transistors should be glued together for best results.

I've seen people get patents on circuits that don't even work based on misconceptions of the relationships between V_{be} and current. It's fair to assume that two matched transistors with the same V_{be} at the same small current will have about the same temperature coefficient of V_{be}. But you wouldn't want to make any rash assumptions if the two transistors came from different manufacturers or from the same manufacturer at different times. Similarly, transistors from different manufacturers will have different characteristics when going into and coming out of saturation, especially when you're driving the transistors at high speeds. In my experience, a components engineer is a very valuable person to have around and can save you a lot of grief by preventing unqualified components from confusing the performance of your circuits.



Photographs by Peggi Willis

A curve-tracer can help you discern the difference *between a "good" transistor and a "bad" one. It can also help resolve the shape of the voltage-current curve of any nonlinear component.*

Another assumption engineers make has to do with a transistor's failure mode. In many cases, people say that a transistor, like a diode, fails as a short circuit or in a low-impedance mode. But unlike a diode, the transistor is normally connected to its leads with relatively small lead-bond wires; so if there's a lot of energy in the power supply, the short will cause large currents to flow and vaporize the lead bonds. As the lead bonds deteriorate, the transistor will ultimately fail as an open circuit.

It's nice to design with high-beta transistors, and, "if some is good, more's better." But, as with most things in life, too much can be disastrous. The h-parameter, h_{rb}, equals $\Delta V_{be}/\Delta V_{cb}$ with the base grounded, and many engineers have learned that as beta rises, so does h_{rb}. As h_{rb} rises, the transistor's output impedance decreases; its Early voltage falls; its voltage gain decreases; and its common-emitter breakdown voltage, BV_{ceo}, may also decrease. (The Early voltage of a transistor is the amount of V_{ce} that causes the collector current to increase to approximately two times its low-voltage value, assuming a constant base drive. V_{Early} is approximately equal to $(1/h_{rb}) \times 26$ mV.) So, in many circuits there is a point where higher beta simply makes the gain lower, not higher.

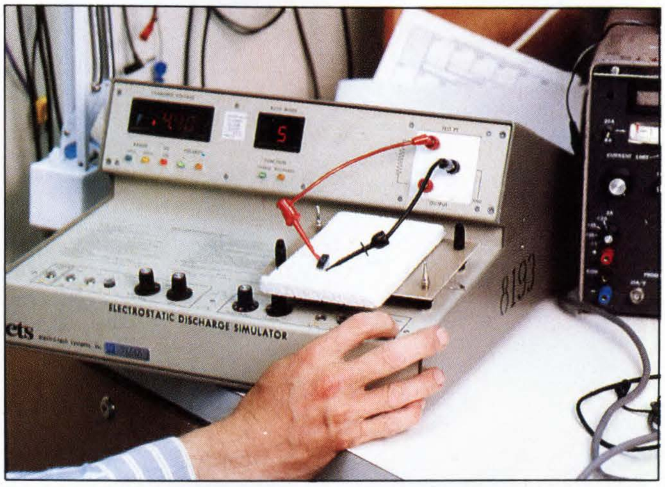
Another way to increase beta is to use the Darlington connection; but the voltage gain and noise may degrade, the response may get flaky, and the base current may decrease only slightly. When I was a kid engineer, I studied the ways that Tektronix made good use of the tubes and transistors in their mainframes and plug-ins. Those engineers didn't use many Darlingtons. To this day, I keep learning more and more reasons not to use Darlingtons or cascaded followers. For many years, it's been more important for many circuits to have matched betas than for them to have sky-high betas. You can match betas yourself or buy four or five transistors on one monolithic substrate, such as a monolithic transistor array.

One of the nice things about bipolar transistors is that their transconductance, g_m, is quite predictable. At room temperature, $g_m = 38.6 \times I_C$. Since the voltage gain is defined as $A_V = g_m \times Z_L$, computing it is often a trivial task. You may have to adjust this simple equation in certain cases. For instance, if you include an emitter-degeneration resistor, R_e, the effective transconductance falls to $1/(R_e + g_m^{-1})$. A_V is also influenced by temperature changes, bias shifts in the emitter current, hidden impedances in parallel with the load, and the finite output impedance of the transistor.

For a given operating current, field-effect transistors normally have much poorer g_m than bipolar transistors do. You'll have to measure your devices to see how much lower. Additionally, the V_{gs} of FETs can cover a very wide range, thus making them hard to bias.

Also be aware that although the transconductance of a well-biased transistor is quite predictable, beta usually has a wide range and is not nearly as predictable. So you have to watch out for adverse performance if the beta is too low or too high and causes shifts in your operating points and biases.

JFETs became popular 20 years ago because you could use them to make analog switches with resistances of 30Ω and lower. JFETs also made good op amps with lower base currents than bipolar devices, at least at moderate or cool temperatures. The BiFET process made it feasible to make JFETs along with bipolars on a monolithic circuit. It's true that the best BiFET inputs are still slightly inferior to the best bipolar ones in terms of voltage-offset temperature coefficient, long-term stability, and voltage noise. But these BiFET characteristics keep improving because of improved processing and innovative circuit design. As a result, BiFETs are very close to bipolar transistors in terms of voltage accuracy and offer the advantage of low input current.



When you hit a component or circuit with a pulse of ESD, *you can never be sure what kind of trouble you'll get—unless you've already tested it with an ESD simulator.*

I recall working on a hybrid circuit that had some JFETs whose gate connections were supposed to be through the back of the dice. I found that some of the dice didn't have proper metallurgical processing, which caused some strange behavior. Initially, the gate acted as if it were connected and would act that way for a long period of time. Then, the gate would act like an open circuit with as much as 1V of error between the actual gate and the bottom of the die. The gate would remain disconnected until a voltage transient restored the connection for another week! The intermittency was awful because nothing would speed up the 1-week cycle-to-failure time. So, we had to go back and add definite lead bonds to the gate's bond pad on the top of the chip, which we had been told was unnecessary. Ouch!

When designing hybrids, you need to make sure to

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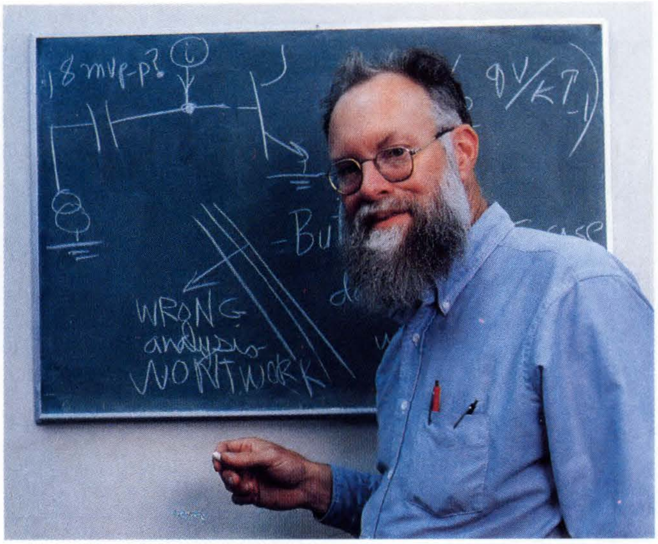


Using equations to analyze circuits *can sometimes help you define a problem. But if the equations are inapplicable, they do a lot more harm than good. This circuit is a version of a patented circuit that was cleverly designed to the highest levels of confidence using equations. The fact that it doesn't work is a mere footnote—except to the engineer who has to troubleshoot it.*

connect the substrate of a chip to the correct dc level. The bottom of a FET chip is usually tied to the gate, but the connection may be through a large and unspecified impedance. You have to be a pretty good chemist or metallurgist to be sure that you don't have to add a bond to the gate's metal. A bipolar-transistor die's substrate is the collector. Most linear and digital IC substrates are tied to the negative supply. Exceptions include the LM117 and similar adjustable positive regulators—their substrate is tied to V_{out}. The LM196 voltage regulator's substrate is tied to the positive supply voltage, V_s, as are the substrates of the MM74HC00 family of chips and most of the dielectrically isolated op amps from Harris. So, be aware of your IC's substrate connection. If an LM101AH op amp's metal can bumps against ground or V_s, you have a problem. Similarly, you shouldn't let an HA2525's case bump against ground or $-V_s$.

MOSFETs are widely used in digital ICs but are also very popular and useful in analog circuits, such as analog switches. Op amps with MOSFET inputs do well in the general-purpose op-amp market. MOSFETs have a bad reputation for excessive noise, but new devices, such as the LMC662, demonstrate that clean processing can cure the problem, thus making MOSFETs competitive with BiFETs. Just be careful not to let ESD near the inputs. MOSFETs do have protection diodes and may be able to withstand 800V, but they can't survive 2000V. If you work with unprotected devices, such as the 3N160, you must keep the pins securely shorted until the device is soldered into its pc board in which the protection diodes are already installed. I do all of that and wash the transistor package with both an organic solvent and soap and water. And, I keep the sensitive gate circuits entirely off the pc board by pulling the gate pin up in the air and using point-to-point wiring. Air, which is a superior dielectric, is also a good insulator (**Ref 2**). So far, I haven't had any blown inputs or bad leakages—at least nothing as bad as 10 fA.

On the other hand, when using CMOS digital ICs, I *always* plug them into live sockets; I *never* use conductive foam; and I *never* wear a ground strap on my wrist. And I've *never* had any failures—with one exception. One time I shuffled across a carpeted floor and pointed an accusatory finger at a CMOS IC. There was a small crack of ESD—probably 5000V—followed by a big SNAP as the IC blew out and crowbarred the entire power supply. Since ESD testing is done with the power OFF, if you did some tests with the power ON, you might get some messy failure modes like the one I just mentioned. Always be wary of any devices that manufacturers claim are safe from ESD.

Power transistors may hog current

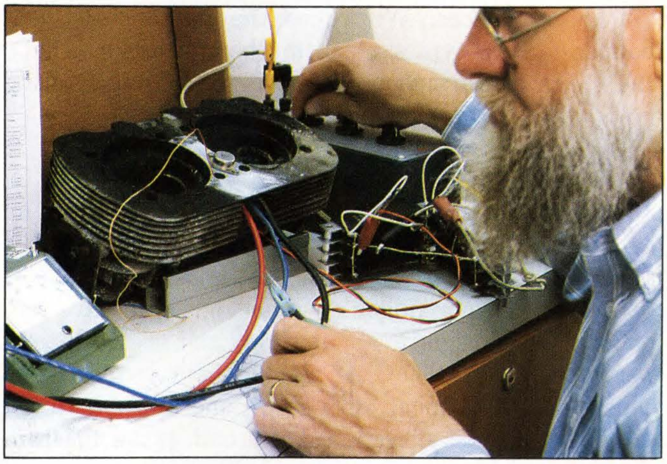
As you build a bipolar transistor bigger and bigger, you may be tempted to go to extremes and make a huge power transistor. But there are practical limitations. Soon, the circuit capacitances cause oppressive drive requirements, and removing the heat is difficult. Still, no matter how big you build power transistors, people will find a use for them. Their most severe problem is secondary breakdown, which is what happens when you drive a transistor outside its safe operating area.

When you operate a power transistor at very high currents and low voltages, the emitter resistance of the device—which includes the resistance of the emitter metal and the inherent emitter resistivity—can cause enough $I \times R$ drop to force the entire emitter and its periphery to share the current. Now, let's halve the current and double the voltage. The amount of dissipation is the same, but the $I \times R$ drop is cut in half. Now continue to halve the current and double the voltage. Soon you'll reach a point where the ballasting (**Fig 1**) won't be sufficient, and a hot spot will develop at a high-voltage point. The inherent decrease of V_{be}

causes an increase of current in one small area. Unless this current is turned OFF promptly, it will continue to increase unchecked. This "current hogging" may cause the area to melt or crater. The designers of linear ICs use ballasting, cellular-layout, and thermal-limiting techniques, all of which can prevent harm in these cases (**Ref** 3). Discrete transistors may someday include these features.

Fortunately, many manufacturers' data sheets include permitted safe-area curves at various voltages and for various effective pulse widths. So, it's possible to design reliable power circuits with ordinary power transistors. The probability of an unreliable design or trouble increases as the power level increases, as the adequacy of the heat sink decreases, and as the safety margins shrink. For example, if the bolts on a heat sink aren't tightened enough, the thermal path degrades and the part can run excessively hot.

High temperature *per se* doesn't cause a power transistor to fail. But, if the drive circuitry was designed to turn a transistor ON and only a base-emitter resistor is available to turn it OFF, then at a very high temperature, the transistor will turn itself ON and there will be no adequate way to turn it OFF. However, I once applied a soldering iron to a 3-terminal voltage regulator and then went to answer the phone. When I came back the next day, I discovered that the TO-3 package was still quite hot—300°C, which is normally recommended for only 10 seconds. When I cooled it off, the regulator ran fine and met spec. So, the old dictum that high temperature will necessarily degrade reliability is not always true. Still, it's a good practice not to get your power transistors that hot and to have a base drive that can pull the base OFF if they do.



When using high-power amplifiers, *there are certain problems you just never have if you use an extremely large heat sink. This heat sink's thermal resistance is lower than 0.5°C/W.*

You can also run into problems if you tighten the screws on the heat sink too tight or if the heat sink under the device is warped or has bumps or burrs or foreign matter on it. If you tighten the bolt too much, you'll overstress and warp the tab and die attach. Overstress may cause the die to pop right off the tab. The insulating washer under the power transistor can crack due to overstress or may fail after days or weeks or months. Even if you don't have an insulating washer, overtorqueing the bolts of plastic-packaged power

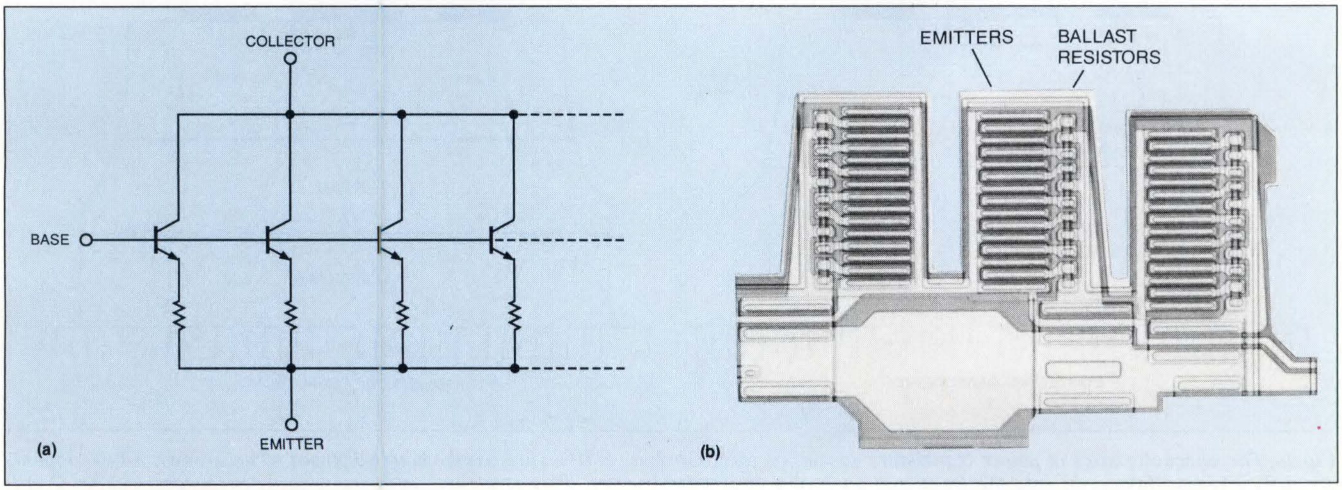


Fig 1—Ballast resistors, also known as sharing resistors, *are often connected to the emitters of a number of parallelled transistors* ***(a)*** *to help the transistors share current and power. In an integrated circuit* ***(b)****, the ballast resistors are often integrated with adjacent emitters. (Photo of National Semiconductor Corp's LM138)*

Mind your Ps and Qs and your Ps and Ns; don't mistakenly insert a pnp transistor in place of an npn, or vice versa.

transistors is one of the standard ways to mistreat and kill these devices. Why does the number 10 inch-pounds max, 5 typ, stick in my head? Because that's the spec the Thermalloy man gave me for the mounting bolts of TO-220 packages.

Apply the 5-second rule

Your finger is a pretty good heat detector—just be careful not to burn it with high voltages or very hot devices. A good rule of thumb is the 5-second rule: If you can hold your finger on a hot device for five seconds, the heat sink is about right, and the case temperature is about 85°C. If a component is too hot to touch, dot your finger with saliva and apply it to the hot object for just a fraction of a second. If the moisture dries up quickly, the case is probably around 100°C; if it sizzles instantaneously, the case may be as hot as 140°C. Alternatively, you can buy an infrared imaging detector for thousands of dollars, and you won't burn your fingers.

Fabrication structures make a difference

Another thing you should know when using bipolar power devices is that there are two major fabrication structures: the epitaxial base and the single diffused **(Fig 2) (Ref 4)**. Transistors fabricated with the single-diffused structure are more rugged and have a wide safe-operating area. Epitaxial-base devices feature faster switching speeds but aren't as rugged as the single-diffused types. A good way to compare the two types is to look at the data sheets for the Motorola 2N3771 and MJ3771. The MJ3771 epi-base device has a current-gain bandwidth 10 times greater than the 2N3771 single-diffused device. The MJ3771 also has a switching speed faster than the 2N3771 when used as a saturated switch, but the 2N3771 has a considerably larger safe area if used for switching inductive loads. You can select which of these characteristics you prefer and order the part according to the specific number.

But there isn't always a clear correlation between the part number and its fabrication structure. For example, the popular 2N3055 is available in both epi-base and single-diffused versions. Since both versions meet and exceed the JEDEC specs, you could end up with either type. If you breadboard with one type and then start building in production with the other, you might suddenly find that the bandwidth of the device has changed by a factor of 10 or that the safe area doesn't match that of the prototypes.

Fortunately, there are ways to order the 2N3055 you want. If you want to buy an ordinary 2N3055—one that meets but does not exceed the device's JEDEC specs—the die will be about 90 mils on a side, the bandwidth will be about 2 MHz, and it will have a nominal safe area because it is an epi-base device. If you want to buy a really gutsy 2N3055, order a 2N3055H from RCA or SGS-Thomson. RCA calls the device's construction hometaxial, which is similar to single diffused. The part's die is about 180 mils on the side, so—obviously—the 2N3055H costs more than the

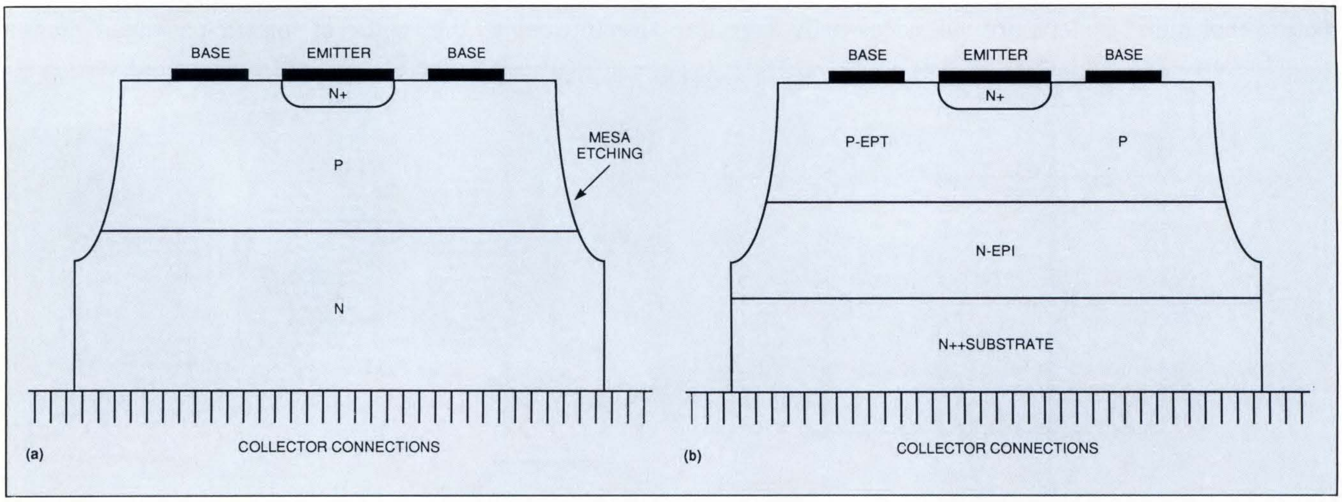
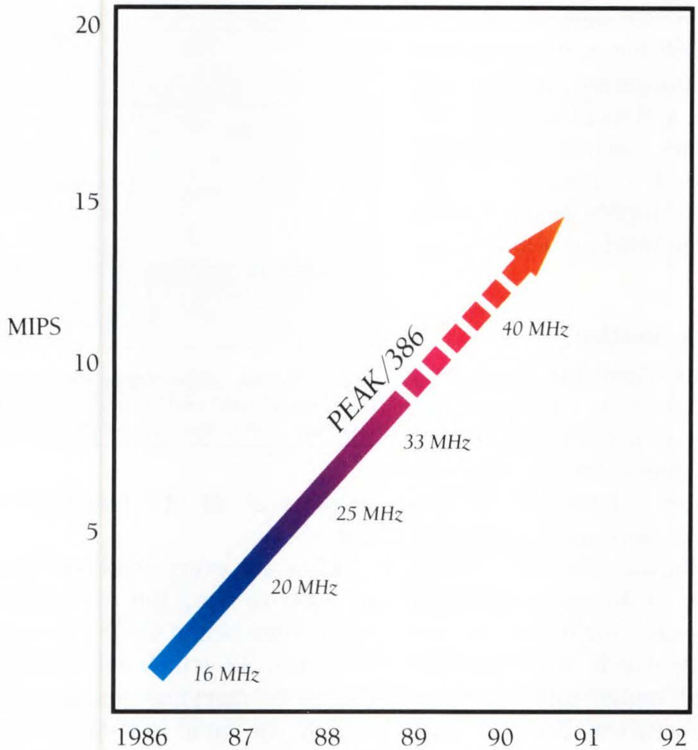


***Fig 2—The characteristics of power transistors** depend on their fabrication structure. In the single-diffused structure **(a)**, n-type dopants are diffused simultaneously into the front and back of a thin p-type wafer. This structure produces rugged transistors with wide safe operating areas. The more modern epitaxial-base transistor **(b)** takes advantage of the properties of several different epitaxial layers to achieve higher beta, faster speed, lower saturation, smaller die size, and thus, lower cost. Both structures involve mesa etching, which accounts for the slopes at the die edges.*

How to make your 386 system scream.



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2N3055. The 2N3055H's bandwidth is only 0.3 MHz, but its safe area is considerably bigger than that of the ordinary 2N3055. Thus, 2N3055Hs are recommended for switching inductive loads.

Be careful not to confuse these epitaxial or single-diffused devices with planar power devices, such as the 2N5039 (**Fig 3**). The 2N5039 has a frequency response around 60 MHz but a considerably smaller safe area than those of the epitaxial and single-diffused devices. As with smaller transistors, such as the 2N2222 and 2N3904, planar devices tend to oscillate at high frequencies. The judicious use of ferrite beads in their emitter or base leads is often required for stable linear operation.

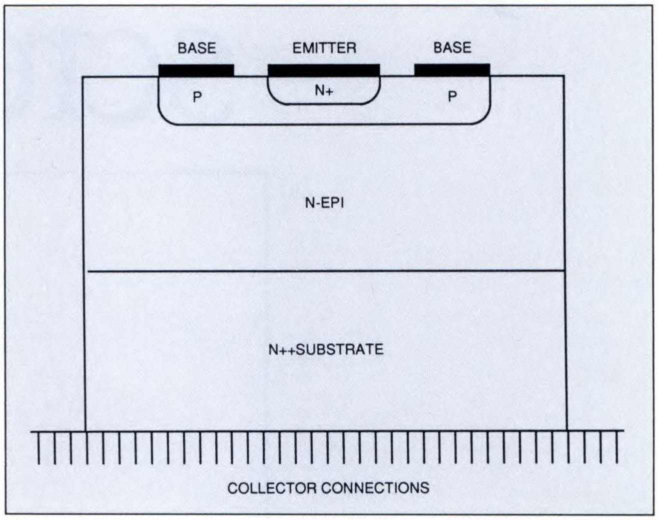

Fig 3—Planar power transistors can achieve very small geometries, *small base-widths, and high frequency responses, but they're less rugged than the single-diffused and epitaxial-base types.*

Power-circuit design requires expertise

For many power circuits, your transistor choice may not be as clear-cut as in the previous examples. So, be careful. Design in this area is not for the hotshot just out of school—there are many tricky problems that can challenge even the most experienced designers. For example, if you try to add small ballasting resistors to ensure current sharing between several transistors, you may still have to do some transistor matching. This matching isn't easy. You'll need to consider your operating conditions; decide what parameters, such as beta and V_{be}, you'll match; and figure out how to match different manufacturers' devices. Such design questions are not trivial.

When the performance or reliability of a power circuit is poor, it's probably not the fault of a bad transistor. Instead, it's quite possibly the fault of a bad or marginal driver circuit or an inadequate heat sink. Perhaps a device with different characteristics was inadvertently substituted in place of the intended device. Or perhaps you chose the wrong transistor for the application.

A possible scenario goes something like this. You build 10 prototypes, and they seem to work okay. You build 100 more, and half of them don't work. You ask me for advice. I ask, "Did they ever work right?" And you reply, "Yes." But wait a minute. There were 10 prototypes that worked, but the circuit design may have been a marginal one. Maybe the prototypes didn't really work all that well. If they're still around, it would be useful to go back and see if they had any margin to spare. If the 10 prototypes had a gain of 22,000, but the current crop of circuits has gains of 18,000 and fails the minimum spec of 20,000, your design is not really a failure. It's not that the circuit isn't working at all, it's just that your expectations were unrealistic.

After all, every engineer has seen circuits that had no right to work but did work—for a while. And then when they began to fail, it was obviously just a hopeless case. So, which will burn you quickest, a marginal design or marginal components? That's impossible to say. If you build in some safety margin, you may survive some of each. But you can't design with big margins to cover every possibility, or your design will become a monster.

MOSFETs avoid secondary breakdown

When it comes to power transistors, MOSFETs have certain advantages. For many years, MOSFETs have been available that switch faster than bipolar transistors with smaller drive requirements. And MOSFETs are inherently stable against secondary breakdown and current hogging because the temperature coefficient of I_{ds} vs V_{gs} is inherently stable at high current densities. If one area of the power device gets too hot, it tends to carry less current and thus has an inherent mechanism to avoid running away. This self-ballasting characteristic is a major reason for the popularity of MOSFETs over bipolar transistors. However, recent criticism points out that when you run a MOSFET at high enough voltages and low current, the current density gets very small, the temperature coefficient of I_{ds} vs V_{gs} reverses, and the device's inherent freedom from current hogging may be lost (**Ref 5**). So at high volt-

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Don't be too quick to blame circuit problems on a transistor; the designer may have made some sloppy assumptions or had false performance expectations.

ages and low current densities, watch out for this possibility.

The newer power MOSFETs are considerably more reliable and less expensive than the older devices. Even though you may need a lot of milliamps to turn the gate ON or OFF quickly, you don't need a lot of amps to hold it ON like you do with a bipolar transistor. You can turn the newer devices OFF quicker, too, if you have enough transient gate drive current available.

However, MOSFETs are not without their trouble spots. If you dissipate too many watts into a MOSFET, you can melt it just as you can melt a bipolar device. If you don't overheat a MOSFET, the easiest way to cause a problem is to forget to insert a few dozen or hundred ohms of resistance or a ferrite bead right at the gate lead of the device. Otherwise, these devices have such high bandwidths that they can oscillate at much higher frequencies than bipolar transistors.

For example, the first high-fidelity, all-MOSFET audio amplifier I ever saw blew up. It worked okay in the lab, but some misguided engineer decided that if a bandwidth of 5 Hz to 50 kHz was good, then 0.5 Hz to 500 kHz was better. Consequently, when the speaker cables were extended from 10 feet to 20 feet for a demonstration, the amplifier broke into a megahertz-region scream and promptly went up in smoke because of the lack of damping at the sources. I was told that after a minor redesign the amplifier was perfectly reliable. The redesign involved cutting the bandwidth down to a reasonable level, adding some ballasting in the sources, and tying antisnivet resistors directly to the gate pins. (Note: A snivet is a nasty, high-frequency oscillation originally found in vacuum-tube TV sets.)

As with bipolar transistors, MOSFETs are very reliable if you don't exceed their voltage, current, or temperature ratings. Dissatisfaction with a device's reliability or performance usually stems from the drivers or the related circuitry. Most MOSFETs have a maximum V_{gs} rating of just 20 or 25V. A MOSFET may temporarily survive operation with 30 or 50V on the gate, but it's not safe to run it up there forever. If you apply excessive gate voltage, gradual gain or threshold degradation may occur. So—please—don't. Also, power MOSFETs are not quite as rugged as bipolars when it comes to surviving ESD transients. A common precaution is to add a little decoupling, clamping, or current-limiting circuitry, so that terminals accessible to the outside world can withstand ESD.

DMOS FETs are so easy to apply that we usually forget about the parasitic bipolar transistor that lurks in parallel with them. If [dV/dt] is too large at the drain, the drain junction is avalanched at too high a current and voltage, or the transistor gets too hot, the bipolar device turns ON and dies an instant death due to current hogging or an excursion from its safe operating area.

But I'm spoiled rotten. I'm accustomed to linear ICs, which have protection transistors built right in, so most of the transistor troubles are left to the IC designer. Discrete designs are appropriate and cost-effective for many applications, but the availability of linear ICs—especially op amps—eases your design task considerably. Next time, we'll discuss the ins and outs and innards of op amps. EDN

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Author's biography

*For information about Bob Pease, see the **box**, "Who is Bob Pease, anyway?" on page 148 of the January 5, 1989, edition of EDN.*

Article Interest Quotient (Circle One)
High 470 Medium 471 Low 472