Mama Did Not Take the Kodachome Away But Charge-Coupled Devices Did

Debra Blake Semmler, 2013 CTI Fellow
East Mecklenburg High School

This curriculum unit is recommended for:
International Baccalaureate Physics III 12th Grade

Keywords: Charged-Coupled Devices, Digital Pictures, Modern Physics, IB Physic, Photoelectric effect.

Teaching Standards: See Appendix 1 for teaching standards addressed in this unit.

Synopsis: In 1826, J.N. Nieprci produced the first photograph using a camera obscure, which required an eight- hour exposure time. In the 175 years since this historical event the methods by which we take pictures has changed. No longer is there a need for eight-hour exposures or even film. A digital device called a charged-coupled device or CCD creates images in today's cameras. In this curriculum unit the physics of how charged-coupled devices produce an image and transfer that image to a digital format is described. The objectives of my curriculum unit are to explain the structure of a charge-coupled device (CCD) and how light causes charge to build up in a pixel. Students will have to define quantum efficiency, magnification and resolution in the operation of a CCD.

I plan to teach this unit during the coming year in to eleven students in IB Physics III.

Mama Did Not Take the Kodachome Away But Charged Coupled Devices Did

Debra Blake Semmler

"They give us those nice bright colors. They give us the greens of summers. Makes you think the world's a sunny day, ..So Mama don't take my Kodachome away"
Paul Simon, 1973 Kodachrome[i]

Introduction

Snap chat, Instagram, Facebook, smart phones with cameras or is it a camera with a phone; billions of people everyday take and share digital images. How many people actually know how these images are created? Most, if not all, of my students have never used a film camera or know what a negative image is; they have never taken a roll of film to a camera store and waited for it to be developed and see if the image appears on the paper as they imagined. Students today will never worry about having to have their Kodachome taken away because it is not manufactured anymore. My curriculum unit will describe the physics of the charged coupled devices (CCD) and how it is possible to take digital images instantly and with the same bright colors of Kodachome.

Classroom and School Environment

I teach at an urban, partial magnet high school with a total population of roughly 1900 students, with approximately 850 students who are part of the International Baccalaureate (IB) magnet. The school is comprised of approximately 52 % Africans American, 25 % white, 16% Hispanics and 6 % Asian. More than 50% of the student population is on free and reduced lunch. I will be using the curriculum unit in my IB physics III class; the students in this course are on their third year in physics, having completed an honors-level physics class as sophomores and as seniors they have completed science courses in biology, earth and environmental science and honors chemistry. The IB physics course is a college level physics curriculum divided over two years that includes a minimum of 40 hours of experimental work.

Rational

The aims of the International Baccalaureate Physics course is to expose students to the most fundamental experimental science, which seeks to explain the universe from the smallest particles to an understanding of the origins of the universe. Yet more importantly, students will study the impact of physics on society, the moral and ethical dilemmas, and the social economic and environmental impact of the work of scientists in a global context. A unit of study in the IB physics core curriculum is on digital technology. Objectives of my curriculum unit are to explain the structure of a charge-coupled device (CCD) and how light causes charge to build up in a pixel. Students will have to define quantum efficiency, magnification and resolution in the operation of a CCD. My students will outline how the CCD image is digitized, stored and retrieved. They will also describe a range of practical uses of CCD's and the advantages and disadvantages compared with the use of film.

Scientific Background

In 1826, J.N. Nieprci produced the first photograph using a camera obscure with an eight-hour exposure time. The negative image was produced on a layer of bitumen, a petroleum product that hardens when exposed to light. Then in 1841, W.H. F. Talbot invented light sensitive papers containing silver salts for obtaining a negative image and then making a copy with another light sensitive paper a positive image. The roll of film was not invented until 1887. The 1908 Noble prize in physics was awarded to B. Lippman for the inventions of the color photo process. When Willard Boyle and George Smith invented the charge -coupled device, CCD, in 1969, the era of film photography begin its decline. In December 2010 Kodak stopped production of its Kodachrome film and filed for bankruptcy in 2012.

Photographic Film

The base of color print film is a long strip of plastic that is about 0,025 mm thick. The backside of the film has coatings that are important to the physical handling of the film in the manufacturing and processing of the film. On the front side of the film is where the photochemistry happens. There are twenty or more individual layers; the majority of is a special binder that holds the imaging components together. The binder is made of gelatin. The imaging layers contain sub-micron sized grains of silver-halide crystals that act as the photon detectors. The silver-halide undergoes a photochemical reaction when they are exposed to various forms of electromagnetic radiation. The silver-halide grains are manufactured by combining silver nitrate and halide salts in a complex way resulting in a range of crystal sizes, shapes and compositions these crystals are then chemically modified on their surface to increase their light sensitivity. Unmodified grains of silver-halide are only sensitive the blue portion of the spectrum and are not very useful as photographic film. Spectral sensitizers are organic molecules that are added to the surface of the grains to make them more sensitive the blue, green and red light. These molecules must adsorb to the grain's surface and transfer the energy from a red, green or blue photon to the silver-halide crystal as a photoelectron. When you make film faster, the trade-off is that the increased light sensitivity comes for the se of larger silver-halide grains. These larger grains can result in a grainy appearance to the picture.[ii]

Photoelectric effect

By the middle of the nineteenth-century scientists had agreed that light propagated as a wave in an invisible medium. Experiments with diffraction, interference and polarization were convincing evidence that light was a periodic transverse wave. This thought was changed with an experiment conducted by Henrich Hertz in 1887. Hertz noticed that when shining an ultraviolet light onto a metal plate sparks of electrons were released. The sparking of electricity was not the surprise in this experiment because metals are good conductors of electricity and electrons can be dislodged by a surge of energy. What was surprising was that different metals required different minimum frequencies of light for the electrons to be released. In addition, to these minimum frequencies, increasing the brightness of the light would produce more electrons as long as the frequencies were above the minimum. Light below the minimum frequencies even using the brightest light, could not cause the release of electrons. Hertz also noted that increasing the frequency of light produced electrons with higher energies, but did not increase the number of electrons produced. The results of this experiment became known as the photoelectric effect, where by shining ultraviolet light on a metal plate created a flow of electrons from the plate. The results of this experiment could not be explained by the wave nature of electromagnetic radiation and created controversy in the science community of the time.

In March of 1905, Albert Einstein, working as a patent clerk in Switzerland, published a paper explaining the photoelectric effect. Max Planck, had solved the problem of black body radiation by showing that each atom making up the walls of a cavity could only absorb or emit radiation in discrete "Quanta" such that the energy of each quantum is an integer multiple of its frequency times a new fundamental constant, we now call Planck's constant, *h*. Einstein extended Planck's quanta to light as a particle he called a photon. Einstein postulated that a light is a beam of particles whose energies are related to their frequencies according to Planck's formulas. When a beam of light particles is directed at a metal, the particles called photons collide with the atoms. If a photon's frequency is sufficient to knock off an electron from the metal, the collision produces the electron current seen in the photoelectric effect. As a particle, light carries energy proportional to the frequency of the wave; as a wave it has a frequency determined by the particle's energy. This is called wave-particle duality. Einstein won the 1921 Noble Prize in physics for this work.[iii]

Einstein's work on explaining the photoelectric effect and the understanding of the particle nature of light has lead to the creation of many of digital technologies of the twentieth century. I want to teach my students about two digital technologies; the photovoltaic cell and the CCD (Charge Coupled Device). Both digital devices are based on the physical behavior of a semiconductor material and the photoelectric effect.

The Nature of Conduction of Current

To conduct electricity through a solid, electrons must be able to move. This movement occurs within the valance and higher bands of the solid material. If the valance band of the atom is completely full, then all the sublevels are completely full. This type of material is called an insulator. In this type of material, an electron has no place to move to because all the sublevel and valance levels are full. If the material is a conductor there are many open sublevels that the conduction electron can enter and move. This is found when either the valence band is unfilled or when there is only a single electron in the s subshell. I will use egg cartons and marbles to teach my students the difference between conductors and insulators.

There is a third type of behavior, this behavior is seen when the valence and higher bands do not actually overlap, but have a small energy separation. Thermal energy may be sufficient to push a few electrons into some of the higher bands. Electrical energy or potential can cause the electrons in either the valence or the higher band to move. This material is known as a semiconductor, better than an insulator but much worse than a conductor in moving electrons. In a pure semiconducting material there will be balance in the number of electrons in the conduction band and vacancies in the valence band. An imbalance in the number of electrons or vacancies can be induced by the presence of a differing atom. This is known as doping. If an atom is replace by another atom that has more valence electrons (donor atom) this will result in an excess of electrons and the extra electron will occupy new energy levels in the gap between the valence and conduction bands. These donor electrons will require less energy to move to the conduction band. The material doped with donor atom creating an electron rich environment is call an n-type semiconductor for the negative electron. Semiconducting material can also be doped with an atom that has fewer valance electrons (an acceptor atom) and the spaces will become available within the valence band and the movement of electrons within the valence band is exactly equivalent to the movement of a positive charged hole in the opposite direction. This type of semiconductor is called p-type for positive holes moving in the valence band.[iv]

The Physics Photovoltaic Cells

In 1839, Edmund Becquerel, was the first scientist that discovered that electric current could be produced by certain materials when exposed to light. The first photovoltaic cell was built by Bell laboratories in 1954 and was called a solar battery but was too expensive for commercial use. In the 1960 the space industry needed the photovoltaic cell for power aboard spacecraft and the cost began to decline. Constructing a p-n junction in a semiconductor material creates photovoltaic cells. The electrons in the conduction band of the n-type material are at a higher energy level than the holes in the valence band of the p-type material. This creates an electric field. When light energy is absorbed by the solar cell electrons-hole pairs are produced in both the p- and n-type material. The electrons in the conduction band in the p- region will be attracted toward the n- region by the potential difference across the junction and they will be free to flow in that direction. The holes in the valence band of the p-type material will be opposed by the potential across the junction and will not move. In the n-type region, the electrons will be trapped while the holes will be pushed across the junction and current is generated. Figure 1 shows the cross section of a photovoltaic cell and the p-n junction.[v]

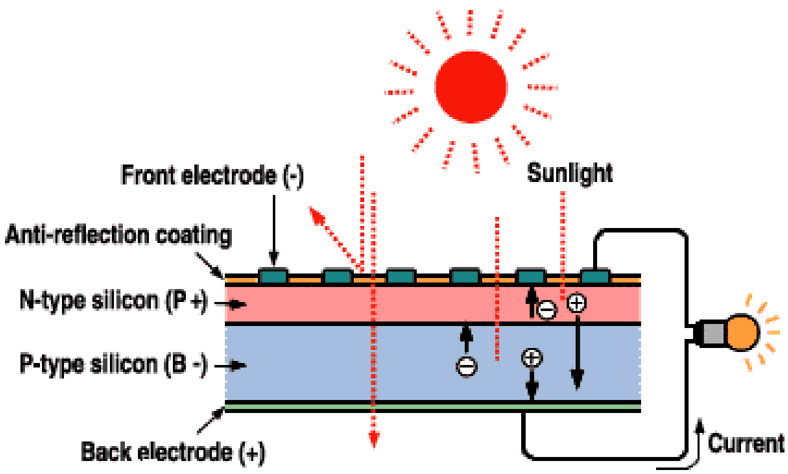

Figure 1 Photovoltaic Cell[vi]

The Physics of Charge-Coupled Devices, CCD's

Willard Boyle and George Smith invented the charge -coupled device, CCD, as a computer memory at the Bell Labs in 1969. The first use of a CCD as an optical detector was in the late 1970's and now CCD technology is used in a variety of video applications ranging from security monitoring to high-definition television and from endoscopy in medical procedures to face-time videoconferencing. Facsimile machines, copying machines, image scanners, still cameras, and barcode readers also use CCDs to turn patterns of light into useful information.

The basic detection method of the CCD is related to the photoelectric effect. Light is incident on a semiconductor material, which produces electron-hole pairs. The electrons are trapped in potential wells and are accumulated until their total number is read out by a charge coupling the detecting MOS capacitor to a single read-out electrode. Figure 2, is a diagram of an individual unit of a CCD. The electrode is insulated from the semiconductor by a thin oxide layer. The electrode is held at a small positive potential that is sufficient to drive the positive holes in the p-type silicon away for its vicinity and to attract the electrons into a thin layer immediately beneath it. The electron-hole pairs produced in this depletion region by the incident light are separated and the electrons accumulate in the storage region. The result is that an electron charge is formed that is proportional to the magnitude of the intensity of light shining on the cell. The cell is a radiation-driven capacitor.

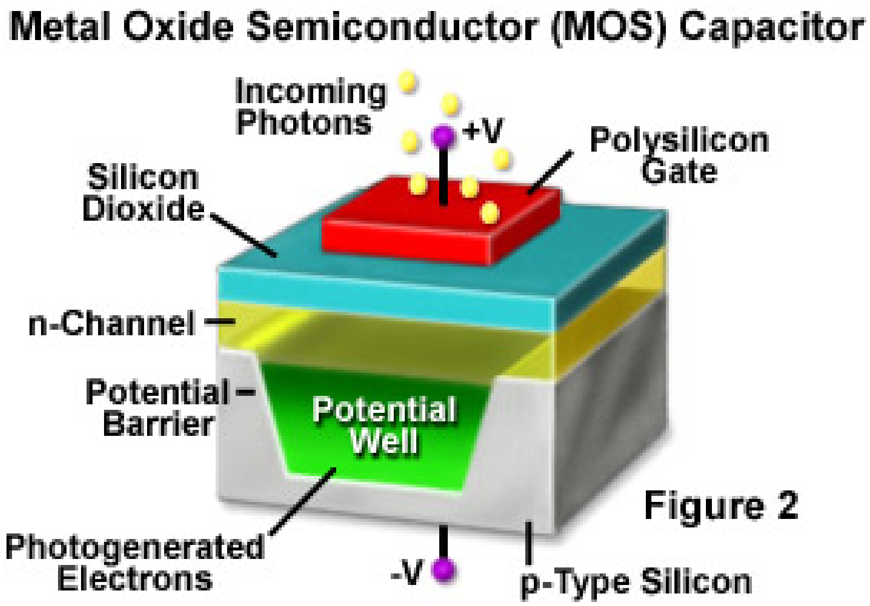

Figure 2 Basic CCD Structure[vii]

If several electrodes are formed on a single silicon chip and zones of very high p-type doping insulate the depletion regions for each other, then each will develop a charge that is proportional to the light intensity. The result is a spatially and electrically digitized reproduction of the original optical image. All that remains is to retrieve the electron image into a useful form.

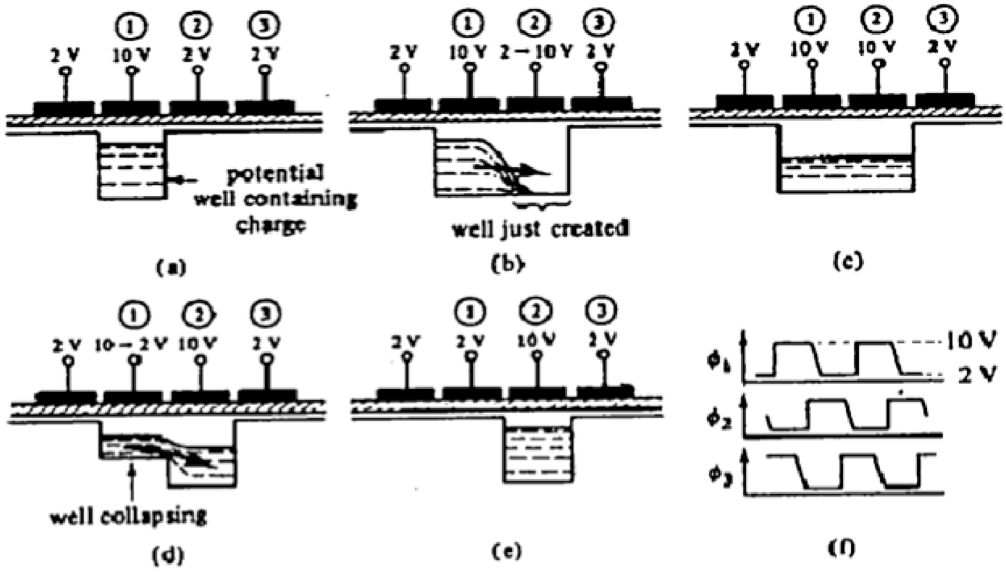

Figure 3 Charge Transfer [viii]

The moving of the electron well image to a visible image is accomplished by charge coupling as shown in Figure 3. Imagine an array of electrodes shown in Figure 3 without their insulating separating layers. If one such electrode acquired a charge, it would diffuse across to the nearby electrodes. If the voltage of the electrodes on either side of the one containing the charge were reduced, then their hole depletion regions would disappear and the charge would once again be contained within two p-type insulating regions as shown in Figure 3 c. This time the insulating regions are not permanent but may be changed by varying the electrode voltage. Thus, the stored electric charge may be moved physically through the structure of the device by sequentially changing the voltages of the electrodes. For example if the voltage on electrode 2 is changed to about +10 V, then a second hole depletion zone will be formed adjacent to the first. The stored charge will diffuse between the two regions until it is shared equally. Now if the voltage on the electrode 1 is gradually reduced to +2 V (Figure 3 d), its hole depletion zone will gradually disappear and the remaining electrons will transfer across to be stored under electrode 2 (Figure 3 e). The charge will move thorough the structure and be brought to an output electrode from where the value of charge is determined by discharging it through an integrating current meter or similar device. With careful design, the efficiency of this charge transfer or coupling may be as high a 99.9999%. The scheme outlined here requires three separate voltage cycles to the electrode to move the charged and is known as a three-phase CCD.[ix] The complete three-phase CCD is a combination of the detecting and charge transfer systems as shown in Figure 3.

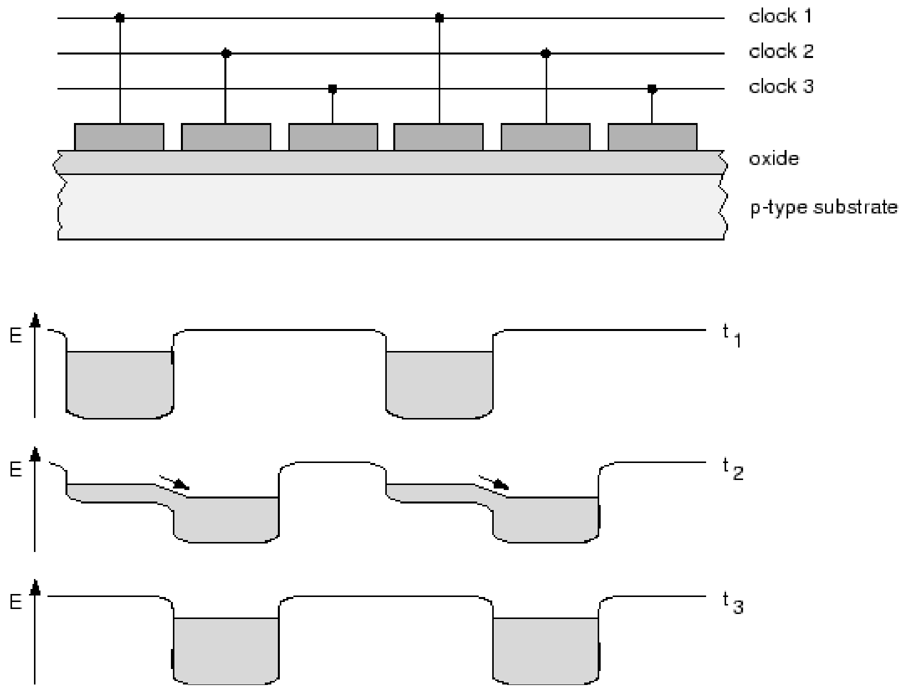

Figure 4 Three-Phase Charge-Couple Device (CCD) Clocking[x]

A complete three-phase CCD is a combination of the detecting and charge transfer systems. Each pixel has three electrodes (1,2,3 on Figure 4) and is isolated from pixels in adjacent columns by insulating barriers. During an exposure, electrode 2 shown in Figure 3 is at its full voltage and the electrons from the whole area of the pixel accumulate. Electrodes 1 and 3 meanwhile are at a reduced voltage and so isolate each pixel from its neighbor along a column. When the exposure is complete, the voltages in the three electrode groups are cycled until the first set of charges reaches the end of the column. At the end of the column, a second set of electrodes running perpendicular to the columns receives the charges into the middle electrode for each column. That electrode is at the full voltage, and its neighbors are at reduced voltages, so that each charge package retains its identity. The voltages in the read-out row of electrodes are then cycled to move the charges to the output electrode where they appear as a series of pulses. When the first row of charges are read, the voltages on the column electrodes are cycled to bring the second row of charges to the read-out electrodes, and so on until the whole image has been retrieved. Figure 4 show the clocking for one-pixel and Figure 5 show how the charge transfer for the whole array.

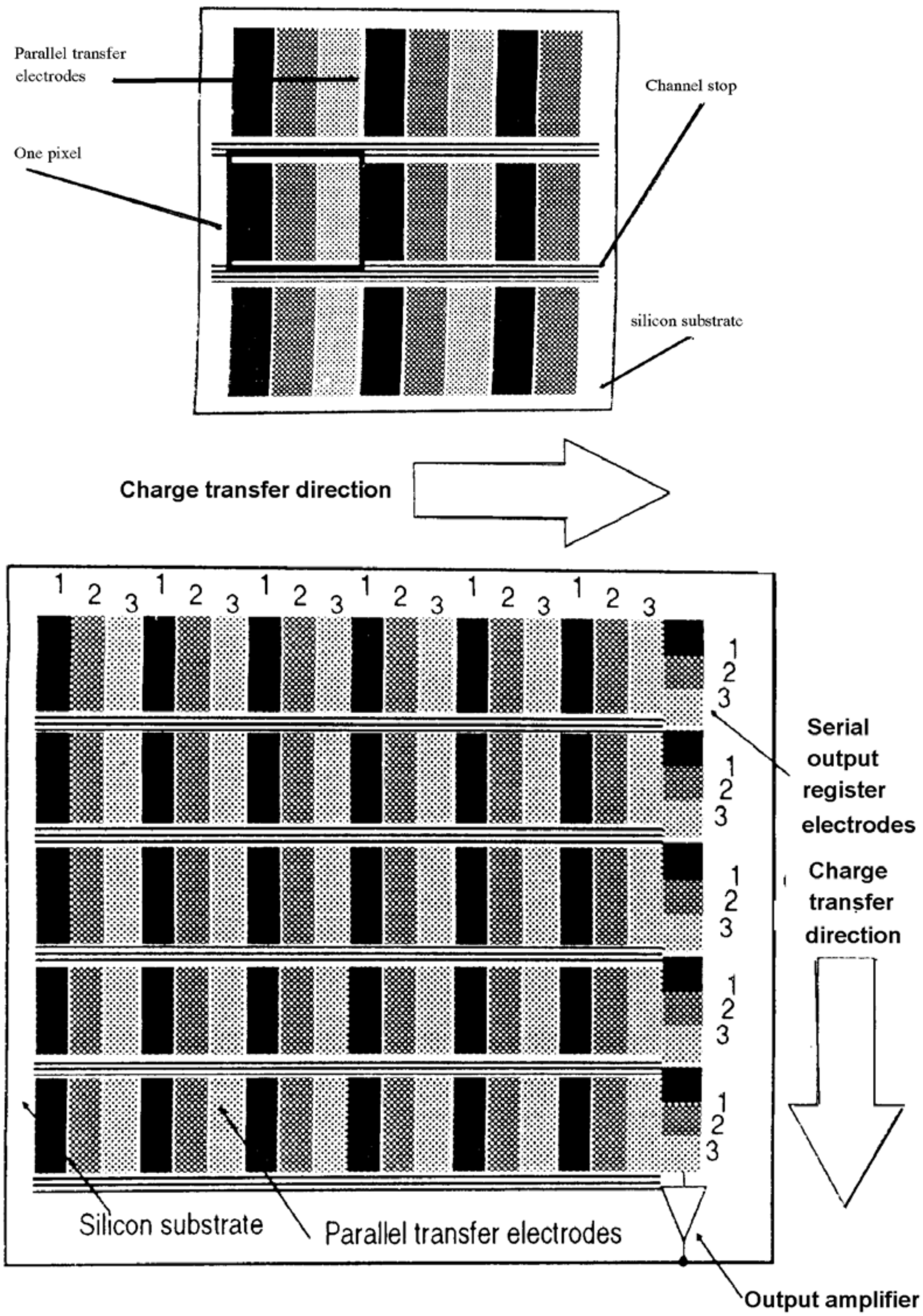

Figure 5 Three-Phase Charge Transfer

Color Images

A CCD only detects total light intensity, which is useful for producing a black and white image, but for a color photograph the incoming light needs to be separated into red, green and blue wavelengths. The first solution is to filter the light into the three colors, using three separated CCDs to capture red, blue and green information and combine then into a full color image. Instead of using three separate CCDs, only one is needed. A single CCD is covered with a filter with read, green and blue pixel sized sections. This creates an image coming out of the CCD that is a mosaic of the three colors. A computer algorithm is applies to estimates the correct colors for each pixel based on the intensity of each color light incidence on the pixel.[xi]

Strategies and Activities

Prior to the study of charge-coupled devices my students have completed a unit of study on quantum physics where they studied the photoelectric effect and atomic energy states. They have also completed units on electrostatics and electric circuits so they have the physics background prior to introduction of CCDs. How CCD work will be introduced to students by displaying a series of old photographs and a group discussion on how film photography works and their experience with film photography. I will include in this power point presentation the song Kodachrome by Paul Simon and ask my students if they have ever heard of Kodachrome. We will all then take pictures with our digital camera phone and try and explain how the image on the phone is created, it quality and how quickly the image is formed. I will then make a power point type of presentation on physics of how CCD's work as described above.

Student Vocabulary and Notes

The quality of the image from a CCD can be assessed in terms of four quantifiable criteria. The principal image quality and their effects are summarize as follows:

Spatial Resolution: Determines the ability to capture fine details without pixels being visible in the image. Pixel count correlates to spatial resolution and CCD sensor is usually described in the megapixels. Digital cameras have a variable relationship between output image resolution and pixel count. The filters used for color images, processing algorithm use to interpolate sensor pixels to image pixels. In addition to the fact that digital sensors are arranged in a rectangular grid pattern making images susceptible to moiré pattern effects, where film has random orientation of its grains and is not effected by moiré patterns

Vocabulary

Light-Intensity Resolution: Defines the dynamic rage or number of gray levels that are distinguishable in the image.

Time Resolution: The sampling (frame) rate determines the ability to follow kinetic processes.

Signal-to-Noise Ratio: Determines the visibility and clarity of the signal relative to the image background.

Quantum Efficiency (QE) is a measure of the likelihood that a photon having a particular wavelength will be captured in the active region of the device.[xii]

The effects of sensor size, the smaller sensors found in digital cameras affect the depth of field, light sensitivity and pixel noise.

Digital cameras are capable of much higher speeds than film, and can perform in low light situations. Digital cameras are fitted with fixed lenses, which makes it harder for dust to get into the image area.

Activity 1

Students will make break-up in to groups of 2 and discuss the advantages and disadvantages of CCDs and film images and make a chart identifying the advantages and disadvantage of film vs. charged- coupled devices they discussed. Each group will share their charts with the class.

Film:

More forgiving of minor focusing issues
More forgiving of exposure problems
Higher resolution
Cameras are heavy and large
Film is a continuing cost

Charge-Coupled devices:

10 megapixels is high enough resolution for very large prints
Can easily lose detail in whites and blacks
Memory cards are small and can store more images then rolls of film
Images can be view immediately
Images can be edited immediately

Can print the images you like
Cameras have built in filters

Activity 2

The experiment I have designed for understanding the coupling of the CCD image will consist of 100 plastic cups and poker chips. The cups will be placed in a ten by ten array representing the pixels on the CCD and the poker chips represent photons of light. An image will be placed on the CCD pixels before students start the lab and the students will act as the changing voltage to transfer the charge in a bucket brigade as displayed in Figure 6. One student will act as the output amplifier and use a ten by ten grid paper to color the corresponding block with the proportional concentration of color for each individual pixel. Ten other students will clock transfer the charge for each column, an additional student will clock transfer the row of electrons to the readout amplifier student. The first image is the school initials and has no variation in intensity. The second image will have a variation in intensity, which is represented by the number of poker chips in each cup

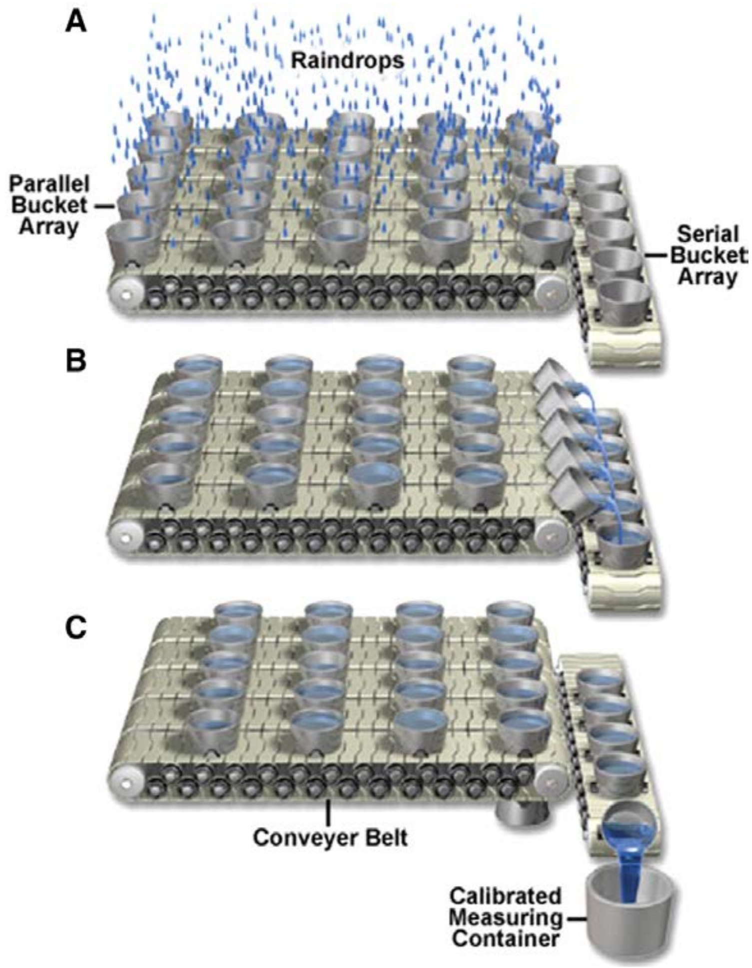

Figure 6 Bucket Brigade Analogy of CCD Readout

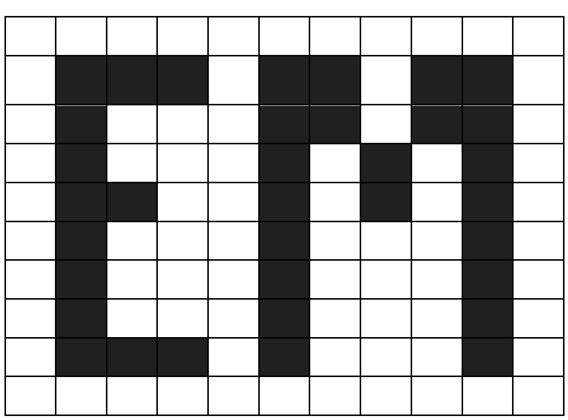

Figure 7 First Experimental Array for Charge Coupling

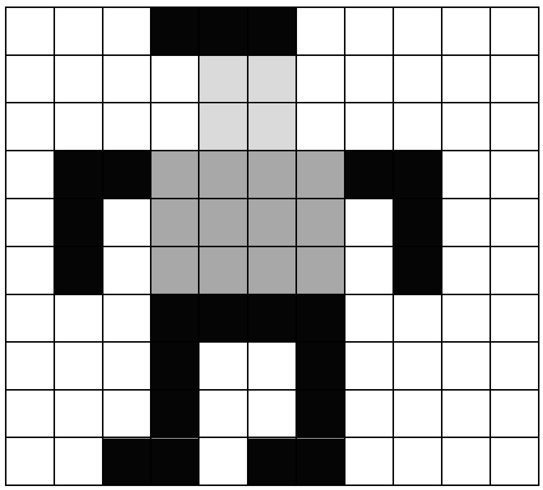

Figure 8 Second Experimental Array for Charged Coupling

More pictures here of the experimental set-up go here

Appendix 1: International Baccalaureate Physics Objectives

14.2. Data Capture; digital imaging using charge-coupled devices (CCDs)

14.2.1. Define capacitance

14.2.2. Describe the structure of a charge-coupled device (CCD).

14.2.3. Explain how incident light causes charge to build up within a pixel.

14.2.4. Outline how the image on a CCD is digitized.

14.2.5. Define quantum efficiency of a pixel

14.2.6. Define magnification

14.2.7. State that two points on an object may be just resolved on a CCD if the images of the points are at least two pixels apart.

14.2.8. Discuss the effects of quantum efficiency, magnification and resolution on the processed image.

14.2.9. Describe a range of practical uses of a CCD, and list some advantages compared with the use of film.

14.2.10. Outline how the image stored in a CCD is retrieved.

14.2.11. Solve problems involving the use of CCDs.

Additional Vocabulary

Fidelity: similarity between the original signal and the reproduced signal.
Perfect reproduction: the recording sounds the same no matter how many times you play it.
ADC: analog-to-digital converter.
DAC: digital-to-analog converter.
Sampling rate: controls how many samples are taken per second.
Sampling precision: controls how many different gradations are possible when taking the sample.

Annotated Bibliography

American Physical Society. "Einstein and the Photoelectric Effect." Edited by Alan Chodos. *American Physical Society News* (APS) 14, no. 1 (01 2005): 1.
Description of the photoelectric effect

Davidson, Michael W. *Molecular Expressions.* Optical microscopy Division of the National Magnetic Fiel Lavoratory. 10 13, 2004.
http://micro.magnet.fsu.edu/micro/about.html (accessed 10 25, 2013).
Dhillon, Vic. *Charge Coupling.* 12 5, 2011.
Complete description with great images of the physics of CCDs

http://www.vikdhillon.staff.shef.ac.uk/teaching/phy217/detectors/phy217_det_coupling.html (accessed 11 11, 2014).
Description on how CCD's work

Hamilton, James. *Careers in Solar Power.* 01 01, 2011.
http://www.bls.gov/green/solar_power/ (accessed 11 21, 2013).
A description on how solar cells work

Hammack, Bill, and Patrick M. Ryan & Nicholas E Ziech. *Eight Amazing Engineering Stories Using the Elements to Create Extraordinary Technologies.* United States: Articulated noise Books, 2012.
Great physics text on how modern technologies.

Kitchin, C.R. *Astrophysical Techniques.* 5th Edition. Boca Raton, Fl: CRC Press Taylor & Francis Group, 2009.
Excellent text on the physics of different imaging techniques

PixCellent Imaging Ltd. *PixCellent.* 11 1, 2006.
http://www.pixcellent.com/CCDROLE5.htm (accessed 11 11, 2013).

Rottinger, Martin. *Dissertation Selected Simulations of Semiconductor Structures.* May 1, 1999. http://www.iue.tuwien.ac.at/phd/rottinger/diss.html (accessed Oct 15, 2013).
Images of CCDs charge transfer

Silicon Far East. *Siliconfareast.com.* 1 1, 2005.
http://www.siliconfareast.com/ccd.htm (accessed 11 11, 2014).
Description on how p-n-junctions work

Simon, Paul. "Songfacts." *Kodachrome.* 1 1, 1997.
http://www.songfacts.com/detail.php?id=1216 (accessed 11 11, 2013).
Word to Paul Simon's song

Spring, Kenneth, Thomas J. Fellers and Michael W. Davidson. *Microscopy U.* 1 1, 2000. http://www.microscopyu.com/articles/digitalimaging/ccdintro.html (accessed 11 11, 2013).
Good description of how CCD and other digital imaging work very good pictures.

Walker, James. *Physics.* San Francisco, Ca: Pearson Addison-Wesley, 2010.
IB physics classroom text book

[i] (Simon 1997)
[ii] (Woodworth 2013)
[iii] (American Physical Society 2005)
[iv] (Kitchin 2009, 11)
[v] (Kitchin 2009)
[vi] (Hamilton 2011)
[vii] (Spring 2000)
[viii] (Dhillon 2011)
[ix] (Kitchin 2009)
[x] (Spring 2000)
[xi] (Bill Hammack n.d.)
[xii] (Spring 2000)