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Introduction

Silicon. This semiconductor material certainly has large implications on our life. Its uses are many, including silicon oil lubricants, implants to change our bodies' outward appearance, electric circuitry of all kinds, nonstick frying pans, and, of course, charge-coupled devices.

Charge-coupled devices (CCDs) and their use in astronomy will be the topic of this book. We will only briefly discuss the use of CCDs in commercial digital cameras and video cameras but not their many other industrial and scientific applications. As we will see, there are four main methods of employing CCD imagers in astronomical work: imaging, astrometry, photometry, and spectroscopy. Each of these topics will be discussed in turn. Since the intrinsic physical properties of silicon, and thus CCDs, are most useful at optical wavelengths (about 3000 to 11 000 Å), the majority of our discussion will be concerned with visible light applications. Additional specialty or lesser-used techniques and CCD applications outside the optical bandwidth will be mentioned only briefly. The newest advances in CCD systems in the past five years lies in the areas of (1) manufacturing standards that provide higher tolerances in the CCD process leading directly to a reduction in their noise output, (2) increased quantum efficiency, especially in the far red spectral regions, (3) new generation control electronics with the ability for faster readout, low noise performance, and more complex control functions, and (4) new types of scientific grade CCDs with some special properties. These advances will be discussed throughout the text.

Applications of infrared (IR) arrays – semiconductor devices with some similar properties to CCDs – while important to modern astronomy, will receive small mention here. A complete treatment of IR arrays is given by Ian Glass in his companion book, *Handbook of Infrared Astronomy*, the first book in this series.

Appendix A provides the reader with a detailed list of other books and major works devoted to CCD information. This appendix does not contain the large body of journal articles in existence; these will be selectively referenced throughout the text. Appendix B provides a list of present day CCD manufacturers that produce both amateur and professional grade CCDs and CCD cameras, observatory websites, and other websites that contain useful CCD information. Finally, Appendix C discusses some basic principles of image display devices. While not directly related to CCDs, computer displays are the medium by which we view and examine the information collected by CCDs. Proper interpretation of the CCD image is only possible if one understands how it is displayed.

1.1 Nomenclature

CCDs are often listed and named by an apparently strange convention. This small section aims to demystify these odd sounding names. CCDs come in various sizes and shapes and are manufactured by a number of companies (see Appendix B).

Figure 1.1 illustrates a number of modern CCDs. Present day CCDs generally come in sizes ranging from 512 by 512 "picture elements" or pixels to arrays as large as 8192 by 8192 pixels. Often the size designations of CCDs are written as 2048×2048 or 2048^2. CCDs are also available as rectangular devices of unequal length and width and with nonsquare pixels. For example, CCDs of size 2048×4096 pixels are produced for spectroscopic applications. We will see in Chapter 2 that each pixel acts as an electrically isolated portion of the silicon array and is capable of incoming photon collection, storage of the produced photoelectrons, and readout from the CCD array to an associated computer as a digital number.

The names or designations of CCDs are usually a combination of the company name with the CCD size. Tek2048, $4K \times 2K$ E2V, and SITe4096 are examples. Instrumentation at observatories almost exclusively includes a CCD as the detector and is specialized to perform a task such as imaging or spectroscopy. Observatories designate these instruments with a name that may or may not include information about the associated CCD detector. The Royal Greenwich Observatory (RGO) on La Palma has the FOS#1A (a 512×1024 Loral CCD used in their Faint Object Spectrograph), and the Tek 2K CCD of the National Optical Astronomy Observatories (NOAO) is a 2048×2048 pixel array used in their 0.9-m telescope imaging camera. Observatories keep lists of each of their instruments and associated CCDs with detailed documentation about the CCD specifications. For examples of such information, check out the observatory websites listed in Appendix B.

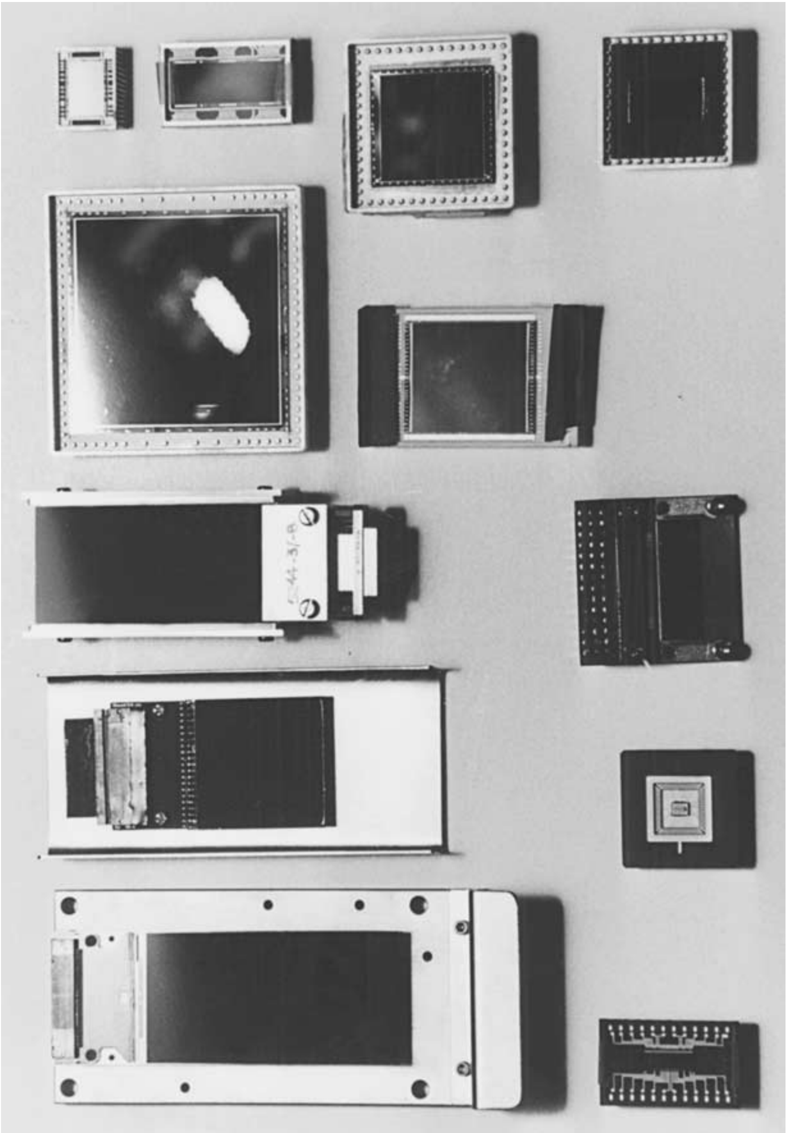

Fig. 1.1. A selection of CCDs of the type that are currently used in astronomical instruments at various telescopes throughout the world. Clockwise from bottom left they are: SITe-002 (2048 × 4096), Loral 2k3eb (2048 × 2048), E2V CCD42-80 (2048 × 4096), SITe-424 (2048 × 2048), GEC P8603 (385 × 578), E2V 15-11 (1024 × 256), TeK1024 (1024 × 1024), Loral 512FT (512 × 1024), E2V-05-30 (1242 × 1152), E2V CCD42-10 (2048 × 512), Loral-64 (64 × 64), and E2V CCD39-01 (80 × 80). E2V Technologies was formerly known as Marconi and prior to that as EEV.

1.2 Why use CCDs?

Most astronomical detectors in use today at professional observatories, as well as with many amateur telescopes, are CCDs. This fact alone gives the reader an impression that there must be something very special or useful about CCDs; otherwise why all the fuss? CCDs have revolutionized modern astronomy. They will take their place in astronomical history along with other important discoveries such as the telescope, photographic plates, prisms, and spectroscopy. The contribution to our knowledge of the heavens brought about by CCDs is astounding, even more so when one considers that they have been in use for only about thirty years.

First introduced as electronic analogs to magnetic bubble memory (Amelio, Tompsett, & Smith, 1970; Boyle & Smith, 1970) at Bell labs, CCDs provided their first astronomical image in 1975 when scientists from the Jet Propulsion Laboratory imaged the planet Uranus at a wavelength of 8900 Å (Janesick & Blouke, 1987). This observation used the University of Arizona 61-inch telescope atop Mt. Lemmon and a prototype version of a CCD made by Texas Instruments Corporation as part of a development project for NASA spacecraft missions.

During the past ten years, tremendous progress has been made in the manufacturing process and therefore in the properties of the CCD itself. These improvements have allowed much lower noise properties for CCDs, thereby increasing their overall efficiency in astronomy. In addition, larger format devices have been produced and the readout times are much shorter, approaching 1-2 seconds even for arrays as large as 1024 pixels square. This latter advance is mainly due to the availability of high-speed, low-power and low-noise CCD controllers (see Chapter 2). The driving technology for CCD manufacturing is for items such as copy machines, TV cameras, and digital cameras, but the requirements for low noise, excellent pixel cosmetics, and nearly perfect performance is still firmly rooted in astronomy. We outline below two of the important reasons why CCDs are considered as essentially the perfect imaging device. Details of the manufacturing techniques and properties of CCDs will be presented in Chapters 2 and 3.

1.2.1 Noise properties

The usefulness of a detector is very often determined by the amount of inherent noise within the device itself. We shall see in Chapter 3 how the noise properties of a CCD are determined, but, suffice it to say here, modern astronomical CCDs are almost noise free. The original line of photosensitive electronic array detectors, such as television-type imaging detectors, vidicons, silicon intensified targets, and image-dissector scanners, all had very high noise properties. For comparison, silicon intensified target imagers (SITs) had a noise level upon readout of 800 electrons per picture element. Some very good systems of this type could be produced with read noise values of only 200 electrons (Eccles, Sim, & Tritton, 1983). The first CCDs had readout noise levels similar to this latter value, while modern CCDs have noise values of ten down to two electrons per pixel per readout. The large noise levels present in early array detectors not only limited the signal-to-noise ratio obtainable for a given measurement, they also severely limited the total dynamic range available to the camera. Another "feature" of older, higher noise CCDs was the decision an astronomer had to make about co-addition of frames. Since the read noise adds as its square to the total noise budget (see Chapters 3 & 4) adding two frames resulted in a much higher read noise contribution. Today, with typical read noise values of 2–5 electrons, co-addition is essentially equal to a single exposure of longer integration time.

1.2.2 Quantum efficiency and band-pass

Quantum efficiency (QE) is the term used to report on the ability of a detector to turn incoming photons into useful output. It is defined as the ratio of incoming photons to those actually detected or stored in the device. A QE of 100% would be an ideal detector with every incoming photon detected and accounted for in the output. Band-pass is a term that means the total spectral range for which a detector is sensitive to the incoming photons. Our eyes, for example, have a very limited band-pass covering only about 2000 Å of the optical spectral range, from near 4500 to 6500 Å.

One of the great advantages of CCDs compared with earlier detectors is their ability to convert a large percentage of incoming photons into photoelectrons. Photographic plates had an intrinsic quantum efficiency of only about 2% (Kodak IIIaJ's reached 3%), with "hypersensitized" plates (plates treated to a black-magic process involving heating and exposure to various "forming" gases) reaching claimed QEs as high as 10%. Because photographic emulsions were originally more sensitive to UV and blue light,[1] numerous dyes and coatings were developed to both extend their band-pass coverage and allow detection of yellow to red optical photons.

[1] The fact that early astronomical imagers (i.e., photographic plates) were blue sensitive is a major reason that most of today's standard stars are blue, the MK spectral classification scheme was initially blue feature based, and why astronomical discoveries such as brown dwarfs and high-z quasars did not happen until recently.

Early solid-state imaging devices and intensified silicon target devices could reach quantum efficiencies as high as 20–40%. These devices relied on television-type tube technology and electron beam scanning for readout of detected photons. Since they used silicon (or similar type materials) as the detector material, their useful spectral band-pass was similar to that of modern CCDs. However, besides the relatively low QE, these early electronic detectors had other drawbacks. For example, image tubes needed high voltage input for electron acceleration and the observed two-dimensional scene was not easily or consistently divided into well-determined x, y positional output (Walker, 1987). Changes in the voltage levels, collected charge, and telescope position resulted in electric and magnetic field variations leading to positional and flux measurement uncertainties.

Even the earliest CCDs (those manufactured by Fairchild or GEC) easily reached peak QEs of 40%. Typical CCD QE curves today not only peak near 90% but are 60% or more quantum efficient over two thirds of their total spectral range. Increased red sensitivity using deep depletion techniques and better thinning and coating processes (blue) will be discussed later. The band-pass available in a modern CCD (with a QE of 10% or more) is about 3000–11 000 Å. Coatings and phosphors deposited on the CCD surface or the use of some form of pre-processor device can extend the band-pass sensitivity limits or increase the QE in specific wavelength ranges (see Chapter 2).

This volume of the Cambridge Observing Handbooks for Research Astronomers will explore the world of CCDs from their inner workings to numerous applications in observational astronomy. Appendices are included to provide ancillary information related to the main text. The chapters will make little assumption as to the reader's previous knowledge on the subject, each attempting to be somewhat self-contained. Chapters 4, 5, and 6 deal directly with astronomical applications while Chapters 2 and 3 are of general interest to those wanting an overall understanding of CCDs as detectors. Chapter 7 discusses the use of CCDs at non-optical wavelengths. In a short treatise such as this, coverage of numerous details and nuances is not possible; thus a detailed reference list to general texts or collections of articles on CCDs is provided in Appendix A. For those wishing to explore a subject at a deeper level, pertinent research articles are cited throughout the text itself.

1.3 Exercises

1. Using the manufacturer websites given in Appendix B, make a list of the various CCDs they produce taking note of the physical and pixel sizes

of each. Can you draw any conclusions about a relationship between the CCD size and the application it is designed for?

2. Using two of the astronomical observatory websites listed in Appendix B, make a list of the types of instrumentation available and the specific type of CCD used in each. Can you draw any conclusions about a relationship between the CCD properties and physical size, and the type of instrument and science it is designed for?
3. Read the article mentioned in Chapter 1 in which the first astronomical CCD image is contained. Discuss how this one advance changed astronomical imaging.
4. What are the two most important reasons that CCDs are the detector of choice in modern astronomy? How do these two properties compare between your eye and those of a typical CCD?

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CCD manufacturing and operation

Before we begin our discussion of the physical and intrinsic characteristics of charge-coupled devices (Chapter 3), we want to spend a brief moment looking into how CCDs are manufactured and some of the basic, important properties of their electrical operation.

The method of storage and information retrieval within a CCD is dependent on the containment and manipulation of electrons (negative charge) and holes (positive charge) produced within the device when exposed to light. The produced photoelectrons are stored in the depletion region of a metal insulator semiconductor (MIS) capacitor, and CCD arrays simply consist of many of these capacitors placed in close proximity. Voltages, which are static during collection, are manipulated during readout in such as way as to cause the stored charges to flow from one capacitor to another, providing the reason for the name of these devices. These charge packets, one for each pixel, are passed through readout electronics that detect and measure each charge in a serial fashion. An estimate of the numerical value of each packet is sent to the next step in this process, which takes the input analog signal and assigns a digital number to be output and stored in computer memory.

Thus, originally designed as a memory storage device, CCDs have swept the market as replacements for video tubes of all kinds owing to their many advantages in weight, power consumption, noise characteristics, linearity, spectral response, and others. We now further explore some of the details glossed over in the above paragraph to provide the reader with a basic knowledge of the tortuous path that the detected photon energy takes from collection to storage. The design of CCD electronics, semiconductor technology, and detailed manufacturing methods are far beyond the level or space constraints of this book. For further information the reader is referred to the excellent discussion in Janesick & Elliott (1992) and Janesick (2001) plus the other technical presentations listed in Appendix A.

2.1 CCD operation

The simplest and very understandable analogy for the operation of a CCD is also one that has been used numerous times for this purpose (Janesick & Blouke, 1987). This is the "water bucket" idea in which buckets represent pixels on the CCD array, and a rainstorm provides the incoming photons (rain drops). Imagine a field covered with buckets aligned neatly in rows and columns throughout the entirety of the area (Figure 2.1). After the rainstorm (CCD integration), each bucket is transferred in turn and metered to determine the amount of water collected. A written record (final CCD image) of the amount of water in each bucket will thus provide a two-dimensional record of the rainfall within the field.

Referring to the actual mechanisms at work within a CCD, we start with the method of charge generation within a pixel: the photoelectric effect.[1] Incoming photons strike the silicon within a pixel and are easily absorbed if

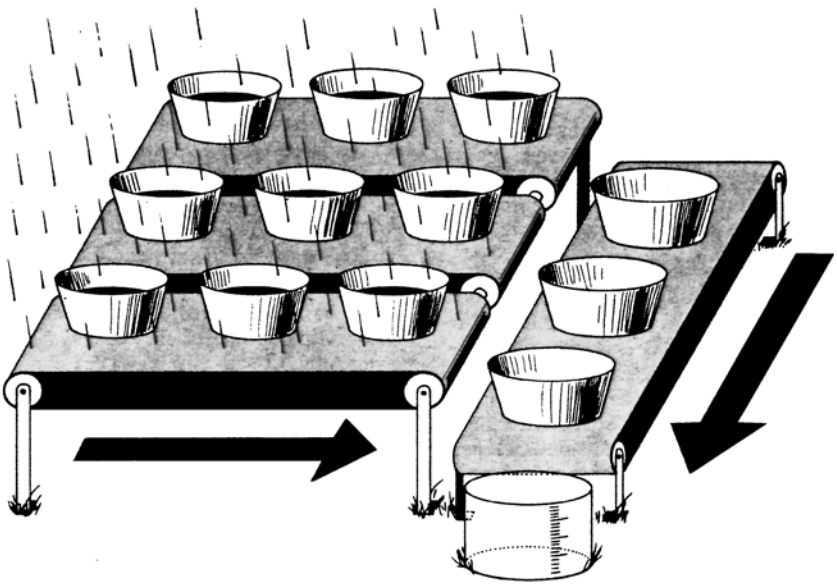

Fig. 2.1. CCDs can be likened to an array of buckets that are placed in a field and collect water during a rainstorm. After the storm, each bucket is moved along conveyor belts until it reaches a metering station. The water collected in each field bucket is then emptied into the metering bucket within which it can be measured. From Janesick & Blouke (1987).

[1] Albert Einstein received his Nobel Prize mainly for his work on the photoelectric effect, not, as many think, for relativity.

they possess the correct wavelength (energy). Silicon has a band gap energy of 1.14 electron volts (eV), and so it easily absorbs light of energy 1.1 to 4 eV (11 000 to 3000 Å).[1] Photon absorption causes the silicon to give up a valence electron and move it into the conduction band. Photons of energy 1.1 eV to near 4 or so eV generate single electron–hole pairs, whereas those of higher energy produce multiple pairs (see Section 2.2.8 and Chapter 7). Left to themselves, these conduction band electrons would recombine back into the valence level within approximately 100 microseconds. Silicon has a useful photoelectric effect range of 1.1 to about 10 eV, which covers the near-IR to soft X-ray region (Rieke, 1994). Above and below these limits, the CCD material appears transparent to the incoming photons.

Once electrons have been freed to the conduction band of the silicon, they must be collected and held in place until readout occurs. The details of the actual construction of each pixel within a CCD, that is, the formation of the MIS capacitor with its doped silicon, layers of silicon dioxide, etc., are beyond the scope of this book (Eccles, Sim, & Tritton, 1983; Janesick & Elliott, 1992), but suffice it to say that each pixel has a structure allowing applied voltages to be placed on subpixel sized electrodes called gates. These gate structures provide each pixel with the ability to collect the freed electrons and hold them in a potential well until the end of the exposure. In a typical arrangement, each pixel has associated with it three gates, each of which can be set to a different voltage potential. The voltages are controlled by clock circuits with every third gate connected to the same clock. Figure 2.2 illustrates this clocking scheme for a typical three-phase device.

We note in Figure 2.2 that, when an exposure ends, the clock voltages are manipulated such that the electrons that have been collected and held in each pixel's +10 volt potential well by clock voltage V3 can now be shifted within the device. Note that electrons created anywhere within the pixel during the exposure (where each pixel has a surface area equal to the total area under all three gates) will be forced to migrate toward the deepest potential well. When the exposure is terminated and CCD readout begins, the voltages applied to each gate are cycled (this process is called clocking the device) such that the charge stored within each pixel during the integration is electronically shifted. A simple change in the voltage potentials (V3 goes to +5 volts, while V1 becomes +10 volts and so on) allows the charge to be shifted in a serial fashion along columns from one CCD pixel to another throughout the array. The transfer of the total charge from location to location within the array is not without losses. As we will see, each charge transfer (one

[1] The energy of a photon of a given wavelength (in electron volts) is given by $E(\text{eV}) = 12\,407/\lambda(\text{Å})$.