June 25, 1946. R. S. OHL **2,402,662**

LIGHT-SENSITIVE ELECTRIC DEVICE

Filed May 27, 1941 5 Sheets-Sheet 1

FIG. 1

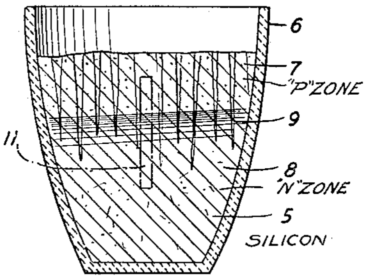
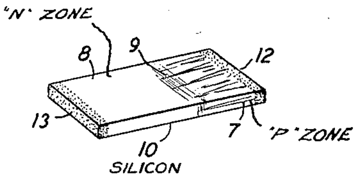


FIG. 2



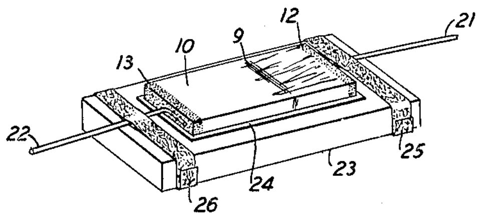


FIG. 5

FIG. 3

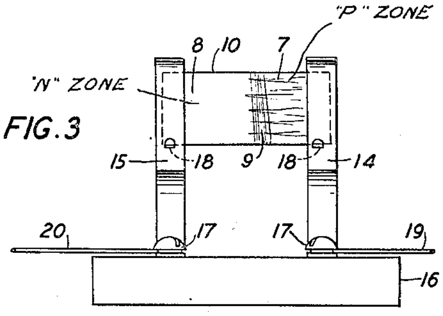


FIG. 4

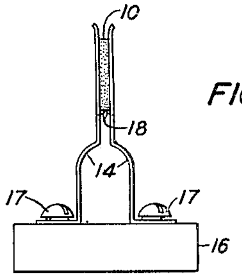


FIG. 6

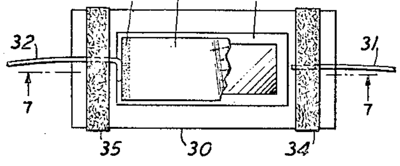
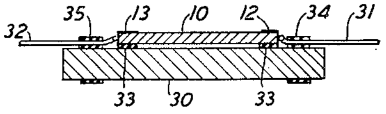


FIG. 7



INVENTOR
R. S. OHL
BY
Stanley B. Kent
ATTORNEY

June 25, 1946. R. S. OHL **2,402,662**

LIGHT-SENSITIVE ELECTRIC DEVICE

Filed May 27, 1941 5 Sheets-Sheet 2

FIG. 8

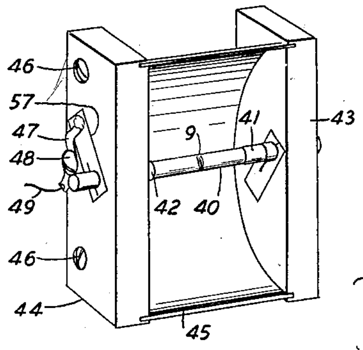


FIG. 9

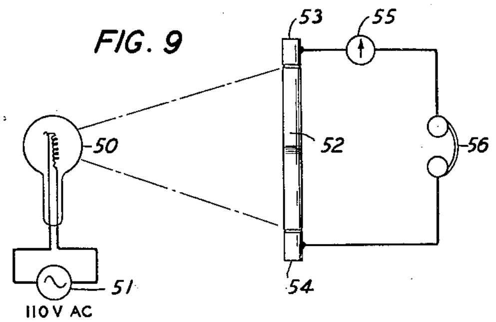


FIG. 10

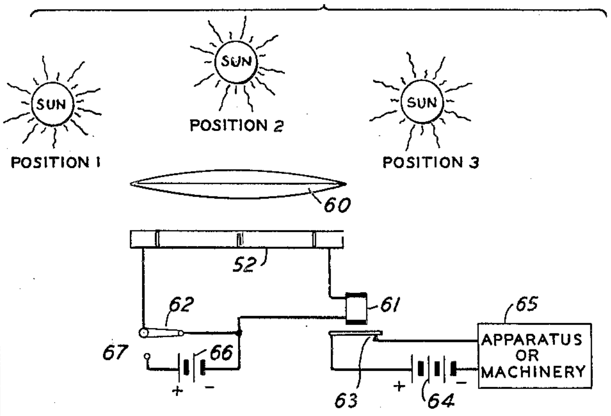


FIG. 11

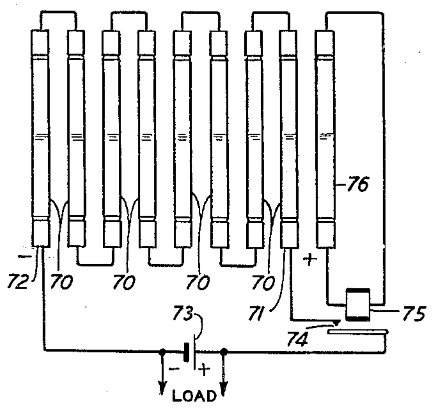


FIG. 13

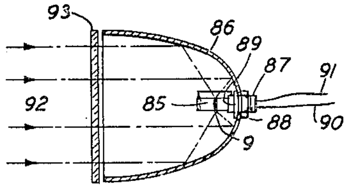


FIG. 12

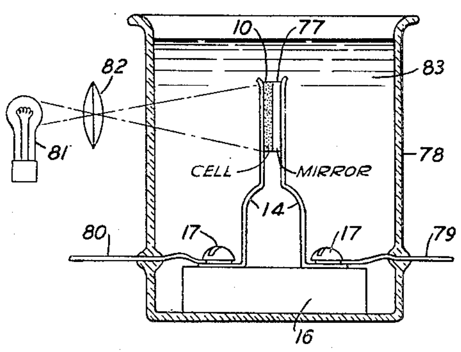
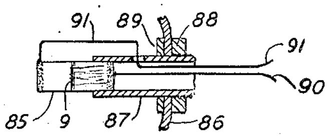


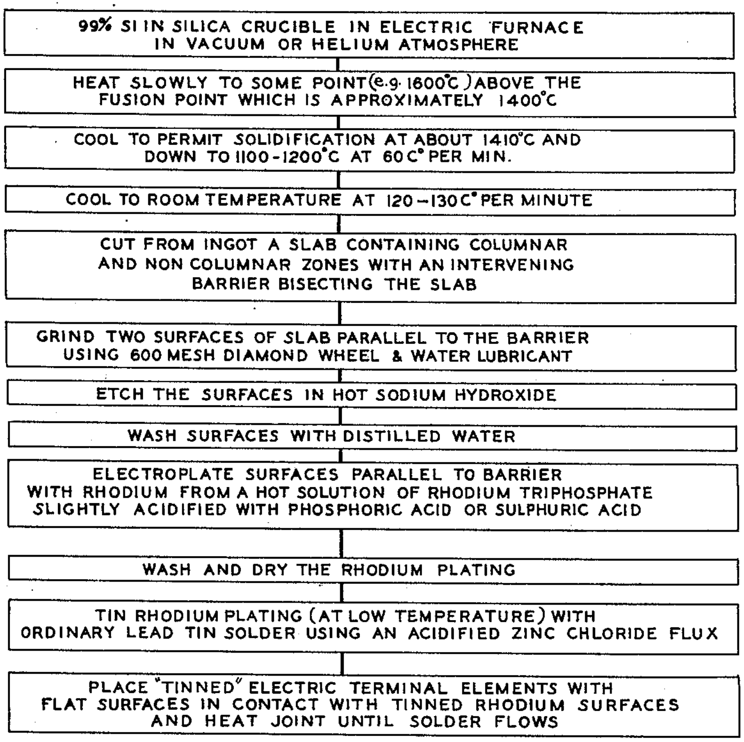
FIG. 13A



INVENTOR
R. S. OHL
BY

Stanley B. Kerr
ATTORNEY

FIG. 14


99% SI IN SILICA CRUCIBLE IN ELECTRIC FURNACE IN VACUUM OR HELIUM ATMOSPHERE

HEAT SLOWLY TO SOME POINT (e.g. 1600°C) ABOVE THE FUSION POINT WHICH IS APPROXIMATELY 1400°C

COOL TO PERMIT SOLIDIFICATION AT ABOUT 1410°C AND DOWN TO 1100-1200°C AT 60C° PER MIN.

COOL TO ROOM TEMPERATURE AT 120–130C° PER MINUTE

CUT FROM INGOT A SLAB CONTAINING COLUMNAR AND NON COLUMNAR ZONES WITH AN INTERVENING BARRIER BISECTING THE SLAB

GRIND TWO SURFACES OF SLAB PARALLEL TO THE BARRIER USING 600 MESH DIAMOND WHEEL & WATER LUBRICANT

ETCH THE SURFACES IN HOT SODIUM HYDROXIDE

WASH SURFACES WITH DISTILLED WATER

ELECTROPLATE SURFACES PARALLEL TO BARRIER WITH RHODIUM FROM A HOT SOLUTION OF RHODIUM TRIPHOSPHATE SLIGHTLY ACIDIFIED WITH PHOSPHORIC ACID OR SULPHURIC ACID

WASH AND DRY THE RHODIUM PLATING

TIN RHODIUM PLATING (AT LOW TEMPERATURE) WITH ORDINARY LEAD TIN SOLDER USING AN ACIDIFIED ZINC CHLORIDE FLUX

PLACE "TINNED" ELECTRIC TERMINAL ELEMENTS WITH FLAT SURFACES IN CONTACT WITH TINNED RHODIUM SURFACES AND HEAT JOINT UNTIL SOLDER FLOWS

FIG. 26

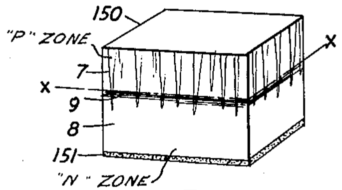


FIG. 27

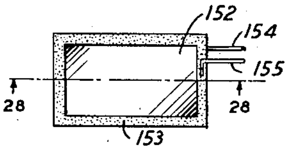


FIG. 28

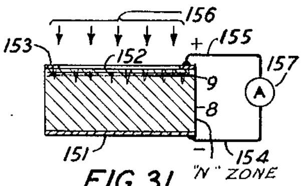


FIG. 29

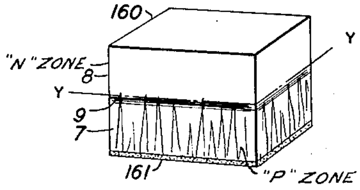


FIG. 30

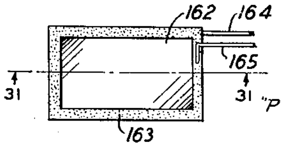
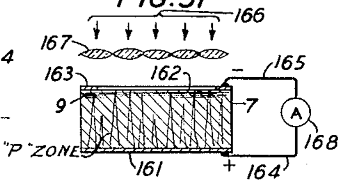


FIG. 31



INVENTOR
R. S. OHL
BY
Stanley B. Kent
ATTORNEY

June 25, 1946. R. S. OHL 2,402,662

LIGHT-SENSITIVE ELECTRIC DEVICE

Filed May 27, 1941 5 Sheets-Sheet 4

FIG. 15

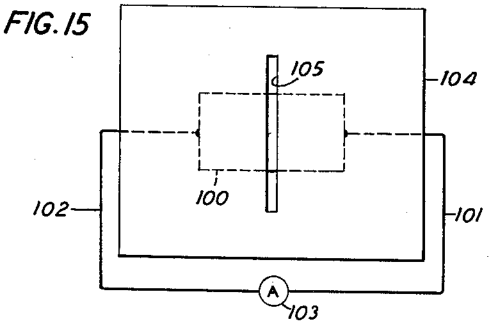


FIG. 17

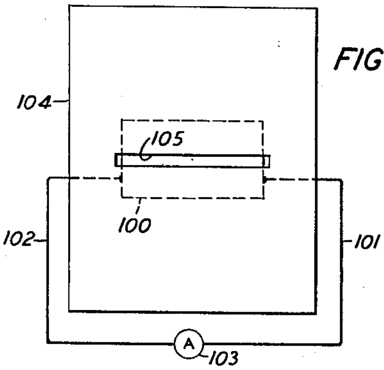
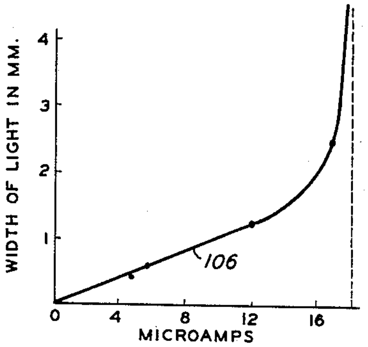


FIG. 16



SLOT (SEE FIG. 15) AT POSITION OF MAXIMUM CURRENT RESPONSE

FIG. 18

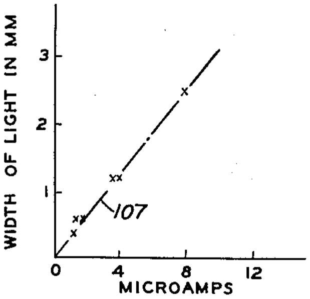
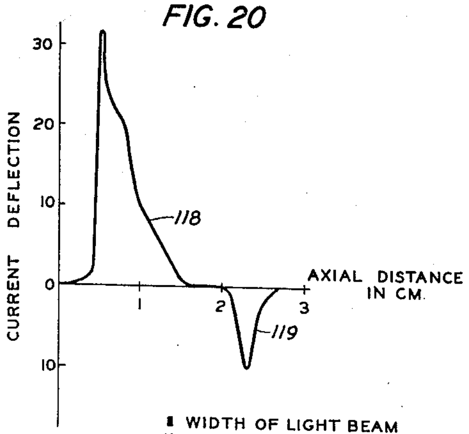
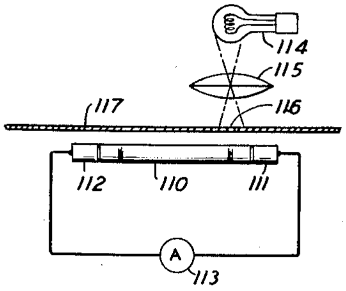


FIG. 20



▮ WIDTH OF LIGHT BEAM
WAVELENGTH OF LIGHT BEAM 1.1 MICRONS

FIG. 19



INVENTOR
R. S. OHL
BY

Stanley B. Kent.
ATTORNEY

June 25, 1946. R. S. OHL 2,402,662

LIGHT-SENSITIVE ELECTRIC DEVICE

Filed May 27, 1941 5 Sheets-Sheet 5

FIG. 21

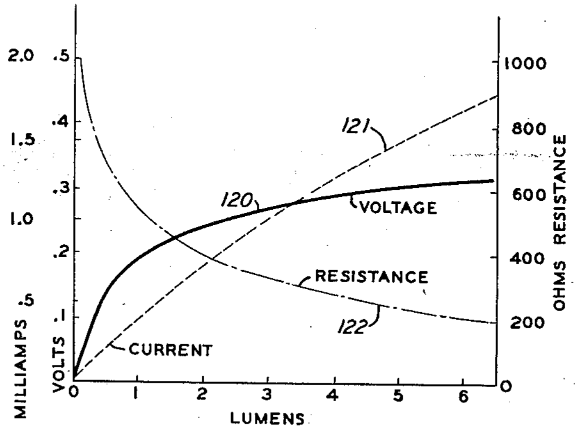


FIG. 22

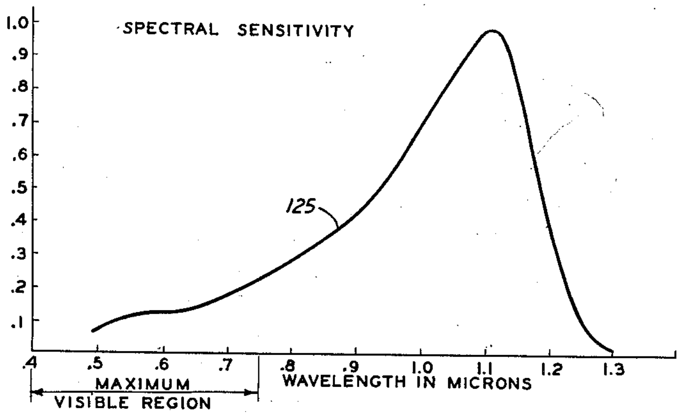


FIG. 23

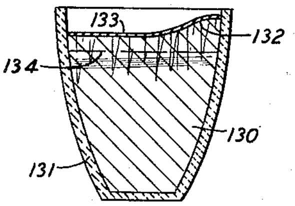


FIG. 24

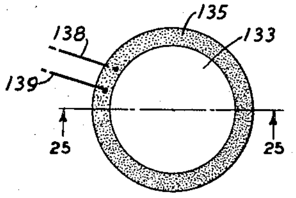
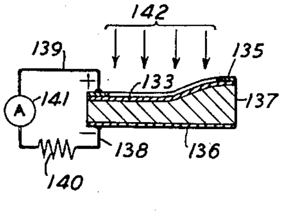


FIG. 25



INVENTOR
R. S. OHL
BY
Stanley B. Kent
ATTORNEY

UNITED STATES PATENT OFFICE

2,402,662

LIGHT-SENSITIVE ELECTRIC DEVICE

Russell S. Ohl, Little Silver, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application May 27, 1941, Serial No. 395,410

24 Claims. (Cl. 136—89)

This invention relates to light-sensitive electric devices and more particularly to photo-E. M. F. cells comprising fused silicon of high purity.

An object of the invention is to provide an improved light-sensitive electric device.

Another object of the invention is to provide an improved method of making light-sensitive electric devices of fused silicon of high purity.

In an example of practice illustrative of this invention, a photo-E. M. F. cell is formed of a portion of a silicon ingot which is provided with conductive terminals. The ingot is produced by fusing metallic silicon in powdered form in a silica (SiO_2) crucible in an electric furnace and slowly cooling the fused material until it solidifies and for a period of time thereafter. The powdered metallic silicon used is of a high degree of purity, say 99 per cent or higher. Certain material which has proved very satisfactory has a purity of approximately 99.85 per cent. Ingots which are suitable for the production of photo-E. M. F. cells possess a characteristic structure which is visible when the surface is suitably prepared in vertical section. The upper portion of the ingot exhibits a columnar crystalline structure while the lower portion is non-columnar, and across the ingot in the lower section of the columnar portion is a striated zone, the striations extending across the ingot. This striated zone has the characteristics of a barrier zone or barrier layer and is conveniently designated simply a so-called "barrier." The portion of the ingot suitable for photo-E. M. F. cells includes this barrier. A slab, square rod or cylinder of material is cut from this portion of the ingot so that the striated or barrier zone lies approximately midway between the ends. Low resistance conductive terminals are secured to these ends on opposite sides of the barrier by plating the ends with rhodium. Circuit connections may be made to the terminals either by friction contacts or by soldering.

The invention will now be described more in detail having reference to the accompanying drawings.

Fig. 1 shows in cross section an ingot of fused silicon within a silica crucible from which ingot photo-E. M. F. cells may be cut;

Fig. 2 illustrates a photo-E. M. F. cell embodying this invention;

Figs. 3 and 4 show the cell of Fig. 2 in one form of mounting;

Fig. 5 shows the cell of Fig. 2 in a modified form of mounting;

Figs. 6 and 7 illustrate another form of mounting wherein a reflecting surface is employed;

Fig. 8 shows a mounting for a cylindrical type of photo-E. M. F. cell;

Figs. 9, 10 and 11 show circuit arrangements of various kinds which embody photo-E. M. F. cells of this invention;

Fig. 12 shows a photo-E. M. F. unit mounted in a tank of distilled water and backed by a glass mirror;

Fig. 13 illustrates an infra-red exposure meter;

Fig. 13A shows a detail of Fig. 13 partly in cross section;

Fig. 14 is an operational diagram of one form of the method employed for producing photo-E. M. F. cells in accordance with this invention;

Fig. 15 is a diagrammatic showing of a test arrangement for determining the longitudinal distribution of the sensitivity of a photo-E. M. F. cell;

Fig. 16 is a plot of data obtained with the arrangement of Fig. 15;

Fig. 17 is an arrangement, similar to Fig. 15, for determining the transverse distribution of the sensitivity;

Fig. 18 is a plot of data obtained with the arrangement of Fig. 17;

Fig. 19 shows diagrammatically a test arrangement for determining the axial distribution of the sensitivity of a cylindrical section cut from an ingot having two barriers;

Fig. 20 is a plot of data obtained with the arrangement of Fig. 19;

Fig. 21 are plots of current, voltage and resistance, respectively, versus lumens of a typical photo-E. M. F. cell embodying this invention;

Fig. 22 is a plot of the spectral response of another typical photo-E. M. F. cell embodying this invention;

Fig. 23 shows in cross section an ingot of fused silicon within a silica crucible in which ingot the top surface is electrically light sensitive;

Figs. 24 and 25 illustrate a form of photo-E. M. F. cell cut from the upper portion of the ingot of Fig. 23;

Figs. 26, 27 and 28 illustrate a modified photo-E. M. F. cell according to this invention in the fabrication of which the columnar material above the barrier and a small amount of light sensitive barrier material is removed; and

Figs. 29, 30 and 31 illustrate still another modification according to this invention in the fabrication of which the material on the non-columnar side of the barrier and some of the barrier material is removed.

Like elements in the several figures of the drawings are indicated by identical reference characters.

During an investigation of the production of fused silicon of high purity and its use for point contact rectifiers applicant discovered that under certain conditions this material was sensitive to visible light, generating an electromotive force independently of any applied voltage. The light-sensitive effects were of a magnitude comparable to the most effective photoelectric substances then known.

The manner of the discovery was briefly as follows:

A considerable number of melts of pure silicon had been made up in connection with the above-mentioned investigation. The material for some of these melts had been heated in a dry helium atmosphere. From each of a plurality of ingots resulting from some of these melts in helium a cylindrical rod had been cut for the purpose of making specific resistance measurements. These rods were about ¾ inch long and ⅛ inch diameter. The rod from one of these melts had been equipped with metal end-pieces by a rhodium plating and lead-tin soldering process hereinafter to be described, to provide a good connection for the specific resistance measurements. Such a measurement was being made on this rod by applicant when he noticed, while viewing on an oscilloscope the wave shape of the 60-cycle current flowing through the rod, that the current in one direction was affected by light from an ordinary 40-watt desk lamp. A battery was then substituted for the 60-cycle current source and a rotating shutter was held between the rod and lamp to produce 20-cycle interruptions. A substantially square-top wave form was seen by applicant in the oscilloscope. Upon reduction and, finally, the elimination of battery voltage the square-top form persisted, although at a reduced amplitude.

This entirely unexpected phenomenon was recognized as of possibly great importance in the art of light-sensitive electric devices and further study of this phenomenon was undertaken forthwith. The outcome of such study is that improved light-sensitive electric devices and particularly photo-E. M. F. cells of high sensitivity and great stability have been made available. The present invention is a result of the above-mentioned discovery.

A form of ingot from which photo-E. M. F. cells can be cut is shown in Fig. 1. The ingot **5** is formed by the solidification of fused silicon in a silica crucible **6**. Such an ingot made from certain kinds of highly purified silicon powder in a manner hereinafter to be described, comprises two zones of visibly different structure. The upper zone **7** has a columnar structure, the columnar grains being of the order of one-half millimeter in width and extending down from the top of the ingot to a distance of 5 or 10 millimeters. The lower zone **8** has a non-columnar structure. The ingot fractures most easily in the lengthwise direction of the columns. The columnar portion of the fracture appears lustrous while the non-columnar portion has the appearance of a grayish mass of smaller crystals. Across the lower portion of the columnar zone **7** some sort of boundary or barrier **9** is found. In this region **9** the columnar portion tends to be striated, the striations extending across as well as between the columns. These striations appear, under a microscope, to have discontinuities at the columnar boundaries.

The above-mentioned barrier **9** is apparently the seat of the photo-E. M. F. effect. The upper zone **7** of the ingot **5** develops, on exposure to light, a positive potential with respect to the lower zone **8**.

The photo-E. M. F. device of Figure 2 comprises a silicon slab **10** cut from the ingot **5** of Fig. 1 at the position indicated by the dot and dash rectangle **11**. This rectangle **11** outlines the section of the slab **10** midway between the edges and parallel thereto. In other words, the slab **10** is so cut from the ingot **5** that the barrier **9** lies approximately midway between the ends of the slab.

The slab **10** may be cut from the ingot **5** by any suitable process, but preferably by a process which conserves as much useful material as possible. The uppermost and lowermost portions of the ingot may be used for other purposes, such as contact rectifiers. The intermediate portion, including the barrier **9**, may be used for photo-E. M. F. cells. A metal wheel charged with diamond particles is suitable for cutting the ingot **5**, a stream of distilled water being used to clear the cut particles from the kerf and to cool the surfaces.

The surfaces of the slab **10** wherein the outcropping of the barrier **9** occurs, may be used in the condition in which they are cut from the ingot **5**. There is an advantage, however, in polishing these surfaces in order to facilitate transmission of the exciting light into the interior of the slab **10**. These surfaces may advantageously be polished in many ways. One method which has been used is as follows: The surface was first roughed flat with 600 mesh aloxite, or M-302 optical powder, using an iron lap followed by 1,000 mesh aloxite, and a lead lap in the subsequent polishing with an optical powder such as for instance No. 95 optical powder. Suitable polishing abrasives are obtainable from the Norton Company, the American Optical Company or the Carborundum Company.

In order to facilitate the use of the slab **10** as a photo-E. M. F. cell, contact terminals **12** and **13** are provided on the ends of the slab by a process of rhodium plating. In a rhodium plating process which has been found to be very satisfactory, the end surfaces of the slab are ground flat using a 600 mesh diamond wheel and water lubrication. Thereafter the end surfaces, including small adjoining portions of the side and edge surfaces, are etched in hot sodium hydroxide solution and washed in distilled water. These etched surfaces are thereupon electroplated with rhodium from a hot solution of rhodium triphosphate slightly acidified with phosphoric acid or sulphuric acid. After washing and drying, the rhodium plating makes excellent contact terminals because it does not loosen from the silicon and is highly resistant to corrosion. Such contacts are remarkably free from noise when used in communication circuits, such as are used to convey sound currents.

The size of the photo-E. M. F. cell or unit **10** of Fig. 2 is not critical, but it has been found that advantageous dimensions are 11 millimeters for length, 5 millimeters for width, and 0.6 millimeter for thickness. The barrier **9** lies advantageously about midway between the terminals **12** and **13**.

One arrangement for mounting the photo-E. M. F. cell of Fig. 2 is illustrated in Figs. 3 and 4.

Two pairs of spring clips **14** and **15** are secured to a block of insulation **16** by machine screws **17**. The photo-E. M. F. cell **10** is slipped between the springs of the pairs of spring clips **14** and **15** with the contact terminals **12** and **13** in contact with the springs. Punched lips **18** prevent the photo-E. M. F. cell **10** from sliding down too far. Conductors **19** and **20** are connected to clips **14** and **15**, respectively. When the barrier **9** of the photo-E. M. F. cell **10** is irradiated, a positive potential is developed in conductor **19** with respect to conductor **20** providing that the columnar end of the unit is in contact with clip **14**, as shown.

Another arrangement for mounting the unit **10** such as illustrated in Fig. 2, is shown in Fig. 5. The unit **10** is provided with terminal conductors **21** and **22** by soldering. In soldering, the rhodium end surfaces **12** and **13** are tinned with ordinary lead-tin solder using an acidified zinc chloride flux. The solder must not be heated much above its melting point or there is danger of the rhodium being completely dissolved. The ends of the conductors **21** and **22** are freely tinned, then placed in contact with the respective tinned rhodium surfaces and the joint heated until the solder flows, the excess solder being squeezed from between the conductor and the rhodium plating. A strong bond results. The unit **10** with the conductors **21** and **22** is then insulatingly mounted on a copper block **23**. "Victron" or other suitable lacquer is used to secure the unit **10** to the block **23** with a sheet of insulation **24**, such as a sheet of cigarette paper, between the unit **10** and the block **23**. The conductors **21** and **22** are advantageously held out of contact with the copper block **23** by wrappings **25** and **26**, respectively, of friction or rubber tape.

Still another arrangement for mounting the unit **10** of Fig. 2 is illustrated in Figs. 6 and 7 which is adapted to make use of reflected light. The unit **10** is provided with conductors **31** and **32** in the manner described in connection with Fig. 5. The polished faces of the unit **10** are treated to reduce the surface reflection losses by the application of approximately a quarter wavelength thickness of "Victron" lacquer. Two dippings of the polished silicon surfaces in "Victron" lacquer is highly beneficial in improving the response of these photo-E. M. F. cells to light. The coated unit **10** is insulatingly mounted on a copper block **30**, the surface of the block adjacent to the unit having been highly polished and advantageously treated to render it highly reflective of the radiation used for energizing the photo-E. M. F. cell. The unit **10** is supported at its edges by a hollow rectangle **33**, cut from an insulating sheet, such as a sheet of cigarette paper. The slab **10**, rectangle **33** and block **30** are cemented together by "Victron" lacquer or other suitable cement, and the conductors **31** and **32** are held out of contact with the copper block **30** by wrappings **34** and **35**, similar to those described in connection with Fig. 5.

A modified form of silicon photo-E. M. F. cell is illustrated in Fig. 8. The photo-E. M. F. unit **40** is a cylindrical rod cut from an ingot, such as ingot **5** in Fig. 1, so that the barrier **9** lies approximately midway between the ends of the rod. The ends of the rod are plated with rhodium by the process hereinbefore described in connection with the plating of the slab **10** of Fig. 2. This unit **40** is supported by cylindrical spring contact clips **41** and **42** which pass through insulating supports **43** and **44**, respectively. The supports **43** and **44** are held apart and in parallel alignment by a curved metal plate **45** the curved edges of which are inserted in grooves in the inside faces of supports **43** and **44**. The supports **43** and **44** are held firmly against the plate **45** by bolts **46** extending through and between the supports. The concave face of the plate **45** is semicylindrical and specularly reflecting. Contact is made with the clip **42** by brush **57**, which is held in place by spring **47** and screw **48**. Flexible conductor **49** is soldered to the spring **47**. Similar contact is made with clip **41** on support **43**. The photo-E. M. F. cell **40** may be effectively illuminated by placing a source of light in front of the concave surface of the plate **45** or by orienting such concave surface toward a source of light.

A silicon photo-E. M. F. cell according to this invention has spectral properties which make it ideal for use with an incandescent light source. A circuit arrangement for using such a cell in this manner is illustrated in Fig. 9. An incandescent light source **50** energized from a 110-volt, 60-cycle source **51** illuminates a photo-E. M. F. cell **52** the contact terminals **53** and **54** of which are connected through an ammeter **55** to a telephone headset **56**. The contact terminals **53** and **54** may comprise coin silver, brass, steel or other suitable metal soldered to the rhodium-plated ends of the silicon cylinder **52**. The process of plating and soldering is advantageously that described hereinbefore in connection with the soldering of contact wires **21** and **22** to the photo-E. M. F. unit **10** of Fig. 5. The combined impedance of the meter **55** and telephone set **56** may be of the order of 1000 ohms, which does not involve the insulation resistance difficulties found in the use of vacuum photoelectric cells, nor does it require the use of a biasing battery. The arrangement of Fig. 9 may be used for reproducing sound from a motion picture sound record by illuminating the sound track, in well-known manner, by light from a source such as source **50** and directing the light passing through the sound track to the photo-E. M. F. cell **52**. Such circuits are remarkably free from noise.

An arrangement using a silicon photo-E. M. F. cell to generate power from sunlight is shown in Fig. 10. These cells are particularly suitable for this purpose because of their spectral properties and because of their great durability and their freedom from moisture deterioration. A silicon photo-E. M. F. cell **52** is placed so that sunlight will strike it, preferably condensed by lens **60** or a reflector, and connected in circuit with a relay **61** and a switch **62**. If the sunlight is sufficiently bright, relay **61** is energized and breaks at contact **63** the energizing circuit including battery **64** for the apparatus or machinery **65**. Whereas, when the sun is obscured or at night, the relay is deenergized and the contact **63** is closed to cause a lamp, for instance, in an airplane beacon to light, a marine warning signal to be sounded or beacon lights in marine lighthouses to be lit. In this kind of service no power is consumed during sunlight, as the sunlight itself is converted into electrical energy by the photo-E. M. F. cell **52** to keep the relay **61** excited.

While the photo-E. M. F. cell **52** of Fig. 10 converts light energy into electrical energy directly, it can be used in connection with a battery **66** by moving the switch **62** to its lower contact **67**. In this alternate arrangement the light is used merely to change the resistance in the circuit. The battery **66** should be so poled as to cause a minimum of current to flow through the silicon unit 52 when it is not illuminated. With such a poling of the battery 66 the maximum change in resistance of the silicon unit 52 takes place when the unit is illuminated. The positive terminal of battery 66 should be connected to the non-columnar terminal of the cell 52.

An arrangement for maintaining a battery in charged condition where sunlight is plentiful is illustrated in Fig. 11. A bank of eight photo-E. M. F. cells 70 are arranged to be energized by sunlight and are connected in series-aiding relationship, that is the columnar zone of each cell is connected to the non-columnar zone of the adjacent cell in the series. Terminal contacts 71 and 72 are connected to the terminals of battery 73, which is to be kept charged, through the contact 74 of a relay 75. The columnar terminal 71, which assumes a positive potential with respect to the non-columnar terminal 72 when the units are illuminated, is connected to the positive terminal of battery 73, while the non-columnar terminal 72 is connected to the negative terminal of battery 73. A similar photo-E. M. F. cell 76 is connected in series with the winding of relay 75. Cell 76 is so mounted as to be illuminated by the same intensity of sunlight as cells 70. The relay 75 is so designed that contact 74 will be closed by energizing current generated in photo-E. M. F. cell 76 when sunlight is intense enough to cause a charging voltage for battery 73 to be produced between the terminals 71 and 72 of the bank of photo-E. M. F. cells 70. The bank of eight cells will develop a potential difference of approximately 2 volts at 2 lumens and a maximum difference of potential of about 2.4 volts. Such an arrangement is useful when direct current in small quantities is required and difficult to obtain, but where sunlight is plentiful.

The silicon photo-E. M. F. cell of this invention has been successfully operated while immersed in distilled water. An arrangement for so operating such cells is illustrated in Fig. 12. A mounting identical with that shown in Figs. 3 and 4 is used. A plane mirror 77 is mounted on one side of the photo-E. M. F. unit 10, which is advantageously composed of a glass plate having the surface remote from the unit 10 silvered and insulated from the clips 14 and 15. The mounted unit 10 is placed in a glass container 78 having conductors 79 and 80 sealed through the side walls and connected to the clips 14 and 15, respectively, by screws 17. Light from lamp 81 is directed by lens 82 through the wall of the container 78 and distilled water 83 to the photo-E. M. F. unit 10. With this arrangement a great intensity of light may be concentrated on the unit 10 without danger of overheating. Immersing in distilled water is also advantageous with the units of Figs. 5, 6 and 7 where the terminal conductors are soldered to the rhodium plating. By limiting the temperature to that of the distilled water danger of melting the solder is obviated. The container 78 may be provided with heat-dissipating means of any well-known type, as, for example, cooling fins, recirculating pipes, or a fan for blowing air upon the container. In lieu of the distilled water a bath of any inert liquid, such as oil, may be used as a cooling agent. The liquid, of course, must be such as to transmit the radiation used for energizing the photo-E. M. F. cell 10.

The cylindrical type of silicon photo-E. M. F. cell, such as the unit 40 of Fig. 8, may be used advantageously for an exposure meter sensitive to infra-red light, as illustrated in Figs. 13 and 13A. A cylindrical rod 85 of silicon having the barrier 9, is mounted within a small parabolic reflector 86 in such a way that the barrier 9 is located at the focal position of the reflector. One end of the cylinder 85 is slipped within and soldered to a supporting metallic tube 87, for example of brass, which passes through a hole in the base of the reflector 86. This tube is secured to the reflector by the nut 88 which clamps the edge of the reflector around the hole between a ring 89 around tube 87 and the nut 88. One terminal conductor 90 is soldered to the rhodium plating of silicon unit 85 within tube 87. The tube 87 is soldered to the silicon unit 85 by the rhodium process described in connection with Fig. 5. The other end of silicon rod 85 is connected to an insulated conductor 91 which passes into and through the tube 87. The connecting wire 91 may be a short length of fine silver wire say #40 B and S gauge or fine enough so that its shadow cast upon the barrier surface is negligible. The energizing radiation is represented by the arrows 92 at the left of Fig. 13. Such a device is useful for infra-red photography in the long wave-length region of 11,000 Ångstroms to which photographic plates now available are sensitive. When used to measure infra-red intensity only, a filter should be used such as can be made of a flat optically polished glass disk 93 about 2 millimeters thick of color filter glass #254, as manufactured by the Corning Glass Works, Corning, New York.

An operational diagram for producing a photo-E. M. F. unit according to this invention is shown in Fig. 14. Silicon of a purity in excess of 99 per cent obtainable in granular form is placed in a silica crucible in an electric furnace in vacuum or helium atmosphere. Because of a tendency to evolution of gas with violent turbulence of the material, it is desirable to raise the temperature to the melting point by heating the charge slowly. Silicon will be found to fuse at a temperature of the order of 1400 to 1410° C.

In order to facilitate the heating process the silica crucible containing silicon may be placed within a graphite crucible which lends itself to development of heat under the influence of the high frequency field of the electric furnace to a much greater degree than does the silica crucible or its charge of silicon. Care must be taken, however, to avoid exposure of the melted silicon to graphite, oxygen or other materials with which it reacts vigorously. In this manner, the melt may be brought to a temperature of the order of 200° C. above melting point. In an example of practice of this process "high form" crucibles of 50 cubic centimeter capacity obtainable from Thermal Syndicate, Ltd., 12 East 46th Street, New York, New York, were employed. A furnace power input of 7.5 to 10 kilowatts was employed, the required time for melting being of the order of ten to twenty minutes, depending upon the power. The power was then reduced in steps and the temperature of the melted silicon dropped rapidly to the freezing point approximately six or seven minutes being required for the melt to solidify. The solid metal was then permitted to cool towards room temperature at the rate of 60 centigrade degrees per minute, this being effected by decreasing the power input at the rate of about one-half kilowatt per minute. When the temperature had been reduced to the order of 1150 to 1200° C., the power was shut off and the temperature then fell at the rate of about 130 centigrade degrees per minute.

In cooling there is a tendency after the upper surface has solidified for extrusion of metal to occur through this surface during the solidification of the remaining material. Upon examination of the cooled ingot it is found that a portion of the grain structure is columnar, as hereinbefore explained. This is, in general, the upper portion of the ingot or the first material to solidify. In the area last to solidify and beyond the columnar grains a non-columnar structure occurs. Between the zone first to cool and that last to cool there is found to be some sort of a boundary or "barrier" which occurs in a plane normal to the columns and this barrier has extremely important light sensitive electric properties. The barrier ordinarily occurs a short distance above where the columnar and non-columnar zones merge so that it extends across the columns near their lower ends. The region above the barrier develops a positive thermoelectric potential with respect to an attached copper electrode and may, therefore, be designated as the "P" zone. The region below the barrier develops a negative thermoelectric potential with respect to an attached copper electrode. It will be designated as the "N" zone.

To prepare a photo-E. M. F. cell, a slab of material is cut from the ingot in such a manner as to be bisected approximately by the barrier. The surfaces of the slab parallel to the barrier may be ground flat and electric terminal elements attached thereto in the manner diagrammed in Fig. 14 and described hereinbefore.

Granulated silicon of high purity now available on the market is produced by crushing material found in a large commercial melt. That supplied by Electrometallurgical Company, 30 East 42d Street, New York, New York, is of a size to pass a 30 mesh screen and to be retained by an 80 mesh screen. The crushed material is purified by treatment with acids until it has attained a purity considerably in excess of 99 per cent. The chemical composition of a typical sample of this material is approximately:

Si	99.35	O	.061
C	.019	H	.001
Fe	.031	Mg	.007
Al	.020	P	.011
Ca	.003	Mn	.002
N	.008		

In some samples amounts up to .03 Ti and .004 Cr have been found.

The results of measurements made in circuits comprising typical photo-E. M. F. cells of this invention will now be given to assist in the understanding of the invention. It is to be understood that these results are actual results obtained with certain specified photo-E. M. F. units. The invention has been embodied in many other units and may find embodiment in many different forms.

Fig. 15 illustrates a test arrangement for determining the location and size of the photo-E. M. F. region in a rectangular slab of silicon cut from an ingot in such a manner that the barrier approximately bisects the slab intermediate the ends thereof. It was a simple matter to determine that the sensitive region was a strip across the face of the slab, probably only a few millimeters wide. This was done by moving a light spot over the face of the slab while the terminals were connected to a milliammeter and noting the positions of the spot for maximum current at a plurality of transverse positions. In order to determine the actual dimensions of the sensitive region pieces of opaque black paper were slotted with variable width slots and slid over the surface of the slab until a maximum response was obtained for a given intensity of illumination of the area exposed by the slot. One such piece of paper is illustrated in Fig. 15. The slab **100** provided with rhodium-plated soldered wire terminals **101** and **102** is connected to a microammeter **103**. A sheet of black paper **104** covers the slab except for the surface exposed by slot **105** which lies transversely across the slab **100**. In order to find the position of maximum current response with a given width of slot **105** and given intensity of illumination of the surface of the slab exposed by the slot, the surface of the slab is explored by moving the paper **104** with the slot **105** lengthwise across the slab. For each width of slot the response would vary as typified by the graph of Fig. 20, but the response graph would differ from the specific shape there shown dependent upon the location of the barrier and the width of the slot. With a certain slab-type of photo-E. M. F. cell, mounted as shown in Fig. 5, which is 11.4 millimeters long, 5.5 millimeters wide and 0.6 millimeter thick, the data of Fig. 16 was obtained. The slot width is plotted as ordinates and the current at the position of maximum response as abscissae. The curve **106** shows that the response is linear for small slot widths up to about 1.5 millimeters, but that beyond this width there is a relatively small increase of response current from 14 microamperes to 18 microamperes for the whole length of the slab which, as mentioned above, was 11.4 millimeters. Therefore, it can be said that for this particular slab a strip of illumination about 1.5 millimeters wide across the slab yields very nearly the total response for a given light flux intensity.

Fig. 17 shows a test arrangement much like that of Fig. 15 but adapted to determine any variation of the photo-E. M. F. region transversely of the slab. The black paper **104** with the slot **105** is rotated 90 degrees with respect to its position in Fig. 15. The data of Fig. 18 was obtained with various slot widths oriented as in Fig. 17 and with the photo-E. M. F. cell described hereinbefore as being 11.4 millimeters long, 5.5 millimeters wide and 0.6 millimeter thick. At the position of maximum response for each slot width, the response is proportional to the width of the light band as shown by curve **107** of Fig. 18. This shows that there is negligible variation in the photo-E. M. F. region transversely of this slab.

It has happened that an ingot was formed with a double barrier one of which was near the top of the ingot and the other near the bottom. A photo-E. M. F. cell cut from such an ingot and including both barriers exhibits a double peaked response when explored with a narrow light spot. A test arrangement for determining such response is shown in Fig. 19. Such a photo-E. M. F. cell **110**, provided with metal terminals **111** and **112**, is connected to an ammeter **113**. A small transverse strip of the cell is illuminated by light from a source **114** directed by lens **115** through an aperture **116** in a sheet of black paper **117**. The cell **110** is moved lengthwise in front of the aperture **116** and the current deflection in the meter **113** is observed. With a certain rod-type of photo-E. M. F. cell, designated rod No. 2, which is 3.15 millimeters in diameter, 30 millimeters long and 24 millimeters between the plated terminals, the data of Fig. 20 was obtained. The width of the light beam was approximately one-half millimeter and its wave-length was 1.1 microns. The current deflection is plotted as ordinates and the distance from one selected end in centimeters is plotted as abscissae. As shown by curves **118** and **119**, this photo-E. M. F. cell exhibits two maxima of current response which are of opposite polarity. If both barriers are illuminated simultaneously the effects are opposing in the series circuit including the meter **113**. In this particular rod, one barrier is more responsive than the other, as indicated by the height of the peaks of curves **118** and **119**. The width of the areas under response curves **118** and **119** is probably due to the fact that the pure silicon of these units is appreciably light transmissive.

The illumination-response characteristics of the photo-E. M. F. cell described in connection with Figs. 15 to 18 as being 11.4 millimeters long, 5.5 millimeters wide and 0.6 millimeter thick, are shown by the curves of Fig. 21. The light source used to obtain this data was a 21-candle-power 6 to 8-volt automobile lamp No. 1130 operated at 7.40 volts and a color temperature of 2930° K. The filament was focused in a spot at the barrier at a magnification of about unity. The flux in this beam was varied by inserting Levy line screens whose transmission was determined in the position used. Curve **120** shows the open-circuit voltage and curve **121** shows the short-circuit current dependence on incident light flux in lumens. The voltage is expressed in volts and the current in milliamperes. Curve **122** shows the value of resistance at which the short-circuit current was reduced to one-half.

The spectral sensitivity of a cylindrical type of single-barrier photo-E. M. F. cell is shown in Fig. 22. This cell is 3.15 millimeters in diameter, 26 millimeters long and 21 millimeters between the terminal platings. Curve **125** shows the spectral sensitivity. The ordinates are equi-energy values, the maximum being unity. The abscissae are wave-lengths of the light in microns. The measurements were made using a small spot of light from the spectrometer focused on the barrier. It will be noted that, while the cell has some sensitivity in the visible region, the maximum is out in the infra-red. Since the light penetrates an appreciable thickness of silicon to reach portions of the barrier, the optical transmission of the silicon has an effect on the shape of curve **125**. Because of this large response in the deep infra-red, the silicon photo-E. M. F. cells of this invention provide a tool not available heretofore in the optical art.

If one is given a chunk of material known to have photo-E. M. F. properties and wishes to prepare it for use, say to demodulate light beams modulated at speech frequencies, the questions of shape, size, etc., immediately arise. In the case of metallic silicon the fabrication methods influence the answers considerably. It is not particularly difficult to cut either parallelepipeds or cylindrical rods from the solid material. Of the two shapes, the rods are the more difficult to fabricate, there is considerable waste of material and they have a higher barrier capacity for a given size of illuminated surface. Therefore, it is advantageous to make the more highly developed cells in the form of rectangular parallelepipeds.

The first parallelepipeds were cut about 3 millimeters thick, 8 millimeters wide and 12 millimeters long. These units gave a good photo-E. M. F. response as light indicating devices, but when they were used as light modulation detectors, the response to high frequencies was very poor. This lack of high frequency response was due to the capacity across the barrier. This effect is especially serious when the light intensity is low. Thinner slabs greatly improve the high frequency response in spite of a reduced current output. The over-all performance was noticeably decreased when the slabs were made thinner than about one-half millimeter. The least important dimensions, namely the width and length of the cell, appear to be determined by the impedance of the circuit into which they would be required to work and the size of the light source as well as other less important physical considerations. The most critical dimension is the thickness.

Below are tabulated relative sensitivity values of a number of thin slabs of silicon which were mounted on brass in a manner suitable for test with speech frequency modulated light. The currents were measured with a 50-ohm meter.

Sample No.	Length	Width	Thickness	Micro-amp.	Approx. active area	Micro-amp. per sq. mm.
	Mm.	*Mm.*	*Mm.*		*Sq. mm.*	
C1	7.9	4.4	.50	9	6.6	1.35
C2	7.8	4.2	.30	6	6.3	.95
C3	8.6	4.5	.30	7	6.7	1.04
C4	8.5	4.1	.50	18	6.2	2.9
C5	7.1	7.1	.25	8	6.4	1.25
D1	12	5	.64	22.5	7.5	3.0

Sample No. D–1 was treated with "Victron" lacquer to reduce surface reflection and mounted on a polished metal plate in a manner hereinbefore described.

The above data show that the thinner plates are somewhat less responsive to a given illumination per unit area than the thicker ones. It is physically difficult to cut the very thin plates and as there seems to be no particular advantage in doing so, it is probably satisfactory to cut the units with a thickness of about one-half millimeter.

During the production of silicon ingots according to the method hereinbefore described it was discovered that in a small proportion of the melts, say 3 to 5 per cent, the top of the melt was covered with material which was extruded from the interior during the cooling process. The top surfaces of some such ingots had a pale yellowish and greenish fluorescent appearance. It was discovered by applicant that if a contact were made to the top surface of such an ingot and some other point of the ingot, an electric current would flow if the top of the ingot were irradiated with infra-red or visible light. The electrons are apparently very efficiently released by the light and driven into the main conducting body of purified silicon. Substantially the full sensitivity is developed whatever may be the size of the surface contact area. This type of photo-E. M. F. cell shows some response for ultra-violet radiation.

An ingot which shows extruded material and the above-mentioned surface layer is shown in vertical section in Fig. 23. The ingot **130** is formed by the solidification of fused silicon powder of high purity in a silica crucible **131**. The extruded material forms a hump **132** in the upper surface of the ingot, while the whole surface is covered by the active layer **133**. The thickness of this layer **133** is necessarily greatly exaggerated in Fig. 23. It is in fact of microscopic thickness.

A photo-E. M. F. cell comprising this sensitive layer **133** may be fabricated by slicing off the top of ingot **130** at the position shown by dot and dash line **134**, and adding contact terminals as shown in Figs. 24 and 25. An advantageous form of contact for the sensitive surface layer comprises a ring of sputtered platinum **135**. Another way to form a contact ring is to use platinum paint and heat or "fire" the unit at a temperature of 500° to 550° C. The sensitive surface layer is not injured by such firing operation. The other contact **136** attached to the body of silicon **137** may be formed as hereinbefore described by electroplating with rhodium to which a copper wire **138** may be soldered. Similarly another copper wire **139** may be soldered to the platinum ring **135**. This photo-E. M. F. cell may be connected to a load circuit **140** in series with ammeter **141** by means of conductors **138** and **139**. The illumination of the light sensitive layer is indicated by the arrows **142**. The whole unit may be dipped in "Victron" or other suitable lacquer. The thickness of the lacquer on the sensitive layer may advantageously be made one-fourth the wave-length of the energizing radiation. Such a thickness reduces reflection.

Another form of photo-E. M. F. cell according to this invention in which the surface of the barrier is illuminated, is illustrated in Figs. 26, 27 and 28. Fig. 28 is a cross section through the cell of Fig. 27 at the plane indicated by the arrows **28**. In fabricating one form of such a cell, the columnar zone of a body of fused silicon is cut away down to the barrier, terminal contacts being made to the resulting exposed surface of the barrier zone and the opposite surface of the non-columnar zone. As shown in Fig. 26, a block of silicon **150** in the form of a parallelepiped is cut from a silicon ingot such as that shown in Fig. 1, having a barrier zone **9** substantially parallel to the top and bottom faces of the block. The columnar zone **7** is at the top and the non-columnar zone **8** at the bottom. The lower surface of the non-columnar zone **8** is provided with an electrical contact **151** by plating with rhodium in the manner hereinbefore described. The upper portion of the columnar zone **7** is then cut away down to the plane represented by the line X—X. This plane extends through the upper layer of the barrier zone, the location of which zone is determined by exploring the vertical surfaces of the block **150** with a small spot of light and noting the current response in a test circuit connected to the upper and lower surfaces of the block **150**. The resulting barrier surface **152** is then highly polished and a narrow strip around the periphery of the polished surface is roughened with M-302 emery. Both the polished and roughened portions of surface **152** are then plated with rhodium in the manner hereinbefore described. The rhodium plating is then rubbed off from the polished portion of the surface **152** leaving a strip of plating **153** around the periphery. This strip **153** serves as an electrical contact for the barrier region of the resulting photo-E. M. F. cell. Conductors **154** and **155** may be soldered to the rhodium contacts in the manner hereinbefore described. The illumination of the light sensitive surface is indicated by the arrows **156**. When illuminated, conductor **155** assumes a positive potential with respect to conductor **154**.

Another photo-E. M. F. cell, similar to that just described but in which the non-columnar material **8** is cut away down to the barrier **9**, is illustrated in Figs. 29, 30 and 31. Fig. 31 shows a cross section of the cell of Fig. 30 at the plane indicated by arrows **31**. In fabricating this form of cell, a block of silicon **160** similar to that of Fig. 26, having a columnar zone **7**, a non-columnar zone **8** and a barrier region **9** is cut from an ingot of fused silicon. The bottom surface of the columnar zone **7**, the columnar zone being at the bottom in Fig. 29, is provided with an electrical contact **161** by plating with rhodium in the manner hereinbefore described. The non-columnar zone **8** is cut away down to the upper portion of the barrier region represented by the plane indicated by the line Y—Y. The resulting barrier surface **162** is polished, roughened around the periphery and plated with rhodium which is partly removed to form contact **163** as explained in connection with the cell of Figs. 27 and 28. Conductors **164** and **165** are soldered to the rhodium platings **161** and **163**, respectively. The polished surface **162** is shown illuminated by light rays **166** passing through 30-degree lenses **167**. When illuminated, conductor **164** assumes a positive potential with respect to conductor **165**.

The edges of the cells of Figs. 28 and 31 may be provided with an opaque insulating coating, such as black pitch, to exclude extraneous light. The 30-degree lenses of Fig. 31 may also be used with the cell of Fig. 28. The use of such lenses is advantageous when these cells are used as exposure meters.

It has been found that individual photo-E. M. F. cells of the kind illustrated in Figs. 28 and 31 are about equally sensitive over the whole exposed barrier surface as determined by exploring the surfaces of several cells with a small spot of light. It is advantageous to cut close to or even into the barrier region. Measurements made on several cells indicate that there is some advantage in cutting away the columnar region of the silicon block as illustrated in Figs. 26, 27 and 28 instead of the non-columnar region as illustrated in Figs. 29, 30 and 31. The columnar material is more transparent than the non-columnar material and accordingly a somewhat larger proportion of the light can reach the light sensitive region. However, both types of cells are useful. The amount of silicon adjacent to the barrier region on the side opposite to that which is illuminated, in these types of cells appears not to be critical.

An ammeter **157** is shown connected to the conductors **154** and **155** of the photo-E. M. F. cell of Fig. 28 and an ammeter **168** is shown connected to conductors **164** and **165** of the photo-E. M. F. cell of Fig. 31.

A coating of "Victron" or other suitable lacquer may be used on the polished surfaces of the cells of Figs. 28 and 31 to reduce reflection losses.

The nature of the boundary or barrier zone and the reasons for its electrical behavior are obscure. There is evidence to indicate that the phenomena observed are dependent not only upon high purity of the silicon but also upon the character of the extremely small amounts of impurities which remain. In the most satisfactory ingots the "N" zone portions have very tiny gas pockets and upon cutting through this zone a characteristic odor of acetylene is observed. Moreover, certain lots of highly pure silicon which have at first appeared to be defective in barrier-forming properties have been satisfactorily conditioned by the introduction of carbon or silicon carbide into the melt in amounts of the order of 0.1 per cent to 0.5 per cent and this should be done if a preliminary sample of a particular lot of material does not form the distinctive barrier structure.

The slow cooling is an important factor as is readily demonstrated upon microscopic examination of sectioned specimens of silicon ingots which have been etched and stained. The barrier zone is evident as one or more striations of a somewhat different appearing material in consequence of its different reaction to the etching acid. In the case of slow cooling the striation extends across the entire ingot, thus dividing the ingot into discrete "P" and "N" zones. Where, however, the cooling is precipitate as in the case of shutting off the heating power suddenly as soon as fusion occurs and permitting the temperature to fall suddenly, the first spots to cool develop "P" zones and these are surrounded by "N" zone matrices in such irregular fashion as to render the resulting ingot quite unsatisfactory for photo-E. M. F. cells. The slow cooling rate is important in developing an orderly striation or barrier. Features of the method of preparing effective silicon materials are described and claimed in the application of J. H. Scaff, Serial No. 386,835, filed April 4, 1941, for improvements in the Preparation of silicon materials. For further information regarding material from which light sensitive electric devices according to this invention may be fabricated, reference is made to the disclosure of this Scaff application.

"Victron" lacquer, which has been referred to hereinbefore, is a solution of polystyrene with the addition of a small amount of resin to produce a good lacquering result. It is a commercial product.

This application is a continuation in part of application Serial No. 385,425, filed March 27, 1941, for Electrical translating devices utilizing silicon.

Subject matter divided from this application is disclosed and claimed in Application Serial No. 458,709, filed September 17, 1942.

What is claimed is:

1. The method of producing a light sensitive electric device which comprises fusing purified powdered silicon in an inert atmosphere in a silica (SiO_2) crucible, cooling the silicon so as to produce an ingot which includes a light sensitive portion intermediate the top and bottom of the ingot on either side of which portion the ingot is visibly different in structure, cutting a section from said ingot which includes some of said intermediate and adjacent portions, and attaching electrical connections to the portions of said section on opposite sides of said intermediate portion.

2. The method of producing a light sensitive electric device which comprises fusing purified powdered silicon in an atmosphere of helium in a silica (SiO_2) crucible, slowly cooling the silicon so as to produce an ingot which includes a light sensitive portion intermediate the top and bottom of the ingot on either side of which portion the ingot is visibly different in structure, cutting a section from said ingot which includes some of said intermediate and adjacent portions, and attaching electrical connections to the portions of said section on opposite sides of said intermediate portion.

3. A light sensitive electric device comprising a light sensitive body of solidified fused silicon having a zone of columnar structure and a second zone of non-columnar structure, an electrical terminal connected to the columnar zone, and a second electrical terminal connected to the non-columnar zone.

4. A light sensitive electric device comprising a light sensitive body of silicon having a purity of the order of 99 per cent and so formed as to have a zone of columnar structure and a zone of non-columnar structure integrally connected together, an electrical terminal connected to the columnar zone, and a second electrical terminal connected to the non-columnar zone.

5. A light sensitive electric device comprising a light sensitive body of silicon having a purity in excess of 99 per cent and an internal structure comprising two zones of very different formation separated by a barrier formed by the fusion and solidification of said silicon the electrical condition of which is modified by light, and an electrical terminal connected to each zone.

6. A light sensitive electric device comprising a light sensitive integral body of silicon having a purity in excess of 99 per cent, the body having a pair of electrical terminal surfaces adjacent one of which the internal structure of the body is columnar and adjacent the other of which it is non-columnar.

7. A photo-E. M. F. cell comprising a slab of solidified fused silicon having a light sensitive barrier produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent and a polished surface in the region of said barrier, electrical terminals connected to the metallic silicon on opposite sides of said barrier, respectively, and a thin coating of transparent lacquer on said polished surface.

8. A light sensitive electric device comprising solidified fused silicon having a light sensitive barrier produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent and a polished surface in the region of said barrier, electrical terminals connected to the metallic silicon on opposite sides of said barrier, respectively, and a layer of transparent lacquer on said polished surface of thickness one-quarter the wave-length of light to which said layer is sensitized.

9. A photo-E. M. F. cell comprising a slab of solidified fused silicon having a light sensitive barrier produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent and a polished surface in the region of said barrier, electrical terminals connected to the metallic silicon on opposite sides of said barrier, respectively, and a layer of transparent lacquer on said polished surface 0.3 micron thick.

10. A photo-E. M. F. cell comprising a slab of solidified fused silicon having a light sensitive barrier produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent and polished side surfaces, a mounting block having a specular surface, means to maintain one of said polished side surfaces close to said specular surface but out of electrical contact therewith, and electrical contacts connected to the metallic silicon of said slab on opposite sides of said barrier, respectively.

11. A photo-E. M. F. cell comprising a section of fused silicon ingot having a transverse barrier sensitive to light produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent, and individual platings of rhodium intimately joined to the metallic silicon on opposite sides of said barrier, respectively.

12. A photo-E. M. F. cell comprising a section of fused silicon ingot having a transverse barrier sensitive to light produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent, individual platings of rhodium intimately joined to the metallic silicon on opposite sides of

said barrier, respectively, and a separate terminal contact attached by lead-tin solder to each of said platings of rhodium.

13. A light sensitive electric device comprising a photo-E. M. F. cell including solidified fused purified silicon having a barrier produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent which barrier is sensitive to light, a liquid container having a light transmitting portion, means to mount said cell within said container with the barrier opposite to said light transmitting portion of said container, and a light transmitting high resistance liquid within said container within which liquid said cell is immersed.

14. A light sensitive electric device comprising a solid body formed by cooling fused silicon having a zone of columnar structure, a zone of non-columnar structure and a zone including striations within the zone of columnar structure near the zone of non-columnar structure which is sensitive to light, said striations being visible on microscopic examination of a suitably etched surface including the three zones and extending transversely to the columnar structure.

15. A photo-E. M. F. cell comprising a solid body formed by cooling fused silicon having a purity in excess of 99 per cent and so formed as to have a "P" zone, an "N" zone and a zone between said "P" zone and "N" zone which is sensitive to light including striations which are visible on microscopic examination of a suitably etched surface extending through said three zones.

16. A photo-E. M. F. cell comprising a right cylinder of solidified fused purified silicon having a barrier sensitive to light and formed by the fusion and solidification of said silicon, and contact terminals connected to the silicon at the respective ends of said cylinder.

17. A photo-E. M. F. cell comprising a plurality of right cylinders of solidified fused silicon each having a barrier sensitive to light and formed by the fusion and solidification of said silicon, and contact terminals connected to the silicon on opposite sides of each barrier, a contact terminal of each cylinder being conductively connected to a contact terminal of another cylinder.

18. A photo-E. M. F. cell comprising a light sensitive body of silicon solidified in two zones of different formations with an integral interposed barrier produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent, rhodium coatings on separated surface portions of said two zones respectively, and elements of a different metal connected by solder to said rhodium coatings respectively.

19. A photo-E. M. F. cell comprising a light sensitive body of silicon solidified in two zones of different formations with an integral interposed barrier produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent, said body being in the form of a right cylinder, rhodium coatings on the ends of said cylinder, and right cylinders of a high conductivity metal soldered to said coatings respectively.

20. A photo-E. M. F. cell comprising a right cylinder of solidified fused purified silicon having a barrier formed by the fusion and solidification of said silicon, and contact terminals connected to the silicon at the respective ends of said cylinder, the barrier having a light responsive characteristic whereby the silicon at one end of the cylinder assumes a potential different from that of the silicon at the other end when the barrier is illuminated.

21. A light sensitive electric device comprising a body of silicon solidified in two zones of different formations with an integrally interposed barrier formed by the fusion and solidification of said silicon, and an electrical terminal electrically connected to each zone, the barrier having a light responsive characteristic whereby the silicon in one of said zones assumes a potential different from that of the silicon in the other of said zones when the carrier is illuminated.

22. A light sensitive electric device comprising a body of solidified fused silicon having a barrier layer formed by the fusion and solidification of said silicon, and conducting means connected to said barrier layer on opposite sides thereof, the barrier layer having a light responsive characteristic whereby the conducting means connected to one side of the barrier layer assumes a potential different from that of the conducting means connected to the other side of the barrier layer when the barrier layer is illuminated.

23. A photo-E. M. F. cell comprising a section of fused silicon ingot having a transverse barrier sensitive to light produced by fusing and cooling granulated silicon of a purity in excess of 99 per cent, and electrical terminals contacting the metallic silicon on opposite sides of said barrier, respectively.

24. A light sensitive electric device comprising a light sensitive solid body formed by cooling fused silicon of a purity in excess of 99 per cent so as to have a light sensitive layer integrally joined to silicon which is relatively insensitive to light.

RUSSELL S. OHL.

Jan. 28, 1930. J. E. LILIENFELD 1,745,175

METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Filed Oct. 8, 1926

Fig.1.

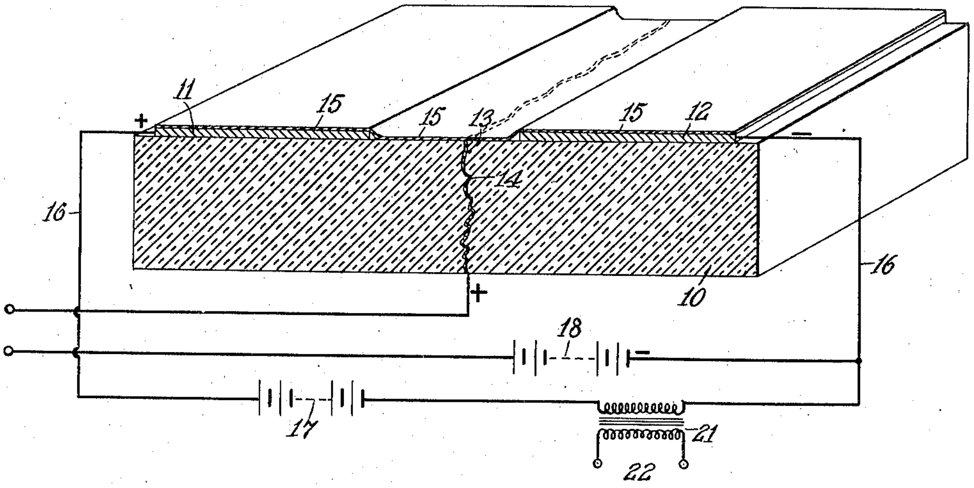


Fig.2.

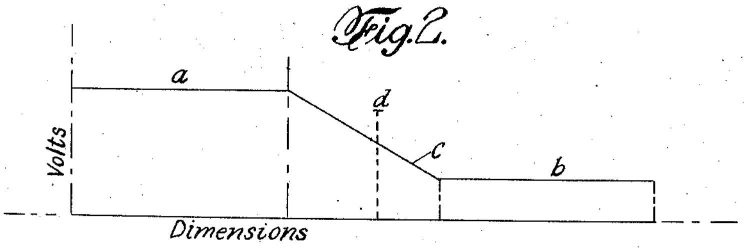
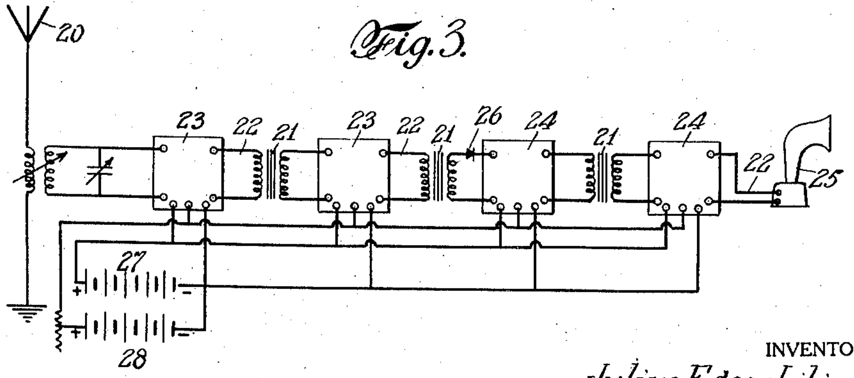


Fig.3.



INVENTOR
Julius Edgar Lilienfeld
BY
ATTORNEY

Patented Jan. 28, 1930 **1,745,175**

UNITED STATES PATENT OFFICE

JULIUS EDGAR LILIENFELD, OF BROOKLYN, NEW YORK

METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Application filed October 8, 1926, Serial No. 140,363, and in Canada October 22, 1925.

The invention relates to a method of and apparatus for controlling the flow of an electric current between two terminals of an electrically conducting solid by establishing a third potential between said terminals; and is particularly adaptable to the amplification of oscillating currents such as prevail, for example, in radio communication. Heretofore, thermionic tubes or valves have been generally employed for this purpose; and the present invention has for its object to dispense entirely with devices relying upon the transmission of electrons thru an evacuated space and especially to devices of this character wherein the electrons are given off from an incandescent filament. The invention has for a further object a simple, substantial and inexpensive relay or amplifier not involving the use of excessive voltages, and in which no filament or equivalent element is present. More particularly, the invention consists in affecting, as by suitable incoming oscillations, a current in an electrically conducting solid of such characteristics that said current will be affected by and respond to electrostatic changes. Means are associated with the aforesaid conducting solid whereby these electrostatic changes are set up conformably with the incoming oscillations which are thus reproduced greatly magnified in the circuit, suitable means being provided, also, to apply a potential to the said conducting solid portion of the amplifier circuit as well as to maintain the electrostatic producing means at a predetermined potential which is to be substantially in excess of a potential at an intermediate point of said circuit portion.

The nature of the invention, however, will best be understood when described in connection with the accompanying drawings, in which—

Fig. 1 is a perspective view, on a greatly enlarged scale and partly in section, of the novel apparatus as embodied by way of example in an amplifier.

Fig. 2 is a diagrammatic view illustrating the voltage characteristics of an amplifier as shown in Fig. 1.

Fig. 3 is a diagrammatic view of a radio receiving circuit in which the novel amplifier is employed for two stages of radio frequency and two of audio frequency amplification.

Referring to the drawings, 10 designates a base member of suitable insulating material, for example, glass; and upon the upper surface of which is secured transversely thereof and along each side a pair of conducting members 11 and 12 as a coating of platinum, gold, silver or copper which may be provided over the glass surface by well-known methods such as chemical reduction, etc. It is desirable that the juxtaposed edges of the two terminal members 11 and 12 be located as closely as possible to each other; and substantially midway of the same there is provided an electrode member 13, which is of minimum dimensions to reduce capacity effect. This member consists of a suitable metal foil, preferably aluminum foil, and may conveniently be secured in position by providing a transverse fracture 14 in the glass and then reassembling the two pieces to retain between the same the said piece of aluminum foil of a thickness approximating one ten-thousandth part of an inch. The upper edge of this foil is arranged to lie flush with the upper surface of the glass 10.

Over both of the coatings 11 and 12, the intermediate upper surface portion of the glass 10, and the edge of the foil 13 is provided a film or coating 15 of a compound having the property of acting in conjunction with said metal foil electrode as an element of uni-directional conductivity. That is to say, this coating is to be electrically conductive and possess also the property, when associated with other suitable conductors, of establishing at the surface of contact a considerable drop of potential. The thickness of the film, moreover, is minute and of such a degree that the electrical conductivity therethru would be influenced by applying thereto an electrostatic force. A suitable material for this film and especially suitable in conjunction with aluminum foil, is a compound of copper and sulphur. A convenient way of providing the film over the coatings

11 and 12 and the electrode 13 is to spatter metallic copper by heating copper wire within a vacuum, or by depositing copper from a colloidal suspension, over the entire upper surface and then sulphurizing the deposited copper in sulphur vapor, or by exposure to a suitable gas as hydrogen sulphide or a liquid containing sulphur, as sulphur dissolved in carbon bisulphide.

To produce the required flow of electrons through the film 15 a substantial potential is applied across the two terminal coatings 11 and 12 as by conductors 16 leading from a battery or like source 17 of direct current. As shown in the diagrammatic view, Fig. 2, the dimensional volt characteristics of the device indicate a substantially steady voltage of value *a* over the coating 11 and a corresponding steady voltage *b* of diminished value over the coating 12, while over the portion of the surface between said coatings the voltage in the film 15 will be according to the gradient *c*. As aforesaid, the electrode 13 is located substantially midway of the inner ends of the terminal coatings 11 and 12 and there is arranged to be supplied thereto a potential indicated by the value *d*, Fig. 2, and somewhat in excess of the voltage prevailing along the gradient *c* at this point. This potential may be applied by means of a battery or like source of potential 18, the negative pole of which is connected to the negative pole of the battery 17. In the circuit of the electrode 13 and source of potential 18 is also included some exterior source of oscillating or fluctuating current, which source is indicated, by way of example, in Fig. 3, as the antenna 20 of a radio communication circuit.

The effect of thus providing an excess positive potential in the electrode 13 is to prevent any potential in the oscillating circuit hereinbefore described from rendering said electrode of zero potential or of a negative potential, which would then permit a current to pass from the electrode edge to the film 15; as in the reverse direction where a positive voltage is maintained, the two members—namely electrode and connecting film—act as an electric valve to prevent the flow. Maintaining a positive potential at this point, however, insures that the flow of the electrons from the piece 11 to the piece 12 will be impeded in a predetermined degree, a variation therein being effected conformably to the changing amount of this potential under the influence of the oscillating or fluctuating current introduced. This effect will be repeated on a greatly magnified scale in the circuit of the conducting coatings 11 and 12 and may be reproduced in various circuits or for various purposes as thru a transformer 21, from the secondary of which leads 22 extend to any suitable device, which, as shown in Fig. 3, may be further amplifiers of this character as the radio frequency amplifiers 23 and audio frequency amplifiers 24, the last of which is shown connected to a loud speaker or similar device 25. A current rectifying member 26, however, is necessary where it is desired to convert the radio frequency into audio frequency oscillations. It will be observed that but two sources of potential 27 and 28—which may be combined into a single, properly tapped source—are required and of potentials approximately 30 and 15 volts respectively for the particular elements employed.

The basis of the invention resides apparently in the fact that the conducting layer at the particular point selected introduces a resistance varying with the electric field at this point; and in this connection it may be assumed that the atoms (or molecules) of a conductor are of the nature of bipoles. In order for an electron, therefore, to travel in the electric field, the bipoles are obliged to become organized in this field substantially with their axes parallel or lying in the field of flow. Any disturbance in this organization, as by heat movement, magnetic field, electrostatic cross-field, etc., will serve to increase the resistance of the conductor; and in the instant case, the conductivity of the layer is influenced by the electric field. Owing to the fact that this layer is extremely thin the field is permitted to penetrate the entire volume thereof and thus will change the conductivity throughout the entire cross-section of this conducting portion.

I claim:—

1. The method of controlling the flow of an electric current in an electrically conducting medium of minute thickness, which comprises subjecting the same to an electrostatic influence to impede the flow of said current by maintaining at an intermediate point in proximity thereto a potential in excess of the particular potential prevailing at that point.

2. The method of controlling the flow of an electric current in an electrically conducting solid of minute thickness, which comprises establishing an electrostatic influence in proximity to said flow in excess of the potential prevailing thereat, and varying the said electrostatic influence to correspondingly vary the said flow.

3. The method of controlling the flow of an electric current in an electrically conducting medium of minute thickness, which comprises subjecting the same to an electrostatic influence to impede the flow of said current by maintaining at an intermediate point in proximity thereto a potential in excess of the particular potential prevailing at that point, and varying the degree of excess potential by an impressed oscillating current.

4. An amplifier for oscillating current, comprising a film of conducting material and an output circuit including a source of potential connected across said film, an electrode associated with the said film for maintaining

at the surface of contact a third potential, means to establish in said electrode a voltage substantially in excess of the voltage in the film at the coacting electrode portion, and means to vary the voltage of said electrode.

5. An amplifier for oscillating current, comprising a film of conducting material and and an output circuit including a source of potential connected across said film, an electrode operating in conjunction with said film intermediate the point of application of the potential thereto to provide an element of uni-directional conductivity thereat, means to maintain said electrode at a voltage substantially in excess of the voltage prevailing at the coacting portion of said conducting film, and an input circuit connected with the said electrode and the negative end of the said film.

6. An amplifier for oscillating current, comprising two insulating members, an intermediate strip of aluminum foil, conducting terminals carried by said insulation members upon either side of the said foil retained thereby, a film of copper sulphur compound extending over said conducting terminals and the edge of the said aluminum strip, output connections to said conducting terminals for applying a potential across the same, and a connection to the said aluminum strip to maintain the same at a higher potential than that prevailing in the film at its portion opposite the aluminum strip.

7. An amplifier for oscillating current, comprising two insulating members, an intermediate strip of aluminum foil, conducting terminals carried by said insulation members upon either side of the said foil retained thereby and in close proximity thereto, a film of copper sulphur compound extending over said conducting terminals and the edge of the said aluminum strip, output connections to said conducting terminals for applying a potential across the same, and a connection to the said aluminum strip to maintain the same at a higher potential than that prevailing in the film at its portion opposite the aluminum strip.

8. An amplifier for oscillating current, comprising a glass block fractured transversely, a strip of aluminum foil retained in the fracture of said block with an edge substantially flush with the corresponding surface of the block, copper terminal coatings carried by the glass block upon opposite sides of said foil and out of contact therewith, a film of copper sulphur compound extending over the surface of said copper terminals and the aluminum edge, output connections to the said copper terminals to apply a potential across the same, and a connection to the aluminum foil to maintain the same at a higher potential than that prevailing in the film at its portion opposite the aluminum strip.

9. An amplifier for oscillating current, comprising a glass block fractured transversely, a strip of aluminum foil retained in the fracture of said block with an edge substantially flush with the corresponding surface of the block, copper terminal coatings carried by the glass block upon opposite sides of said foil and out of contact therewith, a film of copper sulphur compound extending over the surface of said copper terminals and the aluminum edge, output connections to the said copper terminals to apply a potential across the same, a connection to the aluminum foil to maintain the same at a higher potential than that prevailing in the film at its portion opposite the aluminum strip, and a source of fluctuating current in circuit with the aluminum foil.

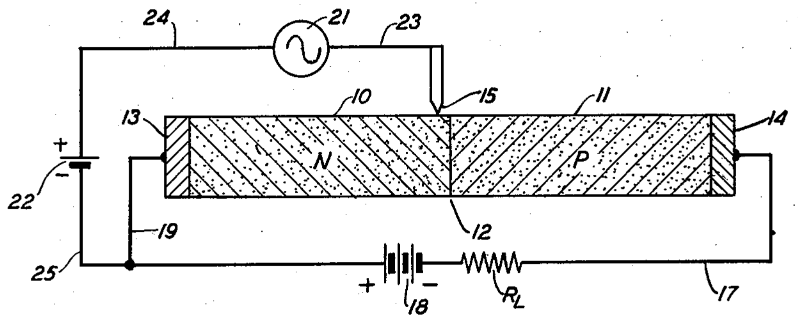
In testimony whereof I affix my signature.

JULIUS EDGAR LILIENFELD.

April 4, 1950 **W. SHOCKLEY** 2,502,488

SEMICONDUCTOR AMPLIFIER

Filed Sept. 24, 1948



INVENTOR
W. SHOCKLEY

BY

ATTORNEY

Patented Apr. 4, 1950 **2,502,488**

UNITED STATES PATENT OFFICE

2,502,488

SEMICONDUCTOR AMPLIFIER

William Shockley, Madison, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application September 24, 1948, Serial No. 50,895

9 Claims. (Cl. 179—171)

This invention relates to means for and methods of translating or controlling electrical signals and more particularly to circuit elements utilizing semiconductors and to systems including such elements.

One general object of this invention is to provide new and improved means for and methods of translating and controlling, for example amplifying, generating, modulating, etc., electric signals.

Another general object of this invention is to enable the efficient, expeditious and economic translation or control of electrical energy.

In accordance with one broad feature of this invention, translation and control of electric signals is effected by alteration or regulation of the conduction characteristics of a semiconductive body. More specifically, in accordance with one broad feature of this invention, such translation and control is effected by control of the characteristics, for example the impedance, of a layer or barrier intermediate the two portions of a semiconductive body in such a manner as to alter advantageously the flow of current between the two portions.

One feature of this invention relates to the control of current flow through a semiconductive body by means of carriers of charge of opposite sign to the carriers which convey the current through the body.

Another feature of this invention relates to a body of semiconductive material, means for making electrical connection respectively to two portions of said body, means for making a third electrical connection to another portion of the body intermediate the first two portions, and circuit means including power sources whereby the influence of the third connection may be made to control the flow of current between the other connections.

A further feature of this invention resides in a body of semiconductive material comprising two zones of material of opposite conductivity type separated by a barrier, means for making external electrical connections respectively to each zone and means for making a third connection to one of the zones adjacent the barrier for controlling the flow of current between the other two connections.

Another feature of this invention involves a semiconductive body which may be used for voltage and power amplification when associated with means for introducing mobile carriers of charge to the body at relatively low voltage and extracting like carriers at a relatively high voltage.

Other objects and features of this invention will appear more fully and clearly from the following description of illustrative embodiments thereof taken in connection with the appended drawings in which:

The single figure shows in section a device suitable for practicing the invention, in connection with an appropriate circuit.

The device of this invention is in some respects like devices illustrated and described in the application of W. Shockley Serial No. 35,423 filed June 26, 1948. Reference is made to said application for a general description and discussion of pertinent principles, suitable materials and certain terms which may be employed in the description and claiming of this invention.

The terms N-type and P-type are applied to semiconductive materials which tend to pass current easily when the material is respectively negative or positive with respect to a conductive contact thereto and with difficulty when the reverse is true, and which also have consistent Hall and thermoelectric effects.

The conductivity type (either N- or P-type) of a semiconductor may be determined in one way by minute quantities of significant impurities as discussed in the previously noted application Serial No. 35,423. Energy relations within the semiconductor may also determine the conductivity type as more fully discussed in the application of J. Bardeen and W. H. Brattain Serial No. 33,466 filed June 17, 1948.

The term "barrier" or "electrical barrier" used in the description and discussion of the device of this invention is applied to a high resistance interfacial condition between contacting semiconductors of respectively opposite conductivity type or between a semiconductor and a metallic conductor whereby current passes with relative ease in one direction and with relative difficulty in the other.

The device shown in the figure comprises a body or block of semiconductive material, for example germanium, containing significant impurities. The block comprises two zones **10** and **11** respectively of N- and P-type materials separated by the barrier **12**. The opposite ends of the block are provided with relatively large area connections **13** and **14** respectively, which may be metallic coatings such as solder, vapor deposited metal coatings, electroplated metal coatings or the like.

Means for making connection to one of the zones closely adjacent to the barrier **12** may comprise a point contact **15** bearing on the surface of the block close to the barrier. The contact point may be of tungsten, Phosphor bronze or the like.

Conductor **17** leads from connection **14** to a load R_L and thence through a power source, such as a battery **18**, and back through conductor **19** to the body at connection **13**. A source **21** of signal voltage and a biasing source **22** are connected from the contact **15** adjacent the barrier to connection **13** by conductors **23**, **24**, **25** and **19**. With N and P zones as shown, the negative pole of source **18** is connected to the P zone and the positive pole to the N zone. The positive pole of biasing source **22** is connected to the contact **15** in order that current may be easily introduced to the N-type material at this point.

With the device and circuit as shown the connections **13**, **14** and **15** may be called the base, collector and emitter respectively in accordance with nomenclature which has been applied to devices of this type. The circuit between the base **13** and the emitter **15** then is the input circuit and that between the base **13** and the collector **14** is the output circuit. The battery **18** in the output circuit may have a voltage of the order of 10 to 100 volts and the bias **22** in the input circuit may be of the order of 0:1 to 1:0 volt.

The current introduced to the N zone at the point contact **15** comprises "holes" as more fully discussed in application Serial No. 35,423 to which reference has been made heretofore. The "holes" injected from the point **15** will diffuse in the N-type material and if they approach the N—P junction they will be drawn across into the P region by the field existing there. Under the conditions of operating bias, there is a steady small current across the junction and this enhances the natural field so that the "holes" entering the N region will tend to be pulled toward the junction by the biasing field produced by the battery. For this reason if the "holes" are injected within a few mils of the junction, they will substantially all be drawn across the barrier into the P region. Consequently, substantially all of the injected current which consists of "holes" will flow into the P region.

Since the point **15** is operated in the forward direction or direction of easy current flow, it has relatively low input impedance. On the other hand, the N—P junction has relatively high impedance so that there is power gain across the device in the usual way as discussed in the previous application Serial No. 35,423.

If a contact such as **15** is made so that it will inject electrons, it should be placed on the P side of the barrier and the device operated with the input and output circuits interchanged and with all of the polarities reversed. Other semiconductive materials than germanium may be used so long as high impedance N—P junctions are obtained and so long as the point injects carriers of the sign not normally present in the region to which it makes contact.

It is to be understood that the specific embodiments of the invention shown and described are but illustrative and that various modifications may be made therein without departing from the scope and spirit of this invention.

What is claimed is:

1. A translating device comprising a body of semiconductive material having zones of opposite conductivity type separated by a barrier, an ohmic connection to each zone remote from the barrier, and a rectifying contact on one zone closely adjacent to the barrier.

2. A translating device comprising a body of

germanium material having zones of opposite conductivity type separated by a barrier, an ohmic connection to each zone remote from the barrier, and a metallic rectifying point on one of said zones closely adjacent to the barrier.

3. A translating device comprising a body of semiconductive material having zones of N- and P-type material separated by a barrier, an ohmic connection to each zone remote from the barrier, and a metallic rectifying point on the N-type zone closely adjacent to the barrier.

4. A translating device comprising a body of germanium material having zones of N- and P-type material separated by a barrier, an ohmic connection to each zone remote from the barrier, and a metallic rectifying point on the P-type zone closely adjacent to the barrier.

5. An amplifier comprising a body of semiconductive material having zones of opposite conductivity type separated by a barrier, a base connection to one zone remote from the barrier, means for introducing current to said one zone including a rectifying contact closely adjacent to the barrier and a source of relatively low voltage between the base connection and the rectifying contact, said voltage poled in the direction of easy current flow into said one zone, and means for extracting current from the other zone including an ohmic connection and a source of relatively high voltage between the base connection and the ohmic connection, said voltage poled in the direction of difficult current flow through said barrier.

6. An amplifier comprising a body of germanium material having zones of N- and P-type material separated by a barrier, an input circuit including a source of relatively low voltage, a rectifying point on the surface of the N-type zone closely adjacent the barrier, and an ohmic base connection to the same zone remote from the barrier, and an output circuit including a source of relatively high voltage, an ohmic connection to the P-type zone remote from the barrier and the base connection.

7. A translating device comprising a body of semiconductive material having zones of opposite conductivity type separated by a barrier, means for introducing current at low impedance into one of said zones including a metallic rectifier point on the surface of said one zone closely adjacent said barrier, and means for extracting current from the other zone comprising an ohmic connection to said other zone remote from said barrier.

8. A circuit element comprising a slab of semiconductive material having zones of opposite conductivity type separated by a barrier intermediate its end, a large area ohmic connection to each end of the slab, and a metallic point contact on the surface of one of said zones closely adjacent to said barrier.

9. A translating device comprising a body of semiconductive material having zones of opposite conductivity type separated by a barrier, means for introducing at low impedance to one of said zones current carriers of opposite sign to those normally found in said zone including a metallic rectifier point on the surface of said zone closely adjacent said barrier, and means for extracting current from said other zone comprising an ohmic connection to said zone remote from said barrier.

WILLIAM SHOCKLEY.

No references cited.

Oct. 3, 1950 J. BARDEEN ET AL 2,524,035

THREE-ELECTRODE CIRCUIT ELEMENT UTILIZING
SEMICONDUCTIVE MATERIALS

Filed June 17, 1948 3 Sheets-Sheet 1

FIG. 1

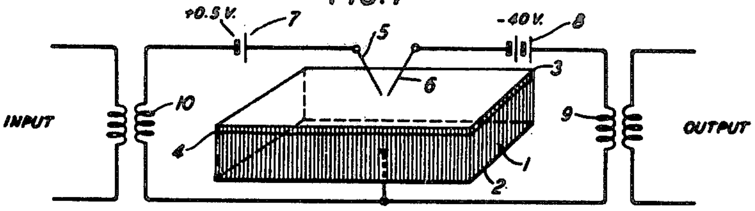


FIG. 1A

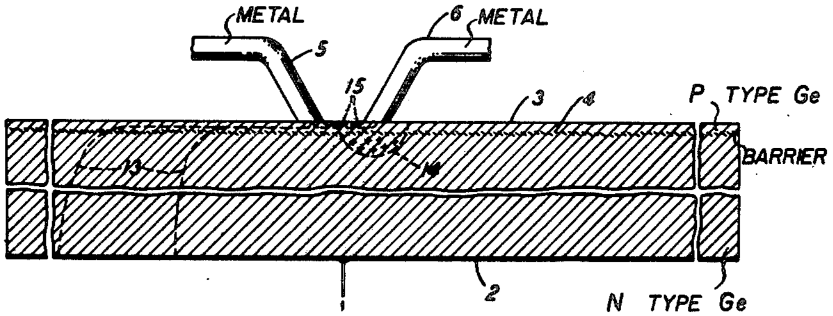


FIG. 2

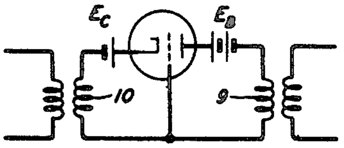


FIG. 10

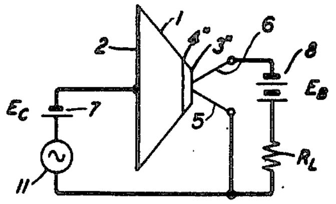


FIG. 11

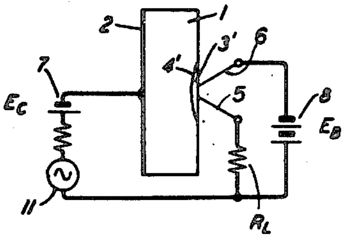
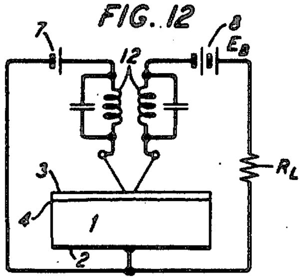


FIG. 12



INVENTORS: J. BARDEEN
W. H. BRATTAIN

BY Harry C. Hart

ATTORNEY

Oct. 3, 1950 J. BARDEEN ET AL 2,524,035

THREE-ELECTRODE CIRCUIT ELEMENT UTILIZING
SEMICONDUCTIVE MATERIALS

Filed June 17, 1948 3 Sheets-Sheet 2

FIG. 3

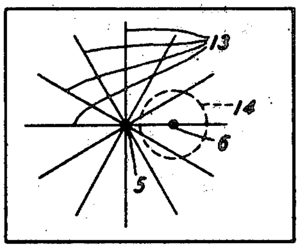


FIG. 3A

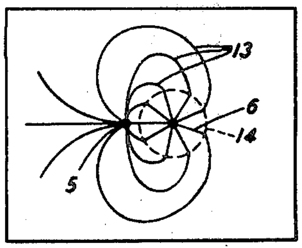


FIG. 4

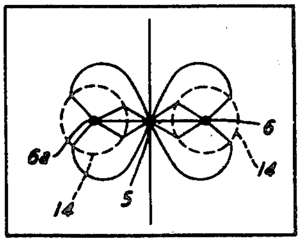


FIG. 5

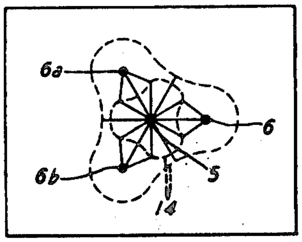


FIG. 6

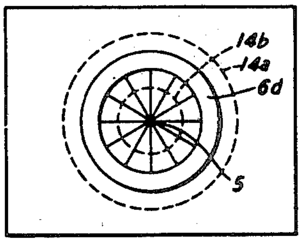


FIG. 7

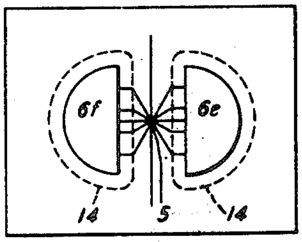


FIG. 8

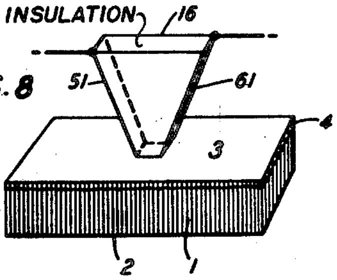
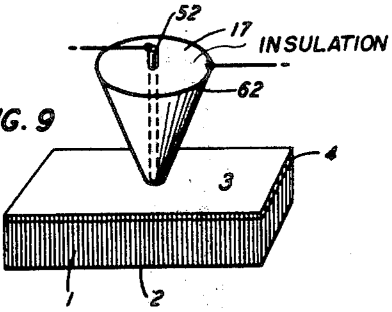


FIG. 9



INVENTORS: J. BARDEEN
W. H. BRATTAIN
BY Harry C. Hart
ATTORNEY

Oct. 3, 1950 J. BARDEEN ET AL 2,524,035

THREE-ELECTRODE CIRCUIT ELEMENT UTILIZING
SEMICONDUCTIVE MATERIALS

Filed June 17, 1948 3 Sheets-Sheet 3

FIG. 13

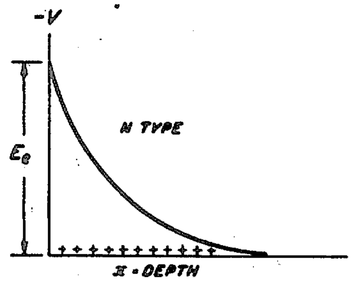


FIG. 14

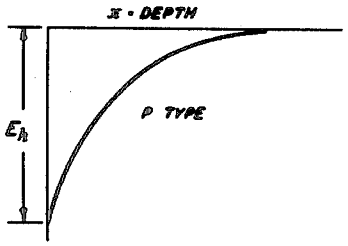


FIG. 15

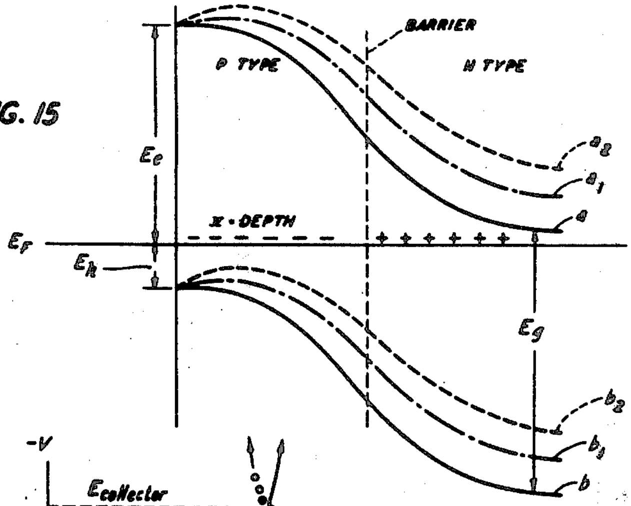
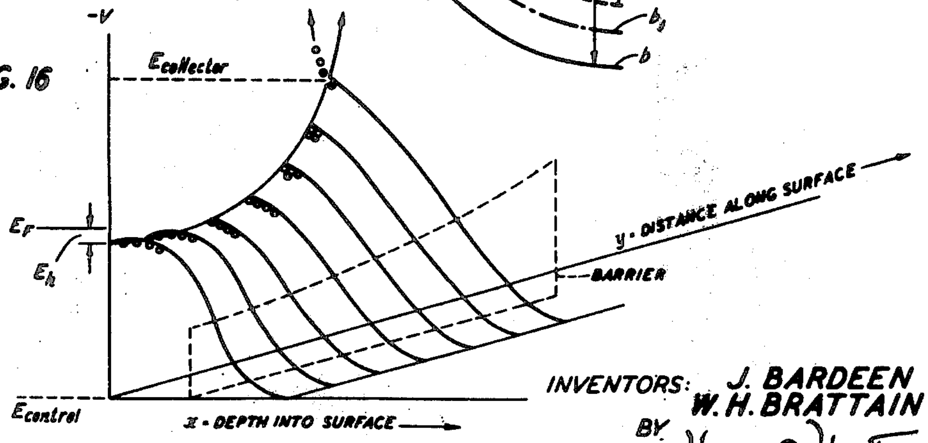


FIG. 16



INVENTORS: J. BARDEEN
W. H. BRATTAIN
BY Harry C. Hart
ATTORNEY

UNITED STATES PATENT OFFICE

2,524,035

THREE-ELECTRODE CIRCUIT ELEMENT UTILIZING SEMICONDUCTIVE MATERIALS

John Bardeen, Summit, and Walter H. Brattain, Morristown, N. J., assignors to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application June 17, 1948, Serial No. 33,466

40 Claims. (Cl. 179—171)

This application is a continuation-in-part of application Serial No. 11,165, filed February 26, 1948, and thereafter abandoned.

This invention relates to a novel method of and means for translating electrical variations for such purposes as amplification, wave generation, and the like.

The principal object of the invention is to amplify or otherwise translate electric signals or variations by use of compact, simple, and rugged apparatus of novel type.

Another object is to provide a circuit element for use as an amplifier or the like which does not require a heated thermionic cathode for its operation, and which therefore is immediately operative when turned on. A related object is to provide such a circuit element which requires no evacuated or gas-filled envelope.

Attempts have been made in the past to convert solid rectifiers utilizing selenium, copper sulfide, or other semi-conductive materials into amplifiers by the direct expedient of embedding a grid-like electrode in a dielectric layer disposed between the cathode and the anode of the rectifier. The grid is supposed, by exerting an electric force at the surface of the cathode, to modify its emission and so alter the cathode-anode current. As a practical matter it is impossible to embed a grid in a layer which is so thick as to insulate the grid from the other electrodes and yet so thin as to permit current to flow between them. It has also been proposed to pass a current from end to end of a strip of homogeneous isotropic semiconductive material and, by the application of a strong transverse electrostatic field, to control the resistance of the strip, and hence the current through it.

So far as is known, all of such past devices are beyond human skill to fabricate with the fineness necessary to produce amplification. In any event they do not appear to have been commercially successful.

It is well known that in semiconductors there are two types of carriers of electricity which differ in the signs of the effective mobile charges. The negative carriers are excess electrons which are free to move, and are denoted by the term conduction electrons or simply electrons. The positive carriers are missing or defect "electrons," and are denoted by the term "holes." The conductivity of a semiconductor is called excess or defect, or N or P type, depending on whether the mobile charges normally present in excess in the material under equilibrium conditions are electrons (Negative carriers) or holes (Positive carriers).

When a metal electrode is placed in contact with a semiconductor and a potential difference is applied across the junction, the magnitude of the current which flows often depends on the sign as well as on the magnitude of the potential. A junction of this sort is called a rectifying contact. If the contact is made to an N-type semiconductor, the direction of easy current flow is that in which the semiconductor is negative with respect to the electrode. With a P-type semiconductor, the direction of easy flow is that in which the semiconductor is positive. A similar rectifying contact exists at the boundary between two semiconductors of opposite conductivity types.

This boundary may separate two semiconductor materials of different constitutions, or it may separate zones or regions, within a body of semiconductor material which is chemically and stoichiometrically uniform, which exhibit different conductivity characteristics.

The present invention in one form utilizes a block of semiconductor material on which three electrodes are placed. One of these, termed the collector, makes rectifier contact with the body of the block. The other, termed the emitter, preferably makes rectifier contact with the body of the block also. The third electrode, which may be designated the base electrode, preferably makes a low resistance contact with the body of the block. When operated as an amplifier, the emitter is normally biased in the direction of easy current flow with respect to the body of the semiconductor block. The nature of the emitter electrode and of that portion of the semiconductor which is in the immediate neighborhood of the electrode contact is such that a substantial fraction of the current from this electrode is carried by charges whose signs are opposite to the signs of the mobile charges normally in excess in the body of the semiconductor. The collector is biased in the reverse, or high resistance direction relative to the body of the semiconductor. In the absence of the emitter, the current to the collector flows exclusively from the base electrode and is impeded by the high resistance of this collector contact. The sign of the collector bias potential is such as to attract the carriers of opposite sign which come from the emitter. The collector is so disposed in relation to the emitter that a large fraction of the emitter current enters the collector. The fraction depends in part on the geometrical disposition of the electrodes and in part on the bias potentials applied. As the emitter is biased in the direction of easy flow, the emitter current is sensitive to small changes in potential between the emitter and the body of the semiconductor, or between the emitter and the base electrode. Application of a small voltage variation between the base electrode and emitter causes a relatively large change in the current entering the semiconductor from the emitter, and a correspondingly large change in the current to the collector. One effect of the change in emitter current is to modify the total current flowing to the collector, so that the overall change in collector current may be greater than the change in the emitter current. The collector circuit may contain a load of high impedance matched to the internal impedance of the collector, which, because of the high resistance rectifier contact of the collector, is high. As a result, voltage amplification, current amplification, and power amplification of the input signal are obtained.

In one form, the device utilizes a block of semiconductor material of which the main body is of one conductivity type while a very thin surface layer or film is of opposite conductivity type. The surface layer is separated from the body by a high resistance rectifying barrier. The emitter and collector electrodes make contact with this surface layer sufficiently close together for mutual influence in the manner described above. The base electrode makes a low resistance contact with the body of the semiconductor. When suitable bias potentials are applied to the various electrodes, a current flows from the emitter into the thin layer. Owing to the conductivity of the layer and to the nature of the barrier, this current tends to flow laterally in the thin layer, rather than following the most direct path across the barrier to the base electrode. This current is composed of carriers whose signs are opposite to the signs of the mobile charges normally in excess in the body of the semiconductor. In other words, when there is a thin layer of opposite conductivity type immediately under the emitter electrode, the current flowing into the block in the direction of easy flow consists largely of carriers of opposite sign to those of the mobile charges normally present in excess in the body of the block; and the presence of these carriers increases the conductivity of the block. The bias voltage on the collector which, as stated above, is biased in the reverse or high resistance direction relative to the block, produces a strong electrostatic field in a region surrounding the collector so that the current from the emitter which enters this region is drawn in to the collector. Thus, the collector current, and hence the conductance of the unit as a whole, are increased. The size of the region in which this strong field exists is comparatively insensitive to variations in the collector potential so that the impedance of the collector circuit is high. On the other hand, the current from the emitter to the layer is extremely sensitive to variations of the emitter potential, so that the impedance of the emitter circuit is low.

It is a feature of the invention that the input and output impedances of the device are controlled by choice and treatment of the semiconductor material body and of its surface, as well as by choice of the bias potentials of the electrodes.

From the standpoint of its external behavior and uses, the device of the invention resembles a vacuum tube triode; and while the electrodes are designated emitter, collector and base electrode, respectively, they may be externally interconnected in the various ways which have become recognized as appropriate for triodes, such as the conventional, the "grounded grid," the "grounded plate" or cathode follower, and the like. Indeed, the discovery on which the invention is based was first made with circuit connections which are extremely similar to the so-called "grounded grid" vacuum tube connections. However, the analogies among the circuits is, of course, no better than the analogy between emitter and cathode, base electrode and grid, collector and anode.

By feeding back a portion of the output voltage in proper phase to the input terminals, the device may be caused to oscillate at a frequency determined by its external circuit elements, and, among other tests, power amplification was confirmed by a feedback connection which caused it to oscillate.

It has been found that the performance of the device is expressed, to a good approximation, by the following functional relations:

$$I_e=f(V_e+R_F I_c) \qquad (1)$$

$$I_c=I_c^0(V_c)+\alpha I_e \qquad (1a)$$

where

I_e=emitter current

I_c=collector current

$I_c^0(V_c)$=collector current with emitter disconnected

V_e=voltage of emitter electrode measured with respect to the base electrode

V_c=voltage of collector electrode measured with respect to the base electrode

R_F=an equivalent resistance independent of bias

α=a numerical factor which depends on the bias voltages

$f(V_e)$ gives the relation between emitter current and emitter voltage with the collector circuit open.

The interpretation of the foregoing Equation 1 is that the collector current lowers the potential of the surface of the block in the vicinity of the emitter relative to the base electrode by an amount $R_F I_c$, and thus increases the effective bias voltage on the emitter by the same amount. The term $R_F I_c$ thus represents positive feedback.

The invention will be fully apprehended from the following detailed description of one embodiment thereof, taken in connection with the appended drawings, in which:

Fig. 1 is a schematic diagram, partly in perspective, showing a preferred embodiment of the invention;

Fig. 1*a* is a cross-section of a part of Fig. 1 to a greatly enlarged scale;

Fig. 2 is the equivalent vacuum tube schematic circuit of Fig. 1;

Fig. 3 is a plan view of the block of Fig. 1, showing the disposition of the electrodes;

Fig. 3*a* is like Fig. 3 but shows the influence of the collector in modifying the emitter current;

Figs. 4, 5, 6 and 7 show electrode dispositions alternative to those of Fig. 1;

Figs. 8 and 9 show electrode structures alternative to those of Fig. 1;

Fig. 10 shows a modified unit of the invention connected for operation in the circuit of a conventional triode;

Fig. 11 shows another modified unit of the invention connected for operation in a "grounded plate" or cathode follower circuit;

Fig. 12 shows the unit of the invention connected for self-sustained oscillation;

Fig. 13 is a diagram showing the electron potential distribution in the interior of an N-type semiconductor in contact with a metal;

Fig. 14 is a diagram showing the electron potential distribution in the interior of a P-type semiconductor in contact with a metal.

Fig. 15 is a diagram showing the electron potential distribution in the interior of a thin P-type semiconductive layer in contact on one side with a metal and on the other side with a body of N-type semiconducting material, for electrons in the conduction band (upper curves) and in the filled band (lower curves); and

Fig. 16 is a diagram showing the variation of the potential distribution of curve *b* of Fig. 15 as a function of distance from the emitter to the collector.

The materials with which the invention deals are those semiconductors whose electrical characteristics are largely dependent on the inclusion therein of very small amounts of significant impurities. The expression "significant impurities" is here used to denote those impurities which affect the electrical characteristics of the material such as its resistivity, photosensitivity, rectification, and the like, as distinguished from other impurities which have no apparent effect on these characteristics. The term "impurities" is intended to include intentionally added constituents as well as any which may be included in the basic material as found in nature or as commercially available. Germanium is such a material which, along with some representative impurities, will furnish an illustrative example for explanation of the present invention. Silicon is another such material. In the case of semiconductors which are chemical compounds such as cuprous oxide (Cu_2O) or silicon carbide (SiC), deviations from stoichiometric composition may constitute significant impurities.

Small amounts, i. e., up to 0.1 per cent of impurities, generally of higher valency than the basic semiconductor material, e. g., phosphorus in silicon, antimony and arsenic in germanium, are termed "donor" impurities because they contribute to the conductivity of the basic material by donating electrons to an unfilled "conduction energy band" in the basic material. In such case the donated negative electrons constitute the carriers of current and the material and its conductivity are said to be of the N-type. Similar small amounts of impurities, generally of lower valency than the basic material, e. g., boron in silicon or aluminum in germanium, are termed "acceptor" impurities because they contribute to the conductivity by "accepting" electrons from the atoms of the basic material in the filled band. Such an acceptance leaves a gap or "hole" in the filled band. By interchange of the borrowed electrons from atom to atom, these positive "holes" effectively move about and constitute the carriers of current, and the material and its conductivity are said to be of the P-type.

Under equilibrium conditions, the conductivity of an electrically neutral region or zone of such a semiconductor material is directly related to the concentration of significant impurities. Donor impurities which have given up electrons to an unfilled band are positively charged, and may be thought of as fixed positive ions. In a region of a semiconductor which has only donor type impurities, the concentration of conduction electrons is equal to the concentration of ionized donors. Similarly, in a region of a semiconductor which has only acceptor impurities, the concentration of holes is equal to the concentration of the negatively charged acceptor ions.

If for any reason there is a departure from electrical neutrality in a region, giving a resultant space charge, the magnitude of the conductivity, and even the conductivity type may differ from that indicated by the significant impurities. It was once thought that the high resistance barrier layer in a rectifier differs somehow in chemical constitution or in the nature of the significant impurities from the main body of the semiconductor. W. Schottky, in Zeits. f. Phys., volume 113, page 367 (1939), has shown that this is not necessary. While the concentration of carriers (mobile charges) in the barrier layer is small, the concentration of ionized impurities (fixed charges) may be the same as in the body of the semiconductor. The fixed charges in the barrier layer act in concert with induced charges of opposite sign on the metal electrode to produce a potential drop between the electrode and the body of the semiconductor. The concentration of carriers at a point depends on the electrostatic potential at that point, and is small compared with the equilibrium concentration in the body of the semiconductor if the potential differs from that in the body by more than a small fraction of a volt. The mathematical theory has been developed by W. Schottky and E. Spenke in Wiss. Veroff. Siemens Werke, vol. 18, page 225 (1939). These authors show that if the variation in electrostatic potential with depth below the surface is sufficiently large, the conductivity passes through a minimum for a certain potential and depth and the conductivity is of opposite type for larger values of the potential corresponding to smaller values of depth. They call the region of opposite conductivity type an inversion region. It is thus possible to have at a rectifier contact a thin layer of one conductivity type next to the metal electrode, separated by a high resistance barrier from the body of opposite conductivity type.

It has been pointed out by J. Bardeen in Phys. Rev., vol. 71, page 717 (1947), that the same sort of barrier layer that Schottky found for rectifying contacts may exist beneath the free surface of a semiconductor, the space charge of the barrier layer being balanced by a charge of opposite sign on the surface atoms. It is possible, for example, to have a thin layer of P-type conductivity at the free surface of a block which has a uniform concentration of donor impurities and which, therefore, has N-type conductivity in the body of the block, even though there ar no actual acceptor impurities.

To distinguish such a situation from the similar one which depends on the presence of significant chemical impurities of opposite type in a thin surface layer, the terms "physical" and "chemical" are employed. Thus the terms "physical layer" and "physical barrier" refer to the layer of opposite conductivity type next to the surface and the high resistance barrier which separates it from the body of the semiconductor, both of which exist as a result of surface conditions and not as a result of a variation in the nature or concentration of significant impurities. The terms "chemical layer" and "chemical barrier" refer to the corresponding situation which does depend on a variation in significant impurities.

Both physical layers and chemical layers are suitable for the invention.

It is known how, by control of the distribution of impurities, to fabricate a block of silicon of which the main body is of one conductivity type while a thin surface layer, separated from the main body by a high resistance barrier, is of the other type. In this case the layer is believed to be chemical rather than physical. For methods of preparing such silicon, as well as for certain uses of the same, reference may be made to an application of J. H. Scaff and H. C. Theuerer, filed December 24, 1947, Serial No. 793,744 and to United States Patents 2,402,661 and 2,402,662 to R. S. Ohl. Such materials are suitable for use in connection with the present invention. It is preferred, however, to describe the invention in connection with the material which was employed when the discovery on which the invention is based was made, namely, N-type germanium which has been so treated as to enable it to withstand high voltage in the reverse direction when used as a point contact rectifier.

There are a number of methods by which the germanium and its surface may be prepared. One such method commences with the process which forms the subject-matter of an application of J. H. Scaff and H. C. Theuerer, filed December 29, 1945, Serial No. 638,351, and which is further described in "Crystal Rectifiers" by H. C. Torrey and C. A. Whitmer, Radiation Laboratory Series No. 15, (McGraw-Hill 1948). Briefly, germanium dioxide is placed in a porcelain dish and reduced to germanium in a furnace in an atmosphere of hydrogen. After a preliminary low heat, the temperature is raised to 1,000° C. at which the germanium is liquefied and substantially complete reduction takes place. The charge is then rapidly cooled to room temperature, whereupon it may be broken into pieces of convenient size for the next step. The charge is now placed in a graphite crucible and heated to liquefaction in an induction furnace in an atmosphere of helium and then slowly cooled from the bottom upwardly by raising the heating coil at the rate of about $\frac{1}{8}$ inch per minute until the charge has fully solidified. It is then cooled to room temperature.

The ingot is next soaked at a low heat of about 500° C. for 24 hours in a neutral atmosphere, for example of helium after which it is allowed to cool to room temperature.

In the resulting heat-treated ingot, various parts or zones are of various characteristics. In particular, the central part of the ingot is of N-type material capable of withstanding a "back voltage," in the sense in which this term is employed in the rectifier art, of 100–200 volts. It is this material which it is preferred to employ in connection with the present invention.

This material is next cut into blocks of suitable size and shape for use in connection with the invention. A suitable shape is a disc shaped block of about $\frac{1}{4}$ inch diameter, and $\frac{1}{32}$ inch thickness. The block is then ground flat on both sides, first with 280 mesh abrasive dust, for example, carborundum, and then with 600 mesh. It is then etched for one minute. The etching solution may consist of 10 c. c. of concentrated nitric acid, 5 c. c of commercial standard (50 per cent) hydrofluoric acid, and 10 c. c. of water, in which a small amount, e. g. 0.2 gram, of copper nitrate has been dissolved. This etching treatment enables the block to withstand high (rectifier) back voltages.

Next, one side of the block is provided with a coating of metal, for example copper or gold, which constitutes a low resistance electric contact. This may be done by evaporation or electroplating in accordance with well-known techniques. As a precaution against contamination of the other (unplated) side of the block which may have occurred in the course of the plating process, the unplated side may be subjected to a repetition of the etching process.

The block may now be given an anodic oxidation treatment, which may be carried out in the following way. The block is placed, plated side down, on a metal bed-plate which is connected to the positive terminal of a source of voltage such as a battery, and that part of the upper (unplated) surface which is to be treated is covered with polymerized glycol boriborate, or other preferably viscous electrolyte in which germanium dioxide is insoluble. An electrode of inert metal, such as silver, is dipped into the liquid without touching the surface of the block, and is connected to a negative battery terminal of about −22.5 volts. Current of about 1 milliampere commences to flow for each square centimeter of block surface, falling to about 0.2 milliampere per cm.^{2} in about 4 minutes. The electrode is then connected to the −45 volt battery terminal. The initial current is about 0.7 milliampere per cm.^{2}, falling to 0.2 milliampere per cm.^{2} in about 6 minutes. The electrode is then connected to the −90 volt battery terminal. The initial current is now about 0.5 milliampere per cm.^{2}, falling to about 0.15 milliampere per cm.^{2} in 10 to 20 minutes.

The battery is then disconnected, the block is removed and washed clean of the glycol borate with warm water, and dried with fine paper tissue. Finish drying has been successfully carried out by placing the block in a vacuum chamber and applying radiant heat. Either the heat or the vacuum may be sufficient, but both together are known to be. If spot electrodes are required on the upper surface as later described, they may be evaporated on in the course of the finish drying process. The germanium block is now ready for use.

The foregoing oxidation process, however, is not essential. Amplification has been obtained with specimens to which no surface treatment has been applied subsequent to the etch, other than the electrical forming process described below.

Fig. 1 shows a block **1** of germanium which has been prepared in the foregoing manner, and Fig. 1*a* shows the central part of the block **1** in section and to an enlarged scale. Referring to Figs. 1 and 1*a* together, the lower part of the block **1**, whose surface is plated with a metal film **2** serving as the base electrode, is known to be of N-type. The thin layer **3** at the upper surface manifests P-type conductivity in which case, as is well known, the boundary **4** separating this P-type layer from the N-type material of the main body of the block behaves like a high resistance rectifying barrier. A first electrode **5**, denoted the emitter, makes contact with the upper face of the block, i. e., with the P-type layer **3**, preferably somewhere near its center, or at least several point diameters removed from the nearest edge. This contact is preferably of the rectifier type with respect to the body of the block **1**. It may comprise a bent wire of springy material, from 0.5 to 5 mils in diameter, preferably pointed at the contact and electrolytically or by grinding. Processes for forming the points on such wires are described in United States

Patent 2,430,028 to W. G. Pfann, J. H. Scaff and A. H. White. The point of the wire is brought into contact with the upper surface **3** of the block with a force of 1 to 10 grams, whereupon a cold flow of the metal of the point takes place, causing it to conform to any minute irregularities of the block surface. To this end the wire of the point should be ductile as compared with the material of the block. Tungsten, copper and phosphor bronze are examples of suitable materials.

A second electrode **6**, denoted the collector, makes contact with the upper face **3** of the block very close to the emitter **5**. Best results have been obtained when the separation, measured along the surface of the block, between the collector and the emitter, is from 1 to 10 mils. This electrode **6** should make rectifier contact with the block and may be a pointed spring wire, formed and placed as above described in connection with the emitter **5**. On the other hand, it may comprise a small spot of metal, for example, gold, which has been evaporated onto the upper surface of the block in the course of the final drying operation, and through which a central hole has been pierced (see Fig. 6) or across which a diametral slot has been cut (see Fig. 7). Evaporation of such a spot or film of metal onto the upper face after completion of the anodic oxidation process described above results in a non-ohmic rectifier junction or connection.

A third connection, termed the base electrode, is made, by soldering or otherwise, to the metal film **2** which has been plated onto the lower surface of the block **1**.

While the unit is now ready for use, its operation can generally be improved by an electrical forming process, in which a potential in excess of the peak back voltage is applied to either one or both of the point electrodes **5**, **6**, i. e., between it and the base electrode **2**. The unit is protected from injury by heavy currents by inclusion of a resistor in series. The effect of this treatment is believed to lie in a concentrated application of electric field and heat to the material in the immediate neighborhood of the point, and so in an improvement of the electrical characteristics of the contact.

Bias voltages are now applied to the electrodes, a small bias, usually positive, on the emitter of the order of a fraction of a volt and a larger negative bias on the collector, usually in the range from -5 to -50 volts, measured, in each case, from the body of the block to the point electrode. These bias potentials may be obtained from batteries **7**, **8** connected as shown or otherwise, as desired.

A load of 1,000 to 100,000 ohms may now be connected in circuit with the collector, for example by way of an output transformer **9**, and a signal to be amplified may be applied between the emitter and the base electrode, for example by way of an input transformer **10**. The connections may be those of the conventional triode as indicated in Fig. 10, or of the so-called grounded plate or cathode-follower, as in Fig. 11. In these figures the input signal is symbolically represented by a source **11** and the load by an output resistor R_L. Discovery of the amplifying properties of the device was made, however, with the grounded base circuit of Fig. 1, of which the vacuum tube counterpart is the so-called "grounded grid" connection of Fig. 2. (The principal distinguishing feature of this circuit as employed with a vacuum tube triode is that the load current flows through the source. This does not hold for the unit of the present invention, because the base electrode may draw substantial current.) The device as thus connected has given power gains of more than a factor of 75. Operating data on three different samples are given in the following table:

Sample No	1	2	3
Input Res. (ohms)	640	500	1,000
Output Res. (ohms)	3×10^4	3×10^4	3×10^4
Input Voltage, A. C. R. M. S.	0.29	0.30	0.10
Output Voltage, A. C. R. M. S.	18	15	3.6
Voltage Gain	62	50	36
Power in (watts)	1.3×10^{-4}	1.8×10^{-4}	1.15×10^{-5}
Power out (watts)	100×10^{-4}	75×10^{-4}	42.5×10^{-5}
Power Gain	80	42	36
Input Bias D. C. (volts)	+0.2	+0.25	+0.2
Output Bias D. C. (volts)	−40	−20	−10

Confirmation of the presence of power amplification has been obtained by feeding back a part of the output voltage to the input circuit, as by way of the coupling between the windings of a transformer **12**, as in Fig. 12 whereupon sustained self-oscillation took place.

It is to be noted that in the case of the No. 1 sample of the foregoing table, the power gain exceeds the voltage gain by a factor of

$$\frac{80}{62}$$

or 1.3. Inasmuch as, in any amplifying device which gives both power gain and voltage gain, the current gain is the quotient of the two, it is evident that sample No. 1 manifests a current gain of 1.3.

Without necessarily subscribing to any particular theory, the following hypothesis is presented to account for the experimentally determined facts, with all of which it is consistent. It is believed that the preparation of the semi-conductor material and its surface treatment result in the formation of an oxide film, and, below it, of a layer or film **3** of P-type conductivity on the surface of the block, separated from the main body, which is of N-type, by a high resistance barrier **4**. The oxide film is removed by washing. This P-type layer is very thin, perhaps 10^{-5} cm. in thickness, but the N-type body of the block provides all necessary support for it, and also provides a low impedance path to the base electrode **2**. Its presence is confirmed by the fact that, particularly with featherweight forces on the contact points **5**, **6** and with small voltages applied to them, P-type rectifier characteristics have sometimes been obtained. (P-type and N-type rectifier characteristics and their significance and differences are discussed in United States Patent 2,402,839 to R. S. Ohl.) But when the mechanical force on the contact point is increased to 10 grams or so and the voltage applied to it is raised to $\frac{1}{2}$ volt or so, the rectifier characteristic is observed suddenly to shift from P-type to N-type. Furthermore, potential probe measurements on the surface of the block, made with the collector disconnected, indicate that the major part of the emitter current travels on or close to the surface of the block, substantially laterally in all directions away from the emitter **5** before crossing the barrier **4**. These measurements indicate the presence of a conducting layer at the surface of the block, which by inference is of P-type. In case the treatment stops with the etching process, the layer is believed to be physical. If it includes the further anodic oxidation step, the layer is believed to be chemical, but its nature has not been definitely established.

It is believed that the P-type layer on the germanium surface of the preferred embodiment is not greatly altered when a contact is made with a metal point. When a small positive bias is applied to the emitter, and a current flows, the carriers are largely those of the surface layer, that is, holes rather than conduction electrons. The potential probe measurements discussed above indicate that the concentration of holes, and thus the conductivity, in the vicinity of the emitter point, increase with increasing forward current. This hole current spreads out in all directions from the emitter **5** before crossing the high resistance barrier **4**. With the collector circuit open, it then makes its way throughout the body of the block to the plated lower surface **2**. (In the N-type body of the block, the current may take the form of a flow of electrons upward to neutralize the downward flow of holes from the P-type layer.) In the absence of the collector electrode **6**, this current is the only current. Its path is indicated in Fig. 1*a* by stream lines **13**.

Now when the collector **6** contact is made, and a negative bias potential is applied to it, of from -5 to -50 volts, a strong electrostatic field appears across the P-type layer **3**, and across the high resistance barrier **4**, being maintained by the fixed positive charges in the N-type body material in the immediate vicinity of the collector. The barrier and the P-type layer together are believed to be of the order of 10^{-4} cm. in thickness. Thus with 10 volts across a space of 10^{-4} cms., the average strength of this field is of the order of 10^5 volts per cm., being greatest at the collector and extending in all directions from the collector, and is indicated in Fig. 1*a* by the broken line **14**, within which some of the fixed positive charges are indicated by plus signs.

It is in order that the material shall be able to support a large voltage drop across this region that material of the so-called high back voltage type is preferred.

Now when the current of positive holes as indicated by stream lines **15** comes within the influence of this field, the holes are attracted to the region of lowest potential, namely, to the point at which the collector electrode **6** makes contact with the layer **3**. There they are picked up by the collector **6** to appear as a current in an external load circuit **8**, **9** connected to the collector **6**. With the large negative bias on the collector **6**, a variation of several volts on the collector makes very little difference in the strength or the extent of the field which surrounds it, and therefore has but a secondary effect on the fraction of the emitter current collected by the collector. In other words the collector operates under conditions which are close to saturation, and the alternating current impedance of the collector circuit is high. As shown in Table I, it has been measured at values from 10,000 to 100,000 ohms. For maximum power output, the external load impedance should be matched to the internal impedance of the collector. On the other hand, variation of the voltage between the emitter **5** and the base electrode **2** by a small fraction of a volt, as by a signal which may be applied to the input terminals and so impressed on these electrodes, for example, by way of the transformer **10**, effects a large variation in the emitter current and therefore in the collector current. Hence an amplified replica of the input signal voltage appears across the load resistor.

As shown in Fig. 1*a*, it is preferred that the area of contact of each of the two point electrodes with the surface of the block be large as compared with the layer thickness. This reduces the actual contact resistance as compared with the resistance encountered by the current flowing laterally in the surface layer itself; i. e., the spreading resistance of the layer.

When the collector electrode **6** is a single pointed wire or an evaporated metal spot, a fraction of the emitter current, after spreading out laterally in the P-type layer **3**, eventually finds its way across the barrier **4** to the plated electrode **2** on the lower face of the block, i. e., to the base electrode. This situation is depicted in Fig. 3 which is a plan view of the block showing current stream lines **13** diverging in all directions from the emitter. The current stream lines **13** are straight in the absence of the collector field. When the collector field **14** is present the current field is distorted as in Fig. 3*a* which shows that even with a single collector electrode **6** more than half of the emitter current can be collected. In fact, the fraction of the emitter current which reaches the collector may in favorable cases be as high as 90 per cent.

To increase this ratio, especially in the case of units in which this ratio is less favorable, requires a modified electrode arrangement. Obviously, if the strong field **14** surrounding the collector **6** were to overlap or include the emitter **5**. substantially all of the emitter current would be collected. This, however, would involve a loss of control. A solution is to provide two collectors **6**, **6*a***, as in Fig. 4, or three **6**, **6*a***, **6*b***, as in Fig. 5, symmetrically disposed about the emitter **5**. Evidently with such an arrangement a considerably greater fraction of the emitter current is collected. In each case the boundaries of the collector field are indicated by broken lines **14**. The several collectors may be connected together and as many may be employed as may seem desirable. Pursuing this solution still further leads to the ring collector **6*d*** of Fig. 6, in which case the collector field **14** bears the shape of a semitorus. Its trace on the plane of the block surface is shown by the broken lines **14*a***, **14*b***. The two semicircular spots **6*e***, **6*f***, of Fig. 7 are the substantial equivalent of the circle of Fig. 6.

Further increase may be made in the effective resistance of the barrier **4** and therefore in the internal resistance of the emitter-base electrode circuit and of the ratio of the collector current to the emitter current by restricting the area of the barrier **4** itself to a comparatively small region surrounding the emitter **5** and the collector **6**. This may be accomplished by restricting the area of the block **1** which is subjected to the anodic oxidation treatment or by machining the block after treatment. In the former case the result is a bowl-shaped P-layer **3'**, bounded by a bowl-shaped barrier **4'**, as shown in Fig. 11, and in the latter case it is a block **1'** having the form of a truncated pyramid, with the barrier **4''** close to the smallest face, as indicated in Fig. 10.

In the event that the spring feature is not desired for the emitter and collector contact points, various alternative structures may be employed. For example, two sides of a wedge-shaped piece of insulating material **16** may be plated with metal films as in Fig. 8, one **51** to serve as emitter and the other **61** as collector. Or a cone-shaped piece **17** may be plated over its conical surface and a wire inserted through a central hole as in Fig. 9. The central wire **52** is preferably employed as the emitter and the surrounding plate film **62** as collector. The cone and the wedge serve to hold the interelectrode capacities to a minimum while keeping the contacts close together where they bear against the surface of the semiconductor.

Further understanding of the considerations which govern the thickness of the P-type surface layer may be had from the following considerations, which apply specifically to a chemical layer. Fig. 13 is a plot of the electrostatic potential within the body of an N-type semiconductor in contact with a metal. As above stated, the N-type material of the semiconductor contains fixed or bound positive charges. They are believed to be distributed with fair uniformity in depth to a certain distance, beyond which the material is electrically neutral, because the bound positive charges are balanced by equal negative (electron) charges. In accordance with Poisson's equation:

$$\frac{d^2V}{dx^2}=-\frac{4\pi\rho}{\epsilon} \qquad (2)$$

where

V is the potential
x is the distance, measured from the metal into the semiconductor
ρ is the charge density, and
ϵ is the dielectric constant of the material.

Assuming the charge density ρ to be uniform, two integrations give the potential as a function of depth. When plotted, it is a parabola. In the figure, negative potential has been plotted upward. The vertical rise E_e from the Fermi level to the terminus of the curve, i. e., to its intercept with the potential axis, represents the energy which must be imparted to an electron to cause it to move from the metal to the semiconductor. These matters are fully explained in the literature, for example, in "Schottky's Theories of Dry Solid Rectifiers," by J. Joffe, published in "Electrical Communication," vol. 22 (1944–1945) at page 217.

Similarly Fig. 14 shows the potential distribution, for positive holes, within a P-type semiconductor in contact with a metal. In this case the height E_h of the terminus of the curve from the Fermi level represents the energy which must be given to a positive hole to cause it to leave the metal and enter the semiconductor.

Fig. 15 is a composite diagram showing, in the upper curves, the electron energy and in the lower curves the hole energy, within a semiconductor which comprises a thin layer of P-type material separated from a body of N-type material by a barrier. The fixed charges are negative in the P-type material and positive in the N-type, and for simplicity are assumed to be distributed uniformly in each zone. Integration of the charge density, twice, in accordance with Poisson's equation gives the lowermost curves, a, b of the two groups, which represent equilibrium conditions and which, but for an additive constant E_g, are alike. The constant E_g represents the energy difference between the filled band and the conduction band for the particular material.

The middle curves a_1, b_1, of each group represent the conditions when a small negative bias is applied to the semiconductor block **1** with respect to the emitter **5**, and the upper curves a_2, b_2, of each group represent the conditions when a signal applied between the emitter and the control electrode further reduces the potential of the block. Evidently the alteration of the block potential with respect to the emitter operates in each case to increase the effective thickness of the P-type layer and so the density of holes and the layer conductivity. Such an increase in conductivity with increase in the forward bias has been observed in connection with the potential probe measurements referred to above.

The rounded peak of the hole potential curve lies below the Fermi level. The greater the thickness of the P-type layer, the more the terminus of this curve falls below the Fermi level, i. e., the greater the magnitude of E_h, and the greater the difficulty for holes to leave the metal of the emitter and enter the semiconductor. Similarly, the thinner the P-type layer, the less is the magnitude of E_h, and the greater the ease with which holes move from the metal of the emitter to the semiconductor and enter it. On the other hand, if the P-type layer is too thin, the conductivity of the layer, which is related to the width of the approximately flat portion of the upper part of the curve b_1 of Fig. 15 will be small. In the vicinity of the collector electrode, the thickness of the P-type layer should be sufficiently small so that the rectification characteristic of the collector is determined primarily by the body of the semiconductor and not by the layer. If, now, the collector is biased in the reverse direction relative to the body, most of the drop from the high voltage on the electrode occurs in the immediate vicinity of the collector, so that the impedance of the collector circuit is high.

The P-type layer is preferably adjusted to an optimum thickness lying between these extremes. Best results are believed to be obtained when its thickness is such that the terminus of the curve falls slightly below the rounded peak. Holes can enter the semiconductor without great difficulty, and tend to collect in the region of greatest negative potential as a cloud of mobile positive charges. They then diffuse away from the emitter—laterally in Fig. 1, perpendicular to the paper in Fig. 15—some of them entering the field **14** of the collector **6**.

Because the right-hand part of the lower curve falls well below the left-hand part, positive holes can cross the barrier only with difficulty. Because the P-type layer is thin, the energy E_h, required to cause holes to enter the layer, is small. Therefore holes enter easily under the influence of the positive bias on the emitter **5** and collect in the layer, like air bubbles as it were, at the top of a liquid in a closed vessel. They may easily travel in the layer and parallel with it.

The sense in which, and the reason why the barrier exists, separating a region of P-type conductivity from a region of N-type conductivity, despite the fact that the semiconductor material itself may be chemically and stoichiometrically uniform, may be explained as follows:

From the elementary considerations, the conductivity is given by

$$C=n_1e_1\mu_1+n_2e_2\mu_2 \qquad (3)$$

where

n_1, e_1, μ_1 are the electron density, the electronic charge, and the electron's mobility, respectively, and
n_2, e_2, μ_2 are the corresponding quantities for positive holes.

It is known that

$$n_1 = A_1 \epsilon^{-\frac{eV_e}{KT}} \qquad (4a)$$

$$n_2 = A_2 \epsilon^{-\frac{eV_h}{KT}} \qquad (4b)$$

where V_e is the height of the electron space potential curve (*a* of Fig. 15) above the Fermi level, and V_h is, correspondingly, the height of the Fermi level above the hole space potential curve (*b* of Fig. 15) and A_1, A_2, K, and T are constants for a given temperature. Inasmuch as the potential difference between the two kinds of space potential curves is a constant E_g, the conductivity may be written

$$C = A_1\mu_1 e_1 \epsilon^{-\frac{eV_e}{KT}} + A_2\mu_2 e_2 \epsilon^{-\frac{e(E_g - V_e)}{KT}} \qquad (5)$$

Since the factor $A_1\mu_1 e_1$ does not differ greatly in magnitude from the factor $A_2\mu_2 e_2$, it is a simple matter of calculation to show that this expression is a minimum when

$$V_e = V_h = \frac{E_g}{2} \qquad (6)$$

i. e., that the restivity of the material is greatest at the depth at which the *a* curves and the *b* curves of Fig. 15 lie at equal distances above and below the Fermi level, respectively; and that, furthermore, the resistivity departs rapidly from this maximum value as the space potentials V_e and V_h depart from equality. If

$$V_e < \frac{E_g}{2}$$

the electron conductivity is greater than the hole conductivity, and the conductivity is N-type. If

$$V_e > \frac{E_g}{2}, \text{ or } V_h < \frac{E_g}{2}$$

the hole conductivity is greater than the electron conductivity, and the conductivity is P-type.

Fig. 16 is a three dimensional representation of the conditions which the holes encounter in the course of their travel in the layer from the emitter to the collector—in the figure, parallel with the Y axis. As in Fig. 15, the X axis represents depth measured into the semi-conductor and the V axis which is drawn to an approximately logarithmic scale, represents negative potential. As the holes approach the collector the peak of the potential curve becomes less and less pronounced until finally, at the collector, the region of lowest potential, to which the holes flow, is the collector itself, where they are withdrawn.

Of that part of the emitter current which crosses the barrier, a certain fraction crosses it again in the vicinity of the collector and is collected, thus forming a part of the collector current. The foregoing hypothesis as to the mechanism by which amplification is obtained applies to this fraction of the current as well as to the fraction which proceeds entirely within the layer.

The collector current contains still another component, which consists of a flow of electrons from the collector to the base electrode, crossing the barrier once on its way. A hypothesis as to the manner in which this current component takes part in the amplification process is as follows:

There is a potential hill at the contact point between the collector electrode and the surface layer which offers an impedance to the flow of electrons from the electrode into the semiconductor. In the absence of bias, the height of this hill, indicated by E_e in Figs. 13 and 15, is the energy required to take an electron from the metal and place it in the conduction band of the semiconductor. When the collector is biased in the reverse direction, the effective height of the hill, and so the impedance of the contact point, are reduced by the electric field across the layer and barrier which acts in such a direction as to pull electrons from the electrode. The effect is to increase the flow of electrons into the semiconductor in a way which is similar to the enhancement of current from a thermionic cathode by field-induced emission. When the emitter is connected, and a current of holes flows to the collector, the accumulation of the positive charges of these holes in the vicinity of the collector tends to make the potential fall more rapidly with depth into the material, and so results in an increase in field and a decrease in the effective height of the hill, i. e., in the impedance of the contact point. Thus any increase in that component of the collector current which originates at the emitter is accompanied by a corresponding increase in the other component of the collector current, namely, in the flow of electrons to the base electrode. Hence the total change in collector current may be greater than the change in the emitter current.

From the foregoing description it will be clear that if it is desired to employ a semiconductor block of which the main body is of P-type so that the conductivity of the thin surface layer, whether due to impurities or to space charge effects, is of N-type, the polarities of all the bias sources of Figs. 1, 10, 11 and 12 are to be reversed. It is also to be understood that the magnitudes of the biases for best operation will depend on the semiconductor material employed and on its heat treatment and processing. Furthermore, it is possible to use a P-type layer of one semiconductor material on an N-type body of some other semiconductor material or vice versa. All such variations are contemplated as being within the spirit of the invention.

The invention is not to be construed as limited to the particular forms disclosed herein, since these are to be regarded as illustrative rather than restrictive.

What is claimed is:

1. A circuit element which comprises a block of semiconductive material of which the body is of one conductivity type and a thin surface layer is of the opposite conductivity type, an emitter electrode making contact with said layer, a collector electrode making contact with said layer disposed to collect current spreading from said emitter electrode, and a base electrode making contact with the body of the block.

2. Apparatus as defined in claim 1 wherein the surface layer is of the same chemical material as the block.

3. Apparatus as defined in claim 1 wherein the block is of germanium.

4. Apparatus as defined in claim 1 wherein the block is of N-type germanium and the surface layer is of P-type germanium.

5. Apparatus as defined in claim 1 wherein the block is of high back voltage germanium and to at least a part of one surface of which an anodic oxidation treatment has been applied.

6. A circuit element which comprises a semiconductive supporting body, a thin surface layer of semiconductor material supported by and in electrical contact with said body and differing in conductivity type therefrom, an emitter elec-

trode making contact with said layer, a collector electrode in contact with a different part of the element from the part contacted by said emitter electrode and disposed to collect current spreading from said emitter electrode, and a base electrode making contact with the body.

7. Apparatus as defined in claim 6 wherein the area of contact of the emitter electrode with the semiconductor layer is large compared with the layer thickness.

8. Apparatus as defined in claim 6 wherein the emitter electrode is a point contact.

9. Apparatus as defined in claim 6 wherein the emitter electrode and the collector electrode are point contacts.

10. Apparatus as defined in claim 6 wherein the emitter electrode and the collector electrode make rectifier contact with the body by way of the semiconductor layer.

11. Apparatus as defined in claim 6 wherein the collector electrode is spaced from the emitter electrode by a distance of the order of 1 to 2 mils.

12. Apparatus as defined in claim 6 wherein the collector electrode is spaced from the emitter electrode by a distance which is small compared with the semiconductor layer area but large compared with the layer thickness.

13. Apparatus as defined in claim 6 wherein the semiconductive supporting body is separated from the surface layer by a high resistance barrier, and wherein the base electrode makes contact with said body over a wide area of a surface thereof which is opposite to the surface bearing the semiconductive layer.

14. In combination with apparatus as defined in claim 6, means for biasing the emitter electrode with respect to said semiconductive layer in a sense to supply charges thereto of the sign for which the layer is conductive, and means for biasing the collector electrode to collect charges of the same sign.

15. In combination with apparatus as defined in claim 6, a work circuit interconnecting the collector electrode with the base electrode, and connections for applying a signal voltage between the emitter electrode and the base electrode.

16. A circuit element which comprises a block of semiconductor material characterized by fixed charges of one side and having a thin surface layer, separated from the main body of the block by a high resistance barrier, characterized by mobile charges of the same sign, a base electrode in contact with said body, an emitter electrode in contact with said layer, a potential source connected to said base electrode and to said emitter electrode to bias said emitter electrode in a sense to supply mobile charges of the same sign to said layer, a collector electrode in contact with said layer, and a potential source connected to said base electrode and to said collector electrode to bias said collector in a sense to establish an electric field across said layer between said collector electrode and fixed charges in the body of said block.

17. A circuit element which comprises a semiconductive body, a thin surface layer of semiconductive material separated from said body by a high impedance conducting barrier, at least two electrodes, of which one is a sharp point of conductive material, in close-spaced contact with said surface layer, and a third electrode in contact with said body.

18. A circuit element which comprises a block of semiconductor material, an electrode making low resistance contact with a part of the surface of the block, a plurality of electrodes making rectifier contact with other parts of the surface of the block, connections including said first-named electrode for applying a forward direction bias to one of said rectifier contact electrodes, and connections including said first-named electrode for applying a reverse direction bias to another of said rectifier contact electrodes.

19. A circuit element which comprises a block of semiconductor material, an electrode making low resistance contact with a part of the surface of the block, a plurality of electrodes making rectifier contact with other parts of the surface of the block, connections including said first-named electrode for applying a smaller forward direction bias to one of said rectifier contact electrodes, and connections including said first-named electrode for applying a larger reverse direction bias to another of said rectifier electrodes.

20. A circuit element which comprises a block of semiconductor material, an electrode making low resistance contact with a part of the surface of the block, a plurality of electrodes making rectifier contact with other parts of the surface of the block and spaced apart by a distance which is not greater than the smallest dimension of the block, connections including said first-named electrode for applying a smaller forward direction bias to one of said rectifier contact electrodes, and connections including said first-named electrode for applying a larger reverse direction bias to another of said rectifier contact electrodes.

21. In combination, a block of semiconductive material, a collector electrode making rectifier contact therewith, a second electrode connected to said block, a circuit including a source of voltage and a load connected to said collector electrode and to said second electrode, said source being so poled as to draw reverse current from the block through said contact, and another electrode making rectifier contact with the block and disposed to control the magnitude of the current from the block through said first contact.

22. The combination recited in the preceding claim in which said semiconductive material comprises germanium.

23. A translating device comprising a semiconductor, three electrodes in contact therewith, a high impedance output circuit including two of said electrodes and making a high-resistance reverse-rectifier contact therewith by way of one of said two electrodes, and a low impedance input circuit including one of the first two electrodes and the third electrode and making a low-resistance forward-rectifier contact therewith by way of the third of said electrodes.

24. A circuit element which comprises a block of semiconductor material, an electrode making low resistance contact with a part of the surface of the block, an emitter electrode and a collector electrode making rectifier contact with other parts of the block, means for biasing the emitter electrode for conduction in the forward direction, means for biasing the collector electrode for conduction in the reverse direction, connections for applying a signal between the low resistance electrode and the emitter electrode to introduce a current of mobile charges into said block at low impedance by way of said emmitter electrode, which charges are of signs opposite to the signs of the mobile charges normally present in excess

in the semiconductor material under equilibrium conditions, connections for withdrawing said charges from said block at high impedance by way of said collector electrode, whereby the voltage across said collector electrode contact contains a component which is an amplified version of the signal voltage, said charges acting, by reason of their accumulation in the block in the vicinity of the collector electrode, to modify the impedance of its contact to current flowing from the low resistance contact electrode to the collector electrode, whereby the current drawn from the collector electrode contains a component which is an amplified version of the signal current.

25. A circuit element which comprises a block of semiconductive material of which the body is of one conductivity type while a thin surface layer is of the opposite conductivity type, an emitter electrode making contact with the surface layer, a collector electrode making contact with the surface layer and disposed to collect current spreading from the emitter electrode, a base electrode making contact with the body of the block, an input circuit including a source connected to the base electrode and to the emitter electrode, respectively, and an output circuit including a load connected to the base electrode and to the collector electrode, respectively.

26. A circuit element which comprises a block of semiconductive material of which the body is of one conductivity type while a thin surface layer is of the opposite conductivity type, an emitter electrode making contact with the surface layer, a collector electrode making contact with the surface layer and disposed to collect current spreading from the emitter electrode, a base electrode making contact with the body of the block, an input circuit including a source connected to the emitter electrode and to the base electrode, respectively, and an output circuit including a load connected to the emitter electrode and to the collector electrode, respectively.

27. A circuit element which comprises a block of semiconductive material of which the body is of one conductivity type while a thin surface layer is of the opposite conductivity type, an emitter electrode making contact with the surface layer, a collector electrode making contact with the surface layer and disposed to collect current spreading from the emitter electrode, a base electrode making contact with the body of the block, an input circuit including a source connected to the collector electrode and to the base electrode, respectively, and an output circuit including a load connected to the collector electrode and to the emitter electrode, respectively.

28. A translating device comprising a semiconductor, two rectifier contacts thereon, another contact thereon, a source of input current variations, a load, sources of bias voltage, a circuit extending between said other contact and the first of said rectifier contacts including at least said source of input current variations and one of said bias sources poled for forward rectifier current flow through said first rectifier contact, and a circuit extending from the other rectifier contact through said load to one of the two other mentioned contacts and including a source of bias voltage poled for reverse rectifier current flow through said other rectifier contact.

29. A translating device according to claim 28 in which said load is included between said other rectifier contact and said other contact.

30. A translating device according to claim 28 in which said load is included between said two rectifier contacts.

31. A translating device according to claim 28 in which said load is included between said two rectifier contacts and in which the first-mentioned circuit is connected to said first of said rectifier contacts independently of said load.

32. A translating device according to claim 28 in which said load is included in a circuit portion that is common to said two mentioned circuits, one terminal of said load being connected to said first of said two rectifier contacts.

33. A circuit element which comprises a block of semiconductor material, an emitter electrode making contact with the block, a region of the body of the block immediately under the contact and engaged by said emitter electrode being characterized by an inversion of conductivity type, a collector electrode disposed in engagement with the block to collect current flowing to the block by way of the emitter electrode, and a base electrode making contact with the body of the block to vary the magnitude of said current.

34. Apparatus as defined in claim 33 wherein said collector electrode makes reverse rectifier contact with the block.

35. In combination with apparatus as defined in claim 6, connections for feeding a current into said body by way of said emitter electrode, connections for withdrawing a current from said body by way of said collector electrode, said current being carried within said body from said emitter electrode to said collector electrode by carriers whose signs are opposite to the signs of the mobile charges normally present in excess in the material of the body under equilibrium conditions, and connections for applying a signal to be amplified between the emitter electrode and the base electrode, whereby the current withdrawn from the collector electrode contains a component which is an amplified version of said signal.

36. A circuit element as defined in claim 6 wherein the semiconductive supporting body has the form of a truncated pyramid and wherein the surface layer covers the smallest face of the pyramid.

37. A circuit element as defined in claim 6 wherein the body has at least one face of substantial area and wherein the thin surface layer occupies a small part of said one face.

38. A circuit element comprising a body of semiconductive material, which material normally contains an excess of mobile charges of one sign over mobile charges of the other sign, a base electrode making low resistance contact with said body, an emitter electrode making contact with said body at a region spaced from said base electrode, an input circuit connected between said base and emitter electrodes and including a source for biasing said emitter electrode with said other sign, thereby to inject into said body charges of said other sign, an output electrode connection to said body, and an output circuit connected between said output electrode connection and one of said emitter and base electrodes and including a source for biasing said output electrode connection with said one sign, thereby to withdraw from said body a current of charges of said other sign introduced into said body through said emitter electrode.

39. A signal translating device comprising a body of semiconductive material, which material normally contains an excess of mobile charges of one sign over mobile charges of the other sign,

collector and base connections to said body, a source of input energy, means separate from said collector and base connections and including said source for applying to a region of said body spaced from said collector connection energy to establish in said region mobile electric charges of said other sign, and an output circuit connected between said collector and base connections, said output circuit including means for applying to said collector connection a bias of the polarity opposite to the sign of said established charges, thereby to attract to said collector connection said established charges.

40. A circuit element comprising a body of semiconductor material, one portion of which is of one conductivity type and another portion of which is of different conductivity type, an emitter electrode engaging the first portion of the body, a collector electrode engaging the body to collect current flowing to the body by way of said emitter electrode, and a base electrode providing a low-resistance connection to said other portion of the body to vary the magnitude of said current.

JOHN BARDEEN.
WALTER H. BRATTAIN.

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Certificate of Correction

Patent No. 2,524,035 **October 3, 1950**

JOHN BARDEEN ET AL.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows:

Column 6, line 54, for "ar" read *are*; column 8, line 73, for "and" read *end*; column 17, line 51, for the word "side" read *sign*;

and that the said Letters Patent should be read as corrected above, so that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 2nd day of January, A. D. 1951.

[SEAL]

THOMAS F. MURPHY,
Assistant Commissioner of Patents.

Dec. 23, 1952 **W. SHOCKLEY ET AL** 2,623,105

SEMICONDUCTOR TRANSLATING DEVICE
HAVING CONTROLLED GAIN
Filed Sept. 21, 1951

FIG. 1

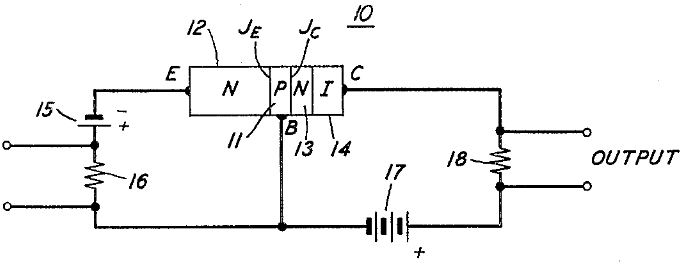


FIG. 2

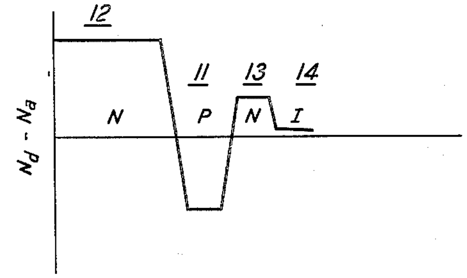


FIG. 3

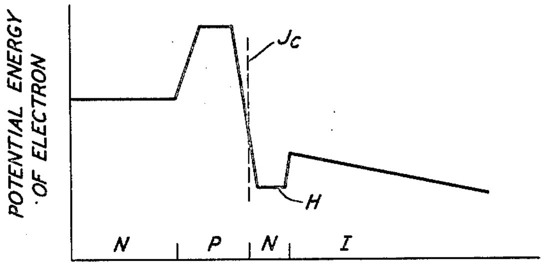
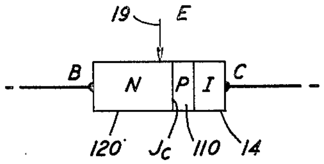


FIG. 4



INVENTORS: W. SHOCKLEY
M. SPARKS
BY

ATTORNEY

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UNITED STATES PATENT OFFICE

2,623,105

SEMICONDUCTOR TRANSLATING DEVICE HAVING CONTROLLED GAIN

William Shockley, Madison, and Morgan Sparks, Basking Ridge, N. J., assignors to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application September 21, 1951, Serial No. 247,676

6 Claims. (Cl. 175—366)

This invention relates to semiconductor signal translating devices and more particularly to such devices of the type known as transistors.

Transistors comprise, in general, a body of semiconductive material and three connections, designated the base, emitter and collector, thereto. In one class, of which the devices disclosed in the application Serial No. 35,423, filed June 26, 1948, now Patent 2,569,347, granted September 25, 1951 to W. Shockley and in Patent 2,502,488, granted April 4, 1950 to W. Shockley are illustrative, the collector includes a PN junction in the semiconductive body. Comprehensive discussions of such junction transistors appear in the article by W. Shockley in the Bell System Technical Journal, July 1949, page 435 and by W. Shockley et al. in the Physical Review, volume 83, page 151.

An important operating parameter for transistors is the current multiplication factor, which is commonly designated α and is defined as the ratio of change in collector current to change in emitter current for a constant collector voltage. Mathematically,

$$\alpha = -\frac{\partial I_c}{\partial I_e}\bigg| V_c = \text{constant}$$

I_c being the collector current, I_e the emitter current and V_c the collector potential. The factor α is dependent upon a number of effects and may be expressed as

$$\alpha = \alpha_i \beta \gamma$$

where

β=the fraction of the injected current reaching the collector

γ=the fraction of the emitter current carried by injected carriers, and

α_i=the instrinsic α, that is the ratio of change in collector current per unit change in minority carrier current arriving at the collector.

For a PN collector junction, the intrinsic factor, α_i, is the ratio of the change in total current across the junction per unit minority carrier arriving at the junction, the minority carriers being electrons when the collector terminal is on the N side of the junction and holes when the collector terminal is on the P side of the junction.

The theoretical maximum for the intrinsic factor, α_i, for an idealized PN junction is unity. This is a consequence of the assumption made for an idealized case that the minority carrier density is very small compared to the majority carrier density in the collector body. The factor β is dependent upon the thickness of the zone opposite that on which the collector terminal appears, inasmuch as the diffusion of minority carriers through that zone varies, in general inversely, with the thickness. For example, in a transistor wherein the semiconductor is of NPN configuration, operation depends upon the diffusion of electrons through the P zone or region and the greater the thickness of this zone the smaller will be the number of electrons which reach the collector junctions. It is possible to design and construct NPN structures in which $\gamma\beta$ differs from unity by two per cent or less by making the P layer thin and keeping lifetimes long. Furthermore, the temperature coefficient of the deviation is relatively small for reasons described in the Physical Review, volume 83, page 158.

One general object of this invention is to improve the performance characteristics of transistors including PN junction collectors. More specifically, one object of this invention is to enable the attainment for a PN junction collector of a stable, intrinsic current multiplication factor of greater than unity.

In accordance with one feature of this invention, there is provided between the collector PN junction in and the collector terminal on the semiconductive body, a region or zone of the semiconductive material and of intrinsic conductivity. Such zone results in the establishment of a potential hook in the vicinity of the junction whereby the ratio of hole and electron currents at the junction is fixed at substantially the mobility ratio for carriers in the intrinsic zone or region. This leads to a stable, intrinsic factor, α_i, for the junction of

$$\alpha_i = 1 + \frac{1}{b}$$

where b is the mobility ratio. This ratio is substantially independent of temperature.

The invention and the above noted and other features thereof will be understood more clearly and fully from the following detailed description with reference to the accompanying drawing in which:

Fig. 1 portrays an amplifier illustrative of one embodiment of this invention, wherein the transistor includes a junction emitter and a junction collector;

Fig. 2 is a diagram showing the relative excess donor and acceptor concentrations in the several zones of the semiconductive element of the transistor shown in Fig. 1;

Fig. 3 is a graph illustrating the potential energy for electrons in the several zones of the semiconductive element shown in Fig. 1; and

Fig. 4 depicts a transistor having a point contact emitter and a junction collector, illustrative of another embodiment of this invention.

In the drawing, for ease of identification and understanding, the emitter, base and collector terminals have been designated as E, B and C respectively; also, the conductivity type of each of the zones in the semiconductive body has been indicated by appropriate characters, namely N=N-type, P=P-type and I=intrinsic.

Referring now to the drawing, the signal translating device illustrated in Fig. 1 comprises a semiconductive body **10**, for example of germanium, having therein an intermediate zone **11** of P-type contiguous with two N zones **12** and **13** and forming junctions J_E and J_C therewith. The body includes also an intrinsic zone **14**. Emitter, base and collector terminals are provided on the zones **12**, **11** and **14** respectively.

The semiconductive body may be fabricated in the manner disclosed in the application Serial No. 168,184, filed June 15, 1950 of G. K. Teal. Briefly, in accordance with the method therein disclosed, a seed of germanium is dipped into a molten mass of germanium and withdrawn therefrom at a rate to draw some of the molten material along therewith. Concomitantly with the withdrawal step, the impurity balance in the melt is altered to effect a controlled variation in the conductivity or inversion in the conductivity type of the melt and, hence, of the withdrawn material. For example, if the melt is of N-type initially, it may be converted to P-type by adding an acceptor material, such as gallium, thereto and then reconverted to N-type by adding a donor material, such as antimony thereto, whereby successive portions of the crystal produced by withdrawal of the seed will be N-type, P-type and N-type respectively. To produce a body of the configuration illustrated in Fig. 1, advantageously the melt should be initially of high purity germanium wherein the donors and acceptors are substantially in effective balance so that the first withdrawn portion will be of intrinsic material, to provide the zone **14**. Suitable initial material may have a resistivity of about 60 ohm centimeters. By addition of appropriate impurities as mentioned above, successive portions of the withdrawn material may provide zones, corresponding to zones **13**, **11** and **12** in Fig. 1, having resistivities of say 10, 1 and 0.01 ohm centimeters respectively. In a typical construction, the zones **11**, **12**, **13** and **14** may be, respectively, .05, 0.2, .05 and 0.3 centimeter thick. The relative difference between donor (N_d) and acceptor (N_a) concentrations for such a construction is depicted in Fig. 2.

As shown in Fig. 1, the emitter junction J_E is biased in the forward direction by a source **15** connected in series with an input impedance **16**; the collector junction J_C is biased in the reverse direction by a source **17** in series with a load indicated generally by the resistor **18**. The emitter bias may be of the order of 0.1 volt and the collector bias of the order of 1 volt.

In brief, in the operation of the device illustrated in Fig. 1, by virtue of the bias across the junction J_E, electrons are injected across this junction into the P zone **11**, pass through this zone, across junction J_C and toward the collector terminal C. The potential energy for electrons in the several regions or zones is as portrayed in Fig. 3. When current flows in the device, there is established in the intrinsic region **14** a field tending to drive electrons to the right, in Fig. 1, and holes to the left. The ratio, in this zone or region, of the hole current to the electron current will be

$$\frac{1}{b}$$

where b is the mobility ratio of the two types of carriers in the bulk of the material constituting the zone **14**. For germanium the ratio of electron mobility to hole mobility is about 2. If the same ratio of hole to electron current does not obtain at the collector junction J_C, holes or electrons will accumulate at the potential hook, indicated at H in Fig. 3, until the ratio noted is established at the junction. It can be shown, then, that there results at the collector junction an intrinsic multiplication factor of about

$$\alpha_i = 1 + \frac{1}{b} = 1.5$$

The factor b is substantially independent of temperature. Hence the intrinsic α_i is very stable.

It is to be noted that a certain current in the collector body **14** is requisite in order that α will stabilize. For small currents some of the electron flow into the intrinsic zone **14** can occur by diffusion. If the velocity due to the current is large in comparison to the diffusion velocity, α will stabilize at the value indicated hereinabove. However, if the current velocity is small in comparison to the diffusion velocity then the current multiplication factor will be of different values, determinable in ways known in the art. Thus, it will be appreciated that devices constructed in accordance with this invention may be transferred from one state of stability to another, each state being characterized by a particular current multiplication factor, by control of the operating current point.

Although in the device illustrated in Fig. 1 the semiconductive body is of NPN configuration, the invention may be embodied also in devices wherein the body is of PNP configuration. For such devices the intrinsic current multiplication factor will be $1+b$ which is about 3. Also, it may be embodied in devices, such as illustrated in Fig. 4, employing a point contact **19** as an emitter in place of the junction emitter J_E as in Fig. 1. As illustrated in Fig. 4, the emitter **19** bears against the N zone **120** and the intrinsic zone **14** is contiguous with the P zone **14**. Alternatively, the emitter may bear against the P zone and the zone **14** be contiguous with the N zone.

It should be noted that a given body of germanium may be intrinsic at one temperature and N-type or P-type at another. If the excess of donors over acceptors is n_o and the concentration of electrons in an intrinsic specimen is $n_i(T)$, then there will be a temperature T_o at which $M_i(T_o)=M_o$. If T increases above T_o, n_i increases rapidly and the ratio of electrons to holes, which is $1+(M_o/M_i)$ approaches unity. The resulting dependence of α_i upon T may be used to make temperature sensitive devices. It may also be used to determine the requirements on the materials intended for operation in a particular temperature range.

What is claimed is:

1. A signal translating device comprising a body of semiconductive material having a PN junction therein, emitter and collector connections to said body on opposite sides of said junction, and a base connection to said body, said body having therein between said junction and said collector connection a zone of substantially intrinsic conductivity.

2. A signal translating device in accordance

with claim 1 wherein said emitter connection includes a second PN junction.

3. A signal translating device in accordance with claim 1 wherein said emitter connection includes a point contact bearing against said body.

4. A signal translating device in accordance with claim 1 wherein said semiconductive material is germanium.

5. A signal translating device comprising a body of semiconductive material having therein an intermediate zone of one conductivity type between and contiguous with a pair of zones of the opposite conductivity type and having also a fourth zone of substantially intrinsic conductivity contiguous with one of said pair of zones, a base connection to said intermediate zone, an emitter connection to the other of said pair of zones, and a collector connection to said fourth zone.

6. A signal translating device comprising a body of semiconductive material having therein a P zone between and contiguous with a pair of N zones, said body having also a zone of substantially intrinsic conductivity contiguous with one of said N zones, and base, collector and emitter terminals on said P zone, said intrinsic zone and the other N zone respectively.

WILLIAM SHOCKLEY.
MORGAN SPARKS.

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The following references are of record in the file of this patent:

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