Charge Coupled Devices

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***Abstract*—An analysis of charge transfer based on the charge control approach has been made for charge coupled devices(CCD's). A general closed form equation for the charge transfer efficiency has been obtained that includes the major mechanisms of an external fringing field, and charge loss due to traps or recombination thermal diffusion. There are many applications for CCD like Astronomy, Color cameras, Sensor sizes, Blooming and Electron-multiplying.**

I. Introduction

Charge Coupled Devices (CCDs) were originally developed at Bell Labs as a solid-state memory device. A CCD is essentially a regular array of large numbers of coupled Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs). Sensitivity to light via the photo-electric effect and the ability to store charge in a regular array format was suitable for application as a 2-D detector. It is well known that the operation of a charge coupled device (CCD) depends on the storage and the absence of minority carriers in semiconductor surface depletion regions created by a series of MOS structures, and the controlled transport of these charges along the surface by unidirectional movement of the potential minima. The transient behavior of the charge transfer from one potential well to the next well has been analyzed by many authors [1]-[2]. The applications of the closed-form equation for the charge transfer efficiency are demonstrated in the estimations of the effect of fringing fields, the charges loss to surface states during transfer, the temperature dependence in the shift-register operation.

II. Preliminaries

A. Theories

1) charge-control theory: the starting point is the integration of the continuity equation over the length L of the discharging potential well

$$\frac{dQ_w(t)}{dt} = -\frac{Q_w}{t_o} + j_n(L,t) - j_n(0,t) \tag{1}$$

$$where \tag{2}$$

$$Q_w(t) = \frac{d}{dt}\int_0^L q_n(x,t)d_x \tag{3}$$

Thus, the transient behavior of the total charge in the discharging potential well is determined by the current boundary conditions and the model used to represent trapping or the recombination of charges by surface states during charge transfer to the next potential well. Note, aside from the current boundary conditions at the ends of the discharging potential well, which determines the mode of operation of the device, no restrictions on the specific where the electric field E can be expressed as a combination of the external fringing field and a contribution due to the gradient of the surface potential

$$\psi = \frac{v_0 - v_f b - (q_n + q_b)}{c_o x} \tag{4}$$

for electron redistribution is just the dielectric relaxation time of the inversion layer. According to Hofsteil and Warfield , a typical value for this response time in 10 Q-cm p-type silicon with a heavy inversion layer is s. Thus, it seems to be reasonable to postulate instantaneous charge redistribution. Mathematical, this results in a separation of variables of the form

$$q_n(x,t) = f(t) * \phi \tag{5}$$

This implies that the shape function 4(x¿ of the charge distribution remains unchanged during the transient I i.e., the mobile charge (electrons) always redistribute,. themselves instantaneously to follow the shape of the initial distribution- the magnitude being weighted the function f(t) that satisfies the integral form of the(3 transport equation

$$q_n(L,t)\frac{d}{dt}q_n(x,t) = -\frac{f(t)\phi(0))^2}{2L} \tag{6}$$

$$Q_w(t) = f(t)\int_0^L \phi(x)d_x = f(t)N \tag{7}$$

$$N = \int_0^L \phi(x)dx \tag{8}$$

The existence of charge loss to surface states has been described first by Strain and subsequently by To sett [Is]. The surface states are characterized by their density N,, capture cross section u, distribution in energy E,, and by the mean thermal velocity of surface carriers Y . Electronic transitions or the filling and emptying of states occur between the states and the semiconductor bands at the surface. Thus, from the rigorous standpoint, we should solve the non equilibrium rate equations for electron trapping in the surface states 1131-[IS], in addition to the continuity equation in the charge-control form. However, in order to obtain a tractable solution we carry out our analysis based on a hypothetical single-level interface state. Such an approach is still preliminary in nature but the details of surface-state effects can be considered more readily. The coupled differential equations, for a single-level interface state are

$$\frac{dQ_w(t)}{dt} = -\frac{dQ(t)}{dt} + j_n(L,t) \tag{9}$$

$$\frac{dQ(t)}{dt} = \frac{Q_w(t)}{t_c} - \frac{Q(t)}{t_o} \tag{10}$$

$$t_c = \frac{1}{(\frac{\sigma v}{x_i})[N - \frac{Q(t)}{qL}])} \tag{11}$$

$$t_c = \frac{1}{\sigma V N_c c} * exp[\frac{E_n}{KT}] \quad (12)$$

implies that the net rate of change of trapped carriers QP(t) is equal to the difference between a the rate at which mobile electrons are captured by surface state traps and the rate at which the trapped electrons leave the surface states indicates [Y] 1 that T , the life time of a mobile carrier, is inversely proportional to the density of empty traps N,-Qg,(t)/qL. The quantities N, and Q8(t) are the total density of surface states per unit area and the total charge trapped in the surface states per unit device. width in the discharging potential well, respectively. The emission rate (the probability per unit time that an occupied surface state will lose its electrons to conduction band) the surface states with respect to the conduction band. The effective density of states in the conduction band is N, and xi is the depth of the inversion layer. A transient solution of the coupled nonlinear differential equations (38) and (39) has been solved used in the plot. The parameter shown is the energy depth of the single trap levels normalized to kT. The: figure indicates that as the trap level becomes deeper, the capture process dominates over the emission process during the charge transfer. Within the validity limit 0.i the hypothetical single-level interface state analysis, there seems to exist a critical range of E,/kT =8 ir. which surface traps degrade signal transfer.I For E,/kT¡ 8 charge is released sufficiently rapidly thal: surface states are of no consequence. For E,/kT ¿ 8 the traps cannot empty sufficiently rapidly; thus using far zeros, the traps remain nearly full and are again of ncl consequence. A simplified approach may be taken if a closed-forrr solution is desired. If charge loss to surface states exists, during charge transfer from one well to the next wel: through the interelectrode region, due to trapping and some possible recombination by the subsequent capture of majority carriers (a rate equation [I91 describing the transition between the surface states and the valence band is required in addition to the previously discussed coupled nonlinear differential equations), we may lump all the complicated mechanisms into a constant effective charge loss parameter T and replace the right-hand

2) TEMPERATURE DEPENDENCE : One of the important questions concerning charge transfer devices is the effect of temperature on their transfer efficiency. If charge loss to surface states is neglected, the only temperature sensitive parameter is the surface mobility. In the temperature range of interest, 0-100°C, it is known that the surface mobility follows the 1/T dependence [7], where the temperature T is in degrees Kelvin. Using (32), in the absence of charge loss to surface states, the explicit expression for the fraction of the charge remaining in the discharging potential well in terms of the temperature is

$$f(t, t_c - \infty) = \frac{(\frac{KT}{q} * exp[-(\frac{\pi^2 * KT}{4L^2 q})\mu t]}{\frac{KT}{q} + (\frac{q_a v}{c_e ff})(1 - exp[-(\frac{\pi^2 KT}{4L^2 q})\mu t]} \quad (13)$$

3) ZERO OPERATION : The effect the digital zero charge level has on CCD operation is discussed in this section. For simplicity, we analyze the case when a digital one follows a digital zero in a shift register and the one is transferred from the with potential well to the (wf1)the potential well. Only one transfer will be considered here. However, our results can be readily extended to the analysis and simulation of the signal transfer characteristics of CCD shift registers. The quantities Qw(0) ;and Qw(T) are used to represent the charge, in the with well, that is associated with a digital bit at the beginning and at the end of transfer, respectively, where T is the transfer pulse width.

B. Facts

based on a metal-oxide-semiconductor (MOS) structure. Fig. 4.5.4A shows an example of CCD structure with a p-type semiconductor body, a thin silicon dioxide insulating layer and an array of gating electrodes. A positive bias voltage applied on a gate electrode repels holes away from the area underneath the electrode, creating a depletion region. Incoming photons are able to generate photoelectrons in the depletion region as illustrated in Fig. 4.5.4B. These photon-induced charges are then shifted programmably in the horizontal direction to one side of the array so that they can be electrically amplified and collected. Charge shifting can be accomplished by progressively shifting gate voltage along the array as shown in Fig. 4.5.4C–F. The gating electrodes of CCD made for imaging are usually arranged in a two-dimensional (2D) array as illustrated. As the imaging sensor, CCD is usually mounted on the focal plane of a camera. After each exposure, a charge distribution pattern is created on the 2D plane of the CCD, which is proportional to the intensity distribution of the image. The readout circuits of CCD performs a parallel to series conversion. The row-shifter circuit shifts the charges recorded by each row downward in the vertical direction into horizontal registers. Corresponding to each step of row shift, the pixel shifter circuit moves the charge stored in the horizontal registers pixel-by-pixel in the horizontal direction into a preamplifier. This process effectively translates the 2D image array into a waveform in the time domain, which can then be digitized, processed, and recorded.

III. Topics

1) Full-frame CCD (FF), this camera has a mechanical shutter: CCD full image This represents the easiest solution to the issue of charge transfer, which is a method that prevents new light from entering the sensor during the process of reading the pulses, and it uses a mechanical shutter that prevents a new image from being taken during transfer. This mechanical shutter we know from the usual cameras as well. Because the CCD sensor with a mechanical shutter takes advantage of the entire area of the chip to record all the image data, that sensor is called a ”Full Frame Transfer CCD”. Sensors that work in this way are used in astronomical observations and in scientific experiments, but the mechanical closure method is sometimes subjected to disruption. The term full-image CCD is applied not only to the internal structure of the CCD sensor, but also to a CCD with an area of 36 mm x 24 mm, which is the same area as the film images of ordinary cameras. But we mean in this article the internal structure of the sensor and the method of reading the image pulses.

2) CCD Frame-Transfer (FT): CCD vector image
The stored charges of the image are transmitted in the Frame-Transfer-CCD (FT-CCD) Immediately after the image is taken, it moves to a dark area of the CCD chip. After that, the recorded image is read line by line. That the time of transferring or shifting the image is much shorter than the time of capturing the image so as not to confuse the first image pulses with the next image. That is why CCD sensors that transmit images that do not use a mechanical shutter are not suitable for shooting with a short image capture time. Video cameras are usually built for professionals and have a rotating shutter that closes periodically. In view of the need for additional space and space in the camera for the dark place of the sensor, the FT-CCD sensor contains cells (voltage wells) equivalent to twice the number of image points and therefore it is also twice the size of the image area.

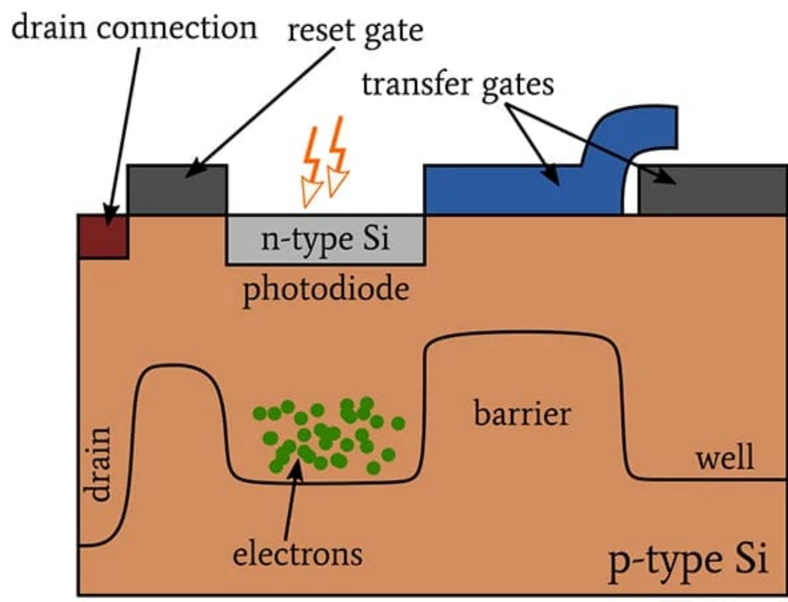
3) CCD Interline-Transfer (IT): In an IT-CCD type, each pixel is shifted sideways to a covered (dark) side storage cell, and this process is done for all pixels at the same time. The charges first move to the dark rows (the so-called ”transport array”) and from there to the amplifier and reader. If a mechanical shutter is used, the image capture time can be set electronically during the offloading of pixels after an image is taken to the transmission array. Thus, it becomes possible to photograph during very short times to take pictures. It takes longer to read the pulses in IT-CCDs compared to CCDs, as the charges stay longer in the storage cells next to the photosensitive pixels. Although the storage cells are covered, but they are also still sensitive to light. By scattering light , photons can reach the storage cells and excite jittery charges. . From it arises ”dots will come” and weaken the contrast of the image.

IV. Structure

The basic device consists of a closely spaced array of metal-oxide-semiconductor (MOS) diodes on a continuous insulator layer (oxide) that covers the semiconductor substrate

A. MOS diode: (known as a pixel)

It is the basic term which consisting of : slice of p-type silicon with thin layer of n-type on one surface (photo diode) The last layer is coated with an insulating layer of silicon dioxide on top of which is deposited an array of metal gates.



B. Metal gates

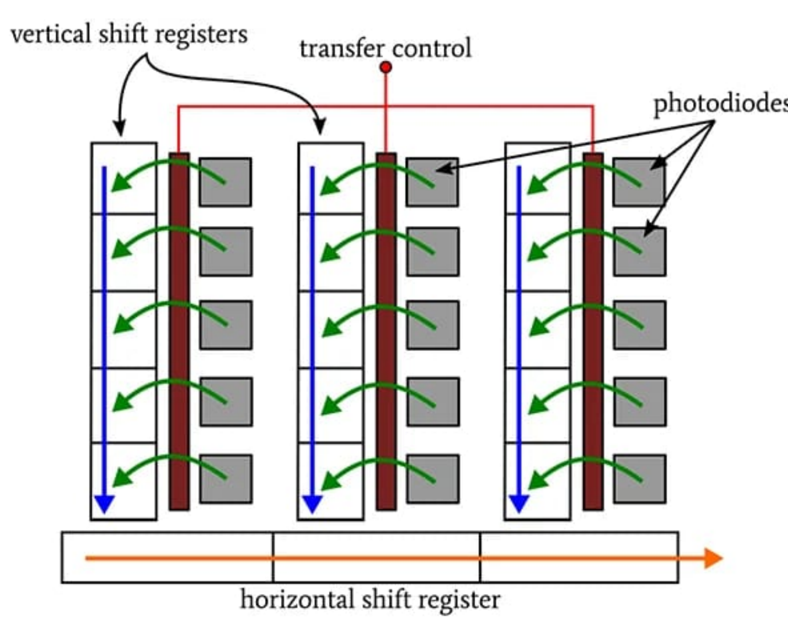
each consisting of a number (usually three) electrodes Transfer gate Reset gate Drain connection

C. A potential well

is a physical area created by applying a positive voltage. The term “well” is used because this positive voltage attracts electrons and repels holes, thereby creating a region into which the light-generated electrons will flow

D. shift register

charge is transferred into vertical shift registers then down to the horizontal shift register



V. Operation

The CCD operates by a mechanism of charge storage and transfer under an array of MOS control electrodes or gates. Information in the form of electric charge is transferred along the silicon surface in clocked shift register fashion by sequential manipulation of the voltages on the control electrodes that constrain this charge. There are basically two types of CCD, surface channel and buried channel. In the surface channel devices, the charge is stored and transferred at the silicon surface whereas in buried channel devices the doping of the silicon substrate is modified such that the storage and transfer of charge takes place in the bulk silicon just beneath the silicon surfaces There are also several different types of electrode structure and clocking techniques commonly used to realise a practical charge-coupled device. Initially, however, the basic operation of the CCD is described for surface channel operation with three-phase electrodes. Buried channel operation and alternative electrode structures and clocking techniques are described later

1) charge storage: 2. The structure of a basic MOS CCD element (surface channel) is shown in figure.1 illustrates the way the element stores charge. The silicon substrate is shown in the figures as being p-type, but obviously n-type devices are also possible. Application of a positive voltage +VG to the electrode has the effect of repelling the positively charged majority carriers in the silicon (holes in our case) away from the vicinity of the electrode. This region beneath the electrode that becomes depleted of holes is called a depletion region. For a given electrode structure and substrate doping concentration, the extent of the depletion region into the silicon is a function of the applied electrode voltage. information is stored in the depletion region in the form of minority carriers

The stored electrons are localized at theS_i/Sio_2 interface because they are attracted to the positive charge on the control electrode. The magnitude of the charge which may be stored under a given electrode is variable up to a maximum value that is dependent upon the electrode size and bias voltage. As the amount of charge stored is increased, the extent of the depletion region decreases in order to preserve overall charge neutrality in the system. The CCD is inherently a dynamic memory since the stored information disappears with increasing time. The mechanism for this is the thermal generation of electron-hole pairs which takes place in any semiconductor (commonly called dark current). This causes the depletion regions to be slowly filled with minority carriers which gradually mask the stored information.

An alternative model, which is sometimes more useful in describing the operation of a CCD, is to consider that the electrons are filling a potential well formed by the potential minimum in the silicon which constrains the electrons to remain under the electrode. This is evident from the energy-band which represent the two conditions. The potential minimum at the silicon interface is generally referred to as the surface potential. The surface Potential for an empty well (the depth of the potential well) is easily derived from well-known MOS equations

$$v_G - V_F B = \phi_s o + \beta \phi_s o$$

$$
\begin{aligned}
&where\\
&\beta = \sqrt{2\epsilon\epsilon_0 q N / C_O}\\
&v_b : flat - band\\
&N : substratedoping\\
&q : electroniccharge\\
&c_o x : oxidecapacitorperunitarea
\end{aligned}
$$

2) CHARGE transfer: Many schemes are used to encourage the charge packets to move cell to cell in bucket-brigade style. The goal is to protect the integrity of each charge packet and to move them on down the line. We do not want to leave any charge behind, and we do not want to contaminate any packet with charges from other packets or any external source. The various techniques are named two-phase, three-phase, four phase, and so on. These names bare a correspondence to the type of clock used for the marching orders. Generally, a cell in the n-phase scheme will have n control wires passing through it. These wires, each connected to one phase of the transfer clock, are used to control the height of the various potential wells. The changing well height is what pushes and pulls the charge packets along the line of CCD s. Of the various charge transfer techniques, I will only describe the three-phase process that is similar to the scheme proposed at Bell Labs by Boyle and Smith in 1969. I show two pixels of a linear CCD. The three clocks(c_1, c_2, c_3) have identical shapes, but differ in phase. Note: A high clock signal represents a large electric field, thus a deep potential well. With three-phase charge transfer, we think of the three gates in each pixel, as one storage gate $(G_2)$and two barrier gates G_1, G_2. All the$G_1'S$ $(G_2'S, G_3'S)$ are connected together as phase 1 (2 , 3) or(P_1, P_2, P_3)Charges move from space A to space B when gate B goes high and gate A ramps low.

Fig. 1: charge storage

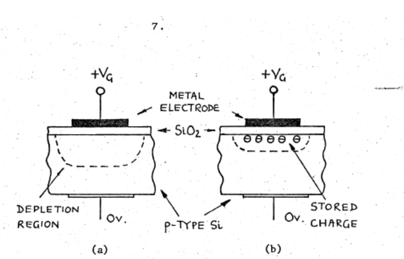


Fig. 2: energy band diagram

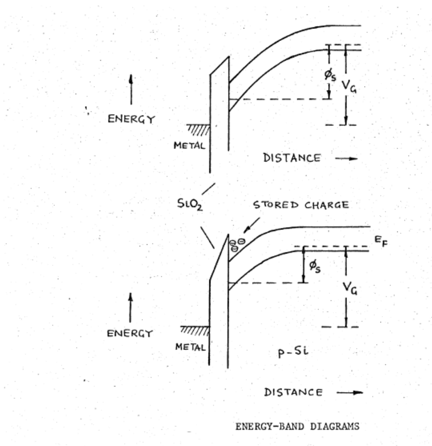
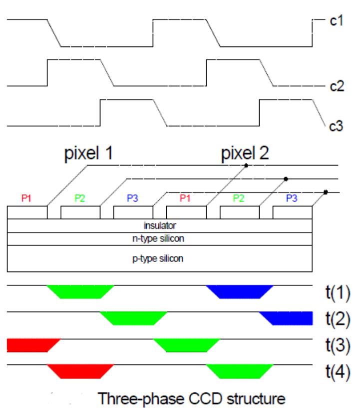


Fig. 3: three phase CCD



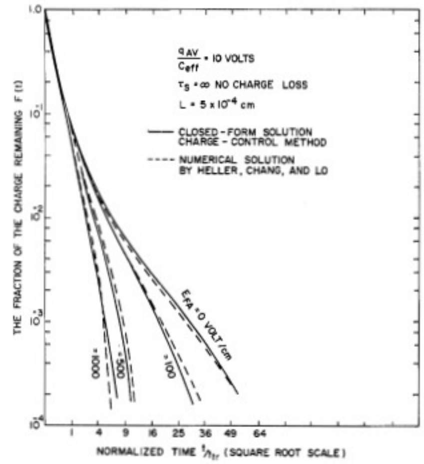
VI. Characteristics

A. Theorem 1:EFFECTS OF THE FRINGING FIELD.

The fringing field effect [3] have formulated the surface fringing field distribution within the potential well and carrier transit time corresponding to the average fringing field in the discharging potential well. The average fringing field can be calculated using this equation.

$$E_f = -13\frac{X_o x V}{L^2}\left[\frac{\frac{5Xd}{L}}{1+\frac{5Xd}{L}}\right]^4 \tag{14}$$

Where x-ox is oxide thickness, L is Electrode center to center spacing, x-d is Depletion depth at the electrode and V is0.5 the total pulse voltage. The fringing field enhanced diffusion constant D-f



B. theorem 2:THE EFFECT OF CHARGE LOSS TO SURFACE STATES

The surface states are characterized by their densityN_s, capture cross section σ , distribution in energy E_s, and by the mean thermal velocity of surface carriers. Electronic transitions and emptying of states occur between the states and the semiconductor bands at the surface. We should solve the non equilibrium rate equations for electron trapping in the surface states, in addition to the continuity equation in the charge control form. However, in order to obtain a tractable solution we carry out our analysis based on a hypothetical single-level interface state. Such an approach is still preliminary in nature but the details of surface-state effects can be considered more readily. The coupled differential equations, for a single-level interface state are

$$\frac{dQs_(t)}{dt} = -\frac{dQs_(t)}{dt} + J_n(L,t) \tag{15}$$

$$\frac{dQs_(t)}{dt} = -\frac{Qw_(t)}{t_c} + \frac{Qs_(t)}{t_e} \tag{16}$$

where

$$t_c = \frac{1}{\frac{\sigma V}{XI}[Ns - \frac{Qs_(t)}{qL}]} t_e = \frac{1}{\sigma V N_C} * exp^{\frac{E_s}{KT}}$$

C. Theorem 3:temperature dependent

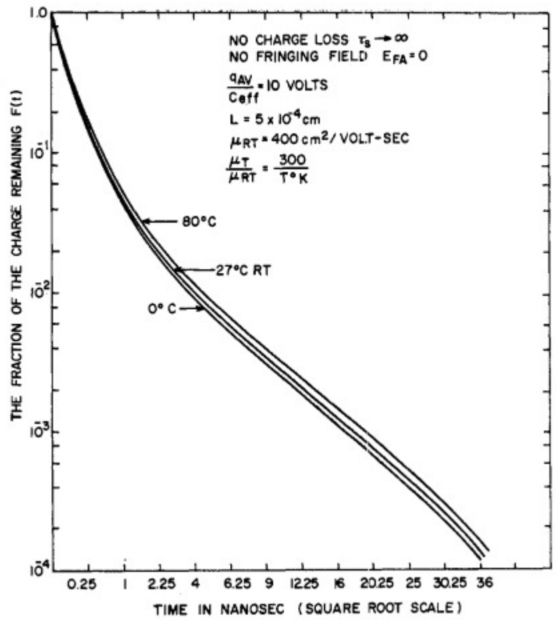
One of the important questions concerning charge transfer devices is the effect of temperature on their transfer efficiency. If charge loss to surface states is neglected, the only temperature sensitive parameter is the surface mobility. In the temperature range of interest, 0-100°C, it is known that the surface mobility follows the 1/T dependence , where the temperature T is in degrees Kelvin. In the absence of charge loss to surface states, the explicit expression for the fraction of the charge remaining in the discharging potential well in terms of the temperature is

$$F(t, T_e - \infty) = \frac{\frac{KT}{q} * exp^[- (\frac{\pi^2 KT}{4L^2 q})\mu_n t]}{\frac{KT}{q} + (\frac{qaV}{2C_e ff})(1 - exp^[- (\frac{\pi^2 KT}{4L^2 q})\mu_n t])} \tag{17}$$

where

$$\mu_n = \frac{300}{T} \mu RT$$

the surface mobility at room temperature is μRT,Note that the exponential term is no longer dependent on the absolute temperature T ,the transfer efficiency becomes a very weak function of temperature[4]-[5].



D. theorem 4:FAT ZERO OPERATION

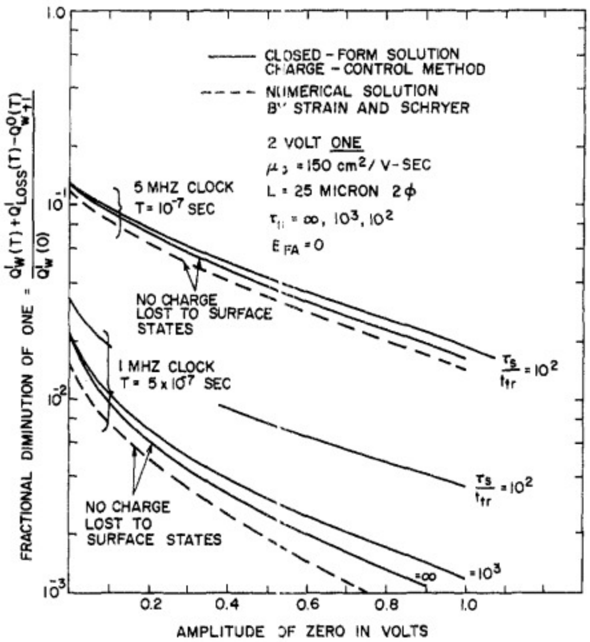
The effect the digital zero charge level has on CCD operation is discussed in this section. We analyze the case when a digital one follows a digital zero in a shift register and the one is transferred from the w the potential well to the (w+1)the potential well. Only one transfer will be considered here. Our results can be readily extended to the analysis and simulation of the signal transfer characteristics of CCD shift registers. The fractional diminution of the one, resulting from the transfer, defined as

$$F_diminution = \frac{Q_W^1(t) + Q_loss(t) - Q_W + T}{Q_W^1(0)} \tag{18}$$

where

$$Q_loss(t) = Q_W(0) F_loss(t - T_s)$$

Q_w represents a digital one or zero,$Q_loss(T)$is the amount of charge lost to surface states during the transfer of the one from the width to the$(w + l)th$ potential well,$Q_w + 10(T)$ is the charge left behind in the$(w+l)th$ well by the zero and the one loses the charge $Q_w^1(T) + Q_loss(T)$and gains the charge left in the (w+l)th well by the zero$Q_w + 10(T)$.



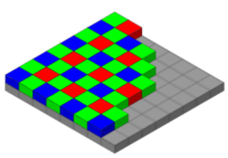
VII. Applications

A. astronomy

Due to the high quantum efficiencies of charge-coupled device (CCD) (the ideal quantum efficiency is 100Thermal noise and cosmic rays may alter the pixels in the CCD array. To counter such effects, astronomers take several exposures with the CCD shutter closed and opened. The average of images taken with the shutter closed is necessary to lower the random noise. Once developed, the dark frame average image is then subtracted from the open-shutter image to remove the dark current and other systematic defects (dead pixels, hot pixels, etc.) in the CCD. Newer Skipper CCDs counter noise by collecting data with the same collected charge multiple times and has applications in precision light Dark Matter searches and neutrino measurements The Hubble Space Telescope, in particular, has a highly developed series of steps ("data reduction pipeline") to convert the raw CCD data to useful images CCD cameras used in astrophotography often require sturdy mounts to cope with vibrations from wind and other sources, along with the tremendous weight of most imaging platforms. To take long exposures of galaxies and nebulae, many astronomers use a technique known as auto-guiding. Most autoguiders use a second CCD chip to monitor deviations during imaging. This chip can rapidly detect errors in tracking and command the mount motors to correct for them. An unusual astronomical application of CCDs, called drift-scanning, uses a CCD to make a fixed telescope behave like a tracking telescope and follow the motion of the sky. The charges in the CCD are transferred and read in a direction parallel to the motion of the sky, and at the same speed. In this way, the telescope can image a larger region of the sky than its normal field of view. The Sloan Digital Sky Survey is the most famous example of this, using the technique to produce a survey of over a quarter of the sky. In addition to imagers, CCDs are also used in an array of analytical instrumentation including spectrometers[30] and interferometers.

B. Color cameras

Digital color cameras generally use a Bayer mask over the CCD. Each square of four pixels has one filtered red, one blue, and two green. The result of this is that luminance information is collected at every pixel, but the color resolution is lower than the luminance resolution. Better color separation can be reached by three-CCD devices (3CCD) and a dichroic beam splitter prism, that splits the image into red, green and blue components. Each of the three CCDs is arranged to respond to a particular color. Many professional video camcorders, and some semi-professional camcorders, use this technique, although developments in competing CMOS technology have made CMOS sensors, both with beam-splitters and bayer filters, increasingly popular in high-end video and digital cinema cameras. Another advantage of 3CCD over a Bayer mask device is higher quantum efficiency (higher light sensitivity), because most of the light from the lens enters one of the silicon sensors, while a Bayer mask absorbs a high proportion (more than 2/3) of the light falling on each pixel location.

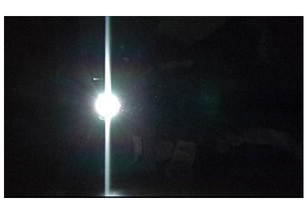


C. Sensor sizes

Sensors (CCD / CMOS) come in various sizes, or image sensor formats. These sizes are often referred to with an inch fraction designation such as 1/1.8 or 2/3 called the optical format. This measurement originates back in the 1950s and the time of Vidicon tubes.

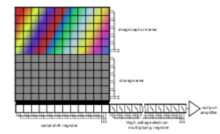
D. Blooming

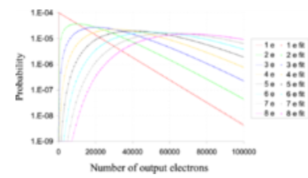
When a CCD exposure is long enough, eventually the electrons that collect in the ”bins” in the brightest part of the image will overflow the bin, resulting in blooming. The structure of the CCD allows the electrons to flow more easily in one direction than another, resulting in vertical streaking



E. Electron-multiplying

Electrons are transferred serially through the gain stages making up the multiplication register of an EMCCD. The high voltages used in these serial transfers induce the creation of additional charge carriers through impact ionisation. in an EMCCD there is a dispersion (variation) in the number of electrons output by the multiplication register for a given (fixed) number of input electrons . The probability distribution for the number of output electrons is plotted logarithmically on the vertical axis for a simulation of a multiplication register.





VIII. Conclusion

We have presented an analysis of the charge transfer in charge-coupled devices using the charge-control approach and obtained a practical closed-form solution for device design tradeoffs and circuit analysis programs. We have also presented many application of CCD such that Astronomy, Color cameras, Sensor sizes, Blooming and Electron-multiplying.

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