NON-CONTACT

Optical Position Sensing Using Silicon Photodetectors

Although the use of silicon photodetectors for making quantitative light measurements has been long established, there exists a body of other measurement capabilities for such devices, which have gone generally unnoticed. These involve measurements of movement, angle, straightness, object location, height, centering, surface uniformity, and distance - which may be generally referred to as optical position sensing.

Various types of silicon photodetectors, which may be used for position sensing, will be examined including common single-element devices, bi-cell and quadrant detectors, lateral effect photodiodes, and multi-element arrays. The basic theory of operation of each type, and its relative advantages will be discussed, and a demonstration of opto-electronic instruments utilizing these sensors will be performed to illustrate some common applications.

The use of silicon photodetectors for making quantitative light measurements has been long established. They are routinely employed by manufacturers of photometers, radiometers, gas chromatographs, reflectometers, densitometers, and fiber optic power meters to name a few. There exists, however, a myriad of measurement capabilities for such devices, which have gone generally unnoticed, and are widely misunderstood. We may loosely refer to this category of applications as optical position sensing. Measurements of movement, angle, straightness, object location, height, centering, surface uniformity, and distance fall into this class.

The relatively scarce implementation of silicon devices in these areas is not due to a lack of acceptance and understanding on the part of users alone. Rather, there is a gap in manufacturers' ability to identify applications and markets, which could use this technology, and to produce affordable instruments and systems tailored to these applications. Affordability must be emphasized since the most widely applied optical position sensing techniques, video and CCD Arrays, are priced beyond the budgets of many would-be users. Furthermore, these techniques have been often utilized to make measurements where simpler, less expensive equipment might easily have been used.

The purpose of this paper is to examine the various types of silicon photodetectors, which may be used for position sensing. These will include common single element devices, bi-cell and quadrant detectors, lateral effect photodiodes, and multi-element arrays. The basic theory of operation of each type, its advantages and disadvantages, and relative cost will be discussed. We will proceed from an economic perspective only in so far as it is believed that the most simple, direct measurement approach is not only often the least expensive, but the most accurate as well.

BASIC SILICON PHOTODETECTOR THEORY

A silicon photodetector is a solid state transducer used for converting light energy into electrical energy. Many techniques for fabricating them are employed, however, for high resolution positioning devices, planar diffused and Schottky barrier constructions prove most effective.

Planar diffused devices are produced by diffusing boron (a P-type dopant) and phosphorous (an N-type dopant) into opposite sides of high resistivity, nearly intrinsic (I) silicon base material (Fig 1). These units are thus often referred to by the acronym as P-I-N diodes. The diffusion of the dopants is performed at high temperatures between 850ºC and 1150ºC, which must be very tightly controlled. The light sensitive region, or active area, is defined by a mask of silicon oxide grown on the diode surface at comparable temperatures. The active area serves as the anode and is generally contacted with a thin aluminum bond wire. A thin metallized layer may often be vacuum evaporated on the bottom of the silicon chip to provide a stable, low resistance cathode contact.

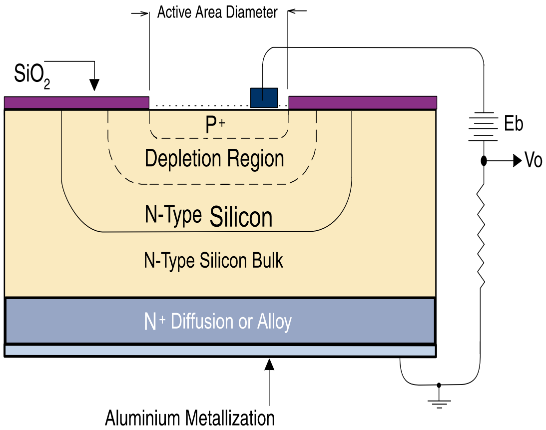


Figure-1

Planar diffused constructions are most prevalent in small to medium area devices since they offer low noise and excellent stability. Thermal processing parameters are also best controlled for devices of this size so that yields are optimized.

Schottky barriers, on the other hand, are formed by vacuum evaporating a thin layer of gold onto high resistivity N-type silicon at near room temperature (Fig. 2). Prior to this gold evaporation phosphorus is diffused into the reverse side of the silicon chip to form an N+ layer over which the rear contact metallization may be performed. Preparation of the silicon surface prior to gold evaporation is crucial in the fabrication of good Schottky devices.

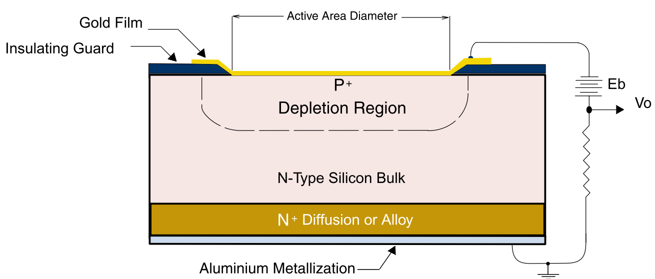
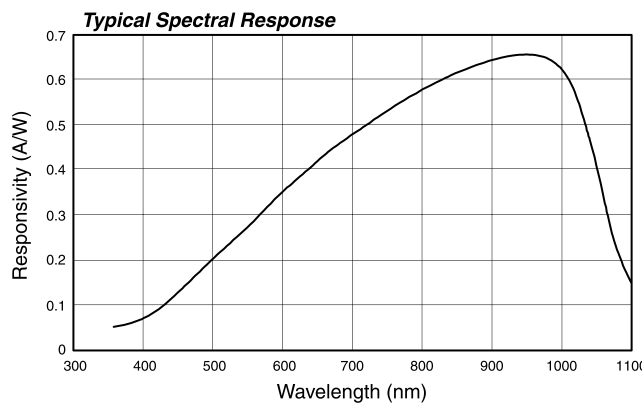


Figure- 2 **Schotttky Barrier**

Generally, large area, single element devices used for position sensing will be of Schottky construction. This is because uniform vacuum evaporation is more readily controlled over a large area than high-temperature diffusion of other P-type dopants. Needless to say, noise currents will be higher in these larger area devices, so that for best resolution one should apply the smallest area diode, which is convenient.

When a photon of light with sufficient energy threshold is absorbed by the photodiode, an electron-hole pair is excited (Fig 3). Photocurrent results when the electron-hole pairs separate, electrons going to the N side, holes to the P side. Separation of the electron-hole pairs is most likely to occur when they are formed in the region of the semiconductor where there is an electric field. This field is strongest in the central region of the diode between the N-type and P-type diffusions. Accordingly, photons absorbed in this region, known as the depletion region, will constitute the bulk of the electron flow through the N-region and into the external circuit as photocurrent. The alternative to separation is for the electron-hole pairs to recombine, which is most likely to happen when carriers are formed outside the depletion region.

For best performance, a photodiode should be made to allow the largest number of photons to be absorbed in the depletion region, i.e. photons should not be absorbed until they have penetrated as far as the depletion region, and should be absorbed before penetrating beyond it. The relative depth to which a photon penetrates is a function of its wavelength. Shorter wavelengths, in the ultra-violet and blue regions, are absorbed near the surface of the material, while those of longer wavelength in the infrared region may penetrate all the way through the crystal. This phenomena governs the spectral response of photodiodes. Silicon has a typical response from 350 to 1100 nanometers, peaking between 700 and 900 nanometers (although some ultraviolet enhanced models may exhibit response down to 200 nanometers and lower) (Fig. 4). These response characteristics make silicon photodetectors optimum for use with a variety of common light sources including helium-neon lasers, laser diodes, light emitting diodes (LED), infrared emitting diodes (IRED), and incandescent or fluorescent lamps.

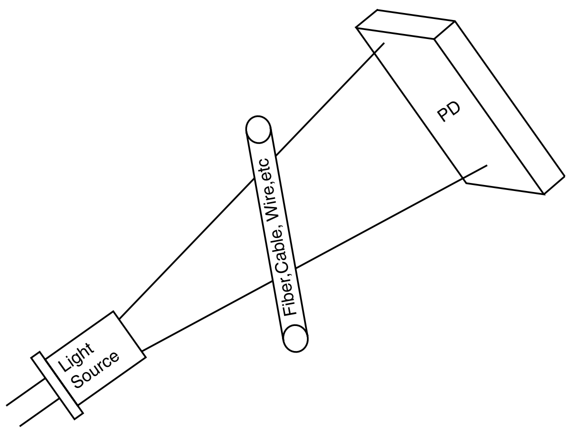


Other favorable characteristics of silicon photodiodes are their excellent speed of response and low noise. Typical devices will exhibit rise times of 5 microseconds or less, and this may be reduced by applying a reverse bias to the P-N junction, thus lowering the junction capacitance. The noise current for these detectors, which as mentioned before is lowest for smaller devices, allow detection of light levels in the nanowatt, and in some cases, picowatt regions (10^{-12} watts).

This basic PIN photodiode configuration is common to almost all units used for optical positioning. The most significant differences between the types to be discussed involve the juxtaposition of active areas to one another, and the manner in which the substrate of the diode is contacted.

POSITION SENSING APPLICATIONS FOR SINGLE ELEMENT DETECTORS

Although single element photodetectors cannot actually resolve the position of a light spot or image over their surface, their exceptional sensitivity to changes in incident light level over a broad range renders them useful for numerous position sensing applications. This is further enhanced by the availability of a variety of detector geometry's. Figure 5 illustrates a simple, yet uncommon technique for measuring diameter. This might involve a length of fiber, wire, cable, tubing, pipe, etc. Each of the detection techniques to be discussed could be applied to such a measurement, and in fact a number of users are known to have used expensive arrays. However, a simple photovoltaic device may be used in most cases with excellent resolution.



In this case, the tubing, which is positioned between the source and photodetector, determines the area of the detector, which is being directly illuminated. The detector exhibits a noise equivalent power (NEP) of less than .1 nanowatt, and a maximum power density of at least 10 milliwatts per square centimeter. We should, as such, be able to resolve 1 part in 1 million comfortably, or if imaging one-to-one on a 1 square centimeter detector, less than 1 micrometer. Source characteristics, ambient lighting, and response nonuniformities must be taken into account; however, for a 0.25 inch diameter length of copper tubing in laboratory conditions, 1-2 micron resolution or better

can be attained with excellent repeatability. Using various detector geometry's, similar measurements could be made for indication of height, width, and liquid or solid level in a translucent or semi-translucent container. In the sample application photodetector cost is approximately $50.00, and it may be read with a common voltmeter.

The light sensitivity of single element devices also makes them useful as an alignment tool. Again, this would involve the positioning of the object to be aligned between the photodetector and light source. A mechanical mask or aperture shaped appropriate to the object is placed in front of the detection surface. The mask may either permit light the shape of the object, or block it (i.e. mechanical negatives of one another), such that either a high-going or low going signal represents perfect alignment. The complexity of the object, working distances, and size of utilized detector area all influence resolution capability, as well as the source and ambient lighting conditions. In general, though, micron-level sensitivity may be obtained if the mechanical tolerances of the mask, photodetector, and fixturing can be optimized.

QUADRANT AND BI-CELL DETECTORS

Quadrant and bi-cell photodetectors work on the principle of having two or four separate photodiode elements separated by a small gap (2-12 micrometers) (Fig. 7). These elements are generally masked onto a common substrate so that their cathode is shared; however, the juxtaposition of discrete devices is also performed on occasion. The anode or active area of each element is individually contacted so that a light spot illuminating a single quadrant may be electrically characterized as being only in that quadrant. As this spot is translated across the detector, its energy is distributed between adjacent elements, and the difference in electrical contribution to each segment defines its relative position with respect to the center of the device. What we are then concerned with is the relative intensity profile over the active area of the device to determine light spot position.

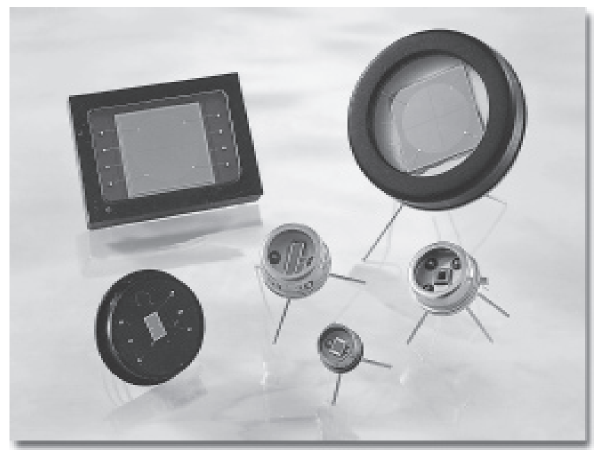


Figure 7

Two important observations should be made regarding this transfer function. First, it may be seen that the detector will provide position information only over a linear distance of twice the spot diameter, or until the edge of the spot has reached the detector gap. Thereafter the spot is known to be in a particular segment, but not

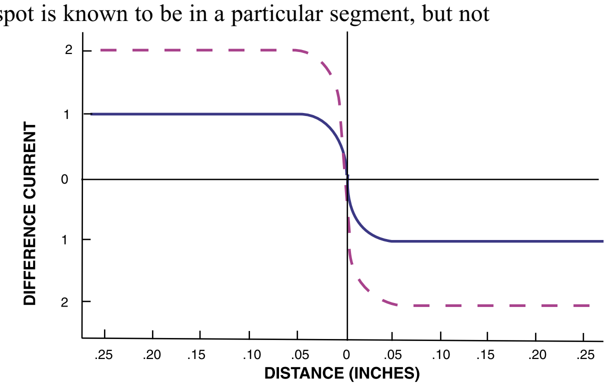


Figure 8

Figure 8 shows the single axis transfer function of a bi-cell detector, the X-axis defining spacial movement of the image across the detector, and the Y-axis the signal difference between the two elements. For quadrant detectors, a similar function exists for the orthogonal direction and so X and Y position is available.

exactly where. Thus in working with lasers or collimated sources, the image may require defocusing to obtain maximum range. Secondly, the transfer function for a circular spot is not a linear, mainly because its linear movement is not proportional to the percentage of its area, which shifts between adjacent segments. We may surmise then, that a line or quadrangle of light would provide best linearity. In any case, this technique presumes the spot intensity distribution is symmetrical.

These limitations are proposed not to deter application of the devices, but to illustrate that they are most effectively used as nulling and centering devices rather than as linear position indicators. And for such applications their performance is unparalleled, since resolutions of 0.1 micrometers or better may be obtained. This is due to the excellent response uniformity from element-to-element, and sensitivity (due to low noise currents) which, in many cases, may approach 1-10 picowatts. Such devices are available in a wide variety of active area sizes, and range in price from $20 to $100 on the average.
Although the signal outputs could be read from each quadrant, and appropriately subtracted to obtain position, electronic modules and complete readout systems are commercially available to perform this task. Such systems utilize a network of analog amplifiers and dividers (Fig. 9), the first stage operated in the transimpedance mode to boost the photodetector current and convert it to a voltage, and the second stage performing the summing and differencing of the various quadrant signals. A 10 x n/D divider is often supplied to divide the sum signals into the difference. The ratioing of these resultant signals is necessary to cancel out the effects of a varying source intensity, which might otherwise be deemed an apparent shift in the spot position. If the source were known to be very stable, it would suffice to measure the difference signals alone.

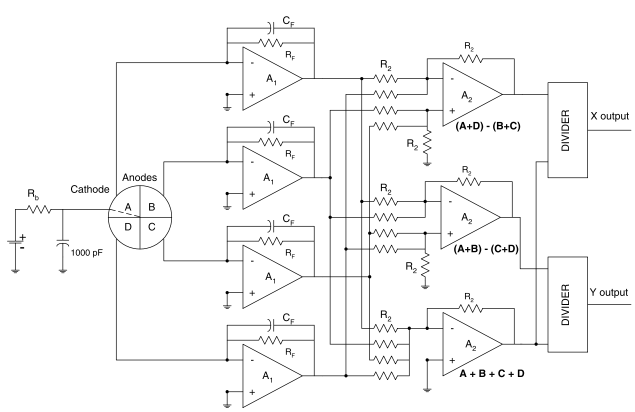
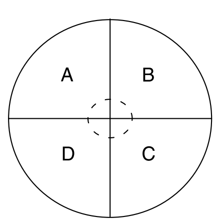


Fig.9

Arithmetically, the X and Y position of the spot as characterized by the circuit can be written as:

$$X = \frac{K \quad (A+D) \; - \; (B+C)}{A+B+C+D}$$



$$Y = \frac{K \quad (A+B) \; - \; (C+D)}{A+B+C+D}$$

Where A,B,C and D are the respective quadrant signal outputs (Fig. 10). For a bi-cell detector with segments termed A and B the expression would be:

$$X = \frac{K \quad (A-B)}{A+B}$$

Digital systems are also utilized with these devices in which case the detector signals are amplified, digitized, and then fed into a microprocessor or computer which may perform the summing, differencing, and division.

Because these detectors are best used as null indicators, the applications for which they are most often applied fall into the category of optical alignment. Although an object may be involved, in most cases the purpose is to align a direct or reflected light source (Fig. 11). In this case, the device is utilized in an autocollimator for aligning and monitoring small angular displacements of mirrors or relatively diffuse surfaces. The light source is an infrared LED (900nm) contained in the collimator body. It is directed by the beam splitter out onto the surface to be measured through the lens. The reflected light is then focussed by the lens through the beamsplitter onto the quadrant detector. The angular coverage and sensitivity are hence determined by the focal length of the lens, the active area of the quad-cell, and its spatial sensitivity. Given a 1 cm2 detector capable of .1 micrometer resolution (at the null point), and a 200mm focal length lens the systems angular sensitivity would be:

$$\frac{.0001}{200} = .\frac{.5 \; microradians}{or}$$

$$.1 \; arc \; seconds$$

This in fact has been verified in certain applications.
Another application for quad and bi-cell detectors, perhaps the one in which they are most commonly used, is for the alignment of laser beams or any collimated source. Their capabilities in this respect are unsurpassed, and generally no front-end optics are required.

LATERAL EFFECT PHOTODIODES

Although the lateral photo effect was discovered by Schottky in 1930, devices utilizing this principle have only become readily available in the last decade or so. They are certainly the least well known and understood of the devices covered herein (Fig. 12).

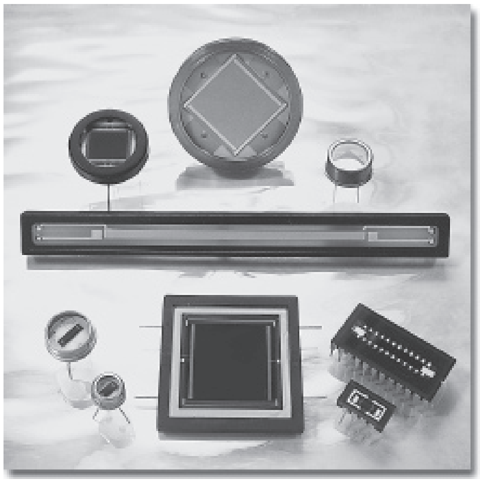


Fig.12

The most striking difference between them and the other detectors capable of resolving light spot position over their surface, is that they consist of a single active element (Fig. 13). Position is derived by dividing photon-generated electrons within the substrate (N-region) of the device, rather than profiling intensity distribution on the surface. This is achieved by applying multiple ohmic contacts on the back layer on the device. Two back contacts are made at opposite ends of the sensor for single axis versions, while dual axis units utilize four contacts coinciding with the extremes of the cartesian axes.

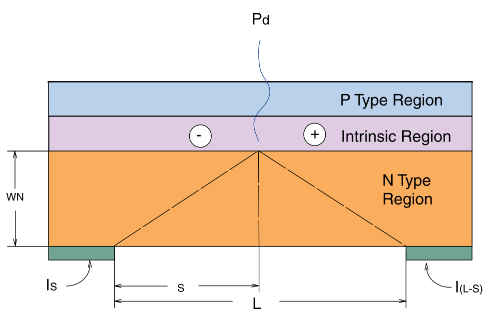


Fig.13

As with the other techniques, carriers produced by incoming photons are separated in the depletion region, the holes returning and recombining at the surface; however, since now there are alternative paths for current flow, the electrons separate according the ohm's law. The current flow through any given contact may be calculated as:

$$I_s = Io \frac{Sinh\ [\alpha\ (L-S)]}{Sinh\ (\alpha L)}$$

Where Io is the photoinduced current, and α, the Lucovsky falloff parameter (a characterization of the N-region). As α approaches zero, a quality common to good lateral units, the above equation becomes:

$$I_s = Io\left(I - \frac{S}{L}\right)$$

This would be an ideal, or perfectly linear device, in which case the current through all lateral contacts is a function only of the distance of the light spot from that contact. With an incident beam centered on the device, the current through each lateral contact would be equal. The device might well be thought of as a light-controlled variable resistor.

In fact, lateral effect diodes are not perfectly linear. Most devices exhibit ± 0.5 linearity over the central 25% of their area, ± 3.0% out to 75%, and ± 5% out to the periphery. The major contributor to this is nonuniformity in the sheet resistance of the device. At the center of the detector where the light spot is equidistant from all contacts, these nonuniformities will tend to average out to a greater extent than at outlying areas on the detector. Also, a shift in linear position of the light spot with relation to the center of the device is not linear with respect to the cartesian axes as defined by the four ohmic contacts. This is not a significant problem in single axis versions. The associated electronics often used to determine position information from a lateral cell are quite similar to those used with bi-cell and quadrant models. The difference lies in the amplifier sequence and the reverse polarity of the detector signals (Fig. 14). For a dual axis detector whose four lateral contacts are labeled A,B,C, and D, the circuit may be arithmetically expressed as:

$$XPosition = \frac{(A-B)}{A+B}$$

$$YPosition = \frac{(C-D)}{C+D}$$

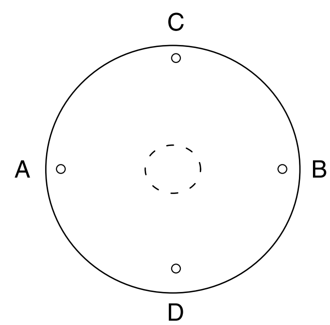


Figure 14

The division is again performed to ratio-out alteration in the incident light level (Fig. 15).

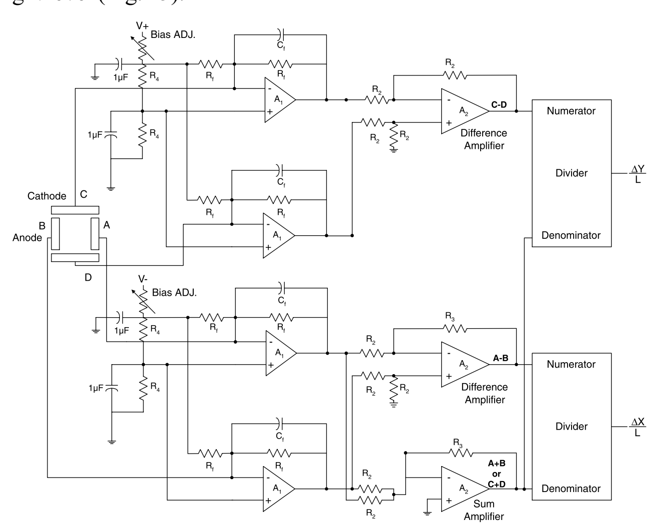


Fig 15

Typical resolutions of ± 2.5 micrometers may be attained with lateral effect photodiodes, although this is contingent upon the active area size, smaller units being more sensitive. Some sophisticated systems have been able to derive .025 micrometers by AC coupling and using the central region of the diode.

The most striking difference between these units and the others discussed is that they provide accurate position information independent of the light spot intensity profile, symmetry, or size. The photoinduced current flowing through the lateral contacts is contributed to by all incident flux based upon relative location and intensity profile, symmetry, or size. The photoinduced current flowing through the lateral contacts is contributed to by all incident flux based upon relative location and intensity over the active area of the diode. What is then derived is the average, or "centroid" of the image spot. And since there is no dead region on the device, no defocusing would necessarily be required. This negates any requirement for front-end optics in many cases, since a wide variety of sizes and geometries are available single axis versions up to 12 inches long, and dual axis versions to 2 inches in diameter.

Accordingly, lateral effect photodiodes prove to be highly versatile, lending themselves to many applications. Figure 16 illustrates the use of such a device to monitor position and motion of an object in space. This might well be a machine tool, robot arm, part of the human anatomy, etc. With appropriate optics, large fields-of-view may be covered at remarkable working distances. The primary consideration is collecting enough light on the detector to optimize signal-to-noise characteristics. High powered infrared LED's prove an excellent choice for such applications, since they are in the peak silicon response region (800-950 nanometers). In this case, the LED is mounted on the object to be monitored, and a 55mm focal length camera lens is used to image the source onto the detector. At one meter the field-of-view of this system is 17cm, in this case using a $1cm^2$ detector. Typical accuracy over the detector surface utilizing analog amplifiers would be 1 part in 2000, yielding a spacial resolution over the entire 17cm of 85 micrometers. In comparable applications where it would be difficult to locate

the light source on the object to be measured, a remote source could be used. A small, approximately lambertian white diffuser would be situated on the object and the movement of the diffuser could in turn be monitored by the photodetector.

Figure 17 depicts another common measurement technique for lateral effect photodiodes that would equally apply to monitoring level, surface uniformity, or displacement. This might involve sensing the level of liquids, solids, molten material, or radioactive wastes, or to characterizing the surface or displacements of glass, metals, computer discs, or any relatively reflective material. Resolution is best enhanced by locating the detector as close to measurement surface as possible, and by maximizing the incident and reflective angles. On the other hand the greatest range would be achieved by minimizing the~~ angle~~se, and distancing the detector from the surface. The source in this case could be a laser, or a focussed LED or lamp, and or for best results an interference filter specific to the source wavelength would be used to reduce detector sensitivity to ambient light. The sensitivity of such a system is contingent upon many variables; however, with stable electronics, and a 45 degree incident angle at a working distance of two to four inches, resolutions of 2.5 micrometers or better may be obtained.

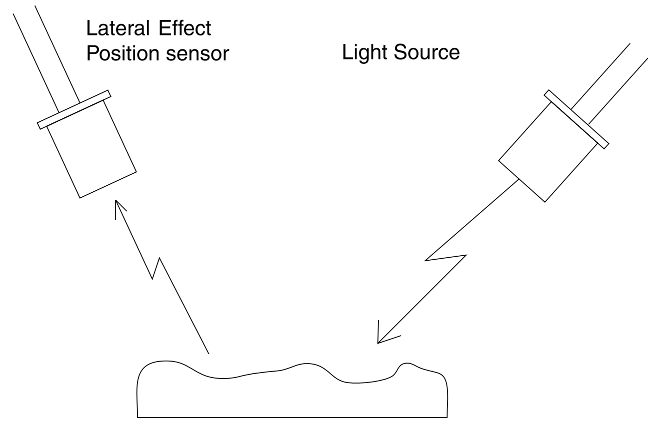
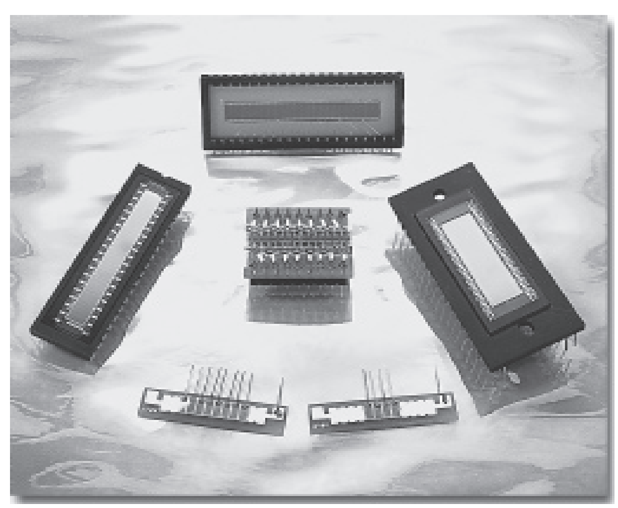


Fig 17

These devices prove similarly useful for numerous other position sensing measurements which have in the past been for the most part performed with vidicons or self scanned arrays. However, lateral effect photodetectors offer the advantage of requiring much simpler electronics and generally less sophisticated optics to operate them. They are also significantly less expensive ranging in price from $60.00 to $300.00 on the average, and complete X-Y electronic detection systems are available in the $2,000.00 range.

MULTI-ELEMENT PHOTODETECTOR ARRAYS

Like quadrant and bi-cell detectors, a silicon array consists of a series of discrete photodiode elements, which are individually contacted. These may be arranged in a line, matrix (two-dimensional), series of annular rings, or numerous other patterns (Fig. 18). Thus, the intent is to produce an electrical analog of the image incident on the array by monitoring the relative intensity from element to element.



elements are standard. In such cases it becomes necessary to scan the individual pixels to produce the series of current pulses corresponding to the pattern of radiation distributed on the unit's surface. This requires the implementation of sophisticated circuitry (in contrast to previously discussed devices) which comprises the bulk of cost for self-scanned array systems.

Figure 19 depicts a simplified circuit diagram for reading a multi-element array. The elements are first fed into individual associated storage capacitors and connected to a common output line through switches which might be an external multiplex switch or on-chip MOS transistor switches. The switches must then be turned off and on sequentially via an integrated shift register scanning circuit. Several shift registers may be utilized and they must be actuated alternately or sequentially when more than two registers are involved. Generally, in two dimensional multi-element devices, each line of pixel information will be accessed by a different shift register.
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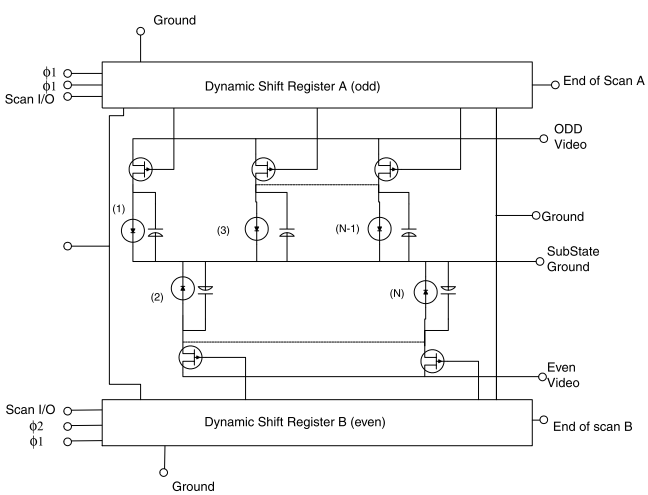

Figure 19

A TTL clock, whose phase is determined by the number and spacing of elements, is used to drive the shift registers. During the interval between the scan start and end of scans clock pulse, the charge on each capacitor is depleted. This is attributed to the reverse current flowing in the associated photodiode, which as previously discussed is a function of the diode's sensitivity to a change in incident light intensity. The amount of charge removed from the capacitor is a function of this sensitivity, and the time between samplings. These output pulse might then be accessed through the video output lines and ultimately processed or displayed.

The versatility of multi-element arrays in image sensing is unparalleled. Not only may they be used to detect the position of a single light spot, but multiple spots, complex patterns, and shadowed regions on an otherwise illuminated background. This may in many cases justify their cost, which may be three of four times that of comparably sized lateral effect photodiodes. The peripheral electronics/systems required to operate self-scanned arrays may easily cost that amount more than the amount more than the analog summing and differencing systems used with quadrant or lateral effect units.

The chief limitation of these units other than price is that the spatial resolution over the array surface is limited by the pixel spacing. Even devices with maximum resolution consist typically of 25.4 micrometer (1 mil) elements or 50.8 micrometer centers. The resolution, as such, cannot be expected to exceed this with a high degree of accuracy.

It might then be argued that the best application of these devices is for character or pattern recognition. A basic system would be comprised of a stable illuminating source for optically contrasting the object on the array, and a basic camera consisting of the array and appropriate lens to focus the image. The associated circuitry, composed of the array drive clock, output circuits, and controller module to process the digital signals, may in turn feed a computer, video display, or other control electronics . A similar approach might well be used to recognize alphanumeric characters, to detect multiple defects, holes, or contaminants on surfaces or opaque materials, or to directly characterize the output pattern of a light source.

SUMMARY

Optical position sensing techniques offer unique solutions in non-contact measurement applications. Silicon photodetectors prove especially useful for such measurements since they may be used with a wide variety of common light sources, and exhibit fast response, low noise, and high light level sensitivity. Many types of silicon detectors are available, each offering specific advantages which lend themselves to certain measurements.

Single element devices are especially sensitive to small fluctuations in light level which renders them useful for monitoring height, width, diameter, or alignment. They are simple to operate and hook up, and are the least expensive of the devices mentioned. Quadrant and bi-cell detectors are exceptional for nulling or centering an incident light spot with maximum sensitivity; while laterial effect diodes provide the best spacial resolution over a wide range, since they are composed of a single active element, and are indifferent to light spot shape or intensity distribution. The required electronics for operating quadrant or lateral effect units are readily available and relatively inexpensive. Multi-element arrays, though often expensive, prove most flexible of the devices discussed, as complete images or multiple spots and shadows may be characterized. They may also be configured in an unlimited number of geometries to be optimized for the particular application.

An awareness of the theory and advantages of each photodetector type and measurement technique, may assist the potential user in selecting the most appropriate, cost effective device or system for his requirements.