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Image Sensor Terminology

INTRODUCTION

This technical note has been written to clarify some of the terminology used to describe the operation and performance of solid state image sensors. It is intended for use by anyone considering using these sensors in a systems design, and particularly for first time users. This note provides only brief explanations of the common terms encountered in image sensor specifications. A listing of suggested readings on solid state image sensors and applications is located at the end of this document.

CONTENTS

Accumulation Mode

CCD Clock

Charge Coupled Devices (CCDs) use input timing signals to setup the electrostatic potentials necessary to transport charge. A two phase CCD will require two input signals, a three phase will require three signals, and a four phase CCD will require four input signals. The amplitude of the CCD input signals, combined with the built in channel potential of each phase, will determine the magnitude of the electrostatic potential under each phase, and the phase relationships between the input clocks will permit the transportation of charge.

For a two phase CCD, two input timing signals are required for operation. For charge to move from phase 1 (Φ1) to phase 2 (Φ2), it is necessary that the phase 1 signal turn ”OFF” (external bias = 0.0 V) and phase 2 signal turn charge packet integrity. Charge coupled devices are ideally suited for use in solid state imagers as a means of transferring integrated photogenerated charge. The CCD may be used to collect the photogenerated charge, or it may be placed adjacent to a array of photodiodes or photocapacitors. A CCD used to directly collect photogenerated charge will have reduced photoresponse at shorter optical wavelengths due to the presence of polysilicon electrodes. Several of the more common CCD structures are described in more detail in other sections of this reference document.

Charge Transfer Efficiency

Charge Transfer Efficiency (CTE) is the fraction of charge which is successfully transferred during one CCD transfer cycle (note that a phase CCD will have two transfer cycles per CCD stage). CTE is equal to one minus the Charge Transfer Inefficiency (CTI), or:

$$\mathrm{CTE} = 1 - \mathrm{CTI} \qquad \text{(eq. 2)}$$

Some manufacturers define CTE as the charge transferred per CCD stage, so care should be taken when comparing different manufacturer’s specifications for CTI and CTE to ensure that both use the same definition. The total charge remaining in a CCD stage after being clocked through the entire CCD is termed the CTE per line for linear imagers or CTE per frame for area array image sensors, and is equal to:

$$\mathrm{CTE_{Line}} = (\mathrm{CTE})^{\mathrm{CCD\_Transfers}} \qquad \text{(eq. 3)}$$

(for Linear Image Sensors)

$$\mathrm{CTE_{Frame}} = (\mathrm{CTE_X})^{\mathrm{X\_CCD\_Transfers}} \times (\mathrm{CTE_Y})^{\mathrm{Y\_CCD\_Transfers}} \qquad \text{(eq. 4)}$$

(for Area Array Image Sensors)

Charge Transfer Inefficiency

Charge Transfer Inefficiency (CTI) is the fraction of charge left behind during a CCD transfer.

Care should be taken when comparing different manufacturer’s specifications for CTI or CTE to ensure that both use the same definition.

Charge Transfer Inefficiency is measured by injecting a sequence of charge packets of known size into a CCD and then monitoring the resultant imager output waveform. Note that a two phase CCD will have two transfers per CCD stage. The injected signal amplitude and the signal lost from the injected signal are then used to calculate CTI as follows:

$$\mathrm{CTI} = \frac{\mathrm{N_{lost}}}{\mathrm{N_{infected}} \times \mathrm{CCD\_Transfers}} = \frac{\mathrm{V_{lost}}}{\mathrm{V_{infected}} \times \mathrm{CCD\_Transfers}} \qquad \text{(eq. 5)}$$

Color Filter Array (CFA)

For color imaging applications, it is necessary to separate the optical spectrum of the incident image into three color bands. In most applications, it is desirable to perform the color separation on the imager. Color separation is typically accomplished by depositing organic dyes on the imager surface. The color dyes, or color filters, can be configured to work in an additive (RGB) or subtractive (YMC) process. That is, the deposited layers may act as transmission filters or as absorbing filters. The deposition of three color filters yields three bandpass filters, which can be designed to occur in any pattern across an imager.

On tricolor linear imagers, a blue bandpass filter is deposited on one whole channel, a green bandpass filter is deposited one another channel, and a red bandpass filter is deposited on the remaining channel. Thus, a single pass scan of an object obtains all color information. Color filter patterns on area arrays can also occur in varying arrangements.

Correlated Double Sampling (CDS)

A schematic diagram of a typical image sensor output stage o phase

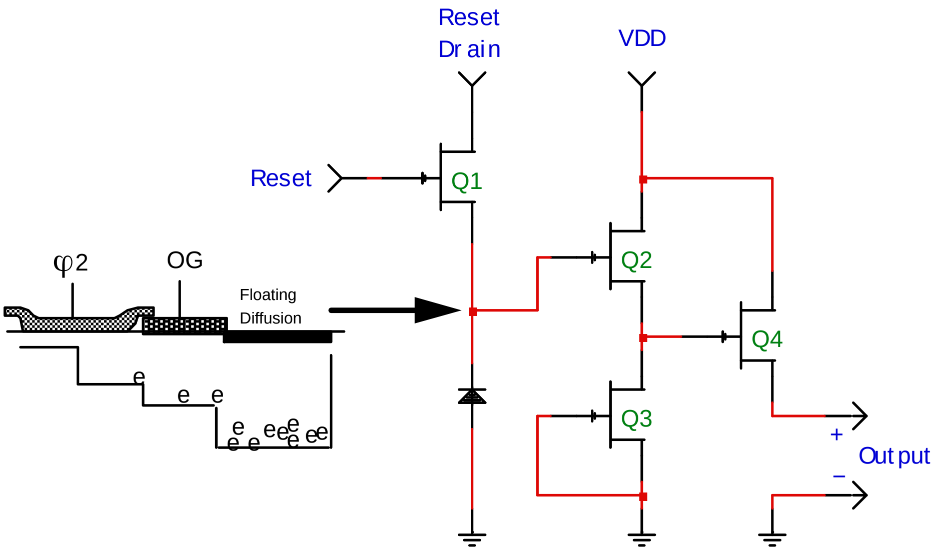


Figure 8. Output Circuitry

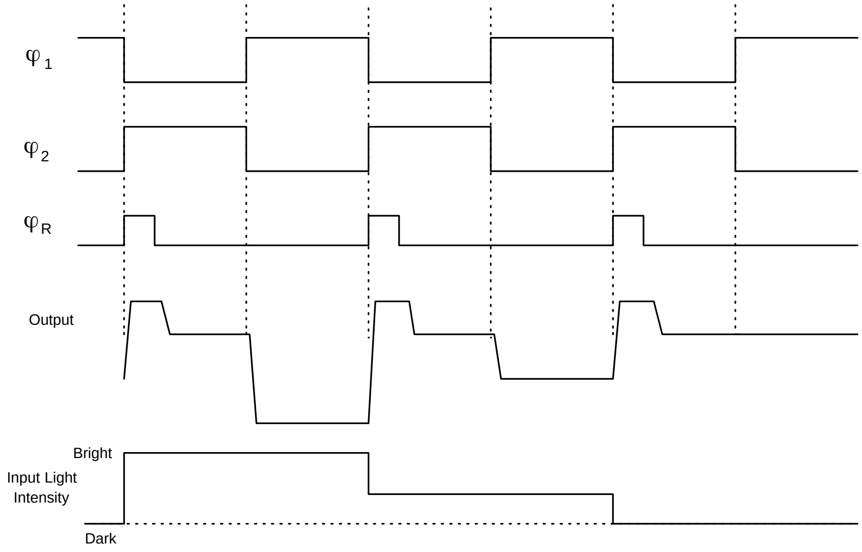


Figure 9. Signal Timing

Typical saturation voltages are in the range of 1 to 3 volts. This makes the lowest level of the output signal about 4 volts (7 − 3). Most analog−to−digital converters will not accept inputs signals in this range, so some signal processing must be performed on the output signal.

The goals of processing the output signal are to (1) remove the reset level noise, and (2) translate the output signal to a level acceptable by analog to digital converters. Goal number 1 is met by performing a differential measurement on each photosite (also known as Correlated Double Sampling, or CDS), and goal number 2 is achieved by converting the output signal to a ground referenced, positive going signal.

The timing required to perform the CDS signal processing is shown below. There are several common circuits used to perform the CDS function; however, all make a differential measurement.

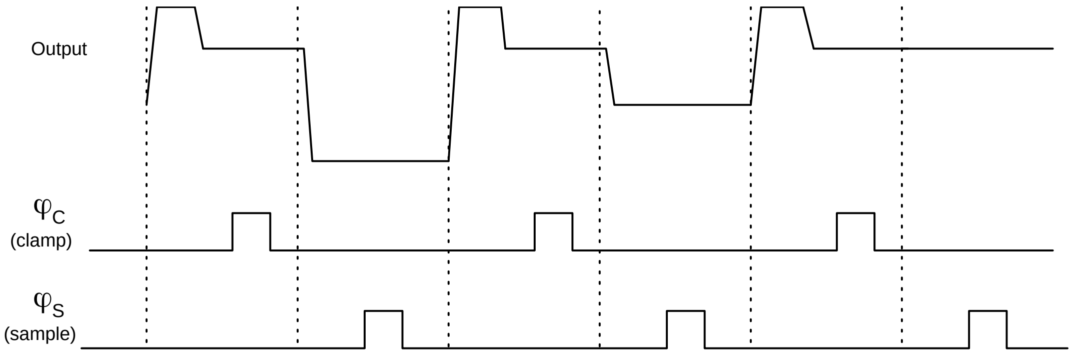


Figure 10. CDS Timing Signals

One method is to AC couple the output signal and then clamp it to ground during the flat reset portion of the signal. Variations in the output which occur after the clamp is complete will be with respect to ground. Then the ground referenced signal is passed through an inverting amplifier, resulting in a positive going ground referenced signal. Only one additional sample pulse is required to complete the processing by sampling the signal during the active portion of the signal (i.e. during the time when the phase 2 CCD input is “OFF”).

The clamped and sampled signal is then ready for direct input into an analog−to−digital converter.

Another method uses two sample pulses to charge one capacitor to the reset level and another to the active portion of the output. The two signals are then fed into an inverting differential amplifier where a difference measurement is performed and the signal is converted to a positive going, ground referenced signal.

Dark Current

Dark signal is a termed used to refer to the background signal present in the image sensor readout when no light is incident upon the image sensor. This background signal is a result of thermally emitted charge being collected in the photosites transfer gates, and CCDs. The magnitude of the dark signal is dependent on the image sensor architecture, mode of operation (see “Accumulation Mode”), and on the image sensor operating temperature. Due to the present of localized defects in the silicon substrate, the dark signal collected in each pixel will vary from pixel to pixel. This variation in dark signal is called the dark signal noise. The average current associated with the readout of a complete dark image is referred to as the dark current. The dark current will double for approximately every 9°C increase in image sensor temperature.

Dark Reference Pixels

Dark reference pixels are groups of photo−sensitive pixels covered by a metal light shield. These pixels are used as a black level reference for the image sensor output. Since the incident light is blocked from entering these pixels, the signal contained in these pixels is due only to dark current. It is assumed that each photo−sensitive pixel (active and dark reference) will have approximately the same dark signal; thus, subtracting the average dark reference signal from each active pixel signal will remove the background dark signal level. Dark reference pixels are typically located at one or both ends of the arrays, as shown below for a linear image sensor.

Figure 11. Single Channel of Linear Image Sensor

Defective Pixel

A defective pixel is one whose response to illumination variations differs significantly from the mean response of all other pixels. The maximum deviation from the mean response permitted is imager as well as application dependent. The number and type of defects acceptable is also application dependent, and can range from zero to as many as 1000 defects in some cases. It is sometimes possible to remove the effect of the defective pixel by applying one of several signal processing defect correction algorithms. One of the simplest such algorithms is to replace the defective pixel with the average response of the two nearest neighboring pixels, i.e.

$$P_d = \frac{1}{2}\left(P_{d-1} + P_{d+1}\right)$$

Dynamic Range

Dynamic P

Fill Factor

The fill factor is the ratio of the light sensitive area to the total photosite area. Fill factor on some types of area arrays can be improved using lenlets (see “Lenticular Array (Microlenses/Lenslets)”).

Fixed Pattern Noise

If the output of an image sensor under no illumination is viewed at high gain a distinct non−uniform pattern, or fixed pattern noise, can be

Interline Image Sensor

An interline image sensor has a light shielded CCD adjacent to each photosite array. An area array interline image sensor and a linear interline image sensor are depicted below. Note that only the photosite arrays are not covered by the aluminum light shield, so while one image is being integrated the previous image can be safely transferred out of the image sensor. Interline imager sensors, unlike full−frame devices, do not require an external shutter.

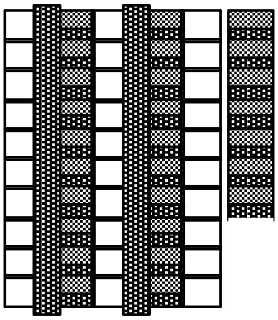


Figure 21. Interline Area Array Image Sensor

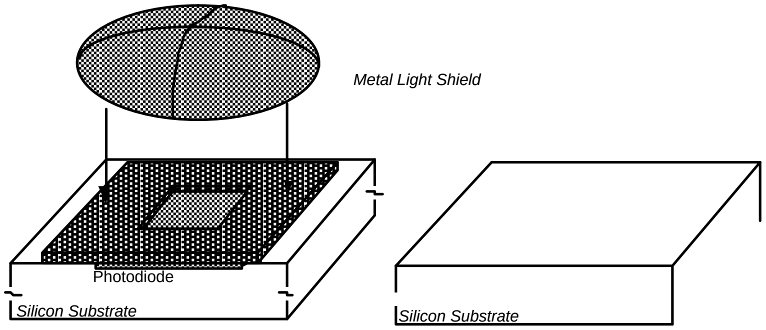
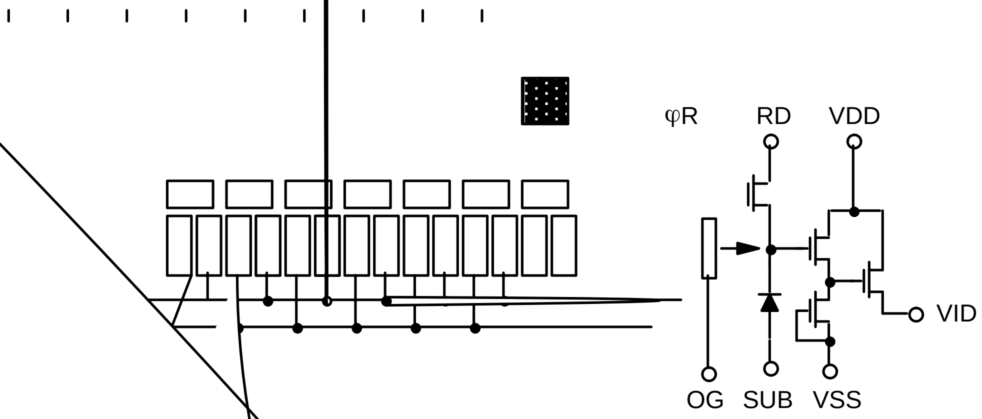


Figure 23. Lenslets are Fabricated over Photodiodes



ngle Channel of a Typical Linear Image Sensor

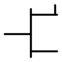


Figure 26. Typical Solid State Imager Output Amplifier

"Pinned" photodiodes, or buried photodiodes, have extremely small lag (< 0.5%), and can be considered to be lag free. The CCD charge transfer inefficiency (CTI) will reduce the amplitude of the charge packet as it is transported towards the output amplifier, with the greatest effect realized at very small signal levels. Modern CCD's have CTE in excess of 0.999999 per CCD transfer; thus, the overall effect on linearity is generally not a concern. If biased properly, the output amplifier will yield a nonlinearity of typically less than 2%.

Non linearity at signal levels beyond the saturation level is expected and can often vary significantly from pixel to pixel.

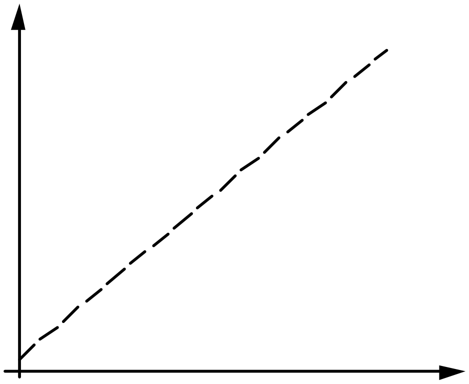


Figure 28. Definition of Non Linearity

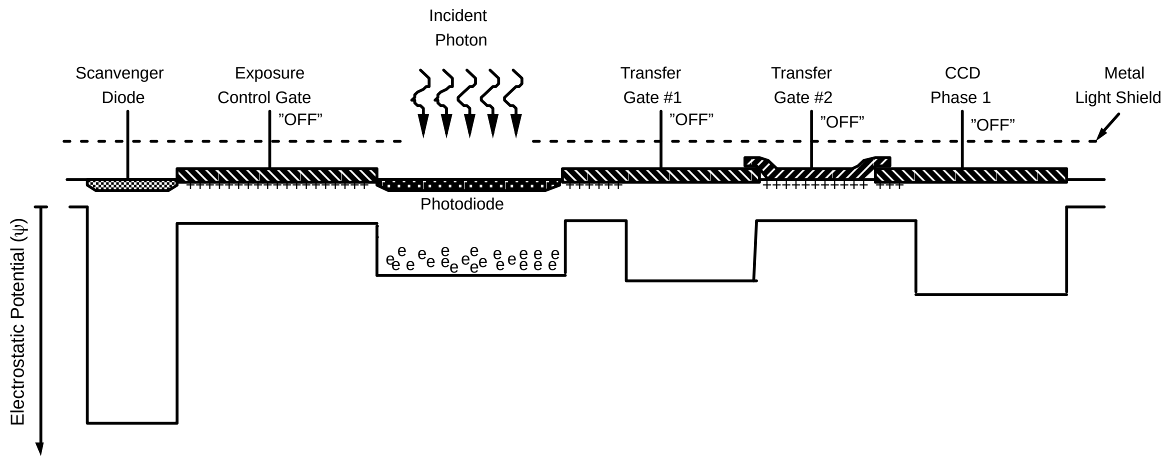


Figure 29. (1) Lag Integrating Bright Line

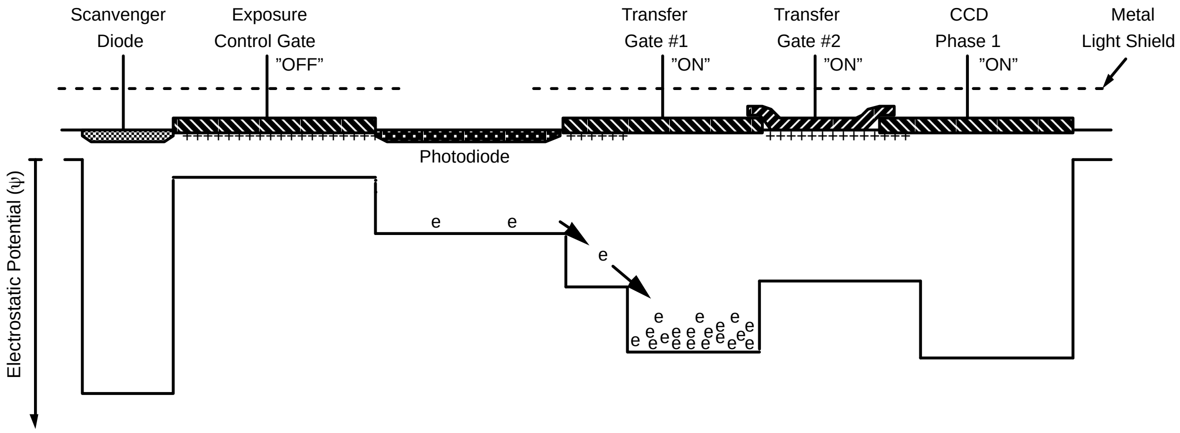


Figure 30. (2) Lag Light Removed, Transfer Begins

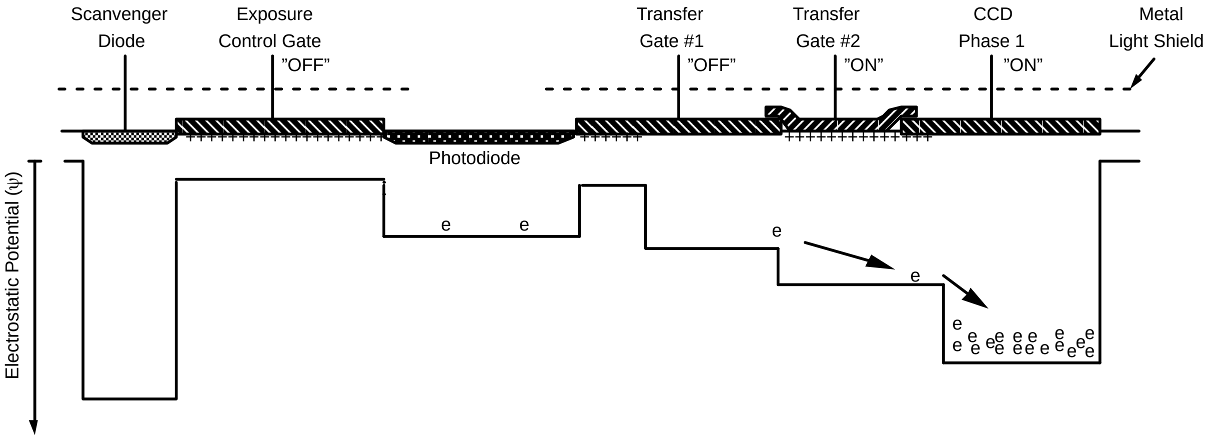


Figure 31. (3) Lag Transfer Continues

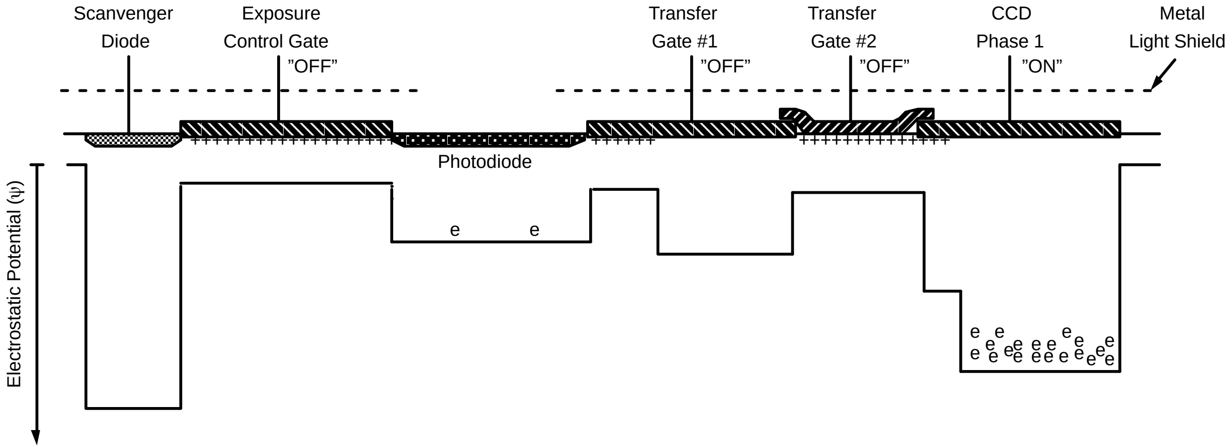


Figure 32. (4) Lag Transfer Complete

Photoresponse Nonuniformity

The peak−to−peak variation in output signal under uniform illumination of the image sensor is called the Photoresponse Nonuniformity (PRNU). PRNU is very small for monochrome imagers (i.e. imagers with no color filters), since the only varying factors are the photosite quantum efficiency, the dark current, and the effective active area. These factors typically are very uniform across an imager. Color imagers have higher PRNU due to slight variations in the external color filters. Variations in color filter thickness will cause some photosites to have higher or

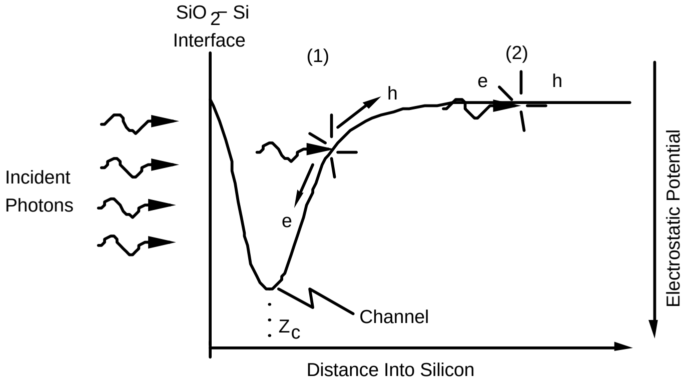


Figure 34. Space Charge Regions 1 and 2

It is known that photons of longer wavelength, such as from red light, have a mean absorption depth greater than photons of shorter wavelength, such as from blue light. This phenomena means that red light will produce higher pixel−to−pixel crosstalk than green light, and green light will produce higher crosstalk than blue light. The percent of photons absorbed within the silicon substrate is shown below as a function of wavelength and absorption depth. A typical photosensitive pixel space−charge region depth is also indicated on Figure 35. As an example, it can be seen that 90% of all 520 nm photons will be absorbed within the space−charge region, but only 42% of all 670 nm photons will be absorbed.

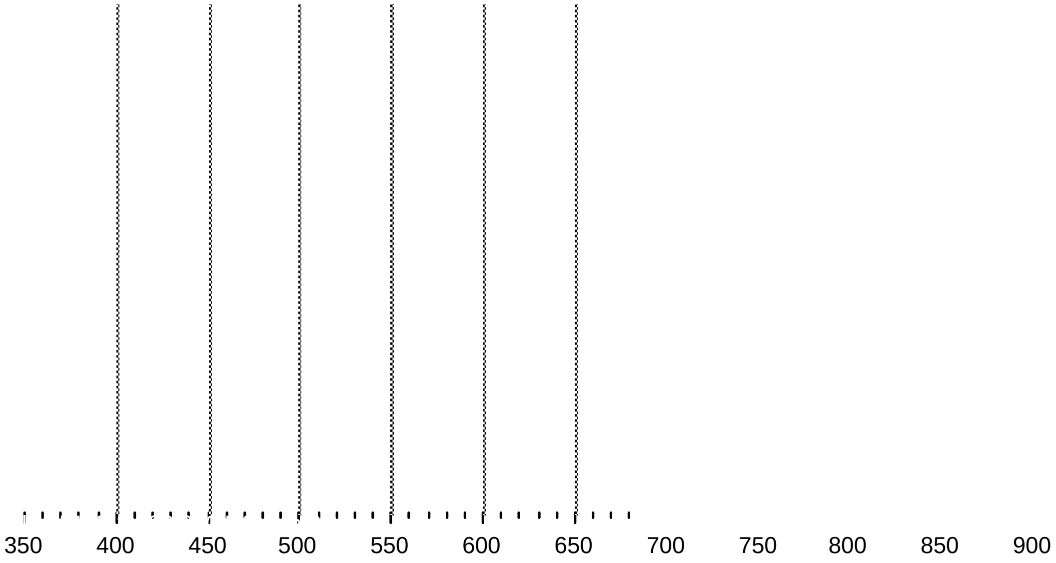


Figure 35. Percent of Photons Absorbed in Silicon versus Wavelength and Depth

Figure 36. Potential Wells in True Two Phase CC D

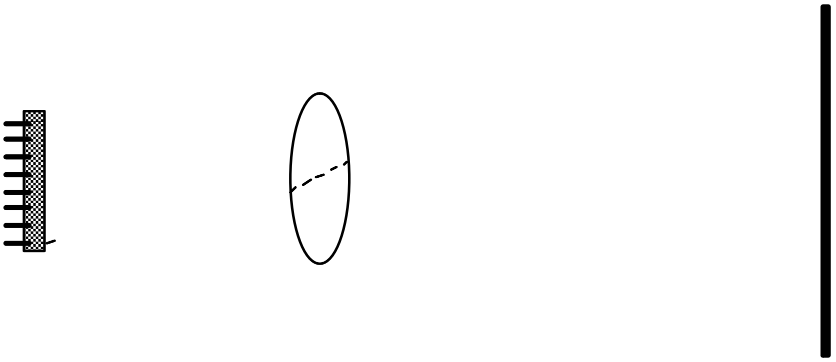


Figure 39. Linear Imager in a Simple Imager System

Transfer Gate Clock

The transfer gate clocks are used to isolate the photogenerated charge collected in the photosite from the adjacent CCD structure. At the appropriate time, the CCD clocking is stopped and the transfer gate biases are applied, causing the photosite charge to transfer to the adjacent CCD cell.

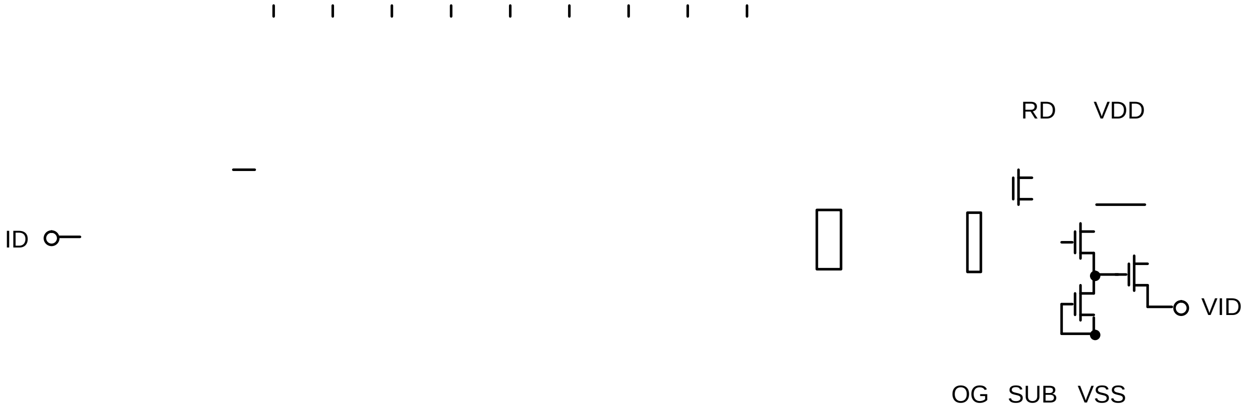


Figure 43. Single Channel of Linear CCD Imager

True Two Phase CCD

Vertical Overflow Drain (VOD)

See “Lateral Overflow Drain (LOD)”.

Wafer Thinning

A process in which the silicon substrate thickness is significantly reduced to enhance the quantum efficiency (sensitivity) to visible and near infrared radiation. After thinning, the backside of the substrate is passivated. In a typical application, the backside of the thinned substrate imager is positioned in the image focal plane so that the image sensor is illuminated through the thinned substrate from the backside of the device.

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1. Beynon, et al, “Charge−Coupled Devices and their Applications”, McGraw−Hill, Berkshire, England, 1980, ISBN 0−07−084522−0.
2. Howes, et al, “Charge−