CHARGE-COUPLED DEVICES

by

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ABSTRACT

The *charge-coupled device* (**CCD**) is, by far, the most common mechanism for converting optical images to electrical signals. In fact, the term **CCD** is know by many people because of their use of video cameras and digital still cameras. The **CCD** has matured over the last thirty years to the point that we can get a reasonable quality picture in an inexpensive "toy" camera. At the other end of the cost curve, we see spectacular telescope pictures returned from the *Hubble Space Telescope* (**HST**)[11]. A number of different device architectures have been developed to optimize resolution, sensitivity and various other performance parameters[4]. This paper gives a brief description of how the more common *charge-coupled devices* work, and it reviews some current developments in **CCD** technology.

INTRODUCTION

The *charge-coupled device* in truly one of the great developments of our time. It is conceptually quite simple. It uses a quantity of electrical *charge* to represent an analog quantity, such as light intensity, sampled at discrete times. The memory function comes from shifting these *charges*, simultaneously, down a row of cells, also in discrete time. The **CCD** is, therefore, a discrete-time device, i.e., a continuous, or analog, signal sampled at discrete times.

CCD's can be used as analog memory, i.e., analog voltage input and analog voltage out. Applications include voice storage as in a telephone answering machine. Also, an analog signal can be delayed a discrete time for synchronization purposes. The more important and universally recognized applications are seen in image sensors. Here, **CCDs** find their way into everything from ten dollar digital cameras to billion dollar space telescopes. As an image sensor a **CCD** generally has an array of cells to capture a light image by the *photo-electric effect*. The packets of *charge* are not initially converted to an electrical signal, but rather moved from cell to cell by the coupling and decoupling of potential wells within the semiconductor that makes up the **CCD**. At the end of the line the *charges*, from all the different *picture elements* (**pixels**), can be converted to electrical signals. The idea here is have a large number (maybe millions) of sensing cells in order to achieve good resolution, but a small number (maybe one) of *readout* cells for practicality.

HISTORY

Invention of CCD – Smith & Boyle 1969

As the story goes, George Smith and Willard Boyle were working in a Bell Labs group interested in creating a new kind of semiconductor memory for computers[6]. Also great hope was then held for the video telephone service, which needed inexpensive *solid-state* cameras. On October 17, 1969 Smith and Boyle mapped out the plan for what was to become the miracle we know of as the **CCD**. On that fateful day in 1969 Smith and Boyle not only described the basic structure and principles of operation, they also predicted its applications in imaging as well as memory.

Buried channel CCD – Smith & Boyle 1974

Smith and Boyle are also credited with inventing the *buried channel* **CCD**, which greatly enhanced the performance of the original *surface channel* **CCD**[6]. As a result of the work of researchers like Smith and Boyle, Bell-Labs now holds many of the relevant patents for *charge-coupled devices*.

Early Video Camera Developments 1970 and 1975

Using the Smith & Boyle **CCD**, Bell Labs researchers built the world's first solid-state video camera in 1970[6]. In 1975, they demonstrated the first solid-state camera with image quality sharp enough for broadcast television.

CCD's Replace Photographic Plates in Telescopes 1983

In the beginning astronomers looked though telescopes with their eyes. Later photographic plates and film generally took over for serious work. In 1983, telescopes were first outfitted with **CCD** cameras. For the last ten years we have been receiving amazing pictures from the Hubble Space Telescope's **CCD** cameras[11].

Digital Cameras Invade the Consumer Market 1995

CCD still cameras have been around since about 1985. In 1991 Kodak released the first professional digital camera system (**DCS**), aimed at photojournalists. It was a **Nikon F-3,** 35 millimeter, camera equipped by Kodak with a 1.3 mega-pixel **CCD** sensor. By 1995, inexpensive, high resolution **CCD**s made possible the consumer digital cameras that are ubiquitous today.

BACKGROUND

The *charge-coupled device* could be considered a subclass of, the broader class, charge transfer device[9]. The fundamental element of every **CCD** is the *metal oxide semiconductor* (**MOS**) capacitor.

MOS Capacitor

Each cell of a **CCD** contains a *metal oxide semiconductor* (**MOS**), the same device that forms the *gate* of a MOS *field effect transistor* (**FET**). Although both surface channel and buried channel MOS capacitors have been utilized in **CCD** construction, virtually all **CCDs** manufactured today are of the buried channel type[8]. The buried channel structure was developed to alleviate the problems caused by surface irregularities at the interface of the oxide and semiconductor. Solid-state electronics has always had its two sides: electrons and holes, n-type and p-type, and so on. Although the duality continues with *charge-coupled devices*, we find that **CCDs** are typically fabricated on a *p-type substrate*. In order to implement the “buried” channel a thin n-type region is formed on its surface. A insulator, in the form of a silicon dioxide layer is grown on top of the n-region. The capacitor is finished off by placing one or more electrodes, also called gates, on top of the insulating silicon dioxide. These electrodes could be metal, but more likely a heavily doped polycrystalline silicon conducting layer would be used.

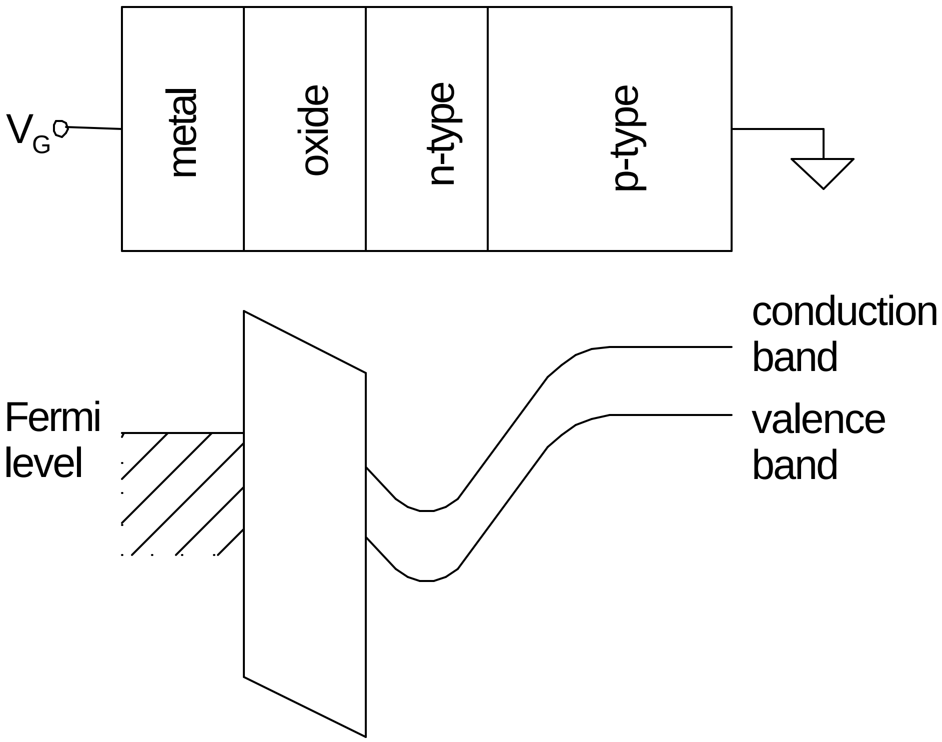

Fig. 1 Buried channel MOS as used in CCD

Note that the minimum of the potential well, where the channel will form, is entirely within the n-type layer, away from the problems that would occur near the interface with the oxide layer!

Single CCD Cell

Of course a single cell **CCD** would be an oxymoron! I suppose, the *Complementary Metal Oxide Semiconductor* (**CMOS**) imaging device could be considered an array of single-cell **CCDs**. The chip in a **CMOS** camera is, in fact, an array of **MOS** capacitors. Each cell also contains enough **CMOS** circuitry to both *address* and *readout* a digital representation of the quantity of *charge* left by the light image. With **CMOS** there is <u>no</u> *bucket-brigade* movement of *charge*!

One cell of a **CCD** would just be a **MOS** capacitor if its function were to just pass along the analog *charges* by *bucket-brigade*. The more general cell would be a **MOS** capacitor that is also light sensitive as in a *photodiode* (**PD**). As an element of a **CCD** the single cell would, in general, be capable of: (1) receiving a quantity of *charge* from an upstream cell, (2) holding the *charge* for a time without appreciable loss, and (3) passing the *charge* to the next cell downstream. In addition, a cell may be required to generate an initial *charge* in response to some outside stimulus. A small number (maybe one) of the cells may also be used for the conversion, to electrical signal, process.

Array of Cells to Form a Device

The simplest, I can think of, **CCD** would be a few **MOS** capacitors (<u>not</u> light sensitive) arranged in a single row. At one end, called the input, we could establish, from an electric signal, the initial *charge* electrostatically for each time slot. Then at the other end, called the output, we reconvert each *charge* back to an electric signal. If all goes well, the output electric signal is a reasonable copy of the input electric signal, but it is sampled at discrete points in time.

Charge Transfer Process

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 **CCDs**. 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**[10]. The three clocks (c1, c2, c3) have identical shapes, but differ in phase. Note: A "high" clock signal represents a large electric field, thus a <u>deep</u> potential well. With *three-phase charge* transfer, we think of the three gates in each pixel, as one storage gate (G2) and two barrier gates (G1 & G2). All the G1's (G2's & G3's) are connected together as phase 1 (2 & 3) or P1 (P2 & P3). *Charges* move from space A to space B when gate B goes high and gate A ramps low.

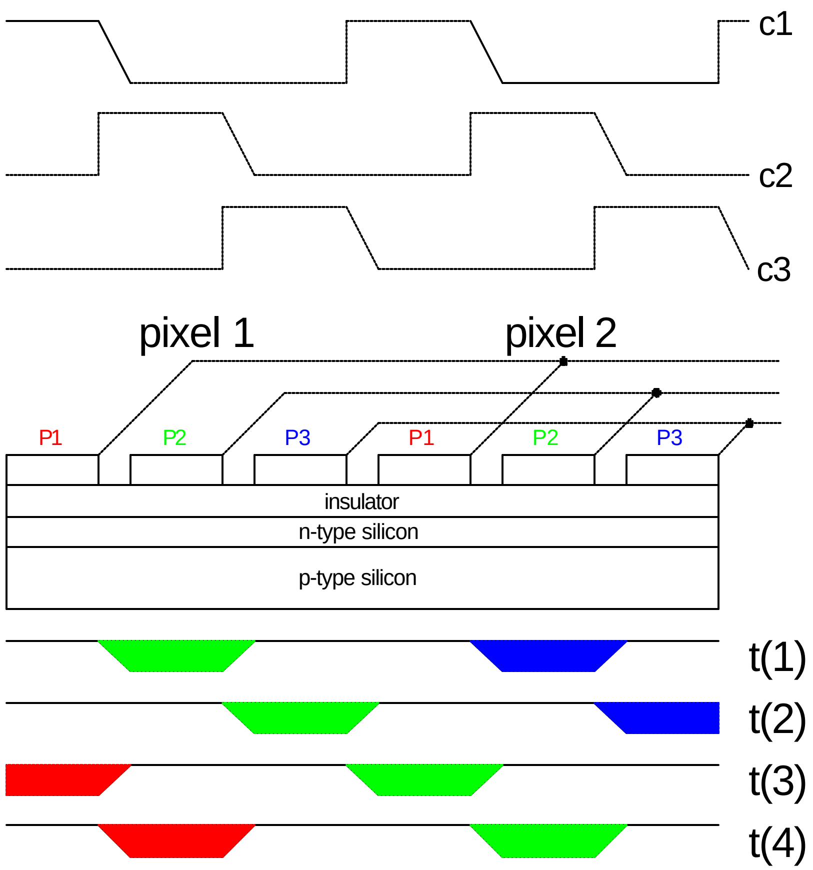

Fig. 2 Three-phase CCD structure

Scanning Formants

In photography speak; image is short for – *two-dimensional image.* Now, this image could be a *view* of a *solid* (*three-dimensional object*), or another *flat* (*two dimensional object*), or it could be the representation of something abstract. Generally speaking, a *n-dimensional object* may be scanned by "n plus one" possible formants. Without much lose of generally, I will stick to *two-dimensional images.* That leaves me with three scanning formants to describe.

The *zero-dimensional* or *point* scan of a *two-dimensional image* is degenerate for the *charge-couple device*. Once we are down to a single point – There is <u>no</u> need to move *charges* and in fact <u>no</u> place to move them! With *point* scanning, the information is collected from a point that scans back and forth as well as up and down over the object. This all takes place while everything is moving in some yet to be mentioned "higher dimension", most likely *time.* With just one collector, there is no need to move information through multiple cells to a single detector; hence point scanning is not used with *charge-coupled devices.*

The *one-dimensional* or *line scanning* is used in some *flatbed* and most *feed-through* page scanners. In this format, a linear **CCD** array could be used to capture one row of *pixels*. The array "scans" down the page in order to complete the *two-dimensional image*. The format found in our video and still cameras is called *area scanning*.

In this arrangement a *two-dimensional* array of *photo detectors* is used to first capture the light image and then to transfer it in *bucket-brigade* style to the output. This transfer is accomplished through the movement of *electrical charge* by alternately coupling and decoupling adjacent cells of the *charge-coupled* array.

Device Architectures

Full Frame Readout. Perhaps the simplest of **CCD** area scanning architectures. In most applications full-frame would require a mechanical shutter, to cut off the light input, in order to prevent smearing during the time the *charges* are passing through the parallel vertical registers or *vertical*-***CCD*** (**V-CCD**). The pixel *charges* are transferred, in parallel, to the *horizontal*-***CCD*** (**H-CCD**) where they are then transferred, in serial, to the output.

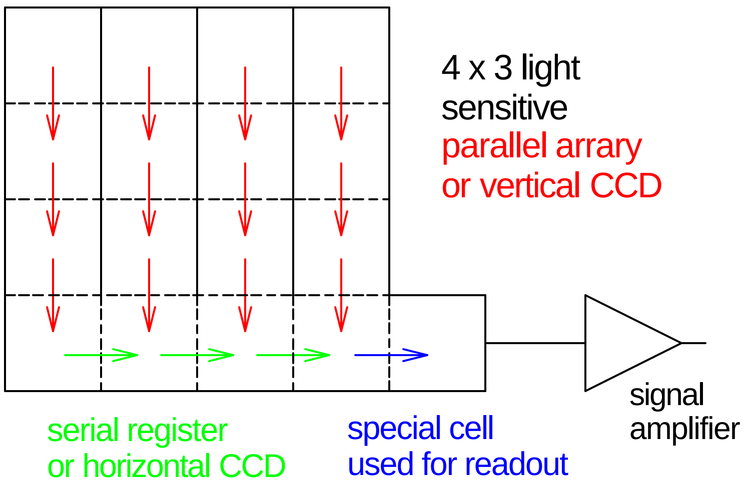

Fig. 3A Full frame

Frame Transfer. The image is transferred from the image array to the opaque frame storage array by the *bucket-brigade* process. This is a relatively fast process as the serial register is not used. From here the slower process, using the serial register, can take place without contaminating the image with additional light.

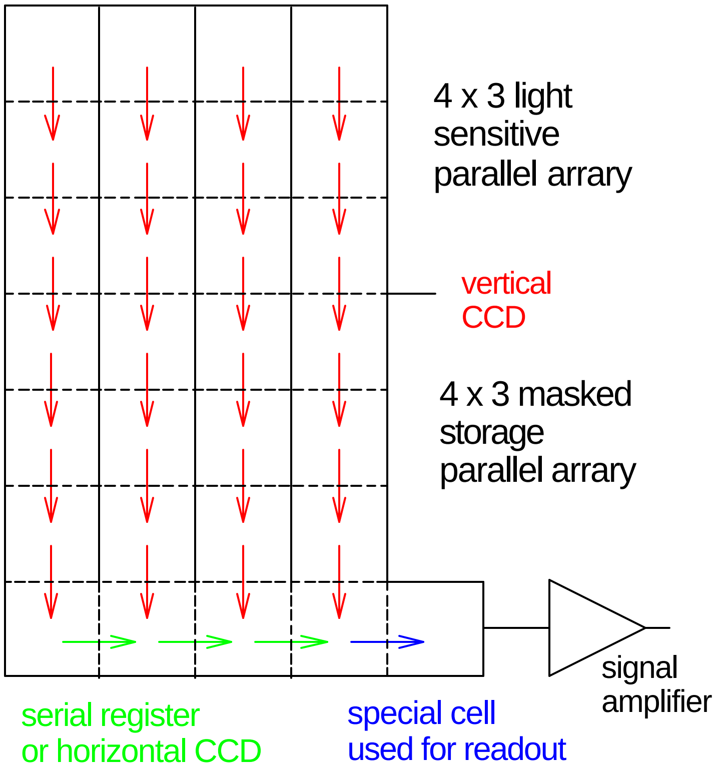

Fig. 3B   Frame transfer

Inter-Line Transfer. Each pixel includes both a *photodiode* and a separate opaque *charge* storage cell. The image charge is first quickly shifted from the light sensitive **PD** to the opaque **V-CCD**. Inter-line transfer "hides" the image in one transfer cycle, thus producing the minimum image smear and the fastest optical shuttering.

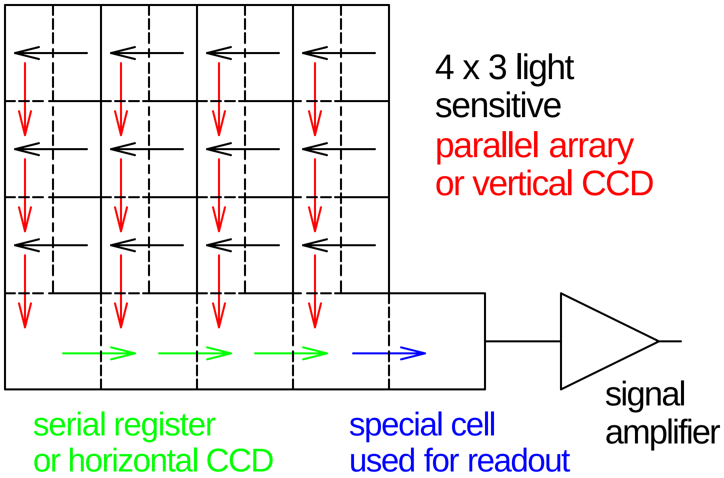

Fig. 3C   Interline transfer

Color

At this point a few words about color are in order. Color, as a red-green-blue (**RGB**) signal, can be provided by using multiple **CCD**s with prisms and/or filters. Cameras have been built using three **CCD**s, each sensitive to a different part of the color spectrum and layered, “sandwich” style. This “sandwich” structure (blue on top, green in the middle, and red at the bottom) works because light of different colors penetrates silicon to different depths. The more common approach in today’s **CCD**s is to use four pixels, arranged in a square, to make up a “color pixel”[4]. The four “sub” pixels are sensitive to the three primary colors, typically one red, two green, and one blue. The readout process for this color **CCD** “knows” nothing of the colors, it just “knows” about *charge*! It is left up to the digital signal processing to put it all back together.

CURRENT DEVELOPMENTS

Every conceivable scheme has been tried to improve the various performance parameters. Indeed, some that would be hard to conceive have been tried and in a few cases these unusual approaches have proved successful. I will point out a few state-of-the-art devices that excel in the more important areas of performance.

Resolution

The term *resolution* is used to denote several different performance parameters. From photography, we get *lines per millimeter* or more generally the smallest feature that can be distinguished on the image plane. In computer speak, we have a count of the number of *pixels* in each of the *horizontal* and *vertical* directions. Also, the product of the two *linear pixel* counts would be a total *pixel* count. Final, there is the *aerial density* of *pixels* on a **CCD**. This is typically in units of *pixels per square centimeter*. More often, we see something like, "one-third inch, 1.3 Mega-pixel". The one-third inch refers to the chip's diagonal measurement.

The professional still camera, **Nikon D1x**, with its 5.47 Mega-pixel **CCD** produces images in 3008x1960 resolution[1]. The chip size (23.7 x 15.6mm) is somewhat smaller than the 36 x 24 mm format of the common (among serious photographers) "F" lenses that this camera in designed to use. Nikon's amateur camera, **D100**, ups the resolution to 6.1 pixels (3008 x 2000).

Soon the Hubble Space Telescope (**HST**) will utilize a new Wide Field Camera (**WFC3**) incorporating 16 Mega-pixel **CCD**[11]. This is a single chip offering 4096x4096 resolution.

Sensitivity

Here we mean the amount of *charge* developed for a given amount of light. Practically speaking – sensitivity would be output signal (millivolts) per integrated light value (lumen-seconds).

Intensified **CCD** (**ICCD**) is the technique most often used in the maximum sensitivity cameras. Roper Scientific (brand name: Princeton Instruments) manufactures some of the most sensitive **ICCD** cameras[7]. These cameras (512 x 512 pixels, frame-transfer architecture) have very high quantum efficiency (**QE**) and are capable of "seeing" single-photon events.

Speed

By speed, we generally mean, frame rate. Of course, when thinking of useful speed, we must consider sensitivity. The speedy motion of a lot of empty cells would not be very useful! A frame rate of 30 *frames per second* **fps** would be adequate for most video cameras (high speed scientific cameras need more). Surprisingly, digital still cameras can benefit from much higher speed (up to 100 **fps**). This demand for great speed comes, <u>not</u> from the desire to take a large quantity of pictures in a small time – but rather speed is needed for the *auto-exposure* (**AE**) and *auto-focus* (**AF**) functions incorporated in virtually all **CCD** still cameras. Other things being equal, as the pixel count goes up the time required to "read" all of the pixels increases.

A interesting "trick" to achieve a high resolution (large pixel count) and still quickly readout enough information to meet the needs of **AE** and **AF** is reported in one of my cited papers[2]. Furumiya et al. report a dual frame rate high-resolution **CCD** that runs in a high-frame-rate skip mode (75 **fps**) to meet the speed requirement of **AE** and **AF**. Using ten (10) phase lines per **V-CCD**, they merge the pixels 5-to-1 vertically. This allows the entire **CCD** to be analyzed in one-fifth the normal time! Of course the resulting image in only one-fifth normal height (in the pixel sense) but that does not matter much for the **AE** and **AF** functions. The **V-CCD** is then operated in "normal" mode (15 **fps**) to "take" the picture. Here we use the common *three-phase transfer-mode* to acquire the full 1308x1032 pixel image.

In looking at A **CCD** diagram, it is clear that the **H-CCD** is the "weak link" in terms of speed. The **H-CCD** must transfer an entire row of pixels, one at a time, before the **V-CCD** can move in the next row. This forces the **V-CCD** to move about one thousand times slower than the **H-CCD**! The obvious answer is to build the **H-CCD** as a specialized, high transfer rate, unit. Furumiya et al. report a 30 **fps** progressive scan device where the relatively slow **V-CCD** is backup by a 49 MHz **H-CCD**[3]. They achieve this performance by using a two-phase drive on the **H-CCD** and different doping for the **H-CCD** vs. **V-CCD**.

Cost

Generally, by cost, we mean the <u>total</u> cost to market.

The least expensive devices, available today, use the **CMOS** technology. But, then again, **CMOS** is not **CCD**! **CMOS** imaging devices have found there way into cheap web cameras and toy digital still cameras. They may soon show up as safety sensors in such items a automatic garage door openers.

CONCLUSION

The device that was first envisioned as a “new-kind” of computer memory has grown up to become the dominant process for image capture. Although other technologies are available, the *charge-coupled device* gives the best performance in terms of resolution, sensitivity and just about every other parameter (with the possible exception being cost).

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