Charge-Coupled Device CCD

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***Abstract*—The operating principles of charge-coupled devices are described in terms of the basic properties of semiconductors. The overall aim is for those unfamiliar with CCD's to understand how they work and thus to appreciate their capabilities as well as their limitations. The topics discussed include charge storage and transfer, electrical and optical inputting of charge and charge sensing, factors governing maximum and minimum operating frequencies, transfer efficiency, basic CCD structure and some of its applications.**

***Index Terms*—charge-coupled devices, CCD, Semiconductors, image sensors, CCD structure, CCD characteristics.**

I. Introduction

The year 1969, the year of the moon landing, the year of Woodstock, was also the year when the first paper about Bucket-Brigade Devices was published. Of course the first two events received much more publicity, but the effect on society might be equal for all three of the milestones.

It is very doubtful whether Sangster and Teer, the inventors of the Bucket Brigade Device, and Boyle and Smith, the inventors of the Charge-Coupled Device, could ever have anticipated the impact of their pioneering work. In 1969 F. Sangster and K. Teer of the Philips Research Labs, the Netherlands, published their findings on a completely new type of device : the Bucket-Brigade Device or BBD. Their original application was as an analog delay line, but Sangster and Teer soon realized that their invention was also capable of being used as a solid-state image sensor.

Basically, the BBD is a charge-transfer device in which charge packets are transported from one transistor to another. In 1970, W. Boyle and G. Smith of Bell Labs, the United States, improved the charge-transfer concept by introducing a transport mechanism from one capacitor to another one. The Charge-Coupled Device or CCD was born! The charge-coupled devices completely covered the same application areas as the bucket-brigade devices : analog delay lines, (programmable) analog filters, analog memories, digital memories and image sensors. Not surprisingly that CCDs and BBDs had so much in common, the BBD was in fact a two-phase CCD.

The charge-coupled device (CCD) is essentially a shift register in which information is stored in the form of electrical charge "packets" in "potential wells" created in an MOS structure as shown in fig1. Under the control of externally-applied voltages, the potential wells, and hence the charge packets, can be shifted through the CCD structure. Since varying amounts of charge can be introduced into the potential wells at one end of the CCD structure, to emerge after some delay at the other end, the CCD is capable of acting as an analogue as well as a digital, shift register. In common with other semiconductor devices, the CCD structure is also sensitive to light, which generates charge packets proportional to the light intensity. Thus information can also be introduced optically and the device can be used as an image sensor. [1]

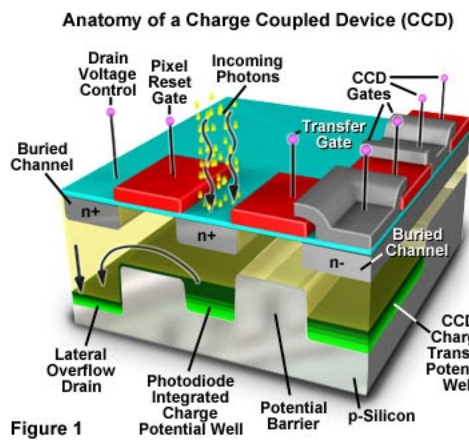


Fig. 1: Anatomy of a Charge-Coupled Device

As the first charge-coupled device was announced in 1970; however, the concept has already been developed to the point where exceptionally complex circuits have been fabricated and CCD's are being actively considered for a very wide range of applications. The purpose of this paper is to outline the general operating principles of CCD's, CCD structure, characteristics and some of its important applications as Medical imaging, Optical microscopes, Astronomy and etc.

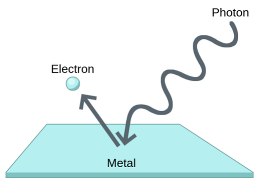
II. Preliminaries

Some concepts and facts are required for understanding the CCD, such as:

- Photoelectric effect
- P and N types semiconductors
- Biasing of semiconductor devices
- Capacitance of MOS structure

A. Photoelectric effect

It is the phenomenon explaining the emission of electrons when electromagnetic radiation falls on a material surface, this radiation can be the visible light for example and the material can be metals. These emitted electrons are called "photoelectrons". The incident light should have a frequency that gives the electron energy more than a specific value to be freed from the surface of the material. This specific energy is called "work function" and it differs from one material to another. This phenomenon has an effective usage in the paper's topic which is the CCD.



B. P and N types semiconductors

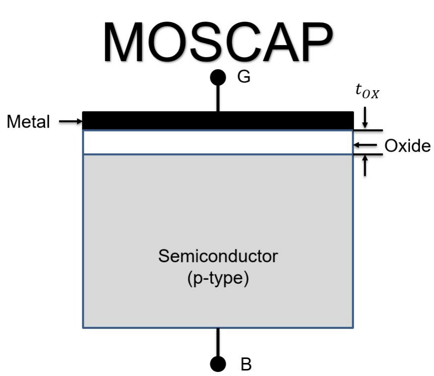
A semiconductor material is a material that has a level of conductivity between that of the metals and the insulators. It can be silicon, germanium and many other elements or materials. A piece of any of these materials can be doped to acquire more conductivity level. Doping means injecting the semiconductor material by a trivalent or pentavalent element in its structure to increase the charges in the material as these charges are responsible for the conductivity process. When the semiconductor is doped with a trivalent element, it's called a "p-type" as this element's atom will accept an electron from a semiconductor atom and leave a hole in the electron's place so the number of positive charges (holes) will increase in this material. On the other hand, when the semiconductor is doped with a pentavalent element, it's called an "n-type" as this element's atom will gives an electron to a semiconductor atom so the number of negative charges (electrons) will increase in this material.

C. Biasing of semiconductor devices

To operate the electronic device which can be a pn-junction or transistor, you need to supply it with a voltage or a current to make the current flow inside it in a certain direction and this direction is based on the biasing direction. so the initial operation of the device is called biasing.

D. Capacitance of MOS structure

From the structure of the MOS we find that it consists of a metal layer and a semiconductor one, separates them an isolating material layer which is the semiconductor oxide. If we applies a negative voltage on the metal, negative charges will be accumulated on it and subsequently positive charges will be accumulated on the semiconductor interface between it and the oxide layer to keep the equilibrium. This is so similar to what happens in a parallel plate capacitor so a capacitive characteristic will appear on this structure.



III. Structure

The fundamental building block of the CCD is the MOS capacitor, in ideal MOS diode, the only charge exist in MOS are those in the semiconductor and those with equal but opposite sign on the metal surface adjacent to the oxide. There is no carrier transport through the oxide under direct current as the resistivity of the oxide is infinite. [2]

When the MOS diode is biased with positive or negative voltage, three cases may exist at the semiconductor surface: accumulation, depletion and inversion, as the energy band diagram in fig 2 [3]

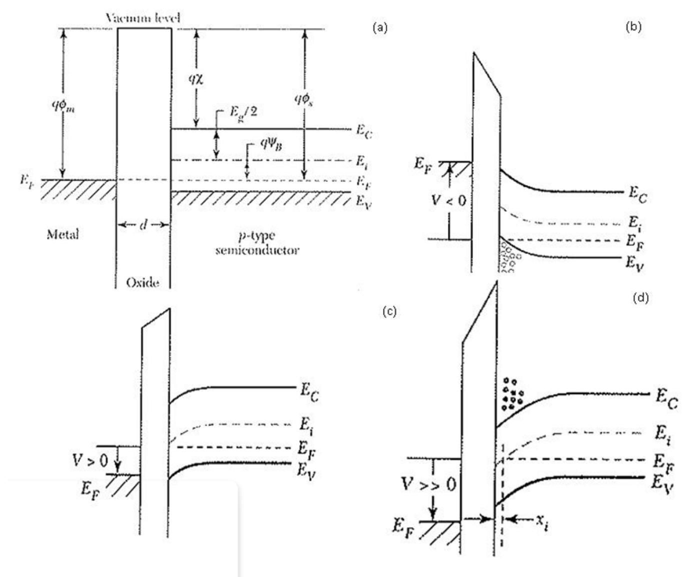
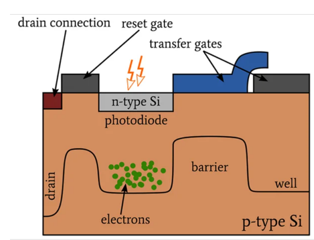


Fig. 2: Energy band diagram as ((a) zero voltage, (b) accumulation, (c) depletion and (d) inversion case)

The following diagram gives you a general idea of how CCDs are constructed and what happens at the semiconductor level



- A pixel's photodiode produces electrical potential in response to incident light. The relationship between light intensity over time and accumulated charge is initially linear but becomes nonlinear as the pixel approaches saturation. Modern CCDs use pinned photodiodes, which include a thin p+ layer that is not shown in this diagram.
- Electrons accumulate in a "potential well" within the p-type silicon underneath the diode.
- 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.

- We create a potential barrier by applying 0 V or a negative voltage. A barrier blocks the movement of electrons.
- Clock signals applied to transfer gates lead to the sequential generation of wells and barriers, and this is the fundamental mechanism by which a CCD directs discrete packets of light-generated charge from individual pixels to the sensor's output terminal.
- The reset gate is a means of clearing the accumulated charge in a pixel.

The basic CCD, composed of a linear array of MOS capacitors. At time t1, the G1 electrodes are positive, and the charge packet is stored in the G1 potential well. At t2 both G1 and G2 are positive,and the charge is distributed between the two wells. At t3 the potential on G1 is reduced, and the charge flows to the second well. At t4 the transfer of charge to the G2 well is completed (see in fig 3)

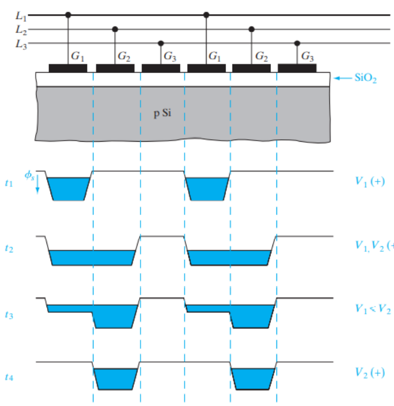


Fig. 3: The basic CCD

A. *improvement on the basic Structure*

Several problems arise in the implementation of the CCD structure of Fig.3. For example, the separation between electrodes must be very small to allow coupling between the wells. An improvement can be made by using an over-lapping gate structure such as that shown in Fig.4. This can be done, for example, with poly-Si electrodes separated by SiO2 or with alternating poly-Si and metal electrodes.

One of the problems inherent to the charge transfer process is that some charge is inevitably lost during the many transfers along the CCD. If the charges are stored at the Si-SiO2 interface, surface states trap a certain amount of charge. Thus if the "0" logic condition is an empty well, the leading edge of a train of pulses is degraded by the loss of charge required in filling the traps which were empty in the "0" condition. One way of improving this situation is to provide enough bias in the "0" state to accommodate the interface and bulk traps. This procedure is colorfully referred to as using a fat zero. Even with the use of fat zeros, the signal is degraded after a number of transfers, by inherent inefficiencies in the transfer process.

Transfer efficiency can be improved by moving the charge transfer layer below the semiconductor–insulator interface. This can be accomplished by using ion implantation or epitaxial growth to create a layer of opposite type than the substrate. This shifts the maximum potential under each electrode into the semiconductor bulk, thus avoiding the semiconductor–insulator interface. This type of device is referred to as a buried channel CCD.

The three- phase CCD shown in Fig.3 is only one example of a variety of CCD structures. Figure5 illustrates one method for achieving a two-phase system, in which voltages are sequentially applied to alternating

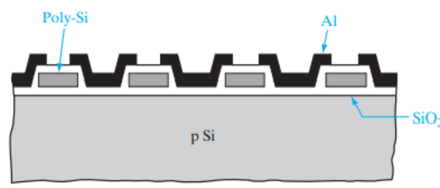


Fig. 4: An overlapping gate CCD structure. One set of electrodes is polycrystalline Si, and the overlapping gates are Al in this case. SiO2 separates the adjacent electrodes

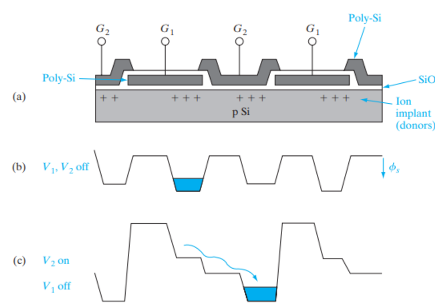


Fig. 5: A two-phase CCD with an extra potential well built in under the right half of each electrode by donor implantation

gate electrodes from two lines. A two-level poly-Si gate structure is used,in which the gate electrodes overlap, and a donor implant near the Si surface creates a built-in well under half of each electrode. When both gates are turned off (b), potential wells exist only under the implanted regions, and charge can be stored in any of these wells. With electrode G2 pulsed positively, the charge packet shown in (b) is transferred to the deepest well under G2, which is its implanted region as (c) indicates. Then with both gates off, the wells appear as in (b) again, except that the charge is now under the G2 electrode. The next step in the transfer process is obviously to pulse G1 positively, so that the charge moves to the implanted region under the G1 electrode to the right.

Other improvements to the basic structure are important in various applications. These include channel stops or other methods for achieving lateral confinement for the stored charge. Regeneration points must be included in the array to refresh the signal after it has been degraded. [4]

IV. Basic Idea of operation

CCDs were initially conceived to operate as a memory device, specifically as an electronic analog of the magnetic bubble device. In order to function as memory, there must be a physical quantity that represents a bit of information, a means of recognizing the presence or absence of the bit (reading) and a means of creating and destroying the information (writing and erasing).
[5]

- In the CCD, a bit of information is represented by a packet of charges.
- These charges are stored in the depletion region of a metal-oxide-semiconductor (MOS) capacitor.
- Charges are moved about in the CCD circuit by placing the MOS capacitors very close to one another(arranging them in an array) and manipulating the voltages on the gates of the capacitors so as to allow the charge to spill from one capacitor to the next.
- A charge detection amplifier detects the presence of the charge packet, providing an output voltage that can be processed.

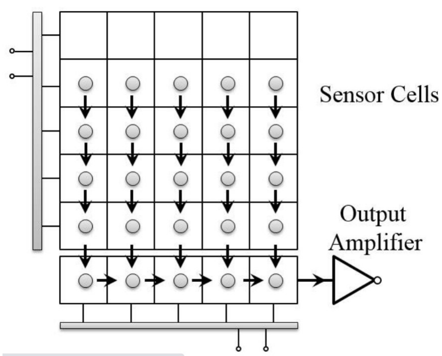
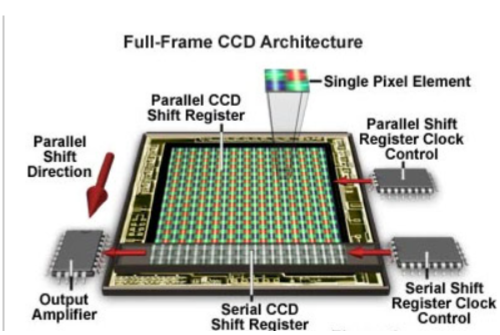
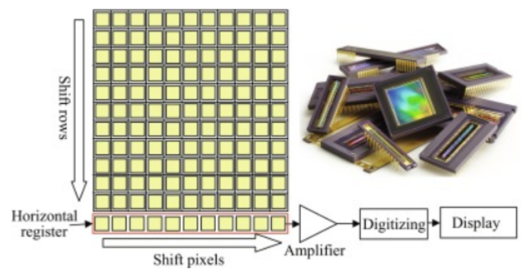


Fig. 6: Diagram of operation

Charge packets can be created by injecting charge that is from an input diode next to a CCD gate or introduced optically(photons) so that the light that is on each of these capacitors is proportional to the electric charge on each one, and that depends on a principle called the photo-electric effect. If a photon with sufficient energy hits an electron in the outer shell of an atom, the transfer of energy to the electron can be enough to free it from the atom altogether, and that is a foundational component of quantum mechanics first analyzed by Albert Einstein in 1905.
[6]



Planetary Nebula 3 CCDs use a thin wafer of silicon to produce electrons from photons because you can free a silicon electron with as little as 1.1 eV. That corresponds to a near infrared photon And it doesn't start reflecting light instead of absorbing it until it reaches over 4.1 eV. That corresponds to blue-violet light . A tiny positively charged capacitor is attached to the silicon wafer in order to collect the freed electrons. If we get one electron for each photon in the range, we'd have full quantum efficiency. The highest quality CCDs can achieve up to 0.9 quantum efficiency. It's interesting to note that the quantum efficiency of the human eye's rods and cones is only 0.01.



V. Characteristics

Even casual users of CCDs have run across the terms read noise, signalto- noise ratio, linearity, and many other possibly mysterious sounding bits of CCD jargon. This part will discuss the meanings of the terms used to characterize the properties of CCD detectors. Techniques and methods by which the reader can determine some of these properties on their own and why certain CCDs are better or worse. [7]

A. *Quantum efficiency*

Quantum efficiency is defined as the percentage of the input photons which contribute to the desired effect. The composition of CCD device is essentially pure silicon, which is responsible for the response of the detector to several wavelengths of light. Silicon absorbs photon with a specific wavelength as shown in fig 7

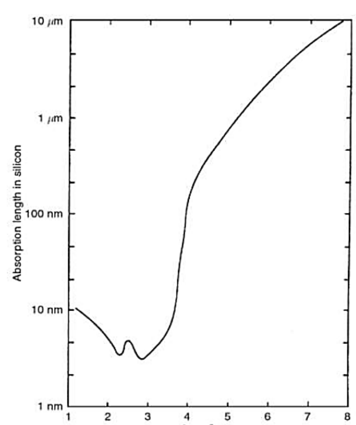


Fig. 7: This figure shows the photon absorption in silicon as a function of wavelength

The photon has three options depending on its wavelength as shown in fig8 :

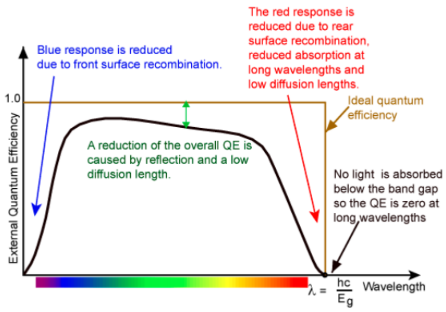


Fig. 8: This figure shows quantum efficiency as a function of wavelength

1) Very short or long wavelength: pass through the silicon.
2) Get absorbed within the surface layers or gate structure.
3) Short wavelength: reflect off CCD surface.

B. Charge diffusion

One important measurement for any CCD that will be used is the amount of “charge diffusion” (the amount of light from one pixel which bleeds through to an adjacent pixel due to electrical effects within the CCD). When a photon entering a CCD. At some point within the CCD, the photon is absorbed, resulting in the generation of a cloud of energetic electrons. Free carriers generated in the bulk of the CCD do not necessarily end up being collected by the corresponding pixel at that position. Some of the free charge moves to neighbor pixels by diffusion and in the end it is converted to an amplifier for measurement.

C. Charge transfer efficiency

Charge transfer efficiency is how well the photoelectrons from one pixel are transferred to the adjacent pixel during a shift operation. If the efficiency is 1, then all the photoelectrons are always transferred without any loss. Normal charge transfer efficiencies 0.999 995 or more which is very good because this means five photoelectrons or less are lost for every 1,000,000 shifts.

The CCD charge transfer efficiency, $\eta \leq 1$, is the fraction of signal charge transferred from one CCD stage to the next, i.e.,

$$\eta = 1 - \frac{Q(t)}{Q(0)}, \tag{1}$$

Where

$$Q(t) = W \int_0^L p_s(y,t)dy \tag{2}$$

Here L and W are the gate length and width of the CCD, respectively.

D. Dark current

Even in the absence of light, some electrons will accumulate in the CCD pixels – this is called ”dark current.” These electrons are not generated by incoming photons, but are randomly generated by thermal excitation and the random motions due to the temperature. Thus, this effect is greatly reduced by cooling the CCD. The dark current should vary according to the relation

$$DC = AT\frac{3}{2}\ e^{-E_g/2KT} \tag{3}$$

Where A is a constant (ADUs per pixel per second), Eg, is the difference in energy between the Fermi level and the bottom of the conduction band for the semiconductor and T is the detector temperature. By measuring the dark current at different detector temperatures, it is possible to determine the values of A and Eg in the equation.

E. Readout noise

CCD can be considered having three noise regimes: read noise, short noise, and fixed pattern noise. Fig9 a plot of the log of the standard deviation of the signal (y-axis)vs. the log of the signal itself (x-axis) for a CCD is called photon transfer curve.

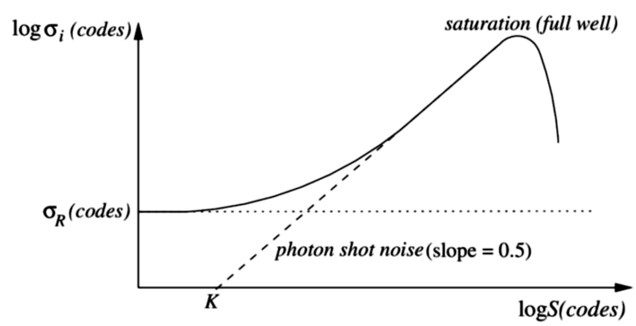


Fig. 9: the log of the standard deviation of the signal vs. the log of the signal itself for a CCD

The Photon Transfer Curve (PTC) of a CCD depicts the variance of uniform images as a function of their average as shown in fig10.

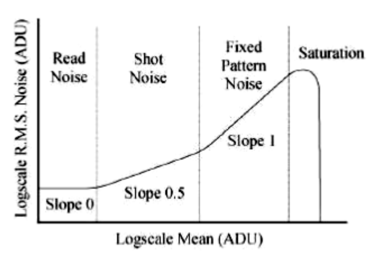


Fig. 10: The Photon Transfer Curve (PTC) of a CCD

Read-out noise occurs when the photoelectrons are converted to a voltage. The electronic amplifiers that do this are not perfect, so they introduce a “noise”, or uncertainty, in the measurement. Typically, each read-out has an uncertainty of between 1 to 10 electrons, depending on the CCD and how it is operated. Read-out noise is one of the limitations on how faint an object a CCD can detect.

F. CCD gain

The gain of a CCD is set by the output electronics and determines how the amount of charge collected in each pixel will be assigned to a digital number in the output. Gain values are given in terms of the number of electrons needed to produce one ADU step within the Analog-to-Digital converter. Listed as electrons/Analog-to-Digital Unit (e-/ADU), common gain values range from 1 photon to 150 or more. One of the major advantages of a CCD as shown in fig 11 is that it is linear in its response over a large range of data values.

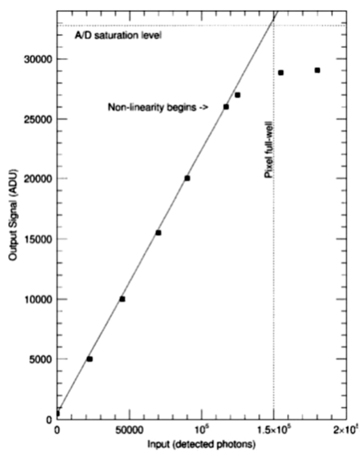


Fig. 11: The figure shows the relation between the input value (charge collected within each pixel) and the output value (digital number stored in the output image)

Linearity means there is a simple linear relation between the input value (charge collected within each pixel) and the output value (digital number stored in the output image). The largest output number that a CCD can produce is set by the number of bits in the A/D converter.

VI. Practical applications

In recent years CCD has become a major technology for digital imaging. In a CCD image sensor, pixels are represented by p-doped metal-oxide-semiconductors (MOS) capacitors. and they are widely used in various applications as Medical imaging,remote sensing application ,electronic appliances,Scientific Applications, Optical microscopes,Astronomy,Digital cameras . All applications are discussed in detail in [8]
Some of these applications briefly

1) Medical imaging
2) Scientific Applications
3) Optical microscopes
4) Astronomy
5) CCD detector

A. Medical imaging

these imaging systems are so accurate so it can be used across all aspects of the life sciences and on almost all biomolecules.Thus it preferably used in medical imaging like advanced X-ray tomography to image bone structures and soft tissue samples. Some specific examples include the ability to take images of cells with contrasting enhancements applied, the ability to collect image samples which have been doped with fluorophores (which cause the sample to fluoresce). to image bone structures and soft tissue samples. [9]
[10]

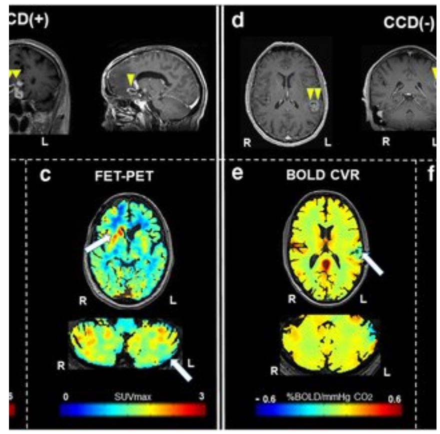


Fig. 12: Exemplary images of CCD

B. Scientific Applications

The CCD camera is becoming the imaging method of choice in biological laboratories for its resolution, versatility and ease of use. example **Optical Tomography System** A tomographic system is a method used for capturing an image of an internal object section. Optical tomography is one method which widely used in medical and industrial fields.

C. Optical microscopes

There are many different CCD cameras used in optical microscopes today, with many cameras possessing over 10 million pixels

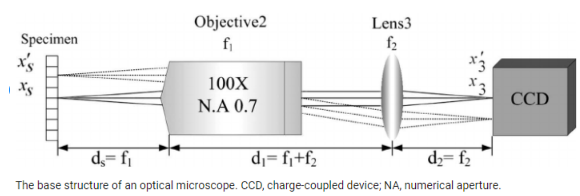


Fig. 13: Optical Microscope using CCD

Advantages

- low noise interference
- high sensitivities
- high spatial resolutions high spectral bandwidths
- high dynamic ranges
- the ability to render color (with the use of filters or extra optical components), high quantum efficiencies (for imaging fluorescence) and the ability to image at many frames per second.

D. CCD detector

A CCD or Charge Coupled Device is a highly sensitive photon detector. It is divided up into a large number of light-sensitive small areas known as pixels, which can be used to assemble an image of the area of interest.
CCDs are widely used beyond sensors in digital cameras. Versions that are used for scientific spectroscopy are of a considerably higher grade, to give the best possible sensitivity, uniformity, and noise characteristics.

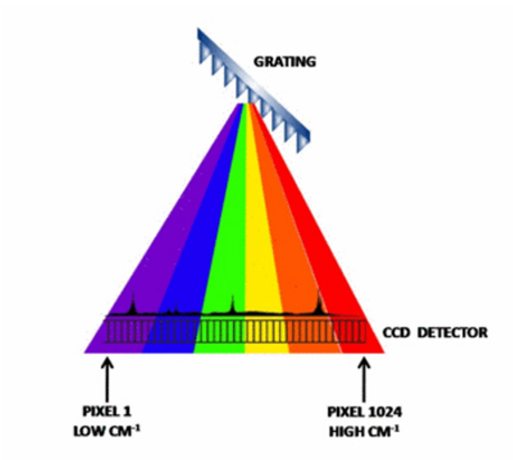


Fig. 14: Raman spectrometer

In a typical Raman spectrometer, the Raman scattered light is dispersed using a diffraction grating. This dispersed light is projected onto the long axis of the CCD array. The first element will detect light from the low cm-1 edge of the spectrum. The second element will detect light from the next spectral position, and so on. The last element will detect light from the high cm-1 edge of the spectrum.
CCDs require some degree of cooling to make them suitable for high-grade spectroscopy. This is typically done using either Peltier cooling, which is suitable for temperatures down to -90oC, and liquid nitrogen cryogenic cooling. Most Raman systems use Peltier cooled detectors, but liquid nitrogen cooled detectors still have advantages for certain specialized applications. [11]

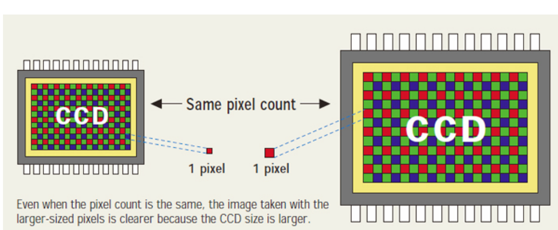


Fig. 15: Pixels

CCD sensor uses a lot time and energy converting each pixel, it can hold a large amount across its surface. However, a downside to CCD is called **blooming** or smearing effect this happens when a light gathering pixel exceeds its capacity to hold captured photons that access spills over the adjacent pixels and produce a spike of light in the image.

E. Astronomy

As well as looking at the small, CCDs are also used in equipment that can take images of very large, and very far away celestial bodies. CCDs have been used in astronomy applications since the 1970s. One example of where this has been used is to take pictures of the Andromeda galaxy (as well as other celestial bodies in the same vicinity as Andromeda). [12]

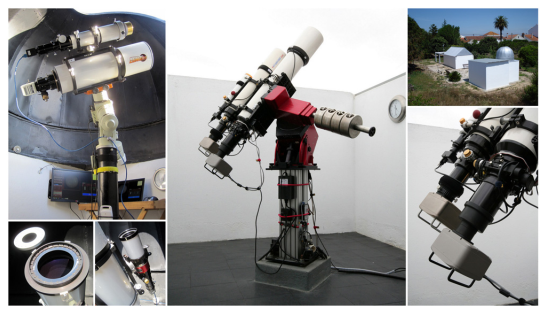
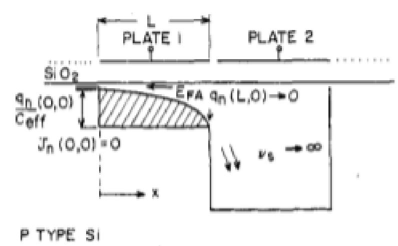


Fig. 16: CCD Astronomy

VII. Numerical Evaluation

A. BASIC CHARGE-CONTROL MODEL



It is assumed that no variation in the charge distribution at the semiconductor surface occurs in the direction perpendicular to the charge transfer as shown is the figure. Following the classical approach of charge-control theory, the starting point is the integration of the continuity equation over the length L of the discharging potential well. We thus obtain

$$\frac{d}{dt}\int_0^L q_n(x,t)dx = -\frac{1}{T_a}\int_0^L q_n(x,t)dx + \int_0^L \frac{d}{dx}J_n(x,t)dx \quad (4)$$

applied to both n- and p-channel devices.

where $\mathrm{gn}(x,t) = qn(x,t)$ is the magnitude of the electron charge distribution per unit area, $\ln(x,1)$ is the electron current density per unit width and T_a is the effective time constant for charge loss.

$$\frac{d}{dt}Q_w(t) = -\frac{Q_w(t)}{T_a} + J_n(L,t) - J_n(0,t) \tag{5}$$

where

$$Q_w(t) = \int_0^L q_n(x,t)dx$$

This results in the following basic charge-control equation. $Q_w(t)$ is the total charge per unit width in the discharging potential well.

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 (recombination centers) or the recombination of charges by surface states during charge transfer to the next potential well.

It's assumed that the current at an instant at the left end of the discharging potential well is zero, namely, J(0, t) = O. This implies that an infinite potential barrier exists that eliminates the back flow of charges and assures unidirectional flow. This is one of the necessary conditions for the successful operation of CCD's. The current boundary condition at the right end of the discharging potential well has to be finite and nonzero.

In charge-transfer devices, the gate producing the next potential well is driven into deep depletion such that in the direction of charge flow there is no potential barrier that impedes the flow of information bearing carriers.

It is assumed that the charge at x = L is approaching zero but moving at an infinite velocity such that the current is finite. Thus, the boundary conditions for the discharging potential well can be expressed as:

$J_n(0,t) = 0$

$$J_n(L,t) = -\lim_{x\to L} V_a q_n(x,t) \tag{6}$$

where $V_a \to \infty$ as $x \to L$ and

$$\lim_{x\to L} q_n(x,t) = 0 \tag{7}$$

The effect of a finite limiting velocity is negligible.

In general, for $0 \leq x \leq L$ the current equation is given by

$$J_n(x,t) = D_n\frac{\partial}{\partial x}q_n(x,t) + \mu_n q_n(x,t)E \tag{8}$$

where the electric field E can be expressed as a combination of the external fringing field Eext and a contribution due to the gradient of the surface potential.

The surface potential based on the one-dimensional analysis can be expressed as

$$\psi_s = V_a - V_F B - \frac{(q_n + q_B)}{C_o x} \tag{9}$$

where q_B is the bulk depletion charge per unit area, C_{eff} is the effective surface capacitance per unit area.

From equations (5),(6)

$$\frac{d}{dt}Q_w(t) = -\frac{Q_w(t)}{T_a} + J_n(L,t) \tag{10}$$

which upon substitution of (7)-(10) results in

$$\begin{aligned}\frac{d}{dt}Q_w(t) = &-\frac{Q_w(t)}{\tau_\theta} + \Big[D_n\frac{\partial}{\partial x}q_n(x,t)\\ &+\frac{\mu_n}{C_{\text{ett}}}q_n(x,t)\frac{\partial}{\partial x}q_n(x,t)\\ &+\mu_n q_n(x,t)E_{\text{ex}}\,\Big]_{x=L.}\end{aligned} \tag{11}$$

As a first-order approximation, we equate the product at $x = L$ to the average value of the product within the discharging potential well. Physically, this is equivalent to setting the charge gradient induced drift current at $x = L$, at any instant, equal to its space average within the discharging potential well.

$$\begin{aligned}&\left[q_n(x,t)\frac{\partial}{\partial x}q_n(x,t)\right]_{x\to L}\\ &\qquad= \frac{1}{L}\int_0^L q_n(x,t)\frac{\partial}{\partial x}q_n(x,t)dx\\ &\qquad= -\frac{1}{2L}\left[q_n(0,t)\right]^2.\end{aligned} \tag{12}$$

this results in a separation of variables of the form

$$q_n(x,t) = f(l)\phi(x) \tag{13}$$

B. GENERAL DERIVATION OF THE CHARGE TRANSFER EFFICIENCY

[13] [14]

Based on the postulate of instaneous charge redistribution, the essential equations in the time-space separated form are the following:

1) The initial condition at x = 0 is:

$$q_n(0,0) = f(0)\phi(0) = q_n 0 \tag{14}$$

2) Using (6), (7), and (12), the boundary conditions; with no fringing fields are:

$$J_n(0,t) = 0 \to \phi'(0) = 0 \tag{15}$$

$$q_n(L,t) = 0 \to \phi(L) = 0 \tag{16}$$

$$q_n(L,t)\frac{\partial}{\partial x}q_n(x,t)|_{x=L} = -\frac{1}{2L}[f(t)\phi(0)]^2 \tag{17}$$

3) The total charge in the discharging potential well is:

$$Q_w(t) = f(t)\int_0^L \phi(x)dx = f(t)N \tag{18}$$

where

$$N = \int_0^L \phi(x)dx$$

4) By substituting (13), (17), and (18) into (11) in the absence of a fringe field we obtain:

$$\begin{aligned}\frac{d}{dt}Q_w(t) = &-\frac{Q_w(t)}{\tau_t} + \frac{D_n}{N}\phi'(L)Q_w(t)\\ &-\frac{\mu_n}{2LC_{\text{off}}\,N^2}\phi^2(0)Q_{w^2}(t).\end{aligned} \tag{19}$$

Since (19) is an ordinary differential equation with constant coefficients, the following solution is readily obtained

$$Q_w(t) = A\frac{C_1 exp[C_1 t]}{C_2(1 - Aexp[C_1 t]} \tag{20}$$

where

$$C_1 = -[\frac{1}{T_a}] - \frac{D_n}{N}\phi'(L)] \tag{21}$$

and

$$C_2 = -\frac{\mu_n}{2LC_{eff}N^2}\phi^2(0) \tag{22}$$

Using (14), (18), and (20), the integration constant A can be found from

$$Q_w(0) = Nf(0)N\frac{q_{no}}{\phi(0)} = Lq_{av} = \frac{AC_1}{C_2(1-A)} \tag{23}$$

where q_{av} is the average initial charge level per unit area after some algebraic manipulations, we obtain

$$A = \frac{\mu_n q_{av}\phi^2(0)}{\mu_n q_{av}\phi^2(0) + 2N^2 C_{eff}[\frac{1}{T_a} - (\frac{D_n}{N})\phi'(L)]} \tag{24}$$

Combining (20)-(24):

$$F(t, T_a) = \frac{Q_w(t)}{Q_w(0)} = \frac{(1-A)exp[C_1 t]}{(1 - Aexp[C_1 t])} \tag{25}$$

Using the Einstein relation we obtain the final form

$$F(t, T_a) = \frac{Kexp[-\frac{Kt}{t_{tr}}]}{K + (\frac{q_{av}L^2\phi^2(0)}{2N^2 C_{eff}})[1 - exp[-\frac{Kt}{t_{tr}}]} \tag{26}$$

where

$$t_{\mathrm{t}} = \frac{L^2}{\mu_n}$$

is the discharging potential well transit time per unit voltage drop and

$$K = \begin{cases} \left[\frac{t_{\mathrm{tr}}}{\tau_s} - \frac{D_n L^2 \phi'(L)}{\mu_n N}\right], & \text{for } \tau_s \text{ finite} \\ -\frac{D_n L^2 \phi'(L)}{\mu_n N}, & \text{for no surface state loss.} \end{cases} \tag{27}$$

The charge transfer efficiency, when there is no surface state loss, is simply one minus the fraction of the charge remaining:

$$\eta(t) = 1 - F\left(t, \tau_t \rightarrow \infty\right). \tag{28}$$

If surface state loss cannot be neglected, the transfer efficiency has to be developed from (10). This results in:

$$\begin{aligned} \eta\left(t, \tau_0\right) = & \frac{-1}{Q_w(0)}\int_0^t J_n(L, t)dt = -\int_0^t \frac{d}{dt}\frac{Q_w(t)}{Q_w(0)}dt \\ & -\frac{1}{\tau_t}\int_0^t \frac{Q_\omega(t)}{Q_w(0)}dt = 1 - F\left(t, \tau_t\right) \\ & -\frac{1}{\tau_0}\int_0^t F\left(t, \tau_t\right) dt \\ = & 1 - F\left(t, \tau_0\right) - F_{\text{loes}}\ \left(t, \tau_0\right) \end{aligned} \tag{29}$$

where F loss $(t, T0)$ is the fraction of the charge lost during transfer due to trapping or recombination and can be obtained by integrating (29). We obtain

$$\begin{aligned} F_{\text{lows}}\ \left(t, \tau_0\right) = & \frac{2(N/L)^2}{\left(\tau_0/t_{\mathrm{tr}}\right)\left(q_{\mathrm{av}}/C_{\mathrm{otf}}\right)\phi^2(0)} \\ & \cdot\left[-K\frac{t}{t_{\mathrm{tr}}} + \ln\frac{1}{F\left(t, \tau_0\right)}\right] \end{aligned} \tag{30}$$

The transient decay due to various transfer mechanisms can be readily obtained from (20)-(24) by using L'Hospital's rule. When there is no fringing field, we have obtained the following special cases. Case 1: By neglecting the drift term in (19) we obtain for the diffusion mechanism acting alone

$$F\left(t, \tau_\theta\right) = \exp\left[-\left[\frac{1}{\tau_\theta} - \frac{D_n}{N}\phi'(L)\right]t\right]. \tag{31}$$

Case 2: For the drift mechanism acting alone

$$F\left(t, \tau_0\right) = \frac{\exp\left[-t/\tau_0\right]}{\left[1 + \left(\mu_n \tau_0 q_{\mathrm{av}}\phi^2(0)/2N^2 C_{\mathrm{ett}}\right)\left(1 - \exp\left[-t/\tau_.\right]\right)\right]} \tag{32}$$

Case 3: When there is no surface state loss and transfer is by drift alone

$$F\left(t, \tau_0\right) = \frac{1}{\left[1 + \left(\mu_{\mathrm{n}} q_{\mathrm{av}}\phi^2(0)/2C_{\mathrm{ett}}N^2\right)t\right]}. \tag{33}$$

The Cosine Distribution

$$\phi(x) = \cos\pi x/2L$$

Using the cosine distribution results in

$$\begin{aligned} \phi(0) &= 1 \\ \phi'(L) &= -\frac{\pi}{2L} \end{aligned} \tag{34}$$

and

$$N = \int_0^L \cos\frac{\pi x}{2L}dx = \frac{2L}{\pi} \tag{35}$$

Substituting (35) into (26) yields

$$F\left(t, \tau_t\right) = \frac{K\exp\left[-Kt/t_{\mathrm{u}}\right]}{K + \left(\pi^2 q_{\mathrm{av}}/8C_{tH}\right)\left(1 - \exp\left[-Kt/t_{t_t}\right]\right)} \tag{36}$$

where

$$K = \left[\frac{\pi^2 D_n}{4\mu_n} + \frac{t_{tr}}{\tau_v}\right]$$

The Polynomial Distribution $\phi(x) = 1 - (x/L)^m$ Using the following substitutions in (28),

$$\begin{aligned} \phi(0) &= 1 \\ \phi'(L) &= -\frac{m}{L} \end{aligned}$$

and

$$N = \int_0^L \left[1 - \left(\frac{x}{L}\right)^m\right] dx = \frac{mL}{m+1}$$

results in

$$F(t, \tau_\theta) = \frac{K \exp\left[-Kt/t_{\mathrm{tr}}\right]}{K + \frac{1}{2}(1+1/m)^2 \left(q_{\mathrm{av}}/C_{\mathrm{ott}}\right)\left[1 - \exp\left(-Kt/t_{\mathrm{tr}}\right)\right]} \tag{37}$$

where

$$K = \left[(m+1)\frac{D_n}{\mu_n} + \frac{t_r}{\tau_e}\right].$$

VIII. Conclusion

The operation, characteristics, and uses of CCD's have been discussed. The fundamental attributes of the charge-coupling concept are simple and flexible. The simplicity lies in the fact that only insulator and metal layers on a semiconductor substrate are required for the operation of a CCD. The flexibility arises from the ability of a CCD to perform sensing and shift register action in analog or digital format. From the detailed descriptions, analyses, and comparisons presented, it is clear that the charge-coupled concept represents a major advance in functional electronics.

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