April 3, 1956 R. E. GRAHAM 2,740,901

DIFFERENTIAL PHOTOCELL DETECTOR USING JUNCTION SEMICONDUCTORS

Filed Dec. 29, 1951

FIG. 1

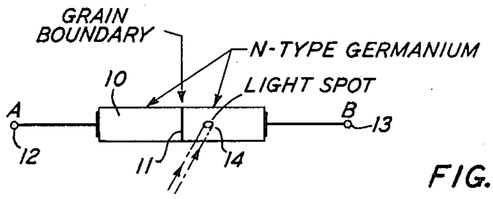


FIG. 2

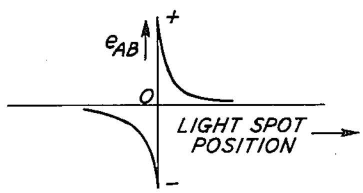


FIG. 3

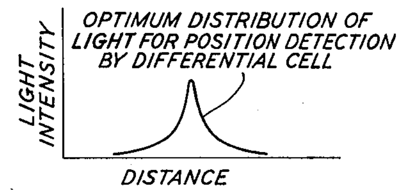


FIG. 7

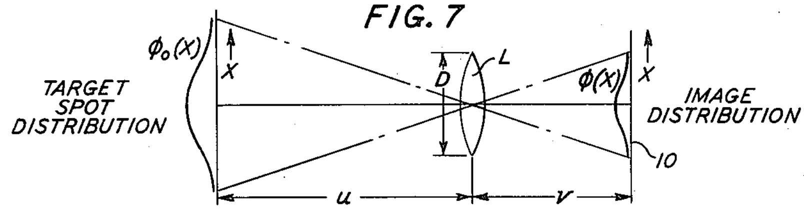


FIG. 4

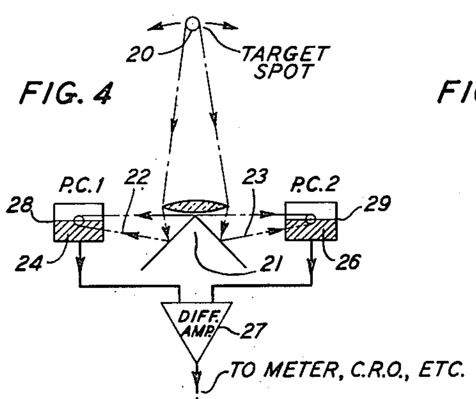


FIG. 5

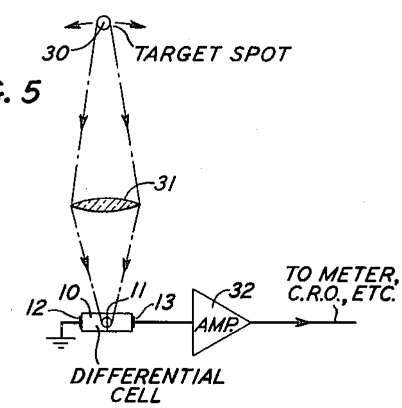
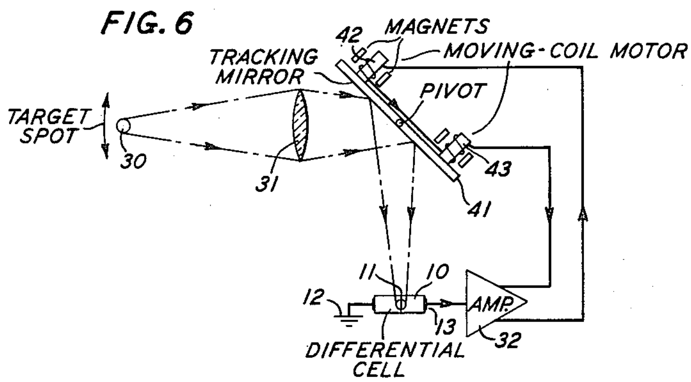


FIG. 6



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DIFFERENTIAL PHOTOCELL DETECTOR USING JUNCTION SEMICONDUCTORS

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5 Claims. (Cl. 250—201)

This invention relates to position detector devices and more specifically to devices of this character using photoelectric members.

The principal object of this invention is to provide an optical position detector employing a compact, stable, zero-center photocell.

Crystals of semiconductive material such as N-type germanium have been found to have an interesting effect which makes them suitable as a stable, efficient differential photocell. When light is near one end of a crystal of the type having a grain boundary therein, a small negative E. M. F. is obtained and as the spot moves towards the grain boundary this negative E. M. F. increases, at first slowly and then rapidly as the grain boundary is approached. In the immediate neighborhood of the grain boundary, the photo-E. M. F. undergoes a sharp reversal from negative to positive, being zero when the spot is centered on the boundary. The E. M. F. then falls off in symmetrical fashion as the spot is moved on toward the other end of the crystal.

It is another object of this invention to take advantage of the property just described in the formation of a zero-center position detector. Since the magnitude of the photo-E. M. F. is proportional to the deviation of the target image from the boundary and since its polarity depends upon the direction of this deviation, this voltage can, in accordance with the invention, be amplified and applied to a meter, cathode-ray oscilloscope, motor, or other utilization device to provide an excellent differential position control. By proper selection of the focal length of the lens used to form an image of the light source on the position detector or by proper shaping of the light source, the distribution current of the image can be made to match a sensitivity curve of the material of the detector, thereby providing a most efficient device.

The invention will be more readily understood by referring to the following description taken in connection with the accompanying drawing forming a part thereof, in which:

Fig. 1 shows schematically a crystal used in the present invention;

Figs. 2 and 3 are graphical representations to assist in explaining the operation of the crystal when light is applied thereto;

Fig. 4 shows schematically a conventional photocell arrangement for detecting the position of a light spot;

Fig. 5 is a schematic representation of an illustrative embodiment of the invention;

Fig. 6 shows an application of the invention to tracking systems; and

Fig. 7 is a schematic diagram, used in a mathematical analysis of the invention.

Referring more specifically to the drawing, Fig. 1 shows an N-type germanium crystal **10** having a grain boundary **11**. Examples of such crystals are known in the art, as evidenced, for example, by Patent 2,402,662, granted June 25, 1946, to R. S. Ohl. When light is directed upon the crystal, a photo-E. M. F. is found across the two

electrodes **12** and **13** (also designated A and B on the figure). In cases, as in the present one, where the crystal comprises a pair of zones of one conductivity type on opposite sides of and contacting a third zone of the opposite conductivity type, the sign of the voltage developed depends upon which side of the grain boundary the point of incidence for the light beam occurs. If the light is concentrated into a small spot **14** and moved along the crystal length, the photo-E. M. F. varies as shown in Fig. 2. When the light is near one end of the crystal, a small negative E. M. F. is obtained. As the spot moves towards the grain boundary (to the right in Fig. 2), this negative E. M. F. increases, at first slowly and then rapidly as the grain boundary is approached. In the immediate neighborhood of the grain boundary **11**, the photo-E. M. F. undergoes a sharp reversal, from negative to positive, for example, being zero when the spot is centered on the boundary. The E. M. F. then falls off in symmetrical fashion as the spot is moved on toward the right. The very sharp transition in the vicinity of the grain boundary makes the crystal an ideal zero-center position detector for a spot of light concentrated on the grain boundary. In Fig. 3, there is shown the spot distribution which yields the best ratio of position-error signal to random noise. The shape of this curve will be described after a mathematical analysis which it appears desirable to reproduce at this point in the description of the invention.

Referring now to Fig. 7, let $B(x,y)$ represent the apparent "brightness" distribution of the target spot. Then one can define the "profile distribution" of the target spot, in the x direction, as proportional to

$$\Phi_0(x)=\int_{-\infty}^{\infty} B(x,y)\,dy$$

The corresponding profile distribution in the image plane, when the lens is assumed to have perfect imaging properties, is

$$\Phi(x)=\left(\frac{D}{u}\right)^2\cdot\frac{1}{m}\cdot\Phi_0\left(\frac{x}{m}\right)$$

(In order for the profile distribution, as given, to be the significant quantity, the detector to be employed must have uniform and adequate extent of coverage in the y direction.)

If $\overline{\Phi_0}(p)$ and $\overline{\Phi}(p)$ are the Fourier transforms (frequency spectra) of $\Phi_0(x)$ and $\Phi(x)$ respectively (p has the dimensions of x^{-1}), then we have

$$\overline{\Phi}_0(p)=\int_{-\infty}^{\infty}\Phi_0(x)e^{-px}dx$$

$$p=i2\pi f$$

$$f=\text{spatial frequency}$$

and

$$\overline{\Phi}(p)=\left(\frac{D}{u}\right)^2\overline{\Phi}_0(mp)$$

Let the received distribution $\Phi(x)$ be gated by a sensitivity characteristic $g(x)$, having a transform $\overline{g}(p)$. Also let the target position be shifted by an amount x_0, so that the new target distribution is $\Phi_0(x+x_0)$, and the new image distribution is

$$\Phi(x+mx_0)=\left(\frac{D}{u}\right)^2\cdot\frac{1}{m}\cdot\Phi_0\left(\frac{x+mx_0}{m}\right)$$

The transform of this latter distribution is

$$\overline{\Phi}(p)\,e^{mx_0p}=\left(\frac{D}{u}\right)^2\overline{\Phi}_0(mp)\,e^{mx_0p}$$

The result of gating the received distribution will be the detector output S. Except for constant factors,

$$S=\int_{-\infty}^{\infty}\Phi(x+mx_0)g(x)\,dx$$

$$=\left(\frac{D}{u}\right)^2\cdot\frac{1}{m}\cdot\int_{-\infty}^{\infty}\Phi_0\left(\frac{x+mx_0}{m}\right)g(x)\,dx$$

Or, by Parseval's theorem

$$S=\left(\frac{D}{u}\right)^2\int_{-\infty}^{\infty}\bar{\Phi}_0(mp)e^{mx_0p}\,\bar{g}(p)\,df$$

where the symbol

$$\bar{g}(p)$$

implies the complex conjugate of $\vec{g}(p)$. For small x_0, the change in S for a shift in target position x_0 will be

$$=\frac{dS}{dx_0}\bigg|_{x_0=0}=m\left(\frac{D}{u}\right)^2\int_{-\infty}^{\infty}p\bar{\Phi}_0(mp)\bar{g}(p)\,df \qquad (1)$$

The effect of "noise" will now be considered. Random errors in the detected signal will be caused by spatial (point-to-point) variations in the surrounding or background light which reaches the detector along with the desired target image. Any time-variations of the background light at fixed spatial regions will be ignored. In other words, the granularity or graininess of the background is taken to be the sole source of statistical error.

It will now be assumed that the background graininess has the following characteristic. The mean square variation (σ^2) of the samples obtained by integrating the target brightness over all background regions having an area A (one can consider the background for this purpose as being located at the plane of the target), is proportional to A. This is a property of photographic films, for example, as described in the literature of this field. Another, substantially equivalent, way of saying this is to specify that the time variation of light obtained by moving a narrow scanning slit across the background at constant speed, has the characteristics of wide band "white" thermal noise.

Now since the σ^2 of the background "noise" is proportional to the area observed, the background area intercepted by the detector will be investigated as the magnification m is varied, keeping D and u constant. The noise is minimized by keeping the y extent of the detector just sufficient to include the target image. That is, the height of the intercepted background area will be constant. The width (x) of the intercepted area in the target plane will not be constant, but will vary as

$$\frac{1}{m}$$

Therefore the σ^2 of the detected noise signal will be proportional to

$$\frac{1}{m}$$

The sensitivity of the detector is not constant in the x direction, but varies as $g(x)$. The proper measure of the effective width of the detector can be shown to be proportional to

$$\int_{-\infty}^{\infty}(g(x))^2dx=\int_{-\infty}^{\infty}\left|\bar{g}(p)\right|^2df$$

in the plane of the detector. Thus the σ^2 of the detected noise can be written as (except for constant factors)

$$\sigma^2=\frac{1}{m}\int_{-\infty}^{\infty}\left|\bar{g}(p)\right|^2df \qquad (2)$$

for constant u and D.

The gate transform $g(p)$ which minimizes σ^2 while maintaining a constant sensitivity

$$\frac{dS}{dx_0}$$

as given by (1) will now be found. This is a straightforward calculus of variations problem. Form the difference of integrals

$$I=\int_{-\infty}^{\infty}mp\bar{\Phi}_0(mp)\bar{g}(p)\,df-\frac{\lambda}{m}\int_{-\infty}^{\infty}\left|\bar{g}(p)\right|^2df$$

The first integral is proportional to the detection sensitivity

$$\frac{d\delta}{dx_0}$$

while the second integral is $-\lambda$ times σ^2, λ being an undetermined constant. What is sought is a function $\vec{g}(p)$ which minimizes I for small arbitrary changes in $\vec{g}(p)$. That particular $\vec{g}(p)$ also minimizes the second integral while holding the first integral constant. First I is rewritten as

$$I=\int_{-\infty}^{\infty}\left[mp\bar{\Phi}_0(mp)\bar{g}(p)-\frac{\lambda}{m}\left|\bar{g}(p)\right|^2\right]df$$

Now introduce a small arbitrary change in $\vec{g}$, represented by $\delta\vec{g}$. Letting

$$\vec{g}=\ e^{i\alpha}$$

G being the magnitude of $\vec{g}$, and α the phase, there is obtained

$$\delta\vec{g}=e^{i\alpha}\delta G+i\vec{g}\delta\alpha$$

and

$$\delta\bar{g}=e^{-i\alpha}\delta G-i\bar{g}\delta\alpha$$

The only restriction upon $\delta\vec{g}$ is that δG must be an even function of frequency and $\delta\alpha$ an odd function of frequency. The variation in I for the assumed variation $\delta\vec{g}$ thus is

$$\delta I=\int_{-\infty}^{\infty}\left(\left[mp\bar{\Phi}_0(mp)e^{-i\alpha}-\frac{2\lambda}{m}G\right]\delta G-[imp\bar{\Phi}_0(mp)\bar{g}]\delta\alpha\right)df$$

I is now set equal to zero to find the minimum σ^2 condition. Since the bracket of the integrand multiplying δG cannot be an odd function of frequency, and since δG is arbitrary, the coefficient of δG is required to vanish. Thus

$$\frac{2\lambda}{m}G=mp\bar{\Phi}_0(mp)e^{-i\alpha}$$

$$\frac{2\lambda}{m}Ge^{i\alpha}=mp\bar{\Phi}_0(mp)$$

or

$$\bar{g}(p)=\frac{1}{2\lambda}m^2p\bar{\Phi}_0(mp)$$

Dropping the

$$\frac{1}{2\lambda}$$

multiplier, one obtains

$$\vec{g}(p)=m^2p\bar{\Phi}_0(mp) \qquad (3)$$

When this relationship is substituted into the part of the integrand involving $\delta\alpha$, this part becomes an odd function of f, and thus contributes nothing to the integration. Therefore Equation 3 fulfills the requirement that $\delta I=0$.

The transform Relation 3 says that the optimum gating characteristic $g(x)$ is

$$g(x)\sim\frac{d}{dx}\Phi(x)=\Phi'(x)$$

That is, the optimum detector sensitivity characteristic from the standpoint of signal-to-noise ratio is the derivative of the received target distribution.

The resulting signal-to-noise ratio can be found by substituting Equation 3 into Equations 1 and 2:

$$\text{Signal amplitude} \sim \frac{dS}{dx_0} \sim m^3 \int_{-\infty}^{\infty} \left| p\bar{\Phi}_0(mp) \right|^2 df$$

$$\text{Signal power} \sim \left(\frac{dS}{dx_0}\right)^2 \sim m^6 \int_{-\infty}^{\infty} \left[\left| p\Phi_0(mp) \right|^2 df \right]^2$$

$$\text{Noise power} \sim \sigma^2 = m^3 \int_{-\infty}^{\infty} \left| p\bar{\Phi}_0(mp) \right|^2 df$$

The ratio of signal power to noise power is thus proportional to

$$\frac{P_s}{P_n} = m^3 \int_{-\infty}^{\infty} \left| p\bar{\Phi}_0(mp) \right|^2 df = \int_{-\infty}^{\infty} \left| mp\bar{\Phi}_0(mp) \right|^2 d(mf) = \int_{-\infty}^{\infty} \left| p\bar{\Phi}_0(p) \right|^2 df \qquad (4)$$

Thus the best obtainable ratio of signal power to noise power is independent of the magnification m, assuming the optimum gate characteristic in all cases. Therefore if we set the gate characteristic at the optimum for some particular magnification $m=m_1$, and then vary the magnification, the maximum signal-to-noise ratio is found at the original magnification m_1.

This analysis will now be applied to the arrangement of Fig. 1 and in a similar manner to the arrangements of Figs. 5 and 6 which will be described hereinafter. By means of a test set, the sensitivity characteristic $g(x)$ of the germanium crystal **10** is obtained. This characteristic will be a plot, as in Fig. 2, of voltage vs. light spot position, and will be antisymmetric about the boundary layer **11**. The curve $g(x)$ will be integrated to obtain a curve such as that shown in Fig. 3. The focal length of the lens (such as the lens L in Fig. 7 and the lens **31** in Figs. 5 and 6) imaging the light spot on the member **10** will then be selected so that the distribution curve of the light image on the crystal **10** substantially matches the integral of $g(x)$. In the situation where the light source can be shaped to produce the desired characteristic, the focal length of the lens need not be varied. During the manufacturing process, the shape of the characteristic of the detector **10** can be varied. In any case, what is desired is to match the image distribution characteristic however obtained (either by spot shaping or lens selection) with the integral of the sensitivity characteristic $g(x)$ which is a characteristic of the material of the detector **10** but which can be different for different detectors, depending on the manufacturing process.

Before discussing in detail the systems shown in Figs. 5 and 6 and which are somewhat more complex embodiments of the invention, reference will first be made, for purposes of comparison, to Fig. 4 which is a schematic diagram of a prior art arrangement. The system illustrated in Fig. 4 is a conventional arrangement for detecting the position of a light spot, employing ordinary photocells and other techniques which are in accordance with the present state of the art. In this standard arrangement, a beam splitting prism **21** is used to produce two identical images **22** and **23** of the light spot **20**, each of these images being directed upon a properly masked photocell (elements **24** and **26**). The outputs of the two cells are then compared in a differential amplifier **27**, so that (ideally) no output is obtained so long as the two spot images are bisected by the photocell mask boundaries **28** and **29**. Movement of the target spot causes movement of the spot images relative to the mask boundaries, thereby unbalancing the light on the two cells and producing a signal at the output of the differential amplifier. A major difficulty in this type of arrangement is that any change in the photo-efficiency of one cell relative to the other causes a false indication of spot movement. Furthermore, if the differential amplifier is

not ideal (as is generally the case in practice), changes in the target spot intensity produce false signals.

The moving target spot shown at **20**, for example, in Fig. 4 may be of any suitable origin. For example, it may be a boat or airplane carrying illumination means. Alternatively, it may be a bright spot on a cathode ray tube, or the spot of light produced by a ray of light intercepted by a screen.

The difficulty and drawbacks inherent in the conventional arrangement of Fig. 4 are obviated by the illustrative embodiment of a position detector in accordance with the invention which is shown in Fig. 5. In this position detector, employing the differential photocell illustrated in Fig. 1 and described in connection therewith, there is no need for a beam splitting prism or for a differential amplifier. A single image of the target spot **30** is projected through a lens **31** onto the grain boundary **11** of the crystal **10**. The focal length of the lens **31** is, as pointed out above, preferably chosen to produce the desired image distribution to match the integral of the sensitivity characteristic $g(x)$ of the crystal **10**. One electrode **12** of the crystal can, in accordance with the invention, be grounded. Thus the other electrode **13** develops a voltage whose magnitude is proportional to the deviation of the target image from the grain boundary, and whose polarity depends upon the direction of this deviation. This electrode voltage is then amplified by an ordinary amplifier **32** to actuate a meter, cathode-ray oscilloscope, motor or other utilization device. In this position detector, the zero-reading point is very stable with time and temperature, and variations in target light intensity can not cause false error signals. It is also in accordance with the invention, although not shown in the figure, to insert a high frequency light chopper in the target beam so that it is not necessary to use a direct-current amplifier, thereby eliminating any drift problem which may be encountered.

One important application of the differential photocell detector of Fig. 5 is a tracking servo system which can, in accordance with the invention, be connected as shown in Fig. 6. In this exemplary arrangement, the tracking member is a mirror **41** inserted in the target light beam. This mirror is rotated about an axis perpendicular to the plane of the drawing, the driving being accomplished by a twin moving coil magnetic motor. (The moving coils are designated by the reference characters **42** and **43** in the figure.) This motor is in turn driven by the amplified error signal from the differential photocell **10**. The servo loop is poled so that the mirror rotates to cancel any deviation of the spot image from the grain boundary due to motion of the target. In accordance with the invention, a data take-off coupled to the mirror can thus register the target position. Since this arrangement is suitable for following only small displacements of the target, in one illustrative embodiment the entire optical system can be mounted on a motor rotated base, this motor also being driven from the error output of the differential photocell. The two driven systems may thus be used to constitute a fast-acting small displacement "vernier" servo and a slow-acting displacement servo. Data take-offs from the mirror and the rotating base can be totalled to indicate the target position.

The advantages of the differential photocell position detector of the invention as compared with conventional present-day techniques are considerable. For one, the system is highly efficient, the quantum efficiency of the cell approaching unity for the region at the grain boundary. Secondly, inasmuch as the zero reading point is accurately located at the grain boundary, the system is very stable. Thirdly, the photo-characteristic is symmetrical about zero, so that there is no steady or bias output obtained at the center position. This zero longitudinal signal is manifestly a highly desirable characteristic. As indicated in the body of the specification, here are numerous other features of superiority in the present invention.

Obviously, many changes can be made in the embodiments described above without departing from the spirit of the invention.

What is claimed is:

1. A photoelectric device comprising a body of semiconductive material having therein a narrow zone of one conductivity type between and contiguous with a pair of outer zones of the opposite conductivity type, terminal connections to said outer zones, and illumination means for said semiconductor body consisting of means for directing against said body a single light beam which has a light distribution characteristic at the body surface which substantially matches in shape the integral of the sensitivity characteristic $g(x)$ of said material, where $g(x)$ is a plot of voltage vs. light position of the spot with respect to said first-mentioned zone.

2. A photoelectric device comprising a body of semiconductive material having therein a narrow zone of one conductivity type between and contiguous with a pair of outer zones of the opposite conductivity type, terminal connections to said outer zones, and illumination means for said semiconductor body consisting of means for directing against said body a single light beam which has a light distribution characteristic at the body surface which substantially matches in shape the integral of the sensitivity characteristic $g(x)$ of said material, where $g(x)$ is a plot of voltage vs. light position of the spot with respect to said first-mentioned zone, said last-mentioned means including a lens with focal length selected to obtain said matching.

3. A photoelectric device comprising a body of semiconductive material having therein a narrow zone of one conductivity type between and contiguous with a pair of outer zones of the opposite conductivity type, terminal connections to said outer zones, illumination means for said semiconductor body consisting of means for directing against said body a single light beam which has

a light distribution characteristic at the body surface which substantially matches in shape the integral of the sensitivity characteristic $g(x)$ of said material, where $g(x)$ is a plot of voltage versus light position of the spot with respect to said first-mentioned zone, said last-mentioned means including a lens with focal length selected to obtain said matching, a mirror positioned between said lens and said material, magnetic coil means for moving said mirror, and means responsive to deviations of the light beam from said first-mentioned zone to cause said magnetic means to return said mirror to a position where the beam strikes said zone.

4. In a photoelectric follow-up system, a first component comprising a body of semiconductive material having therein a narrow zone of one conductivity type between and contiguous with a pair of outer zones of the opposite conductivity type and having terminal connections to the outer zones, a second component comprising a source of light, a third component comprising means for directing a single light beam from said source of light against said body, means for moving one of said three components relative to the other two, and means sensitive to the polarity of the electromotive force resulting from said movement and operative to change the position of one of said other two components and hold the beam substantially on said narrow zone.

5. A photoelectric device as defined in claim 1 including means for providing relative movement between said light beam and said body.

References Cited in the file of this patent

UNITED STATES PATENTS

2,356,579	Gardner	Aug. 22, 1944
2,402,662	Ohl	June 25, 1946
2,482,980	Kallmann	Sept. 27, 1949
2,570,978	Pfann	Oct. 9, 1951
2,641,712	Kircher	June 9, 1953
2,641,713	Shive	June 9, 1953