Home-Made Transistors

Inexpensive Conversion of Selected Germanium Diodes

By P. B. HELSDON, A.M.Brit.I.R.E.

IT is quite practicable to make point-contact transistors at home which compare quite well with those advertised by professional manufacturers. The electrical ratings and characteristics of the type 2N32 represent an attainable target for home-made units. The real difficulty is to make two units with reasonably similar characteristics. Consequently circuits must be tailored to suit the individual transistor if best results are to be obtained.

Even the best available point-contact units require careful handling, both electrically and mechanically; home-made transistors are no exception. If a bought unit dies, that's the end of it, but home-made units can be repaired by rotating the crystal to a new spot and re-forming. One unit has been resuscitated at least six times after circuit mishaps. It now has a current-gain "alpha" of 3 and a collector impedance of 50,000 ohms. Assuming an emitter impedance of 500 ohms, this represents an available power gain of 23.5 db. The alpha cut-off frequency is about 3 Mc/s.

The following materials are required to make one point-contact transistor:—

(a) 1 germanium diode (see below).
(b) 6in of 20 s.w.g. tinned copper wire.
(c) 1in of 36 s.w.g. phosphor-bronze wire.
(d) $\frac{1}{4}$in of $\frac{3}{8}$in diameter synthetic resin bonded paper (s.r.b.p.) rod.
(e) $\frac{1}{16}$in of $\frac{3}{8}$in diameter s.r.b.p. rod.
(f) $\frac{1}{2}$in of $\frac{3}{8}$in i.d. × $\frac{1}{2}$in o.d. s.r.b.p. tube.
(g) 9in insulated tinsel copper flex (hearing-aid cord).
(h) $\frac{1}{8}$in of 1 mm insulating sleeving.
(i) Bee's wax or impregnating wax.
(j) $\frac{3}{64}$ in × $\frac{1}{16}$in × 0.001in mica sheet.
(k) 8 B.A. brass grub screw $\frac{1}{8}$in long.

The tools required are those used generally for light instrument work. In addition, a pocket microscope of magnification 20 to 30 times is essential.

A simple ohmmeter in conjunction with a torch battery ($4\frac{1}{2}$ volts) and a 4.7 kΩ resistor is all the test equipment necessary. The ohmmeter should have an internal 9-volt battery and a half-scale reading of about 5,000 ohms. A Model 7 "Avometer" on the 1-megohm range is suitable. Assembly and forming jigs are described below.

The basis of the home-made transistor is a commercial high-reverse-voltage germanium diode. Diodes with a "turnover" voltage of 80 volts or more are usually necessary.

The basic physical phenomena which permits transistor action is "hole" storage. This is undesirable in diodes since it reduces the efficiency of rectification at high radio frequencies. Recently manufactured diodes appear to have been treated to minimize "hole" storage, consequently they make poor transistors. The best transistors are made from the glass-tube-enclosed type of diode made a year or two ago. The CG4-C and CG1-C with metal end caps and wire leads usually make good transistors. It is not necessary to use new diodes. Burnt out units are satisfactory as long as the crystal surface is unpitted and bright.

The first step is to clean the wax from the brass cap at the crystal (or red) end of the diode. The glass tube is gently broken and the cat's-whisker end of the diode discarded. Every precaution must be taken to avoid touching the face of the crystal since contamination from the fingers or tools may ruin it. The crystal is found soldered to a small brass mounting pin which is held in the brass cap by a set screw and a sealing compound. It is difficult to release the crystal by undoing the screw because the sealing compound holds it fast.

The crystal on its pin mount can be pushed out of the cap by means of a suitable jig and a vice. The jig consists of a metal plate at least $\frac{3}{8}$in thick containing a hole (No. 2 drill) larger than the diameter of the glass tube but too small to pass the brass cap, and the shank of an old twist drill about $\frac{1}{16}$in diameter. The cap containing the crystal is placed so that what remains of the glass tube is in the plate and the drill shank is then placed in the centre of the cap, behind the crystal. This assembly is squeezed in a vice until the crystal on its brass mount is ejected. The brass cap is discarded.

The crystal on its brass mount must be handled only by means of clean tweezers or small instrument pliers. Clean the remains of the sealing compound from the brass pin by scraping with a suitable tool. With a Morse No. 62 drill make a hole centrally in the base of the pin to a depth of $\frac{1}{16}$in. Cut a 1in length of the 20 s.w.g. copper wire and quickly solder it into the hole. This is best done with the wire held vertically in the vice. Only "radio" 60/40 resin-cored solder of low melting point should be used, as acid fumes or excessive heat would spoil the crystal. Test the joint for strength. Slip a $\frac{1}{8}$in length of the 1 mm sleeving up to the joint. Solder 3in of the tinsel flex to the end of the wire, using a heat shunt if necessary to protect the crystal. If the crystal should have been contaminated by dust or soldering smoke it may be possible to clean it on a silicone-impregnated lens tissue.

The collector and emitter contact points are made from flattened 36 s.w.g. phosphor-bronze wire. Cut the wire to two $\frac{3}{8}$in lengths. Straighten if necessary. Flatten the wires by hammering between two hard smooth steel blocks. The flattened wires should be about 0.002in thick. The points are ground with a hand-held carborundum stone.

The stone should be fine, clean and preferably new. Grind one end of each wire to an equilateral V-shaped point. Only a few light strokes are required. Examine the points under the microscope to see that they are clean and sharp. The radius at the tip should be less than 0.0005in and the angle of the V about 60 degrees. The points should be as alike as possible. Do not touch with the fingers.

The body of the unit consists of a ¼-in length of the ⅜-in diameter s.r.b.p. rod. The central hole in the body is drilled No. 44 or 45 to give a sliding fit for the crystal mounting pin. A radial hole is drilled and tapped 8 B.A. to meet the central hole about 3/32 in from the top face. Two holes symmetrical to the tapped hole are drilled No. 64, one on each side of, and parallel to, the central hole at a radius of 7/64 in. These holes must be a tight fit for the 20 s.w.g. copper wire. A ⅛in long brass grub screw is fitted to the tapped hole.

Cut the 20 s.w.g. copper wire to two 2-in lengths and clench each piece about ½in from one end firmly in a pair of point-nosed pliers. The deformation of the wires ensures the necessary very tight fit in the body. Draw the wires into their holes in the body, with the short ends at the top, until they are immovable. The short ends are then bent through a right-angle in opposite directions tangentially and parallel to each other. The bends should be ⅛in from the top face of the body. The bent ends are then cut to be within the projected circumference of the body. With a fine file make flats on top of the bent wires. These flats should be in one plane and parallel to the body face. Tin the flats with a soldering iron and remove excess resin. Cut the ends of the wires projecting below the body to a length of ¾in. Solder to each a 3in length of the tinsel flex.

A cap for the transistor is made from s.r.b.p. tube ⅜in inside diameter, ½in outside diameter and ½in long. A 1/16in slice of the ⅜in diameter rod glued into the top of the cap completes it. The cap should be a light push fit on to the body.

Each cat's-whisker must be bent to make an angle of just over 90 deg. The distance between the point and the bend should be 1/32in less than the distance between the flats on the support wires and the top of the body. The angle to which the cat's-whiskers are bent is important. It should be as close to 90 deg as possible without actually being 90 deg or less.

The cat's-whiskers are soldered in place on the support wires by means of a simple jig. This jig consists of a brass 8 B.A. screw 1½in long, eased down if necessary to be a sliding fit in the central hole. The end of the screw is drilled centrally with a hole 1/64in in diameter and 1/16in deep. The jig is placed in the central hole to project 1/32in above the top face of the body. Tighten the grub screw in the side of the body to hold the jig in place. The head of the jig screw projecting below the body can be held in a vice during the following soldering operation.

With tweezers lay one of the cat's-whiskers on a support wire so that the V-shaped point rests in the 1/64 in hole in the jig. Balance the whisker if necessary by cutting the unpointed end with a pair of scissors. The jig must be set so that the unpointed part of the whisker is parallel to the top face of the body. Solder by placing the iron for a few seconds in contact with the support wire a little distance away from the whisker. The whisker will settle down a little during this operation. The joint must be a strong one since it will be stressed after assembly. There must be no solder on the parts of the whisker not in direct contact with the support wire. This is to maintain the necessary springiness of the whisker.

The second whisker is placed on the other support

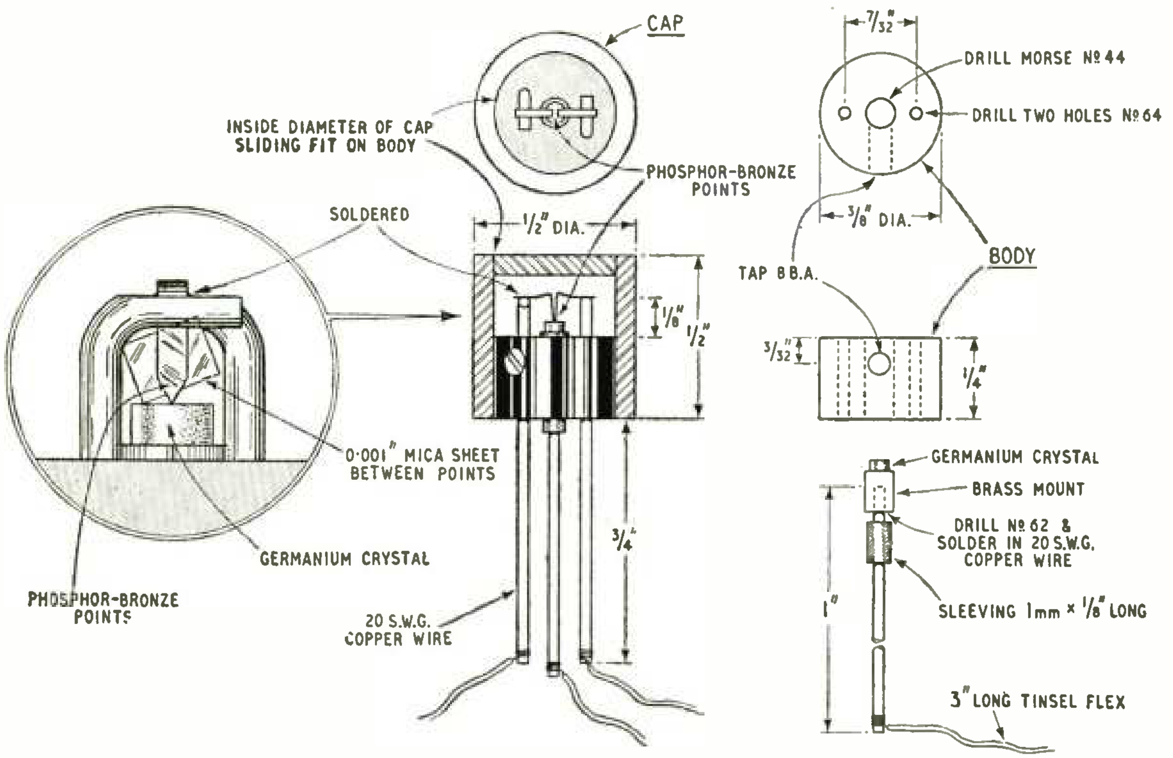


Fig. 1. Constructional details of home-made transistor.

E

in line with the first whisker. The points should be in contact together in the $\frac{1}{64}$in hole. Solder as for the first whisker. Remove the jig from the body and cut the spare ends of the whiskers close to the support wires. Trim with a fine file any projections outside the circumference of the body.

The points examined under the microscope should be within about 0.002in of each other at the tips. The bends should be slightly farther apart. Looked at sideways the two Vs should appear coincident. If the points themselves are in contact it does not matter at this stage.

Cut a rectangle of 0.001in mica about $\frac{3}{64}$in × $\frac{1}{16}$in and carefully place it with tweezers between the whiskers. Friction will hold it in place. The mica should be positioned about 0.01in above the points.

The assembly of the crystal requires care. Insert the crystal on its mount into the central hole until the crystal comes into contact with the points. Increase the pressure until the top parts of the whiskers deflect about 0.01in. Tighten the grub screw. The insulated sleeving should also be inside the central hole as far as it will go. This is to give mechanical stability.

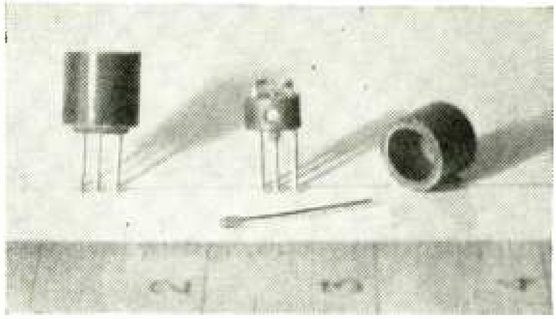
Examine the point spacing under the microscope. Any spacing between 0.0005in and 0.005in will make a transistor, but 0.002in is about optimum. If the points are found to be touching each other, release and partially withdraw the crystal and move the mica spacer down nearer the points. Readjust the crystal-point pressure as before. If the points skate about on the surface of the crystal it means that the angle at which the points meet the surface is incorrect. The angle must be as near normal as possible. Any latent instability of the points can be discovered by smartly tapping the body. The tapping procedure also helps to settle the points into the etched surface of the crystal. After tapping re-examine the point spacing. If satisfactory the cap should be fitted to protect the unit. Do not push the cap on too far or it will damage the points.

After forming and testing (described below) the unit is sealed by melting wax into the central hole and around the base of the cap. The wax must not penetrate as far as the crystal. The insulated sleeving helps to prevent this. The procedure is to place a small pellet of wax on the inverted unit and melt it quickly with a clean soldering iron. As soon as the wax melts, withdraw the iron.

All connections to the transistor must be made through the tinsel flex leads and not directly to the 20 s.w.g. wires. The reason is that the heat of soldering direct to the support wires would probably unsolder the internal joints. Also, if connection is made direct with crocodile clips, the shock of the spring-loaded clip slipping off is sufficient to break the cohesion developed at the points during forming.

The preliminary tests are to establish that a satisfactory double-diode exists. Check with the ohmmeter the resistance between the points, with the crystal lead (base connection) left floating. This is the unformed emitter-collector resistance and is usually about 1 megohm. A short-circuit requires readjustment of the points.

When the "Avometer" is used as an ohmmeter the normally positive (red) terminal has a negative potential. This will be described as the virtual negative terminal in the following text. With the virtual negative connected to the base, measure the resistance to each point. Each should be less than 1,000 ohms. Typical value is 500 ohms. Repeat with the virtual



Appearance of finished transistor, with and without sealing cap.

positive to the base. Each should be greater than 100,000 ohms. Typical value is 1 megohm. These readings should be fairly stable. If there is severe jitter the point pressure should be increased. The final forming process usually removes the last trace of jitter.

The next test is for transistor action. Connect the ohmmeter between one point and the base, with the virtual negative to this point (collector). Between the other point (emitter) and base, connect the 4½-volt battery in series with the 4,700-ohm resistor, making the emitter positive. The indicated collector-base resistance should fall about ten times, when the emitter bias is applied. Any observable drop in resistance is encouraging. If the drop is large, suspect an emitter-collector short-circuit. Repeat with the points interchanged. Choose the arrangement that gives the largest percentage drop in indicated resistance. Mark the collector wire with a spot of paint. If no transistor action can be detected, try a new spot on the crystal or change the crystal. Very few crystals tested by the author failed to give transistor action, and excellent results were obtained with about half of those tested.

The collector point must now be electrically formed to get the current gain (alpha) up to a useful value. The forming process also reduces the collector impedance. The increase in alpha, however, far outweighs the loss in collector impedance with successful forming. For example, forming can increase alpha from 0.1 to 2.5 while the collector impedance drops from 1 megohm to 25,000 ohms, giving an increase in power gain of nearly 16 times.

The theory of forming has been discussed by W. Shockley[3], J. Bardeen[1] and W. H. Brattain, W. G. Pfann[2,4], also by L. B. Valdes[5] and W. R. Sittner[6]. Methods of forming have been described by B. N. Slade[8] and R. W. Haegele[7]. The essence of these theories can be summarized as follows:—

The collector is formed by passing a short heavy pulse of current through it. The intense local heating changes the *n*-type germanium to *p*-type just under the point. In addition, thermal diffusion transfers some of the point material or surface impurities into this *p*-type area and changes an even smaller area in the immediate vicinity of the point back to *n*-type. The result is as if there were an *n-p-n* junction transistor with base input connection acting in cascade with the collector. The current gain is correspondingly high.

A theory that thermal traps are formed under the collector point also accounts for the very high alpha sometimes observed at low emitter currents. "Holes" caught in these traps form a positive space charge which attracts electrons from the collector. The average velocity of the electrons is much greater than that of the trapped "holes," consequently the current gain is that much greater. In practice the traps become saturated for emitter currents much above 50 μA. Consequently, the alpha falls to normal values of 2 or 3 at the more usual emitter current levels of 1 mA or so. In addition, this peak of alpha is very sensitive to temperature. This high alpha at low emitter current is not of much interest in transistors used as high-level amplifiers, but it is very important in the case of switching transistors. It greatly affects the triggering sensitivity in some switching circuits.

The purely thermal conversion to *p*-type material under the point can probably be provided by any short pulse, unidirectional or oscillatory; but better results are obtained when the collector is pulsed negatively, with suitable precautions to prevent the pulse becoming oscillatory. There is considerable scope for experiment in methods of forming.

A typical method of forming, given by B. N. Slade, is to discharge a capacitor of from 0.001 to 0.1 μF between the collector and base. The capacitor should have been previously charged to a voltage of from -75 to -300 volts. A charge/discharge switch is convenient. The emitter bias may be left connected, but the ohmmeter must be disconnected from the collector. Auxiliary contacts on the charge/discharge switch can do this.

Start pulsing at low voltage (80 volts) using the smallest capacitor. After each pulse measure the collector resistance (as before) with and without emitter bias. Increase the pulse in 20-volt steps and increase the capacitor at the end of each voltage cycle. Stop pulsing when the collector resistance, with emitter bias, has fallen to below 1,500 ohms, or when the collector resistance for zero bias has fallen below 10,000 ohms. A good transistor will be greater than 30,000 ohms for zero bias and less than 1,000 ohms with bias. When satisfactory results are obtained seal the unit with wax as described above.

More elaborate tests of the characteristics can be made point-by-point with suitable meters and current supplies.

The following tentative ratings are recommended for the home-made unit:—

Maximum collector voltage (d.c.)	-30 volts.
Maximum collector voltage (peak)	-80 volts.
Maximum collector current (d.c.)	-10 mA.
Maximum collector dissipation ..	50 mW.

These figures can, of course, be modified as experience is gained.

The application of the transistor in circuits requires care if a reasonable life is to be obtained. Inductive and capacitive surges are particularly to be avoided. Switching off a transistor circuit containing a transformer, for example, can easily produce an inductive kick which will "over-form" the collector, with disastrous results. In such circuits it is advisable to replace the usual on-off switch by a potentiometer plus switch, so that the current is slowly reduced to a low value before switching off. In circuits where the transistor is used to discharge a capacitor it is advisable to include a 1,000-ohm resistor in the collector lead to limit the peak current to a safe value. Oscillatory circuits which are liable to "squegg" are dangerous. For this reason one should not lightly attempt to obtain Class C operation by means of a C.R autobias network in the emitter circuit.

Home-made transistors have been applied to several different circuits, such as a saw-tooth generator, a sine-wave audio oscillator, an e.h.t. generator, a bi-stable multivibrator, a medium-wave straight receiver and an audio amplifier. The e.h.t. generator provides 860 volts d.c. for an input to the transistor oscillator of 2.2 mA at 16 volts. It forms part of a megohmmeter which measures up to 20,000 MΩ, and is contained in a box (complete with a hearing-aid type battery) measuring 6in × 4in × 3in.

The e.h.t. supply has also been used in conjunction with an image-convertor tube, and could be used to supply a small cathode-ray tube for oscillographic work.

The medium-wave receiver was, in fact, a crystal set (germanium diode) with one transistor stage of h.f. amplification, and used a loop aerial. A rough measurement of power gain gave a figure of 26 db. Part of this gain was due to positive feedback (reaction), but the circuit was quite as tame as any similar valve circuit. If one allows for the square law of the detector the effective gain was 52 db!

REFERENCES

[1] J. Bardeen and W. H. Brattain, "Physical Principles Involved in Transistor Action," *Phys. Rev.*, Vol. 75, p. 1208; 1949.

[2] J. Bardeen and W. G. Pfann, "Effects of Electrical Forming on the Rectifying Barriers of *n*-and-*p*-germanium Transistors," *Phys. Rev.*, Vol. 77, p. 401; 1950.

[3] W. Shockley, "Theories of High Values of Alpha for Collector Contacts on Germanium," *Phys. Rev.*, Vol. 78, p. 294; 1950.

[4] W. G. Pfann, "Significance of Composition of Contact Point in Rectifying Junctions on Germanium," *Phys. Rev.*, Vol. 81, p. 882; 1951.

[5] L. B. Valdes, "Transistor Forming Effects in *n*-type Germanium," *Proc. I.R.E.*, Vol. 40, No. 4, p. 445; 1952.

[6] W. R. Sittner, "Current Multiplication in the Type-A Transistor," *Proc. I.R.E.*, Vol. 40, No. 4, p. 448; 1952.

[7] R. W. Haegele, "A Visual Transistor Test Method and Its Application to Collector Forming," *Sylvania Tech.*, Vol. 4, p. 61; July 1951.

[8] B. N. Slade, "Factors in the Design of Point-contact Transistors," *R.C.A. Rev.*, Vol. 14, No. 1; March 1953.

ESSAY COMPETITION

Scientific Research in Industry

PRIZES of £100 and £50 are being awarded for the best and second-best entries in an essay competition which is being run by the journal *Research*. The essay has to be about any recent scientific discovery and its applications in industry, or any item of industrial research work that the competitor thinks should be undertaken. Entries have to be about 3,500 words long and must be written without technical jargon so that they can be understood by a board of directors or management committee with no specialist knowledge. Competitors must be able to prove that they are engaged on scientific research, and their essays have to be sent in by 30th June, 1954.

In addition to the ordinary prizes, two special ones of £100 and £50 are to be awarded by the *Sunday Times* for entries which are suitable for publication in a general newspaper and which relate to one of the following subjects: applications of atomic energy; aerodynamics; conservation or utilization of fuel; electronics in business efficiency.

Further details can be obtained from the publishers of *Research*, Butterworths Scientific Publications, 88 Kingsway, London, W.C.2.