CS6640 Computational Photography

5. Digital image sensing

Fundamental process

- **Detect photons via photoelectric effect**
  incident photon may be absorbed and create a free electron
  efficiency of conversion = Quantum Efficiency (%)
- **Collect electrons in a potential well**
  think of this as collecting “photon rain” in little “rain gauges”
- **Measure charge to produce digital pixel value**
  charges are small, measured in thousands of electrons
  amplified to produce a measurable voltage, then digitized

Charge-coupled device (CCD) arrays

- **Array of photodiodes; charge stored in potential wells**
- **Readout process**

  charges are shifted across array, then amplified

  amplified on chip but digitized by separate hardware
- **Full frame, frame transfer, interline transfer**

  different architectures for hiding pixels from light

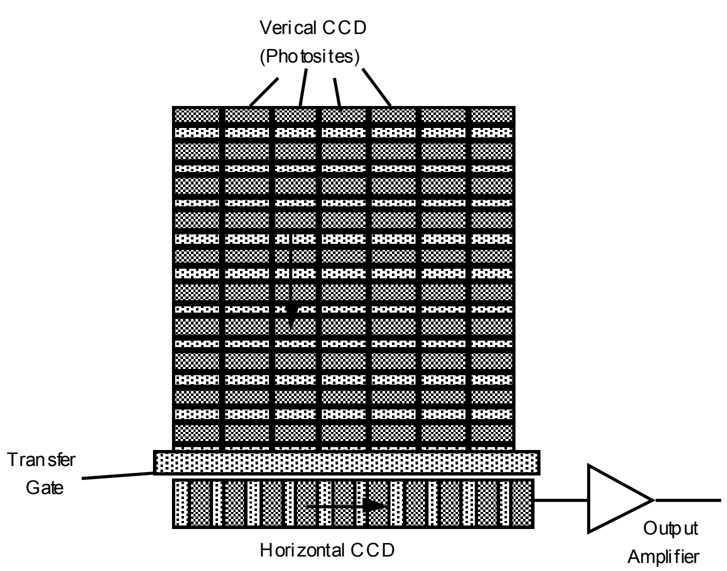


Figure 18: Full Frame Area Image Sensor

full frame

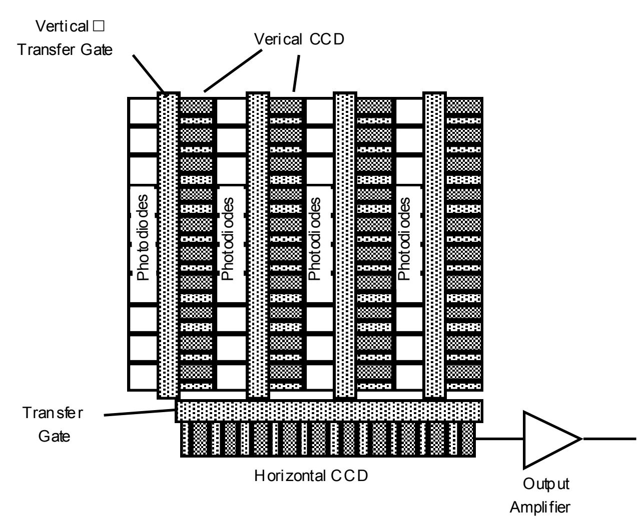


Figure 21: Interline Area Array Image Sensor

interline transfer

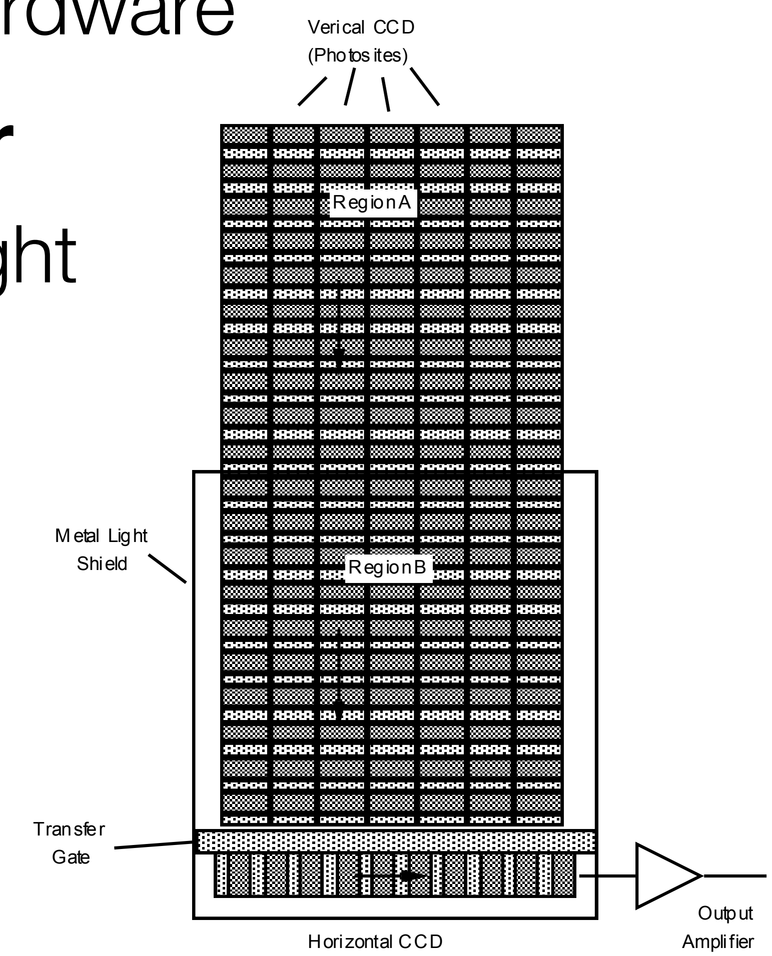


Figure 17: Full Frame Transfer Image Sensor

frame transfer

images: Truesense Imaging, *Image Sensor Terminology*

CMOS image sensors

- **Sensors made in CMOS process**

  same process used for CPUs and other VLSI chips

  analog and digital processing on the same die with sensor

- **Typical arrangement: Active Pixel Sensor (APS)**

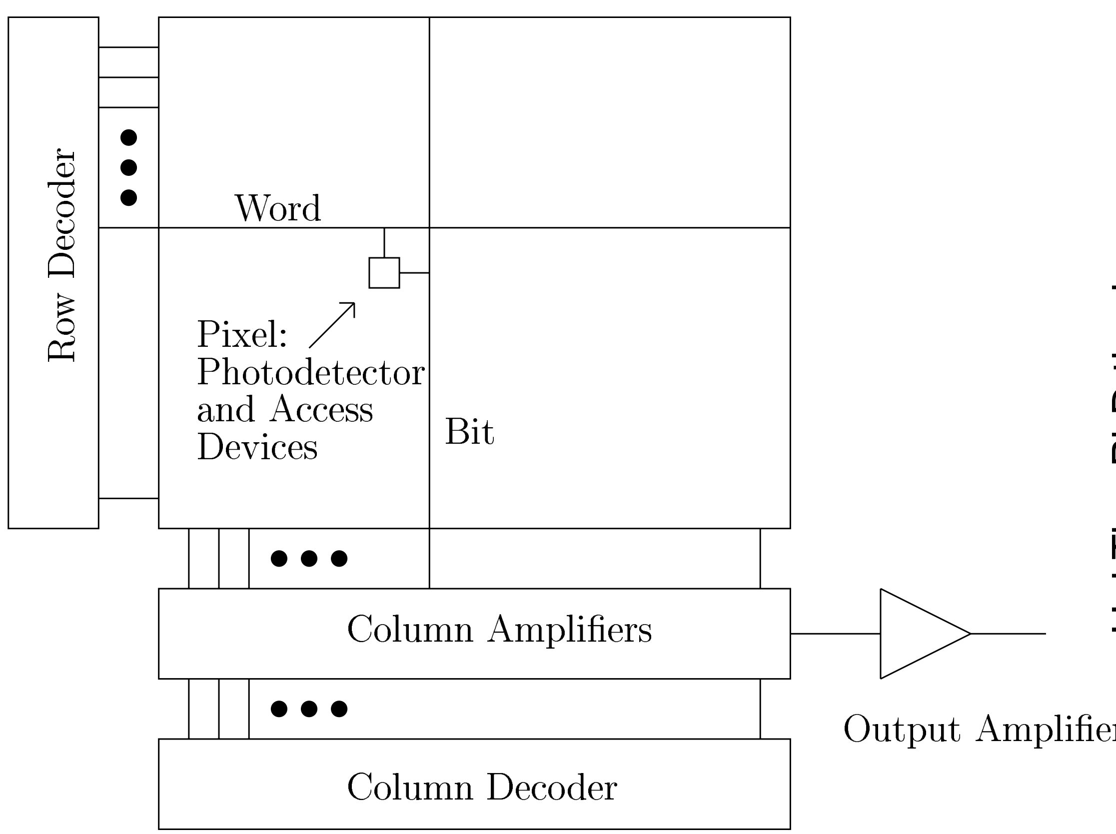
  each pixel has its own charge amplifier

  pixels read out by row/column addressing

  single ADC circuit

- **Other arrangements**

  ADC per pixel (but uses a lot of area)



Hui Tian PhD thesis

Noise sources

- **Dark current**
  temperature-dependent thermal generation of electrons
- **Shot noise**
  from Poisson process of photoelectron generation
- **Reset noise**
  cancel using "correlated double sampling"
- **Readout noise**
  sum of various noise sources in analog electronics
- **Quantization noise**
  error due to rounding to the nearest pixel value in ADC
- **Fixed pattern noise**
  spatial noise due to variations in components

A reasonable noise model

photons

$$E$$

A reasonable noise model

quantum efficiency → χ

photons → E

$$\chi E$$

A reasonable noise model

$$\chi E + t I_d$$

- quantum efficiency: χ
- # photons: E
- exposure time: t
- dark current: I_d

A reasonable noise model

$$y = \chi E + t I_d$$

- y: # electrons
- χ: quantum efficiency
- E: # photons
- t: exposure time
- I_d: dark current

A reasonable noise model

$$y = \chi E + t I_d$$

- y: # electrons
- χ: quantum efficiency
- E: # photons
- t: exposure time
- I_d: dark current

$$y$$

- y: # electrons

A reasonable noise model

quantum efficiency

photons

$$y = \chi E + t I_d$$

electrons

exposure time

dark current

$$y + \eta_g$$

electrons

readout noise (gaussian)

A reasonable noise model

$$y = \chi E + t I_d$$

- y: # electrons
- χ: quantum efficiency
- E: # photons
- t: exposure time
- I_d: dark current

$$y + \eta_g + \eta_p(y)$$

- y: # electrons
- η_g: readout noise (gaussian)
- $\eta_p(y)$: shot noise (poisson; variance = *y*)

A reasonable noise model

$$y = \chi E + tI_d$$

- χ: quantum efficiency
- E: # photons
- y: # electrons
- t: exposure time
- I_d: dark current

$$a(y + \eta_g + \eta_p(y))$$

- a: gain
- y: # electrons
- η_g: readout noise (gaussian)
- $\eta_p(y)$: shot noise (poisson; variance = *y*)

A reasonable noise model

$$y = \chi E + t I_d$$

- quantum efficiency (χ)
- # photons (E)
- # electrons (y)
- exposure time (t)
- dark current (I_d)

$$f(a(y + \eta_g + \eta_p(y)))$$

- quantization function (f)
- gain (a)
- # electrons (y)
- readout noise (gaussian) (η_g)
- shot noise (poisson; variance = *y*) ($\eta_p(y)$)

A reasonable noise model

quantum efficiency

photons

$$y = \chi E + tI_d$$

electrons

exposure time

dark current

quantization function

gain

$$N = f(a(y + \eta_g + \eta_p(y)))$$

digital pixel value

electrons

readout noise (gaussian)

shot noise (poisson; variance = *y*)

CCD vs. CMOS

- **CCDs: older, first technology in high end**
  - – multiple, high supply voltages required; high power consumption
  - – can't integrate processing on die; always need multiple chips
  - \+ easier to achieve low noise
  - \+ better fill factors
  - \+ low fixed-pattern noise

    because all the work is being done by one amplifier
- **CMOS: newer, currently taking over**
  - – much sophistication required to achieve low noise

    prone to fixed-pattern noise because of per-pixel amplifiers

    prone to readout noise because of area-constrained amplifiers
  - – extra circuitry consumes area, decreases fill factor
  - \+ fast, random access readout
  - \+ single, low supply voltage; low power consumption
  - \+ can integrate processing on die to make single-chip cameras

1.8.2. Revenues

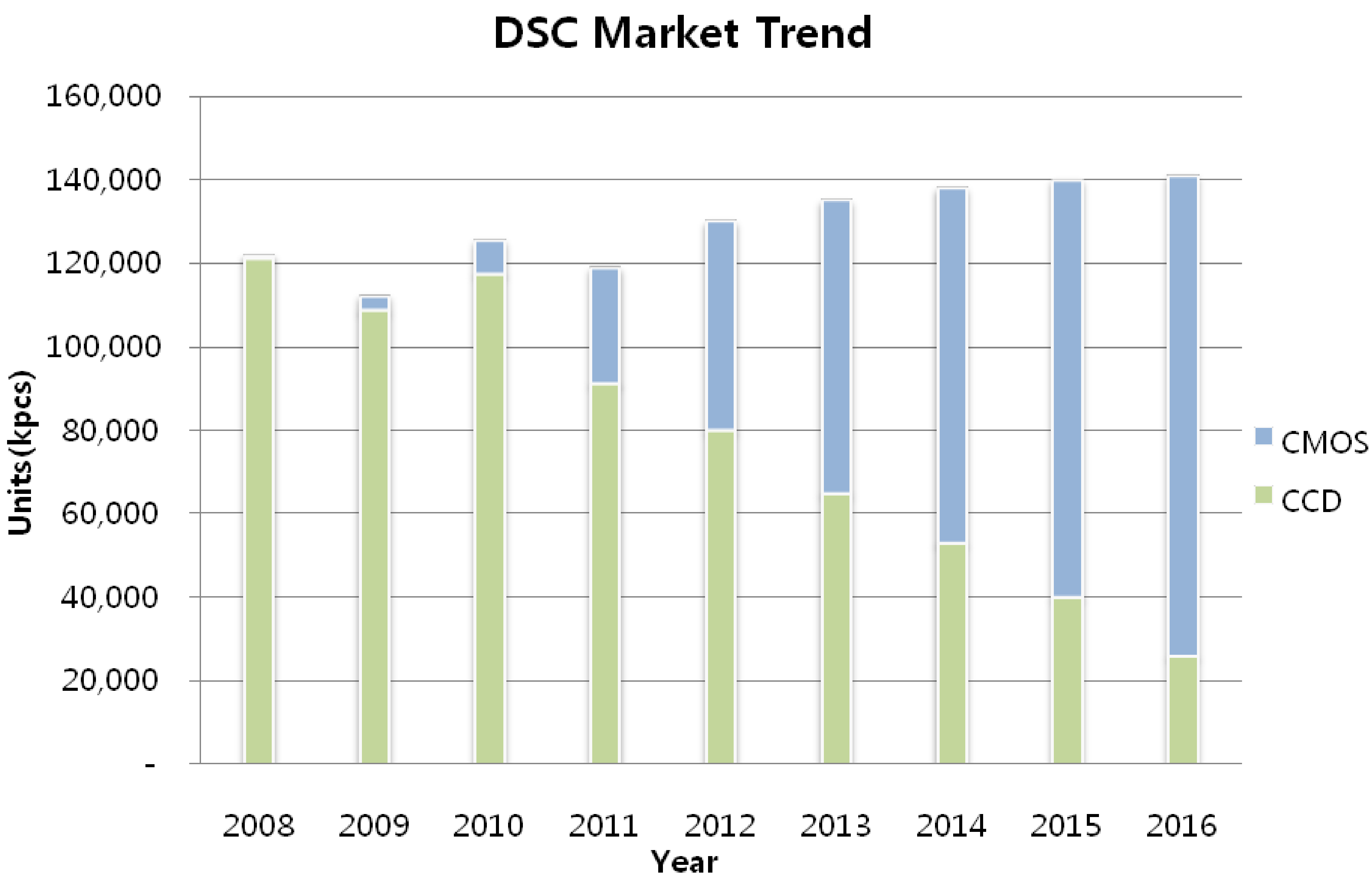
Market Share in 2010 – 2011 Forecast (Revenues)

Unit: US$M

	Total				CCD				CMOS			
	2010	%	2011F	%	2010	%	2011F	%	2010	%	2011F	%
Sony	1,934.8	33.8%	2,663.9	37.3%	841.3	51.8%	650.8	56.4%	1,093.5	26.7%	2,013.1	33.6%
Aptina	391.4	6.8%	440.4	6.2%					391.4	9.6%	440.4	7.3%
Panasonic	523.1	9.1%	458.0	6.4%	420.6	25.9%	281.6	24.4%	102.5	2.5%	176.4	2.9%
OmniVision	582.6	10.2%	615.3	8.6%					582.6	14.2%	615.3	10.3%
Samsung	581.7	10.2%	844.7	11.8%					581.7	14.2%	844.7	14.1%
Canon	611.4	10.7%	874.3	12.2%					611.4	14.9%	874.3	14.6%
Sharp	323.1	5.6%	185.2	2.6%	311.8	19.2%	183.2	15.9%	11.3	0.3%	2.0	0.0%
Nikon	169.0	3.0%	240.7	3.4%					169.0	4.1%	240.7	4.0%
Toshiba	232.3	4.1%	321.4	4.5%					232.3	5.7%	321.4	5.4%
ST Micro	171.9	3.0%	223.1	3.1%					171.9	4.2%	223.1	3.7%
Hynix	70.1	1.2%	126.0	1.8%					70.1	1.7%	126.0	2.1%
FujiFilm	7.8	0.1%	14.8	0.2%	7.8	0.5%	1.3	0.1%		0.0%	13.5	0.2%
Others	119.6	2.1%	137.3	1.9%	43.3	2.7%	36.1	3.1%	76.3	1.9%	101.2	1.7%
Total	5,718.8	100.0%	7,145.1	100.0%	1,624.8	100.0%	1,153.0	100.0%	4,094.0	100.0%	5,992.1	100.0%

※ The revenues above were calculated based on shipments of application devices, which do not match the actual image sensor shipment revenues.

※ The volumes of sensors for Chinese non-brand camera phones are not included in the figures above.



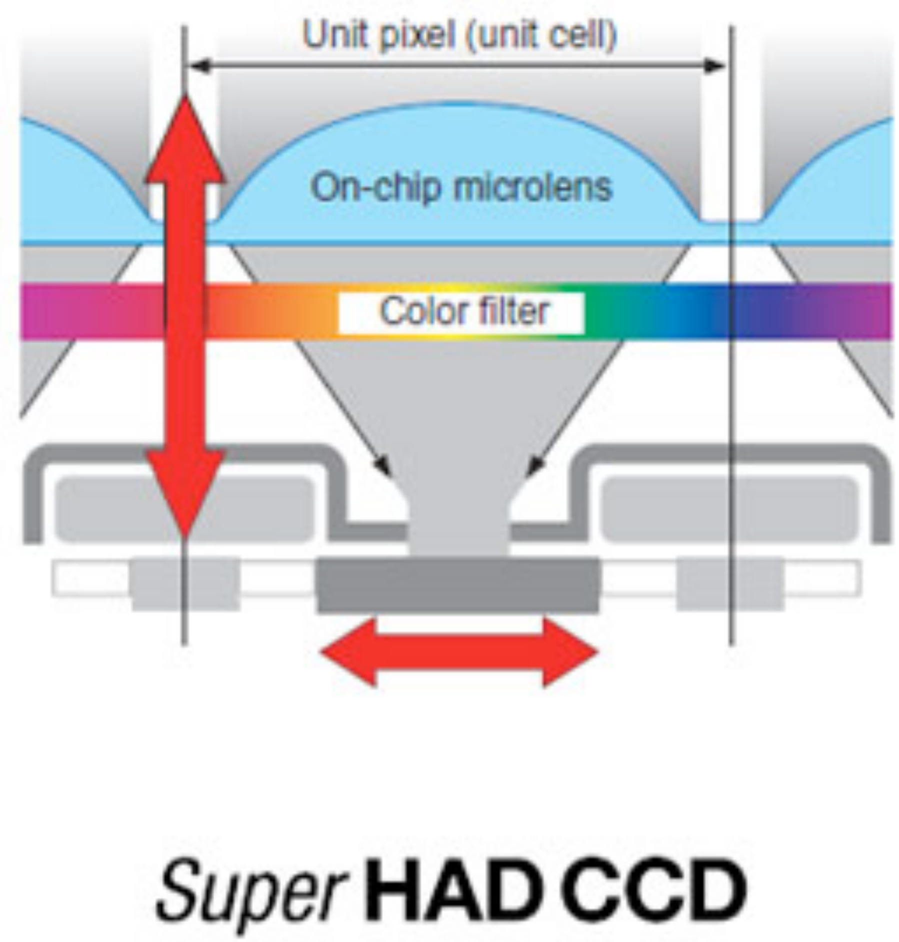
Samsung white paper, *Current Status and Future Perspectives of CMOS Image Sensor*

Microlenses

- **Increase fill factor by focusing incoming light**
- **Produce angularly varying sensitivity**

  no free lunch—larger area comes with smaller solid angle
- **Can interact badly with wide-angle lenses**

  for this reason many DSC lenses are designed to be at least partially telecentric on the image side



Sony product literature

Front vs. back illumination

- **Front illuminated**

  conventional design has interconnects and circuitry in front

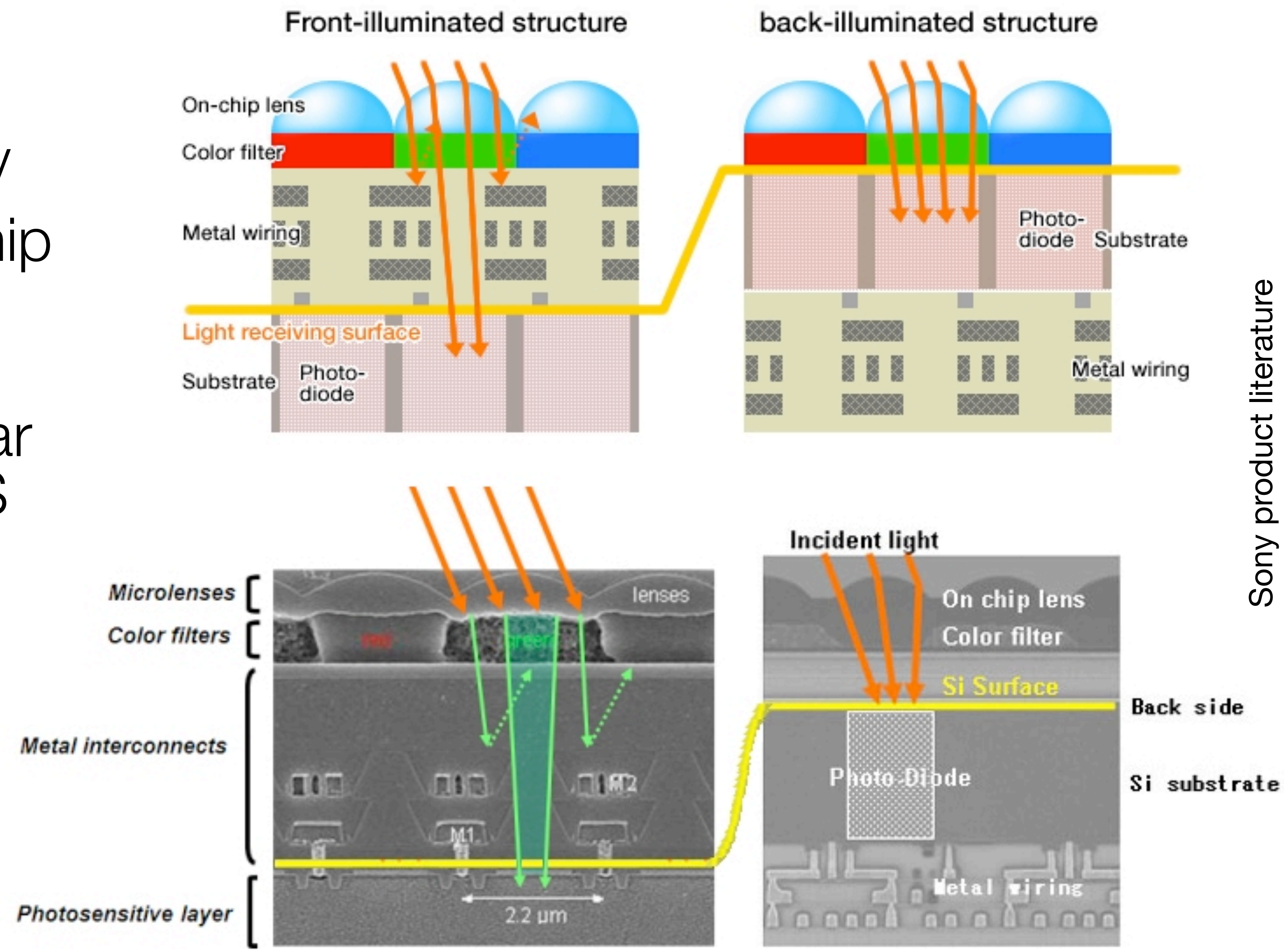
  causes reduced fill factor and QE (particularly for blue)

- **Back illuminated**

  originally an esoteric product for astronomy

  grind away back of chip and illuminate the photosensors directly

  now becoming popular in small-format CMOS sensors



Sony product literature

Summary Specification

KAI-08050 Image Sensor

DESCRIPTION

The KAI-08050 Image Sensor is an 8-megapixel CCD in a 4/3" optical format. Based on the TRUESENSE 5.5 micron Interline Transfer CCD Platform, the sensor features broad dynamic range, excellent imaging performance, and a flexible readout architecture that enables use of 1, 2, or 4 outputs. The sensor supports full resolution readout up to 16 frames per second, while a Region of Interest (ROI) mode supports partial readout of the sensor at even higher frame rates. A vertical overflow drain structure suppresses image blooming and enables electronic shuttering for precise exposure control.

The sensor is available with the TRUESENSE Sparse Color Filter Pattern, a technology which provides a 2x improvement in light sensitivity compared to a standard color Bayer part.

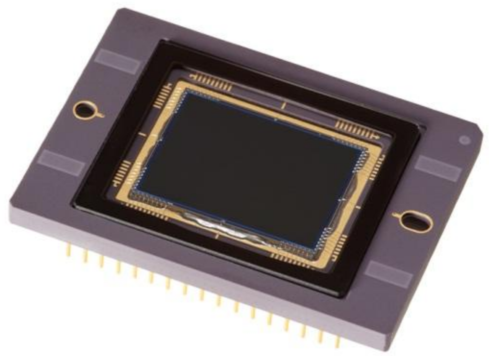
The sensor shares common pin-out and electrical configurations with other devices based on the TRUESENSE 5.5 micron Interline Transfer Platform, allowing a single camera design to support multiple members of this sensor family.

FEATURES

- Bayer Color Pattern, TRUESENSE Sparse Color Filter Pattern, and Monochrome configurations
- Progressive scan readout
- Flexible readout architecture
- High frame rate
- High sensitivity
- Low noise architecture
- Excellent smear performance
- Package pin reserved for device identification

APPLICATIONS

- Industrial Imaging
- Medical Imaging
- Security

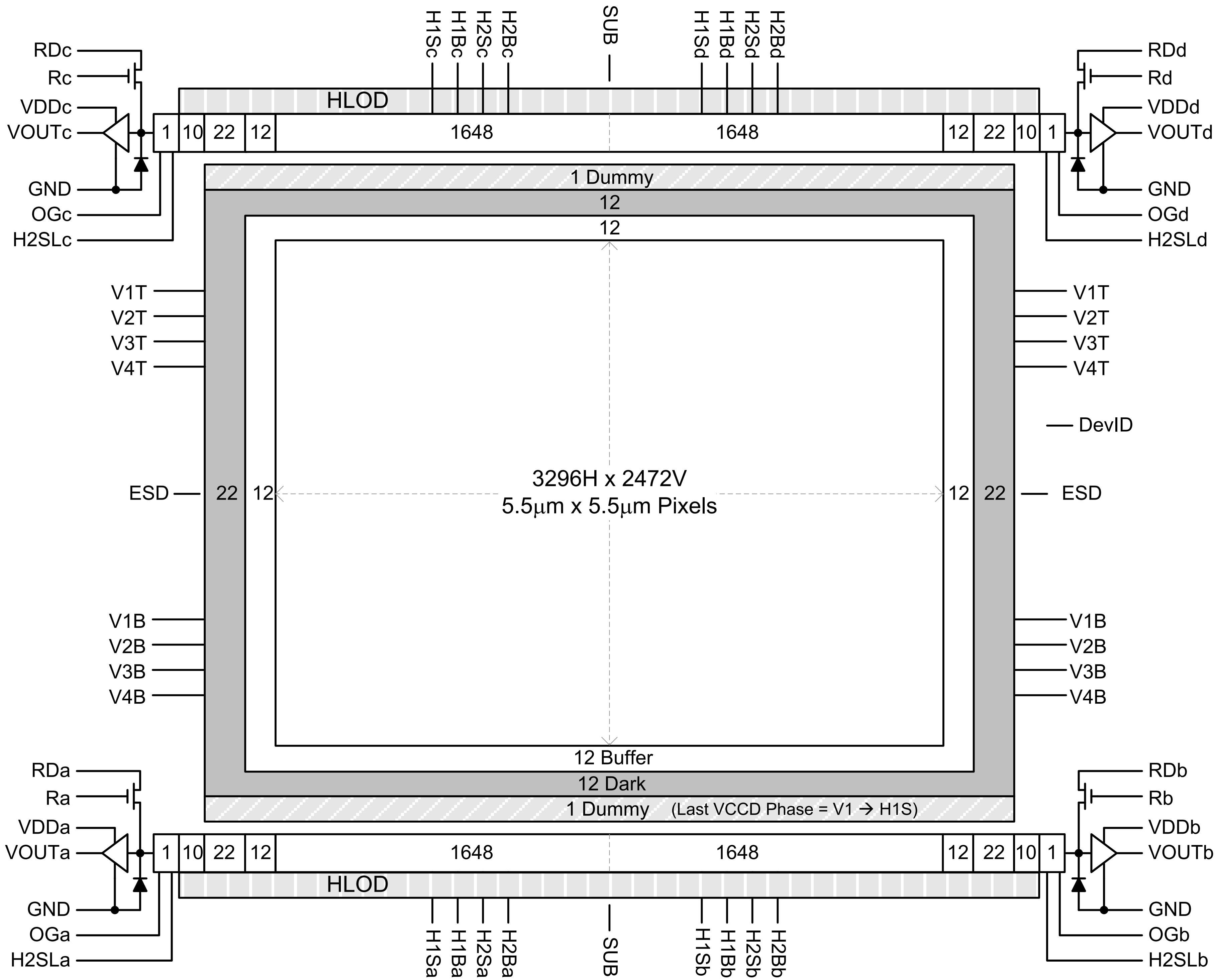


Parameter	Typical Value
Architecture	Interline CCD; Progressive Scan
Total Number of Pixels	3364 (H) x 2520 (V)
Number of Effective Pixels	3320 (H) x 2496 (V)
Number of Active Pixels	3296 (H) x 2472 (V)
Pixel Size	5.5 μm (H) x 5.5 μm (V)
Active Image Size	18.13 mm (H) x 13.60 mm (V) 22.66 mm (diag) 4/3" optical format
Aspect Ratio	4:3
Number of Outputs	1, 2, or 4
Charge Capacity	20,000 electrons
Output Sensitivity	34 μV/e^-
Quantum Efficiency Pan (-ABA, -PBA) R, G, B (-CBA, -PBA)	50% (500 nm) 31%, 42%, 43% (620, 540, and 470 nm)
Read Noise (f= 40MHz)	12 electrons rms
Dark Current Photodiode VCCD	7 electrons/s 100 electrons/s
Dark Current Doubling Temp Photodiode VCCD	7 °C 9 °C
Dynamic Range	64 dB
Charge Transfer Efficiency	0.999999
Blooming Suppression	> 300 X
Smear	-100 dB
Image Lag	< 10 electrons
Maximum Pixel Clock Speed	40 MHz
Maximum Frame Rates Quad Output Dual Output Single Output	16 fps 8 fps 4 fps
Package	68 pin PGA
Cover Glass	AR Coated, 2 Sides

All parameters are specified at T = 40 °C unless otherwise noted

Device Description

ARCHITECTURE



1/2.5-Inch 5Mp CMOS Digital Image Sensor

MT9P031

For the latest data sheet, refer to Aptina's Web site: www.aptina.com

Features

- High frame rate
- Superior low-light performance
- Low dark current
- Global reset release, which starts the exposure of all rows simultaneously
- Bulb exposure mode, for arbitrary exposure times
- Snapshot mode to take frames on demand
- Horizontal and vertical mirror image
- Column and row skip modes to reduce image size without reducing field-of-view (FOV)
- Column and row binning modes to improve image quality when resizing
- Simple two-wire serial interface
- Programmable controls: gain, frame rate, frame size, exposure
- Automatic black level calibration
- On-chip phase-locked loop (PLL)

Applications

- High resolution network cameras
- Wide FOV cameras
- 720P–60 fps cameras
- Dome cameras with electronic pan, tile, and zoom
- Hybrid video cameras with high resolution stills
- Detailed feature extraction for smart cameras

Ordering Information

Table 1: Available Part Numbers

Part Number	Description
MT9P031I12STC	48-pin iLCC 7 deg
MT9P031I12STD	48-pin iLCC ES demo
MT9P031I12STH	48-pin iLCC headboard

Table 2: Key Performance Parameters

Parameter		Value
Optical format		1/2.5-inch (4:3)
Active imager size		5.70mm(H) x 4.28mm(V) 7.13mm diagonal
Active pixels		2592H x 1944V
Pixel size		2.2 x 2.2µm
Color filter array		RGB Bayer pattern
Shutter type		Global reset release (GRR), Snapshot only Electronic rolling shutter (ERS)
Maximum data rate/ master clock		96 Mp/s at 96 MHz (2.8V I/O) 48 Mp/s at 48 MHz (1.8V I/O)
Frame rate	Full resolution	Programmable up to 14 fps
	VGA (640 x 480, with binning)	Programmable up to 53 fps
ADC resolution		12-bit, on-chip
Responsivity		1.4 V/lux-sec (550nm)
Pixel dynamic range		70.1dB
SNR_{MAX}		38.1dB
Supply Voltage	I/O	1.7—3.1V
	Digital	1.7—1.9V (1.8V nominal)
	Analog	2.6—3.1V (2.8V nominal)
Power consumption		381mW at 15 fps full resolution
Operating temperature		–30°C to +70°C
Packaging		48-pin iLCC, die

The 5Mp CMOS image sensor features Aptina's breakthrough low-noise CMOS imaging technology that achieves CCD image quality (based on signal-to-noise ratio and low-light sensitivity) while maintaining the inherent size, cost, and integration advantages of CMOS.

General Description

The Aptina® MT9P031 is a 1/2.5-inch CMOS active-pixel digital image sensor with an active imaging pixel array of 2592H x 1944V. It incorporates sophisticated camera functions on-chip such as windowing, column and row skip mode, and snapshot mode. It is programmable through a simple two-wire serial interface.

T4K05 8-Megapixel BSI CMOS Image Sensor

Highlights

- Major worldwide producer of image sensor technology with more than 25 years of experience.
- Offers advanced BSI technology and ultra-compact chip scale camera module packaging technology.
- Utilizes a proprietary square-pixel design that enables exceptionally high-quality images with low-power consumption.
- Offers a wide range of sensors from VGA to 14-megapixels with higher resolutions in development.
- Makes ongoing investments in capacity and its robust supply chain is a result of tight procurement relationships and experience in designing, developing and manufacturing image sensors.

Description

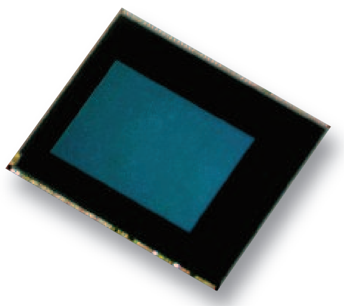
The T4K05 is an 8-megapixel image sensor with backside illumination (BSI) for better light sensitivity and absorption. The image sensor has an optical format of ¼ inch with each pixel measuring 1.12 x 1.12 micrometers. The sensor enables a module as small as 7.5 mm x 7.5 mm and a high speed frame rate of 30 frames-per-second in full resolution mode and 1080p with low power consumption. The TK405 integrates a high dynamic range (HDR) function enabling both bright and dark areas to be captured resulting in a clear and crisp image.

Applications

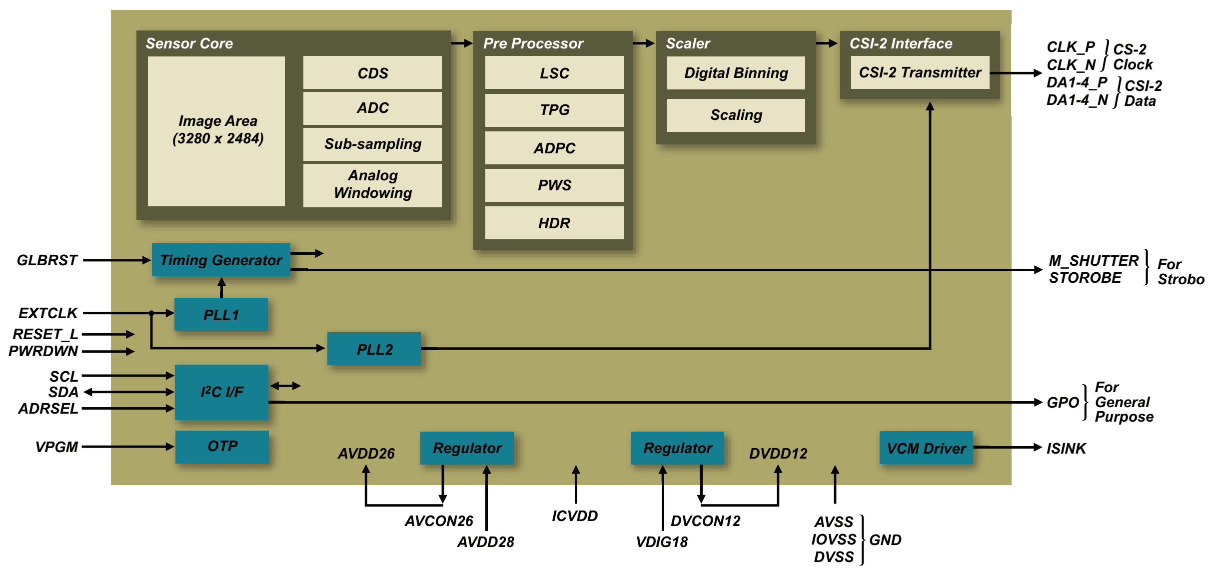
- Cellular and Smartphone

Features

- ¼" 8M resolution (1.12 micrometers)
- Backside Illumination (BSI)
- Progressive scan
- I2C interface
- Sub-sampling: Vertical and horizontal ½", ¼"
- Built-in Phase Lock Loop (PLL) with Dual PLL (second PLL for MIPI® output)
- High Dynamic Range (HDR)
- Lens shading correction
- Defect pixel correction
- Picture flip (horizontal and vertical)
- Context switch
- Built-in VCM driver
- Built-in temperature sensor
- Standby mode, Power down mode
- OTP (4k-bits one-time memory)
- Built-in regulator (1.2V)



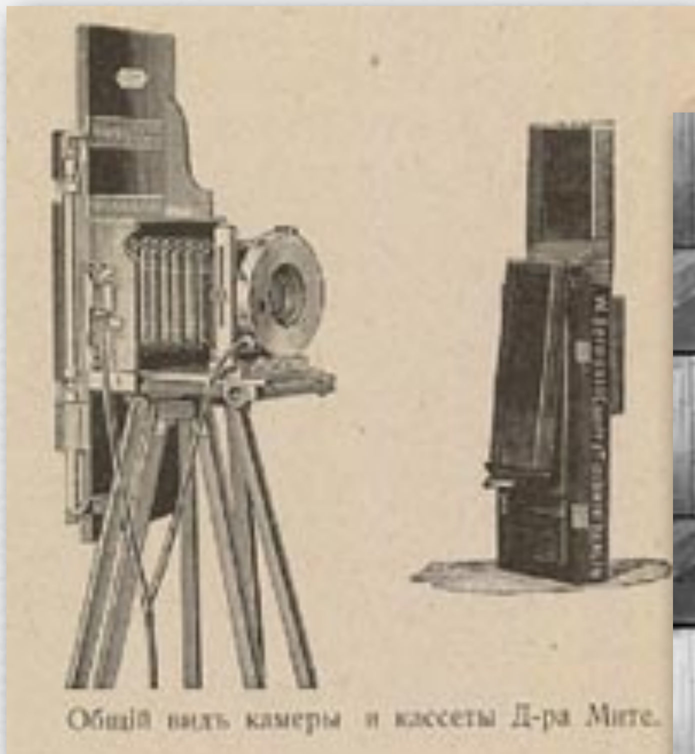
T4K05 System Block Diagram

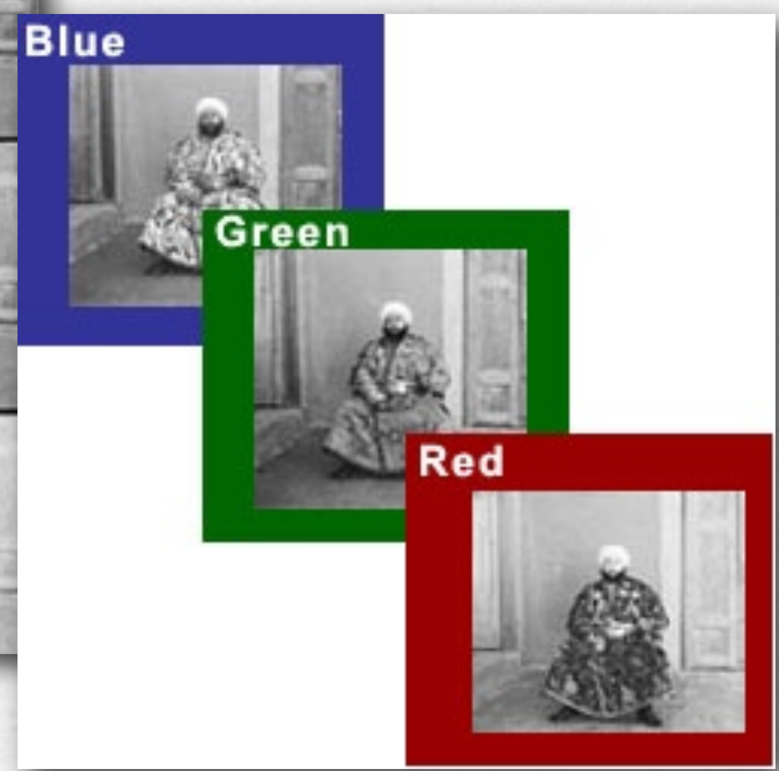


Sensing color

- **Frame sequential**
- **3-chip**
- **Color filter array (CFA)**
- **Multilayer (foveon)**

Sergey Prokudin-Gorsky





- shot sequentially through R, G, B filters
- simultaneous projection provided good color, but available printing technology did not
- digital restoration lets us see them in full glory...

worth a look:
http://www.loc.gov/exhibits/empire/

slide by Marc Levoy, Stanford

Sergey Prokudin-Gorsky, Alim Khan, emir of Bukhara (1911)

Sergey Prokudin-Gorsky,
Pinkhus Karlinskii, Supervisor of the Chernigov Floodgate (1919)

Technicolor

Wizard of Oz (1939)

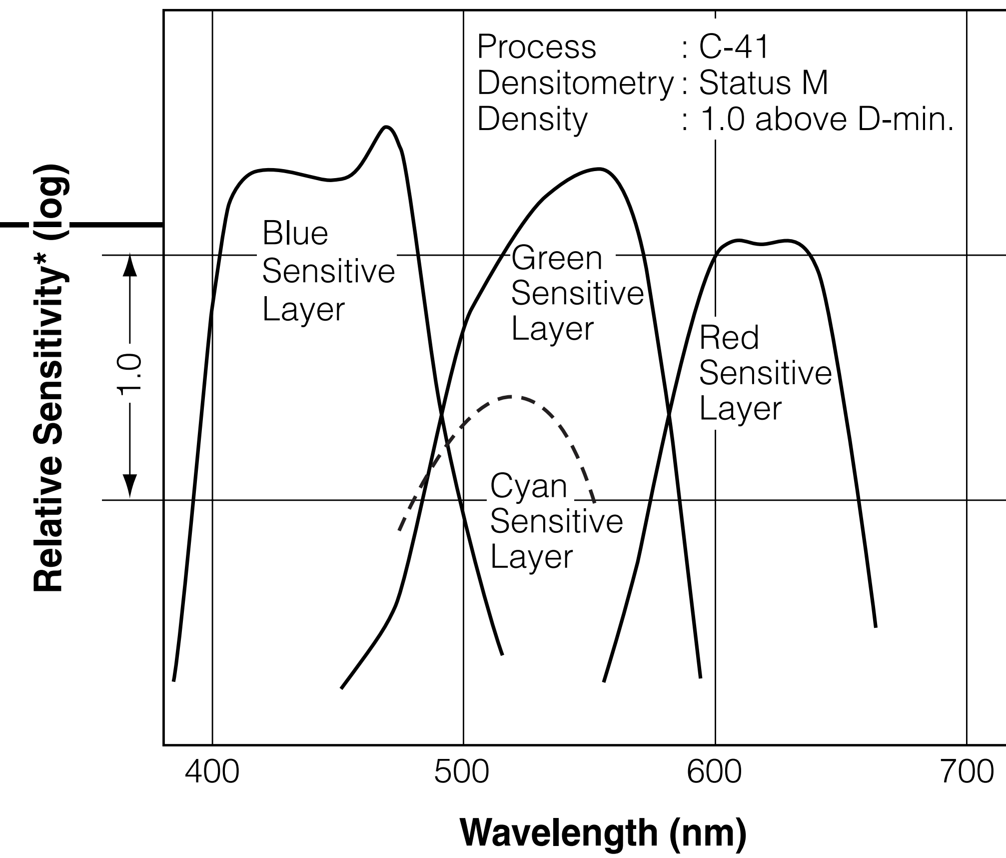
- **3 negatives exposed simultaneously**
  via beam splitter and filters
- **large, heavy cameras; cumbersome printing process**

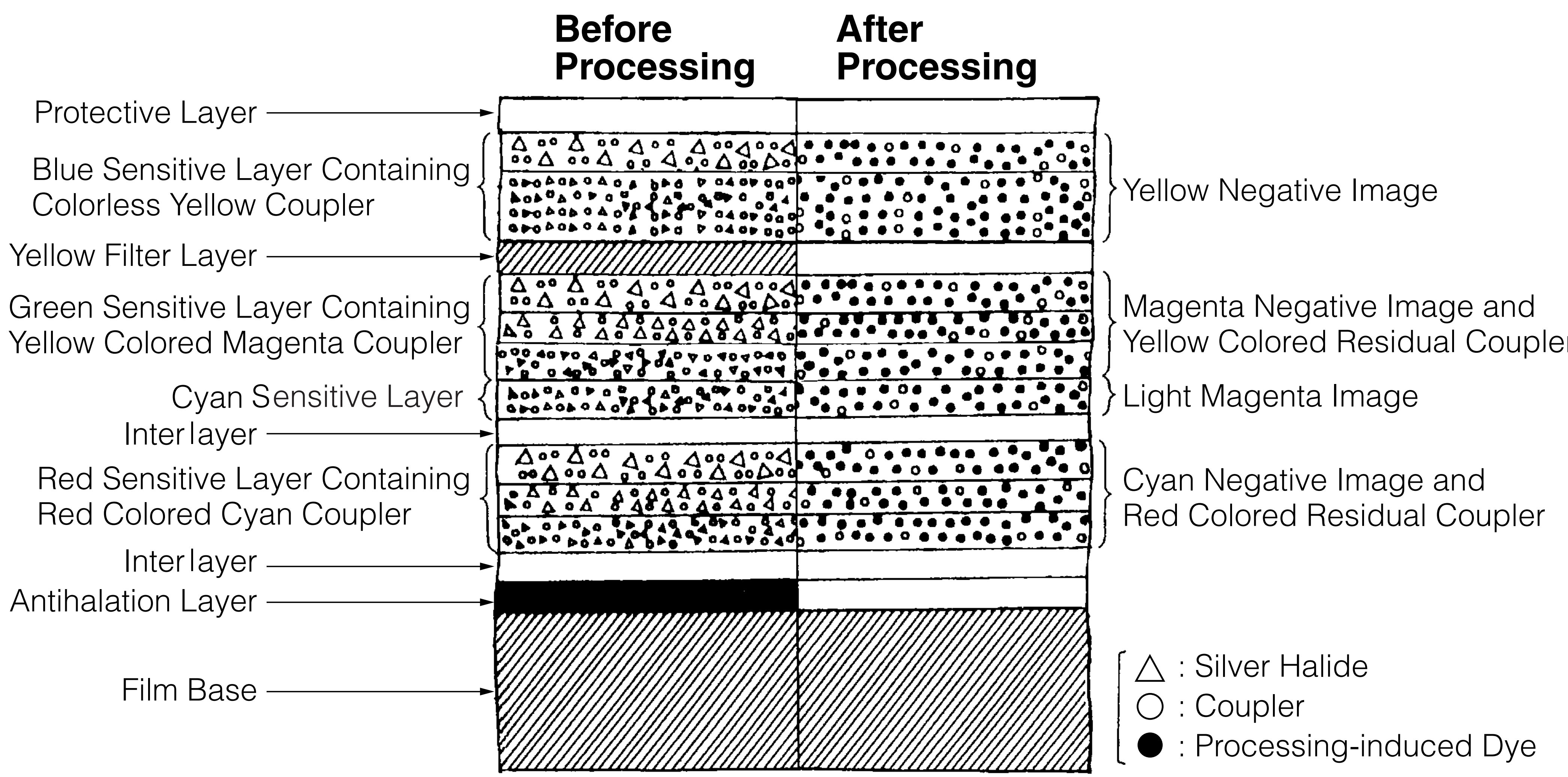
Single-strip color film

- **Color film is an RGB sensing device**

  intricate stack of layers, each sensitive to one band and transparent to others

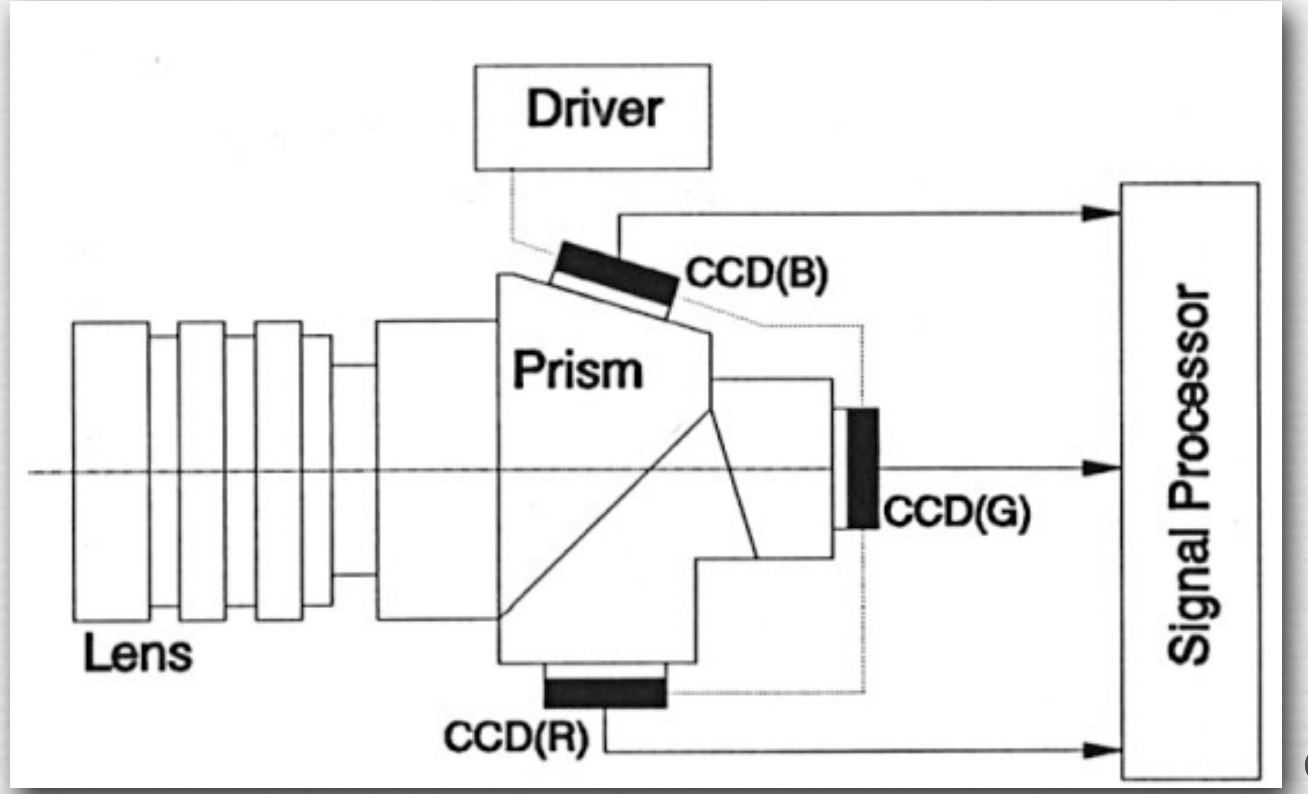
- **Information stored in negative images**





Fujicolor Pro 400 H datasheet

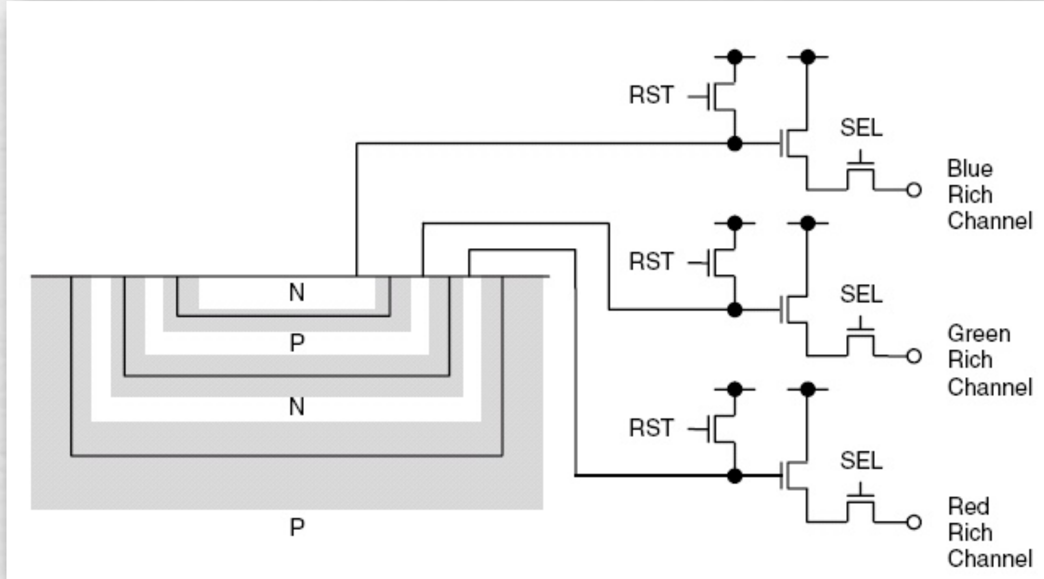
3-chip cameras



(Theuwissen)

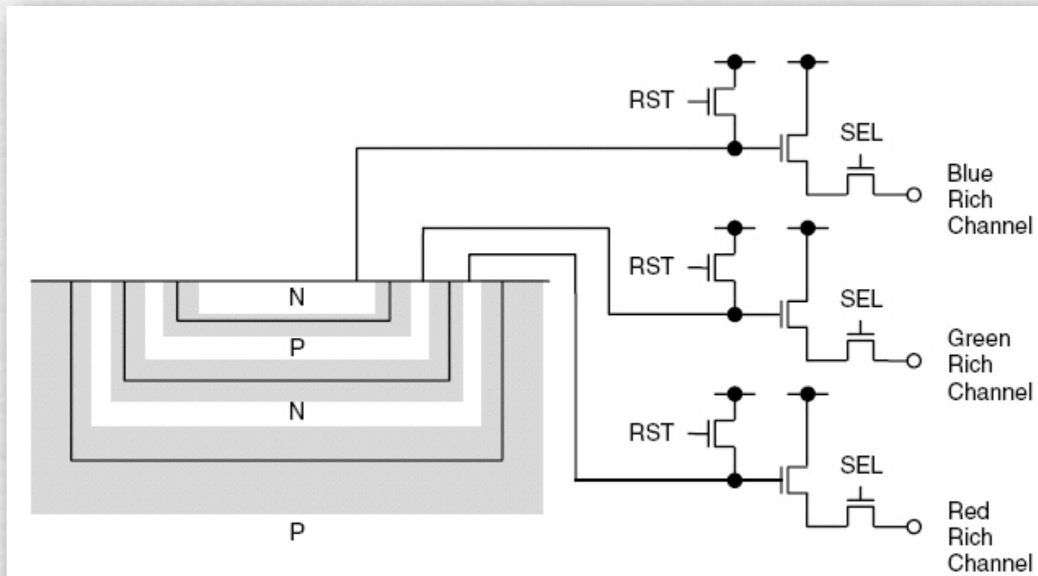
- high-quality video cameras
- prism & dichroic mirrors split the image into 3 colors, each routed to a separate sensor (typically CCD)
- no light loss, as compared to filters (which absorb light)
- expensive, and complicates lens design

Foveon stacked sensor



- longer wavelengths penetrate deeper into silicon, so arrange a set of vertically stacked detectors
  - top gets mostly blue, middle gets green, bottom gets red
  - no control over spectral responses, so requires processing
- fewer moiré artifacts than color filter arrays + demosaicing
  - but possibly worse noise performance, especially in blue

Foveon stacked sensor



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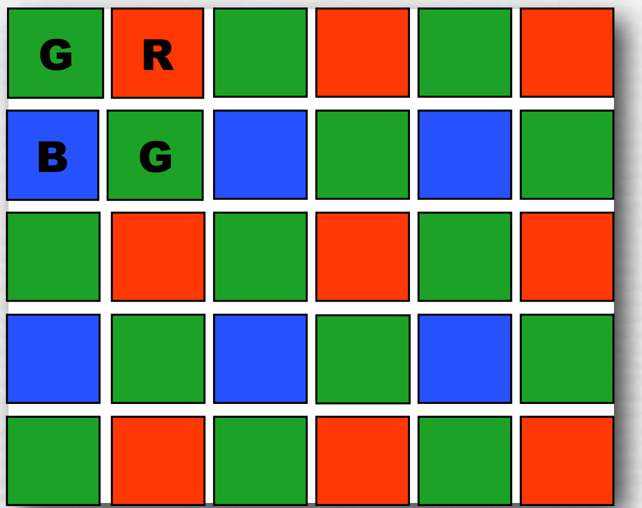
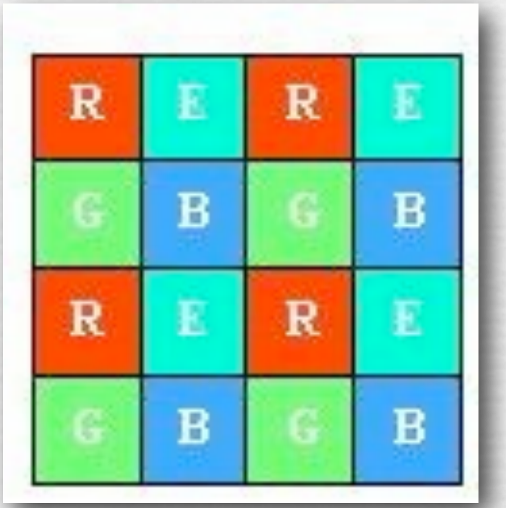
slide by Marc Levoy, Stanford

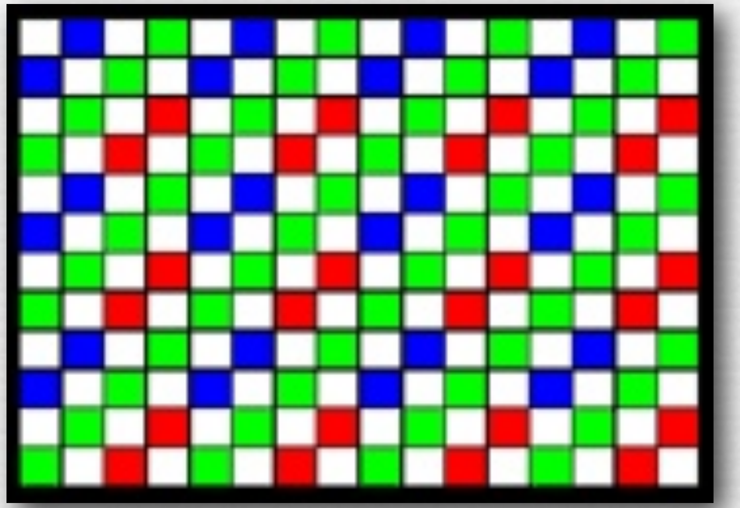
Color filter arrays



Bayer pattern



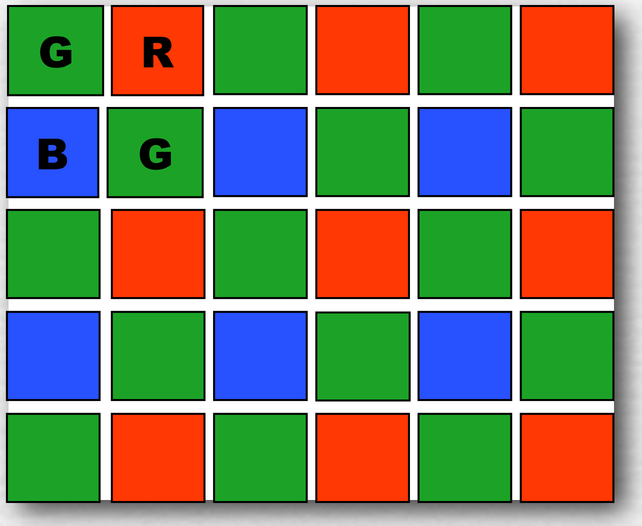
Sony RGB+E
better color



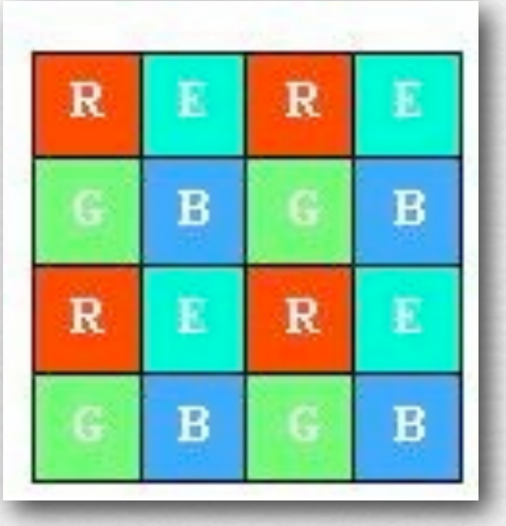
Kodak RGB+C
more dynamic range

slide by Marc Levoy, Stanford

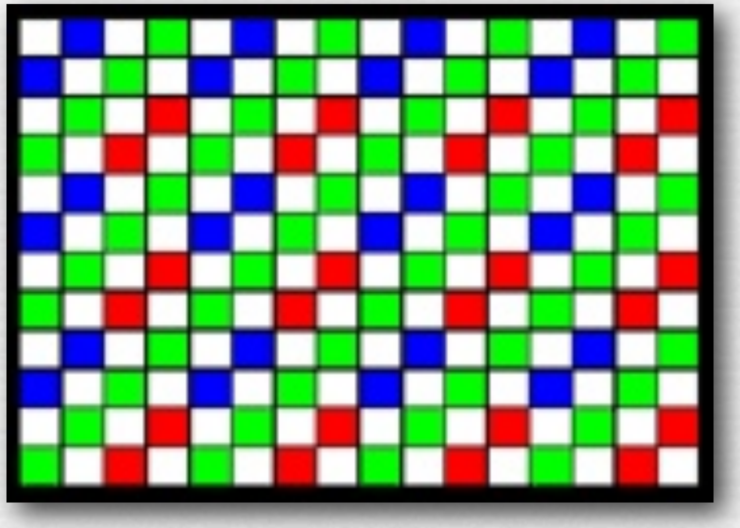
Color filter arrays



Bayer pattern



Sony RGB+E
better color

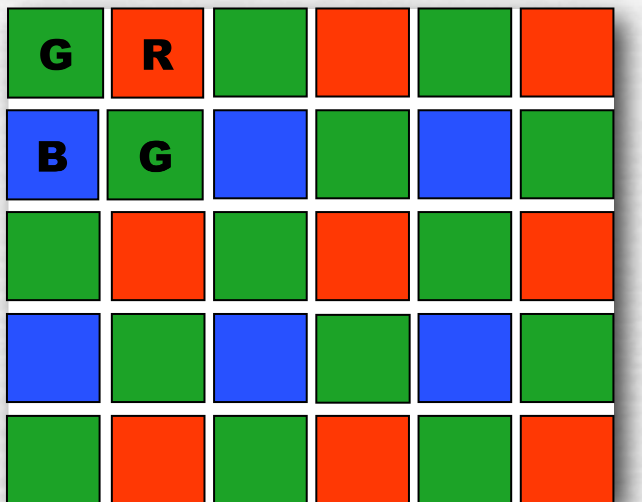


Kodak RGB+C
more dynamic range

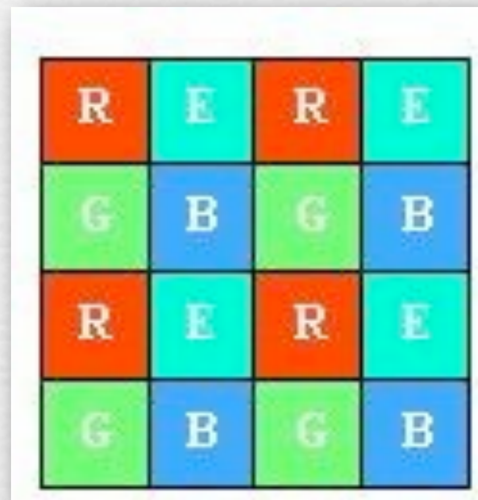
- Why more green pixels than red or blue?

slide by Marc Levoy, Stanford

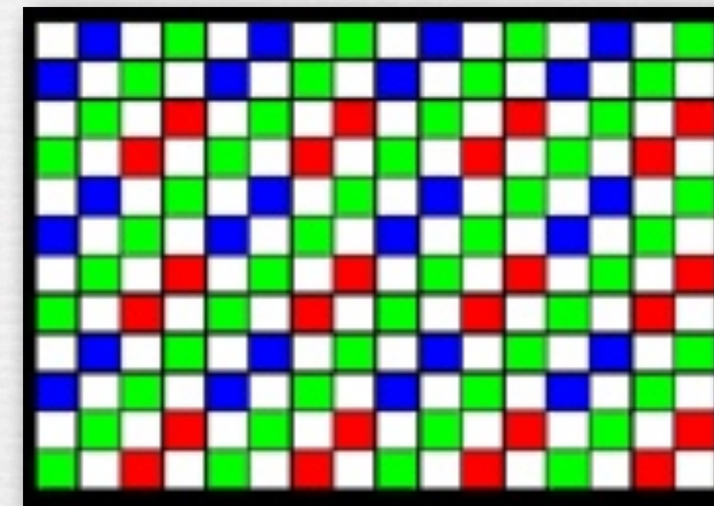
Color filter arrays



Bayer pattern



Sony RGB+E
better color

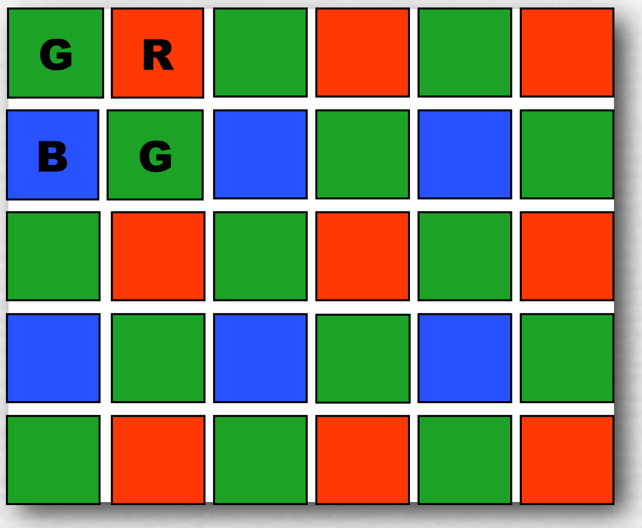


Kodak RGB+C
more dynamic range

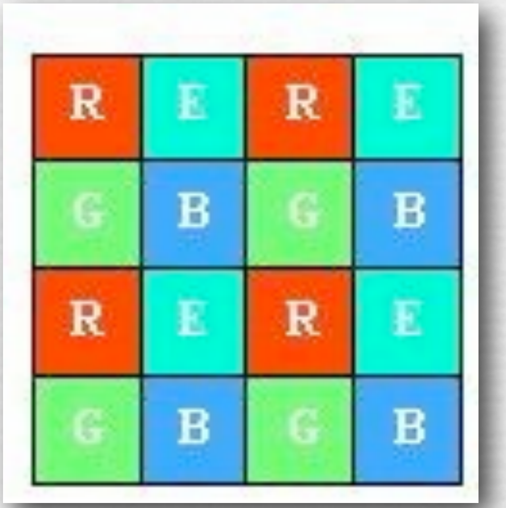
- Why more green pixels than red or blue?
  - because green pixels come closest to measuring luminance

slide by Marc Levoy, Stanford

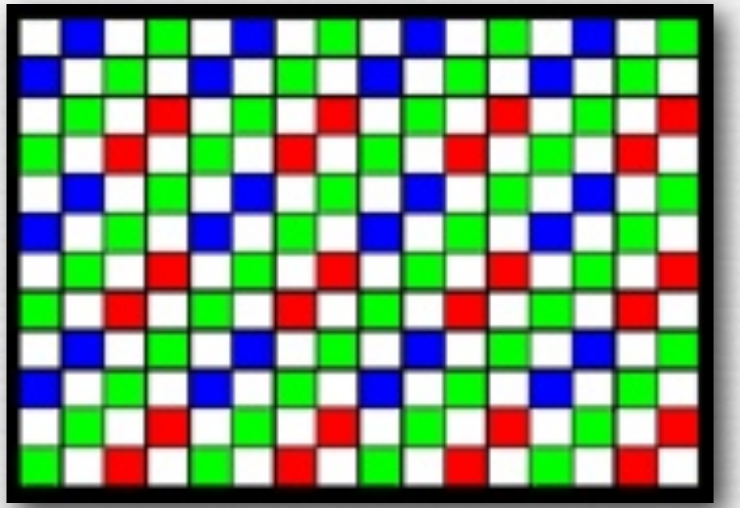
Color filter arrays



Bayer pattern



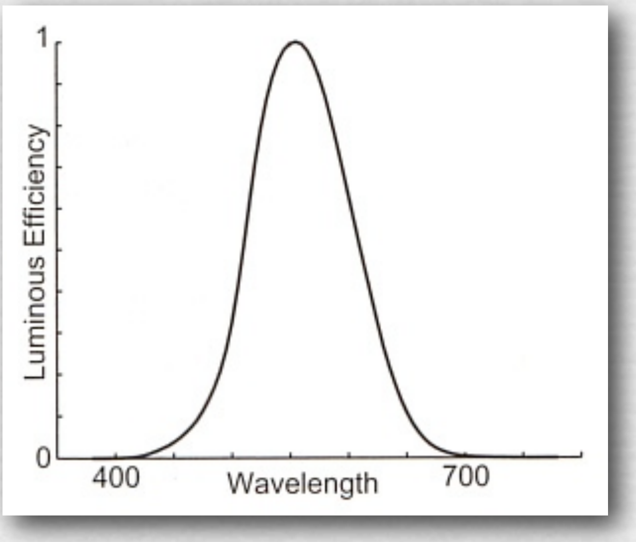
Sony RGB+E
better color



Kodak RGB+C
more dynamic range

- Why more green pixels than red or blue?
  - because green pixels come closest to measuring luminance
  - human eye cares mostly about detailed luminance, not so much for chromaticity

(Stone)



Example of Bayer mosaic image

Small fan at Stanford women's soccer game

(Canon 1D III)

slide by Marc Levoy, Stanford

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Example of Bayer mosaic image

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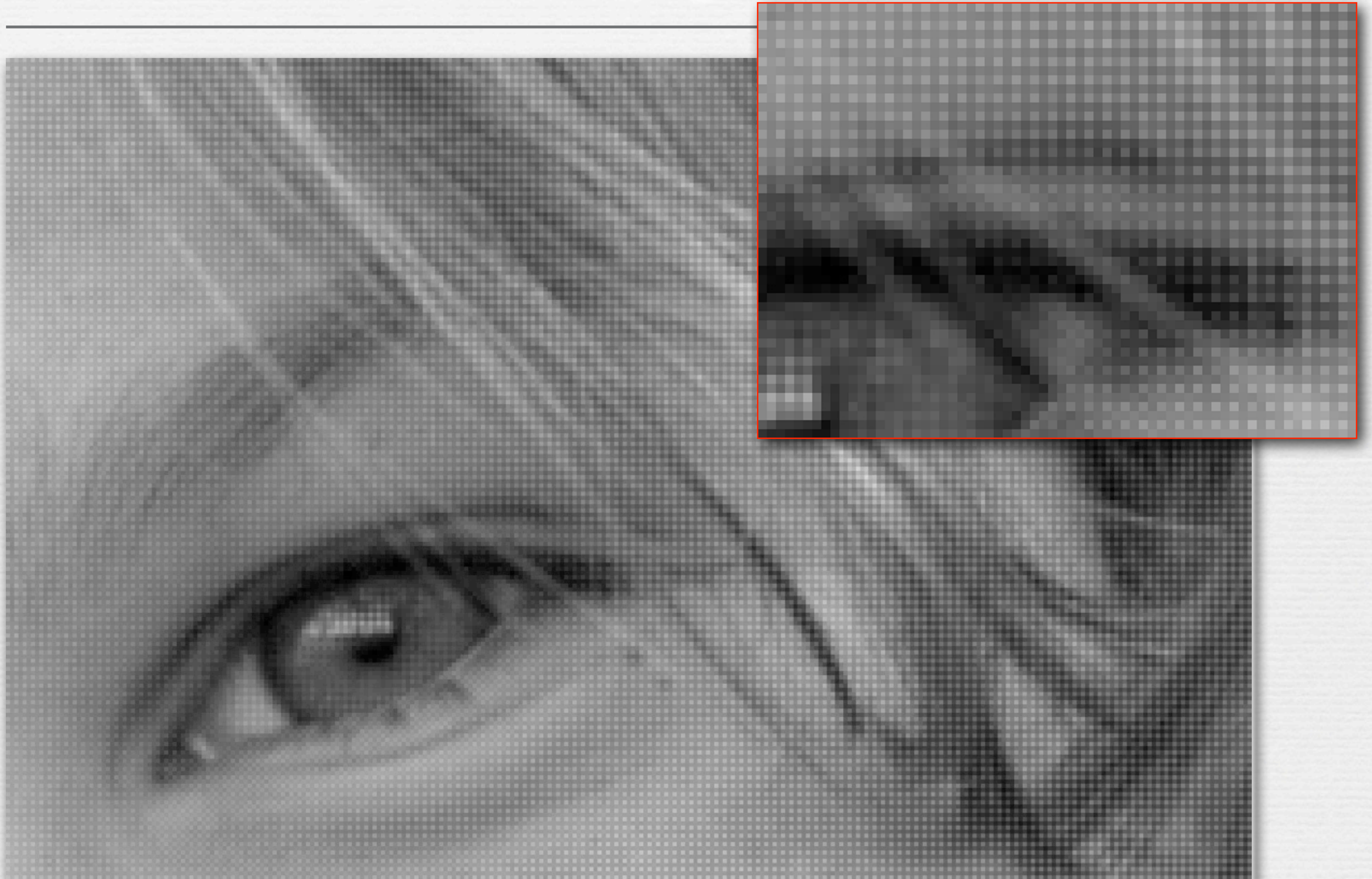
Before demosaicing (`dcraw -d`)

slide by Marc Levoy, Stanford

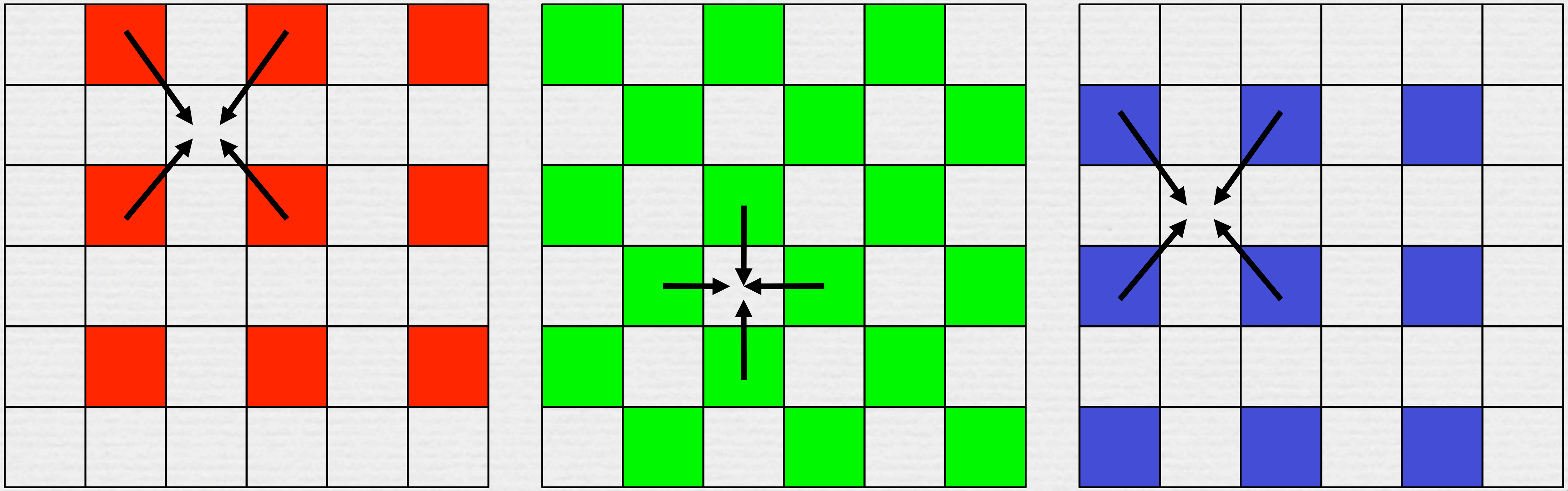
Before demosaicing (`dcraw -d`)



slide by Marc Levoy, Stanford

Demosaicing

- linear interpolation
  - average of the 4 nearest neighbors of the same color
- cameras typically use more complicated scheme
  - try to avoid interpolating across contrasty edges
  - demosaicing is often combined with denoising, sharpening...
- due to demosaicing, 2/3 of your data is "made up"!



slide by Marc Levoy, Stanford

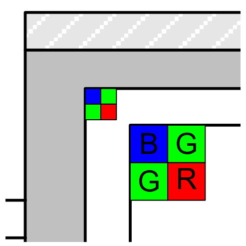
Characterizing a camera

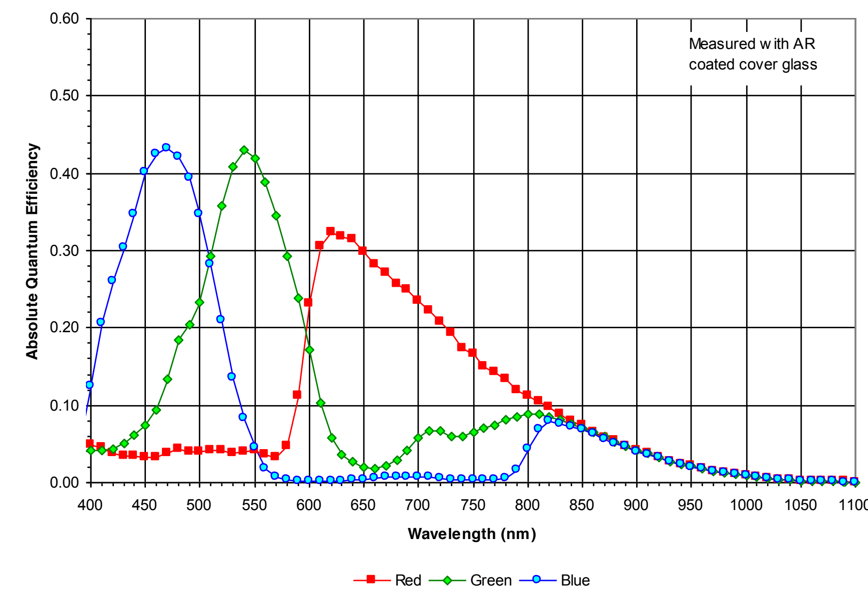
- **Radiometric response function**

  aka. **O**pto-**E**lectronic **C**onversion **F**unction, OECF

- **Spectral response function**

  per pixel, in a repeating pattern

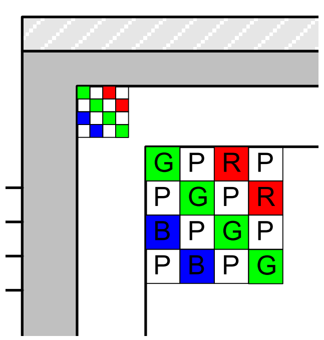


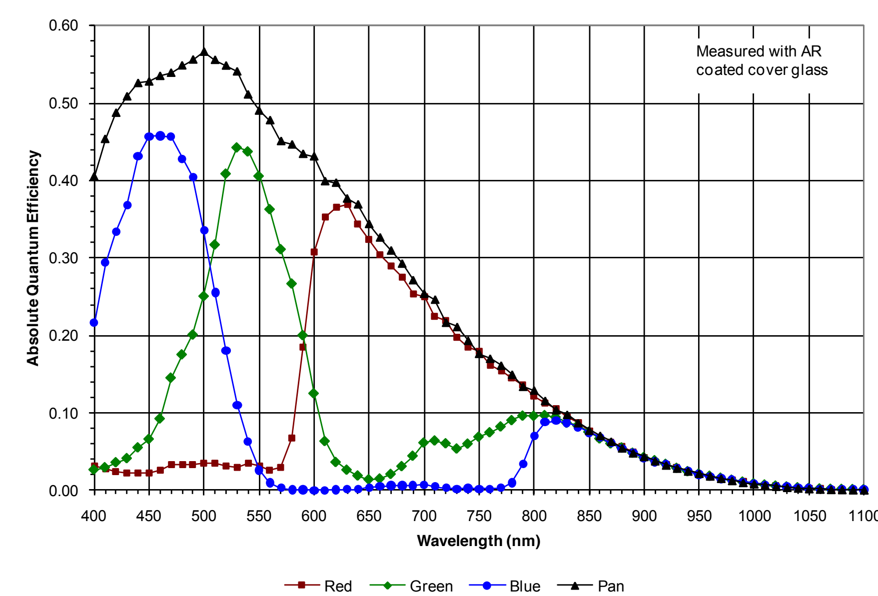


- **Fixed pattern noise**

  per pixel gain and offset
  (incl. hot/dead pixels)

- **Full well capacity**





Truesense KAI-08050 datasheet

- **Random noise**

  readout noise

  dark current

  (shot noise is not a camera characteristic)