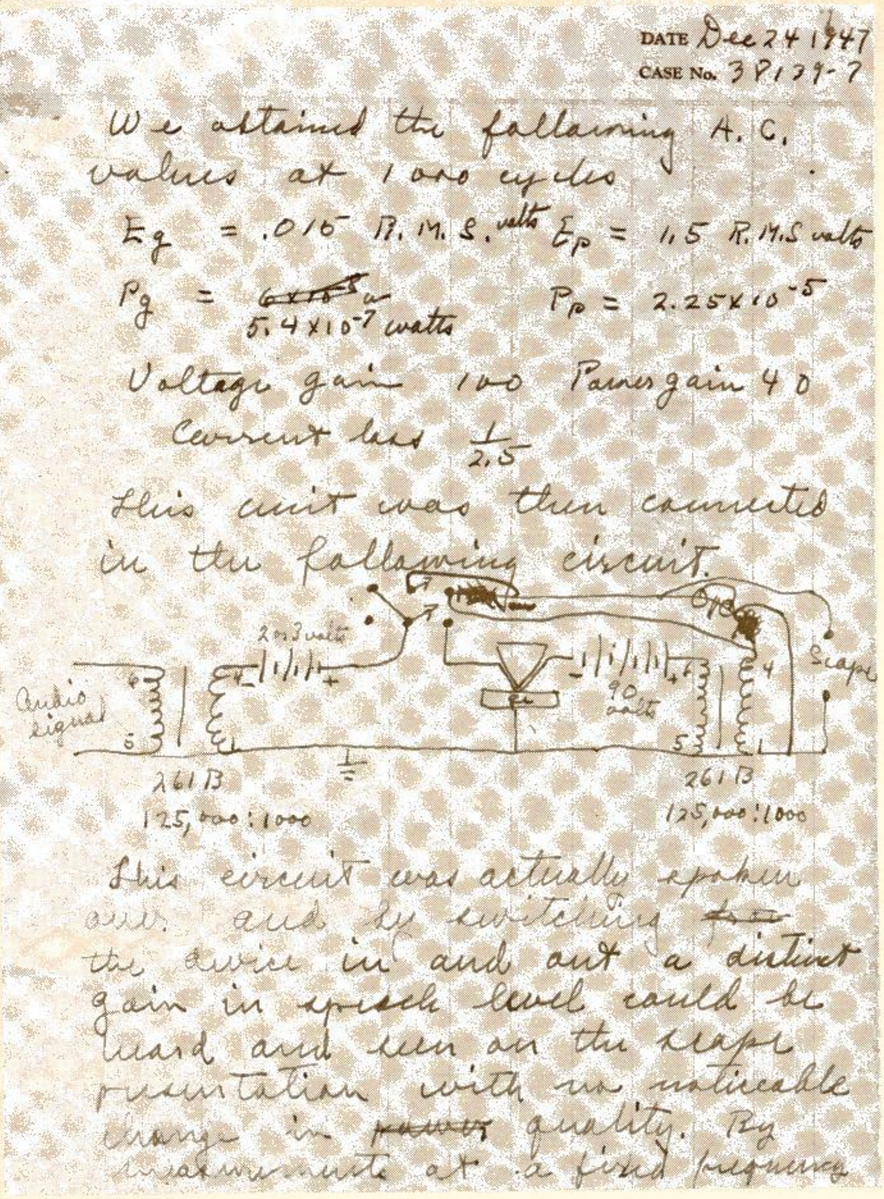


DATE Dec 24 1947
CASE No. 38139-7

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

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

Pg = ~~6×10-5~~ w 5.4×10-7 watts Pp = 2.25×10-5

Voltage gain 100 Power gain 40

Current loss $\frac{1}{2.5}$

This unit was then connected in the following circuit.

This circuit was actually spoken over and by switching ~~the~~ 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 ~~power~~ quality. By measurements at a fixed frequency

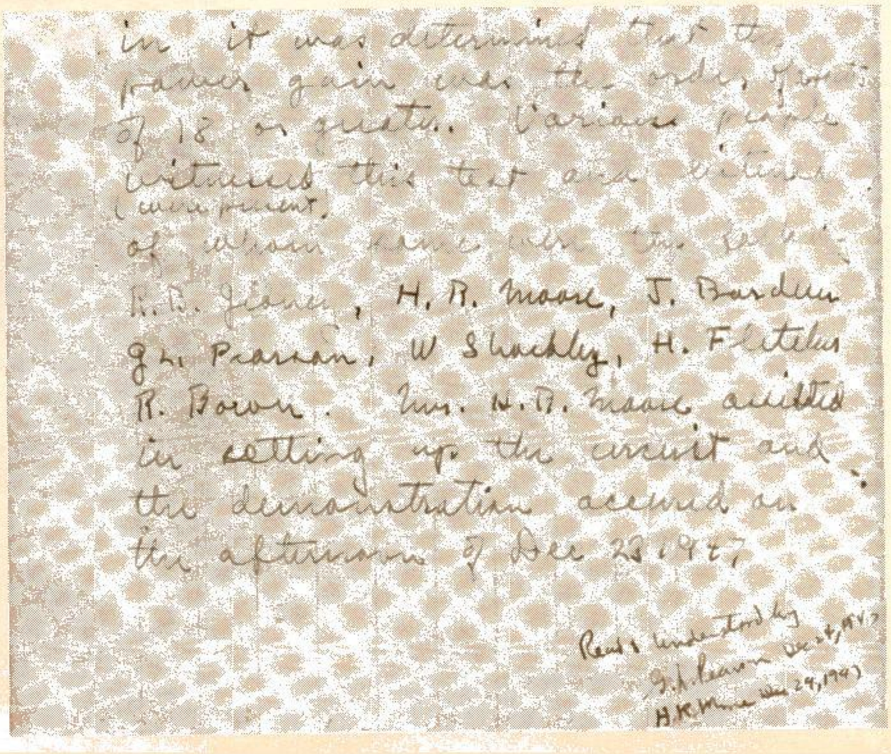
THE TRANSISTOR DID NOT QUITE SPRING on a startled world like a bolt from the blue. It was discovered (on December 23, 1947) by a team of Bell Laboratories scientists—Shockley, Bardeen and Brattain—who were engaged in a project to find just some such thing. Shockley had already worked out in theory and 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)

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

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*Radio News, September, 1924.

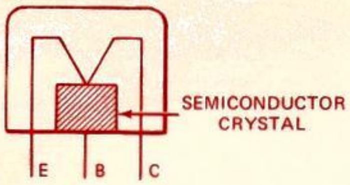


FIG. 1—A POINT CONTACT TRANSISTOR.

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).

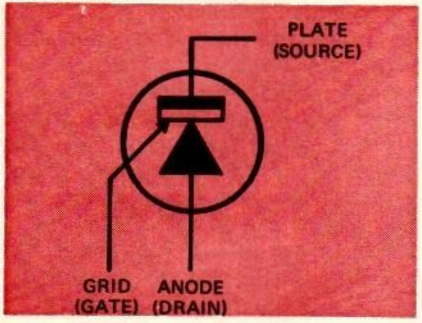


FIG. 2—THE CRYSTRON, the imaginary crystal amplifier dreamed up by Hugo Gernsback.

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.

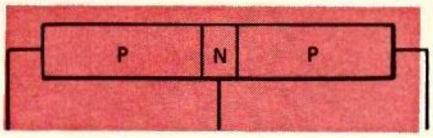


FIG. 3—THE JUNCTION TRANSISTOR overcame many earlier problems and disadvantages.

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 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.

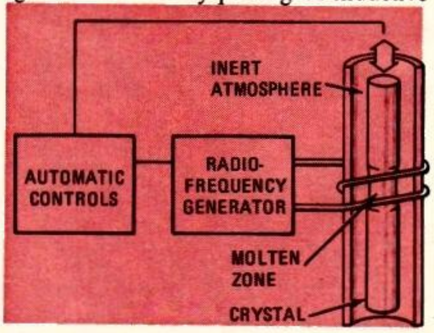


FIG.4—ZONE REFINING, an important step ahead in the development of the transistor.

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. Frequny 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 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.

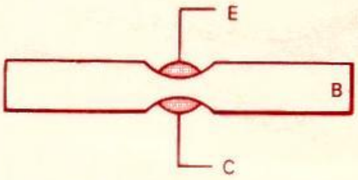


FIG. 5—THE ALLOY TRANSISTOR increased reliability, raised frequency limits.

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

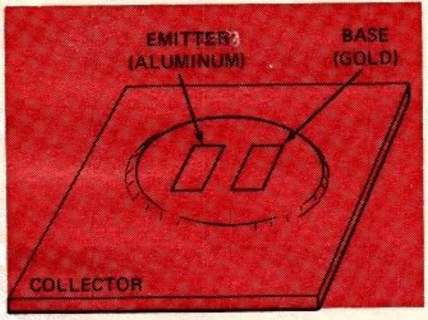


FIG. 6—THE MESA, a diffused transistor.

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.

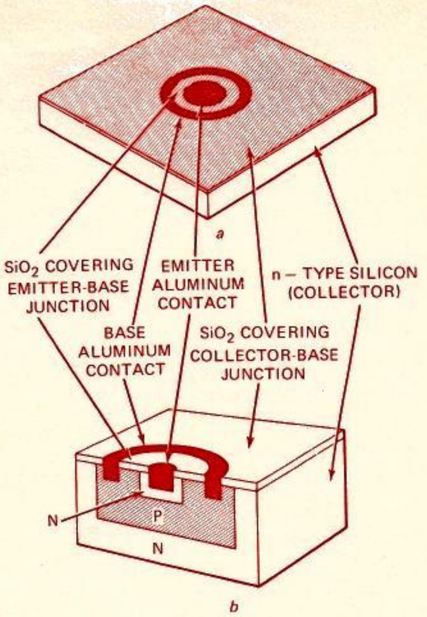


FIG. 7—THE PLANAR TRANSISTOR was an early use of silicon as a transistor material.

The *epitaxial* transistor (Greek: epi = 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).

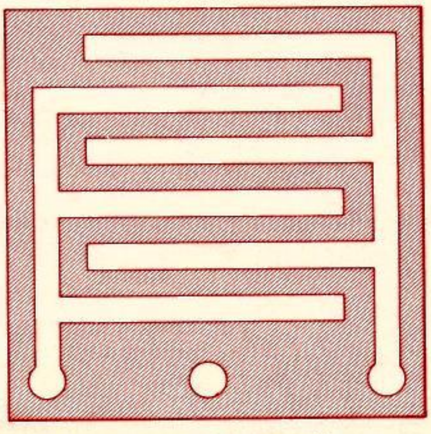


FIG. 8—INTERDIGITAL TRANSISTOR.

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 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.

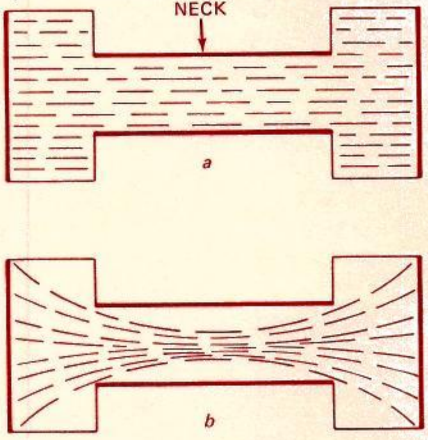


FIG. 9—THE TECNETRON, an early field effect transistor, was of the junction type.

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 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.

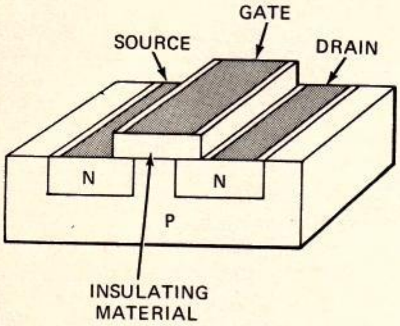


FIG. 10—MOSFET, the metal oxide semiconductor field effect transistor, has a high input impedance, like a vacuum tube. This leads to its use in rf amplifiers at high frequencies.

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 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**

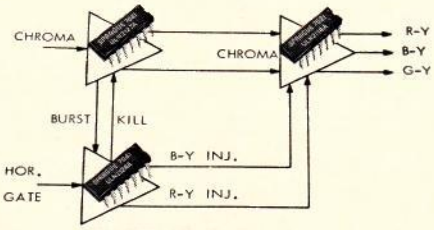
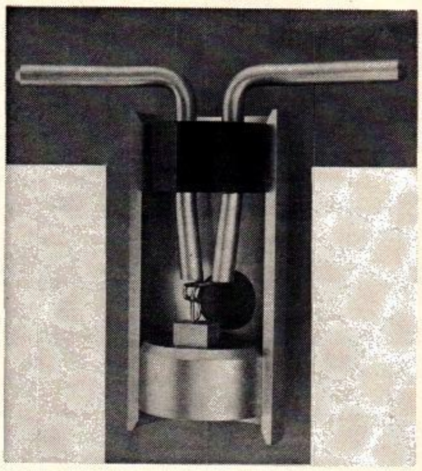
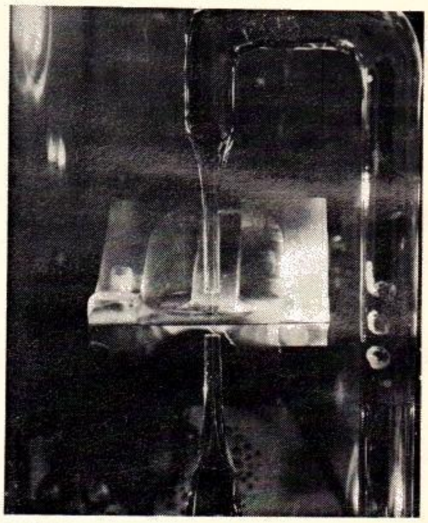


FIG. 11—THREE TINY UNITS make up the whole color section of a television receiver.

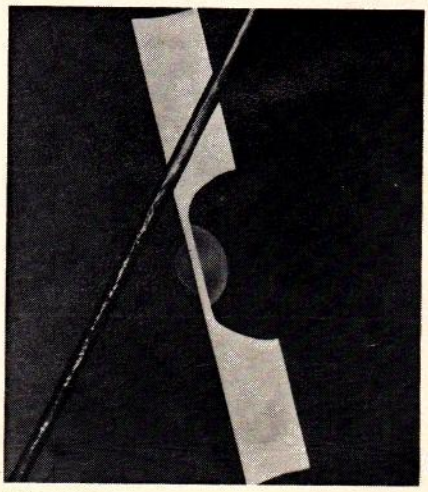
early transistors



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.

PIONEERS OF RADIO

by FRED SHUNAMAN

ELIHU THOMSON

EDWIN HOUSTON

THE EFFECTS OF RADIO WAVES WERE probably first noted by Professor Edwin Houston of Philadelphia, in 1871. Attempting to improve the 6-inch spark from a new induction coil, he attached one end of the secondary to a water pipe and the other to a large insulated conductor, in this case a metal still. This made the spark stronger, though a little shorter. Houston called it a "condensing" (we would say capacitance) effect.

He noted that when the coil was so connected, sparks could be drawn from metal objects in the room, especially grounded ones, and that he could light the gas with the spark that jumped when he brought a finger close to the metal gas jet. He did not understand the effect and referred to it as electrical losses.

Four years later, Edison announced his discovery of "etheric force." He did not believe it was electrical, because it could not be detected with a galvanometer and did not affect the gold-leaf plates of an electroscope.

Houston and his associate Elihu Thomson, chemistry professor at Philadelphia's Central High School, discussed the new force. Thomson decided: "This is not a new force–it is electrical, in the form of sudden impulses reversed rapidly, as it might be termed." Rigging up the 1871 equipment (with a smaller spark coil) they set out to prove the new force was electrical in nature. Professor Thomson was able to draw sparks from doorknobs with a short, sharp lead pencil, first in the same room as the coil and then on succeedingly higher floors till he drew sparks from the observatory library doorknob on the sixth floor, about 100 feet from the "transmitter."

Houston and Thomson debated Edison's conclusions in the *Journal of the Franklin Institute* and in the *Scientific American Supplement*. They explained that the reason Edison's "force" did not act like ordinary (direct current) electricity was that each impulse that produced a spark was succeeded by a reverse impulse, an "inverse current" as they called it. This neutralized any effect the first current would have had on an instrument, if indeed the first current lasted long enough to have produced any effect at all. (If they had known that the first two were followed by a series of "direct" and "inverse" currents of decreasing amplitude, they would have had a complete theoretical explanation.)

Unfortunately for radio, Thomson's great talents led him in other directions. He left teaching and with his friend and associate Houston started designing and manufacturing electric generators and motors, and arc lighting and resistance welding equipment. Their company combined with Edison's in 1892 to form General Electric, though the Thomson-Houston firm name still exists and is important in a number of foreign countries. **R-E**