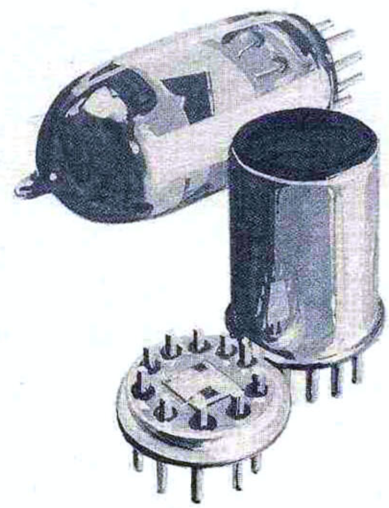
FETRON application note 1

Vacuum tubes yield sockets to hybrid JFET devices



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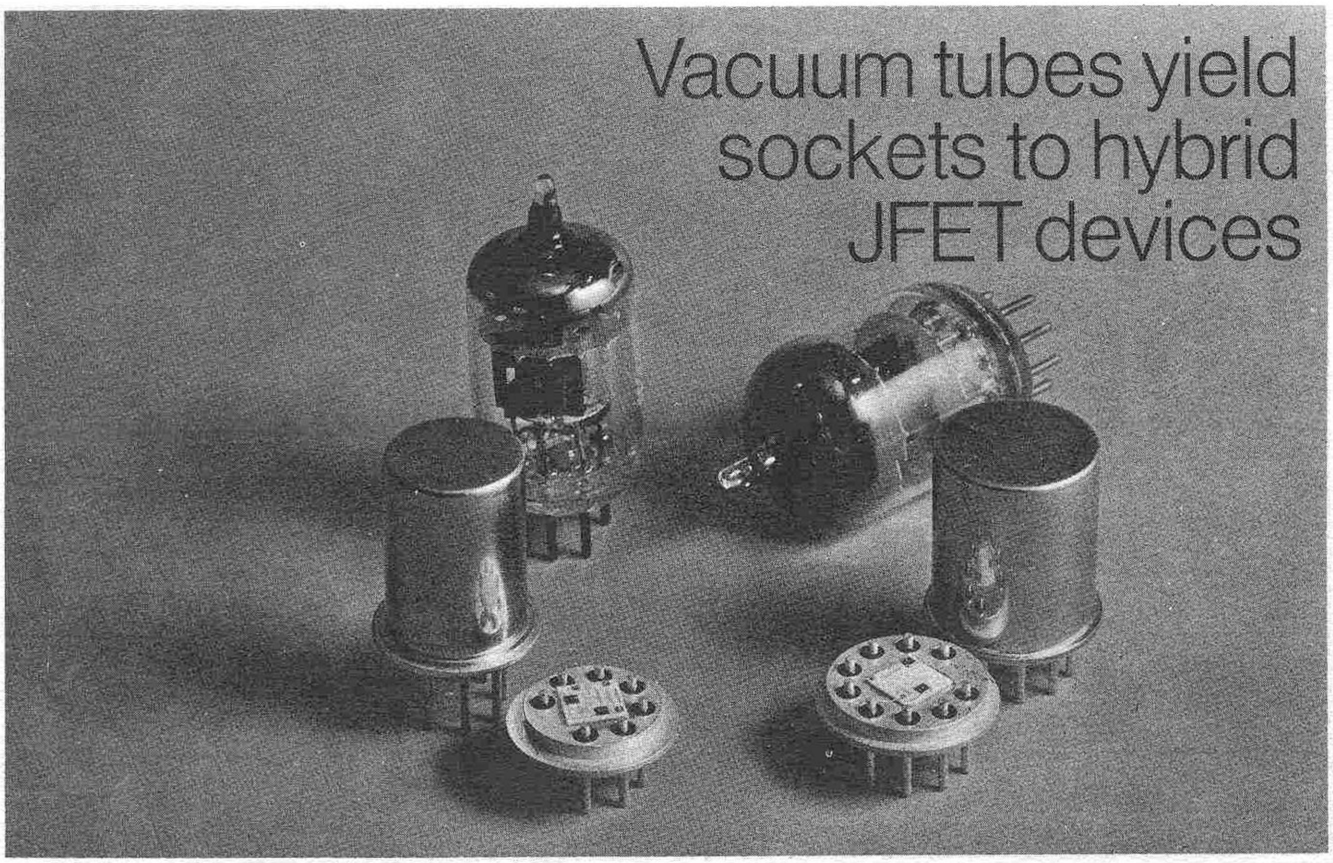
TELEDYNE SEMICONDUCTOR

Vacuum tubes yield sockets to hybrid JFET devices



Tubeless. Hybrid. JFET devices shown above replace tubes on one-for-one basis. Called Fetrons, they plug into unchanged circuit:

Thanks to high-voltage JFET technology, hybrid circuits called Fetrons exhibit virtually no aging, and also offer higher gain than do their vacuum tube counterparts

by Bruce Burman, *Teledyne Semiconductor, Mountain View, Calif.*

☐ A junction-field-effect device called a Fetron has been developed that replaces a vacuum tube in a circuit directly, without requiring major modifications in the circuit. To withstand the tube's high voltage supply (the B+ voltage), the device is built with the high-voltage JFET technology that was developed more than five years ago for military systems requiring breakdown voltages of 200 to 300 volts.

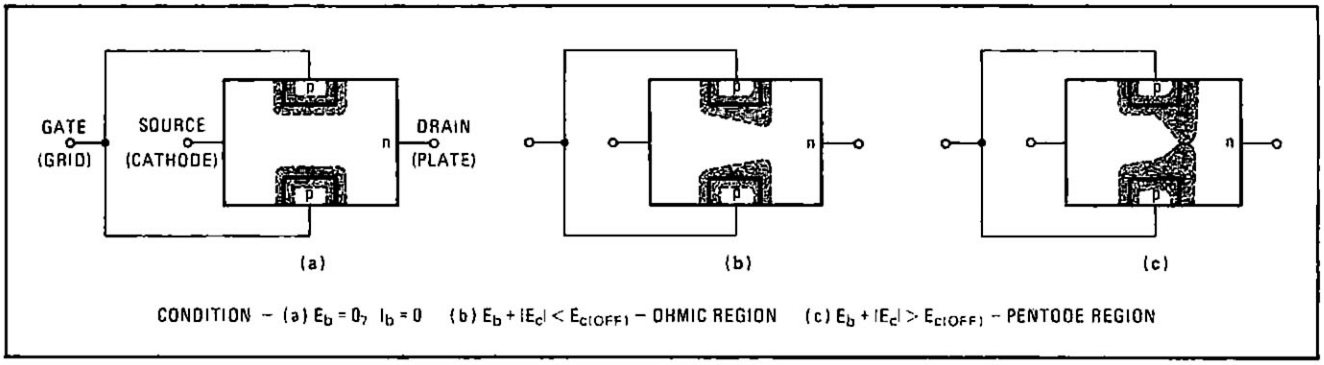
The Fetron package can be either a single JFET or two cascode-connected JFETs in a hybrid IC. Each kind is now being built as one-for-one replacements for such widely used tubes as the 6AK5 and 12AT7, and each goes into an oversized IC metal can that has the same pin configuration as the tube it replaces.

Why the Fetron?

From a design point of view, Fetrons make good sense as replacements for tubes in much communication equipment:

- Having no drift or aging, they can be locked in place for years, whereas the transconductance of many tubes degrades, often making monthly or quarterly adjustments and periodic replacements mandatory.
- Their improved performance includes higher amplification factors and lower noise than many tubes.
- Their low-power operation derives from the absence of heater or screen grids and the power supplies that run them. They also operate at 65 degrees centigrade, instead of the 100° C of tubes.
- The lifetimes of Fetrons are orders of magnitude longer than those of typical tubes—an estimated 30 million hours for Fetrons, 10,000 hours for tubes.
- They're physically tough, too—there's no glass to break in a metal can.

Fetrons make good sense in terms of sales, too. Billions of tubes that the Fetron could replace are still being used in communication and radar equipment. For instance, the utility telephone network in the U.S. alone contains about 150 million tubes within the Fetron's capabilities, creating approximately a $100 million-a-year market. And the maintenance bill of another major



1. Brothers. JFET's elements are analogous to tube elements. The JFET source is comparable to the cathode, its drain to the plate, and gates to the grid. As the grid (plate) voltage goes negative, plate (drain) current drops. The gate's p-regions, growing into the channel, causes pinchoff, which is analogous to tube's cutoff.

telephone system's 50 million 6AK5 and 12AT7 tubes alone is estimated to be $500 million a year. Less than half that amount would be required to replace all these tubes with Fetrons once and for all. Then there are probably another 70 million pentode and triode tubes in use in other equipment that is regularly maintained and regularly tuned—from mobile radios to various types of industrial equipment. The potential market grows toward a billion dollars, without even considering consumer equipment.

Viva la similarity

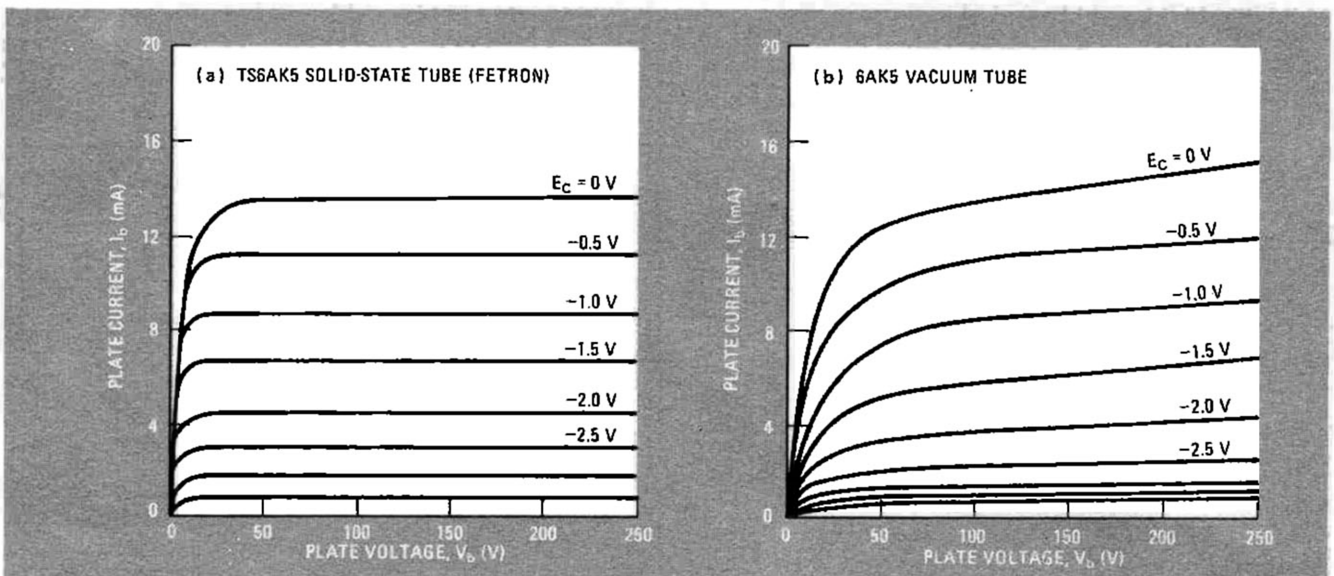
What makes the Fetron so attractive is that the JFET characteristics can be simply chosen to simulate a tube's dynamic performance. The circuit's normal trimmer components are used for high frequency tuning.

Basically, and very conveniently, a vacuum tube pentode and a JFET are brothers under the skin. Both are voltage-controlled devices and, if the differences between tube and transistor terminologies are ignored, both can be designed by using the same equations. Indeed, the operating polarities of n-channel JFETs and pentodes are identical, and they have similar output characteristics. If the JFET's drain and gate voltage are varied, the resultant family of curves will look just like the old familiar pentode plate-voltage-versus-plate-current curves at different values of control-grid voltage.

Even the current-control mechanisms of the two devices are analogous. In a tube, the grid voltage controls the number of electrons emitted from the cathode that reach the plate. In the JFET, the gate potential modulates conduction in a channel that exists between source and drain, as is shown in Fig. 1. The top and bottom gates of the JFET are comparable to the grid of the tube, its source is comparable to the tube's cathode, and its drain is comparable to the tube's plate. As the gate (grid) voltage goes negative, drain (plate) current drops because the gate (grid) p-regions grow into the n-channel region until they eventually pinch off the channel. This pinchoff is analogous to tube cutoff.

Again, the output characteristics of JFET and pentode are very similar, as can be seen in Fig. 2. But since the JFET has no elements comparable to the pentode's screen grid and suppressor grid, it is closer to the simpler triode in construction.

Since a JFET doesn't need a heater, warmup is instantaneous. Also, because of its lower inter-electrode capacitance and low channel resistivity, it can operate at



2. Equal but better. The JFET's output characteristics, although similar to those of a pentode, follow the square law more closely, and give a much cleaner on-off action, as is evident from the sharp cutoff.

much higher maximum signal frequencies than the tube, or at low frequencies with less distortion. The sharp cutoff evident in Fig. 2 gives a much cleaner on-off action, particularly in switching applications.

In short, the Fetron can be considered a better pentode than the vacuum tube pentode, because its drain output curves come much closer to the theoretical ideal.

And two JFETs are better than one

It requires two JFETs in a hybrid package to simulate the performance of one pentode. The JFET must withstand high plate voltage (see Fig. 2) to replace the tube directly. But there is no single high-voltage JFET with enough transconductance g_m to match that of the pentode tube. For example, to simulate the 6AK5 a transconductance of 3,500 to 7,500 micromhos at an operating current of 4 to 10 milliamperes is required.

Moderate g_m at high voltage is expensive to get with JFETs, since they must be physically large and of high-resistance material to yield high breakdown voltages. Then, too, the major barrier to high-frequency performance in semiconductors is the Miller effect—the gate-to-source capacitance. In an amplifier, Miller $C_{gs} = C_{gd}(1 + A)$. This is minimized in pentodes because of the extremely low plate-grid capacitance that exists because the control grid is shielded by the highly positive voltage screen grid.

To get a high-transconductance, high-frequency (low-Miller-effect capacitance) JFET device, it's necessary to bootstrap or cascode two of them (Fig. 3). In such a design, the input transistor is a small-signal JFET, like the 2N3823, chosen for its low capacitance and high g_m; the output device is a high-voltage JFET, such as a 2N4882. The pair is assembled as chips and packaged in cans.

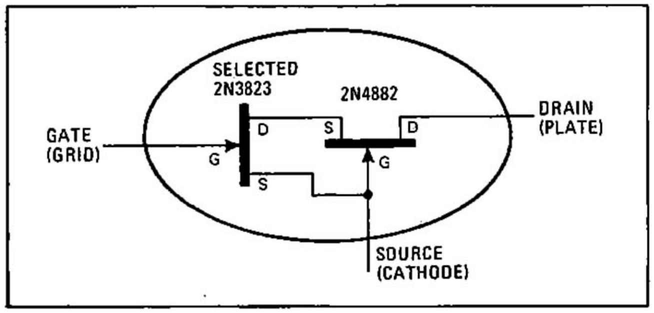
Smooth operator

The operation of the hybrid assembly is simple. The output JFET reduces the plate voltage to a safe level for the input JFET. The former JFET's drain is always connected to the high voltage—the equivalent plate connection in a Fetron—and its gate source connected to the input JFET's gate, which is tied to a low voltage or ground. With this arrangement the input capacitance of the device is just the fairly low capacitance of the input JFET, rather than the much higher capacitance associated with the large high-voltage chip.

With this arrangement assuring equal gains, the Miller-effect capacitance is equal to or lower than that of a tube pentode. The Fetron has only the 0.02-picofarad drain-to-source capacitance of the high-voltage JFET in series with the drain-to-gate capacitance of the unity-voltage-gain low-voltage input JFET. The result: less than 0.02-pF Miller-effect capacitance.

Also, the cascode arrangement boosts the effective output impedance of the Fetron about an order of magnitude above that of a pentode tube. This not only greatly improves the pentode curves, but makes the circuit gain less dependent on Fetron characteristics.

The device's input looks like a reverse-biased semiconductor junction, which provides a very high resistance that's desirable in most applications. Significantly, the effective input impedance is an order of magnitude above a vacuum tube's. This enables a circuit to operate from a high-resistance source without being loaded down.



3. Gaining with cascodes. Most Fetrons are built with two JFETs in a bootstrap or cascode connection to achieve high-gain operation. Miller-effect capacitance is minimized by using a low-capacitance, high-gain input transistor, such as the 2N3823, connected to a high-voltage 2N4882 output device.

Amplification equations

The tube equations apply when the Fetron is plugged into a typical tube biasing network, like the one shown in Fig. 4. (Heater and extra grid connections are left open on the Fetron.)

At any control grid voltage, the plate current will be

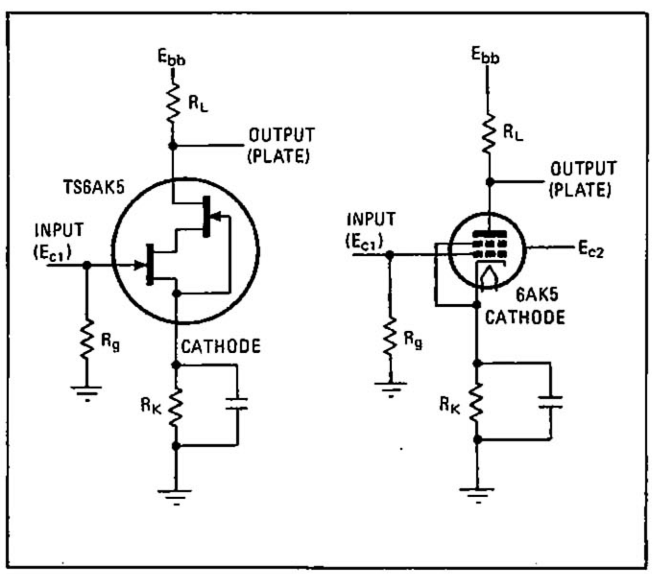
$$I_b = I_{b0}\left[1 - \frac{E_c}{E_{c(off)}}\right]^2$$

where

I_{b0} = plate current at $E_c = 0$ V
I_b = plate current at E_c voltage
E_c = control grid voltage
$E_{c(off)}$ = E_c for 1 μA of I_b

The change of plate current with grid voltage at a constant plate current gives the transconductance. By differentiating the equation for plate current with respect to control voltage:

$$g_m = \frac{\Delta I_b}{\Delta E_c}\bigg|_{E_b = K} = g_{m0}\left[1 - \frac{E_c}{E_{c(off)}}\right]$$



4. Same old circuit. A Fetron (TS6AK5, for example) can directly replace a tube (6AK5, for example) in an unaltered circuit. The heater and extra grid connections are left open on the Fetron.

where g_m = transconductance at operating E_c, and g_{m0} = transconductance at $E_c = 0$ V.

These characteristics give the solid-state device a true square-law characteristic and, because of this, very low harmonic distortion. Higher-than-second-order harmonics are virtually nonexistent.

In contrast, the vacuum tubes have a "three-halves-power" characteristic, and can generate substantially higher-order harmonics and intermodulation products. Interestingly enough, bipolar transistors have even more harmonics than the tube.

The Fetron's very high output impedance, analogous to a vacuum tube's plate resistance r_p, maximizes the voltage gain for a given load R_L. The voltage gain of an amplifier (see Fig. 4) can be expressed as:

$$A_v = \frac{\mu R_L}{r_p + R_L} = \frac{g_m r_p R_L}{r_p + R_L}$$

where $\mu = g_m r_p$ (μ is the tube amplification factor). But since r_p is much higher than R_L, the equation is simply

$$A_v \approx g_m R_L$$

At lower frequencies—less than a few megahertz—the simplified equation is more than 99% accurate for a Fetron.

Fitting the FETs

Versions of the device can be made for both amplifier and oscillator service. (The package for oscillator applications may include a small resistor or RC network for feedback and neutralization.) In practice, many FET characteristics are available, and single or JFET cascode pairs can be made to match the tube's current-voltage curves as shown in Fig. 5.

Although several approaches are available, about 80% of the general-purpose applications considered to date are satisfied by the simple FET #1 approach. This type of JFET is chosen if the application is unknown or if the device must operate around some nominal operating point A (in which case, the JFET curve closely approximates the tube curve over most of the control voltage range). In large-volume applications, where the exact operating point is known, FET #1 can be selected at the factory to coincide exactly with a point anywhere near A on the tube's curve.

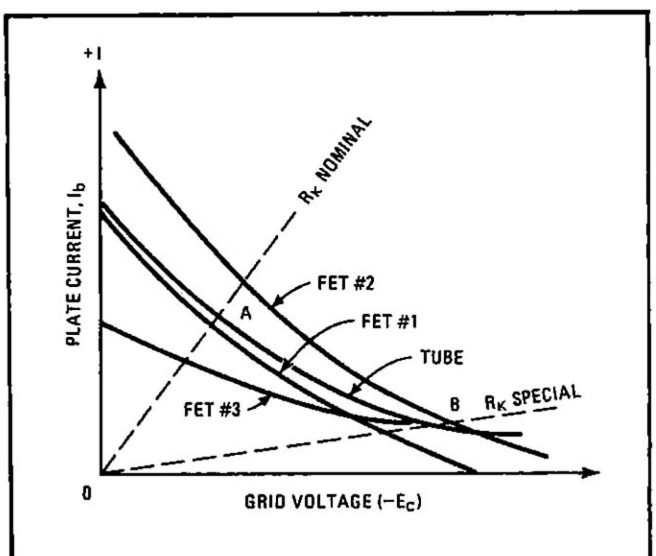
An operating point such as B beyond the normal FET cutoff can be matched by FET #2 or FET #3. FET #2 would provide a higher current for the same control voltage, so it passes through B before cutoff. FET #3 would have to be specially tailored for low, flat current characteristics, or for a narrow range of operation beyond the normal FET's cutoff. It would be a lower-transconductance, higher-cutoff JFET.

In simulating a tube, the dynamic characteristics as well as the operating point must be considered. Depending on the particular application, special attention must be given to transconductance, phase shift, phase margin, operating range, and neutralization requirements.

For amplifier operation, neutralization and operating range are the principle concerns. In most tube circuits, neutralization is used to nullify the effects of feedback capacitance during higher-frequency operation.

When used as an oscillator, the Fetron must provide for positive feedback between the output and input. An internal RC network within the device headers (Fig. 6) acts as a screen grid which is connected to the plate to assure direct replacement.

In Fetrons designed for amplifier operations, how-



5. Choosing a Fetron. Several Fetron types are available to match a tube's application. If the tube operates around a fixed point, such as A, a JFET, such as FET #1, is chosen. To match a tube that operates beyond a FET's cutoff, FET #2 or FET #3 is chosen: FET #2 for high current before cutoff, FET #3 for low, flat current.

Building the high-voltage JFETs

JFETs with breakdown voltages over 300 volts can be made by standard planar processing. But to achieve this high voltage, it is essential to attain the maximum breakdown field for silicon, about 30 volts per micron. Also critical is the epitaxial layer thickness and resistivity.

The channel is formed by the n-type epitaxial layer, which has a resistivity exceeding 5 ohm-cm. Since the channel region where pinchoff occurs is directly under the gate, doping levels in that region must be precisely controlled to limit spreading of the depletion region into the channel. The channel height depends on what final pinchoff voltage is desired.

The voltage from gate to source, V_{GS}, may be as large as −50 V. This V_{DG} value is required to enable the drain to withstand a voltage of up to 400 V. However, this high drain-to-gate voltage can only be achieved if the spacing of the gate, source and drain is held to very close tolerances.

Another difficulty is the need to shape the diffusions so as to minimize any surface field concentrations at the chip. Breakdown should occur in the bulk silicon, not at the surface. The substrate resistivity must be fairly high for good control of depletion spreading, as well. Otherwise, the channel might get pinched off with a very small charge in V_{GS}. At high operating voltages, V_{DS} can vary widely without any change in signal voltage, due to normal supply tolerances.

ever, the RC network is omitted. If needed, a capacitor is added to provide the necessary frequency response. Characteristics of a properly trimmed TS6AK5 Fetron and the tube it replaces are listed in Table 1. Heater voltage is not specified, because those pins are not connected in the Fetron.

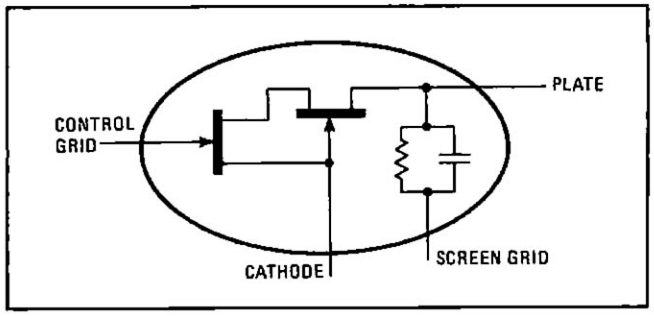
Note the great increases in amplification factor and plate resistance when Fetrons are used. The effect of these differences on the circuit is greatly improved sensitivity—about 4 to 5 decibels—resulting from the higher mμ, lower noise, and low distortion.

Triode simulation

The Fetron will also perform well if configured as a triode, for the three electrodes of a single JFET directly simulate the latter's grid, cathode, and anode. But the JFET's much higher output impedance (hence higher gain) could cause an amplifier circuit to oscillate. Usually, however, the load resistance of a circuit is much smaller than r_p of the Fetron, and there is no problem.

The first Fetron triodes made were equivalents of the 12AT7 and Western Electric's 407 version, which has a 20-volt heater and slightly different pin-out. These Fetrons operate as twin triodes. Figure 7 and Table 2 show their characteristics compared to a single triode. Although the Fetron's transconductance is significantly lower (each of the triodes is a single high-voltage FET), its transconductance is the same as that of the twin triode being replaced. And the design equations given for pentode amplifiers also apply to the triode version.

True, the Fetron output characteristics approximates a pentode's, not a triode's. But it can be used to replace a twin triode—the more common triode application because two of the small inexpensive devices go easily into one glass tube envelope. It's generally not as good an electronic device as a pentode, though many circuit designers use them in cascode to get lower noise than obtainable with a pentode. Now, the Fetron triode upgrades typical circuit performance because of its excellent square-law characteristics throughout the con-



6. Farflung net. This oscillator network is used when Fetrons replace a pentode oscillator. The resistor and/or resistor-capacitor combination simulates screen-grid action. The network is included within the header, permitting 1:1 replacement.

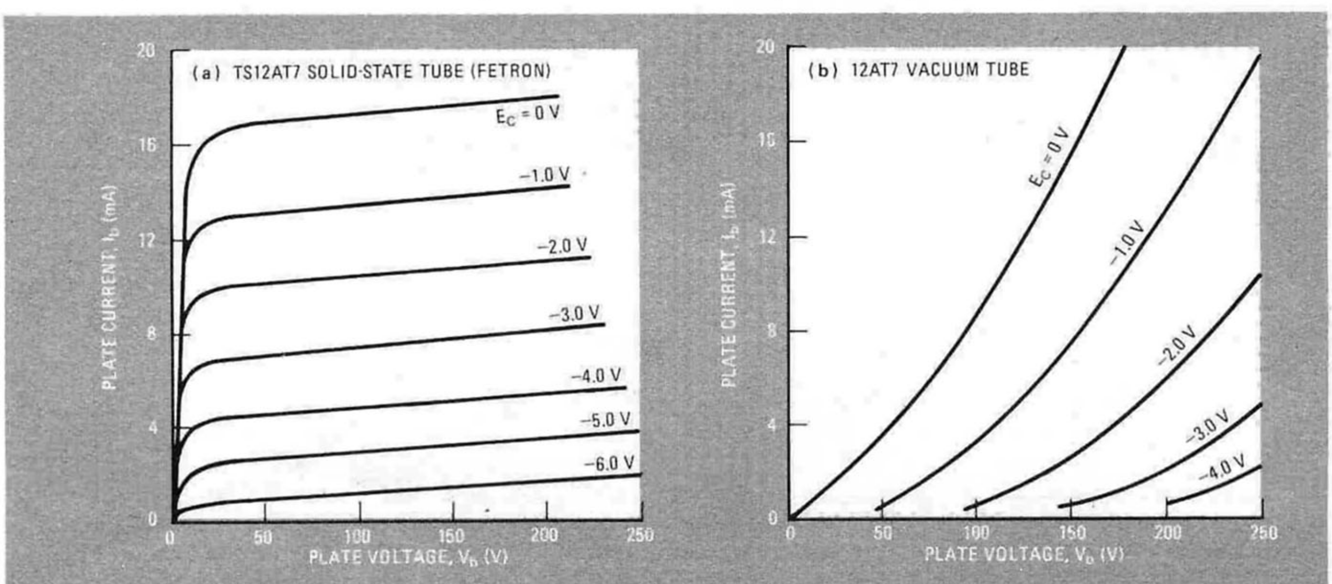
trol voltage range. Power supply regulation can also be relaxed—triodes normally require well-regulated power supplies, because triode operating current depends on operating plate voltage, whereas the Fetron's does not (see Fig. 7a).

It's dependable

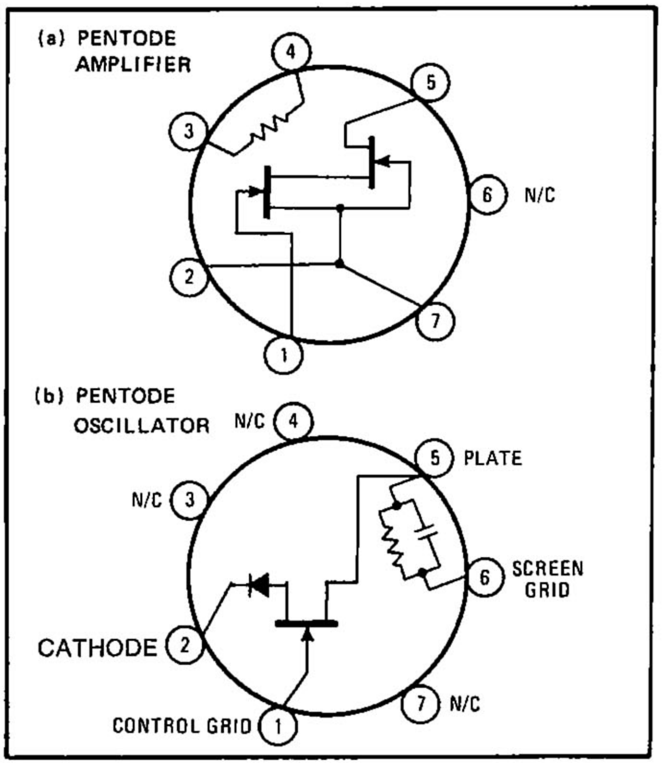
Besides replacing pentode and triode tubes, the Fetron gets higher marks in reliability than either. A high-reliability tube has a life expectance of 5 × 10^4 hours (63% failure point). Preliminary data from burn-in and accelerated life tests on 1,000 Fetrons indicates a life expectancy of 3 × 10^6 hours, or 300 years. Of the 1,000 in the sample, 787 were screened by the type of power burn-in tests generally given high-reliability tubes, and were operated for 20 hours at twice normal dissipation (1,760 milliwatts). The failure rate, or dropout, was only 3.5%, a small fraction of the tube screening dropout rate.

In addition, some 2,500 Fetrons have been shipped to telephone companies for evaluation and trial applications. Many have been in use for as long as eight months, and to date, failures or degradations reported have been statistically unimportant.

Finally, another group was put in a 170° C oven and



7. Just like a triode. Although the characteristics of a Fetron are different from those of a typical triode, they are similar to those of a triode pair and can be used wherever twin triodes are used. In fact, Fetrons were first designed to replace Western Electric's 407 twin triode.



8. Different configurations. The internal configurations depend on whether the Fetron is destined for service as a pentode amplifier (a) or oscillator (b). For oscillator use, an internal RC network provides the required feedback when the Fetron is plugged into sockets.

powered at 1.2 W, a test that keeps the junction temperature at 215°C for 450 hours. One failed and one degraded (leaked), indicating device survival at 25°C for 10^{11} hours.

From these destruction tests, it was found that although normal operating current is 7 mA, it generally takes a steady current above 30 mA, at 350 to 400 V, to induce failure. Surges up to 6 A can be withstood. Internal connections melt at 9 to 10 A, but fusing links can be built into the device so that if it does fail catastrophically, the circuit is protected.

Shock and other physical tests, comparable to normal IC environmental tests, have also been made. The Fetron, because of its hard metal case, is virtually unbreakable. The case is a solid, deep-drawn steel cap welded to a large header. Before welding, the case is evacuated and backfilled with dry nitrogen.

Almost every general-purpose pentode and triode tube type, and various special-purpose ones, may be simulated with Fetrons, by selecting the appropriate FET pair and varying the internal connections and networks. Figure 8 shows two versions.

Variations include:

- The standard amplifier (6AK5 with 6.3-V heater). In amplifier circuits, a cathode resistor is commonly used to adjust the operating point. At frequencies up to 30 MHz, amplifiers don't need a neutralization network. At higher frequencies, an adjustable capacitor is usually available in the circuit. If not, a 2-pF capacitor may be added internally or externally.
- The oscillator, with the screen grid simulated and feedback to input provided by the connection to pin 6.
- The low-gain single-FET pentode.
- The twin-triode amplifier, for low-noise cascoded triode circuits.
- The twin triode, with an RC network inserted for voltage regulator circuits.

The Fetron pentodes have been operated to 500 MHz, exhibit lower i-f noise than the original tubes, and do not suffer from microphonics. Elimination of heater power, and usually all screen grid power as well, cuts supply drain and reduces operating temperature from well over 100°C for the tubes to about 650°C for the Fetron. After some eight months of trial operation, there has been no noticeable degradation in its transconductance.

Fetron triodes will generally be used in low-frequency applications. In most of these, their sharp cutoff improves on the original circuit performance. Naturally, such triodes have the same general noise and power-saving advantages as the Fetron pentodes.

Pacific Telephone Co. recently has converted to Fetrons on a trial basis in a number of repeater lines between San Francisco and Martinez, Calif. In addition, some of the channel equipment for multiplexing and

TABLE 1: TYPICAL PENTODE DEVICE CHARACTERISTICS — R_K = 200 Ω, E_b = 120 V

PARAMETER	UNITS	6AK5 VACUUM	TS6AK5 SOLID-STATE
Plate voltage breakdown	V	350	350
Plate resistance	MΩ	0.5	5.0
Transconductance	μmhos	5,000	4,500
Plate current (R_K = 200 Ω)	mA	7.5	7.0
Grid voltage for I_b = 10 μA	V	−8.5	−5.0
Amplification factor	—	2,500	22,500
Input capacitance	pF	4.0	6.5
Output capacitance	pF	0.02	0.02
Useful frequency limit	MHz	400	600

TABLE 2: TYPICAL TRIODE DEVICE CHARACTERISTICS (EACH SIDE) – R_K = 240 Ω, E_b = 130 V			
PARAMETER	UNITS	12AT7 VACUUM	TS12AT7 SOLID-STATE
Plate voltage breakdown	V	400+	350
Plate resistance	kΩ	15	250
Transconductance	µmhos	4,000	3,000
Plate current (R_K = 240 Ω)	mA	5.0	9.0
Grid voltage for I_b = 10 µA	V	–7.0	–7.0
Amplification factor	—	60	750
Input capacitance	pF	2.2	25
Output capacitance	pF	1.5	3.5

demultiplexing in a carrier office is now equipped with Fetrons.

What next?

There are numerous tube types that can be made with the basic Fetron designs. Types such as the 6JC6 and 6EW6, which have transconductances in the vicinity of 25,000 micromhos and plate currents in the 40-mA range and which have already been made, can be combined with the 6AK5, 12AT7, and their derivatives so as to make Fetron versions of the great majority of popular tube types. Next to be tackled will be the power pentode devices, such as 6AQ5, 6V6, and remote cutoff pentodes, such as 6BA6. Indeed, with volume production and some packaging changes, the Fetron could go on to become a low-cost replacement for most tubes. □

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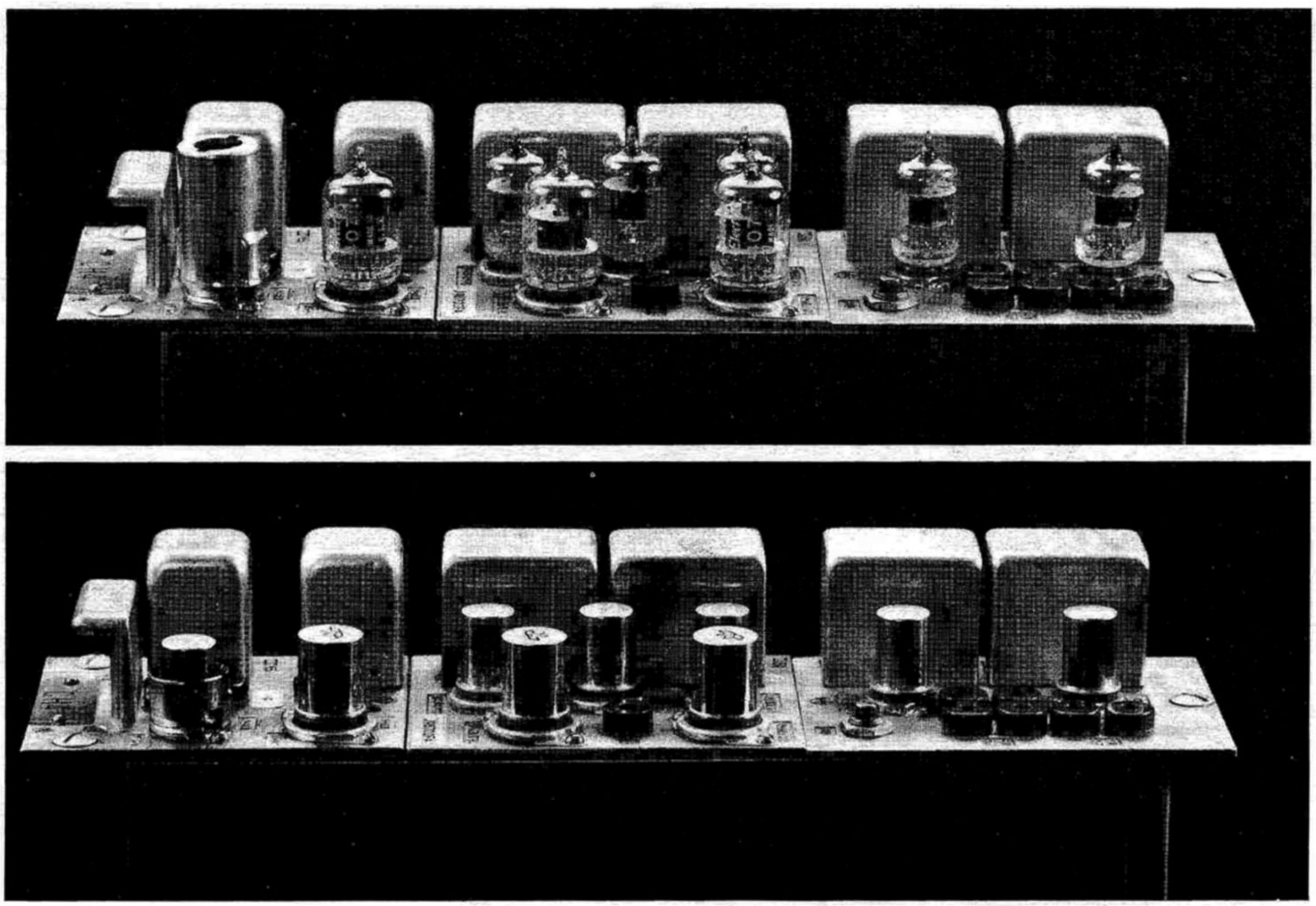

9. Finding their place. In the above amplifier, all the 6AK5 and 12AT7 tubes have been replaced with equivalent Fetrons.