

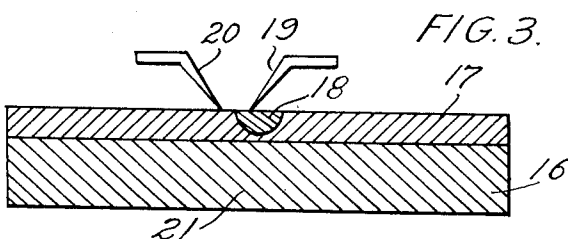
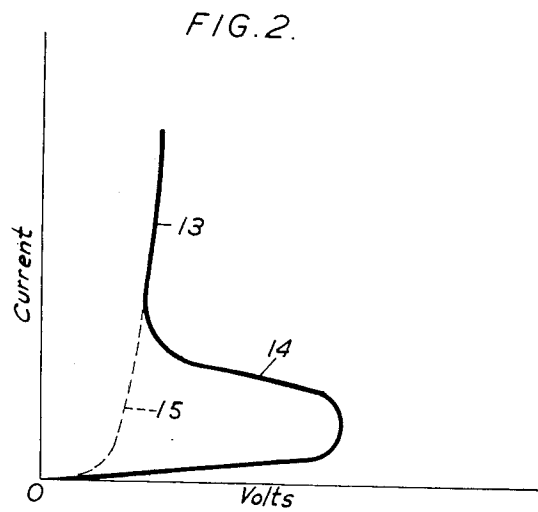
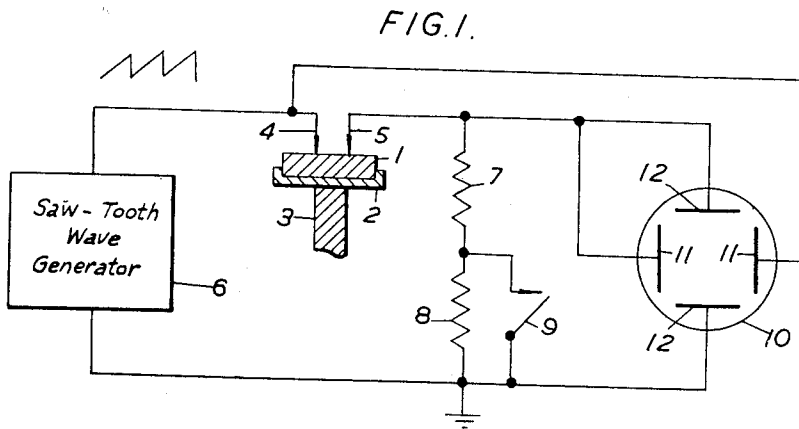
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CRYSTAL TRIODES

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CRYSTAL TRIODES

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The present invention relates to electric amplifying devices employing semi-conductors which have been called for convenience "crystal triodes," this application being a continuation-in-part of our co-pending application 150,412, filed March 18, 1950, and entitled "Electric Semiconductor," now Patent No. 2,653,374.

For the purpose of this specification, a crystal triode means a body of semi-conducting material (such as a crystal of germanium) having in rectifying contact with its surface at least two electrodes placed close together, but not in actual contact. One of these electrodes is called "emitter electrode" and the other is called the "collector electrode." In contact with the semi-conducting body is also a third electrode called the "base electrode" which may take the form of a metal cup or holder on which the semi-conductor is mounted, although the use of the term "base electrode" should not be taken as restricting the invention to such amplifying devices in which the third electrode is of extended area.

The emitter and collector electrodes of a crystal triode may consist of fine wires or "cat whiskers." The emitter electrode may be used as an input electrode of the crystal triode, and the collector electrode may be used as an output electrode.

By means of a suitable associated circuit, a power gain may usually be obtained with a crystal triode but sometimes it also produces a current gain or develops current gain after an overload in normal use, and this is liable to produce unstable conditions in certain applications of the device, and may, therefore be very undesirable. Conversely, while a current gain is desirable in many applications, it has heretofore not always been possible to obtain a current gain with a crystal triode.

The principal object of the present invention, therefore, is to provide improved crystal triodes of two types, one type being capable of giving a large current gain and the other type being capable of giving power or voltage gain, without producing an accompanying unwanted current gain.

A crystal triode is said to give a "current gain" when a given change in the emitter current produces a larger change in the collector current, on the assumption that the output load impedance connected to the collector electrode is zero.

In the study of semi-conducting materials for use as rectifiers, it has been the practice in some circles to divide the materials into two classes, namely N-type materials and P-type materials. In the N-type, the conduction of the current in the material is principally due to the migration of a few free electrons, while in the P-type, it is said to be due to the migration of what are called "positive holes," that is, deficiencies of electrons in a few atoms of the material.

Up to the present, crystal triodes have been generally constructed with N-type material, and germanium has been commonly used as the semi-conductor. In order to operate as an amplifier, it is necessary to treat the sur-

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face by known methods, to produce good rectifying properties.

These methods preferably involve grinding or polishing the surface of the semiconductor, and then etching the polished surface with a solution containing nitric acid, hydrofluoric acid, and copper nitrate. The rectifying properties result from the formation by this means, on the surface of the semiconductor, of a thin layer having the opposite type of conductivity to that of the body of the semiconductor, that is, a P-type layer if the semiconductor is of the N-type, or an N-type layer if the semiconductor is of the P-type.

In constructing a crystal triode from a semiconductor treated as just described, the two cat whisker electrodes already mentioned are arranged in rectifying contact with the treated surface. Then the emitter or input electrode has to be polarised positively with respect to the collector or output electrode when the main body of the semiconductor is of the N-type. It is, however also possible to produce a crystal triode from a semiconductor of the P-type (which, as already explained, will have an N-type layer on the surface after treatment), in which case the emitter electrode must be polarised negatively to the collector electrode.

A particular electroforming process is described below, by means of which the crystal triode may be caused to produce a current gain. This process is also described and claimed in the specification of the above identified application Serial No. 150,412. It is pointed out in that specification that to produce a current gain by means of the electroforming process described, it is necessary that the collector electrode should contain an additive material which acts as a donor or acceptor impurity for the semiconductor when the latter is of the N- or P-type, respectively.

It has already been proposed to employ Phosphor bronze (among other materials such as tungsten and copper) as the material for the cat whisker electrodes of a crystal triode, and also to employ an electroforming treatment. Owing to the manner of its production, Phosphor bronze sometimes contains phosphorus as an impurity, but it is not an essential constituent, and phosphorus is a suitable donor material for germanium. However, in the early proposals already referred to, the use of a donor impurity was evidently not material, since tungsten, for example, was used interchangeably with Phosphor bronze.

The new advance in the art constituted by the present invention, according to one of its aspects, is the recognition that a crystal triode can be caused to give a large current gain if an additional thin layer of the same conductivity type as the main body of the semiconductor is produced on top of the layer of opposite conductivity type produced by the conventional surface treatment normally used.

The additional layer is preferably obtained by applying the electro-forming treatment described below, using a collector electrode containing a donor or acceptor impurity according as the main body of the semiconductor is of the N- or P-type, respectively. The effect of this treatment is to inject some of the impurity from the collector electrode into the surface of the semiconductor, thus producing the second layer of the same conductivity type as the main body of the semiconductor.

While the electroforming process described below is a convenient and preferred process for carrying out the operation under proper controlled conditions, it is not the only process which could be used. It has, for example, been discovered that crystal triodes originally having a voltage gain but no current gain are sometimes found subsequently to acquire a current gain as a result of the application of some accidental pulse, if the collector elec-

trode contains an additive of the proper type, the said pulse driving some of the additive material into the crystal surface. Then the circuit may be found to be unstable. A small amount of phosphorus, antimony or arsenic in the collector electrode would have this effect.

As already pointed out, the object of the invention covered by application No. 150,412 is to provide a particular electroforming process for a crystal triode. The object of the present invention, however, is to provide a crystal triode which can be arranged to produce either a current gain or a voltage gain.

Another object of the invention, as stated above, is to provide a crystal triode having a voltage gain, which will have no tendency to produce a current gain. This object is achieved, according to the invention, by providing the triode with a collector electrode which is free from an impurity which is of the type to act as a donor impurity in the case when the semi-conductor is of the N-type, such as germanium, for instance, or as an acceptor impurity when the semi-conductor is of the P-type. Thus electrodes of pure tungsten will be satisfactory for this type of crystal triode, and this is the preferred material for these electrodes. Pure Phosphor bronze could be used, provided that it is absolutely free from contamination with phosphorus.

Another object is achieved according to the invention by providing a crystal triode in which the surface of the semi-conductor is treated in the usual manner to obtain good rectifying properties, by producing on the surface of the semi-conductor a layer of the opposite conductivity type, and is then provided with a second layer over part of the first layer, with which second layer the collector electrode is in contact, such second layer containing as an additive a donor impurity when the semi-conductor is of the N-type or an acceptor impurity when the semi-conductor is of the P-type.

According to another aspect, the invention provides a crystal triode comprising a body of semi-conducting material of a given conductivity type, having a rectifying surface layer of the opposite conductivity type, a base electrode in contact with the semi-conducting material, and collector and emitter electrodes placed close together on the said surface layer, and making rectifier contact therewith, at least the collector electrode containing as an additive material, a donor or an acceptor impurity, according as the semi-conducting material is of the N- or P-conductivity type, respectively.

The invention will be described in relation to a crystal triode comprising either an N-type or P-type semi-conducting substance in contact with which are the two cat whisker electrodes of small contact area placed very close together.

In one manner of carrying out the invention when a crystal of N-type germanium is used as the semi-conducting substance, the material of the collector electrode contains as an additive a small quantity of phosphorus, or antimony, or arsenic, or other donor type of impurity.

As already mentioned, Phosphor bronze often (but not always) contains phosphorus as an impurity, and if so, it could be used as the material for the collector electrode, and may be used also for the emitter electrode. This is a very convenient material since it can be so easily procured.

Another suitable donor impurity is arsenic, and the collector electrode may comprise, for example, a sharply pointed tungsten wire on the surface of which has been deposited a small quantity of arsenic, either by evaporation, or by deposition from a solution containing arsenic. Antimony has also been successfully used as a donor impurity. The emitter electrode could be a sharply pointed tungsten wire with or without arsenic on its surface. A suitable electroforming treatment is then applied for the purpose of injecting some of the arsenic from the collector electrode into the surface of the germanium, in order to form the second layer already mentioned. A preferred

process will be described below. Previously to electroforming it is necessary that the surface of the germanium crystal should have been suitably treated in known manner in order to produce good rectifying properties.

It is necessary to make clear that once the second layer has been formed by using a pair of electrodes, of which the collector electrode has the donor impurity, and injecting the phosphorus or other donor impurity into the first layer, the said electrodes could, if desired, be replaced by others of which the collector electrode only is placed in contact with the second surface layer, such other electrodes not containing any donor impurity. For example, cat whisker electrodes of pure tungsten could be used in this case, or electrodes plated on in the manner described in the specification of co-pending application No. 228,486, now Patent No. 2,680,220.

When cat whisker electrodes are used, the pointed ends should preferably be placed about two or three thousandths of an inch apart, but with the emitter electrode outside the second surface layer. It has been found that a chisel point obtained by cutting the wire in a plane making a small angle with the axis of wire is satisfactory, though a sharp conical point produced electrolytically can be used.

In making one form of a crystal triode, the germanium is melted and cast into suitable ingots, and a disc of suitable size is cut from an ingot. The usual surface treatment such as is customary to apply to germanium used in a diode rectifier to produce good rectifying properties, is given to the surface to which the point contacts are to be made.

After the germanium surface has been treated and provided with a pair of cat whiskers of which at least the collector electrode contains either an acceptor or a donor impurity, a suitable electroforming process should be applied, for the purpose of injecting some of the impurity into the surface of the germanium.

While the principles of the invention have been described above in connection with specific embodiments and particular modifications thereof, it is to be clearly understood that this description is made only by way of example and not as a limitation on the scope of the invention.

A preferred process will be described with reference to the accompanying drawing in which:

Fig. 1 shows an electroforming and testing circuit for carrying out the electroforming process;

Fig. 2 shows the characteristic obtained on the cathode ray tube used in the testing circuit; and

Fig. 3 is a cross-sectional view greatly enlarged, of a crystal triode according to the present invention.

This, however, is not the only type of process which could be used, according to the invention.

In the forming circuit, Fig. 1, a crystal triode is shown in section and consists of a disc or plate 1 of germanium secured to a metal base 2 having a base terminal lug 3. The emitter electrode is shown at 4 and the collector electrode at 5.

According to one concept of the invention, at least the collector electrode 5 should be constructed of a metal or alloy having a donor material as an additive if N-type germanium is used.

A generator 6 of saw tooth waves, having a low impedance output circuit capable of supplying currents up to about 100 milliamperes, has one terminal connected to ground and the other connected to the emitter electrode 4. The circuit is completed by two resistances 7 and 8 connecting the collector electrode 5 to ground, and a switch 9 is provided by means of which the resistance 8 can be short-circuited.

The testing device comprises a cathode ray tube 10 of conventional type, only the deflecting plates of which are shown. The horizontally deflecting plates 11 are connected respectively to the electrodes 4 and 5, and the vertically deflecting plates 12 are connected across the

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resistances 7 and 8. It will thus be clear that the horizontal deflection of the cathode ray will be proportional to the voltage applied between the emitter and collector electrodes 4 and 5, and the vertical deflection will be proportional to the current which passes between the two electrodes.

It should be carefully noted that for properly forming the crystal triode formed from N-type material; the generator 6 should provide a positive output voltage so that the emitter electrode is always positive to the collector electrode. The saw-tooth waves should preferably be such that the output voltage varies steadily from zero to a positive value which may be between 40 and 100 volts, and then flies back rapidly to zero. It is also very important that the base electrode 3 should be left unconnected.

The resistances 7 and 8 should be chosen so that normally a small current flows in the forming circuit. It is then found that generally the curve traced on the oscillograph screen is at first as shown in Fig. 2 by the full line curve 13, 14. This curve shows the current in the circuit as ordinates plotted against the voltage between the emitter and collector electrodes as abscissae, for the forward or scanning strokes of the saw tooth waves. A different return curve is traced during the fly back strokes, but this is of no interest and is not visible owing to the rapidity of return of the spot to zero. It will be seen that the curve 13, 14 has a loop with a portion 14 having a negative slope, indicating a negative resistance condition between the electrodes 4 and 5.

In order to form the crystal triode, the switch 9 is momentarily closed, thus short-circuiting the resistance 8 and greatly increasing the current in the circuit. This injects some of the donor material into the surface of the crystal. At the same time, the curve traced on the tube 10 will momentarily collapse downwards due to the reduction of the vertical scale by the short-circuiting of the resistance. When the switch is reopened, it will usually be found that the loop of the curve 13 will have become reduced, and in some cases will have completely disappeared, the curve on the screen then being as shown partly by the full line 13, and partly by the dotted line 15. If the loop does not disappear completely the first time, by repeating the process two or three times, the loop can be entirely removed, so that the characteristic curve follows the smooth dotted portion 15. This is the condition under which it will be found that the crystal triode produces the maximum current gain.

It should be particularly noted that the forming process is carried out between the two cat whisker electrodes and not between either and the base 3, which is left unconnected in the forming circuit. Further, the emitter electrode should be positive to the collector electrode during the forming.

It should be added that the use of saw-tooth waves is not essential for forming the crystal triode according to this invention; for example, positive rectangular pulses could be used, or the positive loops of sine waves. However, the use of saw-tooth waves is very convenient when it is desired to carry out the forming and testing process in the same circuit.

It is further to be noted that a low reverse resistance measured between the collector electrode 5 and the base 3 (treated as a simple rectifier) is detrimental to good current and power gain characteristics and should therefore be avoided. This is one of the reasons for forming between the emitter and collector electrode, because it is found that if the electroforming is carried out between the collector electrode 5 and the base 3, a low reverse resistance sometimes results, particularly when using a soft metal for the collector electrode.

It should be pointed out that if the process of forming should be overdone, the loop with the negative slope may reappear. It is found that by repeating the process the

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loop can be made to collapse again so that the smooth curve 15 can always be produced.

A further point to note is that it may occasionally be found that the forming process fails to reduce the loop. The reason for this is not clearly understood, but it will generally be found that the desired results can be obtained by shifting the catwhiskers to another part of crystal. Very rarely no part of the crystal surface can be found which is satisfactory, and in this case the surface should be ground off and re-treated, and the electro-forming repeated when the desired results will generally follow.

It should be understood that the crystal triode may take other forms than that shown in Fig. 1. For example, it may consist of a disc with a very thin central portion, the emitter and collector electrodes making contact with opposite side of the thin portion.

It has been assumed so far that the crystal triode employs an N-type semi-conductor. However, if the semi-conductor should be of the P-type, the arrangements described with reference to Fig. 1 will be the same, except that according to the invention, the collector electrode, should contain an additive of the acceptor type, and that the generator 6 should be arranged to supply a negative voltage to the emitter electrode 4 instead of a positive voltage.

In other words, whichever type of semi-conducting material is used, the potentials of the emitter and collector electrodes should be such that the emitter electrode 4 is biased in the conducting direction when considered as forming a rectifier with the semiconductor.

To sum up, referring to Fig. 3, it may be said that a crystal triode adapted to produce a current gain consists of a semi-conductor body 16 having a surface which has been treated in conventional manner to produce a surface layer 17 of opposite conductivity type in order to obtain good rectification properties, and on this surface is a second layer 18 containing a donor impurity if the semi-conductor is of the N-type or an acceptor impurity if it is of the P-type. The collector electrode 19 is placed in contact with this second surface layer 18, while the emitter electrode 20 is in contact with the first surface layer 17. The usual base 21 is provided.

One way of producing this second surface layer is to provide two electrodes making rectifier contact with the treated surface, the collector electrode at least containing the appropriate impurity, and then to carry out between the electrodes an electro-forming process such as that which has been described.

Conversely, a crystal triode adapted to give a voltage gain without an attendant current gain comprises a semi-conductor which has been treated in the same conventional manner with at least the collector electrode being of a material which is free from an impurity of the type to act as donor or acceptor impurity for the semi-conducting material, accordingly as the latter is of the N-type or P-type respectively.

What we claim is:

1. A crystal triode comprising a main body of semi-conducting material and having on one of its surfaces a first layer of opposite conductivity to the main body, a second layer on said first layer and of opposite conductivity to said first layer, a base electrode in contact with said main body, and two additional electrodes making rectifying contact respectively with said first and second layers.

2. A crystal triode according to claim 1 in which the said additional electrodes are constructed of a Phosphor bronze.

3. A crystal triode according to claim 1 in which the semi-conducting material comprises N-type germanium and in which the additional electrodes contain either phosphorus, arsenic or antimony.

4. A crystal triode according to claim 1 in which the semi-conducting material comprises N-type germanium,

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and in which said second layer comprises either phosphorus, arsenic, or antimony.

5. A crystal triode comprising a body of semi-conducting material of a given conductivity type, having on its surface a rectifying first layer of the opposite conductivity type, a second layer arranged over part of the first layer and containing as additive material a donor or acceptor impurity according as the semi-conducting material is of the N-type or the P-type, respectively, a base electrode in contact with the semi-conducting material, and two additional electrodes, at least one of which consists of sharply pointed tungsten wire having arsenic or an arsenic com-

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pound deposited on its surface to be used as a collector electrode, said electrodes being placed close together, said collector electrode being in contact with said second layer, said additive material associated with said layer having been derived from said collector electrode and the other electrode being in contact with said first layer.

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