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[33] Japan  
[31] 42/49459 and 43/20599

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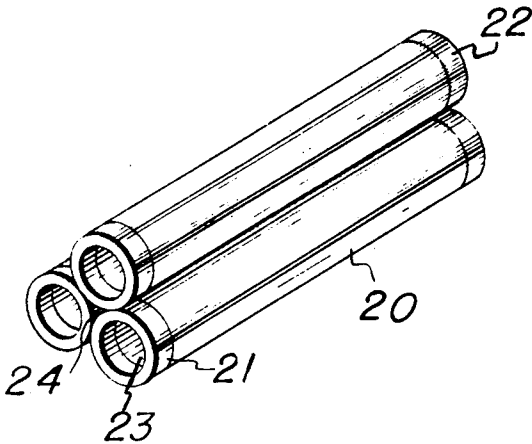
[54] ELECTRON MULTIPLIER DEVICE USING SEMICONDUCTOR CERAMIC  
10 Claims, 10 Drawing Figs.

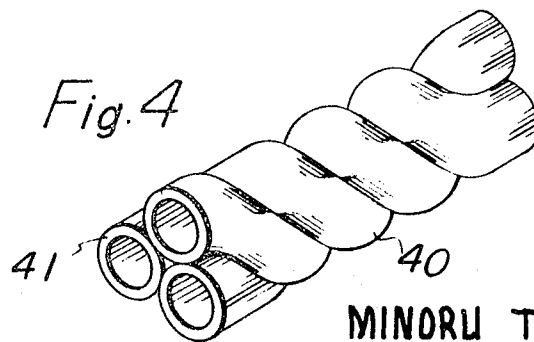
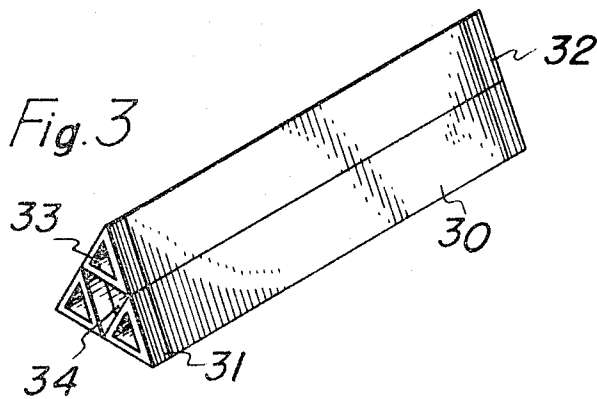
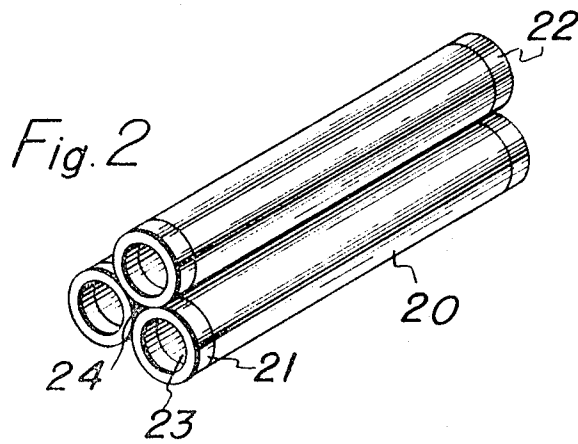
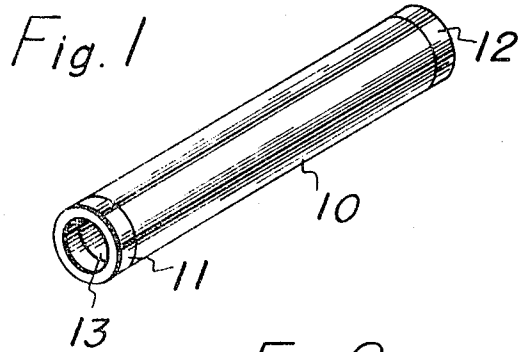
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104, 105, 9.5, 68; 250/207, 213

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**ABSTRACT:** An electron multiplier device. A solid body of barium titanate semiconducting ceramic is formed into a tube or plurality of tubes and at least two electrodes are positioned at spaced points on the tube. The ceramic has a resistance-temperature characteristic which is other than negative, i.e. zero or positive. The device can be used in form of a single tube, or a plurality of such tubes can be bundled together. Electrons fed into the tube or tubes impact with the semiconducting ceramic causing secondary electron emission and a greater number of electrons are emitted than are fed to the device.





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Fig. 5

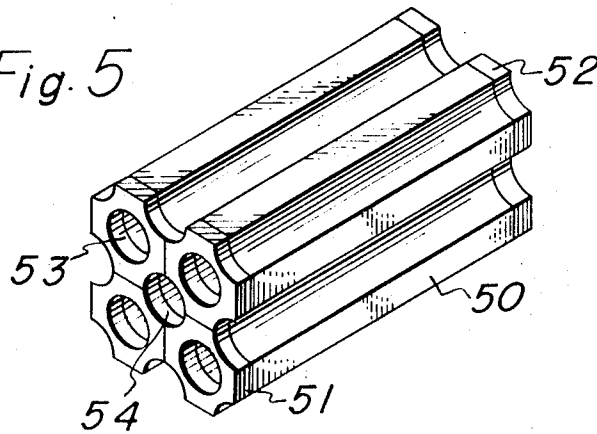


Fig. 6

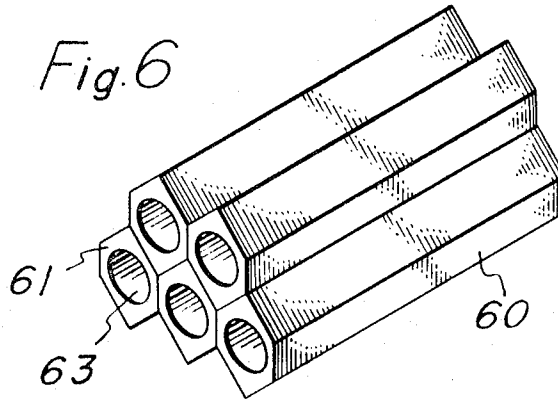
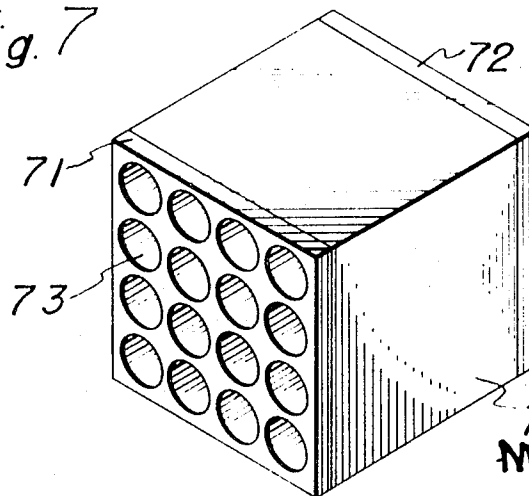
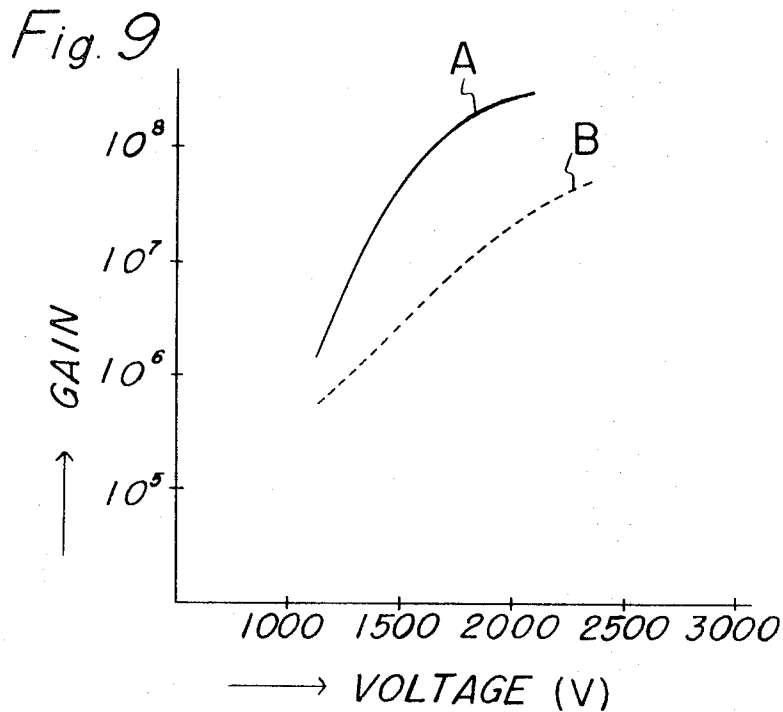
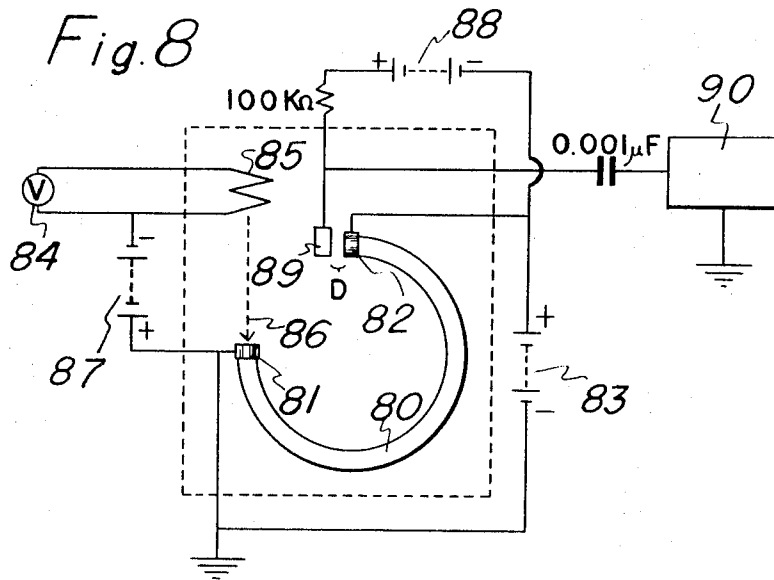


Fig. 7



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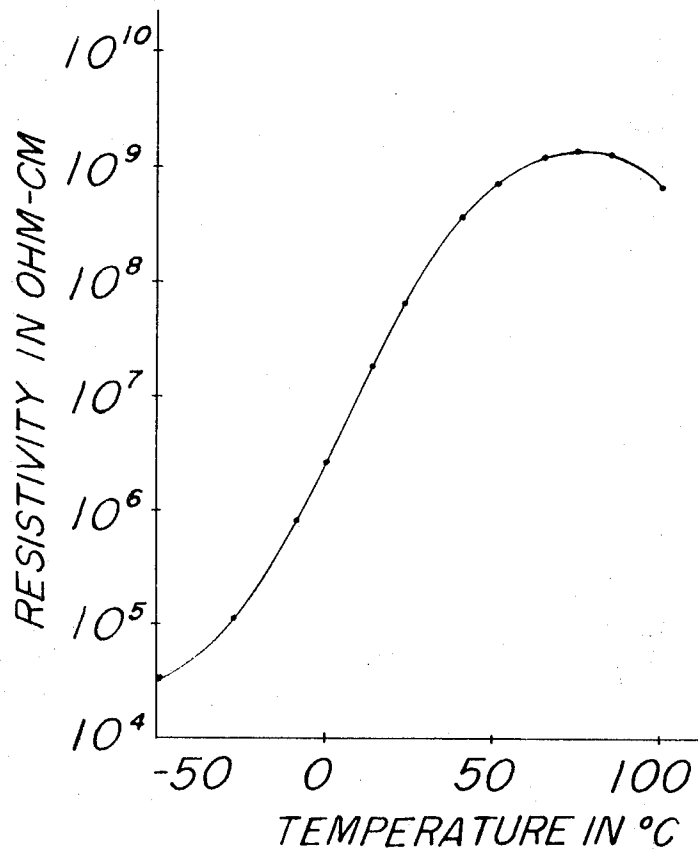


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Fig. 10



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# ELECTRON MULTIPLIER DEVICE USING SEMICONDUCTOR CERAMIC

This invention relates to an electron multiplier device and more particularly to a secondary electron emission multiplier tube or formative body.

In the prior art electron multiplier devices, especially for example, continuous channel type devices, devices constructed by coating high resistive and secondary electron emissive materials, such as tin oxide or a suitable carbon compound, on the inner surfaces of tubes made of insulating materials such as glass have generally been well known.

However, the foregoing thin film type electron multiplier devices have many disadvantages, among which are:

1. they have little resistance to the impact of charged particles or mechanical injury, and lack durability and stableness due to the fact that the layers of highly resistive materials coated on the inner surfaces thereof are thin films;

2. they are complicated, and difficult and expensive to mass produce with the desired thin film having uniform distribution of resistance;

3. when a thin film of highly resistive material with a negative resistance-temperature characteristic is used, when a high potential is applied, the current flow therethrough increases due to self-heating, i.e., they are apt to cause "thermal run away" and to become unstable in operation for this reason, and there is a fairly limited range of values of resistance of the highly resistive materials which can be used. (The details will be explained hereinafter.)

It is an object of this invention to provide an electron multiplier device having a very high electron multiplication gain.

It is another object of this invention to provide an electron multiplier device which is superior in its resistance to impact of charged particles, being durable and stable both mechanically and chemically, therefore being durable and having a long life.

It is a further object of this invention to provide such a device which is not subject to "thermal run away" and in which the selection of the value of resistance of the highly resistive materials is not unduly limited.

It is a still further object of this invention to provide a method of easily and economically manufacturing such a device which has a high gain and high efficiency, which has a strong structure and is stable in its characteristics.

Such an electron multiplier device having a very high electron multiplication gain and which also is free of the prior art disadvantages mentioned above can be made by using a BaTiO<sub>3</sub> family semiconducting ceramic material having positive or zero resistance-temperature characteristics.

Further objects and advantages of this invention will be apparent from a consideration of the following description taken together with the accompanying drawings, in which:

FIG. 1 is a perspective view of one embodiment of an electron multiplier device in accordance with this invention;

FIG. 2 is a perspective view of another embodiment of the invention constituted by a plurality of cylindrical tubes in a bundle;

FIG. 3 is a perspective view of still another embodiment of the invention constituted by a plurality of triangular cross-sectional tubes in a bundle;

FIG. 4 is a perspective view of a further embodiment of the invention constituted by a plurality of cylindrical tubes twisted around one another;

FIG. 5 is a perspective view of another embodiment of the invention constituted by a plurality of octagonal tubes alternate sides of which have concave arc-shaped cross sections and which are in a bundle;

FIG. 6 is a perspective view of still another embodiment of the invention constituted by a plurality of hexagonal tubes in a bundle;

FIG. 7 is a perspective view of a still further embodiment of the invention constituted by a solid block with a plurality of holes therein;

FIG. 8 is a circuit diagram showing a circuit employing the present device;

FIG. 9 is a diagram showing gain-voltage characteristics of one embodiment of an electron multiplier device in accordance with the present invention; and

FIG. 10 is a diagram showing the resistance-temperature characteristics of a BaTiO<sub>3</sub> family semiconducting ceramic used in one embodiment of this invention.

The electron multiplier device according to this invention is characterized by being composed of a body of a BaTiO<sub>3</sub> family semiconducting ceramic material having a resistance-temperature characteristic other than negative, i.e. zero or positive, the body having at least one hole therethrough. By the expression "BaTiO<sub>3</sub> semiconducting ceramic material" is meant the group of ceramics which are barium titanate type ceramic material which have been appropriately doped or reduced so as to be made semiconducting, as described in the article by Saburi, "Journal of the American Ceramic Society," vol. 44, 1961 beginning at page 541.

It is well known in the art that bodies of arbitrary shape, and having specific resistance and resistance-temperature characteristics can be obtained from BaTiO<sub>3</sub> family semiconducting ceramics formed into ceramic semiconductors which are made semiconductive by sintering BaTiO<sub>3</sub> family compositions in a neutral atmosphere or reducing atmosphere, or sintering them in a suitable atmosphere in which the BaTiO<sub>3</sub> family compositions are doped with rare earth elements or elements having a higher valence than group V, for example tantalum or tungsten. I have found that BaTiO<sub>3</sub> family semiconducting ceramics have remarkable secondary electron emissivity, and therefore, in accordance with this knowledge, I have provided an electron multiplier device which is composed of a BaTiO<sub>3</sub> family semiconducting ceramic and its more durable, stable and has a higher gain than in conventional devices of the same shape.

One of the most important features of this invention is the provision of an electron multiplier device made of a BaTiO<sub>3</sub> family semiconducting ceramic which has a positive or zero resistance-temperature characteristic. The fundamental device of this invention can be made of a BaTiO<sub>3</sub> family semiconducting ceramic in the shape of one or more multiplier tubes or a body having at least one hole therein in which secondary electron emission can take place when charged particles are introduced.

Further, for the purpose of causing the body to act as a secondary electron emission device, there must be applied direct voltage in the same direction as the hole extends, and accordingly at least two electrodes made of suitable conductive material must be provided on both ends or any desired portion of the body. When direct potential of any suitable value is applied across the electrodes in the same direction as the hole, charged particles introduced therein from the cathode side will strike the inner wall thereof and cause secondary electron emission, and then these secondary electrons emitted also strike the wall and cause further secondary electron emissions, and a large number of secondary electrons emerge at the anode end thereof. The body with at least one hole need not have a particular shape or construction. In fact, as one example of a simple shape of the body, a cylindrical tube can be used. In addition, the bodies can have such shapes or constructions as shown in the various embodiments of this invention described hereinafter or other shapes producing substantially the same actions as the described embodiments.

Referring to FIG. 1, in which is shown one example of the most simple structure in accordance with the present device, the entire body of a cylindrical tube 10 is composed of a BaTiO<sub>3</sub> family semiconducting ceramic which has the remarkable secondary electron emissivity mentioned above and thus acts as an electron multiplying surface.

Even though the cross-sectional shape of the inner surface of the multiplier tube 10 is polygonal or any other shape other than a cylindrical shape, there is no fundamental difference in its function. The tube can be curved one or more times rather than being straight as is the tube 10 illustrated in FIG. 1. The outer surface of the tube 10 may be coated, but the inner surface of the tube 10 must be entirely or at least partly exposed.

Electrodes 11 and 12 are provided on portions adjacent to both ends of the cylindrical tube 10 by coating a conductive silver paint thereon. A plurality of such electrodes can, if necessary, be provided on desired middle parts of the tube 10, the positions of the electrodes not being limited to the ends of the tube 10. The materials of which the electrodes are formed must be conductive materials, and in addition to the silver paint there can be used an electroless deposited nickel film, fired silver, a rubbed indium-gallium alloy, a conductive carbon coating, an evaporated thin film, and a sprayed aluminum film. Direct current voltage of from about 100 to about 2,000 volts per cm. of length of the tube is applied across electrodes 11 and 12. When electrons are introduced into the hole 13 from the cathode end, there will be a large number of impacts and secondary electron emissions, the number of which are multiplied, and a greater amount of electrons will be emitted from the anode end. Such emitted electrons can be collected by a collector provided at the anode side.

In addition, the device according to the invention can be constructed by bundling together a plurality of tubes of the same length and superior effects can be obtained. The embodiments of FIGS. 2-6 illustrate some such constructions. Shown in FIG. 2 is one of the most fundamental arrangements composed of a plurality of cylindrical tubes 20 (three in the drawing) bundled together and on both end of which are provided electrodes 21 and 22. The whole of the cylindrical tubes 20 are composed of a  $\text{BaTiO}_3$  family semiconducting ceramic with the uniformly distributed resistance, so that both the inner and the outer surfaces have secondary electron emissivity characteristics. Thus not only can the inner surface of the bores 23 through the cylindrical tubes 20, but also the gaps 24 between the plurality of cylindrical tube 20 be effectively utilized for producing electron multiplication, and accordingly the bundle of cylindrical tubes 20 can provide an image intensifier having very high resolving power.

In FIG. 3 there is shown an embodiment in which triangular cross section tubes 30 are bundled in a pyramidal shaped bundle on both ends of which are provided electrodes 31 and 32. This construction, like that of FIG. 2, can produce electron multiplication not only on the inner surface of the bore 33 of the tubes 30, but also in the space 34 defined between the tubes in the bundle.

It is further possible to twist a plurality of tubes 40 (three in the drawing) around one another, as shown in FIG. 4. Such a construction can suppress positive feedback of positive ions from the collector end, and further can increase the effective length of the conductive tube acting as an electron multiplication tube in comparison with the actual overall length of the whole bundle, thus providing the advantages of making the operation stable and providing a very high electron multiplication gain.

Referring to FIG. 5, there is shown an embodiment in which a plurality of octagonal tubes 50 (four in the drawing) is bundled together. Alternate sides of each tube have concave grooves therein, which grooves, when four tubes are bundled with the flat sides in abutment, define a gap 54 formed in the center of each four bundled octagonal tubes 50. The shape of the grooves is such that gap 54 has a circular cross-sectional shape almost identical with the bores 53 in the octagonal tubes 50, and both the bores 53 and the gap 54 can be used for electron multiplication tubes. This embodiment is especially suitable for use in an image intensifier requiring uniformity and regularity of picture elements. Reference numerals 51 and 52 designate electrodes.

Referring to FIG. 6, there is shown an embodiment in which a plurality of hexagonal tubes 60 (five in the drawing) having circular bores 63, are bundled together in such a manner that no gap exists between the layers of assembled tubes 60. The embodiments illustrated in FIGS. 5 and 6 could, of course, if necessary, be twisted in the same manner as the embodiment of FIG. 4.

Referring to FIG. 7, there is shown an embodiment in which a plurality of holes 73 is provided in a rectangular cross sec-

tion body 70 made of a  $\text{BaTiO}_3$  family semiconducting ceramic having electrodes 71 and 72 on opposite ends thereof through which the bores extend. This embodiment acts substantially the same as if a plurality of tubes were made up into a bundle.

FIG. 8 is a circuit diagram for operating the electron multiplier device of the invention. Power source 83 is connected between a cathode 81 and an anode 82 provided by coating a conductive silver paint on both ends of a cylindrical tube 80 which is made of a  $\text{BaTiO}_3$  family semiconducting ceramic and curved in the shape of an arc. The source 83 supplies direct current voltage to the cylindrical tube 80. Electrons 86 emitted from a filament 85 connected to a filament power source 84 are accelerated by an electron accelerating power source 87 and are introduced into the bore of the cylindrical tube 80 from the cathode end 81. Consequently, the electrons carry out a large number of impacts and secondary electron emissions occur and a greater number of electrons are emitted from the anode end 82. The emitted electrons are collected by a collector 89 which is positioned at a point spaced a distance D (about 1 mm.) from the anode 82. The collector 89 is connected to a collector power source 88. The number of emitted electrons are counted by an electron counting device 90. The parts of the circuit are positioned in an evacuated envelope indicated by the dotted lines in FIG. 8, except portions of the power sources and the counting device.

The gain-voltage characteristics of the device according to the invention are shown in FIG. 9.

A cylindrical tube provided with electrodes formed by coating conductive silver paint on both ends thereof, and which had an inner diameter of 1 mm. and an outer diameter of 2 mm., and a length of 50 mm. and was curved with a radius of curvature of 10 mm. and made of a  $\text{BaTiO}_3$  family-semiconducting ceramic having resistance-temperature characteristics as shown in FIG. 10 and volume resistivity at normal temperature of about  $10^6 \Omega\text{-cm.}$ , the composition being  $\text{Ba}_{0.828} \text{Sr}_{0.170} \text{Ce}_{0.002} \text{Ti}_{0.830} \text{Sn}_{0.170} \text{O}_3$  was connected to the circuit shown in FIG. 8. The various parts except the sources and the counting device were positioned in an evacuated envelope having a vacuum of  $10^{-10}$  torr. The voltage of the collector power source was 200 volts. The gain-voltage characteristics were according to the curves shown in FIG. 9. The solid line A shows the gain when the voltage of the electron accelerating power source was 200 volts, and the broken line B shows the gain when the voltage was 50 volts. The ordinate and abscissa of the graph, respectively, shown gain and voltage across the electrodes of the cylindrical tube. The temperature of the apparatus was  $20^\circ \text{C.}$

As described above, the electron multiplier device according to this invention does not require such troublesome steps in the formation thereof as the coating of a thin film of highly resistive material on the inner surface of the tube, and it produces a large electron multiplication gain, i.e.  $10^7$  to  $10^8$ , with a very simple structure.

Further, the electron multiplier tube of this invention is made of a uniform semiconducting ceramic, and thus is not damaged by electron impacts, being durable and stable both mechanically and chemically. Therefore, it has a long life. Because the present device consists of a semiconducting ceramic, even when it is injured for any reason in the course of its use, the injured portions can be repaired with a conductive adhesive so that the device can be reconstructed in a very simple manner.

In the prior art devices, because thin film of a high-resistance material having negative resistance-temperature characteristics has been used, when high voltage is applied thereto, they have been self-heated and frequently destruction has occurred due to such self-heating. Hence, it has been necessary to limit current flow therein so that it is small enough for the value of resistance of the thin film materials. Moreover, when the resistance is high, it causes the disadvantage that the thin film does not become semiconductive, but rather becomes dielectric. Accordingly an accumulation of charged electrons takes place, spaced electrons are

generated, and the time constant becomes larger. For this reason, the range of the values of resistance which can be used becomes narrow and also production becomes difficult. The present device, on the other hand, because it is composed of a material such as BaTiO<sub>3</sub> family semiconducting ceramic with a positive or zero resistance-temperature characteristic is self-protecting and limits current due to self-heating. Further, there is no danger of "thermal run away" taking place, and accordingly, a high gain can be obtained by applying a high voltage.

In comparison with the prior art devices formed by bundling coated glass tubes and the like, the embodiments of the present invention formed by bundling tubes of identical length, as described in connection with FIGS. 2-6, produce superior effects in addition to the aforementioned advantages, as follows:

In this invention the whole of each tube is composed of a BaTiO<sub>3</sub> family-semiconducting ceramic having uniform distribution of resistance, so that both the inner and outer surfaces of the tubes are capable of secondary electron emission, so that the embodiments of FIGS. 2, 3 and 5 of the present invention have the advantage of effectively utilizing as an electron multiplication tube gap which is produced between a plurality of tubes adjacent to one another in the bundle. For that reason, there is no part of the device which is not operating to multiply electrons, and image resolving power can be increased. In the conventional method of bundling glass tubes, on the other hand, the potential distribution across individual tubes may be affected by the resistance distribution in individual tubes, so that the prior art required making uniform the resistance distribution characteristics of each tube to obtain a better multiplier device. On the contrary, in the present device, the whole of each tube is composed of semiconductors, so that individual electron multiplication surfaces can be joined in a parallel by bundling the tubes, so that even though individual tubes have different resistance distribution (or in the extreme case of one tube being broken), the potential distribution is uniform. Further, when providing electrodes on both ends of the tube assembly, it is not necessary to provide electrodes on each tube before assembly. Electrodes can be applied to the ends thereof after bundling. With respect to electrodes 41 and 61 shown in FIGS. 4 and 6, these electrodes need be provided only on the end surfaces of tube assembly. It is not necessary to have them reach the side portions. This is because the whole of each tube of this invention is conductive.

The embodiment shown in FIG. 7 also has the same effects as aforementioned with respect to the properties of the materials used in this invention, and such a construction also has the advantage of being very easily manufactured. In the prior art there have been used insulating materials such as glass, and it is very difficult and expensive to produce such a construction illustrated in FIG. 7 out of glass. On the contrary, the device of the present invention can be produced easily and inexpensively in any shape using ceramics as the material thereof, and thus is suited for mass production.

As mentioned above, the electron multiplier device in ac-

cordance with this invention can be used for the multiplication or output design of various charged particles (i.e., electrons, positive ions, negative ions) in general electron multiplying tubes, or for photoelectron multiplication in cooperation with a suitable photoelectron transducer. The embodiments illustrated in FIGS. 2-7 are especially useful for image intensifiers such as X-ray (hard, soft) multiplication and observing devices which require high-image resolving power, high stability and a high degree of multiplication. Further, this invention, in which the secondary electron emissive body is not a thin film but a solid body, is therefore more effective for hard X-rays than a thin film type device.

It is thought that the invention and its advantages will be understood from the foregoing description and it is apparent that various changes may be made in the form, construction and arrangement of the parts without departing from the spirit and scope of the invention or sacrificing its material advantages, the forms hereinbefore described and illustrated in the drawings being merely preferred embodiments thereof.

What is claimed is:

1. An electron multiplier device comprising a solid body having at least one hole therethrough and at least two electrodes of a conductive material on said body, said body being of a BaTiO<sub>3</sub> family semiconducting ceramic having a resistance-temperature characteristic which is other than negative.

2. An electron multiplier device according to claim 1 wherein said body is a tube.

3. An electron multiplier device according to claim 2 wherein said tube is cylindrical.

4. An electron multiplier device according to claim 2 wherein said tube is polygonal.

5. An electron multiplier device according to claim 1 wherein said body is a rectangular block with electrodes on opposite faces thereof and has a plurality of holes therethrough perpendicular to the electrodes.

6. An electron multiplier device comprising a plurality of hollow tubes each being of a solid BaTiO<sub>3</sub> family semiconducting ceramic having a resistance-temperature characteristic which is other than negative and each having two electrodes of a conductive material thereon, said tubes being bundled together in a bundle.

7. An electron multiplier device as claimed in claim 6 in which said tubes are cylindrical and straight.

8. An electron multiplier device according to claim 6 wherein said tubes are triangular in cross section and straight and are stacked in the shape of a pyramid and define triangular cross-sectional spaces between each three stacked tubes.

9. An electron multiplier device according to claim 6 wherein said tubes are polygonal tubes having grooves in at least some of the sides and said grooves are opposed to corresponding grooves in adjacent tubes in the bundle to form bores through said bundle.

10. An electron multiplier device according to claim 6 wherein the plurality of tubes are mutually twisted around each other.

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