

## DESCRIPTION

## DEVICES AND ARRANGEMENTS COMPRISING SEMICONDUCTOR CATHODES

This invention relates to a semiconductor device for producing an electron current by means of a cathode comprising a semiconductor body having a pn junction between a p-type region and an n-type region which adjoins a major surface of the body, and electrical connections to the p-type and n-type regions for applying a voltage in the reverse direction across the pn junction whereby electrons are generated in the semiconductor body by avalanche multiplication and are emitted from said surface of the semiconductor body. The invention further relates to display arrangements and pick-up devices, e.g. a camera tube, comprising such a semiconductor device.

Semiconductor cathode arrangements are known from the Netherlands Patent Application NL-A 7905470 of the Applicant, laid open to public inspection on 15 January 1981. The operation of these semiconductor cathodes is based on avalanche multiplication of electrons when a pn junction is reverse-biased. The pn junction has at the area of the emitting surface a reduced breakdown voltage and is separated in situ from the surface by an n-type conducting layer having such a thickness and doping that at the breakdown voltage the depletion zone does not extend as far as the surface, but remains separated therefrom by a surface layer which is sufficiently thin to pass the generated electrons.

In NL-A 7905470, inter alia a flat display arrangement is shown provided with a fluorescent screen which is activated by electrons originating from a semiconductor device having a group of cathodes forming emission regions which are organized in an xy matrix and in which, depending upon the drive of each cathode forming a separate emission region, different patterns of electron emission and hence different fluorescent patterns are generated.

The said NL-A 7905470 also discloses an application in which one such semiconductor cathode is used in an electron tube and has an electron-emitting surface region which is substantially annular. With the use of such a semiconductor cathode in conventional cathode-ray tubes, a virtual source is generally not used as in the

embodiment shown therein, but the electrons emitted by the semiconductor cathode meet in a so-called "cross-over". The electrons then move mainly along the surface of the generated beam, which, as described in NL-A 7905470, may be advantageous from an electron-optical point of view.

In general the desired electron current is fixed, depending upon the type of cathode-ray tube in which the semiconductor cathode is used. Electron currents (beam currents) higher than  $100\mu\text{A}$  may be produced, for example, by means of semiconductor cathodes having an annular emitting surface with a diameter exceeding approximately  $20\mu\text{m}$ . The electron current density is then fixed having regard to this electron current, the overall emitting surface and the efficiency of the semiconductor cathode.

This electron current density can become so low that in practice stability problems occur. Any residual gases from the vacuum system (for example  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{O}_2$ ) are adsorbed at the electron-emitting surface and can interact in situ with a mono-atomic layer of caesium, which is generally applied to this surface to reduce the work function of the electrons generated in the semiconductor body, and also interact with the surface of the semiconductor crystal. However, under the influence of the electrons emanating from the semiconductor body, compounds thus formed can be decomposed and adsorbed atoms are drained (desorption). Adsorbed atoms are also drained by diffusion from the emission region under the influence of electric fields (for example the fields produced by the adjustment current for the cathode). In order to ensure that these mechanisms have sufficient influence in overcoming adsorption, it is often required, however, to increase the electron current density by adjusting the adjustment current to a higher value than is practically possible or desirable.

The present invention has for its object to provide a semiconductor cathode which generates the emitted electrons by avalanche multiplication but which has an increased stability.

According to a first aspect of the invention there is provided a semiconductor device for producing an electron current by means of

a cathode comprising a semiconductor body having a pn junction between a p-type region and an n-type region which adjoins a major surface of the body, said surface being provided with a layer having at least one group of openings at each of which openings a separate  
5 electron-emission region is present from which electrons are emitted in the operating condition, and common electrical connections respectively to the p-type and n-type regions for operating the group of separate electron-emission regions in common by applying a common voltage in the reverse direction across the pn junction  
10 whereby electrons are generated in the semiconductor body by avalanche multiplication and are then emitted from the emission regions at said surface of the semiconductor body, the pn junction extending at least at the areas of the electron-emission regions mainly parallel to the major surface and locally having a lower  
15 breakdown voltage at these areas than the remaining part of the pn junction, the parts having the lower breakdown voltage being separated from the surface by an n-type layer which forms part of the n-type region and which has such a thickness and doping that at the breakdown voltage the depletion zone of the pn junction does not  
20 extend as far as the surface but remains separated therefrom by a surface layer which is sufficiently thin as to allow the generated electrons to pass therethrough.

It may be noted that United Kingdom patent specification GB-A 1 335 979 discloses a cathode structure comprising a  
25 semiconductor substrate of n-type conductivity. An arrangement of conductors overlies one surface of the substrate and delineates electron emissive areas of said one surface between the conductors. An arrangement of surface-adjacent p-type regions are formed in the substrate in correspondence with and underlying the conductor  
30 arrangement to provide a potential barrier to the flow of electrons to the conductors when the cathode structure is biased into operation. The cathode employs a forward-biased pn junction for electron emission, and the emission efficiency is increased by the heterogeneous network of conductors which trap few electrons.

35 The present invention is based on the recognition of a quite

different situation, namely that the stability of a semiconductor cathode which generates its emitted electrons by avalanche multiplication with a reverse-biased pn junction is increased by means of the measure according to the invention in which a group of small emission regions can be homogeneously distributed over the surface defining the original emission pattern, the overall surface area of the emission regions being considerably smaller than that of the original pattern. In principle this applies to very small emission region patterns having a surface area of, for example, approximately  $1\mu\text{m}^2$  and also annular patterns having a diameter from approximately  $10\mu\text{m}$  with a ring width of approximately  $0.5\mu\text{m}$ . In a device in accordance with the invention the electron-emission regions may each have a surface area of at most  $100\mu\text{m}^2$ , for example.

The term "common electrical connections" is to be understood herein to mean that such measures are taken that operational adjustment is practically equal for all regions belonging to one group, for example, by the use of common metallizations for corresponding semiconductor zones or highly doped buried semiconductor zones, which interconnect all semiconductor zones of the same type belonging to one group. With an annular type of semiconductor cathode similar to that described in NL-A 7905470, the arrangement can be such that the group of electron-emission regions is homogeneously distributed over an annular region, all p-type regions of the pn junctions are then interconnected in an electrically conducting manner via the metallization on the lower side of the semiconductor body, while the n-type regions are interconnected via deep n-diffusions outside the actual emitting surfaces. However, the acceleration electrode shown in NL-A 7905470 may in turn be subdivided into several parts, which can be brought to separate potentials. However, this electrode may alternatively be omitted entirely or in part.

A preferred embodiment of an arrangement according to the invention is characterised in that the group of electron-emission regions is arranged according to an annular pattern. Such an embodiment is particularly suitable, as stated above, for

electron-optical considerations. Other arrangements of the emission regions are also possible, for example, linear arrangements for display apparatus or the activation of laser material, as described in Netherlands Patent Application No. 8300631 and No. 8400632 of the Applicant.

Due to the said measure in accordance with the invention, a high local current density is obtained, which leads in principle to the desired stability of the cathode. Nevertheless, since the said cathodes have a reverse-biased pn junction, it is desirable that the effective current density is also as high as possible. This means inter alia that the so-called filling factor (quotient of the sum of the surface areas of the emitting regions and the whole surface area) has to be as high as possible.

In this type of cathode, however, an increasing filling factor gives rise to current supply problems due to the series resistance in the n-type region adjoining the major surface. This in turn leads with high currents due to potential differences to inequality of the adjustment of the pn junctions in the various electron-emission regions. Moreover, due to the resistance in the n-type region, the cathode in practice conveys a comparatively low diode current (about 10 to 20% of the maximum permissible current as determined by the construction of the cathode, especially by the series resistance of the p-type region).

Besides, any high current densities in the n-type surface regions may give rise to high electric fields, which may lead to caesium migration, as a result of which again instability and inhomogeneity of the emission may occur.

A particular embodiment of a semiconductor device according to the invention, in which these problems are solved at least for the major part, is characterised in that the n-type region is coated with a layer of electrically conducting material, which contacts the n-type region and is provided with openings at the area of the electron-emission regions.

Thus, a low-resistance current path parallel to the n-type region is obtained so that such a cathode can be operated at a high

effective current density whilst avoiding the aforementioned problems.

A preferred embodiment of such a semiconductor device, by which a high filling factor can be attained, is characterised in that the electron-emitting regions are practically strip-shaped.

The semiconductor body of a device in accordance with the invention may comprise several groups of electron-emission regions, the operation of the groups being separately adjustable.

According to a second aspect of the invention there is provided a camera tube having means for controlling an electron beam which scans a charge image, the electron beam being produced by a semiconductor device in accordance with the first aspect of the invention.

According to a third aspect of the invention there is provided a display arrangement having means for controlling an electron beam which produces an image, the electron beam being produced by means of a semiconductor device in accordance with the first aspect of the invention. Such a display arrangement may have a fluorescent screen which is located in vacuo at a distance of a few millimetres from the semiconductor device, the screen being activated by the electron beam originating from the semiconductor device.

Embodiments of the invention will now be described by way of example with reference to the accompanying diagrammatic drawings, in which:

Figure 1 is a plan view of a semiconductor device according to the invention,

Figure 2 shows a cross-section taken on the line

II-II in Fig. 1,

Fig. 3 shows on an enlarged scale the segment 18 of Fig. 1,

Fig. 4 shows another realization of such a segment,

5        Figures 5, 6 and 7 show in plan view other semiconductor devices according to the invention,

Fig. 8 shows a cross-section taken on the line VIII-VIII in Fig. 7,

10       Fig. 9 is a plan view of a semiconductor device according to the invention having a high filling factor,

Fig. 10 is a cross-sectional view taken on the line X-X in Fig. 9,

Fig. 11 shows a display device manufactured with a semiconductor device according to the invention, while

15       Fig. 12 shows a pick-up device which comprises a semiconductor device according to the invention, and

Fig. 13 is a plan view of still another semiconductor device according to the invention.

20       The Figures are not drawn to scale, while for the sake of clarity, in the cross-sections more particularly the dimensions in the direction of thickness are greatly exaggerated. Semiconductor zones of the same conductivity type are generally cross-hatched in the same direction; in the Figures, corresponding parts are generally designated by  
25       the same reference numerals.

30       The semiconductor device 1 of Figures 1 and 2 comprises a semiconductor body 2, for example of silicon, having at a major surface 3 a plurality of emission regions 4, which in this embodiment are arranged according to an annular pattern indicated in Fig. 1 by the dot-and-dash lines 5. The actual emission regions 4 are situated at the area of the openings 7 in an insulating layer 22 of, for example, silicon oxide.

35       The semiconductor device comprises a pn junction 6 between a p-type substrate 8 and an n-type region 9, 11 consisting of a deep n-type zone 9 and a shallow zone 11. At the area of the emission regions 4, the pn junction is

formed between an implanted p-type zone 10 and the shallow zone, which in situ has such a thickness and doping that at the breakdown voltage of the pn junction 6 the depletion zone of the pn junction does not extend as far as the surface, but remains separated therefrom by a surface layer which is sufficiently thin to pass the electrons generated due to breakdown. Due to the highly doped p-type zone 10, the pn junction has within the openings 7 a lower breakdown voltage so that the electron emission takes place substantially solely in the regions 4 at the area of the openings 7. Furthermore, the arrangement is provided with an electrode 12. This electrode is subdivided in this embodiment into two subelectrodes  $12^a$ ,  $12^b$  so that the generated electrons can be deflected. The electrode 12 need not always be present, however. For contacting the n-type zone 9, a contact hole 14 is provided in the insulating layer 22 on behalf of a contact metallization 13, while on the lower side the substrate 8 can be connected via a highly doped p-type zone 15 and a contact metallization 16. Within the openings 7, a monolayer of caesium is applied to the surface 3 in order to reduce the work function of the electrons.

For a further description of the structure, the operation and the manufacturing method of semiconductor devices of the kind shown in Figures 1 and 2, reference may be made to the said Netherlands Patent Application NL-A 7905470. In an embodiment shown therein, an annular emission pattern is obtained by means of an annular opening in the oxide located on the surface, within which the breakdown of the pn junction is reduced with respect to other areas. Such an annular pattern is indicated in Fig. 1 by the dot-and-dash lines 5. The annular strip defined for this purpose has a strip width of about  $3\text{ }\mu\text{m}$ , while the ring has a diameter of about  $200\text{ }\mu\text{m}$ .

According to the invention, the device does not comprise an annular emitting region, but it comprises a number (about 25) of separate emission regions 4, which are

arranged in a ring having a diameter of about  $200\text{ }\mu\text{m}$ . The separate emission regions 4 are preferably circular and have a diameter of about  $2\text{ }\mu\text{m}$ . The overall emitting surface area is thus reduced from about  $1800\text{ }\mu\text{m}^2$  to about  $80\text{ }\mu\text{m}^2$ .

5 With an unchanged overall emission current, the emission current density is now much larger. Such an increased emission current density contributes to a more rapid desorption of ions, atoms and molecules ( $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{O}_2$ ) adsorbed at the caesium layer 17. At the same time, due  
10 to the smaller dimensions of the emission regions 4, the current density through the n-type regions 6, 11 is higher. The higher electric fields associated therewith accelerate any diffusion of adsorbed ions from the emission region 4. The stability of the electron emission is therefore con-  
15 siderably increased.

Fig. 3 is a plan view of the segment 18 of Fig. 1, only the emission region 4 and the region indicated by the dot-and-dash lines 5 being shown.

Fig. 4 shows a similar segment 18, a cross-section of about  $1\text{ }\mu\text{m}$  being chosen for the emission regions 4. With the same emission current, the number of emission regions increases in inverse proportion to the diameter of the emission regions. With an unchanged pattern 5 having a diameter of about  $200\text{ }\mu\text{m}$ , a device with such small emission  
20 regions comprises about 50 emission regions 4.  
25

In general, the gain in local current density is larger as the diameter of the emission regions 4 is smaller; this diameter preferably lies between 10 nm and  $10\text{ }\mu\text{m}$ .

30 The emission patterns may also be uniformly distributed over an annular pattern, as is shown in Fig. 5, in which a segment of such a pattern is represented with a width of the region 5 of about  $5\text{ }\mu\text{m}$  and a diameter of the emission regions 4 of about  $1\text{ }\mu\text{m}$ .

35 On the other hand, the stability of a semiconductor cathode can be increased by reducing in the same manner as described above for an annular pattern the overall emitting surface area by distributing a number of

smaller emission regions uniformly over this surface.

Fig. 6 illustrates how, for example, a region 5 having an original diameter of about  $1.5\text{ }\mu\text{m}$  can be subdivided into three emission regions 4 having a diameter of about  $0.5\text{ }\mu\text{m}$ . Such a subdivision is particularly suitable for patterns having a diameter of the region 5 smaller than about  $10\text{ }\mu\text{m}$ . For larger diameters ( $10 - 100\text{ }\mu\text{m}$ ) an arrangement similar to that shown in Fig. 5 may often advantageously be used. An arrangement according to the invention, in which this measure is used in a square emission region indicated by the dot-and-dash line 5 is shown in Figures 7, 8. The reference numerals in this case have the same meaning as in Figs. 1, 2 while it is to be noted that the electrode 12 is shown only diagrammatically, which is once more an indication that this electrode need not necessarily be always present.

Instead of being arranged in circular form, the emission regions 4 may also be arranged according to linear patterns, for example when used in display applications or applications such as described in Netherlands Patent Applications No. 8300631 and No. 8400632.

The semiconductor device 1 shown in Figures 9 and 10 comprises a semiconductor body 2 of, for example, silicon having at a major surface 3 a plurality of emission regions, which in this embodiment are strip-shaped and are located within a circular pattern indicated in Fig. 9 by the dot-and-dash line 5. The emission regions are located at the area of openings 7 in the layer 13 of conducting material, such as, for example, tantalum.

The semiconductor device has a pn junction 6 between a p-type substrate 8 and an n-type zone 9, 11 consisting of a deep n-type zone 9 and a shallow zone 11. At the area of the emission regions, the pn junction is situated between an implanted p-type region 10 and the shallow zone, which in situ has such a thickness and doping that at the breakdown voltage of the pn junction 6 the depletion zone of the pn junction does not extend as far as the surface, but remains separated therefrom by a surface layer

which is sufficiently thin to allow the electrons generated due to the breakdown to pass. Due to the highly doped p-type region 10, the pn junction has within the openings 7 a lower breakdown voltage so that the electron emission takes place practically solely in the regions at the area of the openings 7.

Within the openings 7, a monolayer 17 of a material reducing the work function, such as, for example, caesium, is applied to the surface 3.

In this embodiment, the n-type zone 9, 11 is contacted by means of the conducting layer 13 via a contact hole 14 in an insulating layer 22, which covers the surface 3 outside the n-type zone 9, 11. Due to the fact that now the current supply takes place mainly via the layer 13, the effective current density can be considerably increased. The potential differences in the layer 13 also remain small so that secondary effects due to high field strengths, such as, for example, caesium transport, do not occur.

At the lower side, the substrate 8 can be connected via a highly doped p-type zone 15 and a contact metallization 16.

The strip-shaped openings 7 in Fig. 9 have a width of about  $1\mu\text{m}$  and are located at a relative distance of about  $1\mu\text{m}$ . In the configuration shown in Fig. 9, a filling factor of about 50% can then be attained.

For the conducting layer 13, a material is preferably chosen which does not or substantially not diffuse into the silicon, such as, for example, tantalum.

The device shown in Figures 9 and 10 can be manufactured in a simple manner, for example, by first providing the n-type zones 9, 11 by ion implantation.

Subsequently, the metal pattern 13 is provided, for example by means of a lift-off technique. Whilst using the metal pattern thus obtained as a mask, the p-type zones 10 are then provided at the area of the openings 7 by means of ion implantation, as a result of which the

breakdown voltage of the pn junction 6 is decreased in situ. For a more detailed description of the structure and the operation of the semiconductor device shown in Figures 9 and 10, reference may be made to the said Netherlands  
5 Patent Application No. 7905470.

The openings 7 may be chosen to be circular instead of strip-shaped, in which event the emitting surfaces are distributed substantially homogeneously over the whole surface. The cathode stability is increased when  
10 the width of the openings 7 and hence the electron-emitting regions are reduced.

Fig. 11 shows diagrammatically in elevation a perspective view of a flat display arrangement which comprises besides the semiconductor body 2 a fluorescent  
15 screen 23 which is activated by the electron current 19 originating from the semiconductor body. The distance between the semiconductor body and the fluorescent screen is, for example, 5, while the space in which they are located is evacuated. A voltage of the order of 5 to 10 kV is  
20 applied between the semiconductor body 2 and the screen 23 via the voltage source 24, which leads to such a high field strength between the screen and the arrangement that the picture of a cathode is of the same order as this cathode.

25 The emission regions 4 are arranged on the surface of the semiconductor body according to linear patterns 5, which are activated by means of an auxiliary electronic system (not shown), which, if required, is also integrated in the semiconductor body 2.

30 One or more groups, which emit according to linear patterns, are each time driven in the same manner so that in the present embodiment, depending upon the drive, characters are displayed on the screen 23.

Fig. 12 shows diagrammatically a cathode-ray  
35 tube, for example a camera tube, having a hermetically sealed vacuum tube 20, which tapers in the form of a funnel, the terminal wall being coated on the inner side with a

fluorescent screen 21. The tube further comprises focusing electrodes 25, 26 and deflection electrodes 27, 28. The electron beam 19 is generated in one or more cathodes of the kind described above, which are located in a semiconductor body 2, which is mounted on a holder 29. Electrical connections of the semiconductor device are passed to the outside via lead-through members 30.

Of course the invention is not limited to the embodiments shown here, but several variations are possible within the scope of the invention for those skilled in the art.

The emission regions need not always be chosen to be circular or square, but they may have various other forms and may be, for example, rectangular or elliptical, which especially in the device shown in Figures 1 and 2 is favourable from an electron-optical point of view.

Depending upon the possibilities of the semiconductor technology, the diameters of the emission regions may be chosen to be smaller than the value of  $0.5\mu\text{m}$  mentioned in the embodiment shown in Figure 6. On the one hand, the region 5 may then be subdivided into a larger number of emission regions 4, whereas on the other hand with unchanged number a smaller diameter may be chosen for the region 5.

In the same manner as the round pattern 5 of Figure 6 may be advantageously replaced in certain cases by a circular (i.e. annular) pattern, the strip pattern 5 of Figure 7 may be replaced by a rectangular pattern 5 as shown in Figure 13.

Further, in the arrangement of Figure 8, the emitting regions 4 may be obtained by a uniform n-type layer 11, which adjoins a contact diffusion 9, a reduced breakdown voltage being locally obtained within the openings 7 by means of, for example, a boron implantation.

## CLAIM(S)

1. A semiconductor device for producing an electron current by means of a cathode comprising a semiconductor body having a pn junction between a p-type region and an n-type region which adjoins a major surface of the body, said surface being provided with a layer having at least one group of openings at each of which openings a separate electron-emission region is present from which electrons are emitted in the operating condition, and common electrical connections respectively to the p-type and n-type regions for operating the group of separate electron-emission regions in common by applying a common voltage in the reverse direction across the pn junction whereby electrons are generated in the semiconductor body by avalanche multiplication and are then emitted from the emission regions at said surface of the semiconductor body, the pn junction extending at least at the areas of the electron-emission regions mainly parallel to the major surface and locally having a lower breakdown voltage at these areas than the remaining part of the pn junction, the parts having the lower breakdown voltage being separated from the surface by an n-type layer which forms part of the n-type region and which has such a thickness and doping that at the breakdown voltage the depletion zone of the pn junction does not extend as far as the surface but remains separated therefrom by a surface layer which is sufficiently thin as to allow the generated electrons to pass therethrough.
2. A semiconductor device as claimed in Claim 1, characterised in that the group of electron-emission regions is distributed substantially homogeneously over a part of the major surface.
3. A semiconductor device as claimed in Claim 1 or Claim 2, characterised in that the group of electron-emission regions is arranged according to an annular pattern.
4. A semiconductor device as claimed in any one of the preceding Claims, characterised in that the semiconductor body comprises several groups of electron-emission regions, and the operation of the groups is separately adjustable.
5. A semiconductor device as claimed in any one of the



preceding Claims, characterised in that the electron-emission regions each have a surface area of at most  $100\mu\text{m}^2$ .

5 6. A semiconductor device as claimed in any one of the preceding Claims, characterised in that the layer with which the surface is provided is an electrically insulating layer having openings aligned with the electron-emission regions and having within the openings the parts of the pn junction with the lower breakdown voltage.

10 7. A semiconductor device as claimed in Claim 6, characterised in that at least one electrode is provided on at least a part of the insulating layer.

8. A semiconductor device as claimed in any one of Claims 1 to 5, characterised in that the layer with which the surface is provided is of electrically conductive material, and the n-type  
15 region is coated with this layer of electrically conducting material which contacts the n-type region and which is provided with openings at the area of the electron-emission regions.

9. A semiconductor device as claimed in Claim 8, characterised in that the electron-emission regions are substantially  
20 strip-shaped.

10. A semiconductor device as claimed in Claim 8 or Claim 9, characterised in that the electron-emission regions are distributed over a substantially circular surface region.

11. A semiconductor device as claimed in any one of the  
25 preceding Claims, characterised in that the major surface is coated at the area of the electron-emission regions with a layer of material reducing the electron work function.

12. A camera tube having means for controlling an electron beam which scans a charge image, characterised in that the electron  
30 beam is produced by a semiconductor device as claimed in any one of Claims 1 to 11.

13. A display arrangement having means for controlling an electron beam which produces an image, characterised in that the electron beam is produced by means of a semiconductor device as  
35 claimed in any one of Claims 1 to 11.



14. A display arrangement as claimed in Claim 13,  
characterised in that it has a fluorescent screen which is located  
in vacuo at a distance of a few millimetres from the semiconductor  
device and the screen is activated by the electron beam originating  
from the semiconductor device.

15. A semiconductor cathode substantially as described with  
reference to Figures 1 to 3, or Figures 7 and 8, or Figures 9 and  
10, or any one of Figures 4,5,6 or 13.

16. A display arrangement including a semiconductor device as  
claimed in Claim 1 and substantially as described with reference to  
Figure 11.

17. A camera tube including a semiconductor device as claimed  
in Claim 1 and substantially as described with reference to Figure  
12.

