

Charge Coupled Devices— Digital Cameras

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Abstract—The definition of CCDs (Charge Coupled Devices) and operation principles are presented. The implementation and features of CCDs used in digital cameras are explained as an instance, comparing with conventional cameras and CMOS.

Index Terms—CCD, CMOS, frame, potential well, pixel.

I. INTRODUCTION

CCDs (Charge Coupled Devices) are fundamentally silicon based arrays of MOS (Metal-Oxide-Silicon) diodes which have the ability to store and transfer information through several charge packets [1]. Although CCD was originally invented in 1969 by Willard Boyle and George Smith at AT&T Bell Labs as a “semiconductor bubble” memory device, it is more intended to be used as an image sensor, which is the result of its advantage of light sensitivity. In fact, immediately after 1969, it was realized by the researchers that it is able to capture images using an important property of CCD which was well known as photoelectrical effect. Several companies, like Texas Instruments and Fairchild Semiconductor at that time began to invest in the development and research on commercial devices employing CCDs [2, 3]. Mainly based on CCD, in the past twenty years, digital camera turns out to be one of the most typical instances built in the principle of converting analog signals to digital information. CCDs make the transfer of image from camera to computers to be possible, which was never thought about when the conventional cameras were dominant.

II. WORK PRINCIPLE OF CCD

A. Structure of CCD

CCD can be built on either n-type or p-type semiconductor substrate, according to which CCD is named n-type or p-type, respectively. Actually, there is another silicon dioxide layer above the substrate on which several “closely based” [1] electrodes are placed, forming an array. We can easily see that the structure of CCD is very similar to the structure of MOS (Metal Oxide Silicon). Therefore, it is reasonable to regard CCD as MOS device [1].

B. Potential well

Suppose we are dealing with p-type CCD. When applying a positive voltage named V_1 at the electrodes, there will be a depletion region since the majority carries (holes) are pushed away from the surface of the p-type substrate. In the case of

standard operation, for each series of three metal electrodes (gates), the bias positive voltage is significantly greater at the center gate compared with each of the other two neighbors [1]. Through this method, the depletion region right beneath the center gate will extend more deeply. This deepened depletion region is called a potential well. When light excites, electrons from the valence band to the conduction band, the electrons will be immediately captured by the potential well, generating a charge packet.

However, the implementation of directly placing oxide layer above the substrate may cause some problems of surface irregularities. An n-type “buried” channel can be used to solve this problem. In order to implement the “buried” channel a thin n-type region is formed on the surface of substrate. Therefore, the minimum of the potential well where the channel will be formed is totally inside the n-type layer, which will decrease surface irregularities. Also note that the electrodes used could be metal, however, not necessarily, since in most cases a heavily doped polycrystalline silicon layer is employed [4].

C. Pixel

To constrain each captured charge in the position of the incident photon, heavily p-doped material, named channel stops, are often implanted near the surface of the p-type substrate, forming parallel narrow columns [5]. Under each channel stop, there is usually a p^+ doped region to provide further barrier to the electrons in the charge packets. Providing that the channel stops are parallel to the “charge carry” regions, and combining with the implementation of applied voltage at the gates (much higher at center than the other two nearby for each three series gates in one column), the maximum potential wells are isolated in two dimensions, creating a pixel, or picture element. As photons strike a pixel, the excited electrons are trapped by the nearby potential well, generating a charge packet which is constrained by the barrier mentioned above. The number of electrons captured in one pixel thus corresponds to the number of photons which strike this pixel, providing a tiny cell of information we want to know for a certain image.

D. Readout

For the simplest way of the readout operation, charge is shifted along each column to the register at the corner of each pixel array where a single circuit is provided to measure the charge captured by each pixel. This process is fulfilled through pulsating the bias voltages sequentially. The shifted charges

along a column are then dumped to another pixel series called serial line at the bottom and is perpendicular to the columns. For an N-column array, there will be N shifts along the serial line for each shift along a column. Finally, the charge is dumped to a capacitor in the corner of the pixel array, where the caused voltage of the charge is detected and amplified for the last step through an Analog-to-Digital Converter (ADC) [3].

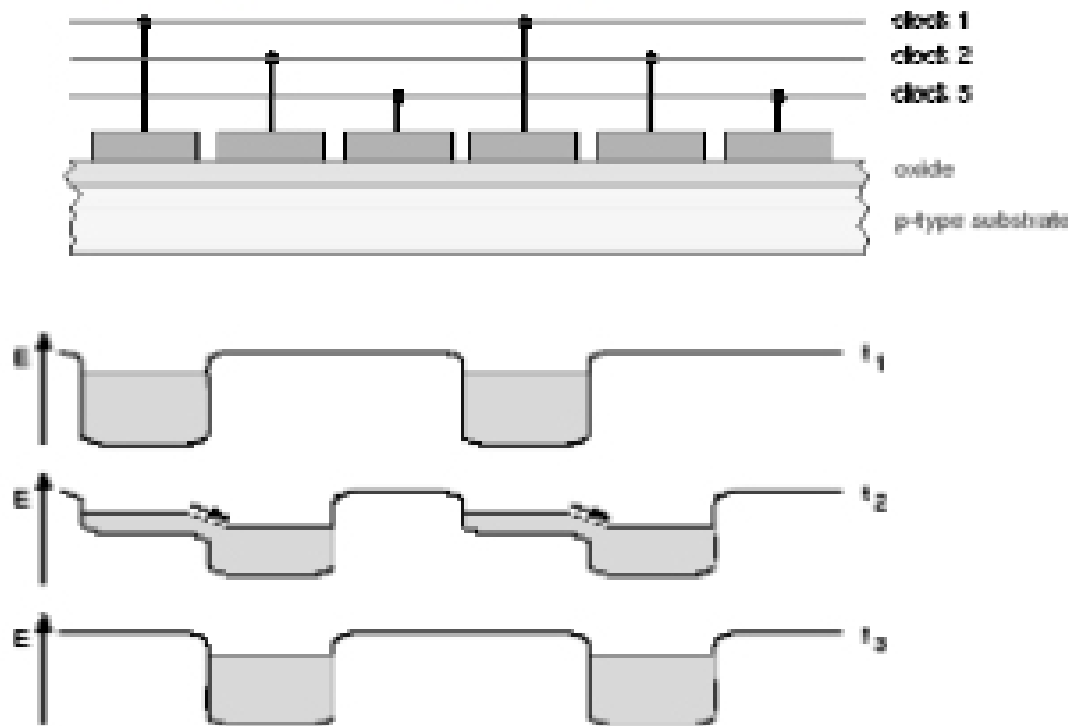


Figure 1. The simplified process of charge transfer from one pixel to another.

E. ADC (Analog-to-Digital-Converter)

The resulting analog signal is converted to digital information which can be used in one's computer. An Analog-to-Digital-Converter (ADC) turns the analog value of each pixel to the digital value which is binary form. In fact, this process conceals the most attractive property of CCDs, which leads to the robust of digital cameras.

III. DIGITAL CAMERAS

Based on the operation principle of CCD discussed above, the implementation of digital cameras is totally different from that of the conventional cameras. Conventional cameras depend entirely on chemical and mechanical process without any operation related to electrical mechanisms whereas digital cameras employ electrical devices to get an image. They sample the light which bounces off the subject and turn the light (photon) into a series of pixel values (charge packets) and then break them down to digital representation of data as we introduced for the principle of all the CCDs.

A. CCD architectures used in digital cameras [6]

Full frame CCDs—The simplest architecture. The whole area of the sensor is photosensitive and the process of readout is the same as we introduced in the second part of this paper. Full frame CCDs are the most sensitive sensor in many ways. However, while the charge is shifted (transferred) to the readout register the light is still falling on the sensor, which will cause the smear of the image. Sometimes, a mechanical shutter is used, covering the sensor while the cumulated charge is in the readout process, although there may be some other situation which does not need shutter, e.g., when a source of pulsed light

is used.

Frame Transfer CCDs—An opaque mask is used to cover half of the area of the sensor (silicon area). This area can also be considered as a storage area. Without mechanical shutter, the image is transferred from the area without mask (active area) to the storage area with only a little smear (a few percent). Then the charge is flipped to the readout from the storage area. At the same time, the signal is integrated on the light-sensitive part of the sensor. Frame transfer CCDs have the advantage of less smearing compared with full frame CCDs, the cost for which is twice as large as the area of silicon and thus a very high price.

Interline transfer CCDs—Interline masks are incorporated in this kind of sensor. The interline masks can be regarded as charge transfer channels cover every other column of silicon area for storage. Therefore, only one shift is needed for the cumulated charge to be transferred from the active area to storage area thus no mechanical shutter needed and much less smearing will be caused. However, the price for this advantage is a so small light sensitive area which will result in dropping the effective quantum efficiency by approximately 50%. Microlenses arrays are being used to compensate this disadvantage to increase the photodiode fill factor.

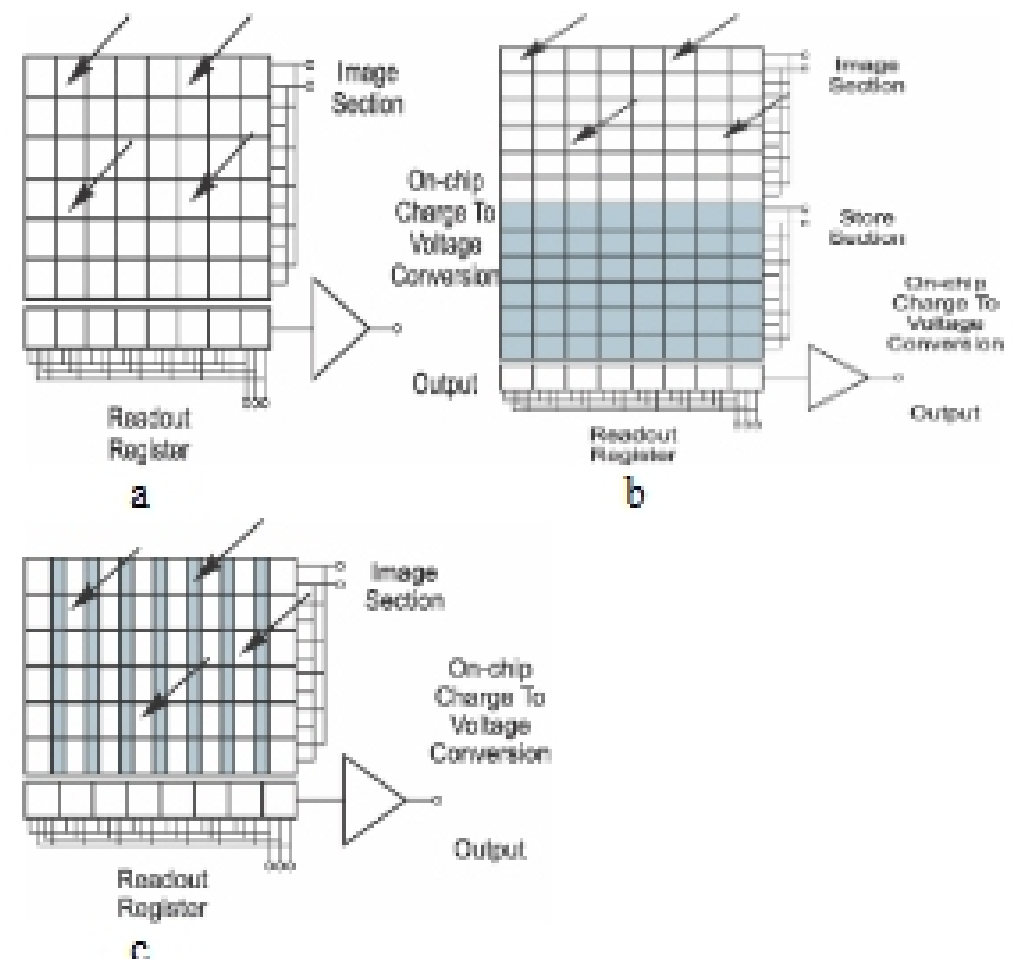


Figure 2. Three types of CCD sensor architectures. a. Full frame architecture, b. Frame transfer architecture, c. Interline transfer architecture

Unfortunately, no matter which architecture of sensor is used, the image received from the converting process is without color since the sensor can only record the intensity of light, i.e., the amount of the photons strike the surface of CCD. Therefore, for digital cameras, they need filters to capture the color for a certain image.

B. Types of ways to capture color [3, 7]

There are three kinds of colors to form a full image, which are green, red and blue, which are commonly named primary colors.

One method for capturing color image, three separate sensors with three differently colored filters (each in one primary color) can be used to implement a camera. A so-called beam splitter “guides” the light to three sensors. The filter above each sensor will then separate the primary color from the light to each sensor. In other words, each sensor of the three can only detect one of the three primary colors but since the light is equally separated, every sensor will have the equal knowledge of a certain image. The use of three sensors plus three filters makes the camera really bulky and expensive. Therefore, this method is usually used for the applications which require very high quality image.

The second solution employs an idea to rotate a series of primary colors, red, blue and green ahead of only one sensor. The “spinning disk” rotates extremely fast so that the sensor is able to record three separate image almost at the same time. At each pixel of the sensor, information in the colors of red, blue and green will all be detected. Although this idea sounds great, if we think about the practical application, it turns out to be not that attractive since in fact the three separate images won't be captured at exactly the same moment.

The last but most important method for color capturing is to place a “color filter array” above each of the “photosites” [3]. A Bayer filter is the most widely used filter to fulfill this implementation. This filter is separated to several rows and columns in the colors of red, blue and green. Since the human eye is more sensitive to green than to other two primary colors, the pixels in green is twice as many as pixels in blue or that of red. By interpolation (a method to analyze the information in order to get a reasonable estimate about the information of a certain position), it is fundamentally possible to obtain very accurate information of the full color spectrum at the certain location, i.e. pixel. In this method, only one sensor is required. It absolutely guarantees that the colored information (red, green and blue) is recorded at exactly the same time. It is more practical, useful and much smaller.

The choice of different types of CCD architectures and filters depends on applications as well as the consideration of several elements, e. g., price, weight, size and some other focuses. As has been discussed, CCD sensors have several properties lead it to be widely used in digital camera applications. However, some cameras implement another technology called CMOS (Complementary Metal Oxide Semiconductor) instead. The comparison of the two different technologies turns to be important.

IV. CCD VS CMOS [8, 9]

CCD and CMOS are different technologies to digitally capture image. Both CCD and CMOS image sensors base on the work principle to convert light into electrical charges although the structures of them are different.

As introduced above, CCD sensors use a register in the corner of each pixel array to collect charges which are then converted to digital values by ADC. It is to say, there are usually only one output node for a CCD sensor which outputs

off-chip analog signal. Different from this, for CMOS image sensors, there are several charge-to-voltage conversions (transistors) and the sensor also has amplifiers and circuits for digitalize signals. In other words, CMOS image sensors can output off-chip digital signal without ADC. Comparisons of features of CCD and CMOS are shown as table 1.

TABLE I
FEATURES AND PERFORMANCE OF CCD AND CMOS

Feature	CCD	CMOS
Signal out of pixel	Charge Packet	voltage
Signal out of chip	Analog	Digital
Fill factor	High	Moderate
System Noise	Low	Moderate
Sensor Complexity	Low	High
Relative R&D Cost	Lower	Higher
Uniformity	High	Low to Moderate
Speed	Moderate to High	Higher

We can see that, for the technologies of CCD and CMOS, each has certain advantage and disadvantage on some aspects. It is unreasonable to prefer one technology while discarding the other. Although most digital cameras choose CCDs, there is also a bright future for CMOS technology.

V. CONCLUSION

The advantages of CCDs make it to be favored by many vendors and research organizations. In their application of digital cameras, the requirement of smaller size and lower power consumption are the trend of CCDs design [10] since there is always a tradeoff between the size of sensor and the quality of image.

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