• *First Steps In Radio*

The Magic of Transistors

Part 8: Invented by Bardeen, Shockley and Brattain at Bell Labs in 1947, the transistor has made our modern electronic world possible. Let's look at how they're used in Amateur Radio.

By Doug DeMaw,* W1FB

Doesn't everything today have transistors in it? Well, not quite. The vacuum tube remains "king of the hill" in terms of power versus cost in some applications. But, most small electronics gadgets and home-entertainment devices rely 100% on transistors or versions of the transistor (integrated circuits, or ICs).

Why is a transistor better than a tube? There are many reasons: greater reliability, increased longevity, lower cost, smaller size and reduced heating. The vacuum-tube equivalent of a 2N3904 transistor (available these days for as little as 15 cents, and smaller than a pea) would be as large as a tube of lipstick, and would cost $8 or $10 new. Furthermore, the tube would be fragile, whereas the transistor could take a pretty heavy buffeting before it became damaged. If we were to regress in the technology, and attempt to build a personal computer or a calculator from vacuum tubes, it would fill an entire living room with racks of equipment and large power supplies. I helped develop one of the first military computers in the early 1950s while employed in a research lab. Known as the MIDAC computer (Michigan digital automatic computer), it was used for BOMARC missile guidance. It filled a huge room, and stood in 6-foot equipment racks lined up side by side in 10-foot rows![1] The same system today could be reduced to the size of an office typewriter (without the radar display tube and electrical joysticks). Dozens of vacuum tubes were used in but one of the many circuits. Today, a single postage-stamp-size IC could be used in place of the tubes.

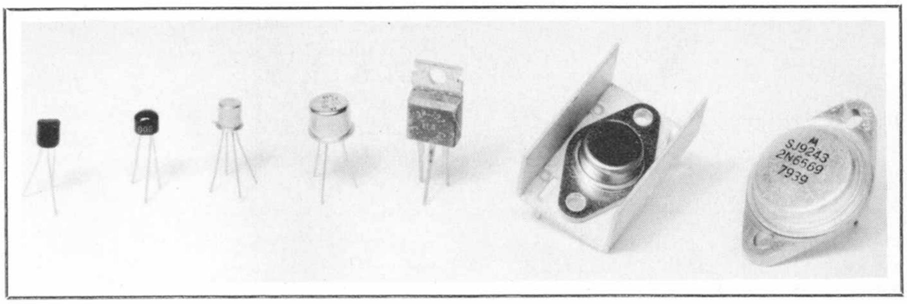

Fig. 1 — Left to right are low-power, medium-power and high-power transistors. There are many case styles for transistors.

What is a Transistor?

A transistor is an active semiconductor with three or more terminals. The name was derived from "transresistor" for "transfer resistor." It is made from silicon or germanium crystals that are usually formed into a junction or sandwich, as are the diodes we discussed last month in *QST*. The main difference is that a transistor has three elements (emitter, base and collector), whereas the diode has only a cathode and anode. The transistor can amplify signal current, but the diode cannot. Also, a transistor requires an operating voltage (it is an *active* device) for it to amplify. A diode, on the other hand, is a passive device; it does not need an operating voltage to make it rectify or clamp. It does, however, need an *applied* voltage if it is to perform a task for us. Junction transistors are commonly referred to as "bipolar transistors," sometimes abbreviated BJT (bipolar junction transistor). Fig. 1 illustrates a variety of styles and sizes of bipolar transistors.

How does a transistor compare to a tube in general terms? Look at Fig. 2 and you will observe a similarity in the symbols for the two components. Each one contains three working terminals, but the tube has two additional terminals (filaments), which are necessary for heating the cathode. Without the heaters or filaments, the tube cannot function. The transistor needs no heater. Some tubes have what are called "directly heated cathodes." They have no cathode element, and the filaments serve double duty as the heater and cathode. Those tubes reach operating conditions

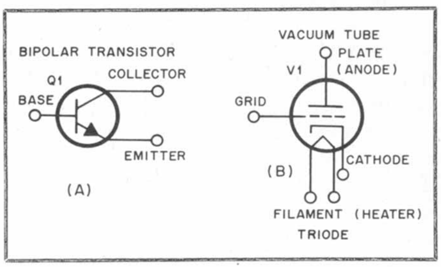

Fig. 2 — Symbol (A) for a bipolar transistor. A triode vacuum-tube symbol is included (B) for illustrating the similarity between the two triode devices.

[1]m = ft × 0.3048.

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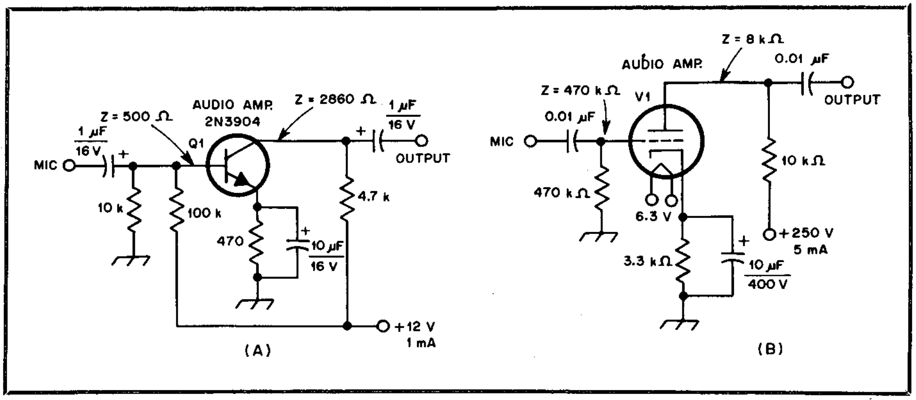

Fig. 3 — A practical circuit example for a transistorized audio amplifier (A) and a tube amplifier (B). Note the differences in the operating voltages and impedance levels (see text).

(from turn-on) almost as quickly as transistors do.

The example of Fig. 2B shows a triode tube that requires a warm-up time. It has separate filament and cathode elements. The transistor of Fig. 2A can be compared to the triode tube. That is, the base equates to the grid, the collector to the plate and the emitter to the cathode. Both are triodes (three electrodes), and both devices amplify ac or RF energy. The transistor amplifies current, however, while the tube amplifies voltage (ac).

Additional differences are (1) the transistor requires much lower operating voltage than does the tube, and (2) the tube has higher impedances at its terminals than does a transistor. For example, the input impedance of the transistor might present an effective impedance (ac equivalent of dc resistance) of 500 ohms at the base (base to ground), but the tube in a similar circuit could have a grid-to-ground input impedance of 1 megohm or greater. Similar comparisons can be made between the transistor collector and tube plate. Therefore, different design methods are needed for the two devices.

Let's look for a moment at Fig. 3. It shows a transistor and a tube in similar circuits. Note the differences in the operating voltages and terminal impedances. You can see there is quite a difference between the two circuits, even though they are each capable of providing approximately the same amount of amplification. The term "Z" is electronic shorthand for "impedance." You will run across this expression many times in your studies. You will observe also from Fig. 3 that the values of the resistors and capacitors are substantially different for the pair of circuits.

Additional Transistor Types

Actually, there are two types of bipolar transistor. One is called an NPN transistor, and the other is a PNP device. Symbols for the two varieties are given in Fig. 4. The NPN (negative-positive-negative) unit requires a positive operating voltage on the base and collector, but the PNP (positive-negative-positive) device needs a negative voltage on the base and collector. The distinguishing feature in the symbol that separates the two types is the direction of the emitter arrow. Observe that the arrow points out for an NPN transistor, while it points in for the PNP unit. Most transistors today are of the NPN kind, except those used for audio work. At the beginning, most transistors were PNP types, because germanium was used instead of silicon for the internal structure.

There are numerous types of tubes — some containing more than three elements. Some have four elements (two grids), and they are known as tetrodes. There are also pentodes and heptodes. In a like manner, we have transistors with an additional element. A common example is the dual-gate FET (field-effect transistor). The symbols for that and a single-gate JFET (junction FET) are shown in Fig. 5. As is the case with bipolar transistors, we have N- and P-channel FETs. The arrow in the symbols indicates the polarity of the device. At A of Fig. 5, we can see a JFET. It has an internal sandwich type of junction, as does the bipolar transistor. The dual-gate MOS (metal-oxide silicon) FET at B of Fig. 5 has a thin layer of oxide as insulating material between the gates and the remainder of the device. The drawing at C of Fig. 5 illustrates in simple terms the names of the elements within an FET. We can equate the FET to the triode tube by saying that the gate and grid are related, as are the drain and plate, and the source and cathode. The major difference between FETs and bipolar transistors is that the input impedance of the FET is similar to that of a triode tube — usually 1 megohm or greater. The effective Z is usually determined by the value of the gate-to-ground resistor used. A practical comparison between a tetrode tube and a dual-gate FET is shown in Fig. 6. We can see that the two transistor gates are used in a similar manner to the pair of grids in the tube example. A popular dual-gate MOSFET is the RCA 40673. Another is the Texas Instruments 3N211 device. When it comes to JFETs, you may recognize the

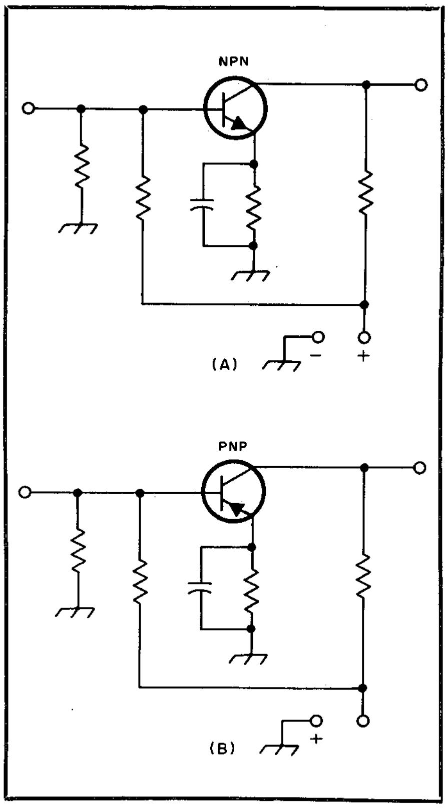

Fig. 4 — An NPN transistor (A) uses a positive collector voltage. The PNP transistor (B) requires a negative collector potential. Note the direction of the arrows for the two devices.

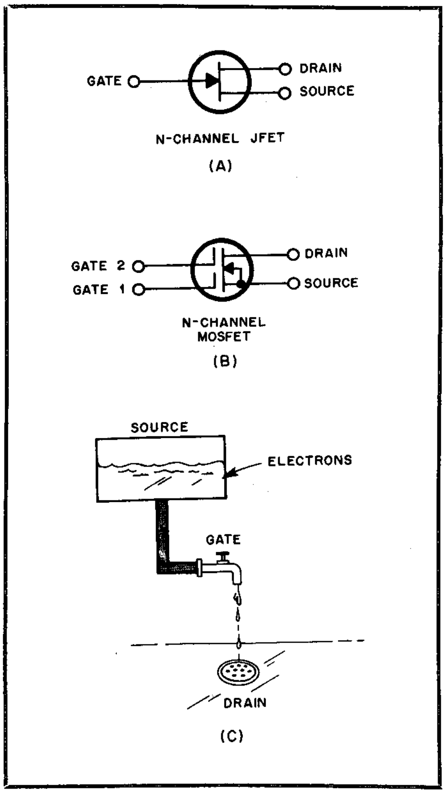

Fig. 5 — A JFET symbol is shown at A. A dual-gate MOSFET symbol is seen at B. The drawing at C shows how an FET operates.

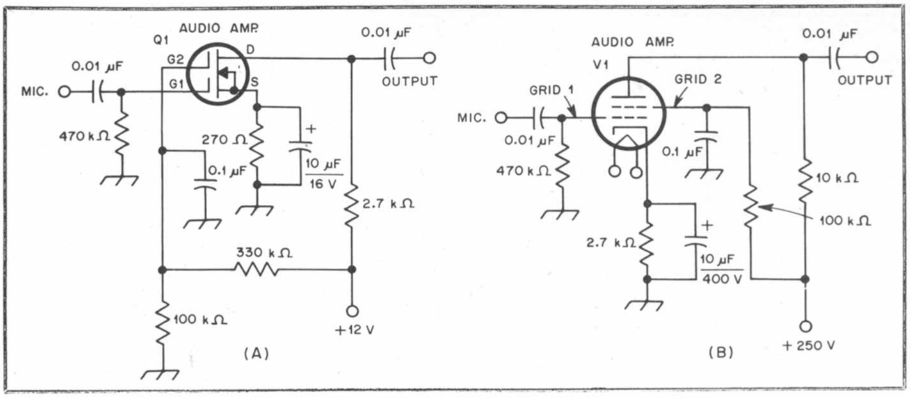

Fig. 6 — Circuit examples of a dual-gate MOSFET (A) and a tetrode tube (B) to show the similarity between the two devices.

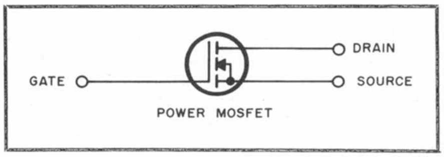

Fig. 7 — Circuit symbol for an MOS power FET of the enhancement-mode variety.

number MPF102, which is an almost generic type of JFET nowadays.

Power Transistors

Thus far we have discussed only those transistors used for small-signal (low-power) applications. But, transistors can also accommodate large amounts of power. By combining many power transistors, we can build audio or RF amplifiers that deliver more than 1000 W of output power. Although no single transistor can do that job by itself, it is entirely possible to obtain more than 1000 W of output power from a single vacuum tube. It is in this area that the tube is still "king of the mountain."

There are high-power bipolar transistors and high-power MOSFETs, too. The electrical symbol for a power FET is somewhat different from that of a small FET (see Fig. 7). FETs with the three lines in place of the single drain-source line (as in Fig. 5B) are called "enhancement-mode FETs." When a single drain-source line is used it signifies a "depletion-mode FET." The difference is beyond the intent of this discussion, but it is worth mentioning to help avoid confusion.

Power transistors can generate a large amount of internal heat when they are operating. For this reason we need to use *heat sinks* to help keep them cool. Cooling fans are used on big tubes for the same reason. Excessive heat is the enemy of all electronics parts. A heat sink is a metal device that conducts the internal heat of the transistor outward. Many heat sinks are made from extruded aluminum, and they may have several rows of cooling fins on them. The transistor must be mated firmly to the heat sink to reduce "thermal resistance." Otherwise, the heat sink may be ineffective and the transistor will be destroyed. A thin layer of silicone grease is generally applied between the transistor body and the heat sink to aid the thermal bond. Some typical heat sinks are shown in the photograph of Fig. 8.

A power transistor can draw several amperes of current when a relatively low operating voltage is applied. Conversely, most power tubes require very high voltage, but draw milliamperes, rather than amperes, of current. The input and output impedances of high-power transistors are very low, often less than 1 ohm! This makes it quite difficult to work with them unless special input and output matching techniques are employed.

Combining Transistors

Everyone has heard about integrated circuits. You may think of them as large families of transistors residing under one roof. It is possible to have literally hundreds of transistors within a single IC. ICs help reduce the parts count in a circuit, leading to more-compact assemblies. The shortfall is that if one tiny internal transistor fails, the entire IC must be replaced! A number of ICs are shown in Fig. 9. ICs are available for amplifying signals to a moderate power-output level, but they are not as husky in that respect as big discrete (individual) transistors are.

ICs may contain MOSFET or bipolar transistors, or a mixture of both. They also contain diodes, resistors and capacitors. The internal workings of a simple IC are shown in Fig. 10. It is designated U1. U, the standard symbol for an IC, stands for "unrepairable." The innards we see at A of Fig. 10 are those of an RCA CA3045 transistor-array IC. Since all of the transistor leads come out of the case separately, we can use this IC in the same

Glossary

heat sink — a metal clip or plate to which a transistor can be attached for the purpose of conducting heat away from the transistor.
heptode — a type of vacuum tube that contains seven electrodes.
JFET — a junction field-effect transistor.
MOS — abbreviation for metal-oxide silicon.
MOSFET — a field-effect transistor that uses MOS material as the gate insulation.
NPN — designator for a bipolar transistor that requires a positive base and collector operating voltage.
pentode — a type of vacuum tube that contains five electrodes.
PNP — designator for a bipolar transistor that requires a negative base and collector operating voltage.
substrate — the crystalline foundation (usually silicon) on which an IC is formed.
tetrode — a vacuum tube that has four electrodes.
thermal resistance — the effective resistance to the passage of heat between two objects bonded together.
Z — abbreviation for impedance.

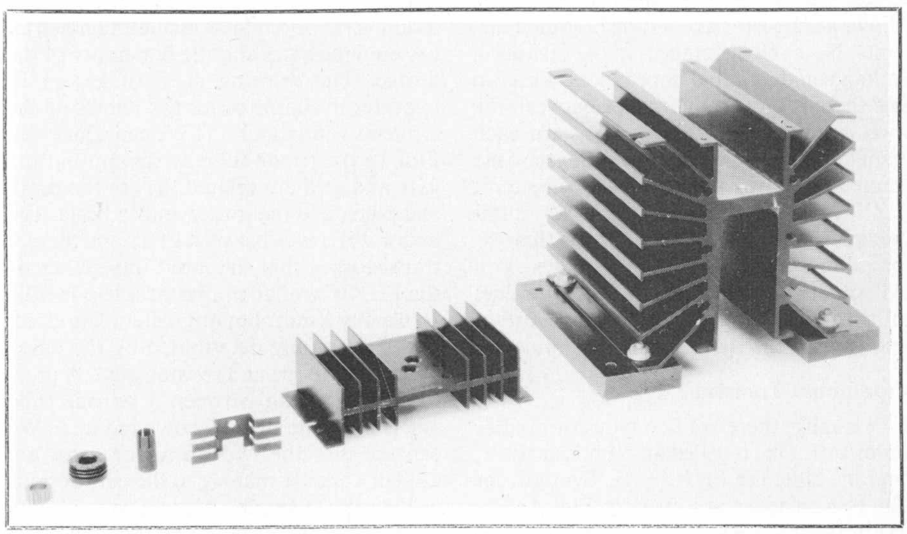

Fig. 8 — Transistor heat sinks, like transistors themselves, come in a variety of shapes and sizes.

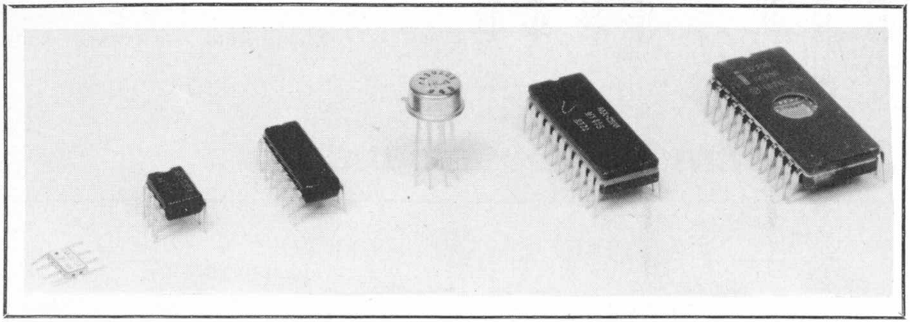

Fig. 9 — Some ICs. Each pin on the case is connected to an internal component, such as a transistor, diode, capacitor or resistor.

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manner as five discrete transistors. Yet they are all contained in a compact assembly. The illustration of Fig. 10B is the physical format of a 14-pin, dual-in-line-package (DIP) IC. The CA3045 is one of the very simple ICs. Hundreds of transistors, resistors, capacitors and diodes can be similarly housed. The really big ICs are called LSI chips (large-scale integration). They may have as many as 40 pins coming from the case. Many LSI ICs can be found in computers and similar equipment.

There are two prominent classes of ICs. Those designed expressly for use in ac and RF circuits are referred to as linear ICs, and those meant for digital and logic applications are called logic ICs. Some hams refer to them as "analog chips" and "digital chips," respectively. The loose term "chip" refers to a piece of silicon crystal on which the IC is formed. This material is known as the "substrate."

Transistor Housing

There are numerous trappings in which a transistor may dwell. You will read about and hear mention of such things as TO-5, TO-3, TO-220, TO-92, TO-18, TO-59 and many other numbers. Don't let this confuse you. It merely signifies the physical format of the case in which the device is contained. The greater the power capability of the transistor, the larger the case it is built into. Many of the cases are designed

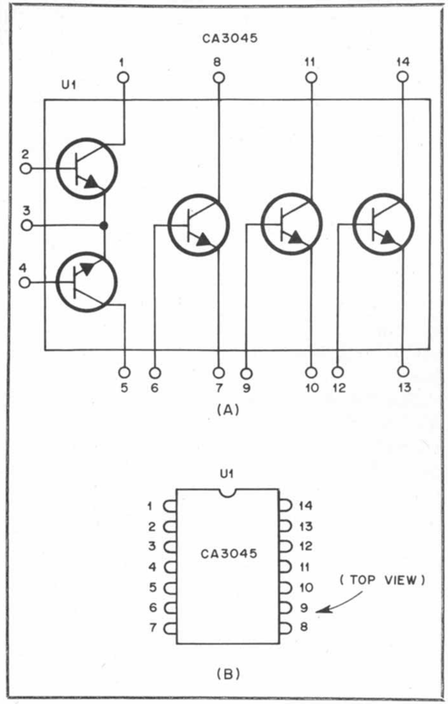

Fig. 10 — Internal circuit (A) of a simple IC. It resembles the device at B when it is enclosed in its case.

to permit the transistor body to be mated with a heat sink. Small transistors may be in tiny metal or plastic cases, since they need no heat sinks.

Final Comments

We have skimmed the surface in our discussion of transistors. But, for those of you who are new to radio, this treatment should lay the groundwork for further learning. QST