WORCESTER POLYTECHNIC INSTITUTE
MECHANICAL ENGINEERING DEPARTMENT

Optical Metrology and NDT
ME-593n/ ME-5304, C'2025

Introduction: digital cameras

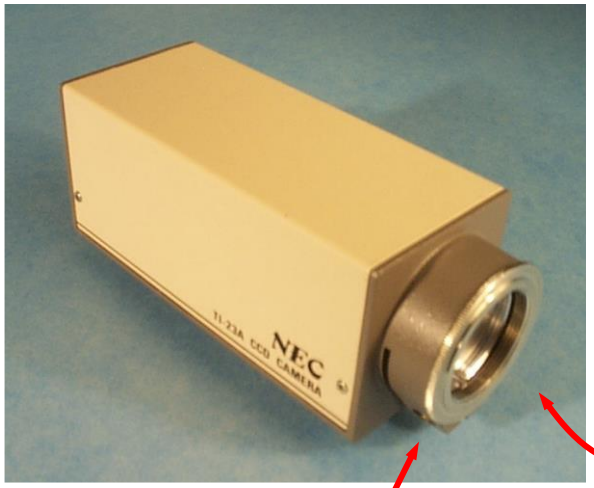
January 2025

The CCD/CMOS camera

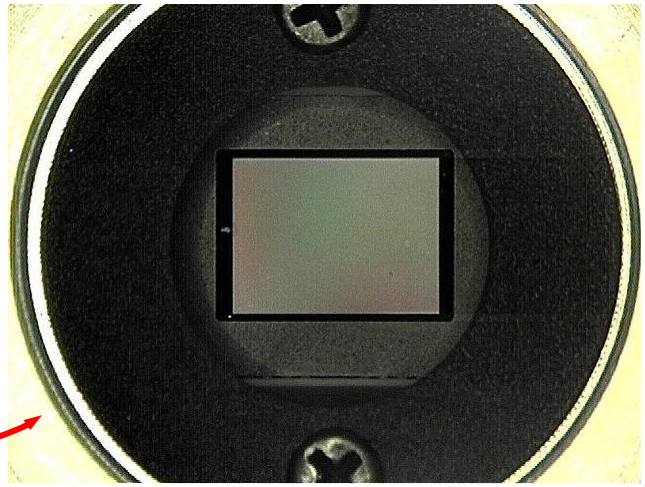
CCD – charged-coupled device

CMOS – complementary metal-oxide-semiconductor

General view



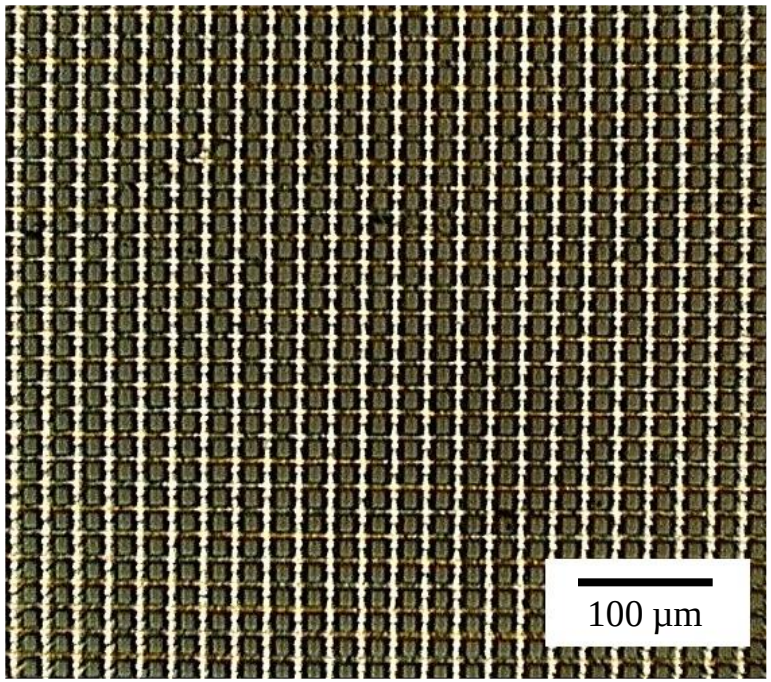
1/2" CCD array (diagonal)

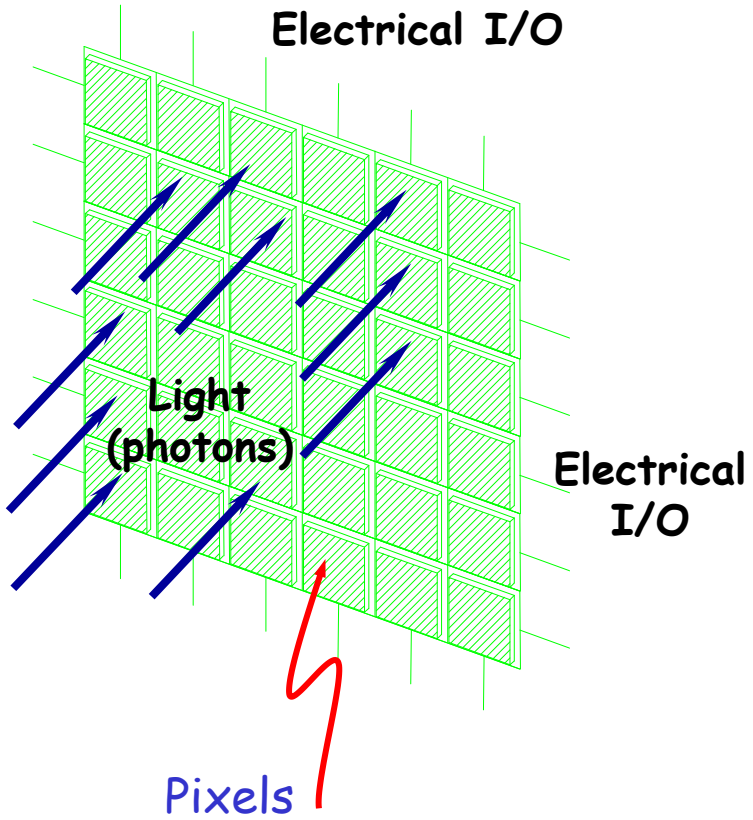


C-mount adapter

The CCD/CMOS camera

Detail section of a CCD detector



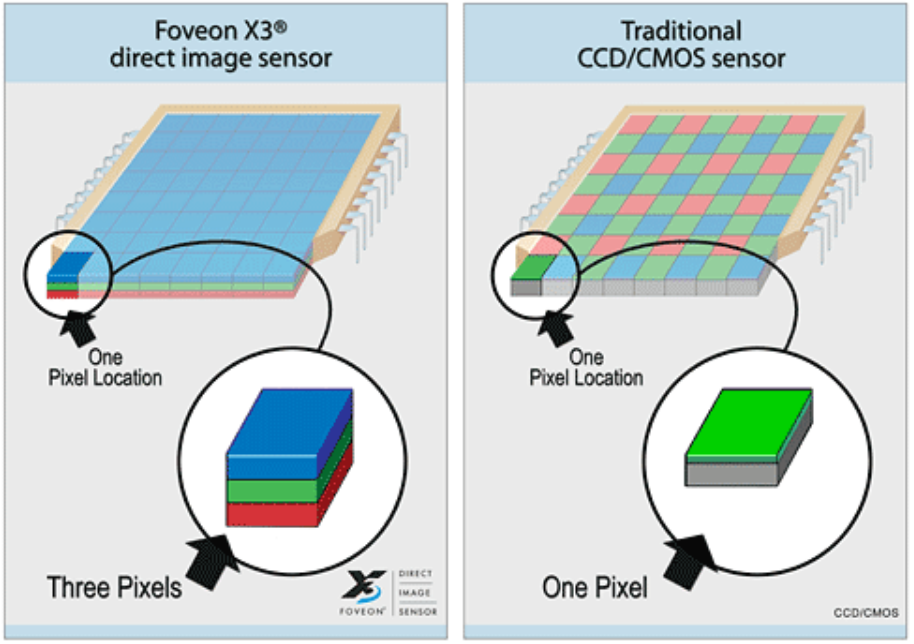


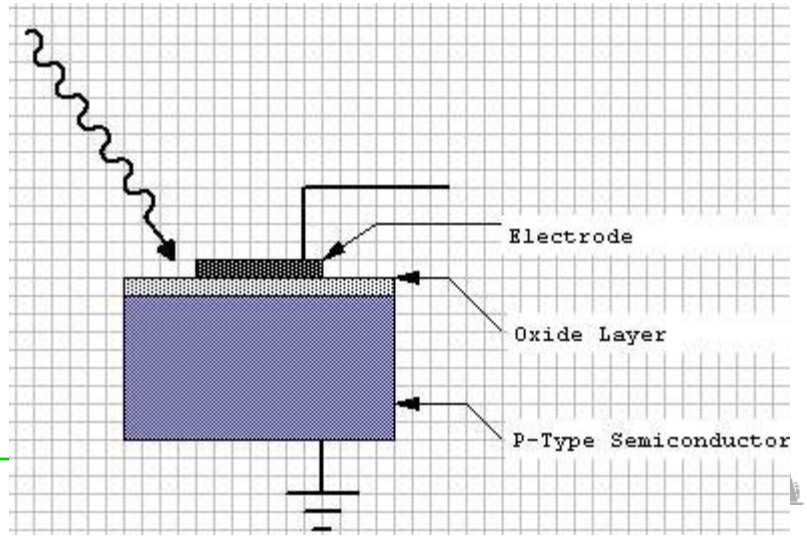
CCD cameras

Basic operation/description

- A CCD detector chip consists of an array of square or rectangular metal-oxide-semiconductor (MOS) capacitors (pixels) fabricated on a semiconductor surface

- As light strikes the CCD array, each capacitor on the chip collects photons of light over a period of time (frame time) and converts the photon count into a proportional electrical charge level

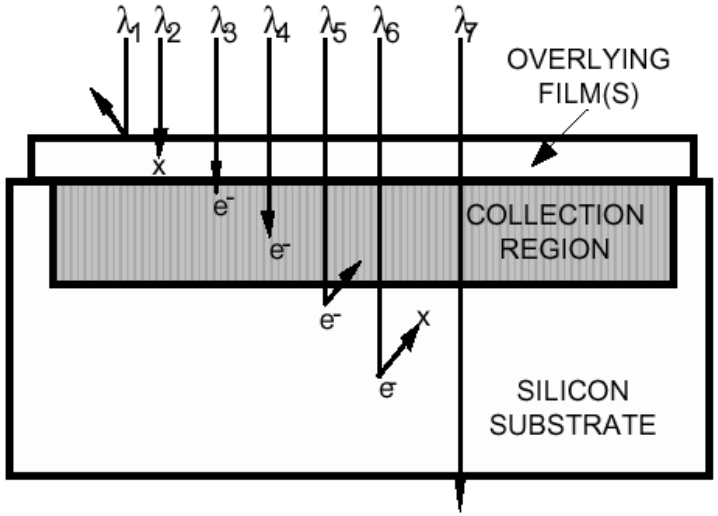




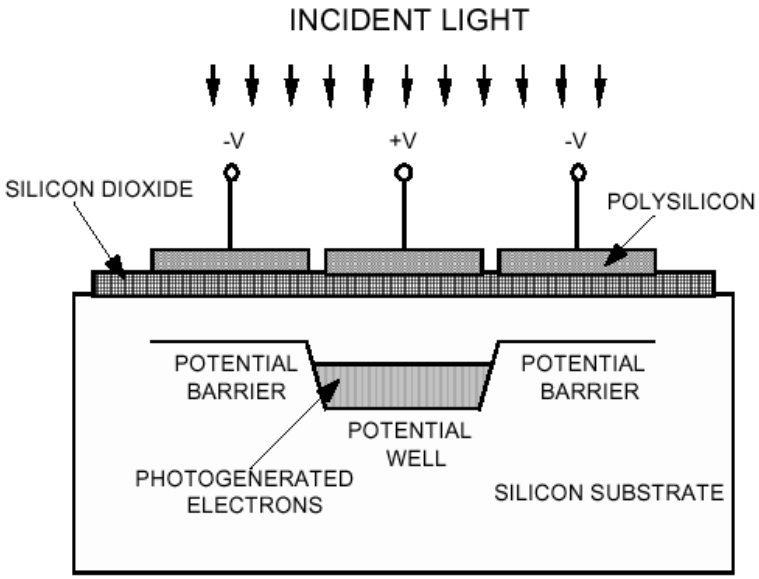
WPI

CCD cameras

Basic operation/description



Photon interaction with a silicon substrate: note different wavelength sensitivity



Potential well and barriers

An image is acquired when incident light (photons) fall onto an array of pixels. The energy associated with each photon is absorbed by the silicon substrate (or potential well) and causes the creation of an electron-hole charge pair

CCD cameras

Basic operation/description

Photon-energy equation: $$E = \frac{h\,c}{\lambda}$$

- E = the energy of a single photon (joules/photon)
- h = Planck's constant, 6.63x10 $^{-34}$ J-sec
- c = the speed of light, 3.0x10 ^{8} m/sec
- λ = the wavelength of the light, in meters

Inverting photon-energy equation: $$N = \frac{\lambda}{h\,c}$$ (photons/Joule)

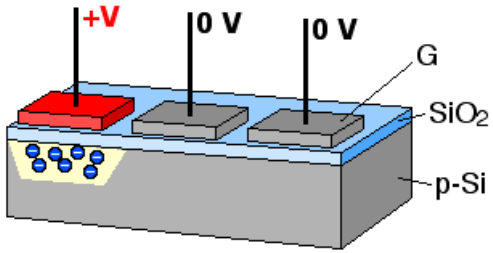
Defining quantum efficiency of potential well : Φ (Joules/sec·cm^2)

Number of photons per unit time per unit area is: $$P_N = \Phi \cdot N$$ (photons/sec·cm^2)

CCD cameras

Basic operation/description

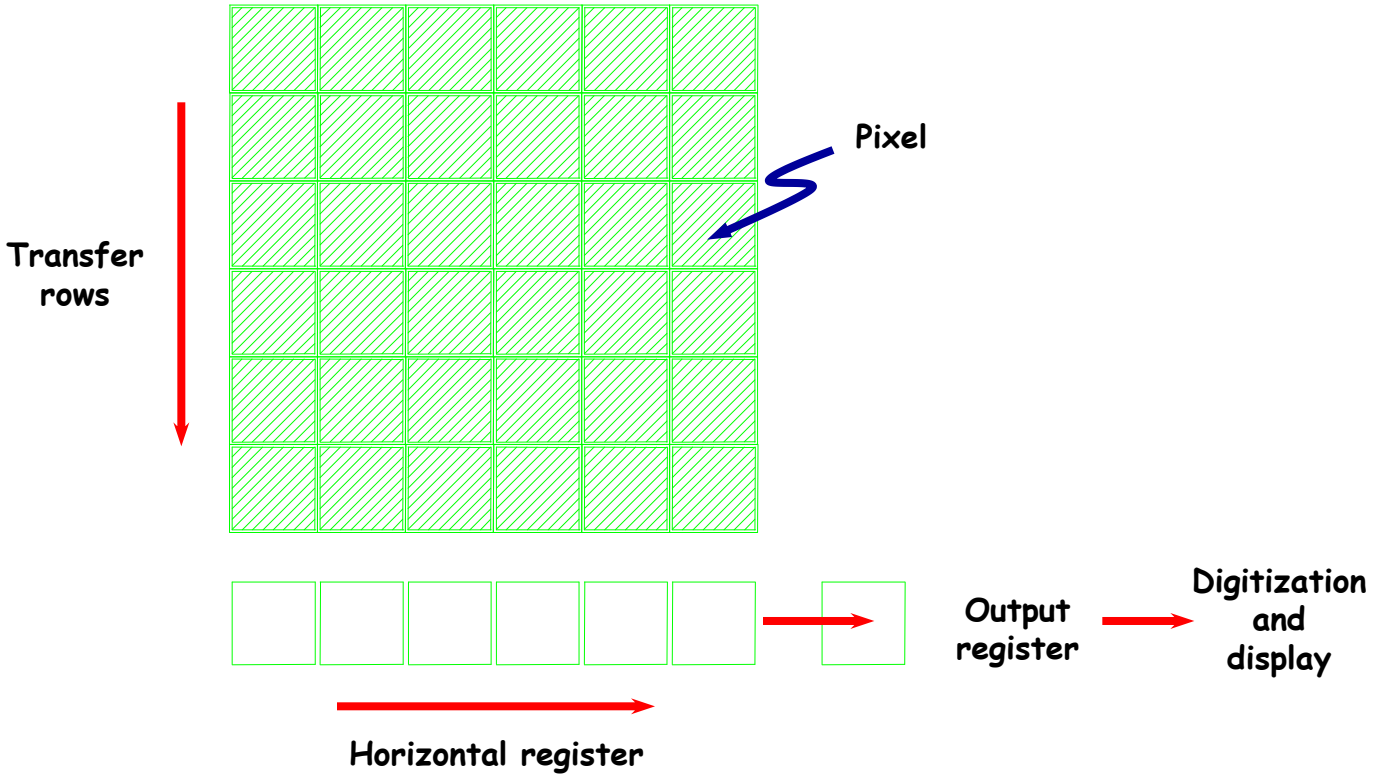
- The accumulated charge on each pixel is then transferred to a vertical charge storage site, which gets shifted downwards, row by row, to a horizontal row of charge storage registers
- Charge transfer rate characterizes operational frequency of camera
- Once transfer is completed, the array is reset and photon collection is begun for the new frame



- At the same time, the previous frame charge values are transferred out to the edge of the chip and then, row by row, to an amplifier which converts the charge level of each pixel into an equivalent voltage for transmission off the chip
- The output voltage is an analog signal, which can later be digitized and displayed

CCD cameras

Basic operation/description: charge transfer



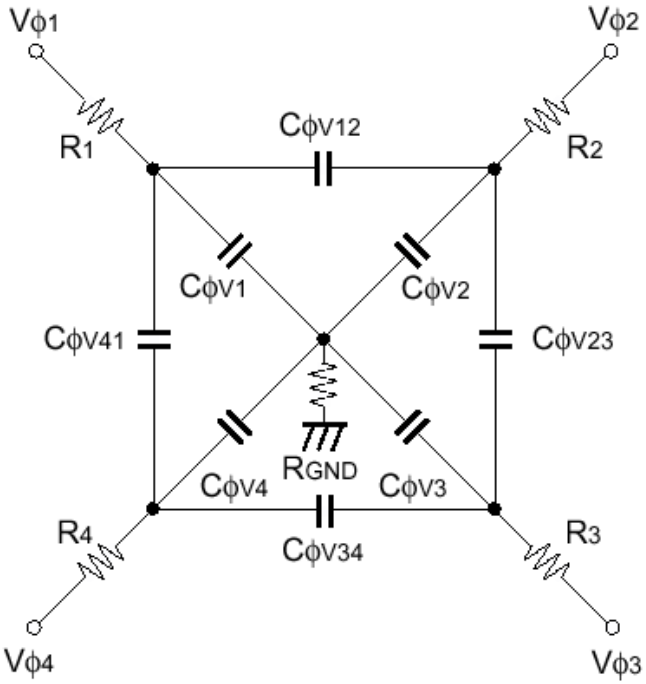
Transmission of accumulated electrical charges on a CCD array to an output register. Charges are transferred row by row to horizontal and output registers for amplification. The output is an analog signal, which can be digitized and displayed

CCD cameras

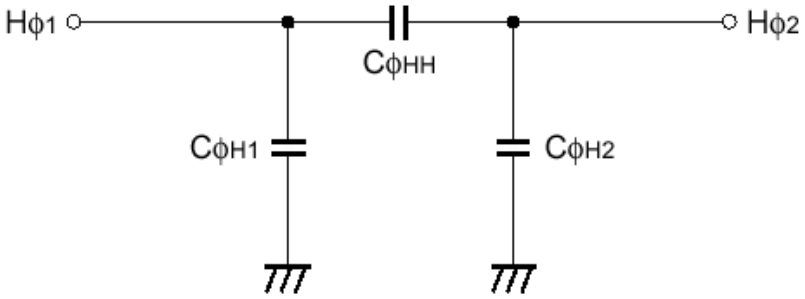
Vertical and horizontal clock circuits

Typical transfer frequencies: ***Horizontal transfer 15.734 kHz; Vertical transfer 59.94 Hz***

(These data are used to determined frame rate of the camera… ***how?****)*



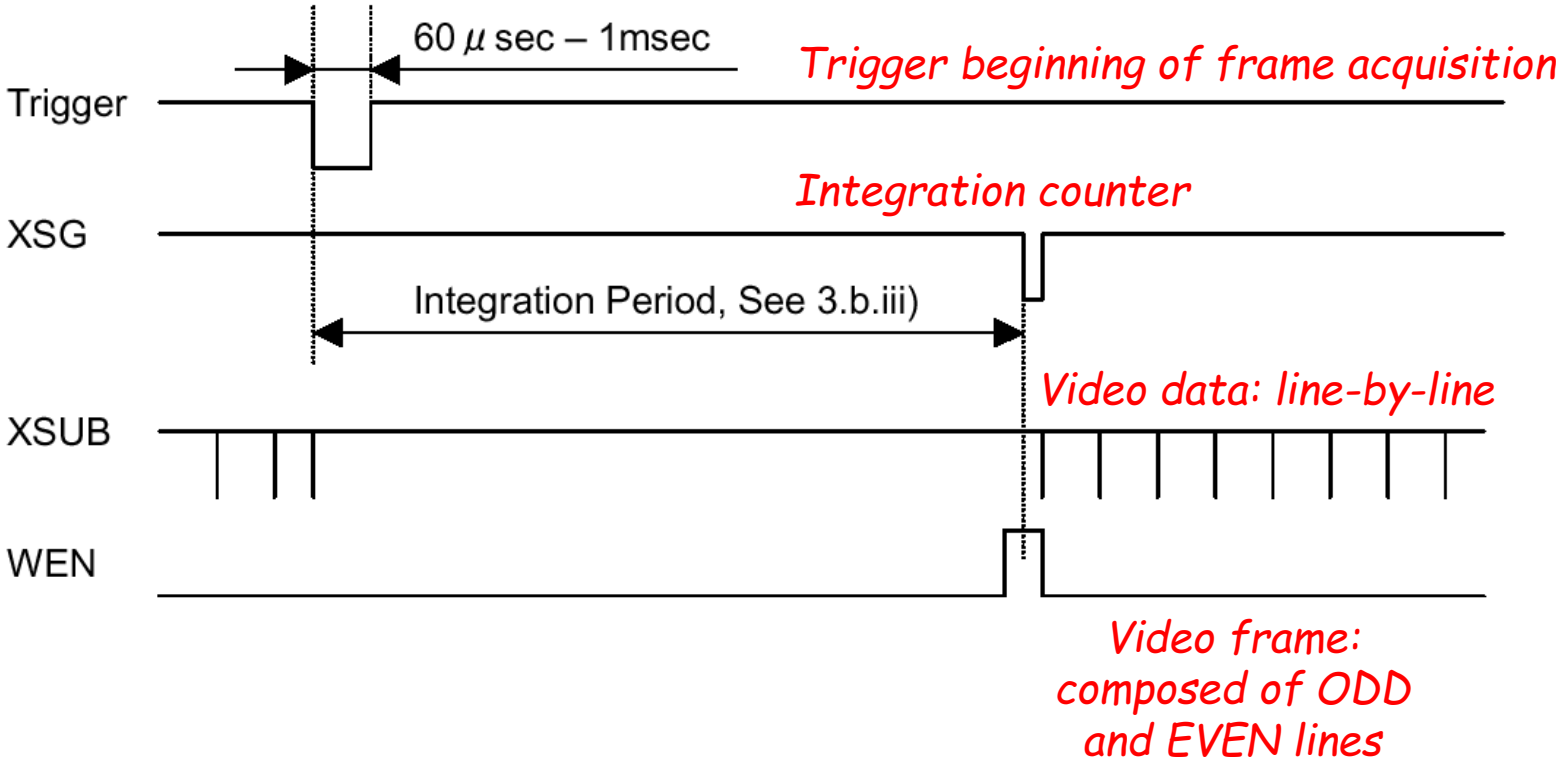
Vertical transfer clock equivalent circuit



Horizontal transfer clock equivalent circuit

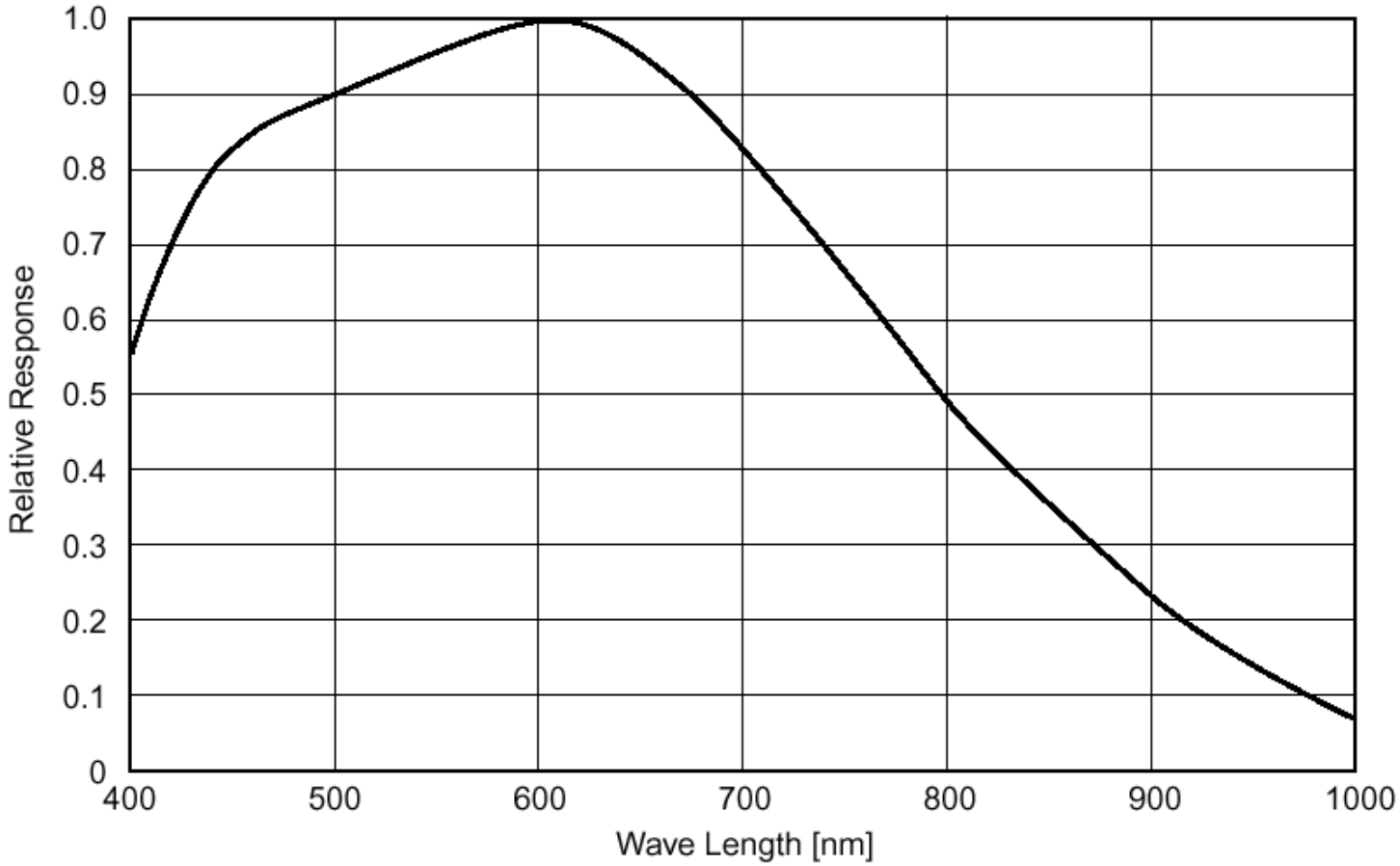
CCD cameras

Typical video signal timing chart



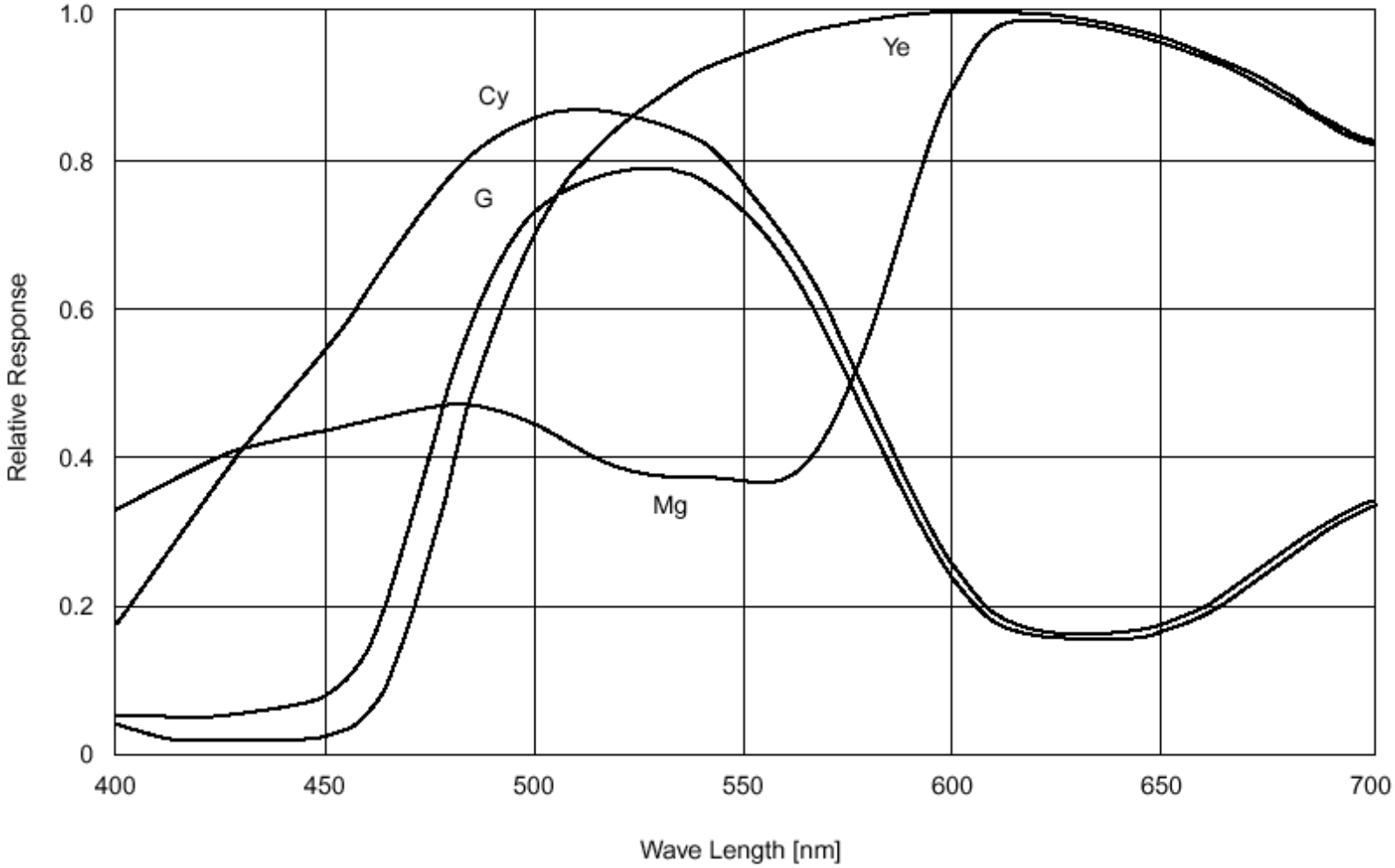
CCD cameras

Spectral sensitivity characteristics: B/W camera



CCD cameras

Spectral sensitivity characteristics: color camera



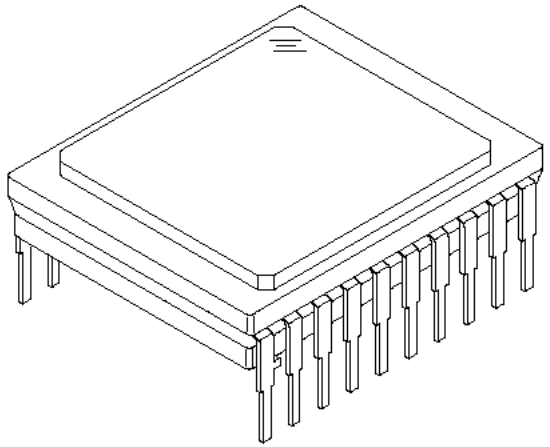
CCD cameras

Typical specifications: B/W camera

General specifications

- Interline CCD image sensor
- Optical size: Diagonal 8mm (Type 1/2)
- Number of effective pixels: 752 (H) × 582 (V) approx. 440K pixels
- Total number of pixels: 795 (H) × 596 (V) approx. 470K pixels
- Chip size: 7.40mm (H) × 5.95mm (V)
- Unit cell size: 8.6µm (H) × 8.3µm (V)
- Optical black: Horizontal (H) direction: Front 3 pixels, rear 40 pixels
  Vertical (V) direction: Front 12 pixels, rear 2 pixels
- Number of dummy bits: Horizontal 22
  Vertical 1 (even fields only)
- Substrate material: Silicon

20 pin DIP (Cer-DIP)



Additional specifications of particular interest for metrology

- High sensitivity
- Low smear
- High D range (+1dB compared with the ICX249AL)
- High S/N
- High resolution and low dark current
- Excellent antiblooming characteristics
- Continuous variable-speed shutter
- Substrate bias: Adjustment free (external adjustment also possible with 6 to 14V)
- Reset gate pulse: 5Vp-p adjustment free (drive also possible with 0 to 9V)
- Horizontal register: 5V drive

CCD cameras

Typical specifications: color camera

General specifications

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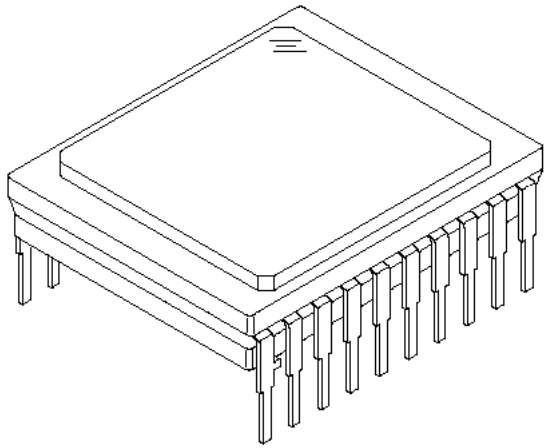

Additional specifications of particular interest for metrology

- High sensitivity (+3dB compared with the ICX249AK)
- Low smear (–4dB compared with the ICX249AK)
- High D range (+1dB compared with the ICX249AK)
- High S/N
- High resolution and low dark current
- Excellent antiblooming characteristics
- Ye, Cy, Mg, and G complementary color mosaic filters on chip
- Continuous variable-speed shutter
- Substrate bias: Adjustment free (external adjustment also possible with 6 to 14V)
- Reset gate pulse: 5Vp-p adjustment free (drive also possible with 0 to 9V)
- Horizontal register: 5V drive

CCD cameras

Selection: some parameters to consider for metrology

- ***data transfer rate***. In order to acquire a video frame, the times required to expose the CCD array, charge transfer and amplification, digitization, transfer to computer memory, and display have to be taken into consideration. These times are especially important in the investigation of rapid transient phenomena

- ***pixel size***. In general, sensitivity of a CCD array is proportional to the pixel size since a larger pixel area can accumulate a larger number of light photons. Sensitivity is important, especially in the investigation of phenomena involving low-level light conditions as well as in the investigation of rapid transient phenomena in which exposure times are very short

- ***camera resolution***. The dimensions of the CCD array determine the spatial resolution of the image plane (u,v) where u and v are integers. It is clear that a larger CCD array provides with better spatial resolution characteristics, however, it may provide with a lower light sensitivity due to smaller pixel sizes

CCD cameras

Selection: some parameters to consider for metrology

- ***CCD arrays suffer from readout noise***. Implicit electronic noise during photon collection, charge transfer, and amplification can reduce the signal to noise ratio sampled by the camera, which may affect the resolution and accuracy of a processed image

- ***digitization errors***. The amplified output from a CCD array is an analog signal, which indicates that for further processing of a video frame with digital computers, digitization has to take place.

- **digitization can either be performed by an analog to digital conversion board within the camera, or by a separate frame grabber board**. Typical video frame digitization yields 8 and 10 bits per pixel providing an integer number of grayscale levels of 256 and 1024, respectively. From sampling theory (Holman and Gajda, 1989), the smaller the number of bits per pixel during digitization may generate under sampling errors. Currently available digital cameras can provide a resolution of 12, 14, and 16 bits per pixel, however, data transfer rates are reduced. Data transfer rates are important when video data need to be processed at video rate speeds