60¢ ■ DEC. 1972

Radio-Electronics

FOR MEN WITH IDEAS IN ELECTRONICS

BUILD A "ZERO DISTORTION" STEREO PREAMP

ELECTRONIC CALCULATORS
From Fingers to LED's

OPERATIONAL AMPLIFIERS
10 Audio Circuits

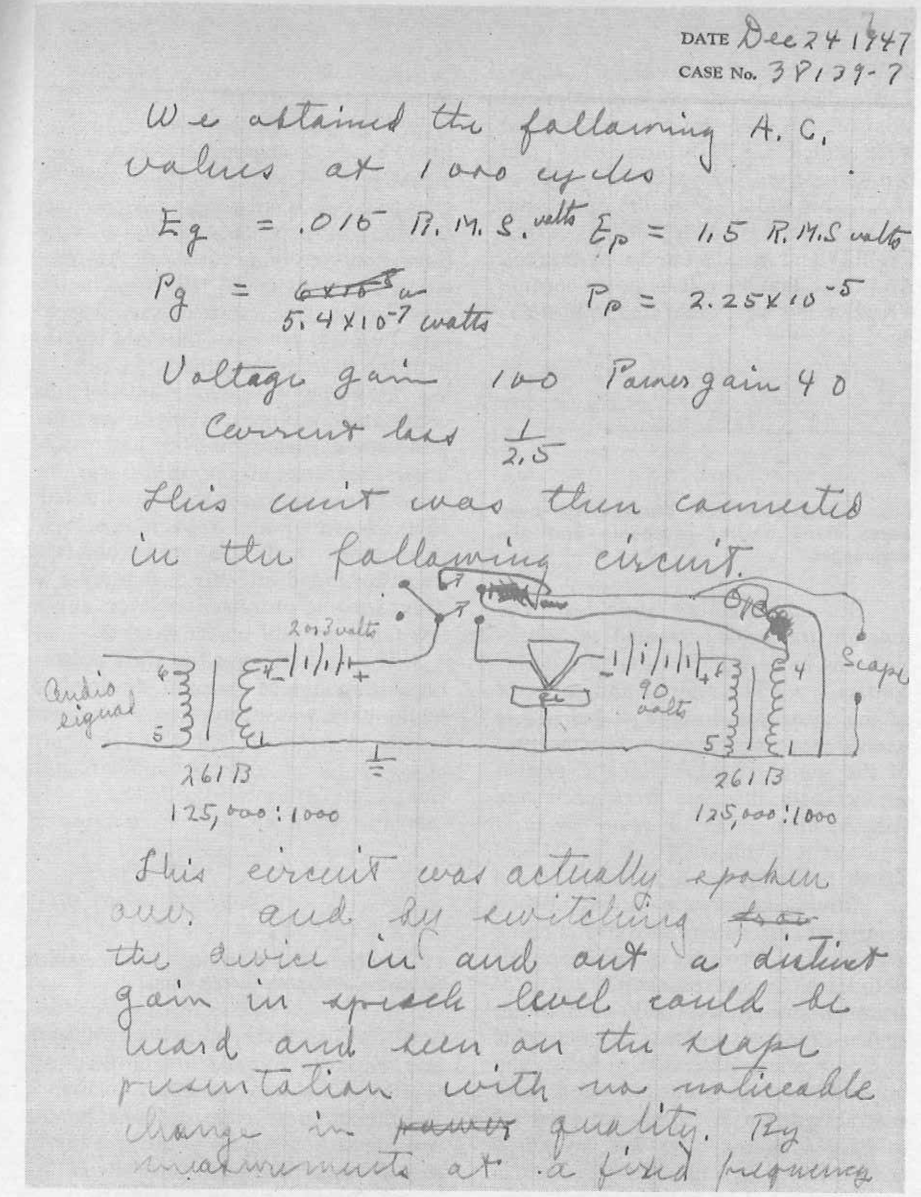
DIGITAL IC BREADBOARD
Build It Yourself

THE TRANSISTOR
It's 25 Years Old

PLUS

Jack Darr's Service Clinic
Using A Color-Bar Generator
Step-By-Step TV Troubleshooting
Lou Garner's State of Solid-State

A GERNSBACK PUBLICATION


DATE Dec 24 1947
CASE No. 38139-7

We obtained the following A.C. values at 1000 cycles

Eg = .015 R.M.S. volts Ep = 1.5 R.M.S volts

Pg = 5.4x10-7 watts Pp = 2.25x10-5

Voltage gain 100 Power gain 40

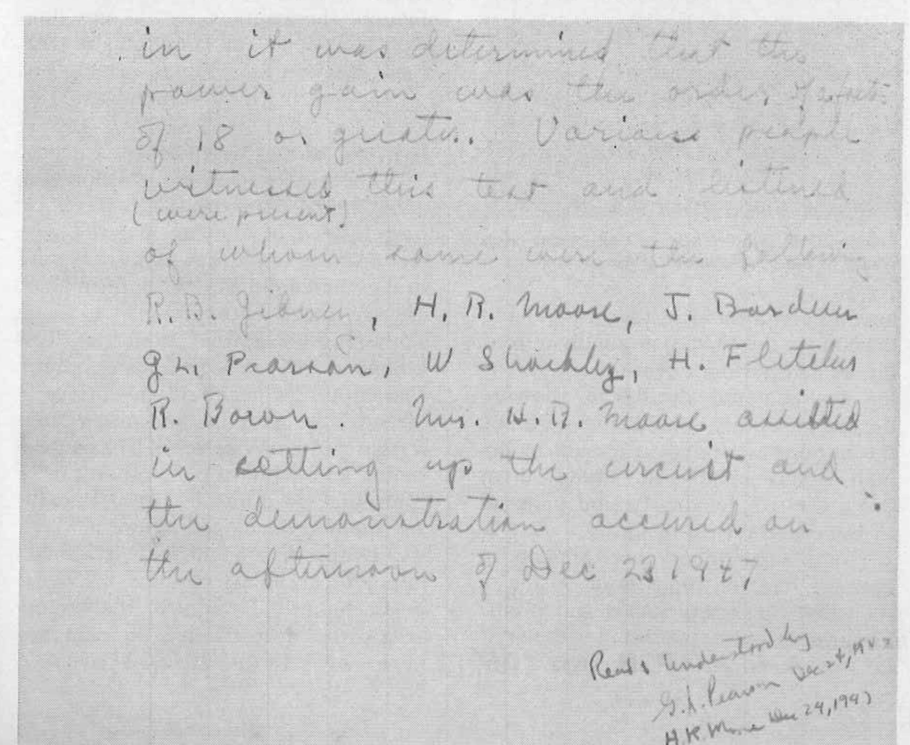
Current loss 1/2.5

This unit was then connected in the following circuit.

Audio signal — Scope — 261B 125,000:1000 — 261B 125,000:1000 — 90 volts

This circuit was actually spoken over and by switching the device in and out a distinct gain in speech level could be heard and seen on the scope presentation with no noticeable change in quality. By measurements at a fixed frequency

THE TRANSISTOR—25 YEARS OLD


in it was determined that the power gain was the order of a factor of 18 or greater. Various people witnessed this test and listened (were present) of whom some were the following

R. B. Gibney, H. R. Moore, J. Bardeen, G. L. Pearson, W. Shockley, H. Fletcher, R. Bown. Mr. H. R. Moore assisted in setting up the circuit and the demonstration occurred on the afternoon of Dec 23 1947

Read & understood by G. L. Pearson Dec 24, 1947
H R Moore Dec 24, 1947

On the left are the original lab notebook pages outlining the discovery of the transistor. From such humble beginnings we now have devices that threaten the continued need for vacuum tubes. Here's a short 25-year history of how it happened

by FRED SHUNAMAN

THE TRANSISTOR DID NOT QUITE SPRING on a startled world like a bolt from the blue. It was discovered (on December 23, 1947) by a team of Bell Laboratories scientists—Shockley, Bardeen and Brattain—who were engaged in a project to find just some such thing. Shockley had already worked out in theory and sketched a semiconductor device that might amplify, and it was while testing and modifying that device (which surfaced some years afterward as a field-effect transistor) that the point-contact transistor (Fig. 1) was born.

But "coming events cast their shadows before," and there had been hints of amplification in semiconductor devices in the past. Earliest was possibly the "oscillating crystal" of zincite announced in 1924 by Lossev. It was described in U.S. magazines*, but apparently nobody but Lossev could make it work. Since the effect of impurities in a crystal structure was then unknown, nobody realized that Lossev succeeded because he happened to have a particular sample of zincite, and the "oscillating crystal" was passed over and forgotten.

In 1930, Dr. Julius Lilienfeld actually patented a solid-state amplifier (U.S. Patent 1,745,175) based on a semiconductor. Though probably his own experimental amplifier worked, Dr. Lilienfeld's invention was never "reduced to practice," probably also due to the general ignorance of the action of semiconductors and impurities.

(turn page)

*Radio News, September, 1924.

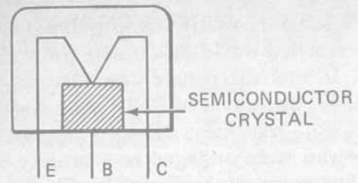


FIG. 1—A POINT CONTACT TRANSISTOR.

Only about a year before the actual invention of the transistor, Hugo Gernsback described in one of his April Fool stories, a remarkable "crystal amplifier" which he called the Crystron. As Fig. 2 shows, this was a forecast of the FET (field-effect transistor).

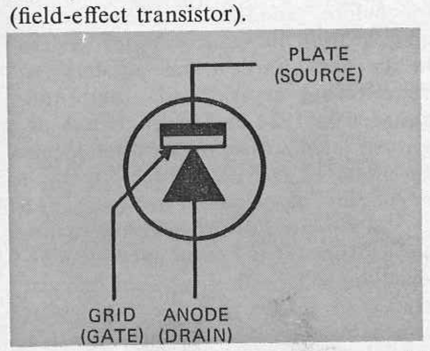


FIG. 2—THE CRYSTRON, the imaginary crystal amplifier dreamed up by Hugo Gernsback.

In an editorial in the May 1928 issue of **Radio-News** Hugo Gernsback had speculated, "Then, too, there is always the chance that a totally new discovery will come along that, in itself, will obliterate the vacuum tube in one way or another; and it is even within the bounds of possibility that there will be invented some new device that will require so little power that a small dry-cell battery will operate it for a considerable length of time. This, in turn, would again make the radio set independent of the lighting current and make it more transportable. But all these things are yet in the future." (Perhaps he knew!—*Editor*)

The first transistors

Less than a year after the transistor was invented, Western Electric put a few on the market for experimental purposes. These first crude devices (sold at $15 each) fell far short of what scientists predicted for the transistor. They were short-lived for the most part, though it had been suggested that their life might be indefinitely long. They were noisy. Their characteristics often varied with time. Gain was far below what was said to be theoretically possible. The frequency range was limited, and for a time it seemed that the transistor would be entirely an audio device.

And no two transistors were alike! A tube manufacturer could tool up to make a run of, say, 6L6's, and be reasonably sure of the output. The early way to make transistors was to make a run, test the units, and decide what to call them as a result of the tests. Raytheon, for example, put out a CK-series. Those that most closely approximated what the design engineers had in mind were called CK721's and were sold commercially. Those that fell short or varied too widely from the specs, but seemed still usable, were called CK722's and sold to the hobby market. And those that were least noisy became CK227's and were dedicated to hi-fi audio use.

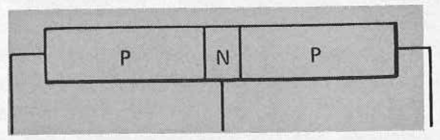


FIG. 3—THE JUNCTION TRANSISTOR overcame many earlier problems and disadvantages.

But improvement came fast. The junction transistor (invented by Shockley) was more reliable than the point-contact type. The emitter and collector of this transistor, instead of being fine wires contacting the base, became part of the same crystal, making a perfect contact with the base from each side (Fig. 3).

Zone refining

Shortly afterward—about 1954—control of impurities in the crystal made a great leap forward. W. G. Pfann, of Bell Labs, discovered that if a rod of crystal material (invariably germanium at that time) was melted, and then part of it solidified, it tended to leave any impurities in the melted portion, concentrating them in the last bit of metal to harden. Using a process he called zone refining, he melted a portion of a germanium rod by putting an inductive

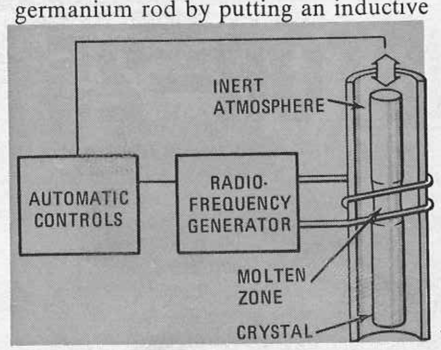


FIG.4—ZONE REFINING, an important step ahead in the development of the transistor.

heating coil around it, then by moving the coil (or the crystal) gradually moved the melted portion down the rod, melting new material ahead and allowing the rod to solidify behind (Fig. 4). Since the impurities tended to remain in the melt, it was possible to "sweep" them down the rod, leaving behind material of hitherto-unheard-of purity.

The same theory was applied in making junction transistors. Using a melt that contained both n and p-type impurities, it was found that if the crystal was grown slowly, there was a tendency to take up the n-type impurities in the growing crystal, making it an n-type. Now, if the process were speeded up, the p-type impurities that had collected just below the crystal would be swept up into it, creating a p-type zone. By alternately speeding up and slowing down the growth, sections of the right width for bases could be grown in the crystal. All that was necessary was to saw it up into pieces of the right length, with the base in the center.

This type of junction transistor was considered an improvement on the point-contact transistor, but had weaknesses. Control of impurities was inexact. Frequncy range was limited. Methods were found to overcome these weaknesses, and the grown-junction transistor faded into the background. It never became obsolete, however, and a few types are still on the market.

The next step was the alloy transistor. A thin slab of material, destined to be the base, was etched from both sides

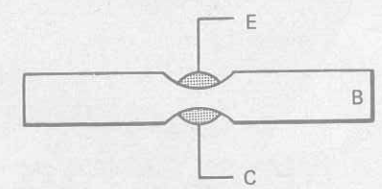


FIG. 5—THE ALLOY TRANSISTOR increased reliability, raised frequency limits.

until it became very thin. The collector and emitter "buttons" were then alloyed into the base, as shown in Fig. 5. For the first time, transistors that would operate at frequencies in the megahertz region were produced. In Philco's famous "surface-barrier" transistors, a thin stream of etching fluid was directed on opposite sides of the strip, making a sort of pit on each side. When the partition between the two pits became thin enough, the composition of the fluid was changed to one containing a saturated solution of indium, which was "plated" on the base material.

A great step forward

The next step in the development of better and faster transistors was *diffusion*. Instead of alloying material with the desired impurities onto the substrate, the impurities were introduced directly into it by exposing it to a gas containing the desired impurities. This is done in an oven at high temperatures. The impurities penetrate the surface of the substrate material, and may change it from p to n or vice versa. The concentration and depth of penetration can be controlled by diffusion better than by any method developed before it.

Diffusion brought with it another important technical advance, the *masking* technique. To control the boundaries of the diffused area, an insulating layer of silicon dioxide (quartz, roughly) is laid down over the surface of the crystal. This is covered with a *photoresist*, a layer that resists etching acids if exposed to light. A *mask* with the desired pattern is placed over the surface and light projected onto it, to activate the photoresist. The unexposed areas are then etched away, making "windows" to the surface below, into which impurities can be diffused over sharply bounded areas.

Masking, incidentally, not only led to more varieties of transistors, but to other devices, the ultimate of which is our present large-scale integrated circuitry. A large number of maskings, etchings and diffusions are used to make an integrated circuit.

Diffusion also led to *drift* transistor, in which the base material is heavily doped near the emitter, and gradually more lightly doped as the collector is approached. The resultant electric field across the base speeds up carrier flow, and the possibility of doping the area near the emitter heavily and that near collector more lightly reduces capacitive charging time, again increasing the upper frequency limit.

The mesa transistor

The base area may now be diffused into the collector material. Early transistors of this type had a diffused gold stripe contacting the base as a non-rectifying (ohmic) contact. A diffused aluminum stripe, forming a rectifying contact, became the emitter. The area around the base was etched away to reduce collector-base capacitance. (Fig. 6), leaving the region sitting on top of

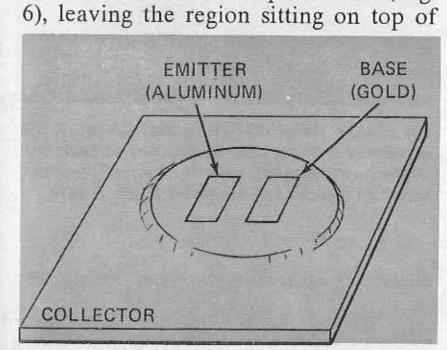


FIG. 6—THE MESA, a diffused transistor.

the collector in a way that caused it to be called a *mesa* transistor.

The next step was to diffuse the emitter as well as the base into the crystal. Once the base was laid down, the emitter was diffused into it. A standard formation was a ring-shaped base around a smaller center emitter, with the collector as the substrate. Note in Fig. 7 that the base not only surrounds the emitter, but extends under it, forming a base region between the emitter above and the collector below. This *planar* transistor, which appeared in the early '60's, reached an upper frequency limit above 800 MHz by 1964.

The *epitaxial* transistor (Greek: epi

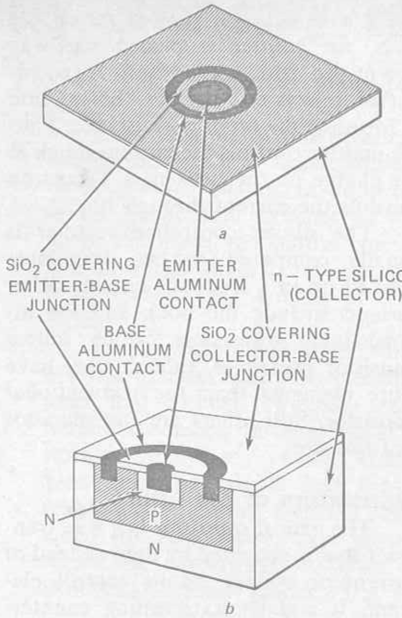


FIG. 7—THE PLANAR TRANSISTOR was an early use of silicon as a transistor material.

= upon; taxis = arrangement, structure) was next. Like the ordinary diffused type, this transistor is made in a heated chamber, Base atoms are deposited on the collector material atom by atom, in such a way that the added material continues the original crystal structure. This reduces the resistance. In some transistors, a thin epitaxial collector layer is grown on top of the original collector, the epitaxial layer being more lightly doped than the rest of the collector material. The base is then grown on the epitaxial collector layer. Transistors made this way have a higher breakdown voltage.

New approaches

Note that about this time we find the base taking shapes other than that of the "dot" or "button" used to describe emitter and collector and base areas up to that time. The reason for irregular shapes is that it is desirable to have the boundary between the two regions (the junction) as large as possible in comparison to the total area of the section. In late designs, this approach has been carried out to the point where the emitter and base regions look like the teeth of two combs pushed together (Fig. 8). The engineers call this *interdigitation* (fingers between each other).

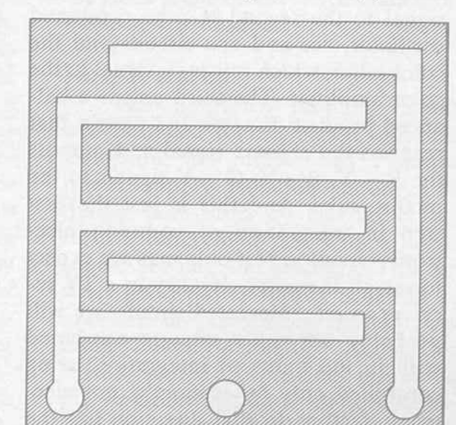


FIG. 8—INTERDIGITAL TRANSISTOR.

This technique has become important in both increasing the frequency limits and greatly increasing the power handling capacity of the transistor. In some high-power transistors, emitters are counted by the hundreds. They are bonded together with aluminum strips, which overlay the rows of emitter buttons (giving the unit its name of *overlay transistor*). In microwave transistors, the width of the "digits" and the spacing between them has been reduced to a thousandth of an inch or so.

Another kind of transistor

Experiments with field-effect transistors had been underway, and began to bear fruit in the early 1960's. The FET is actually older than the ordinary transistor. Lilienfeld's device was a kind of FET, as well as Gernsback's imaginary Crystron, and also the device designed on paper by Shockley that set engineers on the trail of the first transistor in 1947.

The first FET's were junction types, the earliest being the Tecnetron, invented in France. It was a cylindrical device of n-type semiconductor (Fig. 9-a). It resembled a resistor, which in fact

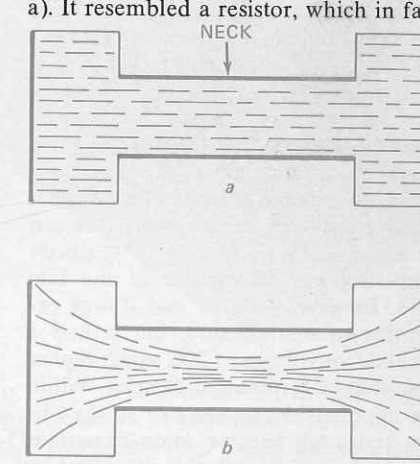


FIG. 9—THE TECNETRON, an early field effect transistor, was of the junction type.

it was. A ring or "neck" of indium around the center was the control element. With no voltage on the neck, the unit had a certain resistance. If now the neck were given a negative bias, its electrons would drive away the electrons immediately below it (Fig. 9-b) creating a *depletion region* and reducing the current through the cylinder, the conductive area of which had now been reduced. With enough negative bias, the field, or depletion region, could extend to the center of the material, *pinching off* the current entirely.

The modern metal-oxide-semiconductor FET has largely superseded the earlier junction (J-FET) type. It consists of *channels* of either n or p material, with a control element placed above, and insulated from, the channels. (Fig. 10). Charges applied to this *gate* can produce a depletion effect like that of

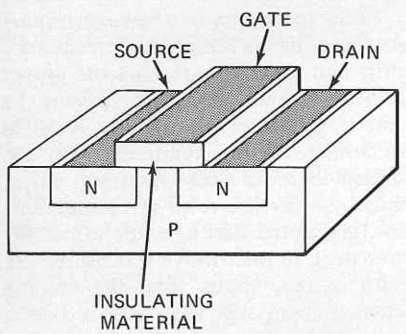


FIG. 10—MOSFET, the metal oxide semiconductor field effect transistor, has a high input impedance, like a vacuum tube. This leads to its use in rf amplifiers at high frequencies.

the Tecnetron. This is a *depletion-type* FET. In an *enhancement* type, the process is opposite. If the channels are n-type, a positive voltage applied to the gate attracts electrons into the p-type area beneath it, changing the p-area in effect into an n-region. The resistance between the channels is decreased and current flows. If the channels are p-type, the region beneath the gate is of n-type material, and the gate is forward-biased by a negative voltage. Metal-oxide-semiconductor (MOS) FET's are often used in complementary circuits, an n-p-n and a p-n-p in parallel to produce a push-pull output.

Silicon enters the field

Up to about 1960, germanium transistors dominated, despite the fact that there are dozens of materials that can be classed as semiconductors. A silicon transistor was announced in the late '50's. Its gain was low and it was expensive to manufacture, but it had a breakdown voltage of 300, much higher than that of germanium devices. Within the next half-dozen years or so the silicon transistor became more important than its germanium opposite number, and today silicon transistors with an upper frequency limit of over 4 gigahertz at low power levels and a power dissipation of more than 300 watts are in common use. Larger transistors have been built for specialized purposes. Silicon n-p-n transistors with a current rating of 250 amperes have been produced, as well as units with a breakdown rating of 1500 volts.

Transistors and near-transistors

Several variants fall just outside the definition of transistor, though very close to it in function. One of these is even called the "unijunction transistor," though its other name, double-based diode, would seem more exact. In its simplest form, it is a rod of semiconductor material, which acts as a resistor when a voltage is placed across the ends. An emitter is placed part-way down the rod, and when forward-biased, injects electrons or "holes" into it, lowering the original resistance. Thus the emitter controls the current much as the charge on the neck of a Tecnetron controls the current through it.

The silicon controlled rectifier is usually compared to two transistors hooked up in a feedback circuit. Other variants include the hook and the intrinsic-layer transistors, which follow transistor principles, though they have more elements than the conventional transistor. Still others are the spacistor and trinistor.

Transistors of the future

The *optical transistor* is a true transistor that is activated by light instead of current or voltage on its control element. It and its transmitting counterpart, the light-emitting diode, form the base of a whole new division of the art, *opto-electronics*. Applications of the optical transistor include detection of infrared and visible light transmissions, spectroscopy, surveillance in space and a host of others.

But probably the most important transistors of today (and of the future) are the tiny ones imbedded in integrated circuits. Made by masking and diffusion, as previously described, they are replacing discrete components in all branches of the industry. As an example, a complete integrated circuit chroma system for color TV receivers is now available in the form of three dual in-line IC's (Fig . 11). One of them is

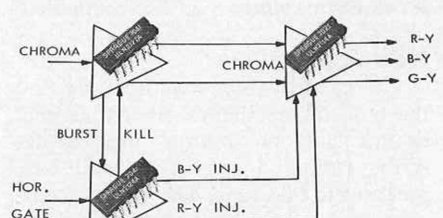
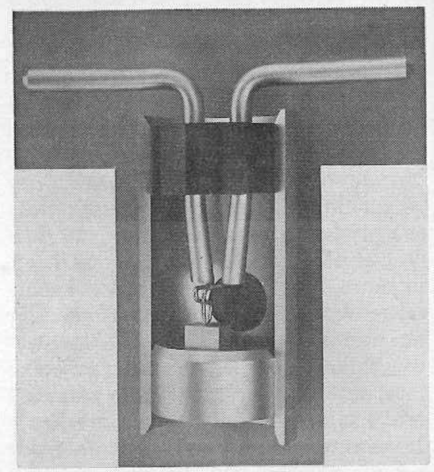


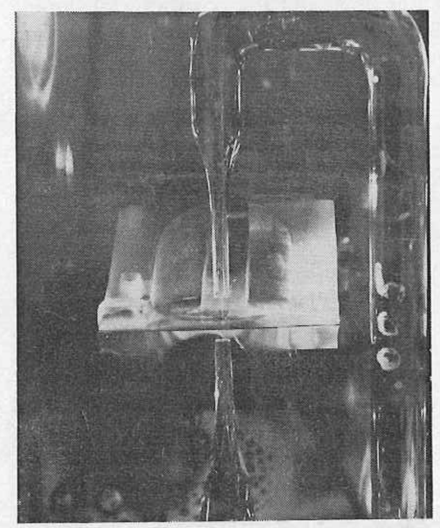
FIG. 11—THREE TINY UNITS make up the whole color section of a television receiver.

the chroma amplifier, supplying a burst signal to the second IC, the combined oscillator, acc and apc circuits and the color killer, which returns a signal to the color amplifier. The third unit is a balanced product detector and matrix that receives the chroma signal and outputs the R – Y, B – Y, G – Y signals to the picture tube. And this is just the first step in integration of common electronic circuitry. Not only may we expect to see all the color circuitry in a TV receiver in *one* integrated circuit—we will probably see other circuits combined with it, the limits of integration being controlled only by economic, not electronic factors. In that direction lies the future of the transistor. **R-E**

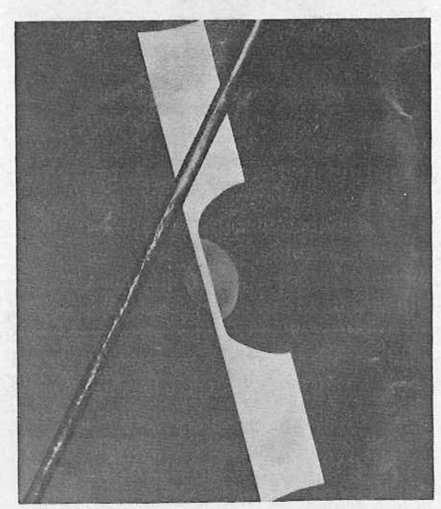
early transistors



ONE OF THE EARLIEST TRANSISTORS, this point-contact type was mounted in a case like that of the diodes in use at the period.



AN ALLOY TRANSISTOR in the making. A thin stream of etching fluid is directed at each side of the base material, wearing it thin. Then "buttons" of indium are alloyed into each side.

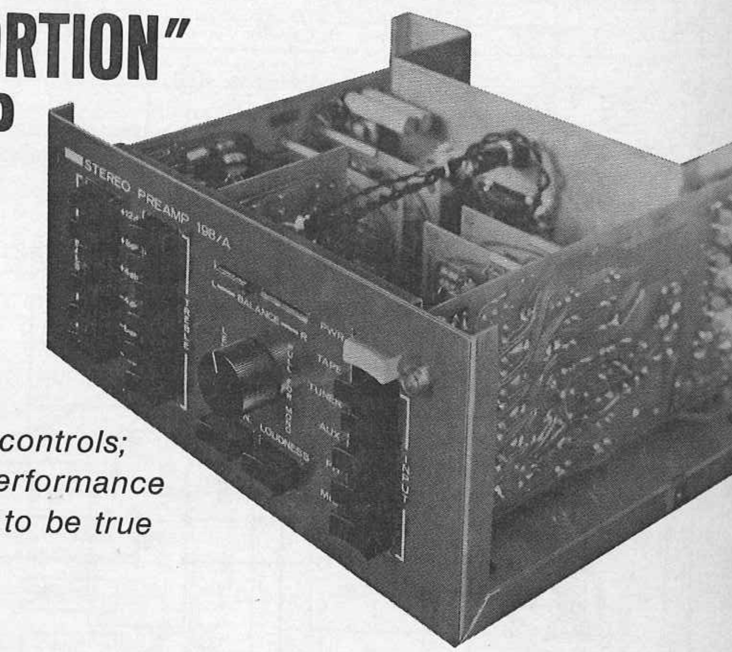


BASE OF THIS ALLOY TRANSISTOR is thinner than the human hair in front of it. The "bumps" are emitter and transistor buttons.

BUILD A "ZERO DISTORTION" STEREO PREAMP

by GARY KAY

Stereo preamp has push-button tone controls; printed-circuit board construction and performance specifications that are almost too good to be true



INTERESTED IN BUILDING A HIGH-quality stereo preamplifier for a price well under the cost of commercial units having comparable features? It's not just an ordinary preamp, but an attractive, easy to build unit based on state-of-the-art circuit design techniques that deliver noticeable advantages over conventional preamps.

Most preamps use a series of capacitor-coupled class-A amplifier stages using local feedback for equalization and to control the gain of the individual stages. The distortion and frequency response characteristics of this type of construction are not the best, and some designers are using operational amplifier integrated circuits. The operational amplifier technique works very well (see article on page 58 of this issue). The idea is to use feedback on an active device with a very high open-loop gain. The feedback controls the closed-loop gain, and greatly enhances the distortion, noise and frequency response characteristics of the device. Unfortunately, inexpensive IC's are inherently noisy and although the feedback helps, the noise is still at a level that makes it undesirable for use in high-quality audio equipment. The key to this preamp's operation is a unique gain module recently described in a British periodical ("Audio Preamplifier using Operational Amplifier Techniques" by Daniel Meyer, *Wireless World* magazine, July 1972). This gain module is actually a high-gain amplifier built using operational amplifier techniques but constructed from discrete components. It provides all of the advantages of high open-loop gain devices with the added bonus of low noise.

Each channel of this preamp uses two of these gain modules, which plug on to mother boards. In addition, all of the pushbutton switches as well as all of the input and output connectors are soldered directly to the circuit boards, reducing wiring to a minimum.

Functionally, the preamp has an internal power supply, pushbutton BASS and TREBLE switches, external BALANCE control, internal LEVEL controls on the TAPE, TUNER, AUX, and TAPE MONITOR inputs and the TAPE and PREAMP outputs. Switches are provided for POWER-OFF, TAPE MONITOR-NORMAL, LOUDNESS-VOLUME, and MONAURAL-STEREO modes. The power switch controls power for the preamp as well as for two ac receptacles on the rear panel. All input-output jacks are the RCA-phono type and are orientated so the unit can be nearly flush mounted against the back panel of a bookshelf if desired.

How it works

The amplifier module circuitry was designed for high gain, minimum distortion, low noise, and maximum power supply isolation among other things. Transistors Q1 and Q2 (Fig. 1) form a differential pair with a current source feeding the emitters. This provides good power-supply isolation and operates the transistors in their optimum low-noise region. Active load current source Q3 provides power supply isolation and is a high-impedance load for transistor Q1, thus insuring high gain. Transistor Q4 operates as an emitter follower to reduce loading on Q1 while Q5 acts as a class-A amplifier operating into active load current source Q6, for maximum gain and improved linearity. The closed loop gain of the circuit is set, as on other operational amplifier circuits, by the use of feedback. One of the feedback resistors, R13 is already provided on the board. Capacitor C3 in series with R13 decreases the gain to unity at dc no matter what the ac gain has been chosen to be. The other feedback component(s) X_{eb}, is inserted between points C and B. The ratio X_{eb} + R13/R13 sets the ac gain of the amplifier. If X_{eb} is composed of reactive components the gain can be made to vary as a function of frequency to provide equalization or tone control.

The overall circuit operation can best be understood from the block diagram, Fig. 2 and the schematic in Fig. 3. Amplifier module 1 boosts the audio level from either a magnetic phono cartridge, mike, or high-level input to a level compatible with the input of the second amplifier module. The input-selector-pushbutton-switch channels the desired input into the amplifier module 1 and simultaneously connects the appropriate feedback network to provide equalization. All high-level inputs are fed into the amplifier through a 1-megohm resistor and trimmer resistor. This guarantees a minimum input impedance of 1 megohm and enables the user to set each individual level control for a uniform audio level whenever changing inputs. The output of amplifier module 1 then passes through a balance control, tape monitor switch and a