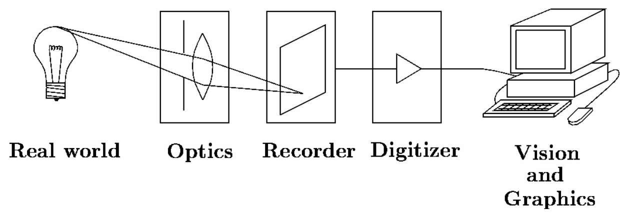
Solid state imaging sensors

Overview



Solid state imaging devices:

CCD imagers
CMOS imagers
Sensor characteristics
Color

Solid state sensors

Evolution of electronic imaging sensors:

- 1930s: Vacuum-tube-based TV cameras
- 1960s: Passive CMOS sensors
- 1970s: CCDs
- 1980s: Active CMOS sensors

Solid state sensors have several advantages:

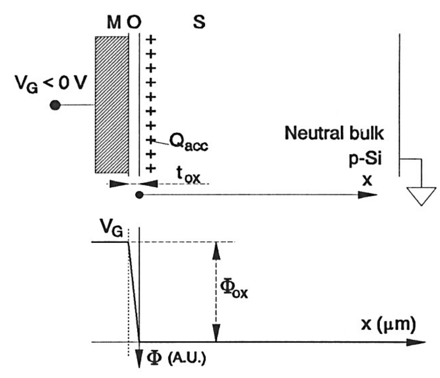
- Image is readily digitized
- Photodetectors respond linearly to irradiance
  - *But, camera makers often re-map the values to correct for TV monitor gamma or to behave like film*
- Available at low cost

Key elements:

- Photodetector
- Charge transfer and readout mechanism

A MOS capacitor can do both of these…

MOS capacitor

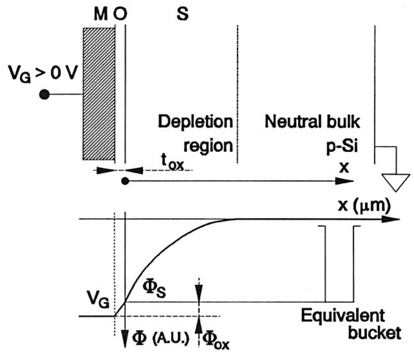


Theuweissen 1995

Negative gate voltage:

Majority carriers (holes) plentiful, and the gate behaves like a capacitor that stores positive charge near the oxide.

MOS capacitor in deep depletion



Theuweissen 1995

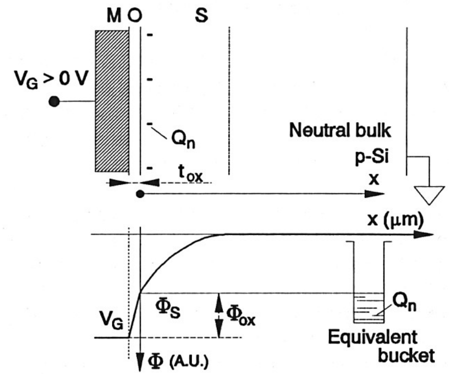
Positive gate voltage:

No minority carriers (electrons) to balance the voltage.

Holes are repelled, leaving negative charged ions in the depletion region.

Voltage drop in the silicon is like an empty bucket waiting to be filled by electrons. Bucket depth is proportional to applied voltage.

MOS capacitor in weak inversion



Theuweissen 1995

Positive gate voltage + new electrons:

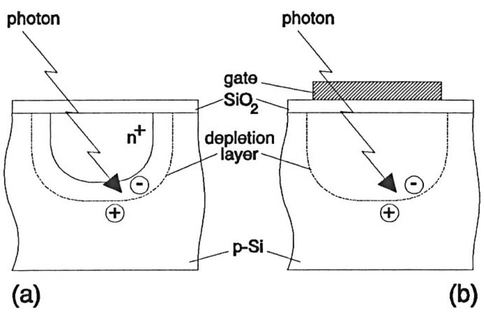
Electrons are made available through a process such as photoelectric generation of hole-electron pairs.

Electrons in the depletion region move to the oxide surface.

The addition of electrons is equivalent to filling the bucket.

Photo-conversion

Depletion regions in semiconductors collecting electrons and holes:



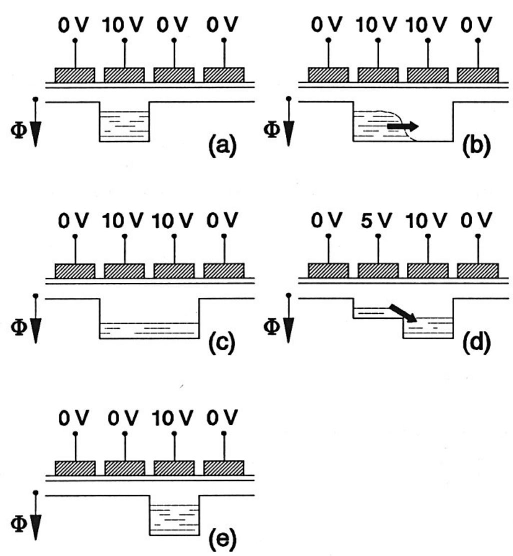
Theuweissen 1995

A diode has an inherent depletion region without applying a voltage. Can be used as a **photodiode**.

When a MOS capacitor is biased into depletion, it can collect charge generated by photons.

Charge transfer

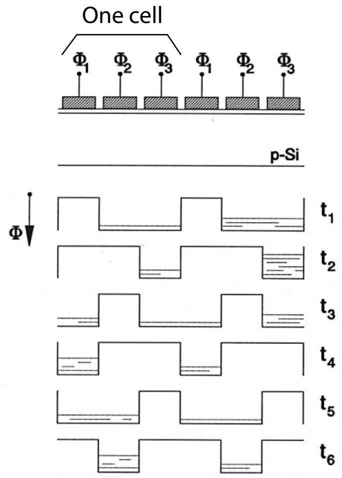
By manipulating voltages of neighboring cells, we can move a bucket of charge one gate to the right.



Theuweissen 1995

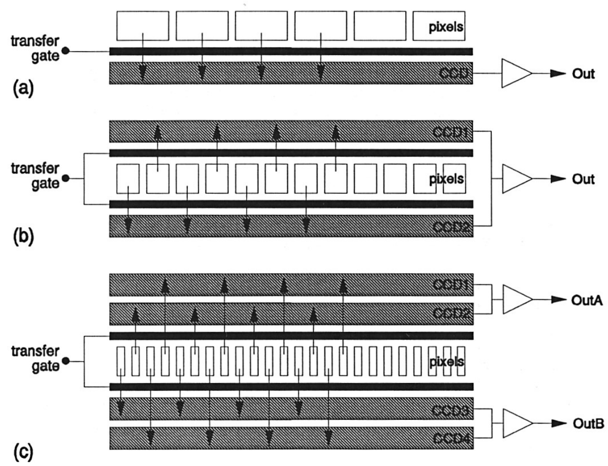
Three-phase clocking system

With three gates, we can move disjoint charge packets along a linear array of CCD's.



Theuweissen 1995

Linear array sensors



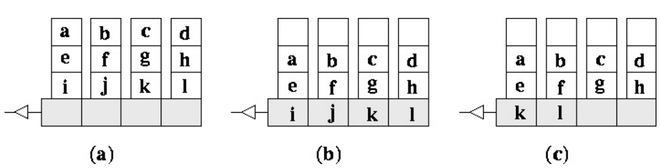
(a) Linear imager

(b) Bilinear imager

(c) Qudralinear imager

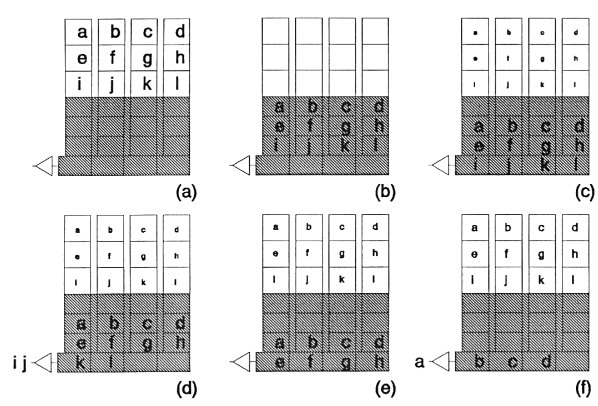
Theuweissen 1995

Full frame CCD



Q: What shortcoming(s) does this design have?

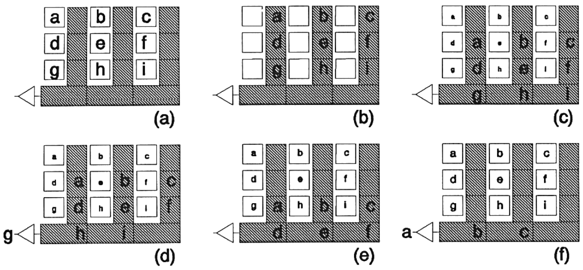
Frame transfer (FT) CCD

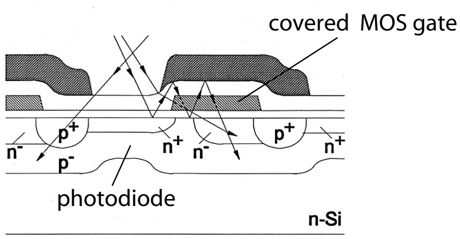


Theuweissen 1995

Q: What shortcoming(s) does this design have?

Interline transfer (IT) CCD

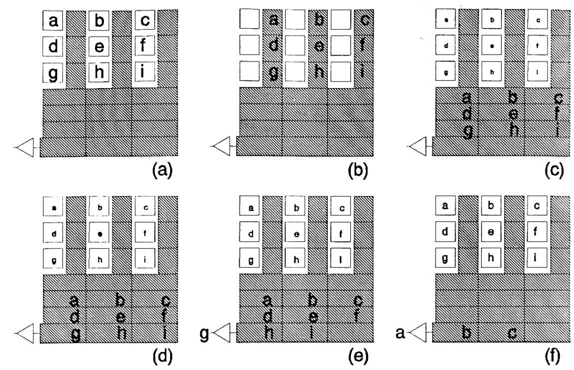




Theuweissen 1995

Q: What shortcoming(s) does this design have?

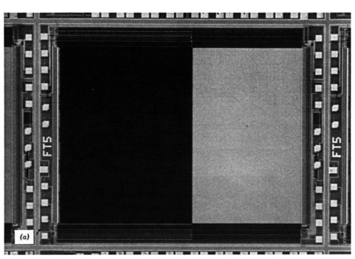
Frame interline transfer (FIT) CCD's



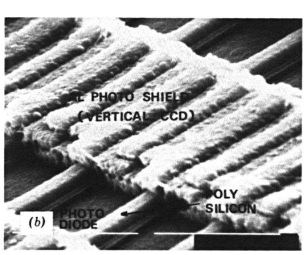
Theuweissen 1995

Q: What shortcoming(s) does this design have?

A closer look...



Frame transfer CCD



Interline transfer CCD
(SEM photograph)

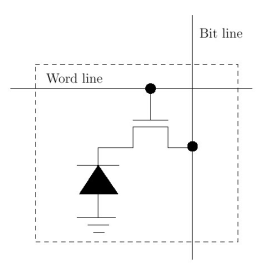
Muller and Kamins 1985

CMOS sensors

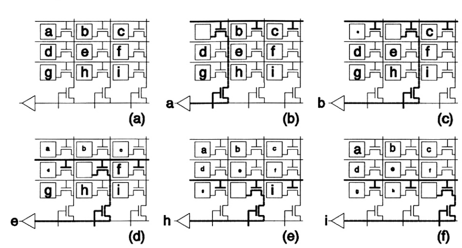
An alternative to CCD imaging arrays are CMOS sensors:

- Use established CMOS foundries
- Lower power consumption
- Can build in more special circuitry
- Greater flexibility in readout

First CMOS chips used Passive Pixel Sensors (PPS's) and addressable array readout:



Liu 2002



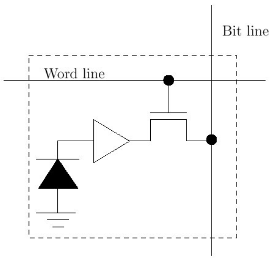
Theuweissen 1995

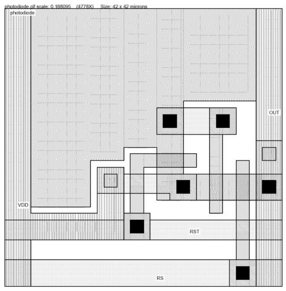
CMOS sensors

PPS sensors were too slow.

Active Pixel Sensors (APS's) place an amplifier by the photodector. Voltage on the "bit line" can be moved faster than charges.

Liu 2002



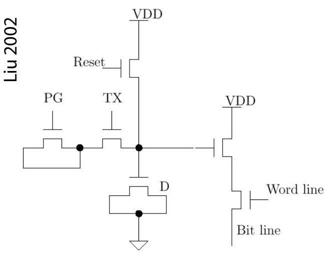


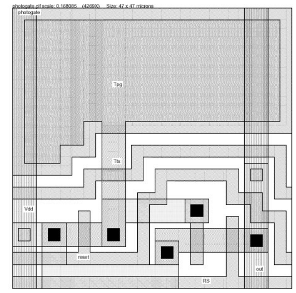
Kamal 2001

CMOS sensors

Fancier APS's shift charge to a "holding cell."

Liu 2002

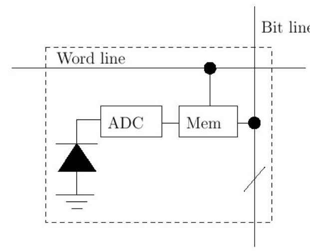




Kamal 2001

Finally, Digital Pixel Sensors (DPS's) actually do A/D conversion and store result in local memory:

Liu 2002



Sensor characteristics

Geometry and capacity

Spectral sensitivity

Smear and blooming

Diffusion

Noise

SNR and dynamic range

Geometry and capacity

Pixel size (5 to 10 μm; scientific up to 20 μm)

Fill factor (25% to 100%)

- reduced by non-light-sensing components in the pixel

Full well depth (saturation charge; 45 to 100 ke⁻)

- depends on the pixel size

Can increase effective fill factor (but not well depth) with microlenses:

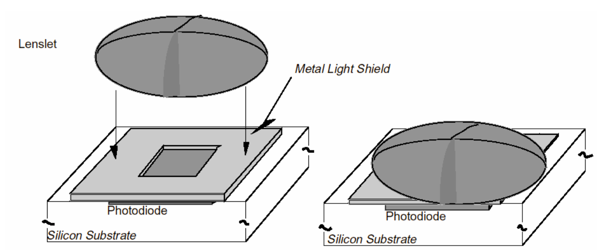


image: Kodak application note DS00-001

Spectral sensitivity

Spectral sensitivity is measured in terms of *quantum efficiency*, i.e., rate at which photons generate electron-hole pairs as a function of wavelength.

Key factor: photons must land in depletion region.

Photon Absorption Depth

Wavelength (Nanometers)	Penetration Depth (Microns)
400	0.19
450	1.0
500	2.3
550	3.3
600	5.0
650	7.6
700	8.5
750	16
800	23
850	46
900	62
950	150
1000	470
1050	1500
1100	7600

Spectral sensitivity

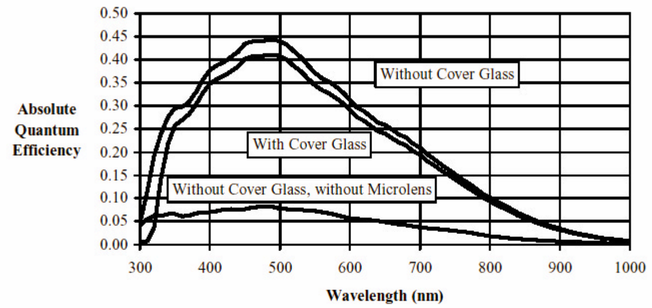
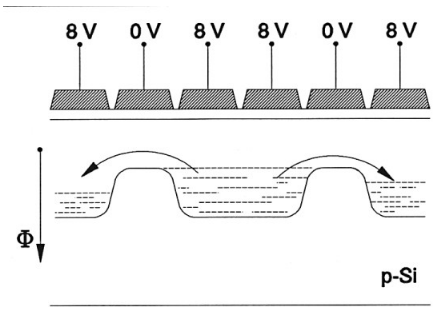


Figure 10 - Wavelength Dependence of Quantum Efficiency

source: Kodak KAI-2000m data sheet

Blooming



Blooming

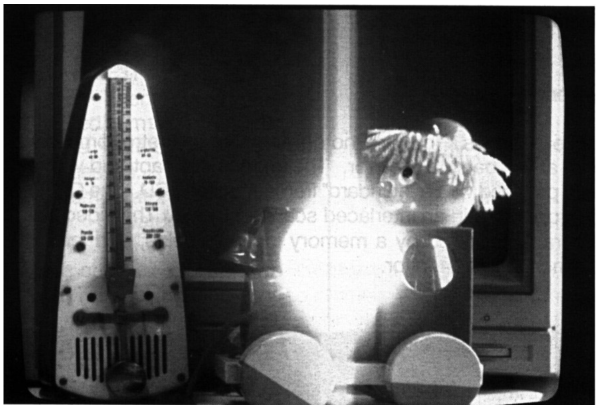
Theuseissen 1995

Over-exposure causes charges to leak into neighboring cells.

Can be reduced with “anti-blooming” technology.

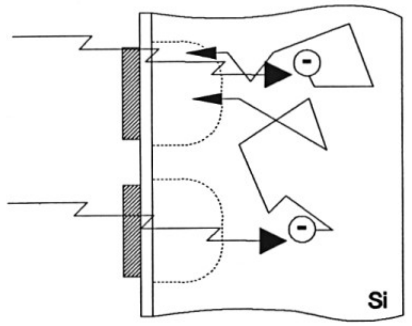
CMOS sensors don’t tend to have this problem.

Example: smear and blooming



Theuseissen 1995

Diffusion

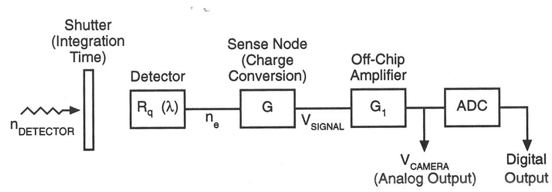


Theuseissen 1995

Electrons generated outside the depletion region may wander into neighboring cells.

Noise

Here is a diagram of a solid state sensing process:



Holst 1998

Q: What kind of noise sources might you expect?

Dark current and photon shot noise

Electron-hole pairs are generated according to:

$$n_{photon} = t_{INT} \eta A_p I$$

where:

- I = irradiance of the light
- η = quantum efficiency
- A_p = area of pixel
- t_{INT} = integration time

They are also generated due to thermal agitation, yielding a “dark current”:

$$n_{dark} = t_{INT} A_p c T^2 e^{-E_\Delta / kT}$$

where:

- T = temperature
- c = constant of proportionality
- K = Boltzmann’s constant
- E_Δ = energy constant that depends on materials

Dark current doubles for every 8 degrees C around room temperature.

Dark current and photon shot noise

The electron generation process is a discrete counting process with unknown arrival times.

Such processes are described by Poisson statistics.

For a random variable obeying Poisson statistics, the variance equals the mean:

$$\sigma^2 = \mu$$

Thus we have:

$$\sigma_{photon} = \sqrt{n_{photon}}$$

$$\sigma_{dark} = \sqrt{n_{dark}}$$

Q: How should noise vary over an image?

Shot noise example

Original image

Variance (x32)

Photos taken by Yung-Yu Chuang 2001

Amplifier readout out noise

Noise crops up in a number of other places.

Many of the noise sources fall into the category of Fixed Pattern Noise and can be subtracted away with some success.

The most significant remaining source of noise is due to amplifier readout:

- Does not depend on signal strength or duration of integration.
- Has standard deviation σ_{read}

SNR and dynamic range

SNR and dynamic range

Color

So far, we've only talked about monochrome sensors.

Color imaging has been implemented in a number of ways:

- Field sequential
- Multi-chip
- Color filter arrays

Field-sequential color

Field-sequential color

- simplest to implement
- only still scenes

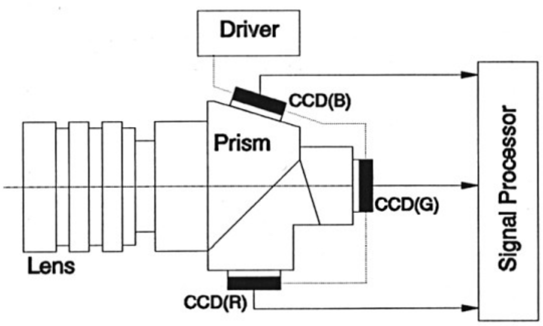
image: Proudkin-Gorskii, 1911
(Library of Congress exhibition)

3-chip color cameras

Split beam into three: one per sensor.

Dichroic mirrors divide light into wavelength bands

Does not remove light: excellent quality but expensive



Theuseissen 1995

Embedded color filters

Color filters can be manufactured directly onto the photodetectors.

Quantum efficiency now depends on embedded filter type:

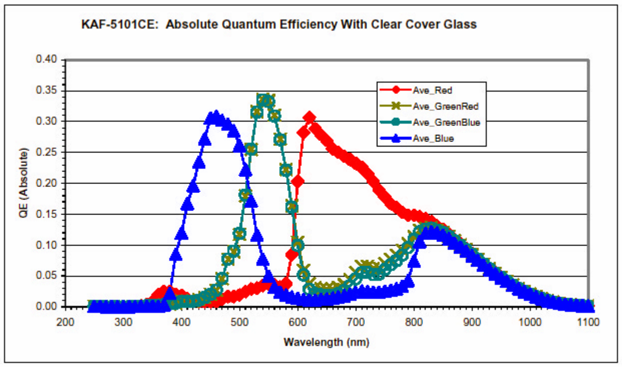


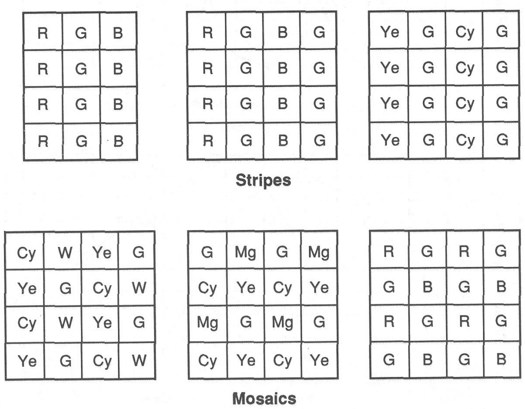
Figure 7. Typical Quantum Efficiency Curves (Clear Coverglass)

source: Kodak KAF-5101ce data sheet

Q: What happens when illumination has strong IR?

Color Filter Arrays

The filters can be distributed over a chip in several ways. These distributions are called Color Filter Arrays (CFA's) or Color Filter Mosaics.



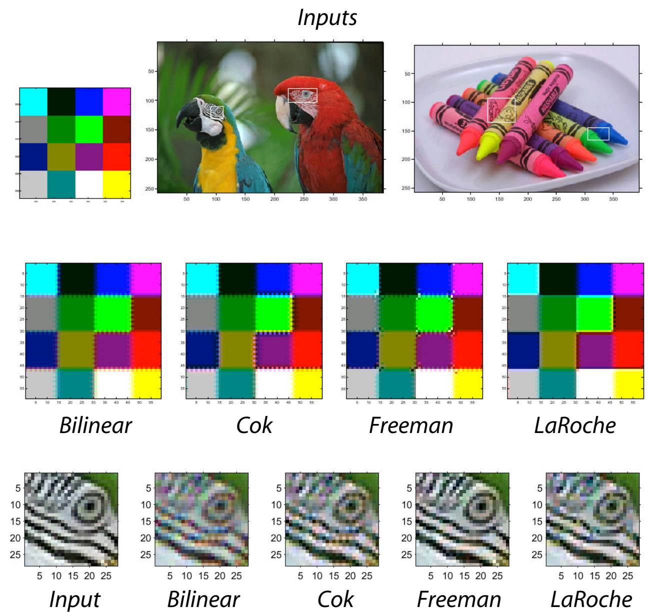
Theuseissen 1995

Q: Why is green channel often more densely distributed?

Demosaicking CFA's

Color aliasing arises, because color bands are spatially separated.

Bilinear interpolation yields "rainbowing" artifacts at edges.



Ramanath 2003

Demosaicking CFA's

(Bi)-linear interpolation:

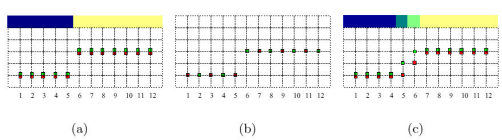


Fig. 4. Illustration of fringe or zipper effect resulting from the linear interpolation process. An edge is illustrated as going from navy blue (0,0,128) to yellow (255,255,128). The zipper effect produces green pixels near the edge (a) Original image (only 2 colors, blue constant at 128) (b) one scan line of subsampled Bayer pattern (choose every other pixel) (c) result of estimating missing data using linear interpolation. *Observe color fringe in locations 5 and 6*

Freeman method:

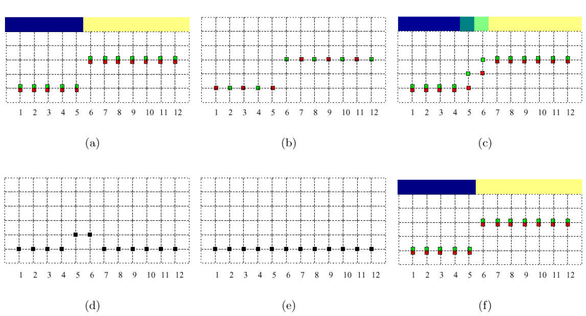


Fig. 5. Illustration of Freeman's interpolation method for a two channel system, as in fig.4 an edge is illustrated as going from navy blue (0,0,128) to yellow (255,255,128) (a) Original image (only 2 colors, blue constant at 128) (b) one scan line of subsampled Bayer pattern (choose every other pixel) (c) result of linear interpolation (d) Green minus Red (e) median filtered result of the difference image (f) reconstructed image

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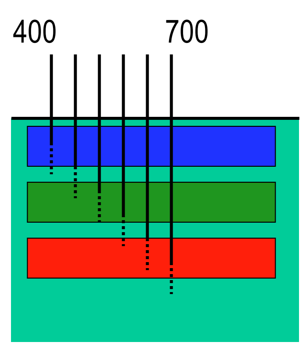
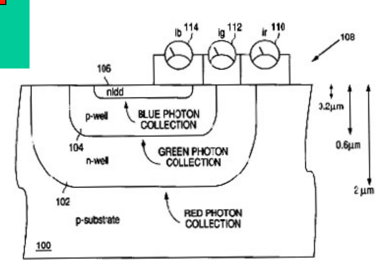
Foveon sensor

3-layer sensor (Foveon)

- takes advantage of silicon's wavelength selectivity
- light penetrates to different depths for different wavelengths
- multilayer CMOS sensor gets 3 different spectral sensitivities





Color processing

After color values are recorded, more color processing usually happens:

- White balance
- Color matrix to approximate CIE coordinates
- Non-linearity to approximate film response or match TV monitor gamma

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