POINT-CONTACT and JUNCTION TRANSISTORS

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RAYTHEON

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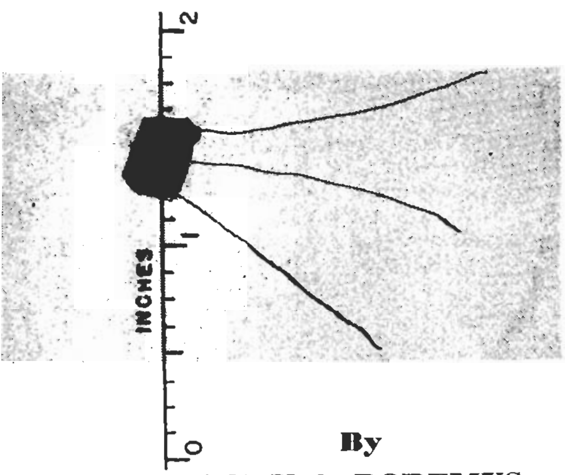

Transistors are superior to vacuum tubes in many respects, but also have certain limitations which must be considered in designing new equipment.

By
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THOSE WHO work in the communication phase of this industry sometimes have the feeling that "there's nothing wrong with electronics that the elimination of a few vacuum tubes would not fix!" This is a sordid thought to have concerning the element around which the industry revolves. Yet many basic short-comings can be traced back to the vacuum tube.

A vacuum tube has a limited and unpredictable life. A piece of communication equipment is often called on to operate continuously for years, and it is desirable that this equipment be completely unattended; yet tube failures require constant and costly maintenance.

The fact that a vacuum tube consumes power inefficiently is well known in the television industry. Very large power transformers are required for many television sets, a good share of the size being required to provide heater power for 15 to 20 tubes. Mechanically, too, a tube is bulky and fragile.

Now, for the first time, there is an alternative device which can be considered a legitimate contender to the throne that has been occupied by the vacuum tube for over 35 years. It can do many of the jobs now done by vacuum tubes and do them more efficiently and more dependably. This device is called a *transistor*.

What is a Transistor?

Transistor is the name given to a crystal-type amplifying element made of a semi-conductor such as silicon or germanium. It is interesting to note that the name was derived from the fact that this device had been called a "transit resistor" by early workers in the field who were really searching for new ways of making nonlinear resistors. At present, a transistor is equivalent to a triode. Its physical embodiment can be extremely small, since its ability to amplify does not depend upon its size. It is very rugged.

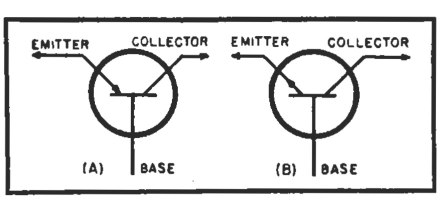
The ability of a transistor to amplify depends upon the unusual property of semi-conductors to support two kinds of conduction simultaneously: one, the travel through the material of excess electrons, and two, the travel through the material of "holes," which are really the lack of electrons and therefore constitute an equal positive charge. In a semi-conductor, electrons travel much more slowly than they do in a conductor and "holes" travel even more slowly than the electrons.

Transistors are constructed in two distinctly different types. One is called the point-contact type; the other is called the junction type. Their construction results in different performance characteristics which will become apparent as this story unfolds.

What Can It Do?

In most circuits, the transistor will do the same job as a vacuum tube while consuming 1/1000 as much power. Take, for example, a radio or television set. In all stages up to the second detector the signal level is less than a milliwatt and in most of them less than a microwatt. Yet an average of a watt or more heater power and a watt of plate and screen power are burned up in order to obtain the desired amplification.

Fig. 1. Schematic representation of (A) the point-contact transistor and (B) the junction transistor.



Transistors can give 20 to 50 db of gain, depending upon the type, while consuming less than two milliwatts of power. The junction type of transistor is about ten times more efficient than the point-contact type for small-signal amplification.

As the transistor has no filament or heater, there are no problems of filament burn-out. Transistor life has been predicted in several ways, all of these predictions pointing toward a figure of 70,000 to 90,000 hours, or approximately ten years. Since a transistor does not stop working suddenly, there being nothing to burn out, the life figure above has been based on the time at which its gain will drop 3 db. For most applications, this is not necessarily the end of its useful life.

Table 1 gives a tabulation of the properties of both the point-contact and junction types compared with vacuum tubes. As will be seen from this tabulation, transistors can do a better job than tubes within the limits of power and temperature up to 30 mc.

Photo Transistors

The boundary in a junction type transistor is extremely photosensitive and therefore can be made into an attractive photocell. The first photocells of this type were simply diodes.

One important characteristic of a transistor photocell is its spectral sensitivity which is most strong in the red and infrared regions. A second important characteristic is its efficiency. A PN junction unit (diode) has a sensitivity of 30 ma./lumen, and 10 to 15 milliwatts of a.c. can be obtained from a simple circuit using this type of unit. An NPN photo transistor can give a light conversion efficiency about 30 times greater than this, or about 1 ma./millilumen.

Why the Excitement?

Transistors are causing a great deal of excitement at this time because:

1. Production of practical quantities of the point-contact units has begun.
2. Large advances in circuit design have been made in the past year.
3. The bringing of the junction transistor out of the laboratory and the readying of it for production opens even newer and broader fields of application.
4. Stability of design has been established.
5. Dependability of units has been assured by uniform production.
6. Designability has been established. Units can now be designed to a certain set of parameters.
7. There is a need to alert the industry to the impact of this element so that circuit design work can now be done to take advantage of transistors.
8. Manufacturers believe that most rapid progress can be made under pressure of circuit designs to stabilize types.
9. Five manufacturers are already "in the business." These are *Western Electric, General Electric, Raytheon, Sylvania* and *RCA*.

How Does It Work?

The operation of the transistor can best be understood by reviewing some of the characteristics of semi-conductors. Certain elements in the fourth column of the Periodic Table exhibit properties whereby they seem like insulators under certain conditions, while under other conditions they seem like conductors. These elements have been called semi-conductors.

In the molecular structure of a material like diamond, all valence bonds are satisfied, so the material behaves like an insulator. If the crystal is heated, the thermal excitation can cause a valence electron to be knocked out of its usual place, leaving this electron (negative charge) free to move about in the crystal. The place from which the electron came is called a "hole," and this area exhibits a local positive charge. Under this condition, the diamond behaves somewhat like a conductor. Eventually, the electron and the hole may recombine. At all times, however, the entire crystal is electrically neutral.

Certain other elements in the fourth column of the Periodic Table, like silicon and germanium, require less energy to knock electrons out of the valence bond positions; in fact, at normal temperatures, electrons and holes are being liberated and recombined continuously. These are called intrinsic semi-conductors.

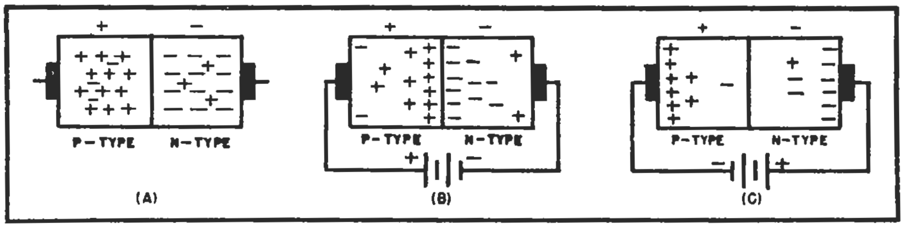


Fig. 2. Schematic representation of a junction between P-type and N-type germanium, showing action of electrons and "holes" with various battery polarities.

If an electric field is applied to an intrinsic semi-conductor, the electrons move toward the positive terminal and the holes move toward the negative terminal. Holes can be treated exactly like electrons except that their charge is of opposite sign.

It was learned early that the presence of certain impurities in a semi-conductor greatly changed its conductivity. These impurities were identified and the following two effects catalogued.

If an impurity from the fifth column of the Periodic Table is present, atoms of this impurity replace atoms of the semi-conductor in the crystal structure. Since fifth column elements have five valence electrons, the extra electrons are free to migrate throughout the crystal. This is called an N-type (negative) semi-conductor and the impurity atoms are now called donors or donators.

If an impurity from the third column of the Periodic Table is present, the impurity atoms similarly replace atoms of the original material in the crystal. Third column elements have only three valence electrons and, consequently, one valence bond is left unsatisfied. The holes thus formed are also free to move about in the crystal, and the material is now called a P-type semi-conductor. These impurity atoms are generally referred to as acceptors.

It is interesting to note that only a few donor or acceptor atoms are required to produce substantial changes in the resistivity of a semi-conductor.

Two other properties of semi-conductors are important:

1. Holes can be introduced into an N-type semi-conductor, and electrons can be liberated in a P-type semi-conductor by passing current into it.
2. Electrons travel much more slowly in a semi-conductor than they do in a conductor, and holes travel even more slowly than electrons.

Now, examine the operation of a PN junction rectifier (Fig. 2). This may be made up of a single crystal of germanium, for example, the two parts of which contain different impurities. One part is N-type and the other part is P-type. If a potential is applied to the two ends of this rectifier so that the positive terminal is connected to the P material and the negative terminal to the N material, the electrons and holes move toward each other and recombine. The voltage source keeps this going. The apparent resistance is very low, and a high current flows.

If we reverse the polarity of the applied potential, the effect is much different. The holes and electrons are pulled away from the junction and away from each other, and the unit tends to become an insulator. Very little cur-

Table 1. A tabulation of the various characteristics of the point-contact and junction transistors compared with the characteristics of conventional vacuum tubes.

	Point-Contact Type	*Junction Type*	*Tubes*
Gain	20 — 30 db	30 — 50 db	20 — 50 db
Efficiency (Class A)	30%	45 — 49%	.1 to 25%
(Class C)	90%	95%	70%
Life	70,000 hrs.	90,000 hrs.	5000 hrs.
Vibration	100 g	100 g	
Shock	20,000 g	20,000 g	
Uniformity	± 3 db	± 2 db	± 3 db
Minimum powers	1 mw.	1 microwatt	1/10 watt
Temperature	70°C	70°C	500°C
Frequency	30 — 70 mc.	3 — 5 mc.	60,000 mc.
Gain × bandwidth	1000 mc.	120 mc.	1000 mc.
Noise figure	45 db	15 db	10 — 30 db
Power	100 mw.	1 watt	1 megawatt

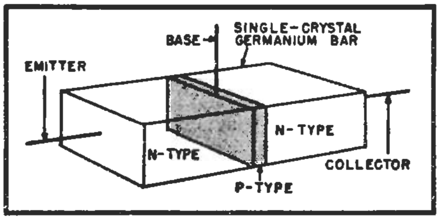


Fig. 3. Basic construction and nomenclature for junction transistors.

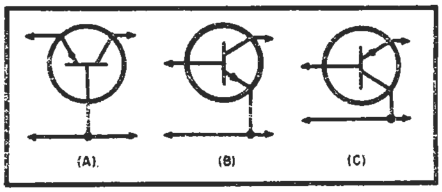


Fig. 4. Three possible methods of connecting the junction transistor: (A) Grounded base; (B) Grounded emitter; (C) Grounded collector.

rent flows. Therefore, this type of junction is a very good rectifier.

Next, pass on to the junction type transistor (Fig. 3). Here, there are two junctions made very close together —usually from a single crystal of the semi-conductor.

The left-hand junction is biased in its forward direction, forming a very low resistance path for the flow of current. To insure an efficient emitter, the N-type material is more strongly N than the P-type is P. An excess of electrons is generated, and these travel into the center region.

The right-hand junction is biased in its non-conducting direction. The electric field across this junction makes it attractive for the excess electrons liberated at the emitter junction to continue on across the collector junction to the collector terminal.

Variations in the emitter current will cause variations in the number of free electrons available and thus cause variations in the collector current. The Greek symbol alpha (α) has been established as the transfer current gain of the transistor. α may be defined as the change of collector current for a specific change in emitter current at a constant collector potential.

$$\alpha = \left(\frac{\Delta I_c}{\Delta I_e}\right)_{V_c}$$

The factor α is dependent upon the efficiency of the emitter, the transport ratio and the efficiency of the collector.

$$\alpha = \gamma \times \beta \times A$$

γ = emitter efficiency
β = transport ratio
A = collector efficiency

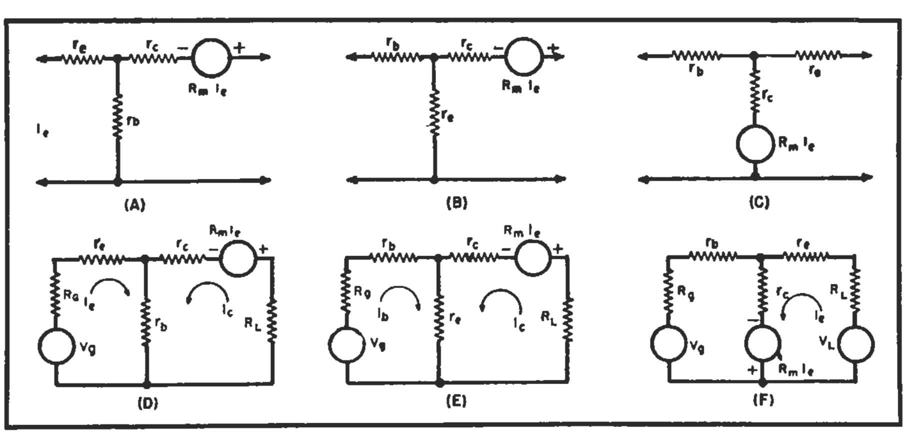
If the emitter current were all electrons and none recombined with holes in the center, P-region, and all of them reached the collector, then α could attain a maximum value of unity. In practice, α values of .95 to .98 can be achieved.

As mentioned previously, the emitter (or input) junction has a very low impedance, but the collector (or output) junction has a very high impedance. The variation of a current through the high impedance collector circuit by an almost equal current variation in the low impedance emitter circuit constitutes an appreciable power gain. Junction transistors have been made with up to 50 db of power gain.

Now, consider the point-contact type of transistor. This is basically a block of semi-conductor material, such as germanium or silicon, where two pointed probes are placed very close together on top of the block. During manufacture, the contact areas are "formed" by passing current pulses through them. This creates small areas of P-type material directly under the points, and the resulting transistor is essentially a PNP unit.

Operation is similar to that described for the NPN transistor except that all supply potentials are of opposite polarity and the important conduction is principally by holes instead of electrons. However, because of the geometry of this unit and the relative mobilities of holes and electrons, α values as high as 3 to 4 can be obtained in commercial units.

Fig. 5. Equivalent circuits for the various junction transistor connections: (A) & (D) Grounded base; (B) & (E) Grounded emitter; (C) & (F) Grounded collector.



A transistor, therefore, possesses two mechanisms whereby power gain can be obtained when it is used as an amplifier. One of these is due to the fact that the output impedance is considerably higher than the input impedance; the other is due to α, the current gain possible in point-contact types and the newer hook-collector types of units.

Transistor Characteristics

The transistor is definitely a three-terminal device. Unlike the vacuum tube, the fact that the transfer characteristics are bilateral cannot be forgotten, even for equivalent circuits. Changes in output conditions affect the input characteristic as changes in input conditions affect the output characteristic.

The transistor is definitely a voltage amplifier. By varying an input voltage, a much larger variation in an output voltage is obtained. Too, transistors like best to see constant current power supplies whereas tubes work best with constant supply potentials.

As mentioned previously, the emitter circuit of a transistor is a diode biased in its forward or conducting direction. The bias supply for this element must be of a constant current nature to prevent self-destruction.

The alternating current equivalent circuit of a transistor for most applications is represented as a three-terminal network with two series resistances, r_e and r_c, and one shunt resistor, r_b, as shown in Fig. 5. These parameters are resistive at normal audio frequencies. The truest representation of the transfer generator would be a current supply having the value αI_e shunted across r_c. Since it is inconvenient to work with current generators, this may be replaced with an equivalent voltage source in series with r_c having the value $R_m I_e$.

The input impedance of a transistor is equivalent to the sum of r_e and r_b and has practical values from 200 to 600 ohms. The output impedance is equivalent to r_c plus r_b. This may be from 20,000 ohms to over a megohm.

Like a vacuum tube, a transistor has an upper frequency limit caused by the capacities between the elements. Because of the close spacing, these capacities are somewhat greater than in vacuum tubes. Capacity effect on the emitter is not serious because of its inherently low impedance, but the capacity effect upon the collector is somewhat more important, especially in junction types. The principal frequency limitation in a transistor, however, is due to another cause, namely, the slow transit speed of the electrons and holes in the semi-conductor material. These two effects define an upper frequency limit for junction type units at 3 to 5 mc., while point-contact units have been used up to 70 mc.

Temperature provides another serious limitation to the environment of a transistor. At elevated temperatures, the noise generated within the unit becomes important in magnitude, and the thermal agitation causes a large change in the collector impedance, thereby affecting the amplification.

Much has been said about noise in transistors, which is evidence that research has only begun on the fundamental causes of this noise. This noise, like other random noise, decreases as frequency increases. A point-contact type unit shows a noise factor of 40 to 50 db while junction type units have a much better noise figure, 10 to 15 db, which compares favorably with tubes.

Practical Circuits

Like the vacuum tube, the transistor lends itself readily to all types of circuits including amplifiers, oscillators and switching circuits. In many cases, the transistor shows improved flexibility since there is no common filament supply to consider. Low input impedance minimizes shielding problems.

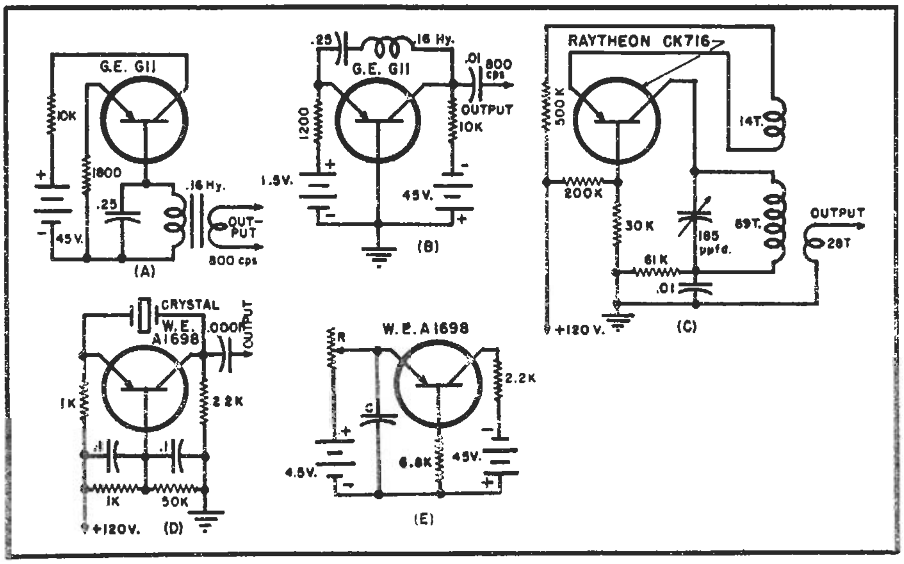


Fig. 6. Several practical point-contact transistor circuits: (A) and (B) are oscillators having an output of 800 cps. (C) is a broadcast superhet oscillator. (D) is a crystal-controlled oscillator. (E) is a multivibrator in which C is adjusted for the desired frequency and R is adjusted for proper operation.

The commonly used grounded base connection is equivalent to a grounded grid vacuum tube circuit. In this connection, the principal problem is stability. Base resistance is common to both input and output circuits. Since there is no phase reversal in the transistor element, the common base resistance constitutes a regenerative feed-back path—most important in units with an α greater than unity.

The value of r_b has been controlled in all units currently being manufactured to provide inherent stability when no external resistance is added to the base circuit.

In the grounded base connection, between matched impedances, up to 20 to 30 db gain per stage is easily achieved. Because the impedance transformation through a transistor amplifier is a step-up, it is always necessary to use an interstage stepdown transformer to realize full power gain.

At a large sacrifice in gain, it is possible to cascade grounded base transistor stages directly. In this sort of an amplifier, 6 to 8 db gain per stage is possible.

Another popular circuit is the grounded emitter circuit, equivalent to a conventional grounded cathode tube circuit. Input and output impedances are both on the same order of magnitude —from 4000 to 10,000 ohms. Output impedance is negative if α is greater than one and must be stabilized.

This circuit has a transfer phase shift of 180°. Practical amplifiers can be built with 20 to 30 db gain per stage. Cascaded stages without interstage transformers show an improvement over the grounded base connection.

The transistor may also be used in a grounded collector circuit. This circuit, which has a high input impedance and a low output impedance, is equivalent to a cathode follower tube amplifier.

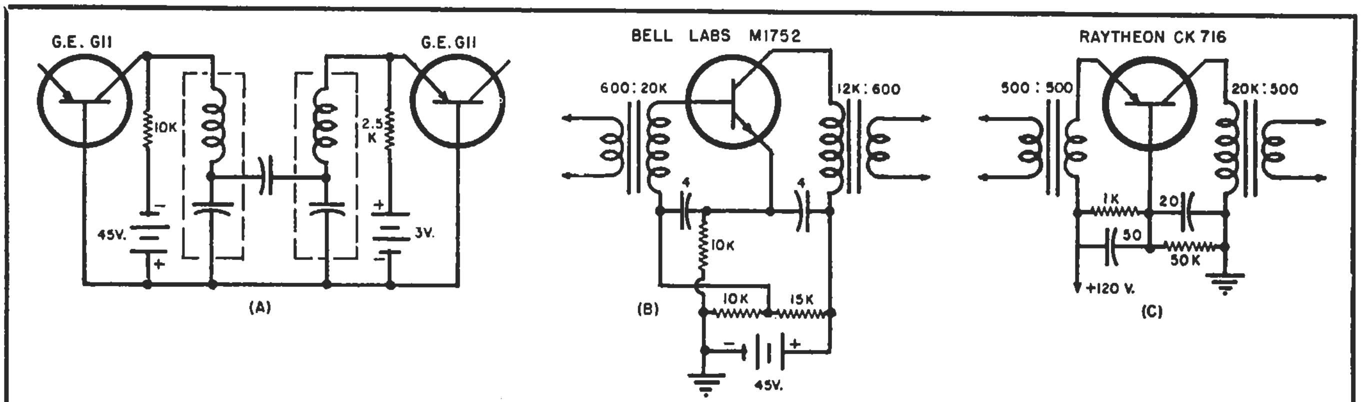
Both input and output impedances may be negative in this connection, but the circuit can be stabilized with external resistors. It is interesting to note that this circuit has a phase reversal going through it in one direction while it has no phase shift going through it in the opposite direction. It is possible to make an amplifier of this type with 15 db of gain in both directions.

To produce low noise input, higher power output and more gain per stage without interstage transformers, combinations of grounded base followed by grounded collector stages and grounded emitter followed by grounded collector stages may be used.

For oscillators, several circuits have shown good performance. A parallel resonant circuit in the base is a very popular circuit. Coupled series-resonant circuits in the emitter and collector leads produce a TE-TC oscillator.

A few conventional circuits that have

Fig. 7. (A) A practical 455 kc. i.f. amplifier. Note that the two i.f. coils are in separate cans. (B) An audio amplifier using a junction transistor. Output level, 10 dbm; gain, 30 db; battery power, 0.2 watts. (C) Audio amplifier using point-contact transistor having a gain of 20 db and an output level of 50 mw.



been used in practice are shown in Figs. 6 and 7.

Another important application of transistors is in switching circuits. With a vacuum tube, plate impedance can be controlled from several megohms to a few thousand ohms, while a gas tube can provide a switch from several megohms to a few hundred ohms. The transistor, on the other hand, can provide a switch which is capable of several megohms in its non-conducting condition to a fraction of an ohm in its conducting condition. This is the most effective electronic switch known to date. It can be made to operate in a fraction of a microsecond and be stable in either the open or closed condition much like a flip-flop circuit.

This application makes the transistor extremely useful in computers, telephone switching circuits and many industrial control operations. Experimental circuits have been built using transistors to replace the vibrator in an automobile radio power supply.

The transistor provides miniaturization of the major element of electronic circuits, thus shifting the impetus for improvement back to the transformer manufacturers and, more particularly, to the condenser manufacturers. Transistor circuits require the use of high-capacity, low-voltage coupling capacitors which at present are neither small, inexpensive, nor dependable.

The transistor also throws out an interesting challenge to the battery manufacturers to produce a constant current source rather than a constant potential source. At the present time, 80% of the power used in transistor circuits is wasted in the dropping resistors required to provide the constant current supplies from a constant voltage source.

Amplifier and oscillator circuits are limited at the present time to about 70 mc. This is a problem which is being worked on by all those engaged in transistor research.

The elimination of heat in the equipment employing transistors is a problem which does not have a very attractive solution. Obviously, it is not desirable to locate a transistor next to a red-hot 6L6. On the other hand, in equipment using all transistors and no tubes, the heat dissipated will be extremely small and will solve some of the currently existing aspects of the problem.

Summary

In conclusion, it can be said that the transistor is an adequate substitute for the vacuum tube with attractive improvements in power required, efficiency and dependability. At the present time, its application is confined to the limits of 70°C, 70 mc. and about 70 milliwatts.

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Table 2. Data sheet showing characteristics of several point-contact and junction transistors.

Manufacturer's number	CK 716	G11	A1698	M1689	M1725	M1729	M1752[2]	TA161B
Transistor type	Contact	Contact	Contact	Contact	Contact	Contact	Junction	Contact
Manufacturer	*Raytheon*	*GE*	*WE*	*BTL*	*BTL*	*BTL*	*BTL*	*RCA*
Type of service			Switching	Switching	Audio & Carrier	Audio & Carrier		
Diameter	.255	.16	.239	*.125	.239	.239	3/8x5/32	
Height (over-all)	.775	0.55	.750		.750	.750	7/32	
Mounting	*Cinch* 8749	5 pin subminiature	*Cinch* 8672	solder	*Cinch* 8672	*Cinch* 8672	solder	5 pin subminiature
Characteristics								
Collector current, ma.	4	2	15	40	20	20	5	
Collector voltage (neg.)	40	40	100	50	50	50	50	
Collector dissipation (mw.)	100	25	120	80	200[1]	200[1]	50[1]	140
Emitter current (ma.)	10	1	15	40	15	15	5	
Cutoff frequency (mc.)		5	5		5	5		
Input (emitter) resistance, r_e	250	50		800	195	190	25	300
Output (collector) res., r_c	15K	20K		10K	8K	15K	13M	15K
Feedback (base) resistance, r_b	75		200	500	115	75	240	120
Forward resistance, r_m	25K			15K	16K	32K	13M	
Current amplification factor α	2.5				2.1	2.5	.98	2
Operation (*Grounded Base*)								
Emitter current (ma.)	0.5	1			1.5	1/2[3]		1.5
Collector voltage	10	22			5	30		20
Collector current (ma.)	1.5	1.5			4	5/7		3
Average power gain[4] (db)	18	*19			18	20/18		22
Average power output (mw.)	3	20			4.5	/50		50
Noise figure (db) at 1000 cps.	45	55			48	54		55
Input termination	500	400			500	300		450
Output termination	20K	20K			1000	15K/15K		20K

* Approximate.
(1) at 50 degrees C ambient.
(2) Specifications, not data.
(3) Lower right values are strong signal conditions. Upper left values are weak signal conditions.
(4) Grounded base connection.

RAYTHEON GERMANIUM JUNCTION TRANSISTORS

Since publication of this article in Radio and Television News, Raytheon Manufacturing Company has announced availability of two Junction Transistors -- types CK721 and CK722.

The CK722 is immediately available in quantity; the CK721 is available in limited quantities until April 1953.

TYPE CK721

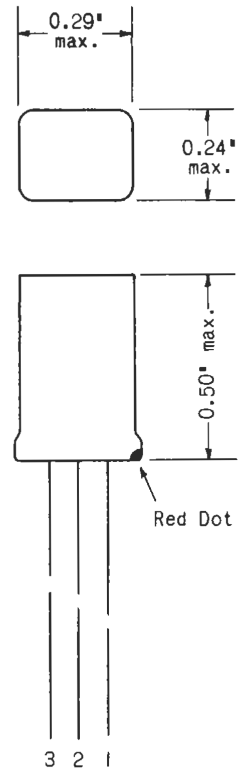
MECHANICAL DATA

CASE: Plastic and Glass

BASE: None (0.016" tinned flexible leads.** Length: 1.5" min. Spacing: 0.08" center-to-center)

TERMINAL CONNECTIONS: *(Red dot is adjacent to lead 1)*

Lead 1 Collector
Lead 2 Base
Lead 3 Emitter



ELECTRICAL DATA

RATINGS - ABSOLUTE MAXIMUM VALUES:

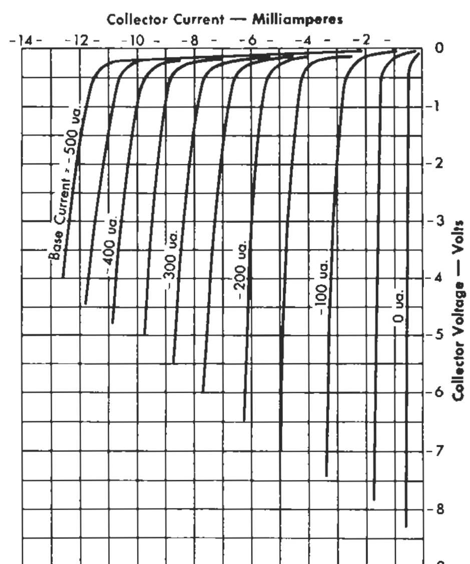
Collector Voltage	-20	volts
Collector Current	-5	ma.
Collector Dissipation (at 30°C)	30	mw.
Emitter Current	5	ma.
Ambient Temperature	50	°C

AVERAGE GAIN CHARACTERISTICS - GROUNDED EMITTER: (at 30°C)

Collector Voltage	-1.5	volts
Collector Current	-0.5	ma.
Base Current	-6	ua.
Current Amplification Factor	40	
Power Gain*	38	db
Noise Factor # (1000 cycles)	22	db

AVERAGE OUTPUT CHARACTERISTICS - GROUNDED EMITTER: (at 30°C)

Collector Voltage	-3	volts
Collector Current	-2	ma.
Base Current	-30	ua.
Load Resistance	1250	ohms
Distortion	8	percent
Power Output £	2.8	mw.



TYPICAL COLLECTOR CHARACTERISTICS CK721

* *Source: 1000 ohms; Load: 20,000 ohms.*

\# *At -1.5 volts (-1.0 ma.) to the collector.*

£ *With a driving power of 6 microwatts from a source of 1000 ohms.*

** *Socket types: Cinch Nos. 14148 & 14273 or equivalent*

TYPE CK722

MECHANICAL DATA

CASE: Plastic and Glass

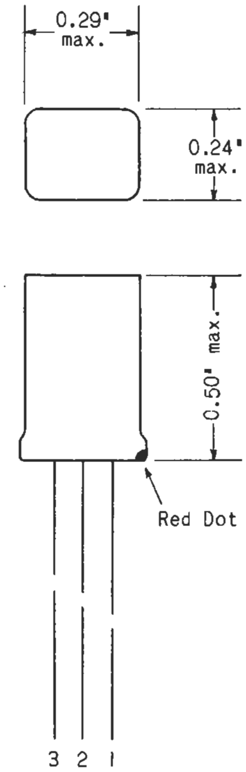
BASE: None (0.016" tinned flexible leads.** Length: 1.5" min.
Spacing: 0.08" center-to-center)

TERMINAL CONNECTIONS: *(Red dot is adjacent to lead 1)*

Lead 1 Collector
Lead 2 Base
Lead 3 Emitter

WEIGHT: 0.025 ounces

MOUNTING POSITION: Any



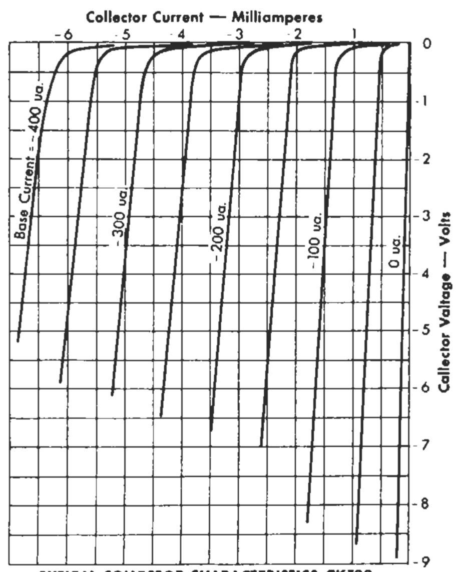
ELECTRICAL DATA

RATINGS - ABSOLUTE MAXIMUM VALUES:

Collector Voltage	-20	volts
Collector Current	-5	ma.
Collector Dissipation (at 30°C)	30	mw.
Emitter Current	5	ma.
Ambient Temperature	50	°C

AVERAGE GAIN CHARACTERISTICS - GROUNDED EMITTER: (at 30°C)

Collector Voltage	-1.5	volts
Collector Current	-0.5	ma.
Base Current	-20	ua.
Current Amplification Factor	12	
Power Gain*	30	db
Noise Factor # (1000 cycles)	22	db



TYPICAL COLLECTOR CHARACTERISTICS CK722

* *Source: 1000 ohms;*
Loas

* *Source: 1000 ohms;*
Load: 20,000 ohms

\# *At -1.5 volts (-1.0 ma.) to the collector.*

** *Socket types: Cinch Nos. 14148 & 14273 or equivalent.*