Standard Terminology for Scientific Charge-Coupled Device (CCD) Detectors[1]

This standard is issued under the fixed designation E2642; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This terminology brings together and clarifies the basic terms and definitions used with scientific grade cooled charge-coupled device (CCD) detectors, thus allowing end users and vendors to use common documented terminology when evaluating or discussing these instruments. CCD detectors are sensitive to light in the region from 200 to 1100 nm and the terminology outlined in the document is based on the detection technology developed around CCDs for this range of the spectrum.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E131 Terminology Relating to Molecular Spectroscopy

3. Significance and Use

3.1 This terminology was drafted to exclude any commercial relevance to any one vendor by using only general terms that are acknowledged by all vendors and should be revised as charge-coupled device (CCD) technology matures. This terminology uses standard explanations, symbols, and abbreviations.

4. Terminology

4.1 *Definitions:*

advanced inverted mode operation (AIMO), *n*—a commercial tradename given to a method of reducing the rate of generation of dark current. Also known as **multi-pinned phase** operation.

analog-to-digital (A/D) converter, *n*—an electronic circuitry in a CCD detector that converts an analog signal into digital values, which are specified in terms of bits that can be manipulated by the computer.

anti-blooming structure, *n*—a structure built into the pixel to prevent signal charge above full-well capacity from blooming into adjacent pixels.

Discussion—Anti-blooming structures bleed off any excess charge before they can overflow the pixel and thereby stop blooming. These structures can reduce the effective quantum efficiency and introduce nonlinearity into the sensor.

antireflective (AR) coating, *n*—a coating applied to either the front surface of the CCD or the vacuum window surfaces, to minimize the amount of reflected energy (or electromagnetic radiation) so as to maximize the amount of transmitted energy.

back-illuminated CCD (BI CCD), *n*—a type of CCD that has been uniformly reduced in thickness on the side away from the gate structure (see Fig. 1b) and positioned such that the photons are detected on that side.

Discussion—A BI CCD leads to an improvement in sensitivity to incoming photons from the soft X-ray to the near-infrared (NIR) regions of the spectrum with the highest response in the visible region. However, compared to a front-illuminated CCD, it suffers from higher dark currents and interference fringe formation (etaloning) usually in the NIR region. Also called back-thinned CCD.

binning, *n*—the process of combining charge from adjacent pixels in a CCD prior to read out.

Discussion—There are two main types of binning: *(1)* vertical binning and *(2)* horizontal binning (see Fig. 2). Summing charge on the CCD and doing a single readout results in better noise performance than reading out several pixels and then summing them in the computer memory. This is because each act of reading out contributes to noise (see **noise**).

CCD bias, *n*—the minimum analog offset added to the signal before the A/D converter to ensure a positive digital output each time a signal is read out.

Discussion—The CCD bias is set at the time of manufacture and remains set over the lifetime of the camera.

charge, *n*—measure of number of electrons that are contained in a pixel potential well.

charge-coupled device (CCD), *n*—a silicon-based semiconductor chip consisting of a two-dimensional matrix of photo sensors or pixels (see Fig. 3).

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[1] This terminology is under the jurisdiction of ASTM Committee E13 on Molecular Spectroscopy and Separation Science and is the direct responsibility of Subcommittee E13.08 on Raman Spectroscopy.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

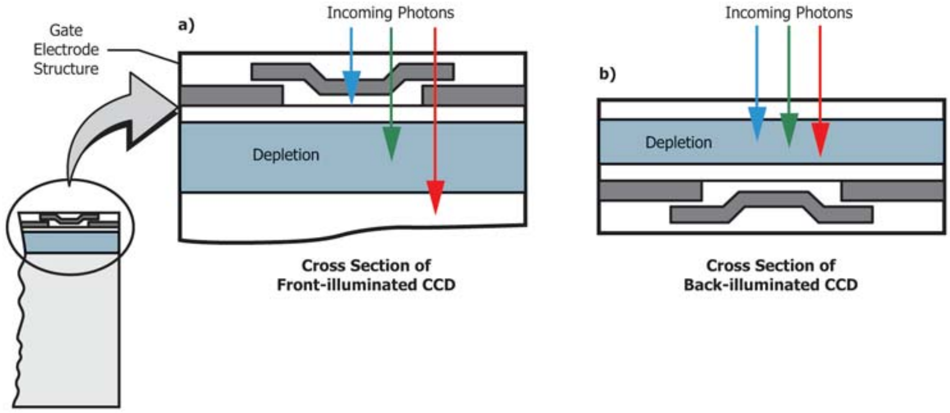


FIG. 1 Cross Sections of Front-Illuminated (a) and Back-Illuminated (b) CCDs

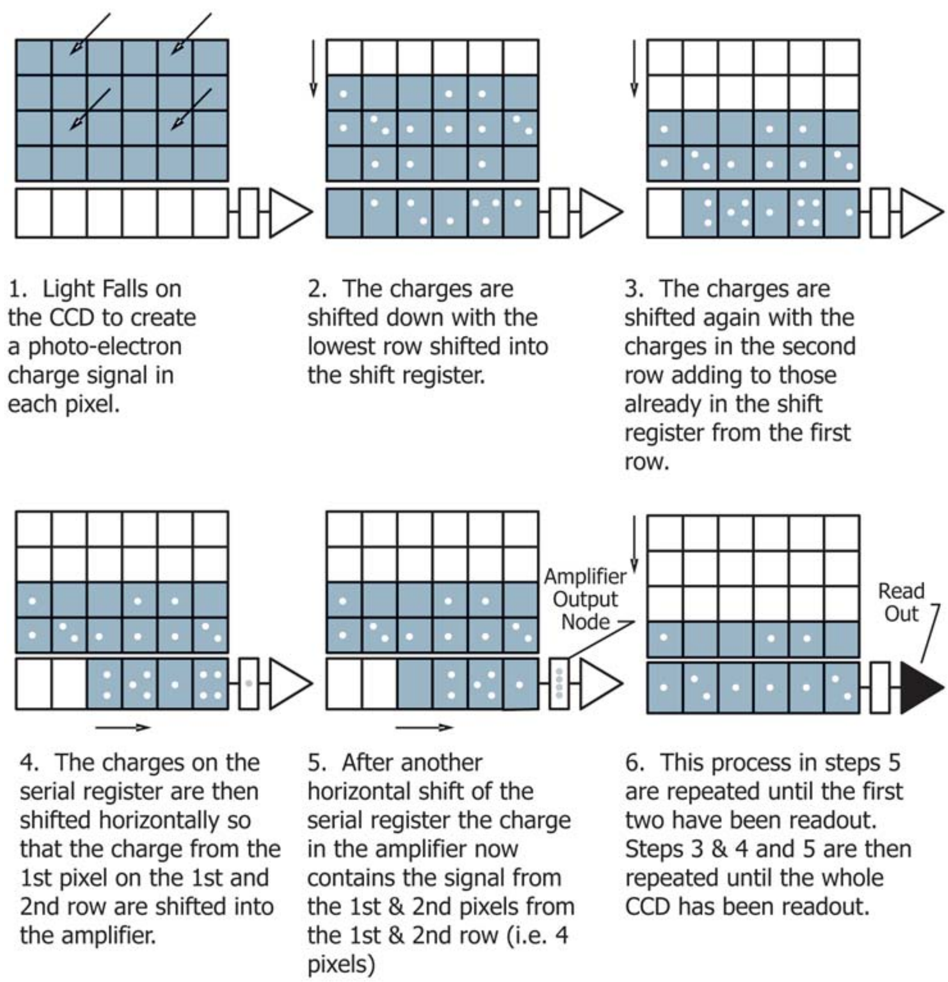


FIG. 2 Example of a 2 × 2 Vertical and Horizontal Binning Methodology

DISCUSSION—The matrix is usually referred to as the image area. Electronic charge is accumulated on the image area and transferred out by the application of electrical potentials to shielded electrodes. The size of pixels in the sensor is typically 26 × 26 µm; however, sensors can be manufactured in a variety of different pixel sizes ranging from 6 × 6 µm to 50 × 50 µm. Although mathematically incorrect, the dimension unit of a square pixel is typically given in square microns (for example, a pixel of dimension 26 × 26 µm is specified as 26 × 26 μm^2).

charge transfer, *n*—the process by which a CCD moves electrons or charge from one pixel to the next.

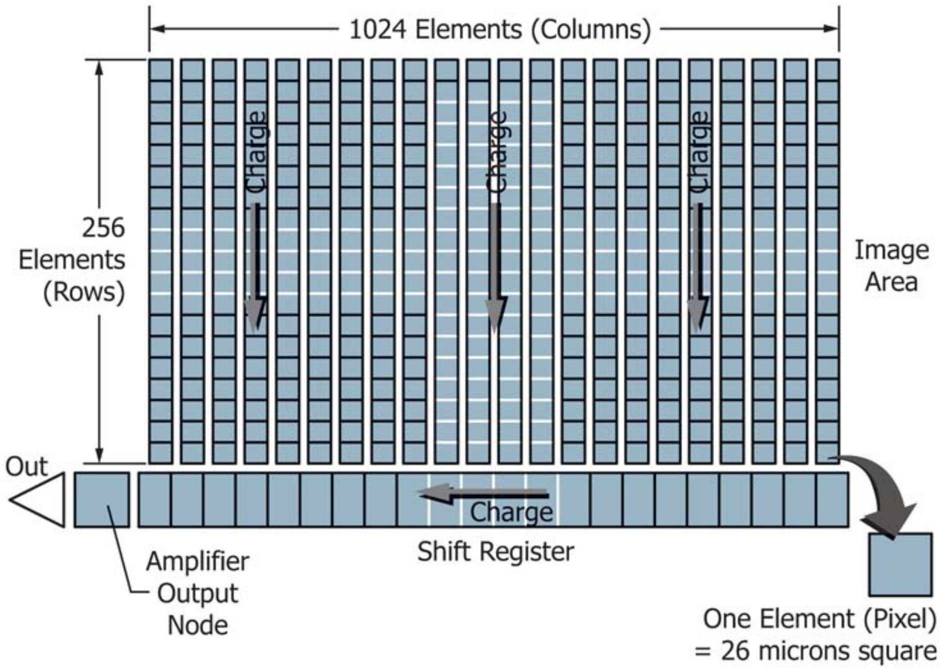


FIG. 3 Typical 1024 × 256 (26 × 26 µm² pixel) Element CCD Sensor Used for Spectroscopy

charge transfer efficiency (CTE), *n*—measure of the ability of the CCD to transfer charge from the point of generation to the device output.

Discussion—It is defined as the fraction of the charge initially stored in a CCD element that is transferred to an adjacent element by a single clock cycle. The value for CTE is not constant but varies with signal size, temperature, and clock frequency.

column, *n*—a line of pixels in the CCD's image area that is perpendicular to the horizontal register.

complementary metal oxide semiconductor (CMOS), *n*—technology widely used to manufacture electronic devices and image sensors similar to CCDs. In a CMOS sensor, each pixel has its own charge-to-voltage conversion circuit, and the sensor often also includes amplifiers, noise-correction, and digitization circuits. Due to the additional components associated with each pixel, the sensitivity to light is lower than with a CCD, the signal is noisier, and the uniformity is lower. But the sensor can be built to require less off-chip circuitry for basic operation (see Fig. 4).

correlated double sampling, *n*—a readout sampling technique used to achieve higher precision in CCD readout.

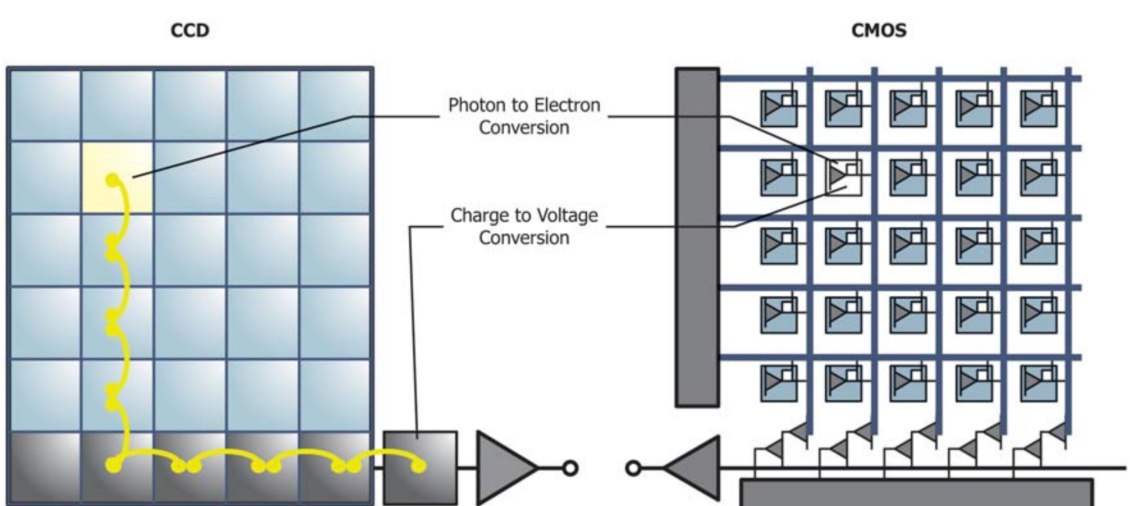


FIG. 4 Typical Architectures of CCD and CMOS Sensors

DISCUSSION—The sampling circuit is set to a predetermined reference level and then the actual pixel voltage is sampled in order to find the difference between the two. The resulting correlation minimizes read noise, especially in ultra-low-noise CCD detectors.

cosmic event, *n*—a spurious signal caused by a cosmic ray or particle hitting the CCD sensor. It is typically observed to result in a high intensity signal coming from a single pixel or small group of pixels.

dark current, *n*—a current that occurs naturally through the thermally generated electrons in the semiconductor material of the CCD. It is intrinsic to semiconductors and is independent of incident photons.

DISCUSSION—Dark current is dependant on the CCD's temperature. It is expressed in electrons/pixel/unit time.

dark noise, *n*—the shot noise associated with the dark current for the given exposure time, and is approximately equal to the square root of the dark current times the exposure time used. It is usually expressed in terms of number of electrons.

deep depletion CCD, *n*—a CCD that has been designed with a thicker active area to provide enhanced sensitivity in the NIR and hard X-ray regimes.

DISCUSSION—Both front-illuminated and back-illuminated CCDs can be manufactured with a deep depletion process to enhance the NIR response; however, such devices cannot be operated in AIMO and are also more susceptible to cosmic rays. A back-illuminated deep depletion CCD will have reduced etaloning effects that are typically observed in back-illuminated devices exposed to NIR signals (see Fig. 5).

dynamic range, *n*—the ratio of the full well saturation charge to the system noise level. It represents the ratio of the brightest and darkest signals a detector can measure in a single measurement.

DISCUSSION—A true 16-bit detector will have a dynamic range of 65 535:1.

electron-multiplying CCD (EMCCD), *n*—type of CCD that has a two-way readout register, that is, the shift register and the gain register, each with its own output amplifier. When the charge is read out through the shift register, the detector works like a standard CCD detector, and when the charge is read out through the gain register, it undergoes charge amplification as a result of a different electrode structure embedded underneath the pixels of this register (see Fig. 6).

DISCUSSION—Passing charge through the gain register allows the signal to be amplified before readout noise is added at the readout amplifier, thus improving the signal-to-noise ratios making the camera highly sensitive in the low-light regime.

etaloning, *n*—a phenomenon by which constructive and destructive interference fringes are produced in a back-illuminated CCD caused by internal reflections between the two parallel surfaces of the CCD. Typically BI CCDs experience etaloning effects when subjected to NIR signals (see Fig. 5).

DISCUSSION—This effect causes the device to become transparent to incoming photons in the NIR region.

exposure time, *n*—the length of time for which a CCD accumulated charge.

frame, *n*—one full image that is read out of a CCD.

frame-transfer CCD, *n*—a type of CCD whose active image area is divided into two sections, that is, image area and the storage area. The image area is the light sensitive area of the CCD and the storage area is masked to make it insensitive to light (see Fig. 7).

DISCUSSION—During operation the charge accumulated in the image section is rapidly transferred to the storage section at the end of the

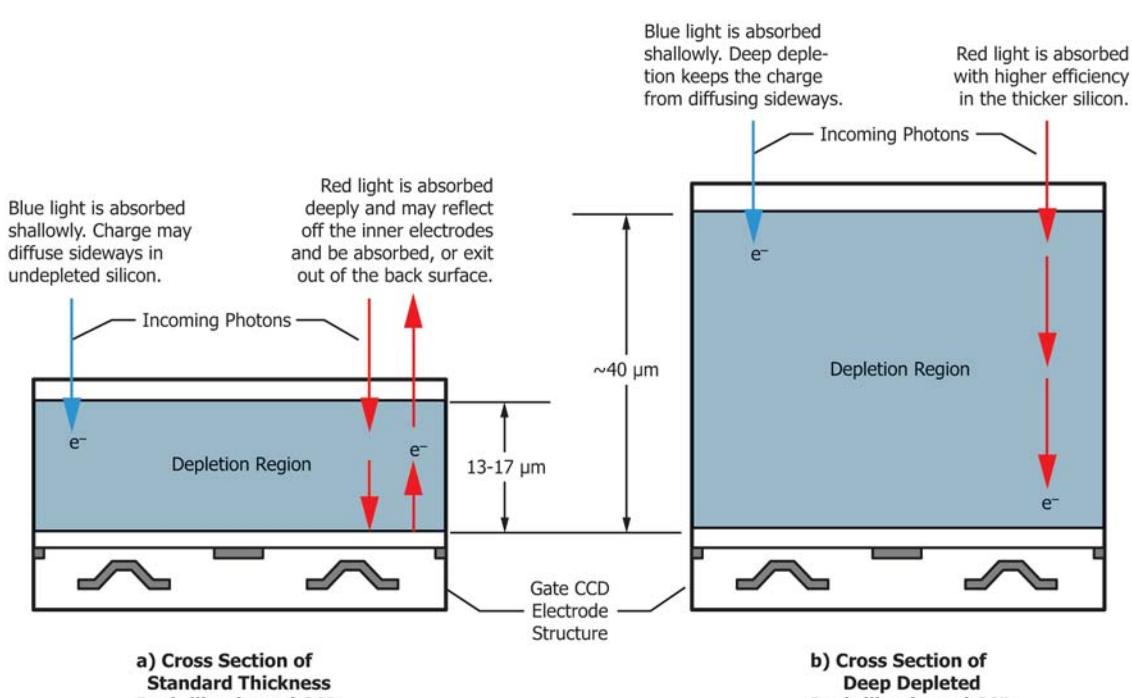


FIG. 5 Cross-Sections of Back-Illuminated (a) and Back-Illuminated Deep Depletion (b) Devices

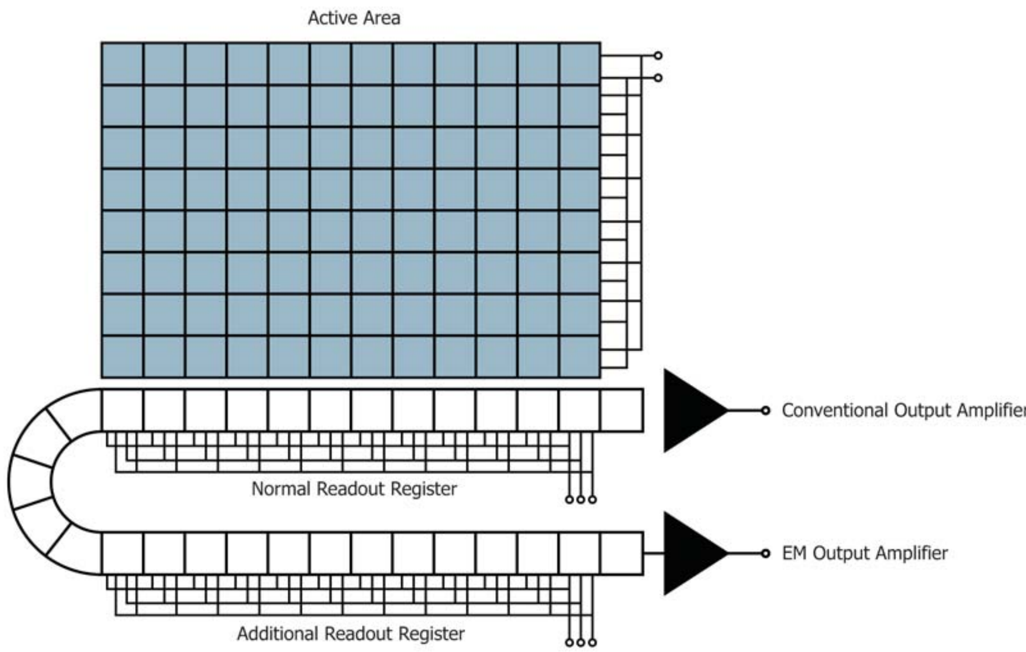


FIG. 6 Typical Sketch of Full-Frame EMCCD Sensor

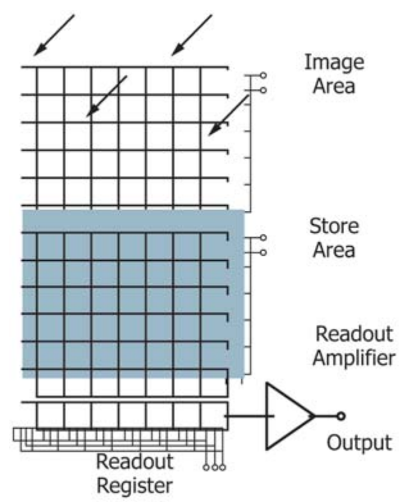


FIG. 7 Typical Sketch of a Frame-Transfer CCD

exposure time. The storage area is then readout as the image section accumulates charge for the next exposure. This type of CCD reduces or eliminates the need for a shutter, depending on the speed of the transfer from image to storage.

front-illuminated CCD (FI CCD), *n*—a type of CCD in which the photons are detected through the gate structure located in front of the silicon material of the semiconductor (see Fig. 1a).

DISCUSSION—This type of CCD has moderate quantum efficiency (see Fig. 8) over the spectral range it covers and it is also free from any etaloning effects that occur in the back-illuminated CCD when subjected to NIR signals. These devices are relatively less expensive to manufacture than the back-illuminated type.

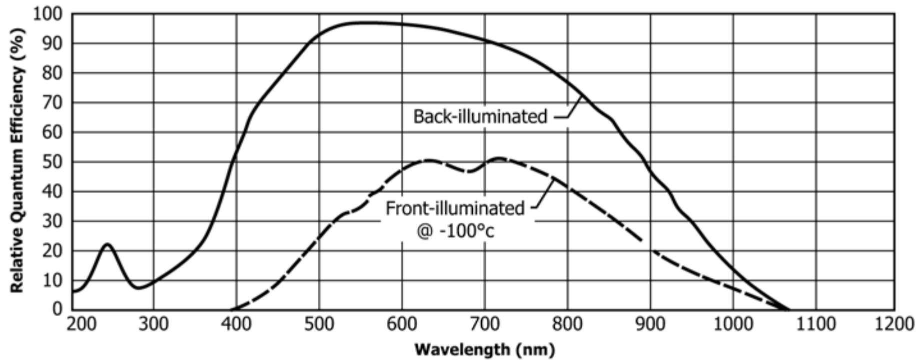
full-frame CCD, *n*—a type of CCD that uses the entire silicon active area for photon detection. A shutter is required to eliminate image smear (see Fig. 3).

full well capacity, *n*—the maximum number of photoelectrons that can be collected on a single pixel in the image area or in the horizontal register of a CCD. It is typically specified in terms of number of electrons.

gate structure, *n*—a polysilicon arrangement of electrodes that create pixels and move charge.

horizontal binning, *n*—the process that allows charge from a row of pixels to be combined on the CCD chip prior to readout (See Fig. 2). Horizontal binning is commonly used in spectroscopy to increase the signal level of a data point, when less horizontal (or wavelength) resolution is not of concern.

horizontal register, *n*—a row of light insensitive pixels that is located below the CCD's image acquisition area into which



NOTE 1—Image used courtesy of E2V Technologies, 106 Waterhouse Lane, Chelmsford, Essex CM1 2QU, England, http://www.e2v.com.

FIG. 8 Typical QE Curves for FI and BI CCD Sensors

charge from the pixel columns is clocked and subsequently passed on to the output node to be read out. Also called the **serial register** or readout register.

indium tin oxide (ITO), *n*—a transparent conductive material used in some CCD designs to provide an increase in quantum efficiency (QE) in the blue-green region of the spectrum.

intensified CCD (ICCD), *n*—a type of CCD camera that has an intensifier block attached in front of it. An ICCD is used to amplify the incoming signal without varying the image size so as to provide single-photon sensitivity and it can be electronically gated down to nanosecond ranges (see Fig. 9).

DISCUSSION—Intensifiers were initially designed for the military for night-vision ability and are now being widely used in applications that need nanosecond gate widths or single-photon sensitivity or both. The intensifier consists of a photocathode, multichannel plate and phosphor. A large potential difference is applied across the ends of the multichannel plate to amplify the signal. There are two main types of intensifiers: Gen II and Gen III. The main difference between them is in the material used in the photocathode. The Gen III models are a more advanced design and they provide higher quantum efficiencies than the Gen II models.

interline transfer CCD, *n*—a type of CCD designed with columns of pixels alternated with masked storage registers so as to increase the rate of acquisition. The storage registers occupy a portion of the pixel area reducing the fill factor of the diodes under the pixels, and hence, such a CCD architecture has typically lower quantum efficiencies that other types of CCDs (see Fig. 10).

linear array CCD, *n*—a type of CCD that is comprised of a single row of pixels that are used as the active area for capturing incident photons.

multi-pinned phase (MPP), *n*—mode of operation in CCDs that reduces dark charge.

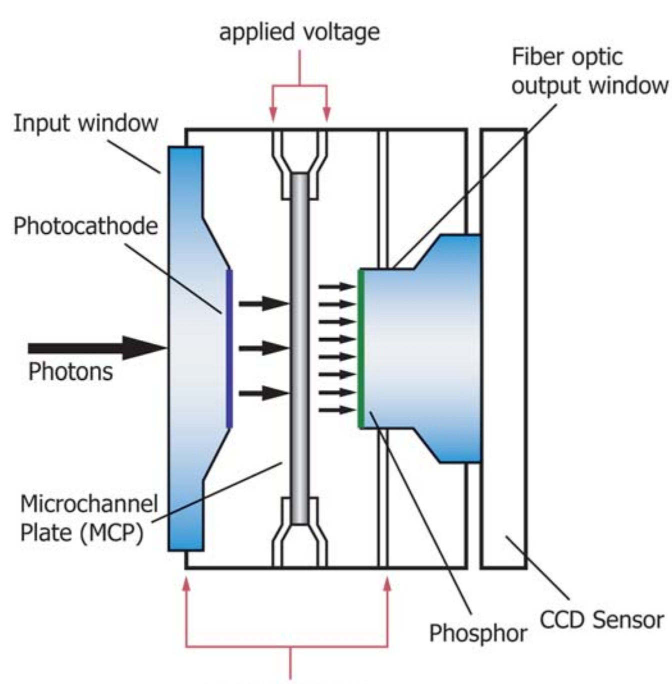


FIG. 9 Schematic of a Typical Intensifier Fiber Optically Coupled to a CCD Sensor

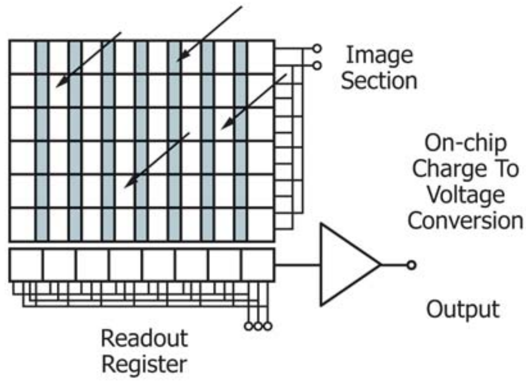


FIG. 10 Typical Sketch of an Interline CCD Sensor

Discussion—Also known as **advanced inverted mode operation (AIMO)**.

noise, *n*—unwanted random variations of output signal that are added to the real signal and are not subtractable. Noise arises from the statistical variations of both thermal and photon-generated signal as well as from electron conduction through resistive material, and variations in the readout electronics.

Discussion—The total noise in a signal measured by a CCD detector is referred to as "system noise" and is the equal to the square root of the sum of the squares of each of the individual noise components. The major noise components present in CCD devices are: read noise caused by the system's output amplifier and electronics, shot noise from the light signal itself, and dark noise (shot noise from the dark signal). See **read noise**, shot noise, and **dark noise** for further details.

open electrode CCD (OE CCD), *n*—type of front-illuminated CCD in which the electrodes are patterned such that a portion of every pixel on the sensor remains open to direct illumination from incident photons (see Fig. 11). This minimizes absorption of charge between layers and leads to higher QEs.

outgassing, *v*—gradual release of gaseous molecules in a vacuum chamber that degrades long-term vacuum performance.

Discussion—The use of vacuum-grade materials and advanced vacuum-processing techniques will reduce the rate of outgassing and result in a high-performance vacuum.

output amplifier, *n*—the electronic structure in the CCD that amplifies the signal from the output node prior to being passed onto the A/D converter.

Discussion—The readout noise is mainly caused by the signal amplification that occurs in the output amplifier.

output node, *n*—electronic region, often a single pixel at the end of the horizontal register in which charge is collected and presented to the output amplifier.

parallel shift, *n*—movement of charge in a CCD column from one or more pixels from one row to the next, towards the serial register. The movement continues until the number of pixels to be binned (specified by the user) are emptied into the serial register. Also called as vertical shift.

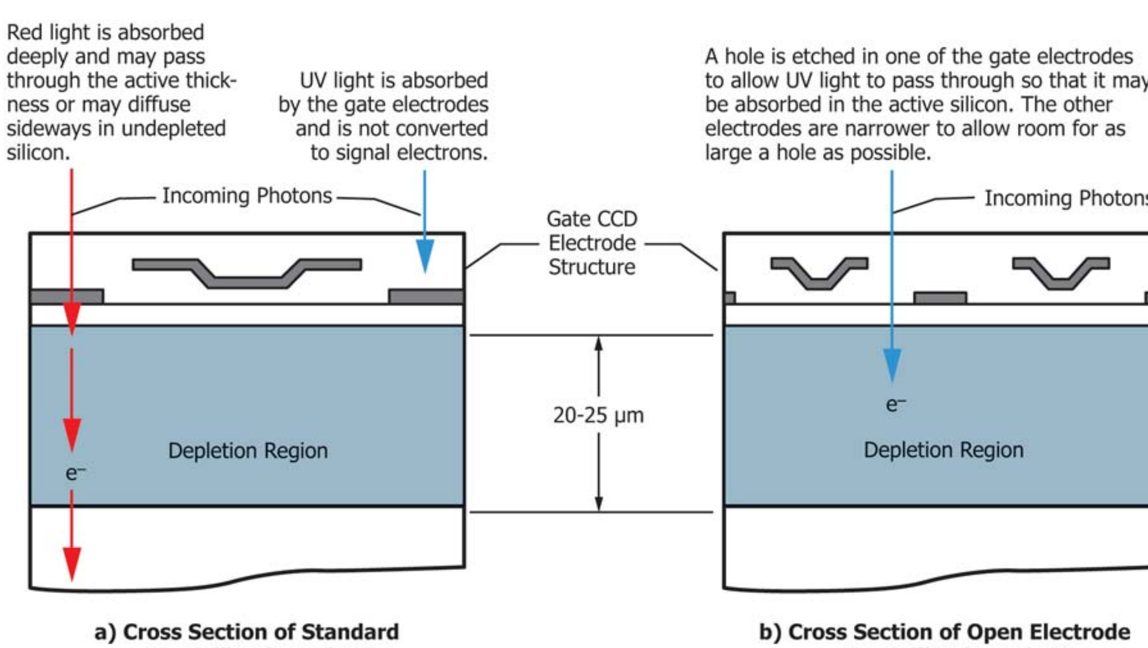


FIG. 11 Cross Sections of Standard Front-Illuminated (a) and Open-Electrode (b) CCDs

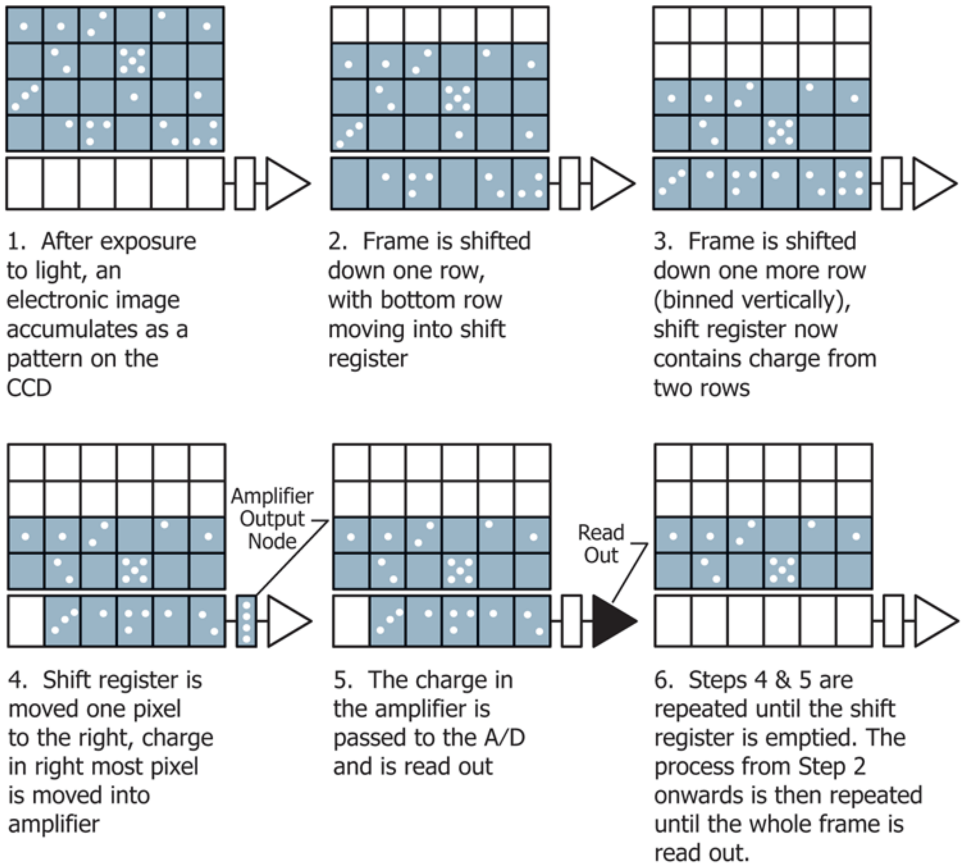


FIG. 12 Steps Depicting Vertical Binning of Two Rows

Peltier cooler, *n*—solid-state device that uses the Peltier effect to cool a CCD.

Discussion—The Peltier cooler has a hot and cold side. The cold side is connected to the back of the CCD. This enables the temperature of the CCD to be reduced. The hot side is connected to a heat sink which enables excess heat to be dissipated.

pixel, *n*—abbreviation for picture element. The smallest unit in an optical device in which charge is collected as a signal. CCD detectors typically have 26 µm square pixels, however, pixel sizes of 8, 13, 16, and 20 µm square are also available.

pixel non-uniformity, *n*—is the degree to which each pixel responds when exposed to uniform intensity of illumination. Pixel non-uniformity cannot be corrected by a dark subtraction. The non-uniformity of pixel response increases with increased intensity of illumination. It is also known as fixed pattern noise.

Discussion—Pixel non-uniformity can be corrected by creating a correction based on illumination of the CCD with uniform white light. The correction procedure used is called “flat fielding” when only the detector is used for correction and “instrument response correction” when a complete spectrometer system (including reflectance and wavelength response of all optical components) is being used.

potential well, *n*—incoming photo-electrons are stored on a temporary basis in each pixel during the exposure time of the CCD. The semiconductor structure of the pixel and the voltage bias applied to the pixel results in an electronic potential well, the depth of which establishes the capacity for the number of electrons that can be stored in the pixel.

quantum efficiency (QE), *n*—a measure of the sensitivity of the CCD chip to convert photons to photoelectrons at a given wavelength. It is defined as the ratio of the detected to the incident photons at the given wavelength and is normally expressed as a percentage (see Fig. 8).

read noise, *n*—a type of noise that is generated by the CCD detector’s output amplifier during the readout process. It is expressed in terms of number of electrons.

Discussion—The magnitude of read noise is dependant on the speed of readout. It is also referred to as “pre-amplified noise” or “readout noise”.

readout rate, *n*—clock frequency of the horizontal register or the rate at which pixel charge from the horizontal register is transferred to the A/D converter. It is usually expressed in kHz or Mhz. It is also known as serial shift rate.

region of interest (ROI), *n*—user-defined portion of the image area in which data will be acquired. The remainder of the image area will be discarded.

row, *n*—line of pixels in the CCD detector’s image area that is parallel to the horizontal register.

serial register, *n*—a row of non light-sensitive pixels that resides outside of the CCD sensor’s image area into which the rows are clocked in the readout process and passed on to the output node to be read out. Also called the **horizontal register** or readout register.

shot noise limit, *n*—the detection level where the minimum measurable signal is limited by the shot noise and not by the CCD detector's electronics-related noise sources.

signal-to-noise ratio (SNR), *n*—measure of the signal quality expressed as a ratio of the measured signal to the root mean square noise level.

DISCUSSION—SNR can be optimized by selecting a detector that provides for the highest quantum efficiency for the wavelength of interest and adds the least amount of noise for the selected speed of readout. This definition overlaps with the one in Terminology E131; however, since this definition is critical to CCD detector users, it has been covered in this list as well.

silicon, *n*—a tetravalent, semiconducting element whose crystal is used in the fabrication of integrated circuits including CCDs.

slow-scan CCD, *n*—type of CCD that uses special circuits for readout so as to reduce the readout noise and optimize the charge transfer efficiency by reducing the readout rate below 30 frames per second.

spectral rate, *n*—a value describing the number of fully vertically binned spectra per second that can be produced by the CCD. Usually expressed in spectra per second or Hz.

thermoelectric cooling, *n*—method to reduce the temperature of a CCD by direct or near direct contact with a Peltier cooling device.

thinning, *n*—process of uniformly reducing the thickness of a CCD chip so that an image can be focused on the backside of the chip, converting it into a back-illuminated CCD.

vertical binning, *n*—a process that allows charge from a column of pixels to be combined on the CCD chip prior to readout (see Fig. 12).

DISCUSSION—Vertical binning is commonly used in spectroscopy. The vertical dimension is normally parallel to the spectrograph slit or perpendicular to the spectral dispersion direction. The charge from all of the vertical pixels in one column is combined to give the total signal at the given wavelength.

4.2 *Abbreviations:*

A/D—analog to digital

AIMO—advanced inverted mode operation

AR—antireflective

BI CCD—back-illuminated CCD

CMOS—complementary metal oxide semiconductor

CTE—charge transfer efficiency

EMCCD—electron-multiplying CCD

FI CCD—front-illuminated CCD

ICCD—intensified CCD

ITO—indium tin oxide

MPP—multi-pinned phase

NIR—near infrared

OE CCD—open electrode CCD

QE—quantum efficiency

ROI—region of interest

SNR—signal-to-noise ratio

5. Keywords

5.1 CCD; CCD detector; charge-coupled device detector