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COMPLETE SPECIFICATION.

Solid State Field-Effect Devices.

We, RADIO CORPORATION OF AMERICA, a Corporation organized under the laws of the State of Delaware, United States of America, of 30, Rockefeller Plaza, City and State of New York, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to solid state field-effect devices.

In the article entitled, THE TFT—A NEW THIN FILM TRANSISTOR, Proceedings of the Institute of Radio Engineers, by P. K. Weimer, Vol. 50, pages 1462—1469, June 1962, an insulated gate field-effect thin-film transistor is described. It is desirable to provide other solid state thin-film devices which can be formed with the same type of processing steps and at the same time as the thin-film transistors.

It is the object of this invention to provide new and improved solid state field-effect devices.

According to one aspect of the present invention, there is provided a solid state field-effect device comprising: a layer of semiconductive material of single conductivity type; a film of high resistivity material on a portion of one side of said semiconductive layer; and two metallic electrodes, including a first electrode in contact with said semiconductive layer and making an ohmic contact thereto and a second metallic electrode having a portion in contact with said semiconductive layer and defining with said first electrode the ends of a current path through said semiconductive layer, and having another portion extending adjacent to a por-

tion of said current path and separated from said semiconductive layer by said film of high resistivity material.

According to another aspect of the invention, there is provided a solid state field-effect device comprising: a layer of semiconductive material of single conductivity type; a film of high resistivity material on a portion of one side of said semiconductive layer; and two metallic electrodes, including a first electrode in contact with said semiconductive layer and making an ohmic contact thereto and a second metallic electrode having a portion which makes either a blocking contact or an ohmic contact to said semiconductive layer and defines with said first electrode the ends of a current path through said semiconductive layer, said second electrode having another portion extending adjacent to a portion of said current path and separated from said semiconductive layer by said film of high resistivity material.

The invention will now be described with reference to the accompanying drawings, in which:

Figure 1 is a cross-sectional view of a solid state field-effect device according to one embodiment of the invention;

Figures 2 to 8 are cross-sectional views of field-effect devices according to other embodiments of the invention; and

Figure 9 is a graph of the output current versus the applied voltage for a field-effect device according to the invention.

Similar reference numerals have been applied to similar elements in the several Figures.

The field-effect device according to Figure 1 may be prepared on an insulating support or substrate 10. On one face 11 of sub-

strate 10, there are provided two spaced metallic electrodes 14 and 16.

A high electrical resistivity film 18 is arranged on a portion of one electrode 16. The high resistivity film 18 may conveniently be deposited by evaporation.

A layer 12 of single conductivity type semiconductive material is arranged on the face 11 of insulating support 10 so as to cover part of electrode 14, the gap between electrodes 14 and 16, the high resistivity film 18, and part of electrode 16. The semiconductive material utilized for layer 12 is a crystalline substance which exhibits a periodic potential field, at least on an atomic scale, and may be either monocrystalline or polycrystalline.

A conductor 15 is attached to electrode 14, and a second conductor 17 is attached to electrode 16. The conductors 15 and 17 may conveniently be bonded to electrodes 14 and 16 respectively by a silver paste. Alternatively, when the device is to be part of an array, or of an integrated circuit comprising a plurality of diodes and other solid state devices such as thin film transistors and the like, the lead wires 15 and 17 may be omitted, and suitable connections to other devices made by evaporating conductive metal strips as extensions of electrodes 14 and 16 to the terminals of other units deposited on the same substrate 10.

The solid state device illustrated in Figure 1 is a field-effect diode having a rectifying action which may be explained as follows:

Consider first the case of an N-type semiconductor 12, such as cadmium sulphide, which has an electrical conductivity that is large enough to give an appreciable current between the electrodes 14 and 16 when the drain electrode 16 is biased positively with respect to the source electrode 14. The principal electron flow in the semiconductor is along the bottom surface of the semiconductor from the inner edge (labelled "s" in Figure 1) of the source electrode 14 to the closest point of contact (labelled "d") of the drain electrode 16 with the semiconductor layer 12. No direct flow of electrons through the semiconductor can occur from the inner edge s of the source electrode 14 to the point d' on the drain electrode 16 which is closest to s. This is due to the high resistivity film 18 in the direct path between the electrode 16 and the semiconductor layer 12 at d'.

lower
The current flow in the semiconductor layer 12 produces a voltage drop along the lower surface of the semiconductor layer 12 from point d on the drain electrode 16 (at +V volts to points s on the source electrode 14 (at 0 volts). Therefore, the portion of semiconductor layer 12 lying directly over the high resistivity film 18 (the portion between d and d') is somewhat negative with respect to the underlying drain electrode

16. The effect of the underlying drain electrode 16 therefore is to enhance the conductivity of the portion of semiconductor layer 12 over the drain electrode 16, thereby increasing the drain current still more by field-effect action. This polarity of drain voltage (positive with respect to the source electrode 14) is called the forward-biased condition of the diode.

In the reverse-biased condition, the partially insulated drain electrode 16 is placed at a negative potential relative to the grounded source electrode 14. Electrons now tend to flow along the bottom surface of semiconductor layer 12 from drain electrode 16 to source electrode 14. However, the voltage drop in the semiconductive layer 12 makes the portion of semiconductor layer 12 between electrodes 14 and 16 positive with respect to the electrode 16. In this case, the field-effect action of electrode 16 reduces the conductivity of that portion of semiconductor layer 12 which lies over the insulated portion of electrode 16, thus holding the drain current to a very low value.

If the semiconductor layer 12 is P-type, the same reasoning can be used to explain the field-effect action of the electrode 16 upon the hole conductance in the P-type semiconductor. In this case, the forward direction of the diode is that in which the electrode 16 is negative with respect to electrode 14, while the reverse bias direction occurs when electrode 16 is positive with respect to electrode 14.

It is to be noted that the rectifying action of the diode illustrated in Figure 1 is obtained entirely by field-effect modulation of a semiconducting layer 12, and not by the use of dissimilar materials for the two electrodes 14 and 16. In conventional diodes, one electrode is ohmic, and the other is rectifying, while in the device of Figure 1, both contacts are ohmic. This feature permits simplification of the fabrication of integrated circuits, since field-effect diodes can be evaporated simultaneously with thin film triodes on the same insulating substrate. Moreover, when diodes are made in the conventional manner, requiring one electrode to make a rectifying contact with the semiconductor, an additional evaporation and more processing steps are required over that of the present diodes.

A further advantage of the thin film field-effect diode over conventional rectifying contact thin film diodes is that the ratio of forward conductance to capacitance is higher in the field-effect diodes. It may be noted that, for some applications requiring the maximum ratio of forward to reverse current, it may be desirable to combine the action of the field-effect and of the rectifying contact by utilizing for the electrode 16 a

material which makes a rectifying contact to the semiconductive layer 12.

In the construction of the field-effect diode illustrated in Figure 1, the spaced electrodes 14 and 16 may be deposited on the substrate 10 as thin films by masking and evaporation. Alternatively a paste containing metal particles may be painted or silk-screened on selected portions of the face 11 of the substrate 10. Other techniques such as sputtering may also be used.

The thickness of the electrodes 14 and 16 may vary from 0.005 micron to 0.5 micron. In the illustrated device of Figure 1, the electrodes 14 and 16 consist of gold and are approximately 0.05 micron thick. The gap between the electrodes is 8 microns. This gap is preferably between 0.1 micron and approximately 250 microns.

For efficient operation, the high resistivity film 18 should preferably be less than two microns thick. Advantageously film 18 is 0.005 to one micron thick. In the illustrated example of Figure 1, film 18 consists of silicon monoxide and is 0.03 micron thick. Materials which have been found particularly suitable for the high resistivity film 18 are insulators such as silicon monoxide, silicon dioxide, aluminium oxide, calcium fluoride and like insulators. Materials which are usually classified as semiconductors such as zinc sulphide may also be utilized for the film 18, providing that they exhibit high resistivity.

In Figure 1, the semiconductive layer 12 consists of polycrystalline cadmium sulphide and the electrodes 14 and 16 both make ohmic contacts to the layer 12. The layer 12 is preferably between 0.005 and 25 microns thick. Suitable semiconductive materials for the layer 12 include elemental semiconductors such as germanium, silicon, and germanium-silicon alloys; III-V compound semiconductors such as the phosphides, arsenides and antimonides of aluminium, indium and gallium; and II-VI compounds such as the sulphides, selenides and tellurides of zinc and cadmium. Zinc oxide may also be classed as a II-VI compound.

It is not necessary for the two electrodes 14 and 16 to consist of the same material. However, the materials used for layer 12 and the source electrode 14 should be selected so that the electrode 14 makes an ohmic contact to the semiconductor 12. An ohmic contact is conductive for majority carriers in both directions.

The drain electrode 16 may make either an ohmic contact or rectifying contact to the semiconductor 12. A rectifying contact between an N-type semiconductor such as cadmium sulphide and a large work function metal such as platinum is a type of contact wherein the flow of the majority charge carriers is blocked from entering the semi-

conductor when the semiconductor is biased positively with respect to the electrode. When the electrode is biased positively with respect to the semiconductor, a large flow of electrons from the semiconductor to the electrode occurs.

When a high resistivity material such as aluminium oxide is interposed between a metal electrode and a semiconductor, the high resistivity material acts as a potential barrier and prevents the flow of electrons either from the metal to the semiconductor or from the semiconductor to the metal.

As mentioned above, the thin films utilized may be deposited by any convenient technique. While evaporation is presently the most useful method of depositing uniform thin films, other processes, such as sputtering, may also be employed.

It can be shown that the upper limit on high frequency performance is related to the average transit time for charge carriers moving in the active semiconductive layer 12 between the electrodes 14 and 16. The transit time can be reduced either by increasing the mobility of majority charge carriers in the semiconductive layer, or by reducing the gap or spacing between the two electrodes.

In the embodiment illustrated in Figure 1, the various device components are arranged so that the electrodes 14 and 16 rest directly on the substrate 10, and both electrodes are beneath the semiconductive layer 12, making contact to the lower surface of the semiconductive layer.

The arrangement of the device components may be reversed, so that the electrodes 14 and 16 are in contact with the upper surface of the semiconductive layer 12, as described with respect to Figure 2.

Referring now to Figure 2, a solid state field-effect diode according to another embodiment of the invention is illustrated. The crystalline semiconductive layer 12 is arranged on the face 11 of an insulating support 10. The layer 12 is made of cadmium selenide, and is approximately 0.2 micron thick.

The high resistivity film 18 is arranged on a first portion of the exposed surface of layer 12. The film 18 is made of aluminium oxide and is approximately 0.02 micron thick.

The first metallic electrode 14 is arranged on a second portion of the exposed surface of layer 12, and is in direct contact therewith. The electrode 14 is made of aluminium and is approximately 0.05 micron thick.

The second metallic electrode 16 is spaced from the electrode 14 and is arranged on a portion of the insulating film 18 and also on a portion of the exposed upper surface of layer 12. The second electrode 16 also is made of aluminium and is approximately 0.05 micron thick. The two electrodes 14 and 16

polycrystalline

are spaced with adjacent edges a distance between 0.1 and 250 microns apart.

If desired, a pair of conductors (not shown) may be attached to electrodes 14 and 16 respectively, in a manner similar to that shown in Figure 1. Alternatively, strips of conductive material (not shown) may be deposited from each of electrodes 14 and 16 over face 11 of substrate 10 to other solid state devices deposited on the substrate.

The operation of the field-effect device illustrated in Figure 2 is the same as that shown in Figure 1. Similarly, the same materials that were suggested above for the semiconductive layer, the electrodes, and the high resistivity film may be used in this embodiment.

The illustration of the electrical conductors connected to the electrodes 14 and 16 is to be understood and will not be illustrated in the remaining Figures.

In the device illustrated in Figures 1 and 2, the electrodes 14 and 16 are on the same side of the layer 12. Devices embodying the invention may be fabricated in a staggered arrangement with one electrode on one side of the semiconductive layer and the other electrode on the other side of the layer 12. Such embodiments are shown in Figures 3 and 4, respectively.

In Figure 3, the materials of electrode 14 and of the semiconductive layer 12 are selected so that the contact between them is ohmic in character.

Referring now to Figure 4, in this embodiment the adjacent edges of electrodes 14 and 16 are positioned so as to just overlap vertically in the drawing. The electrodes 14 and 16 are therefore separated by the combined thickness of the layer 12 and of the film 18.

In the device illustrated in Figure 4, the interelectrode capacitance is increased as compared to the embodiment shown in Figure 3. In operation both of the embodiments in Figures 3 and 4 operate on the same principle as that discussed with respect to Figure 1.

Referring now to Figure 5, a solid state field-effect diode may be provided in a sandwich configuration by depositing a portion of a first metallic electrode 16a on one face 11 of the insulating support 10; depositing the layer 12 of crystalline semiconductive material on said one face 11 so as to cover a portion of the electrode portion 16a and of said one face 11; depositing a second metallic electrode 14 on one portion of the exposed upper side of layer 12; depositing a film 18 of high resistivity material on a second portion of the exposed upper side of layer 12; and depositing a metallic electrode 16b on a portion of the high resistivity film 18 and on a portion of the exposed upper

side of layer 12. The electrode 16b merges with the first metallic electrode 16a to form a single electrode 16 wrapped around opposing sides of semiconductive layer 12.

Referring now to Figure 6, it can be seen that in this embodiment the high resistivity film 18 and the electrode 14 are on opposite sides of semiconductive layer 12, while in the embodiment of Figure 5, film 18 and electrode 14 are on the same side of the layer 12.

Referring now to Figure 7, another embodiment of the solid state field-effect diode is shown wherein the adjacent edges of electrode 14 on the lower side of layer 12 and of electrode 16b on the high resistivity film 18 overlap vertically as viewed in Figure 7. The electrodes 14 and 16 in this embodiment are thus separated by the combined thickness of semiconductive layer 12 and high resistivity film 18. The device of this embodiment is similar in this respect to the device of Figure 4.

The rectification ratio (ratio of current in the forward direction to current in the reverse direction for a given applied voltage in the two directions) can be made as high as 10^6 for the field-effect diodes in any of the illustrated embodiments.

Figure 9 is a plot showing the variation in current with applied voltage for a field-effect diode comprising a layer of cadmium sulphide on a glass substrate, a high resistivity calcium fluoride film on the cadmium sulphide layer, and two spaced aluminium electrodes on the cadmium sulphide layer, one electrode being partly in contact with the cadmium sulphide layer and partly over the calcium fluoride film. The semiconductive cadmium sulphide layer, the high resistivity calcium fluoride film, and two spaced electrodes in this device were arranged on an insulating support as illustrated in Figure 6. Since the current in the reverse direction is small compared to the current in the forward direction, the scale of the graph ordinate in Figure 9 is changed from milliamperes above zero to hundredths of milliamperes below zero.

Referring now to Figure 8, a solid state device is illustrated which combines the characteristics of a field-effect diode with that of a thin film transistor.

A solid state device as shown in Figure 8 is provided by depositing the first metallic electrode 14 on face 11 of the insulating substrate 10; depositing the crystalline semiconductive material forming layer 12 on said face 11 so as to cover a portion of electrode 14; depositing the film 18 of high resistivity material on a portion of the exposed upper side of layer 12; depositing the second metallic electrode 16 on a first portion of film 18, and also on a portion of the exposed upper side of layer 12; and depositing a third metallic electrode 20 on a second part of

the film 18 between electrodes 14 and 16.

Electrode 14 may serve as the source; electrode 16 may serve as the drain; and the third electrode 20 may serve as the gate.

5 If desired, electrical conductors (not shown) may be attached to electrodes 14, 16 and 20. Alternatively, these electrodes may be electrically connected to other devices on the same substrate by depositing strips of
10 conductive metal (not shown) from each electrode over face 11 of substrate 10 to the electrodes of other devices.

The operating characteristics of the thin film transistor shown in Figure 8 differ from that of the conventional Thin Film Transistor in that useful currents are obtained only if the partially insulated electrode is positively biased for an N-type semiconductor, or negatively biased for a P-type semiconductor. With the opposite voltages applied, substantially no current is obtained. A conventional thin film transistor, as described in the above mentioned I.R.E. publication, has the same characteristics regardless of which
25 electrode is positively biased.

It will be understood that the above examples are by way of illustration only and not limitation. Other materials may be utilized for the substrate, the semiconductive layer, the high resistivity film, and the electrodes. The semiconductive layer 12 may consist of evaporated tellurium, which is a P-type semiconductor. In the sandwich construction illustrated in Figures 5, 6 and 7, the electrode 16 may consist of two different metals, for example aluminium for that portion 16a of electrode 16 which is directly on face 11 of the support 10, and gold for that portion 16b of electrode 16 which is on the high resistivity film 18 and on the upper surface of semiconductive layer 12. In the diodes illustrated in Figures 2, 3 and 4, the electrode 16 may be partially underneath the high resistivity film 18, as well as partially over it.

WHAT WE CLAIM IS:—

1. A solid state field-effect device comprising: a layer of semiconductive material of single conductivity type; a film of high resistivity material on a portion of one side of said semiconductive layer; and two metallic electrodes, including a first electrode in contact with said semiconductive layer and making an ohmic contact thereto and a
50 second metallic electrode having a portion in contact with said semiconductive layer and defining with said first electrode the ends of a current path through said semiconductive layer, and having another portion extending adjacent to a portion of said current path and separated from said semiconductive layer by said film of high resistivity material.

2. A solid state field-effect device comprising: a layer of semiconductive material

of single conductivity type; a film of high resistivity material on a portion of one side of said semiconductive layer; and two metallic electrodes, including a first electrode in contact with said semiconductive layer and making an ohmic contact thereto and a
70 second metallic electrode having a portion which makes either a blocking contact or an ohmic contact to said semiconductive layer and defines with said first electrode the ends of a current path through said semiconductive layer, said second electrode having another portion extending adjacent to a portion of said current path and separated from said semiconductive layer by said film of high resistivity material.

3. A solid state field-effect device according to Claim 1 or Claim 2, wherein said film of high resistivity material consists of a material selected from the group consisting of silicon monoxide, silicon dioxide, calcium fluoride, zinc sulphide, and magnesium oxide.

4. A solid state field-effect device according to any one of Claims 1 to 3, wherein said semiconductive layer is arranged on a face of an insulating substrate, and at least a portion of said high resistivity film is interposed in the direct path through said semiconductive layer between adjacent edges of said first and second electrodes.

5. A solid state field-effect device according to any one of the preceding Claims, wherein said film of high resistivity material is less than two microns thick.

6. A solid state field-effect device according to any one of the preceding Claims wherein said semiconductive layer is between 0.005 and 25 microns thick, said film of high resistivity material is between 0.005 and one micron thick, and said first and second electrodes have a lateral gap of between 0.1 and about 250 microns therebetween.

7. A solid state field-effect device according to Claim 4, wherein said electrodes are arranged on one side of said substrate, said film of high resistivity material is arranged on one of said electrodes and said semiconductive layer covers said high resistivity film, a portion of each said electrode, and the gap
115 between said electrodes.

8. A solid state field-effect device according to Claim 6, wherein said electrodes are arranged on opposite sides of said semiconductive layer with their respective inner edges in overlapping relationship.

9. A solid state field-effect device according to Claim 4, wherein one of said electrodes is arranged on a portion of said film, on a portion of the exposed upper surface of said semiconductive layer, and on one face of said substrate to form a single electrode on both sides of said semiconductive layer.

the film 18^a between electrodes 14 and 16.

Electrode 14 may serve as the source; electrode 16 may serve as the drain; and the third electrode 20 may serve as the gate. If desired, electrical conductors (not shown) may be attached to electrodes 14, 16 and 20. Alternatively, these electrodes may be electrically connected to other devices on the same substrate by depositing strips of conductive metal (not shown) from each electrode over face 11 of substrate 10 to the electrodes of other devices.

The operating characteristics of the thin film transistor shown in Figure 8 differ from that of the conventional Thin Film Transistor in that useful currents are obtained only if the partially insulated electrode is positively biased for an N-type semiconductor, or negatively biased for a P-type semiconductor. With the opposite voltages applied, substantially no current is obtained. A conventional thin film transistor, as described in the above mentioned I.R.E. publication, has the same characteristics regardless of which electrode is positively biased.

It will be understood that the above examples are by way of illustration only and not limitation. Other materials may be utilized for the substrate, the semiconductive layer, the high resistivity film, and the electrodes. The semiconductive layer 12 may consist of evaporated tellurium, which is a P-type semiconductor. In the sandwich construction illustrated in Figures 5, 6 and 7, the electrode 16 may consist of two different metals, for example aluminium for that portion 16a of electrode 16 which is directly on face 11 of the support 10, and gold for that portion 16b of electrode 16 which is on the high resistivity film 18 and on the upper surface of semiconductive layer 12. In the diodes illustrated in Figures 2, 3 and 4, the electrode 16 may be partially underneath the high resistivity film 18, as well as partially over it.

WHAT WE CLAIM IS:—

1. A solid state field-effect device comprising: a layer of semiconductive material of single conductivity type; a film of high resistivity material on a portion of one side of said semiconductive layer; and two metallic electrodes, including a first electrode in contact with said semiconductive layer and making an ohmic contact thereto and a second metallic electrode having a portion in contact with said semiconductive layer and defining with said first electrode the ends of a current path through said semiconductive layer, and having another portion extending adjacent to a portion of said current path and separated from said semiconductive layer by said film of high resistivity material.

2. A solid state field-effect device comprising: a layer of semiconductive material

of single conductivity type; a film of high resistivity material on a portion of one side of said semiconductive layer; and two metallic electrodes, including a first electrode in contact with said semiconductive layer and making an ohmic contact thereto and a second metallic electrode having a portion which makes either a blocking contact or an ohmic contact to said semiconductive layer and defines with said first electrode the ends of a current path through said semiconductive layer, said second electrode having another portion extending adjacent to a portion of said current path and separated from said semiconductive layer by said film of high resistivity material.

3. A solid state field-effect device according to Claim 1 or Claim 2, wherein said film of high resistivity material consists of a material selected from the group consisting of silicon monoxide, silicon dioxide, calcium fluoride, zinc sulphide, and magnesium oxide.

4. A solid state field-effect device according to any one of Claims 1 to 3, wherein said semiconductive layer is arranged on a face of an insulating substrate, and at least a portion of said high resistivity film is interposed in the direct path through said semiconductive layer between adjacent edges of said first and second electrodes.

5. A solid state field-effect device according to any one of the preceding Claims, wherein said film of high resistivity material is less than two microns thick.

6. A solid state field-effect device according to any one of the preceding Claims wherein said semiconductive layer is between 0.005 and 25 microns thick, said film of high resistivity material is between 0.005 and one micron thick, and said first and second electrodes have a lateral gap of between 0.1 and about 250 microns therebetween.

7. A solid state field-effect device according to Claim 4, wherein said electrodes are arranged on one side of said substrate, said film of high resistivity material is arranged on one of said electrodes and said semiconductive layer covers said high resistivity film, a portion of each said electrode, and the gap between said electrodes.

8. A solid state field-effect device according to Claim 6, wherein said electrodes are arranged on opposite sides of said semiconductive layer with their respective inner edges in overlapping relationship.

9. A solid state field-effect device according to Claim 4, wherein one of said electrodes is arranged on a portion of said film, on a portion of the exposed upper surface of said semiconductive layer, and on one face of said substrate to form a single electrode on both sides of said semiconductive layer.



10. A solid state field-effect device according to any one of the preceding Claims, comprising a third electrode on a second portion of said high resistivity film.

5 11. A solid state field-effect device substantially as herein described with reference

to and as illustrated in any one of Figures 1 to 8 of the accompanying drawings.

A. M. & WM. CLARK,

Chartered Patent Agents,

5, Stone Buildings,

Lincoln's Inn, London, W.C.2. 152

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