Power Transistors*

N. H. FLETCHER†

Summary.

The factors which limit the power handling capacity of ordinary transistors are examined and it is shown how these limitations can be overcome. By making use of the geometrical freedom afforded by the alloy junction process, transistors can be constructed to handle powers in the kilowatt range.

1. Introduction.

The transistor is now almost ten years old, and in those ten years has developed from a basically low power, low frequency device to one capable of operating at frequencies of hundreds of megacycles on the one hand, or powers in the kilowatt range on the other.

The story of this development has three main branches, all equally interesting and important today. In the first place there has been the fundamental study of the physics of semiconductors and the development of techniques for their production and processing. Secondly we have the extension of transistor design and manufacturing technology to the production of devices operating at higher and higher frequencies, though usually at modest power levels. The third line of development has been the extension of transistor power handling capacity from the milliwatt to the kilowatt range. It is this third branch of the story which we shall follow here.

2. Power Limitations.

By the end of 1952 three types of transistor had established themselves as practicable. These were the original point contact transistor, the grown junction transistor and the more recent alloy junction transistor. Of these the point contact type was obviously unsuitable for powers of more than a few hundred milliwatts and could be immediately dismissed as a high power transistor type. Similarly the grown junction transistor with its large series resistances in emitter and collector current paths and the difficulty of making an efficient base contact seemed unsuitable for further development.

This left the alloy junction transistor as the one reasonable starting point for power transistor development, and it has been on this type that all subsequent work has been done. Apart from being free from the obvious drawbacks of the other types, the alloying technique itself with its geometrical flexibility has made this type of transistor very easy to work with.

Concentrating, then, upon this type, let us first look at the factors which limit its power handling capacity and then see how these limits can be extended.

Figure 1 shows in slightly exaggerated form a typical set of output characteristics for an alloy junction transistor in the grounded emitter configuration. The curves are drawn for constant increments of base current I_b. The current gain β is defined in the usual way by

$$\beta = \alpha/(1-\alpha) = \partial I_c/\partial I_b \tag{1}$$

where

$$\alpha = \partial I_c/\partial I_e \tag{2}$$

From examination of these characteristics it is easy to see that power output is limited by two main factors. Firstly the collector voltage is limited by breakdown of the collector diode (or by a multiplication process having the same effect), and secondly the collector current is limited by crowding of the characteristics indicating a fall in β.

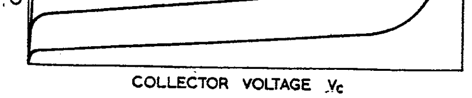

Figure 1.—Typical output characteristics for a junction transistor in grounded emitter configuration. Curves are for equal increments of base current I_b.

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*Presented before Sydney Division of the Institution of Radio Engineers Australia on February 26, 1958.

†C.S.I.R.O., Radiophysics Laboratory, Sydney, N.S.W.

Manuscript received by the Institution March 25, 1958.
U.D.C. number 621.314.7.

Since power gain is important as well as power output we must also consider this. To a first approximation in a grounded emitter circuit the input resistance at large current is just the extrinsic base resistance r_b'. If the input current is I, then the output current is βI and this flows in the load resistance R_L. The power gain is then approximately

$$G \simeq \beta^2 R_L/r_b' \tag{3}$$

Similarly in the grounded base configuration

$$G \simeq \beta R_L/r_b' \tag{4}$$

R_L is fixed by the supply voltage and output power, so that the gain is determined by β and r_b'. Acceptable gain requirements may therefore similarly limit power handling capabilities.

Finally we must consider dissipation rating. Transistors, unlike vacuum tubes, are relatively temperature sensitive, and performance deteriorates rapidly above an active element temperature of about 85°C for germanium and about 150°C for silicon. This essentially means that the devices should be derated to zero dissipation at these temperatures, though the exact interpretation depends upon the efficiency and performance degradation which can be tolerated. Even storage for short times at temperatures near 160°C for germanium transistors usually results in their destruction through melting of the indium electrodes.

Apart from these absolute temperature limits, stability considerations may impose their own restrictions. Suppose a transistor is operating at collector voltage V_c and current I_c, then a small increase $\triangle T$ in temperature gives an increase $\triangle P$ in dissipation, where

$$\triangle P \doteq V_c \frac{I_c}{\partial T} \triangle T \tag{5}$$

If the thermal resistance between the collector junction and the ambient is R, then this increase $\triangle T$ allows an additional flow of heat

$$\triangle H = \triangle T/R \tag{6}$$

For stability we must have $\triangle P < \triangle H$ which implies

$$V_c \frac{\partial I_c}{\partial T} < \frac{1}{R} \tag{7}$$

The term $\partial I_c/\partial T$ is dominated by the increase of the saturation current I_{co}, which is exponential with temperature, so that this equation limits the collector voltage which can be applied at a given junction temperature for a given package (i.e. value of R).

These considerations all limit the attainable power output, and as many as possible of the restrictions must be overcome to produce a really high power transistor. We shall now go on to see how this can be done.

2.1 *Voltage.*

Whilst collector voltage is limited ultimately by breakdown, the limit imposed by stability considerations is often more severe. For stability V_c should be low, but for high power gain and output it should be high. Improved materials make breakdown voltages of the order of 100 volts fairly readily attainable today.

In most cases, however, the voltage to be used is defined by the application, and most power transistors are required to operate on either 6, 12 or 28 volts. This requirement allows us to side-step to a large extent the problem of increasing the operating voltage.

2.2 *Current.*

The variation of the current amplification factor β with emitter current has been explained by Webster[1] in terms of surface recombination, emitter efficiency and bulk lifetime in a manner which we shall not go into in detail. Referring to Figure 2 which shows a typical β vs I_e curve for a small alloy junction transistor, Webster has shown that the initial rise is due to a surface effect, and that the fall-off at high currents is primarily caused by reduced emitter efficiency. Since we are concerned mainly with the fall at high currents we shall consider this a little further.

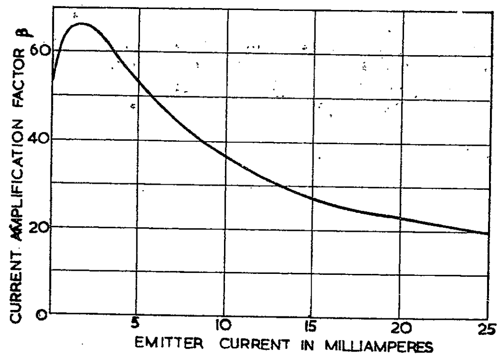

Figure 2.—Typical variation of current amplification factor β with emitter current for a small alloy junction transistor.

At low currents the emitter efficiency (which is the differential ratio of injected emitter current to total emitter current) is determined by the conductivity and diffusion length of the emitter region and conductivity and thickness of the base region. For good emitter efficiency one wants a high conductivity emitter of long diffusion length and a thin, low conductivity base region. The rate of fall of β is determined by the base width and conductivity and by current density.

To keep the degradation small we require a high conductivity, long diffusion length emitter and a thin base, and we require that the current density be kept low.

The first requirement has been met by the introduction of new alloying materials[2], notably gallium and aluminium, which are added to the indium of the emitter. These materials are much more soluble in germanium than is indium and produce a much more highly conducting emitter region.

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1. Webster, W. M., "On the variation of junction transistor current amplification factor with emitter current," Proc. I.R.E., **42**, June, 1954, 914-920.
2. Armstrong, L. D., Carlson, C. L., and Bentivegna, M., "PNP transistors using high-emitter-efficiency alloy materials," R.C.A. Rev., **17**, March, 1956, 37-45.

The base thickness can be reduced and kept uniform by careful manufacturing procedures and the current density can be kept small simply by increasing the emitter area. We shall see later that there is a limit in this direction, but initially the increased area produces the desired result.

2.3 *Power gain.*

The two main quantities controlling power gain are, as we discussed above, the current amplification factor β, and the extrinsic base resistance r_b'. We have already seen how a high value of β can be maintained, and we now consider means of reducing r_b'. This resistance is primarily due to the thin sheet of relatively low conductivity germanium between the active region and the base contact. Matters can be improved by increasing the conductivity of the base region material, but since this has a bad effect upon emitter efficiency and collector breakdown voltage, changes in this direction are limited. The most significant improvement is achieved by changing the geometry so that the base connection becomes a ring surrounding the emitter as closely as possible. This proximity to the active region brings its own problems since the base contact must now be of high quality; this is easily achieved however by making it of the NN+ type. By this geometrical rearrangement, base resistance can be reduced from the 100 ohms or so typical of small transistors to a figure nearer to 10 ohms, with consequent large improvement in power gain.

2.4 *Dissipation.*

Various means have been tried to reduce the thermal resistance R between the junction and the ambient, but unquestionably the most successful solution has been to solder the collector directly to the copper base of the transistor can and bolt or clamp this securely to a metal chassis. The chassis then transfers the heat, mostly by convection, to the environment. In cases where the transistor collector must be electrically insulated from the chassis a thin mica washer has been found to give adequate electrical isolation without seriously increasing R.

For pulse operation and in similar applications where the duty cycle is very low, the simple concept of a thermal resistance path is inadequate, and the heat capacities of the various elements of the transistor and its environment must be considered, giving $R.\ C$ combinations and associated time constants. It is usually simple to do this for particular cases.

3. Medium Power Transistors.

When the design considerations we have discussed are incorporated into the design of a particular device, this becomes typical of the ordinary power transistors of the present day as shown in Figure 3. These may operate typically on 12 or 28 volt supplies, have maximum current ratings of 1-5 amperes and have dissipations, when clamped to an average chassis, of 5-10 watts. With a sine wave signal, typical outputs are 2-10 watts per transistor, with a gain of about 20 db in grounded base and 30db in grounded emitter circuits. When used as a switch a few tens of watts can be controlled. Frequency response is limited to a few hundred kc/s in grounded base and a few tens of kc/s in grounded emitter circuits.

These transistors are valuable components for the output stages of car radios, for medium power control applications and for square wave oscillators in power supplies.

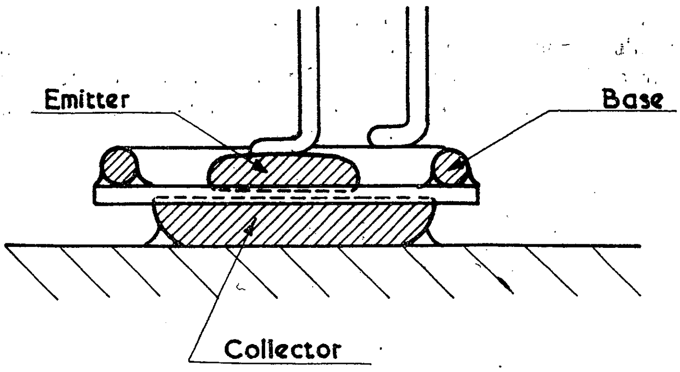

Figure 3.—Basic power transistor design.

4. High Power Transistors.

At this stage one may wonder why the dimensions of the transistor cannot be increased indefinitely to obtain larger and larger current carrying capacity. The reason, briefly, is that in a very large transistor the base current has to flow for a considerable distance through a thin base layer before reaching the edge of the emitter and the base contact electrode. In a high current transistor this base current may be quite large, and when flowing through the base layer it produces an ohmic voltage drop which reduces the forward bias on parts of the emitter distant from the base electrode. This results in most of the emitter current flowing in a very narrow strip around the edge of the emitter, with the rest of the emitter region remaining inactive.

This phenomenon has been treated in detail by the present author[3,4] and it can be shown that for a very large transistor with otherwise typical properties, the current density falls off away from the edge of the emitter as shown in Figure 4. Half of the total current is carried by a strip less than a millimetre wide at the edge of the emitter.

This suggests that the most efficient arrangement would be to make the emitter in the form of a long strip with a base electrode in the form of two long strips parallel to it and on either side as shown in Figure 5. A typical width for the emitter strip would be 1 mm. This arrangement was proposed some time ago by the author[3] and even before this a somewhat similar structure was suggested on rather different grounds by Hall[5]. Since then it has become ap-

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[3] Fletcher, N. H., " Some aspects of the design of power transistors," Proc. I.R.E., 43, May, 1955, 551-559.

[4] ——, " Self-bias cutoff effect in power transistors," Proc. I.R.E., 43, November, 1955, 1669.

[5] Hall, R. N., " Power rectifiers and transistors," Proc. I.R.E., 40, November, 1952, 1512-1518.

parent that a slightly more convenient structure results if the emitter is bent to form an annulus, the base electrodes then forming concentric annuli.

A transistor of this design using germanium as the base material and with an indium-gallium emitter has been constructed at this laboratory in small quantities[6]. This transistor is capable of passing collector currents up to 45 amperes whilst retaining an average β value as high as 15. This transistor was designed for pulsework so that whilst pulse power was in the kilowatt range, average power was only a few watts. Figure 6 shows this transistor before mounting to illustrate the construction principle.

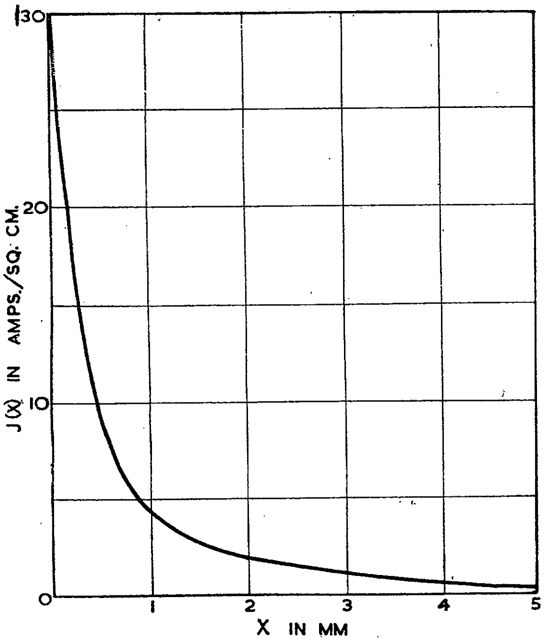

Figure 4.—Fall-off of current density away from the edge of the emitter for a large transistor with otherwise typical parameter values (indium emitter, base width 5 x 10^{-3} cm).

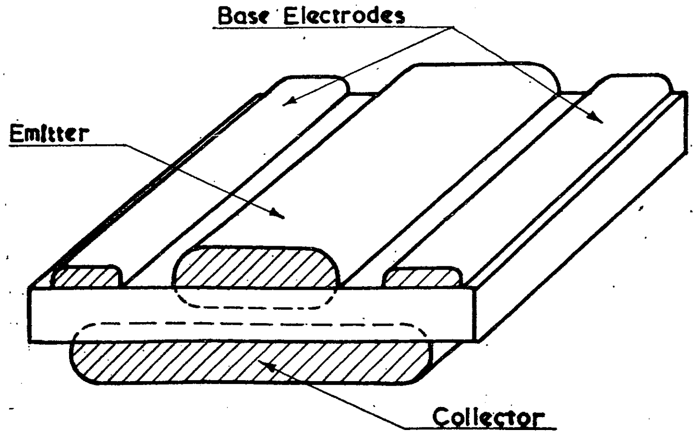

Figure 5.—Basic high power transistor design.

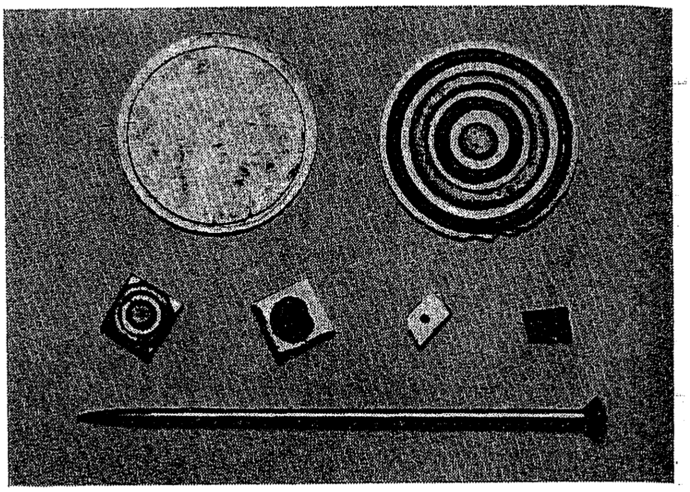

Figure 6.—Experimental kilowatt pulse transistor. Emitter rings show gray, base rings black. Collector side is shown alongside. Also shown are typical medium and low power transistor elements and a one-inch pin to fix the scale.

Transistors having approximately this geometry are now available commercially to carry currents of 10-20 amperes and give outputs of some hundreds of watts. More recently Emeis and Herlet[7] have discussed an alloyed silicon transistor of this construction having a current gain of 10 at 20 amperes. The frequency response of all these units is usually confined to a few hundred kc/s.

5. The Power Tetrode.

The tetrode originally entered the transistor field as a high frequency grown junction device, in which the emitter current was confined to a small area by the application of a transverse field to the base region. The basic structure of Figure 5 allows a transverse field to be applied in the base region of the power transistor by the application of a voltage between the two base electrodes. This configuration, bent to annular shape, constitutes the power tetrode discussed by Maupin[8].

The application of transverse bias modifies the emitter current distribution, and, when coupled with the self bias field we discussed above, leads to a set of β vs I_e curves some of which are much flatter than those of the triode connection. The advantages of this improvement in linearity are obvious.

6. Prospects.

Whilst it is rather a dangerous procedure to make any predictions about even the immediate future of an electronic device, a few extrapolations can be made with reasonable confidence. It seems likely that in the near future it will become possible to make junction transistors with output powers approaching 10 kW, at any rate on pulses.

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[6] Fletcher, N. H., " A junction transistor for kilowatt pulses," Proc. I.R.E., 45, April 1957, 544.

[7] Emeis, R. and Herlet, A., " Die effektive Emitterfläche von Leistungs-transistoren," Z. Naturforschung, **12a**, December, 1957, 1016-1018.

[8] Maupin, J. T., " The tetrode power transistor," Trans. I.R.E., **ED 4**, January, 1957, 1-5.

Whether this becomes economically sound is another matter, since at some stage it becomes advantageous to operate several smaller devices in parallel, rather than to use a single very large device. Just where this point comes can only be decided by experience.

A new technique has recently been described by Henkels and Strull[9] in which aluminium is evaporated as a thin film onto germanium and then alloyed by heating. Because of the very good geometrical control inherent in this process it is ideal for making large flat junctions of complex shapes and may well improve the efficiency and frequency limit of transistors of this type.

Similar advantages may be expected from the application of diffusion techniques to large transistors, and the narrow basewidths attainable by this process should increase the frequency range very greatly.

7. Conclusion.

The transistor has now developed to the stage of being classed as a high power device, and most of the factors defining its performance are well understood and controlled. Because its characteristics make it ideal for use in many control systems, it seems likely that the high power transistor will soon find a place in many commercial products.

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[9] Henkels, H. W. and Strull, G., "Very high power transistors with evaporated aluminium electrodes," Trans. I.R.E., ED 4, October, 1957, 291-294.

The Author :

Neville H. Fletcher was born in Armidale in 1930 and educated at the New England University College where he gained a B.Sc. degree in 1951, sharing the Sydney University medal in Physics. In 1952 he went to the United States on a Fulbright grant and a Fellowship at Harvard University where he did research work in solid state physics, obtaining the M.A. degree in 1953 and a Ph.D. in 1955.

Whilst in the United States, Dr. Fletcher was associated with the research laboratory of Clevite Transistor Products where in 1955 he was assistant head of the development section. During this time he worked on the design of power transistors and power diodes for the U.S. Signal Corps.

Since returning to Australia in 1956 he has been with the C.S.I.R.O. Radiophysics Laboratory working on the basic properties of semiconductors and semiconductor devices, and more recently on the physics of the growth of ice crystals.

Transistor Monostable Multivibrator for use with Counting Registers

R. E. AITCHISON, S.M.I.R.E. (AUST.)*

Summary.

The use of monostable multivibrators using transistors for the operation of counting relays is considered.

A suitable design is given in which the pulse width can be readily controlled and is relatively independent of variations of transistor parameters.

A specific example has a maximum counting ratio of 20 pulses per second, requiring a standby current of 6 ma and a maximum current of 18 ma from a 12 volt supply, and is suitable for use with transistor decade scaling units, in equipment for the measurement of frequency or nuclear radiation.

1. Introduction.

The application of transistors in counting equipment and computing circuits is increasing rapidly. In counting equipment for the measurement of frequency, and in counters for the measurement of nuclear radiation, the accuracy is increased by extending the counting period. Wherever the counting period is of the order of many seconds, the use of a counting relay is the most economic method of increasing the total counting capacity of the equipment. For maximum speed, the mechanical counter must be driven from a source which produces a pulse of accurately determined width, and in general a mono-

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*Electrical Engineering Department, University, Sydney, N.S.W.

Manuscript received by the Institution February 10, 1958.
Revised manuscript received March 4, 1958.
U.D.C. number 621.314.7 : 621.374.3.