

# PATENT SPECIFICATION

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## (54) PHOTOELECTRIC TRANSDUCER

(71) We, EASTMAN KODAK COMPANY, a Company organized under the Laws of the State of New Jersey, United States of America of 343 State Street, Rochester, New York 14650, 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 photo-electric signal transducers, and more particularly, to a photosensitive semiconductor array.

An object of this invention is the provision of an improved photo-electric signal transducer.

According to the present invention, there is provided a photo-electric transducer comprising first and second photosensitive semiconductor devices, each device comprising a common region of a first semiconductor type and a further region of a second semiconductor type, intrinsic semiconductor material separating the common region from each further region, and means for electrically isolating the further semiconductor regions from each other, and first and second means transmissive of first and second wavelength regions of radiation to the photosensitive junction of the first device and of the second device respectively, whereby the first device responds to radiation of the first wavelength region incident thereon to produce a first signal and the second device responds to radiation of the second wavelength region incident thereon to produce a second signal.

There is further provided an apparatus for deriving signals indicative of the colour content of an image comprising means for illuminating the image, means for producing a beam of out-of-focus radiation from the image, and a photo-electric transducer as above, located in said beam.

[Price 33p]

The term light, in the context of the specification and claims, may be defined as an electromagnetic radiation in the wavelength range including infrared, visible and ultra-violet radiation.

The invention will be described further, by way of example, with reference to the accompanying drawings, in which:—

Fig. 1 is a perspective view of a photo-electric transducer in accordance with the present invention in use in a telecine apparatus;

Fig. 2 is a cross-section in partial perspective of a PIN photodiode array of the transducer of Fig. 1 taken along lines 2-2 of Fig. 1;

Fig. 3 is a schematic illustration of the equivalent electrical circuit of the transducer of the present invention; and

Figs. 4 and 5 are plan views of further embodiments of a photo-electric transducer in accordance with the present invention.

Referring now to the drawings, and firstly to Fig. 1, there is shown, in partial perspective, a view of the telecine apparatus incorporating the optical-to-electrical signal transducer of the present invention. It will be understood that the elements of Fig. 1 may not be in scale but are depicted in a working relationship. A light image results from the illumination of a point 10 on an information storage medium such as a frame of motion picture film 12 by a beam of light 14 generated by a flying spot scanner tube 16 and focused upon the point 10 by a lens assembly 18, as shown in U.S. Patent Nos. 2,776,335 and 2,808,456 for example. The beam of light 14, radiated from the faceplate of the flying spot scanner tube 16, is scanned in the well-known television raster pattern sequentially to illuminate each point in the film frame 12 and is sharply focused by the lens assembly 18 on the point 10 of the film frame 12 where the light image

is modulated by the information content of the point 10. The lens assembly 18 is similar in structure and operation to that lens assembly identified as 4 in the aforementioned U.S. Patent No. 2,808,456. A collector lens 20 forms an unsharp image of, and directs the modulated light image of the point 10, through the filter assembly 21 to a photosensitive semiconductor array 22, regardless of the scanning position of point 10 in the frame 12.

Further information regarding the operation of exit pupils of lens systems may be obtained from the treatise *Modern Optical Engineering, The Design of Optical Systems* by Warren J. Smith, published by McGraw-Hill Book Company.

The photosensitive semiconductor array 22 develops electrical signals representative of the intensity of the colour components of the image forming light directed thereon. The electrical signals are amplified by video amplifiers 24, 26 and 28 and the amplified electrical signals are applied to further color signal processing circuits that, for example, as shown in U.S. Patent 3,548,099, may ultimately control the operation of a television receiver 32 to display a colour image of the motion picture film frame.

The photosensitive semiconductor array 22 may comprise three photodiodes or other photosensitive semiconductor devices having respective photoreceptive surfaces 34, 36 and 38, in the form of sectors that are each isolated from the others by an insulator 40. The conductors 42, 44 and 46 are electrically bonded to arcuate electrodes 48, 50 and 52, respectively, by ball bonding techniques well known in the manufacture of semiconductor devices, and a common electrode 54 on the opposite surface of the photodiode array 22 is connected to ground potential. Associated with the photoreceptive sector surfaces 34, 36 and 38 are respective filters 56, 58 and 60 of the filter assembly 21, in the form of sectors. The filters 56, 58 and 60 may consist of red, green and blue colour transmission filter materials, respectively. Thus the photodiodes of the photosensitive semiconductor array 22 are sensitive to red, green and blue wavelengths of light transmitted by the filters 56, 58 and 60 of the filter assembly 21 respectively. For ease in illustration, the filter assembly 21 is shown displaced from the photosensitive semiconductor array 22, but it will be understood that, in actual practice, the filter assembly 21 may be oriented in the position shown with respect to the photosensitive semiconductor array 22 but in close physical proximity thereto. Furthermore, the filter materials may be deposited as layers upon the photoreceptive surfaces 34, 36 and 38.

The collector lens 20 images the exit pupil of the lens assembly 18 onto the entire surface of the filter assembly 21 and photosensitive semiconductor array 22. In other words, regardless of the position of the scanning beam 14 of the flying spot scanner tube 16, the collector lens 20 images the image forming light from the scanned point 10 in the film frame 12 through the filters 56, 58 and 60 of the filter assembly 21 and upon the photoreceptive surfaces 34, 36 and 38 of the photosensitive semiconductor array 22, this image forming light being out of focus at the photosensitive semiconductor array 22. Since the collector lens 20 images the exit pupil of the scanning lens 18 upon the photosensitive semiconductor array 22, the colours in the image forming light from any scanned point 10 in the film frame 12 are uniformly mixed and equally divided in intensity among the three photoreceptive surfaces 34, 36 and 38.

Referring now to Fig. 2 there is shown a cross-section taken along the lines 2-2 in Fig. 1 of the representative photosensitive semiconductor structure of PIN photodiode configuration. This figure is for the purpose of explanation only and is not to scale. The relative proportions have been deliberately distorted for the sake of clarity.

The photosensitive semiconductor array 22 of Figs. 1 and 2 consists of a first electrode layer 54 consisting of a metal such as gold which covers a first surface of the first common region or body 62 of semiconductor material and which is connected to ground potential. The first common region 62 of semiconductor material may consist of an N-type semiconductor such as N-type silicon.

A layer 64 of intrinsic semiconductor, or I-type material separates the second surface of the first common region 62 of semiconductor material and the first surface of a second region or body 66 of semiconductor material. The second region 66 of semiconductor material may consist of a P-type silicon layer deposited or diffused in the second surface of the layer 64 and may have an outer surface formed of silicon dioxide. Deposited on and electrically contacting the second surface of the second semiconductor region 66 are second electrode layers 48, 50 and 52 (as shown in Fig. 1) which may or may not cover the entire photoreceptive surfaces 34 and 38 of the second semiconductor body 66, depending upon the light transmissivity of the electrode material. As shown in Figs. 1 and 2, the second electrodes 48, 50 and 52 are arcuate, covering the peripheral area of the circular photosensitive semiconductor array 22, and may consist of gold.

The PIN photodiode structure depicted

in Fig. 2 also includes an etched channel, which constitutes the aforementioned insulator 40, through the second semiconductor region 66 and the intrinsic layer 64 which provides the electrical isolation between the surfaces 34 and 38 of the depicted PIN photodiodes. The channel 40 may be filled with highly non-conductive insulating material differing from the material of the intrinsic layer 64. Thus the layer 64 and second semiconductor region 66 are electrically divided into three parts.

A negative bias voltage source, depicted in Fig. 2 as the battery 68, is electrically connected to the second electrodes 48, 50 and 52 of each of the three PIN photodiode sectors of the photosensitive semiconductor array 22. Thus three separate electrical circuits are defined by the negative bias voltage sources, the common first electrode layer 54, the common first semiconductor region 62 and the three isolated intrinsic layers 64, second semiconductor regions 66 and second electrodes 48, 50 and 52.

As shown in Fig. 1 the image forming light from a point 10 in the film frame 12 is collected by collector lens 20 and passed through filter assembly 21 and strikes the photoreceptive surfaces 34, 36 and 38 of the photosensitive semiconductor array 22. The PIN photodiodes respond to photons of light penetrating the photoreceptive surfaces 34, 36 and 38 and generate photocurrents representative of the intensity of such light in a manner that is described, for example, in the article entitled "High Frequency Photodiodes" by G. Lucovsky and R. B. Emmons in *Applied Optics*, vol. 4, no. 6 June 1965, pages 697-702, and in the *Applications Note* 915 — "Threshold Detection of Visible and Infrared Radiation with PIN Photodiodes", published by Hewlett-Packard, Inc. As shown in Fig. 2, a photon of the image forming light travelling in the path of the arrow 70 penetrates the photoreceptive surface 38 of the second semiconductor region 66 and is absorbed by the intrinsic layer 64. When the photon is so absorbed, it produces an electron-hole pair depicted at 72, and the hole and the electron are separated, as shown, by the electric field established in the intrinsic layer 64 by the negative bias voltage 68. The hole tends to drift towards the photoreceptive surface 38, and the electron tends to drift towards the body 62 of semiconductor material. The photo-current signals appear at the external conductors 42, 44 and 46 in response to the drift of the hole and electron towards the photoreceptive surface 38 and the body 62 of semiconductor material, respectively, through the circuits defined by the common first electrode 54, common first semiconductor region 62, and isolated intrinsic layers 64, second semiconductor regions 66 and second

electrodes 48, 50 and 52. Since the electron tends to drift at a faster rate than the hole, the photocurrent is carried primarily by the drifting electrons.

For the highest quantum conversion efficiency (electrons produced per photon), it is desirable to have the P-type layers, that is the semiconductor regions 66, as thin as possible so that photons readily penetrate the P-type layer and are absorbed in the intrinsic layer 64. Consequently, it is also desirable that the intrinsic layer 64 be as thick as possible. The physical thickness of the intrinsic layer 64 may be controlled during the manufacturing diffusion process by which the photo diode is produced. However, the effective thickness of the intrinsic layer 64 may be increased by the increase in magnitude of the electric field provided by the negative bias source 68. As the negative bias voltage is increased from zero, there are three beneficial effects: (1) the hole and electron transit time decreases; (2) the conversion efficiency increases slightly; and (3) the shunt capacitance per sector  $C_p$  decreases.

Referring now to Fig. 3 there is shown a schematic diagram of the equivalent electrical circuit of the PIN photodiodes of the photosensitive semiconductor array 22 biased by the negative bias voltage sources 68. The three photodiodes of the photosensitive semiconductor array 22 are represented by the three parallel circuits 78, 80 and 82 and the circuit parameters noted in Fig. 3 may be defined as follows:

(a)  $I_p$  is the external current resulting when a single photodiode is illuminated;

(b)  $I_n$  is the noise current in each photodiode;

(c)  $I_d$  is the dark current of each photodiode which has a value determined by the construction and dimensions of the particular diode type;

(d)  $R_p$  is the shunt resistance of each photodiode, usually greater than 10 gigohms (10,000 megohms);

(e)  $C_p$  is the shunt capacitance per sector, usually a value from 2-5 picafarads, depending on the diode type and reverse bias voltage;

(f)  $R_s$  is the series resistance per photodiode and affects high frequency performance; and

(g)  $F_c$  which is the sector cut-off frequency is equal to

$$\frac{1}{2 R_s C_p}$$

The thickness of the P-type semiconductor region 66 determines the value of the parasitic series resistance  $R_s$  in Fig. 3. The thinner the P-type semiconductor region 66, the higher the  $R_s$ . Since  $R_s$  affects high frequency performance there is therefore a design trade-off between quantum efficiency and bandwidth determined primarily

by the relationship of the sector cut-off frequency  $F_c$  to the series resistance  $R_s$  and shunt capacitance  $C_p$  as shown in the formula above. Once the design trade-off is settled, the desired depth of diffusion of the P-type semiconductor region 66 is then controlled during the manufacturing diffusion process.

The equivalent circuits, characteristics and structure of each PIN photodiode of the PIN photodiode array 22 set forth above conforms to the description of such PIN photodiodes as disclosed in the aforementioned *Applications Note 915* — "Threshold Detection of Visible and infra-red Radiation with PIN Photodiodes", published by Hewlett-Packard, Inc.

Referring now to Figs. 4 and 5 there are shown plan views of further photosensitive semiconductor arrays 22' and 22'', respectively. Array 22' consists of annular photoreceptive surfaces 34', 36' and a circular photo receptive surface 38' which are electrically isolated from each other by insulating rings 40'. Suitable filters may be provided over the surfaces 34', 36' and 38'.

Array 22'' of Fig. 5 consists of three photoreceptor surfaces 34'', 36'' and 38'' which are electrically isolated from each other by the insulating bars 40''. Again, suitable filters may be provided over the photodiodes.

Because, as stated hereinbefore, the image forming light from any scanned point in the film frame is uniformly mixed in color and is directed upon the entire area of the photosensitive semiconductor arrays 22, 22' and 22'', the photodiodes of each array receiving the light may be altered in shape and in relative area to center for differing colour sensitivities and formed in any desired configuration as shown in Figs. 1, 4 and 5. Furthermore, the shape and configuration of the depicted arrays and the number of photodiodes in each such array constructed in accordance with the present invention may be altered as desired to suit any particular requirements.

Attendant advantages of the described PIN photodiode arrays include small size, low power supply requirements, and cost, broad spectral response, low noise, ruggedness and stability. Further information concerning the manufacture and operation of PIN photodiodes may be obtained from the afore-mentioned Hewlett-Packard application note.

#### WHAT WE CLAIM IS:—

1. A photo-electric transducer comprising first and second photosensitive semiconductor devices, each device comprising a common region of a first semiconductor type and a further region of a second semiconductor type, intrinsic semiconductor material separating the common region

from each further region, and means for electrically isolating the further semiconductor regions from each other, and first and second means transmissive of first and second wavelength regions of radiation to the photosensitive junction of the first device and of the second device respectively, whereby the first device responds to radiation of the first wavelength region incident thereon to produce a first signal and the second device responds to radiation of the second wavelength region incident thereon to produce a second signal.

2. A transducer as claimed in Claim 1 wherein in use, the first and second signals are related to the relative intensities of the radiation in the first and second wavelength regions.

3. A transducer as claimed in Claim 1 or 2 wherein the respective further semiconductor regions are permeable to radiation incident thereon.

4. A transducer as claimed in Claim 1, 2 or 3 wherein the common semiconductor region comprises N-type semiconductor material, and each of the further semiconductor regions comprises P-type semiconductor material.

5. A transducer as claimed in any of Claims 1 to 4 wherein the first and second means for respectively transmitting radiation of the first and second wavelength regions comprise first and second colour filters respectively overlying the photosensitive junctions of the first and second devices.

6. A transducer as claimed in any preceding Claim, further including a third diode having a further semiconductor region and sharing the common semiconductor region and having means isolating the further semiconductor region thereof from the further semiconductor regions of the first and second photosensitive semiconductor devices, and a respective radiation transmitting means.

7. A photo-electric transducer substantially as hereinbefore described with reference to and as illustrated in Figs. 1, 2 and 3 or Figs. 1, 2 and 3 as modified by Fig. 4 or Fig. 5 of the accompanying drawings.

8. An apparatus for deriving signals indicative of the colour content of an image comprising means for illuminating the image means for producing a beam of out-of-focus radiation from the image, and a photo-electric transducer as claimed in any of Claims 1 to 7 located in said beam.

9. A telecine apparatus comprising a source of radiation, means for scanning an original to be reproduced with said radiation, means for producing an out-of-focus image of the scanned original at a location, and a photoelectric signal transducer as claimed in any of Claims 1 to 8 at said location.



by the relationship of the sector cut-off frequency  $F_c$  to the series resistance  $R_s$  and shunt capacitance  $C_p$  as shown in the formula above. Once the design trade-off is settled, the desired depth of diffusion of the P-type semi-conductor region 66 is then controlled during the manufacturing diffusion process.

The equivalent circuits, characteristics and structure of each PIN photodiode of the PIN photodiode array 22 set forth above conforms to the description of such PIN photodiodes as disclosed in the aforementioned *Applications Note 915* — "Threshold Detection of Visible and infra-red Radiation with PIN Photodiodes", published by Hewlett-Packard, Inc.

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Array 22'' of Fig. 5 consists of three photoreceptor surfaces 34'', 36'' and 38'' which are electrically isolated from each other by the insulating bars 40''. Again, suitable filters may be provided over the photodiodes.

Because, as stated hereinbefore, the image forming light from any scanned point in the film frame is uniformly mixed in color and is directed upon the entire area of the photosensitive semiconductor arrays 22, 22' and 22'', the photodiodes of each array receiving the light may be altered in shape and in relative area to center for differing colour sensitivities and formed in any desired configuration as shown in Figs. 1, 4 and 5. Furthermore, the shape and configuration of the depicted arrays and the number of photodiodes in each such array constructed in accordance with the present invention may be altered as desired to suit any particular requirements.

Attendant advantages of the described PIN photodiode arrays include small size, low power supply requirements, and cost, broad spectral response, low noise, ruggedness and stability. Further information concerning the manufacture and operation of PIN photodiodes may be obtained from the afore-mentioned Hewlett-Packard application note.

#### WHAT WE CLAIM IS:—

1. A photo-electric transducer comprising first and second photosensitive semiconductor devices, each device comprising a common region of a first semiconductor type and a further region of a second semiconductor type, intrinsic semiconductor material separating the common region

from each further region, and means for electrically isolating the further semiconductor regions from each other, and first and second means transmissive of first and second wavelength regions of radiation to the photosensitive junction of the first device and of the second device respectively, whereby the first device responds to radiation of the first wavelength region incident thereon to produce a first signal and the second device responds to radiation of the second wavelength region incident thereon to produce a second signal.

2. A transducer as claimed in Claim 1 wherein in use, the first and second signals are related to the relative intensities of the radiation in the first and second wavelength regions.

3. A transducer as claimed in Claim 1 or 2 wherein the respective further semiconductor regions are permeable to radiation incident thereon.

4. A transducer as claimed in Claim 1, 2 or 3 wherein the common semiconductor region comprises N-type semiconductor material, and each of the further semiconductor regions comprises P-type semiconductor material.

5. A transducer as claimed in any of Claims 1 to 4 wherein the first and second means for respectively transmitting radiation of the first and second wavelength regions comprise first and second colour filters respectively overlying the photosensitive junctions of the first and second devices.

6. A transducer as claimed in any preceding Claim, further including a third diode having a further semiconductor region and sharing the common semiconductor region and having means isolating the further semiconductor region thereof from the further semiconductor regions of the first and second photosensitive semiconductor devices, and a respective radiation transmitting means.

7. A photo-electric transducer substantially as hereinbefore described with reference to and as illustrated in Figs. 1, 2 and 3 or Figs. 1, 2 and 3 as modified by Fig. 4 or Fig. 5 of the accompanying drawings.

8. An apparatus for deriving signals indicative of the colour content of an image comprising means for illuminating the image means for producing a beam of out-of-focus radiation from the image, and a photo-electric transducer as claimed in any of Claims 1 to 7 located in said beam.

9. A telecine apparatus comprising a source of radiation, means for scanning an original to be reproduced with said radiation, means for producing an out-of-focus image of the scanned original at a location, and a photoelectric signal transducer as claimed in any of Claims 1 to 8 at said location.



10. An apparatus as claimed in Claim 9 wherein the source of radiation comprises a cathode ray tube arranged to produce a raster on its face.

5 11. An apparatus as claimed in Claim 9, wherein the scanning means comprises a field lens for imaging the raster at a gate whereat a transparent original is located.

10 12. An apparatus as claimed in Claim 11, wherein the transparent original is a frame of a motion picture film and wherein means are provided for transporting the film through the gate.

15 13. An apparatus as claimed in Claims 11 or 12, wherein the means for producing an out-of-focus image comprises a second lens arranged to focus an image of the

exit pupil of the field lens on the transducer.

14. An apparatus as claimed in any of Claims 9 to 13 as appendent to Claim 6, 20 the devices having respectively a red, a green and a blue filter wherethrough radiation passes to the respective photosensitive junction, a respective video amplifier for each device, and colour processing circuits 25 having an output for a colour television receiver.

15. A telecine apparatus substantially as hereinbefore described with reference to and as illustrated in Fig. 1 or Fig. 1 as 30 modified by Fig. 4 or Fig. 5 of the accompanying drawings.

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