CCDs in Digital Imaging Technology

Charge-coupled devices (CCDs), like microprocessor and memory integrated circuits, are fabricated on silicon wafers in a series of elaborate steps using photolithography to define and build various functional elements within the micro circuitry. Each wafer contains tens to hundreds of identical devices, each fully capable of producing a single CCD chip for use in digital cameras. This section of the Molecular Expressions Photomicrography Primer contains links to illustrated discussions of important CCD concepts, which are critical in forming a complete understanding of digital imaging techniques.

Anatomy of a Charge-Coupled Device

Digital image sensor technology is centred on the semiconductor charge-coupled device, which is fabricated in a manner similar to that used in the production of integrated circuits ranging from microprocessors to memory chips. This section discusses common features of CCD anatomy and the basic principles of device operation.

Binning

Pixel binning is a clocking scheme used to combine the charge collected by several adjacent CCD pixels, and is designed to reduce noise and improve the signal-to-noise ratio and frame rate of digital cameras. The binning process is performed by on-chip timing circuitry that assumes control of the serial and parallel shift registers prior to amplification of the CCD analogue signal.

CCD Saturation and Blooming

Saturation and blooming are related phenomena that occur in all CCD image sensors under conditions in which either the finite charge capacity of individual photodiodes, or the maximum charge transfer capacity of the CCD, is reached. Once saturation occurs at a charge collection site, accumulation of additional photo-generated charge results in overflow, or blooming, of the excess electrons into adjacent device structures. A number of potentially undesirable effects of blooming may be reflected in the sensor output, ranging from white image streaks and erroneous pixel signal values to complete breakdown at the output amplification stage, producing a dark image.

Dynamic Range

In a charge-coupled device (CCD) or complementary metal oxide semiconductor (CMOS) image sensor, dynamic range is typically specified as the maximum achievable signal divided by the camera noise, where the signal strength is determined by the full-well capacity, and noise is the sum of dark and read noises. As the dynamic range of a device is increased, the ability to quantitatively measure the dimmest intensities in an image is improved. The dynamic range represents the spectrum of intensities that can be accommodated when detector gain, integration time, lens aperture, and other variables are adjusted for differing fields of view.

Quantum Efficiency

The quantum efficiency of a charge-coupled device (CCD) is a property of the photovoltaic response defined as the number of electron-hole pairs created and successfully readout by the device for each incoming photon. This property is especially important for low-light imaging applications such as fluorescence microscopy where illumination is sparse and secondary emission photon wavelengths are often in the 375-550 nanometre range and have a relatively high absorption coefficient.

CCD Noise Sources and Signal-to-Noise Ratio

Charge-coupled device (CCD) sensors have numerous advantages over photographic film in scientific imaging applications such as astronomy and optical microscopy. By directly producing images in digital format, suitable for immediate computer processing, CCD-based image capture systems are ideally suited to a wide range of current microscopy and image analysis methods. In particular, the much greater sensitivity of such sensors compared to film is invaluable in low-light techniques, for which every available signal photon may be significant. Noise, arising from a variety of sources, is inherent to all electronic image sensors, and careful control of noise components, both in the design and operation of the CCD system, is necessary to ensure that the signal level relative to noise is adequate to allow capture of accurate image information. For any electronic measuring system, the signal-to-noise ratio (SNR) characterizes the quality of a measurement and determines the ultimate performance of the system.

Charge-Coupled Device (CCD) Linearity

An important characteristic of a scientific imaging system is the linearity in response to incident light, particularly when applied for quantitative photometric analysis. In digital camera systems employing charge-coupled device (CCD) sensors, the fundamental function of the CCD is to convert photons carrying image information into an electronic signal. After digitization, the signal output should ideally be linearly proportional to the amount of light incident on the sensor.

Electronic Shutters

Electronic shutters are employed in charge-coupled devices (CCDs) to control integration time (exposure) of the photodiode array and reduce smear when capturing moving objects in the microscope.

Charge Transfer Clocking Schemes

Charge transfer through CCD shift registers occurs after integration to relocate accumulated charge information to the sense amplifier, which is physically separated from the parallel pixel array. Several clocking schemes, three of which are discussed below, are utilized to transfer charge from the collection gates to the output node.

- Four-Phase CCD Clocking - A four-phase CCD incorporates four individual polysilicon gate electrodes in each pixel cell, each of which requires a separate input clock signal to properly transport accumulated charge.
- Three-Phase CCD Clocking – Three-phase CCD clocking improves spatial resolution over that obtained in four-phase devices, yet requires only three gates per pixel. This scheme differs from four-phase clocking by using only one storage gate and two barrier gates, which allows for faster frame rates and the fabrication of higher density and resolution CCDs.
- Two-Phase CCD Clocking - A two-phase charge transfer CCD clocking scheme employs four gates for each pixel, with adjacent gates connected together as pairs. Each gate pair is connected to an alternate clock line and one of the gates in each pair is designed with an increased n-type doping level beneath the gate. When voltage is

applied to the gate pair, the gate having the increased doping level has a more positive potential, which increases the depth of the charge storage area and results in a "step" in the potential energy profile.

CCD Scanning Formats

Charge-coupled device (CCD) digital imaging sensors are capable of acquiring images in one of three formats: point scanning; line scanning, and area scanning. Each of these formats has specific applications in digital photography and scanning of documents and images.

Full-Frame CCD Architecture

Full-frame charge-coupled devices feature high-density pixel arrays capable of producing digital images with the highest resolution currently available. This CCD architecture has been widely adopted due to the simple design, reliability, and ease of fabrication.

Frame-Transfer CCD Architecture

Frame-Transfer charged coupled image sensors have architecture similar to that of full-frame CCDs. These devices have a parallel register that is divided into two separate and identical areas, termed the Image and Storage arrays.

Interline Transfer CCD Architecture

Interline charge-coupled device architecture is designed to compensate for many of the shortcomings of frame-transfer CCDs. These devices are composed of a hybrid structure incorporating a separate photodiode and an associated CCD storage region into each pixel element.

Sequential Colour CCD Systems

Three-pass sequential colour CCD imaging systems employ a rotating colour wheel to capture three successive exposures in order to obtain the desired RGB (red, green, and blue) colour characteristics of a digital image. The major advantage of this technique is the ability to fully utilize the entire pixel array of a CCD imaging chip, by using one pass for each colour.

Digital Camera Readout and Frame Rates

Recent imaging applications in wide-field fluorescence and confocal microscopy have increasingly centred on the demanding requirements of recording rapid transient dynamic processes that may be associated with a very small photon signal, and which often can only be studied in living cells or tissues. Technological advances in producing highly specific fluorescent labels and antibodies, as well as dramatic improvements in camera, laser, and computer hardware have contributed to many breakthrough research accomplishments in a number of fields. As high-performance camera systems, typically employing low-noise cooled charge-coupled device (CCD) detectors, have become more capable of capturing even relatively weak signals at video rates and higher, certain performance factors necessarily take on greater importance. A camera system's readout rate and frame rate are interrelated parameters that are crucial to the ability of the system to record specimen data at high temporal frequency.