Atatürk Üniversitesi
Anadolu Fizik ve Astronomi Dergisi
(ISSN: 2791-8718)
Cilt 2, Sayı 1, 51-59
Atatürk University
Journal of Anatolian Physics and Astronomy
(ISSN: 2791-8718)
Volume 2, Issue 1, 51-59

JAPA

Working Principles of CCD and CMOS Sensors and Their Place in Astronomy

***1Ahmet Polatoğlu, 1İmam Can Özkesen**

*1Atatürk University, Faculty of Sciences, Department of Astronomy and Space Science, 25240 Erzurum, Turkey.

ORCID*1: https://orcid.org/0000-0002-6562-8566
ORCID1: https://orcid.org/0000-0002-3454-5442

Research Type: Review Article

Received: 17.03.2022, Accepted: 22.04.2022

*Corresponding author: ahmet.polatoglu@atauni.edu.tr (A. Polatoğlu)

Abstract

In this article, information about the properties, working principles and recent developments of CCD and CMOS sensors used in astronomy are given. Until the development of camera technology, sky observations were made using photographic plates in telescopes. With the development of CCD sensors in the 1960s, photographic plates were replaced by powerful cameras with CCD and CMOS sensors. Even today, all observations made in the optical field are made with the data taken by placing these cameras in the ocular part of the telescope. It is of great importance to understand the sensor technology in order to understand the observation techniques. This article has been prepared to fill this gap.
Key Words: Astronomy, Telescope, Sensor, CCD, CMOS.

CCD ve CMOS Sensörlerin Çalışma Prensipleri ve Astronomi Alanındaki Yeri

Özet

Kamera teknolojisinin gelişmesine kadar, teleskoplarda fotoğraf plakaları kullanılarak gökyüzü gözlemleri yapılmıştır. 1960'larda CCD sensörlerinin geliştirilmesiyle, fotoğraf plakalarının yerini CCD ve CMOS sensörlü güçlü kameralar aldı. Bugün bile optik alanda yapılan tüm gözlemler, bu kameraların teleskoplara monte edilerek alınan verilerle yapılmaktadır. Gözlem tekniklerini anlamak için sensör teknolojisini anlamak büyük önem taşımaktadır. Bu makalede CCD ve CMOS sensörlerin özellikleri, çalışma prensipleri ve son gelişmeler hakkında bilgi verilmiş ve sensör teknolojisinin astronomide kullanımı incelenmiştir.
Anahtar Kelimeler: Astronomi, Teleskop, Sensör, CCD, CMOS.

1. Introduction

Photosensitive digital cells are called sensors or optical sensors. CCD and CMOS sensor technology are used today in camera systems, cameras of mobile phones, digital cameras and many systems that are sensitive to image creation. As a result of the demand for these systems, sensor technology is gaining momentum day by day.

The sensors convert the incoming optical image into electronic signals. They consist of light-sensitive cells called photodiodes on sensors. Photodiodes receive light and convert photons into electrical signals. The resolution/pixel of the sensor is proportional to the number of photodiodes. For example, 10 megapixels means 10 million photodiodes. The higher the resolution, the higher the detail quality. If the sensor is produced in small sizes, the photodiodes will be smaller and accordingly less light will be received. Thus, it is understood that sensors with high pixels do not always have high quality. Light sensitivity needs to be increased in order to both use small photodiodes and improve image quality [1].

It is important in terms of image quality that the sensors used in astronomy are produced in large sizes. However, due to the widespread use of mobile products and being more commercial/economical products, small-sized sensors are produced more [2]. Especially silicon sensor technology is used in the field of astronomy. Due to the need for large focal planes in astronomy, large CCD sets have been produced. Newly produced CCD and CMOS sensors are designed with low noise and high measurement accuracy. This feature is also important for obtaining accurate data in astronomical observations [1,3].

2. Material and Methods

2.1. Fundamentals of Sensor Technology

Sensors are devices or subsystems that detect events/information in their environment and send them to other electronic devices (processors). The sensors are used compactly with other electronic devices. In addition to numerous applications, it is also used in everyday objects such as lamps that darken or brighten when touched. With the development of micro-devices and simple-to-use microcontrollers, the use of sensors has moved beyond the very general pressure, humidity or flow measurements. Sensors are generally designed to have little effect on what is being measured. Reducing the size of the sensor often makes it better and provides convenience. Technological developments have opened the door to the production of more sensors at microscopic scale with micro sensors using MEMS technology. Oftentimes, a micro-sensor provides a very fast and short measurement time and higher precision results compared to large systems. Today, the demand for fast, economical and reliable information has increased. Thus, the importance of disposable sensors has increased recently. Using them, important analytical data can be easily obtained by anyone without any problems [1].

There are two basic types of sensors used in almost all digital camera/measurement systems. One of them is CCD (Charge Coupled Device) sensor and the other is CMOS (Complementary Metal Oxide Semiconductor) sensor. CMOS sensors are divided into two main groups as passive pixel sensors and active pixel sensors. There is also a type of sensor that can capture three colors in a single pixel [4]. We will discuss on CCD and CMOS in this article.

2.2. CCD (Charge Coupled Device)

CCD (Charge Coupled Device) sensors, which were discovered by Willard Boyle and George Smith in 1969, have been developed with the advancement of technology and have come to the present day. The working logic of the CCD sensor is to capture the photons coming from the light source. These captured photons form photoelectrons. The resulting photoelectrons are collected in cells called photocells. These electrons formed in the cells are counted and stored together with their coordinates [4].

There are versions of CCD sensors produced and put into use in different ways. One of them, One Chip-One Shot technology, has three basic color-sensitive filters, RGB (Red-Green-Blue) on the sensor. In this way, basic color separation is done on the CCD. CCDs produced by this method are mostly used in entry-level products. It has relatively low costs. In addition to the Two-Chip method RGB filter, there is also a second sensor for brightness. Another method is One Chip-Three Shot technology. In this, after the light falling on the sensor is divided into three parts, RGB, it is exposed with a special filter. Regardless of the technology, CCD sensors are expensive to manufacture, require more energy than other sensors, and require a large area for use. Therefore, CCD sensors are not generally preferred in mobile phones. CCD sensors are more preferred in fields such as special astronomy, as they give relatively higher quality and clear images [5].

2.2.1. Working Principle of CCD

CCDs are based on Metal Oxide Semiconductor (MOS) capacitors technology. Embedded channel capacitors are used for manufacturing. A thin n-type embedded channel is formed by ion doping on the surface of a p-type substrate. A silicon dioxide insulator layer is formed over the n-region and metal or heavily doped polycrystalline silicon gates are placed on top of the CVD (chemical vapor deposition) insulated SiO_2 to fill the capacitor. The main material of CCDs is mostly silicon semiconductors. These sensors are extremely sensitive to light. Capturing photons from the light source, a CCD cell performs four tasks: It takes the charge from the cell above the layer, holds the charge for a while, transfers this charge to the cell below the layer, and produces its own energy. It charges by reacting to external factors such as light [1].

Rays from the light source form photoelectrons. The resulting photoelectrons are collected in the cells in photocells. These electrons formed in cells are counted and stored together with their coordinates. CCD sensors, whose raw material is usually silicon semiconductors, have a light sensitive structure. They convert light into electronic signals and are sent to image processors for processing with this sensitivity. The signals processed on the image processor are converted into digital signals and stored on memory cards [1][4].

The speed, sensitivity, resolution, and cost of a CCD sensor affect its performance. Which CCD type to choose depends on the areas where the devices will be used. Frame transfer structure is used in astronomy because maximum light must be captured. However, the most used in cameras is the interline transfer structure. The three structures used to apply the value read from the CCD array can be described as follows:

i. Full Frame: The entire CCD array acts as the active area. Charges pass through vertical CCDs in parallel and are then removed in series from horizontal CCDs, using a shutter mechanism to block light from reaching the elements. This process takes a lot of time.

ii. Frame Transfer: Half of the adjacent array area is used for exposure and the remaining half is opaque. Loads are transferred from the active region to the opaque region in a short time and are read from there. This operation is faster than full frame reading. However, it has a disadvantage that it uses twice the silicon area.

iii. Interline Transfer: Each pixel has an active area and an adjacent opaque area. Charges are quickly transferred from the photosensitive photodiode to the adjacent vertical CCD unit. There is also the disadvantage of increasing silicon area here. However, with modern developments, it is possible to increase the quantum efficiency of the array by using micro lenses that direct the light away from the opaque regions [7]

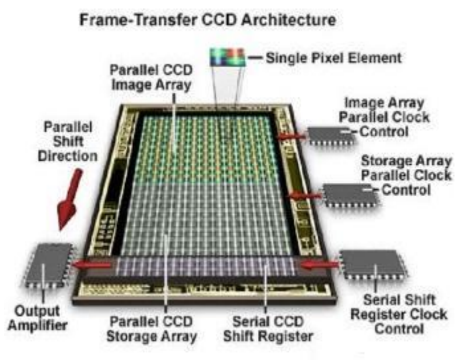

Figure 1. Frame Transfer CCD Architecture [6].

The sensitivity of a CCD device is usually a function of its operating temperature. As the temperature increases, the leakage light-free current also increases, thus decreasing the sensitivity. In devices with a CCD sensor, Signal Noise Ratio (SNR) degradation may occur due to photon noise, readout noise, or a combination of these. CCD arrays are only sensitive to density, not color. Filters are used to obtain color images. Color images can be obtained using a Bayer filter or a 3CCD and dichroic beam splitting prism [8].

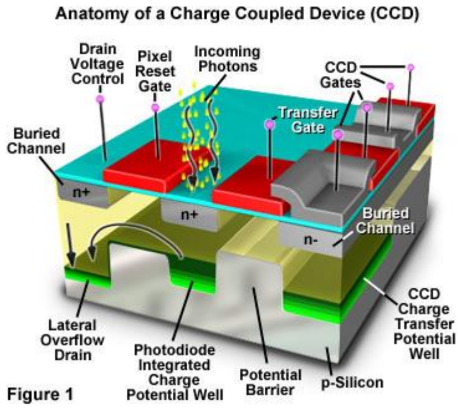

Figure 2. Anatomy of a CCD [6].

2.3. CMOS (Complementary Metal Oxide Semiconductor)

CMOS sensors were discovered by Frank Wanlass in 1963. Like CCDs, they convert light into electronic signals. These sensors consist of hundreds of transistors. Each pixel is generated by a separate transistor. CMOS sensors are widely used. The reason for this is that they have been widely used in devices other than cameras for years and show a continuous development [10],

With this widespread use, CMOS sensors, which can be produced at affordable prices, are often preferred especially in entry-level digital cameras. Especially small floor coverings are one of the most important reasons for this. It is a product frequently encountered in mobile phones, tablets, compact machines and DSLR devices. In addition, factors such as low energy need and not taking up much space play an important role in the preference of these sensors [10,11].

2.3.1. Working Principle of CMOS

CMOS sensors, just like CCD sensors, work according to the photoelectric effect system to convert light into electricity. All CCDs and CMOS sensors perform the same basic tasks: charge generation and collection (light to charge conversion), measurement and conversion to voltage or current, finally signal output.

CCD sensors move the photographic charge from pixel to pixel and convert it to voltage at an output node, as shown in the diagram below; CMOS imagers instantly convert the charge inside each pixel to voltage. Modern CMOS sensors also contain an amplifier for each pixel. After amplification, the voltage output of the pixel is transferred over a micro wire at the output of the chip [11].

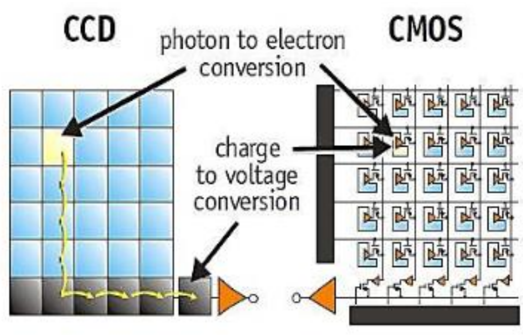

Figure 3. Working differences of CMOS and CCD [11].

2.4. Differnces Between CCD and CMOS

Since CMOS sensors do not take up much space, they are preferred especially in small devices (such as mobile phones, tablets). CMOS sensors can operate with less energy. This means longer battery life. Because CMOS sensor technology is used in many devices, it is inexpensive and easy to manufacture.

CCD sensors generally operate with much lower noise than CMOS sensors. The light sensitivity of CCDs is much higher than that of the CMOS sensor. Therefore, although CMOS gives successful results in bright environments, they give worse results in low light conditions than CCD sensors. CCD sensors produce low noise and high quality images. However, CMOS sensors catch up with the technology and approach CCD technology in terms of quality [12].

3. The Place of CCD and CMOS Sensors in Astronomy

Image quality and low noise are very important in astronomy, as small arcsecond fields are precisely observed. The sensors that meet these conditions have always been CCDs. Although CMOS sensors have been used in astronomy in recent years, CCD use is older and more common.

The use of CCD cameras in astronomy is one of the best detectors we have with current technology, although the CCD chip is not an optically ideal detector. Therefore, it is a detector mostly used in telescopes. External factors such as sensor readout noise, thermal noises, and cosmic rays can alter pixels in the CCD array. So to counter such effects, astronomers take several exposures with the CCD shutter closed and open so that the CCD-acquired images can be analyzed. The average of images (Bias) taken with the shutter closed is required to reduce noise. After the Dark Frame average image is taken, it is subtracted from the light shutter image to clear dark current and other structural defects (dead pixels, hot pixels, etc.) in the CCD. For these processes, images (Bias, Dark, Flat) specific to each CCD are calibrated [12].

3.1. Historical Process and Importance

From the 1900s to the present, there have been great developments in astronomical instruments with telescopes. Telescopes with larger mirror diameters have been produced. Since there are no CCD detectors to record the observation data, photographic images are obtained by using photographic plates (glasses coated with silver halide) placed on the focal plane of the telescope. In addition, the glass wedge placed in the focal plane of the Telescope is adjusted until the intensity of the star is equal to the light intensity of a preselected standard star, and the images taken are calibrated by comparing this glass wedge, and in photographic photometry the brighter the star image on a plate, the larger the star size. Some instruments such as micrometers and thermocouples are used with these photographic plates. In addition, the blink microscopes used for comparison were used to distinguish the differences in the plates by rapidly rotating the plates taken at different times. Although CCDs came into our lives in the 1970s, these methods were used until the end of the 1900s and CCDs replaced photographic plates in astronomy [13].

CCDs were first produced at Bell Laboratories in the 1970s. The first CCD 1969 Willard Boyle and George Smith single array 8 pixel detector. Later, in 1973, the Jet Propulsion Laboratory (JPL), NASA and TI jointly started a large-area CCD development program for Astronomy. The first commercial CCD device was produced by Fairchild in 1974. In 1974, the Moon was imaged using an 8 inch Telescope with a Fairchild CCD (100x100 pixels), and this is the first astronomical CCD image. Among the earliest astronomical applications of a CCD for ground observation were made at the University of Arizona in 1976 (Smith 1976). The first CCD-based reconnaissance satellite, KH-11 KENNAN, was launched in 1976. CCD development continued over the years, and in 1979 Radio Corporation of America (RCA) developed a liquid nitrogen-cooled CCD system [14].

Continuing developments from the 1980s to the present have led to devices with over 100 million pixels, read noise as low as an electron, quantum efficiency close to 100%, and useful sensitivity close to X-rays to IR. While CCDs have fallen out of favor with CMOS imagers for commercial imaging applications, they are still cutting-edge sensors for astronomical imaging due to their size, efficiency and low noise. Over the years, scientists who make astronomical instruments have developed CCDs specific to their areas of interest [1,14].

In 1983, CCDs began to replace photographic plates in astronomical telescopes. Kodak produced CCD-based professional cameras until affordable, high-resolution cameras began to hit the market in 1995 [1].

3.2. Basic Definitions

There are special requirements for astronomical imaging, astronomers have often made special CCD sensors for their own observing needs. These special requirements are:
Pixel Size: Larger than normal pixels are used in astronomy due to sensors, large full well capacity and dynamic range.
Dark Current: Exposures taken with the CCD's diaphragm closed. The electron flow resulting from the heating of the CCD and electronic parts is called black current. The exposure time for Dark is given

as much as the exposure time of the object to be observed. eg. If we are going to observe the Polaris star with exposures of 20 seconds, images are taken with an exposure time of 20 seconds for the dark.

Quantum Efficiency: It is the ratio of the number of photons measured to the number of all incoming photons. If this value is 1, it means that all incoming photons are captured by the detector, and there is no such perfect instrument. An instrument with a quantum efficiency of 90% is considered sensitive.

Bias: It is the exposure taken in zero seconds while the aperture is closed. Returns the electronic noise value in the CCD [12]. Raw Biased Frames are created with zero light to the camera. Science frames are created that take zero-second exposures (shortest exposure) in the same grouping mode (1x1, 2x2). After creating a Master Bias, it can be used until the ambient temperature is too high to regulate the CCD temperature anymore or a change is made to the electronic path of the system.

Dark: The thermal movements of electrons within the chip produce signals gradually, proportional to the exposure time, not because they are exposed to optical light, but because these thermal electrons have a chance to accumulate in each pixel over time. The Dark Frame is made to measure the "dark current" or thermal signal in the CCD chip so that it can be extracted from the data images.

Flat: Not every pixel in the CCD has the same sensitivity. The middle pixels are brighter and the edges are dimmer. These are images taken to correct for different distribution. The exposure time is given as half the saturation level of the pixels. In which filter the object to be observed will be observed, flat is taken in the same filter [12].

4. New Developments

CCD and CMOS sensors have made great advances in recent years. Low noise ratio, high resolution and quality images are provided. CMOS sensors, on the other hand, have caught up with CCD sensors at a better viewing point, although they are made in smaller sizes.

Thinned CMOS sensors have been produced for use in astronomy. Examples of these are TAOS-II CIS113 sensor, NGSD/LGSD CIS112 sensor, CIS115 sensors. For large space programs, sensor technologies such as GAIA CCD91, Euclid CCD273, Plato CCD270, Rosetta have been developed. Studies are also underway on EMCCD and Red Sensitive CCDs [2, 16].

5. Conclusion

What makes a digital camera digital is the image sensor in the camera. That is, an image sensor converts the light captured by the camera's lens into a digital signal. This digitized light is processed and stored in the camera's memory as a digital file that you can view on the computer later. Next to the lens, the image sensor is the key element that ensures quality video. There are two main types of camera image sensors: CCD and CMOS. Both types of image sensor technologies contain hundreds of thousands or even millions of pixels. We can think of a pixel as a small bucket that captures light and converts it into an electrical signal. CCD and CMOS sensors have different advantages, but technology is evolving rapidly and the situation is constantly changing. Therefore, the best strategy for a camera manufacturer is to constantly evaluate and test the sensors for each camera. The field of astronomy is also an area that can no longer progress without sensor technology. With each passing day, we will see that more powerful sensors are produced.

Conflicts of Interest

The authors declare that there are no potential conflicts of interest relevant to this article.

References

[1] Gourab Sen Gupta, (2008). Smart sensors and sensing technology. 1st ed. Springer.

[2] Jorden P.R., Jordan D., Jerram P.A., Pratlong J., Swindells, I. (2014). e2v new CCD and CMOS technology developments for astronomical sensors. High Energy, Optical, and Infrared Detectors for Astronomy VI, ed. by Andrew D. Holland, James Beletic, 9154(91540).

[3] Büttgen, B. (2005).. CCD/CMOS Lock-In Pixel for Range Imaging: Challenges, Limitations and State-of-the-Art. Researchgate.

[4] Litwiller D. (2001). CCD vs CMOS: Facts and Fiction.

[5] CCD ve CMOS nedir? [Internet]. 2022 [25 February 2022]. Access Link: https://birkarefotograf.com/cmos-ve-ccd-nedir/

[6] Hamamatsu [Internet]. 2022 [12 March 2022]. Access Link: https://hamamatsu.magnet.fsu.edu/articles/ccdanatomy.html

[7] Astro [Internet]. 2022 [05 February 2022]. Access Link: https://www.astro.rug.nl/~ndouglas/teaching/JAFFE/reduce.htm

[8] Aavso [Internet]. 2022 [2 March 2022]. Access Link: https://www.aavso.org/sites/default/files/publications_files/ccd_photometry_guide/CCDPhotometryGuide.pdf

[9] CCD nedir [Internet]. 2022 [1 January 2022]. Access Link: https://www.elektrikport.com/makale-detay/ccd-sensor-nedir/21967#ad-image-1

[10] Lesser, M. A Summary of Charge-Coupled Devices for Astronomy, Publications of the Astronomical Society of the Pacific, 2015; (127)-957.

[11] CMOS Image Sensors, Moazalhosny [Internet] 2017. Access Link: https://www.researchgate.net/publication/316986687_basic_description_of_CMOS_camera_sensor_and_color_precnible.

[12] Astrophotography [Internet]. 2022 [3 January 2022]. Access Link: https://practicalastrophotography.com/a-brief-guide-to-calibration-frames/.

[13] Andor [Internet]. 2021 [25 December 2021]. Access Link: https://andor.oxinst.com/learning/view/article/ccd-sensor-architectures.

[14] Observational Astronomy [Internet]. 2021 [24 February 2021]. Access Link: https://en.wikipedia.org/wiki/Observational_astronomy.

[15] Petrov B. [Internet]. 2021 [16 December 2021]. Access Link: https://www.astro.bas.bg/~petrov/galaxies_files/astroinst.html.

[16] Jorden P.R., Jordan D., Jerram P.A., Pratlong J., Swindells I. (2016). e2v new CCD and CMOS sensors and systems designed for astronomical applications. High Energy, 900-915.