Photographic Technology

PhotoTechEDU series

Lecture 05: Feb. 21, 2007

Silicon image sensors

Richard F. Lyon

Google Research

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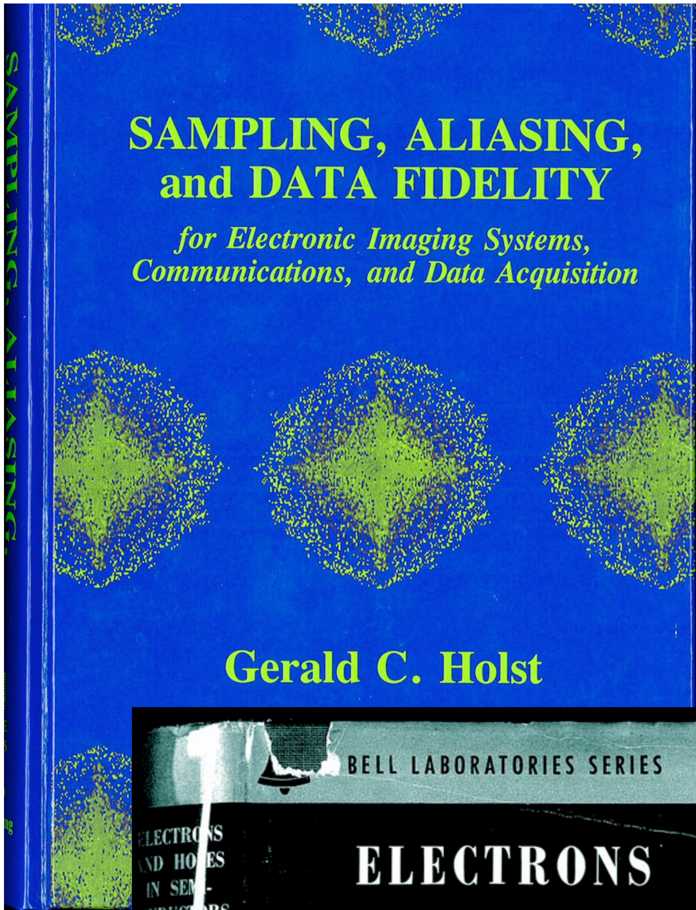
Books



SAMPLING, ALIASING, and DATA FIDELITY
for Electronic Imaging Systems, Communications, and Data Acquisition
Gerald C. Holst

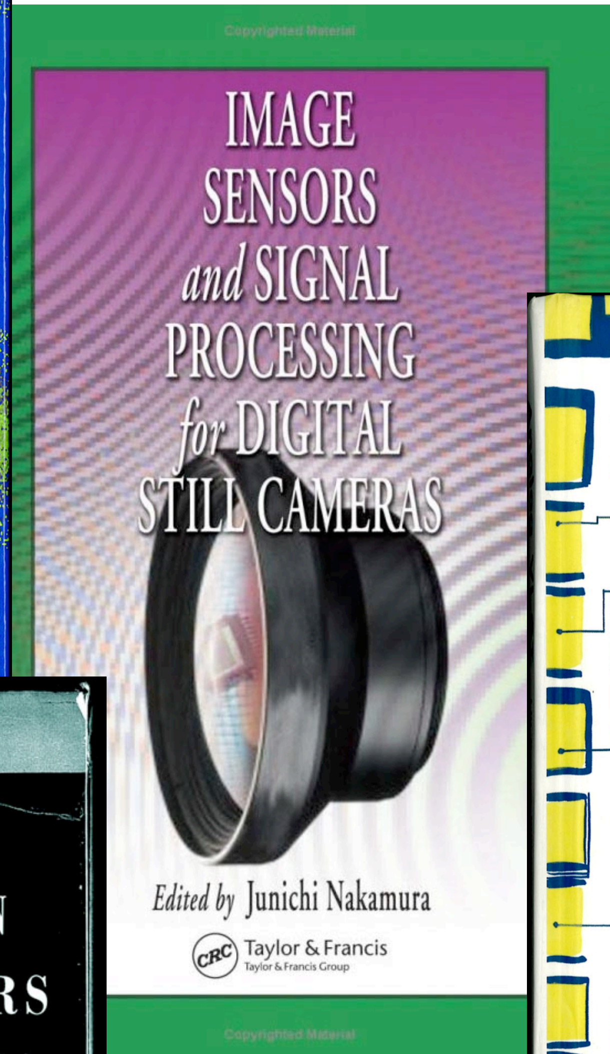
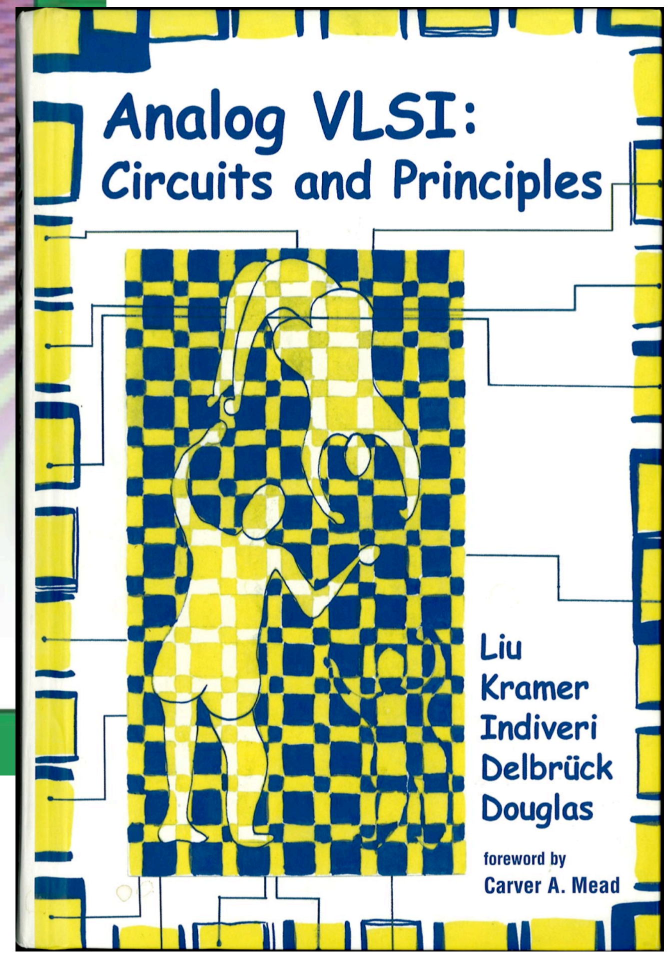
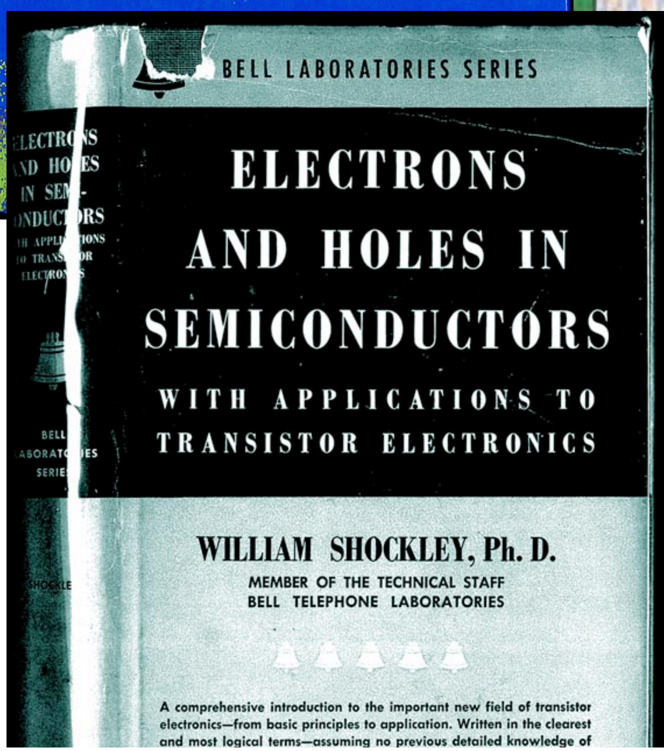


IMAGE SENSORS and SIGNAL PROCESSING for DIGITAL STILL CAMERAS
Edited by Junichi Nakamura
CRC
Taylor & Francis
Taylor & Francis Group



Analog VLSI:
Circuits and Principles
Liu
Kramer
Indiveri
Delbrück
Douglas
foreword by
Carver A. Mead



BELL LABORATORIES SERIES
ELECTRONS AND HOLES IN SEMICONDUCTORS
WITH APPLICATIONS TO TRANSISTOR ELECTRONICS
WILLIAM SHOCKLEY, Ph. D.
MEMBER OF THE TECHNICAL STAFF
BELL TELEPHONE LABORATORIES
A comprehensive introduction to the important new field of transistor electronics—from basic principles to application. Written in the clearest and most logical terms—assuming no previous detailed knowledge of

A good source of tutorials and papers: York University VISOR Laboratory

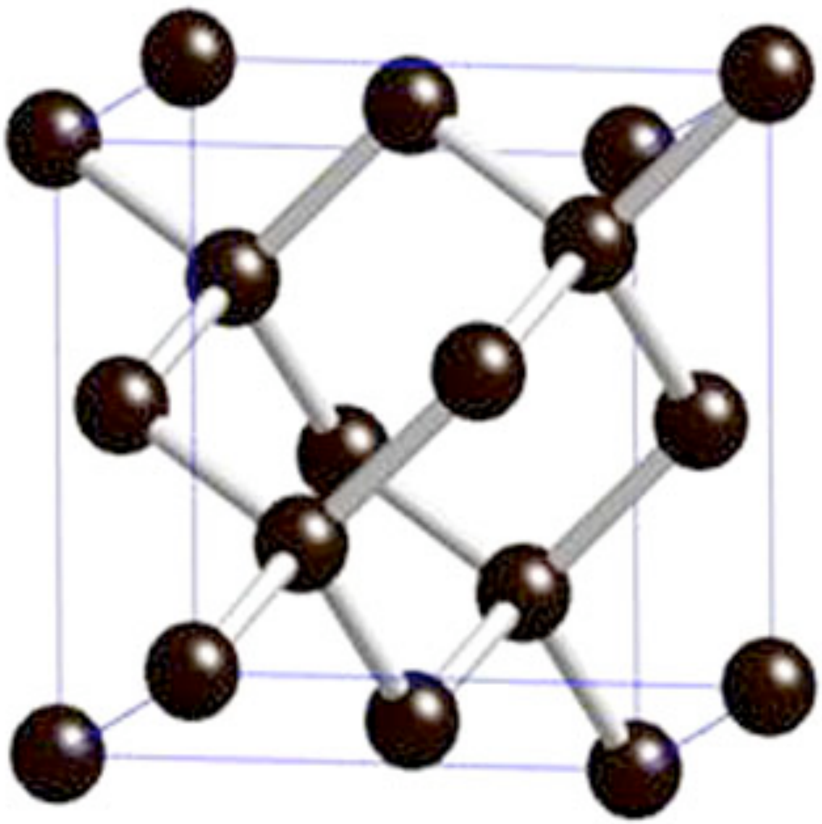
http://www.cse.yorku.ca/~visor/pubs.html

Short Course Notes

Two-day short course presented at the Waterloo Institute for Computer Research, May 1999.

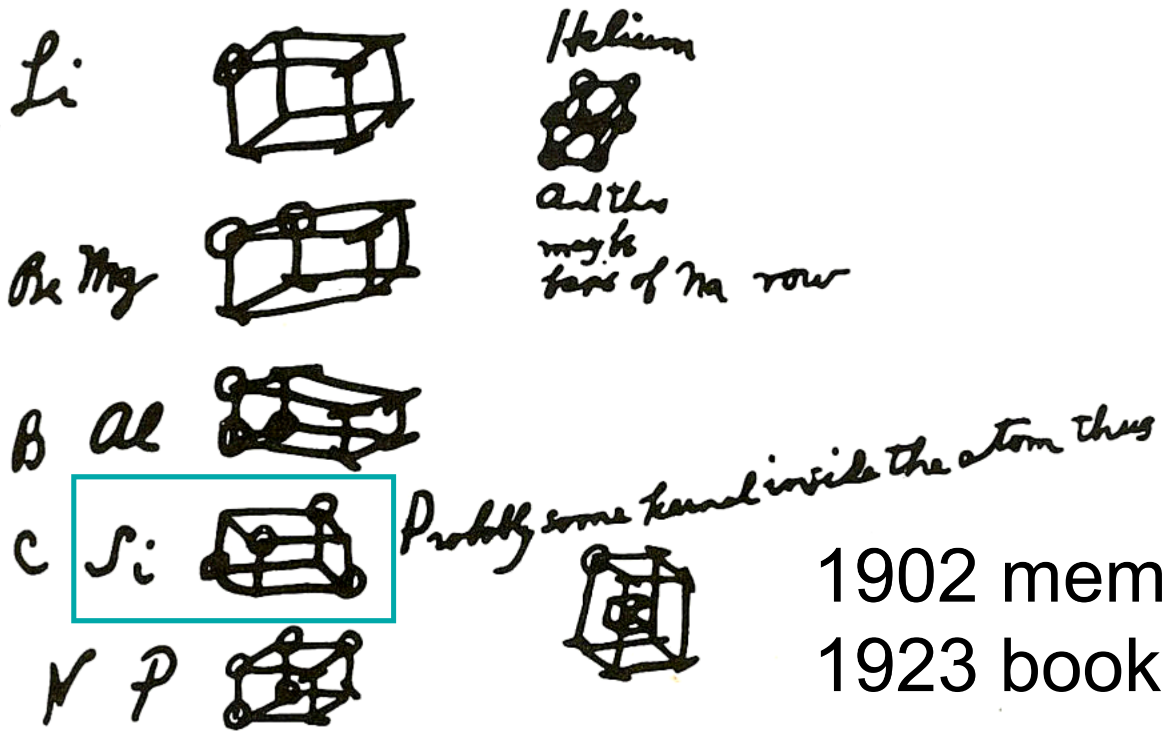
- **Background and Principles of Optical Detection**
- **Fabrication Technology and Pixel Design**
- **Noise in Image Sensors**
- **Imaging System on a Chip**
- Appendix A - CMOS Fabrication Technology
- **Appendix B - CCD Technology**
- **Appendic C - Other sensor types**

Silicon crystal: the closest thing to magic that we'll need



	boron 5 B	carbon 6 C	nitrogen 7 N	oxygen 8 O
	aluminium 13 Al	silicon 14 Si	phosphorus 15 P	sulfur 16 S
nc 0 n	gallium 31 Ga	germanium 32 Ge	arsenic 33 As	seleniu 34 Se
nium 8 d	indium 49 In	tin 50 Sn	antimony 51 Sb	telluriu 52 Te

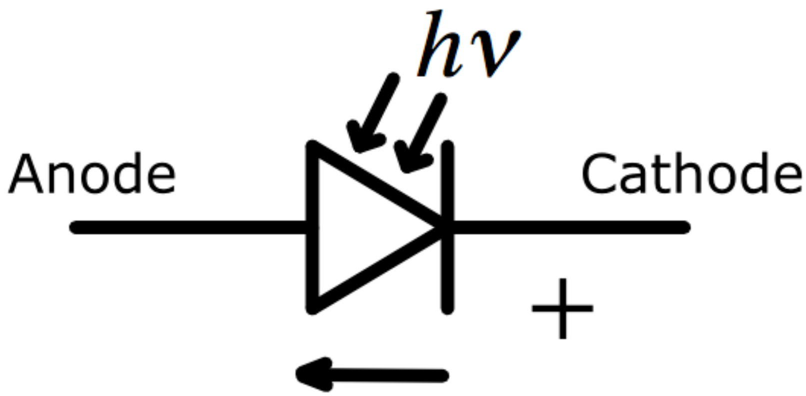
Gilbert Newton Lewis: *valence, photon, etc.*

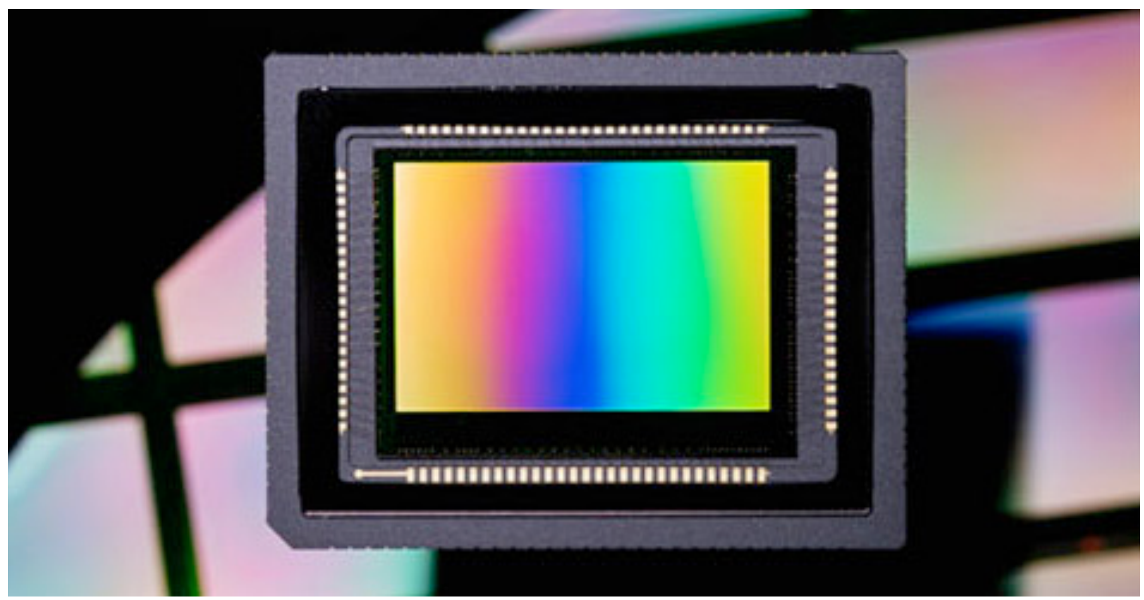


1902 memo, from
1923 book ***Valence***

"I therefore take the liberty of proposing for this hypothetical new atom, which is not light but plays an essential part in every process of radiation, the name ***photon***." —Gilbert N. Lewis, *Nature* 1926

Photodiode (reverse-biased PN junction) and Image Sensor





Electron–hole pair generation and separation in a reverse-biased PN junction

(Tobi Delbrück and Jörg Kramer chapter in *Analog VLSI: Circuits and Principles*)

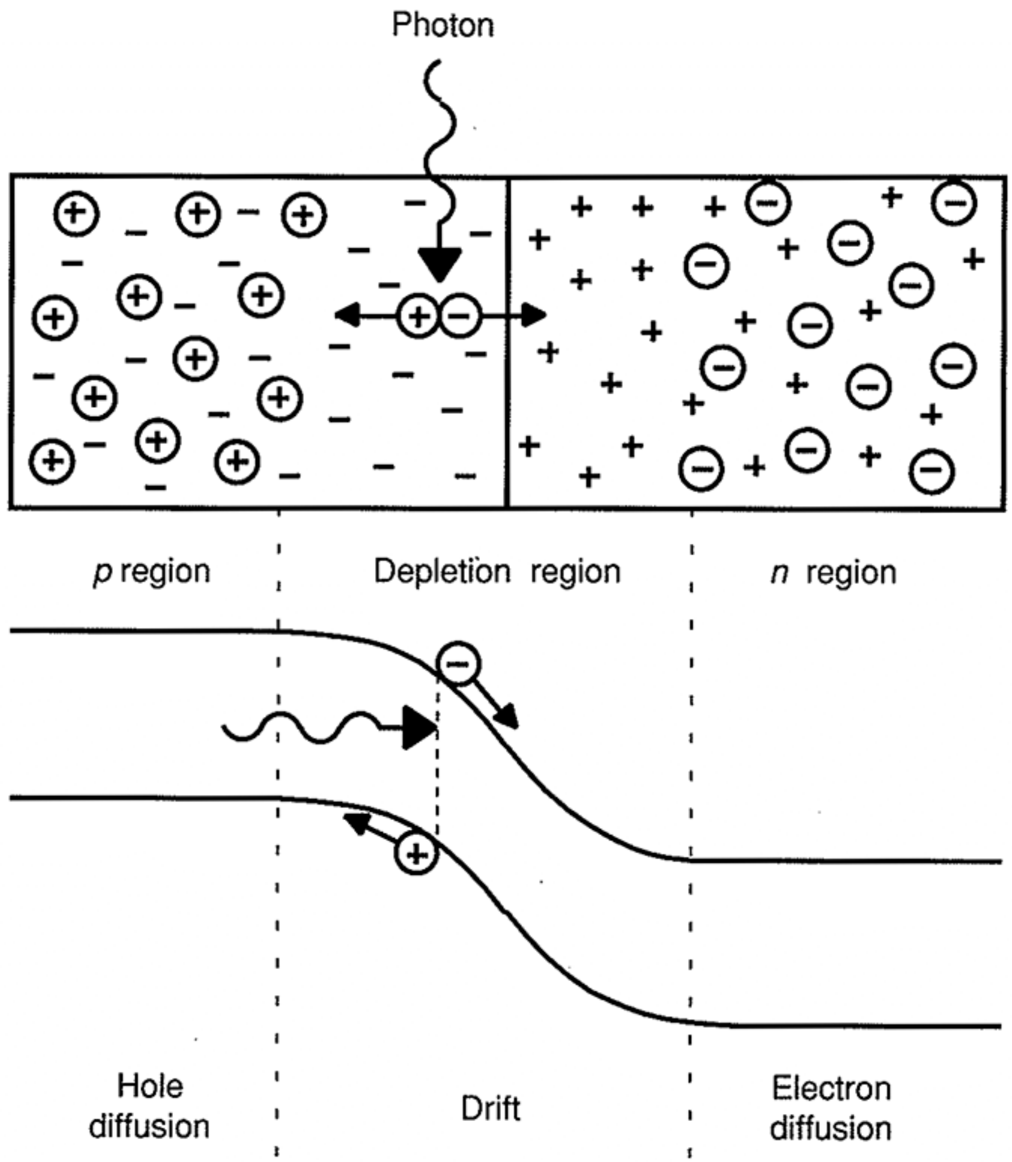


Figure 10.1
Principle of operation of a photodiode. Electron-hole pairs generated by incident photons in or within a diffusion length outside the depletion region become separated and contribute to a reverse generation current.

Cross-section of a pixel sensor on a silicon substrate

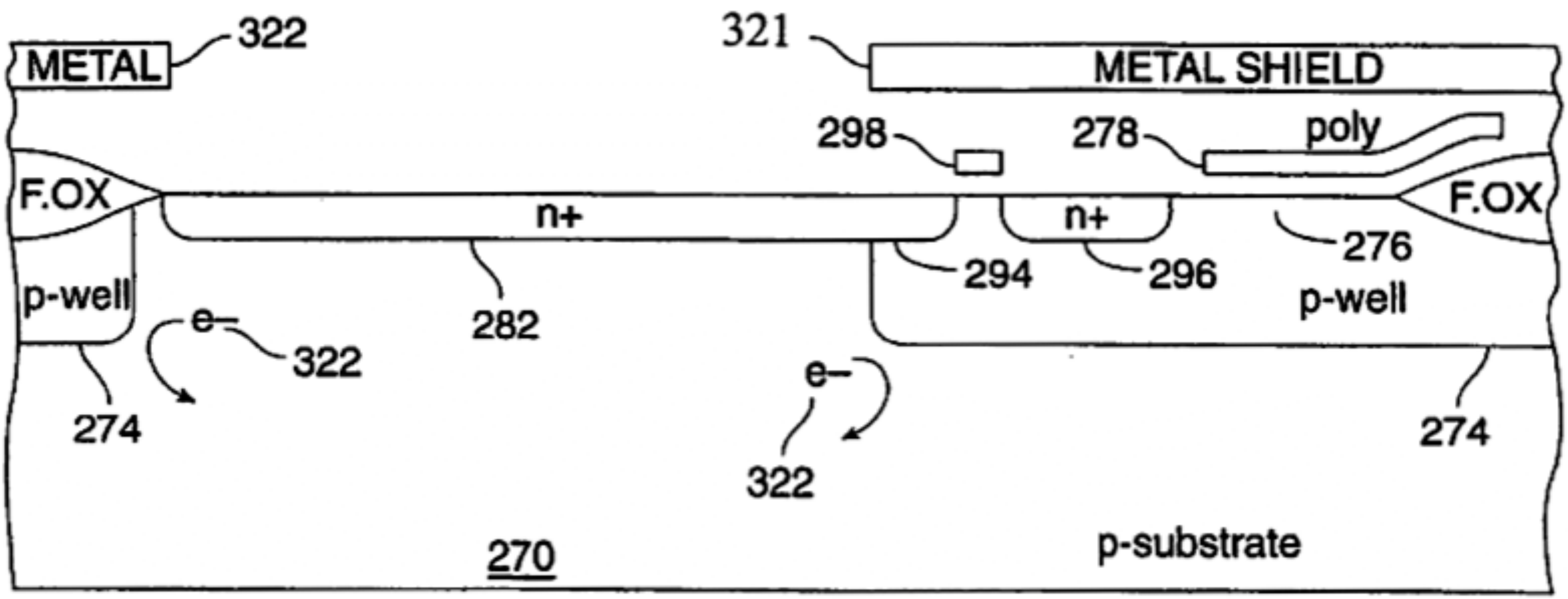


FIG. 12B

Light Quanta: Photons

can be computed using energy per quantum

$$E = h\nu = \frac{hc}{\lambda}$$

$E =$ photon energy

$\nu =$ frequency of light

$\lambda =$ wavelength of light

$c = 3\times10^{8}$ m/s speed of light

$h = 6.626\times10^{-34}$ J$\cdot$s Planck's constant

$h = 4.135\times10^{-15}$ eV$\cdot$s Planck's constant

Other things can be computed, too;
for example, the wavelength corresponding to Silicon's bandgap energy:

E = 1.12 eV is Silicon's bandgap energy

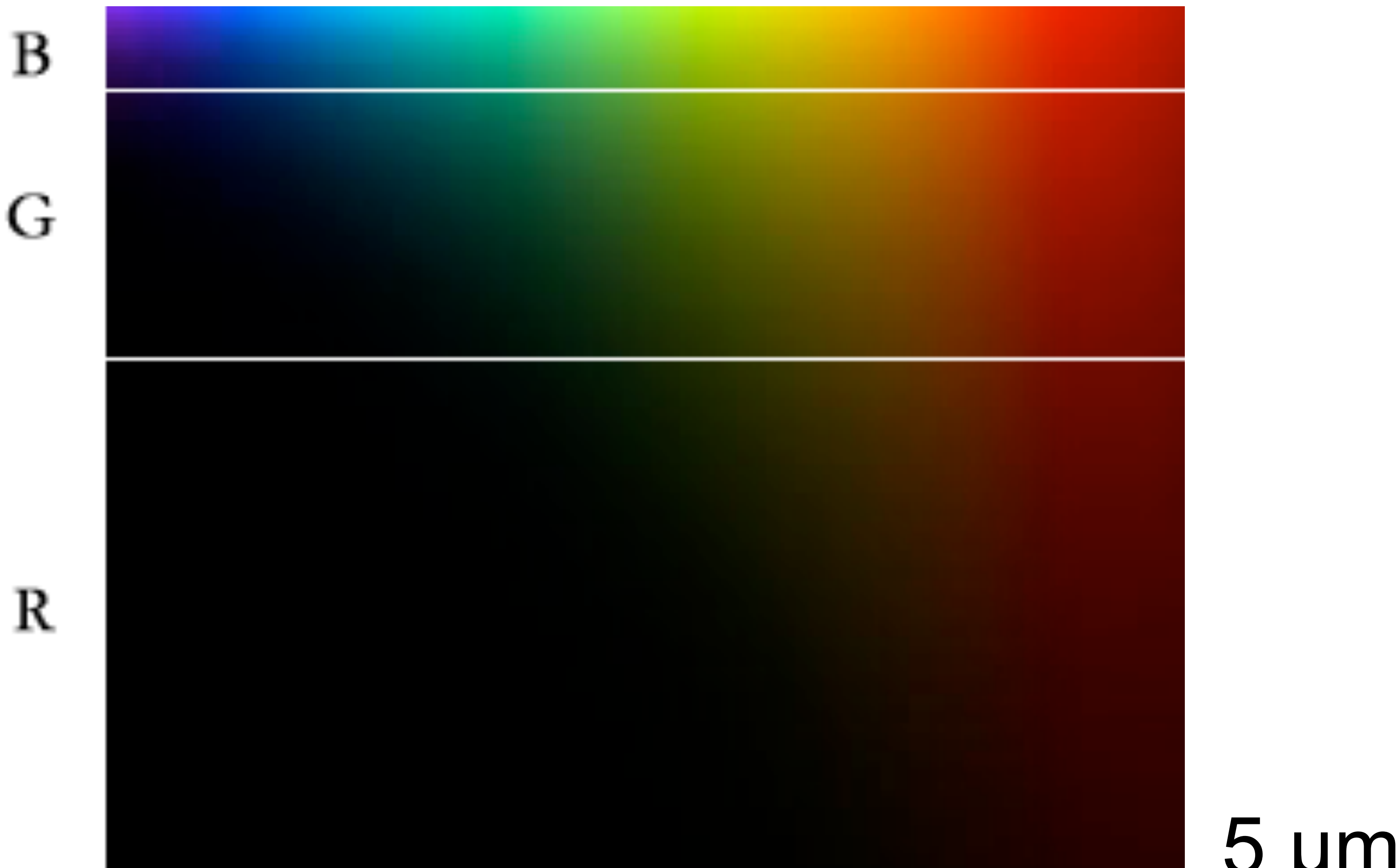
Wavelength $\lambda = (h \bullet c)/E$

$= (4.135 \bullet 10^{-15}$ eV s $\bullet\ 3 \bullet 10^{8}$ m/s$)/1.12$ eV

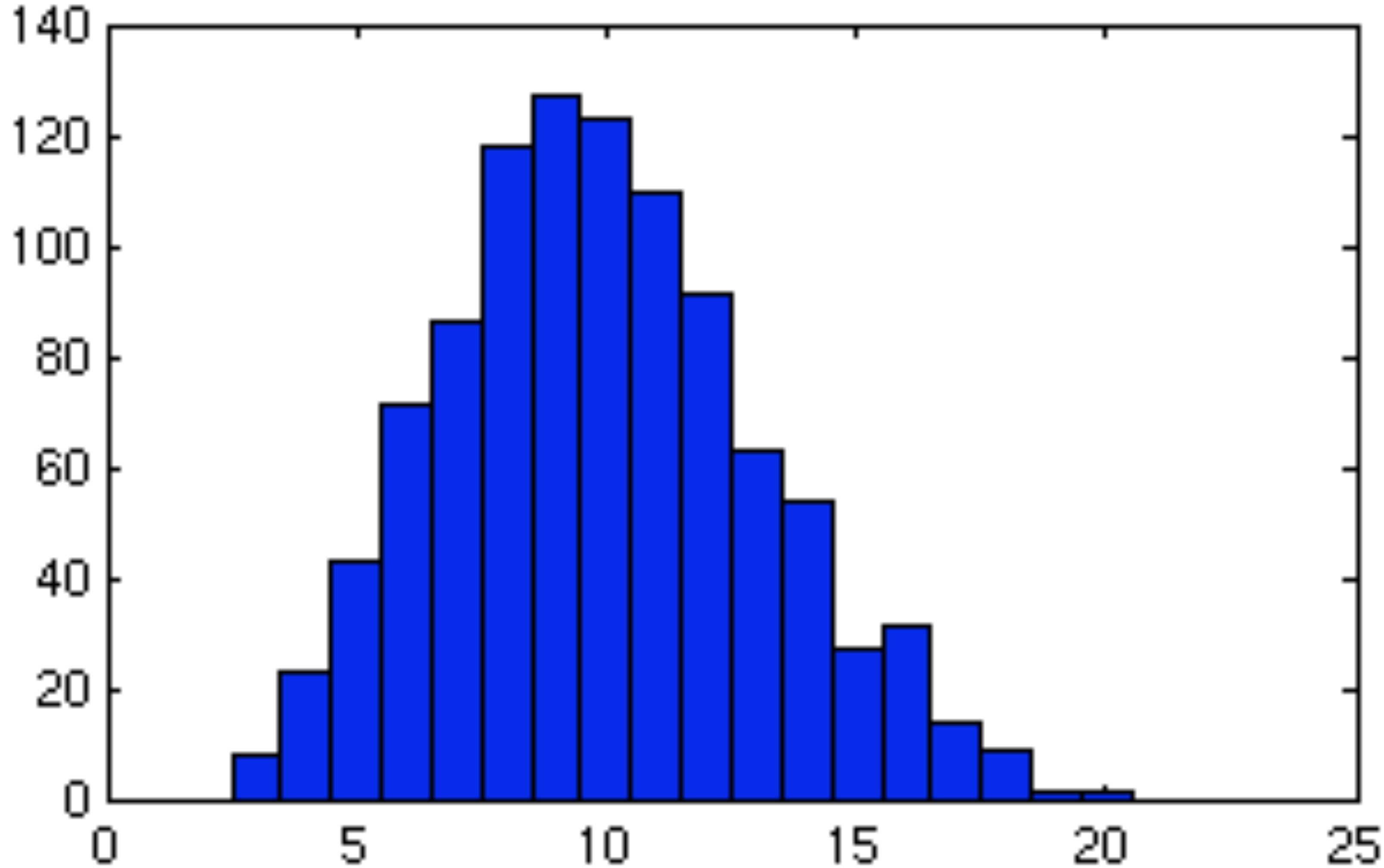
= 1110 nm (compare to 400–700 nm visible range)

which means that photons corresponding to longer (infra-red) wavelengths do not have enough energy to kick an electron up from the valence band to the conduction band; the silicon is transparent to these long waves

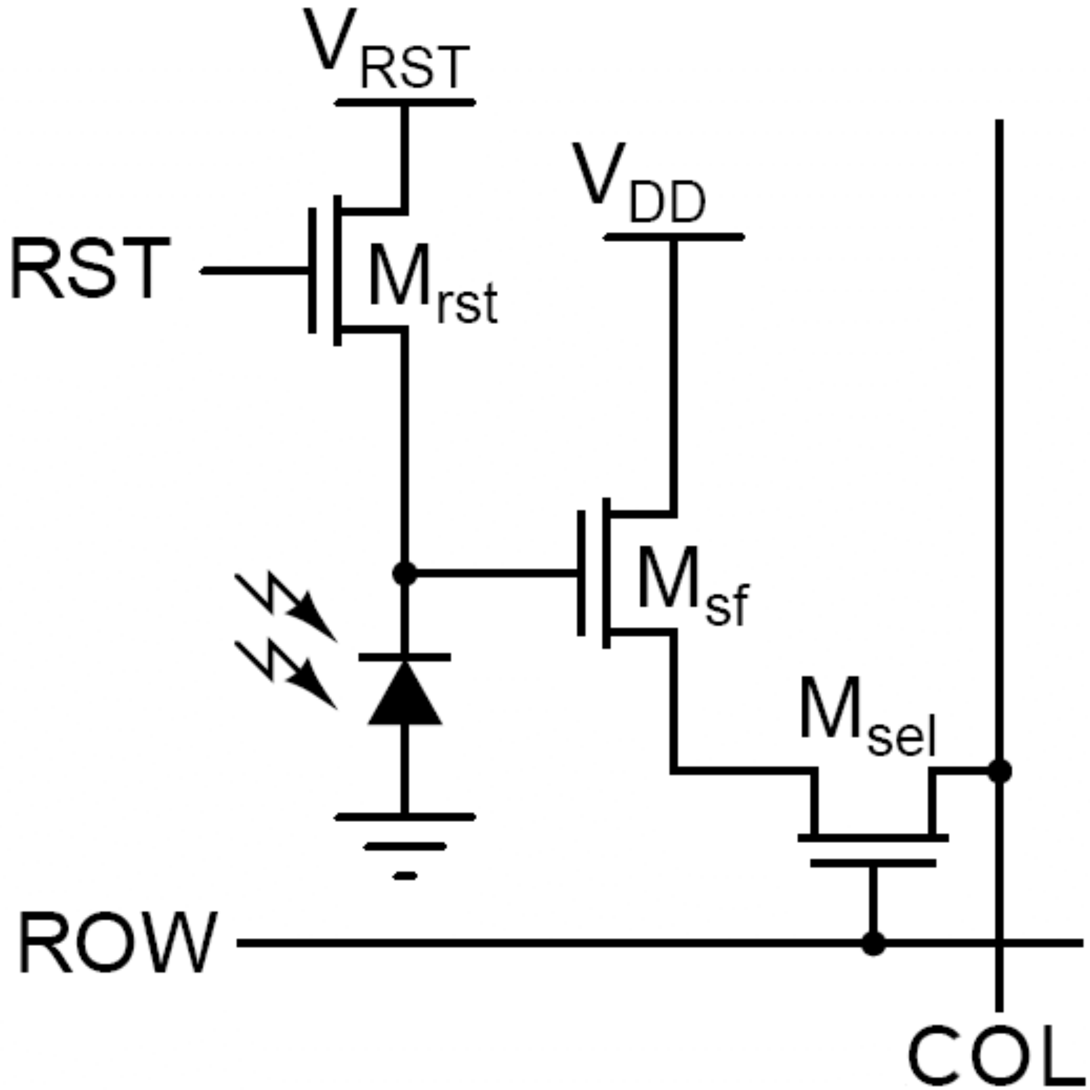
Interaction strength and penetration depth depend on wavelength; photon absorptions are independent events



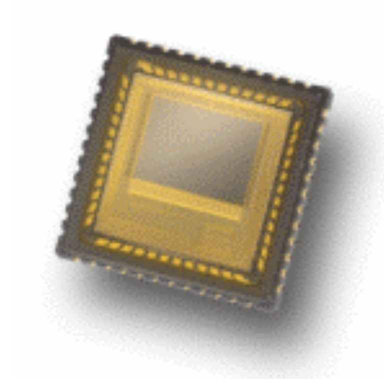
Photon shot noise: example histogram of event counts, 1000 trials, mean rate 10 independent events per trial

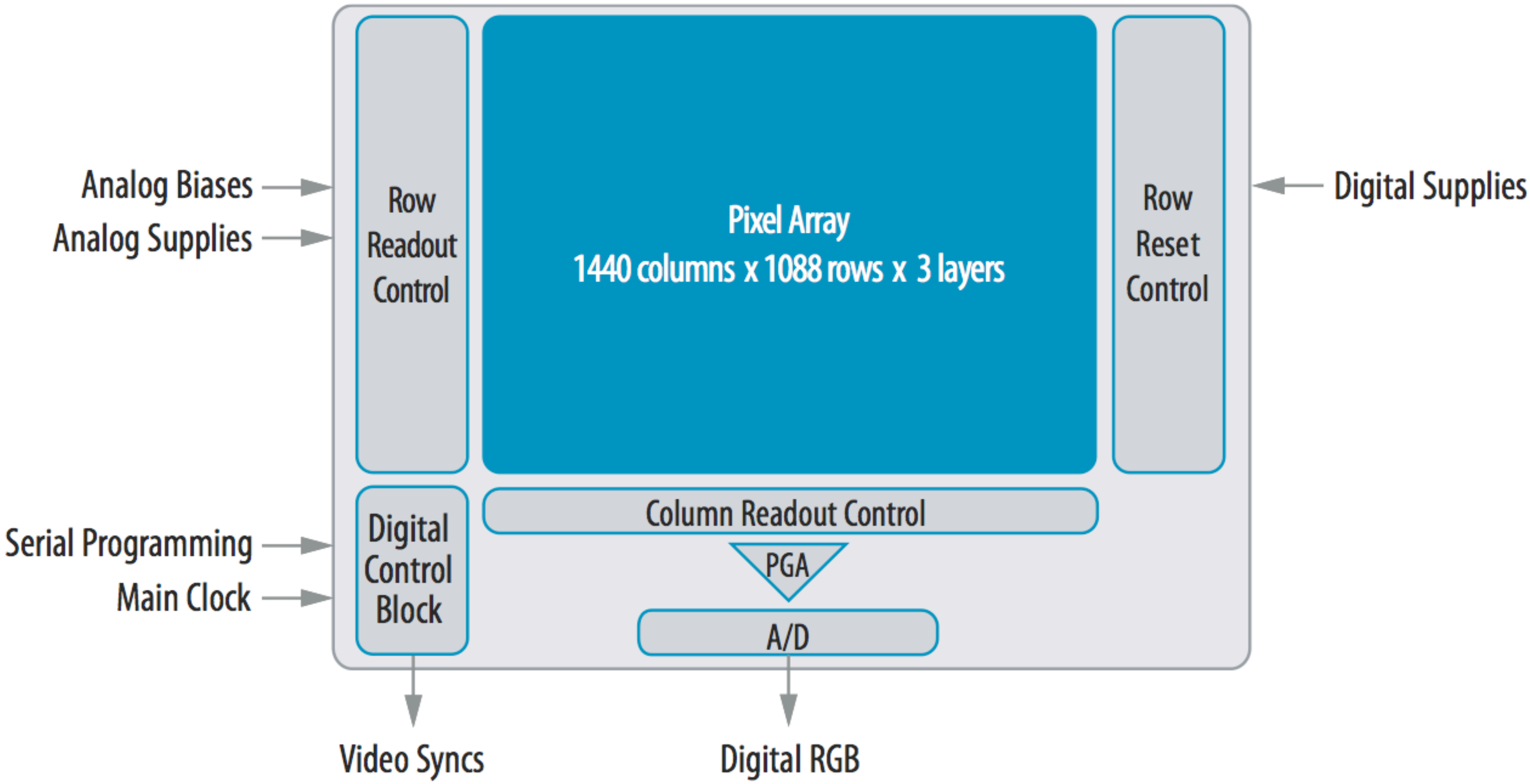


Classic 3-transistor active pixel sensor



Array architecture of an image sensor: Foveon F19





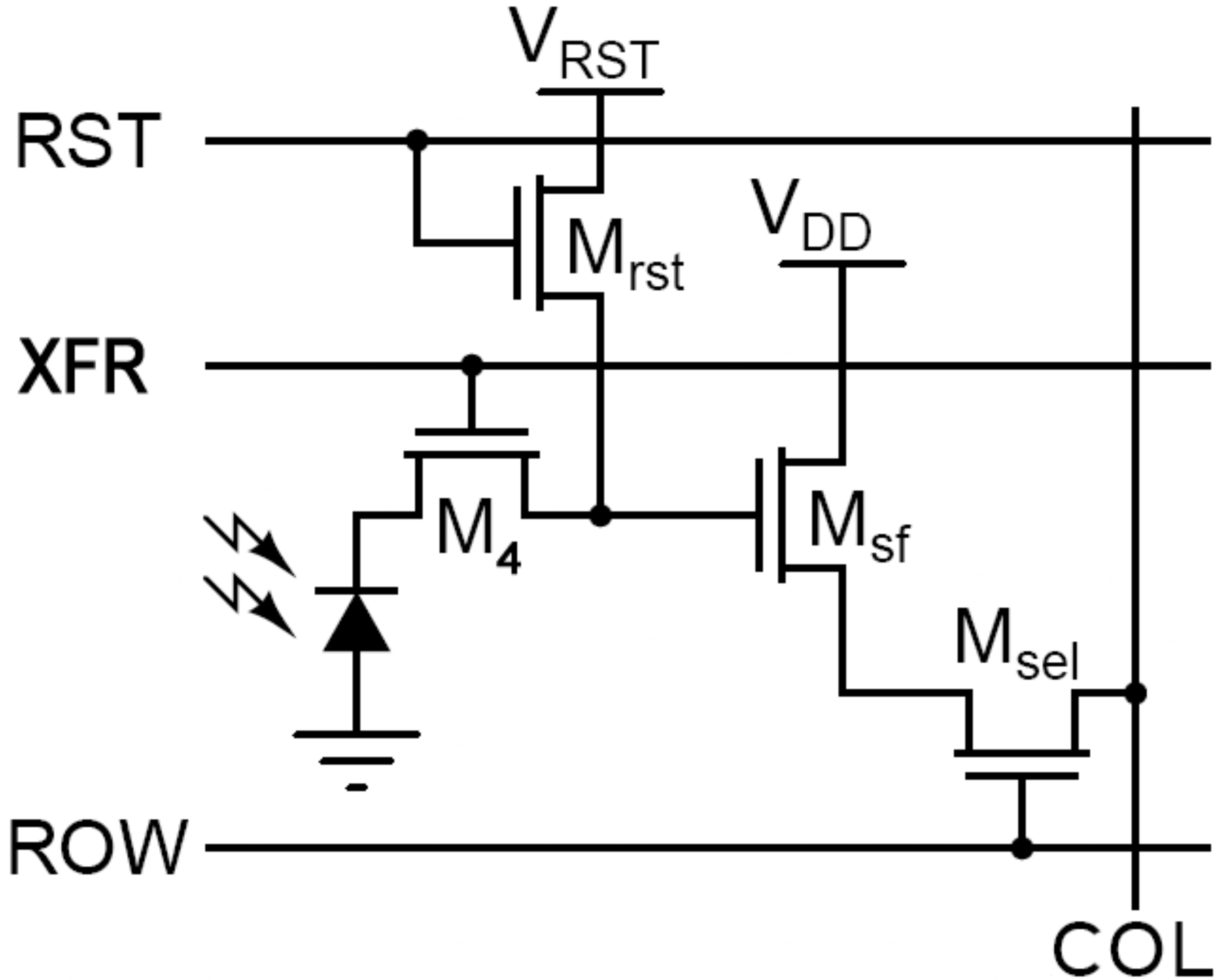
Sensor noise sources

- Photon shot noise (variance = count)
- Reset noise at photodiode capacitance (charge variance = kTC)
- PRNU: photo-response non-uniformity
- Dark-offset fixed pattern
- Readout amplifier thermal and 1/f noise
- Dark current and its shot noise
- ADC quantization noise (variance = 1/12 $(LSB)^2$)
- ADC differential nonlinearity
- Pickup of stray EM interference

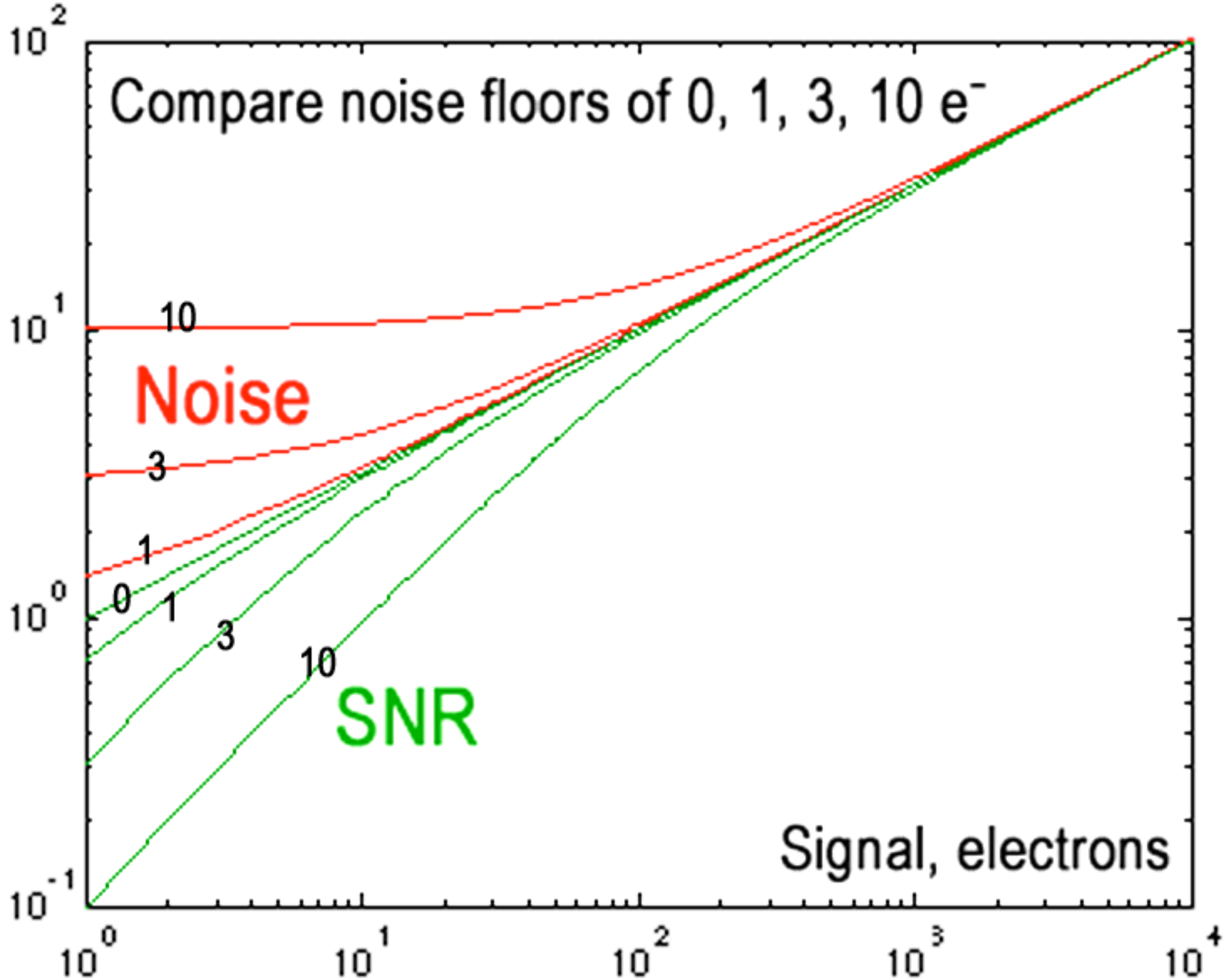
Noise in electrons

- Convert all noises to input-referred electrons
- Add up variances (in electrons^2)
- Plot it all versus signal electrons, since dominant noise changes over the range
- Only the largest few noise sources matter, so try to reduce or cancel those
- Convert outputs to electrons using gains like μV/e^-, DN/e^-

4-T pixel sensor allows reset noise cancellation via correlated double sampling



Noise floor determines low end of usable dynamic range



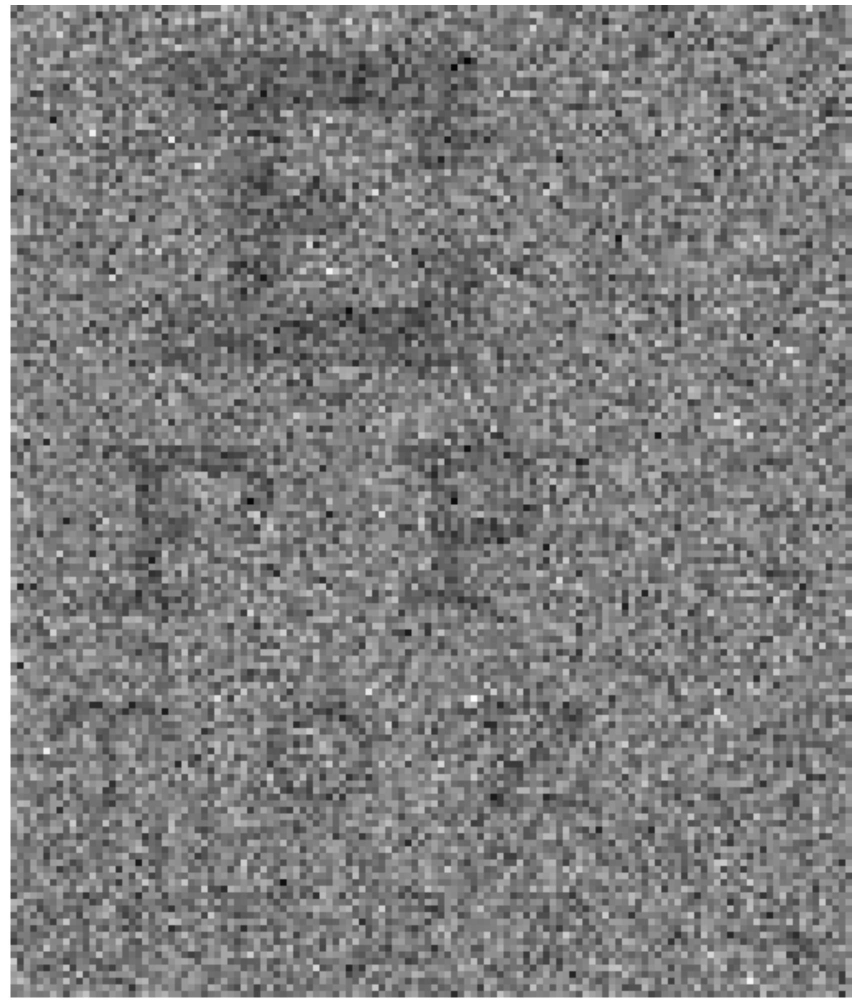
Low SNR: Signal = 4e⁻ with Poisson Noise;

Read Noise = 2e⁻

net SNR = 1.4

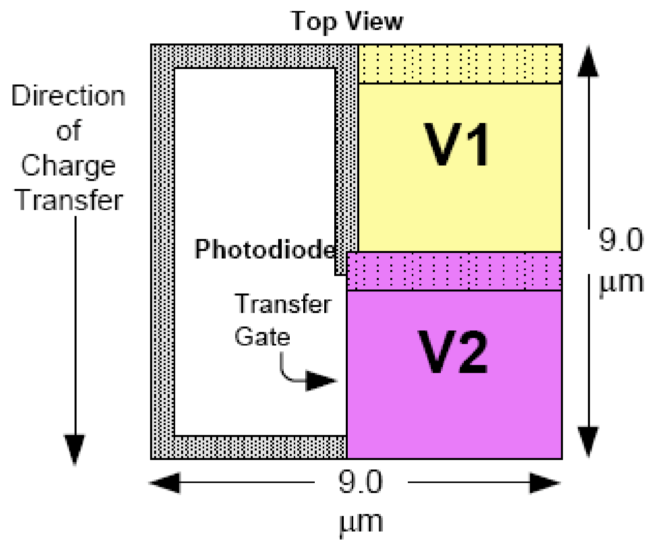
Read Noise = 4e⁻

net SNR = 0.9

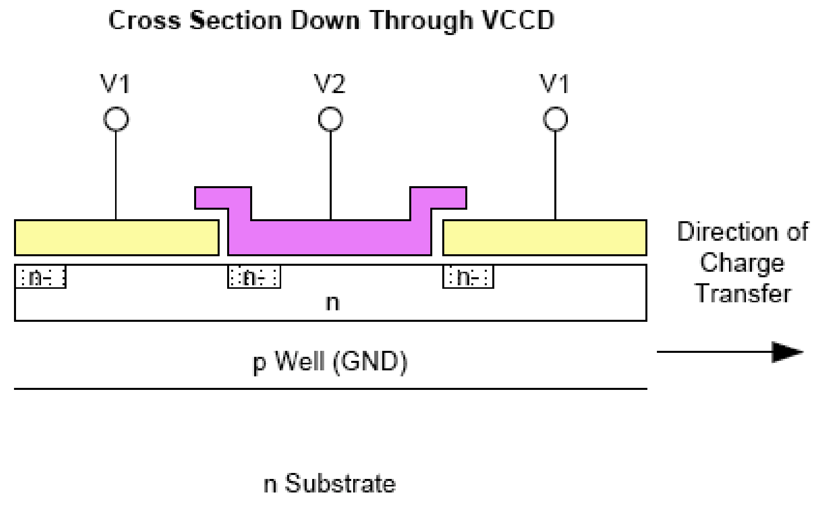


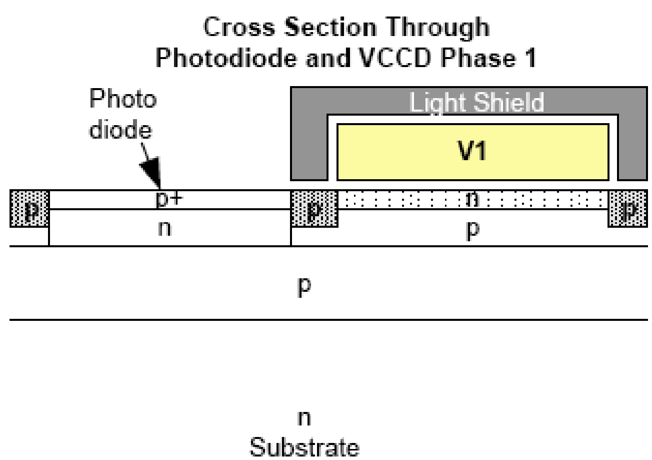
Kodak KAI-11002 (interline-transfer CCD) pixel architecture

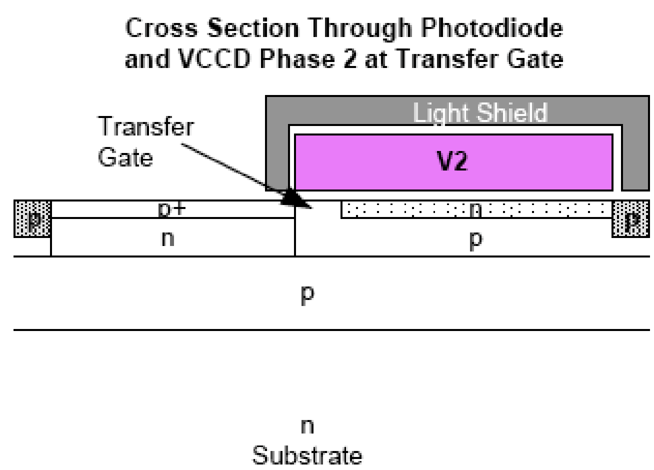
PIXEL



True Two Phase Burried Channel VCCD
Lightshield over VCCD not shown

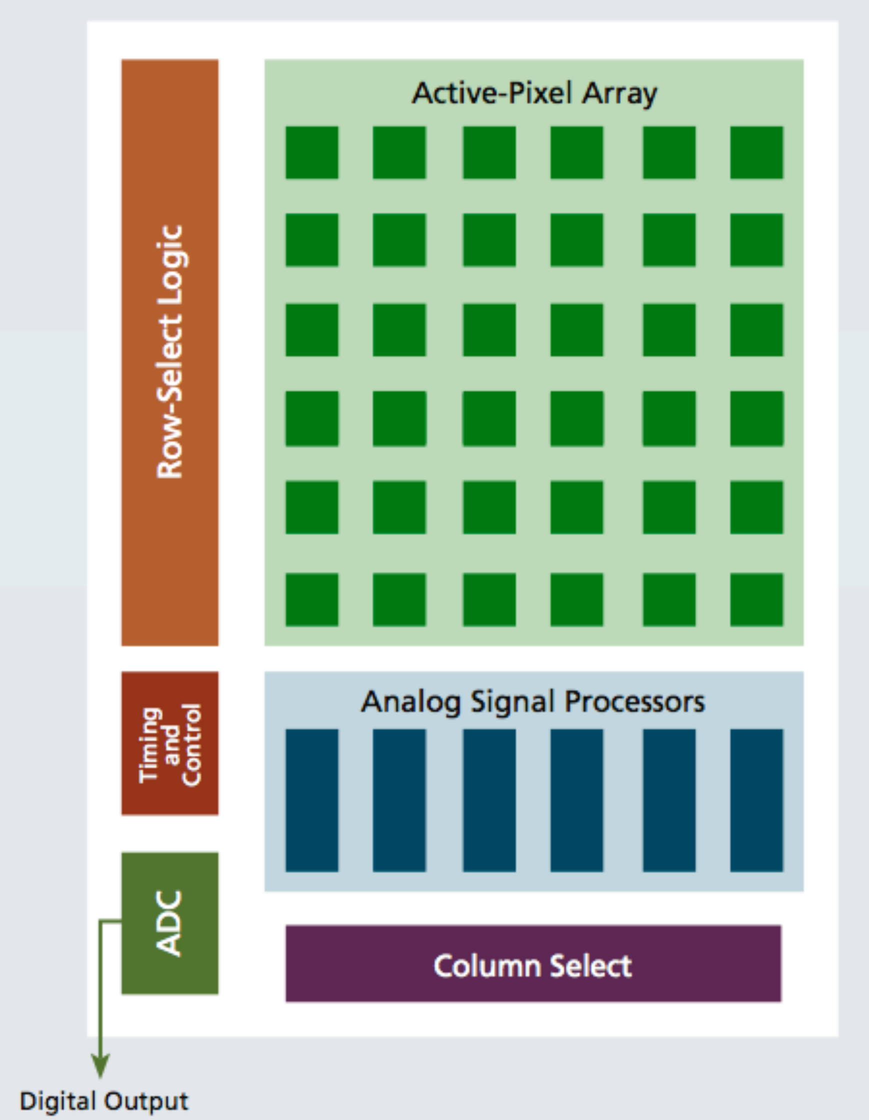




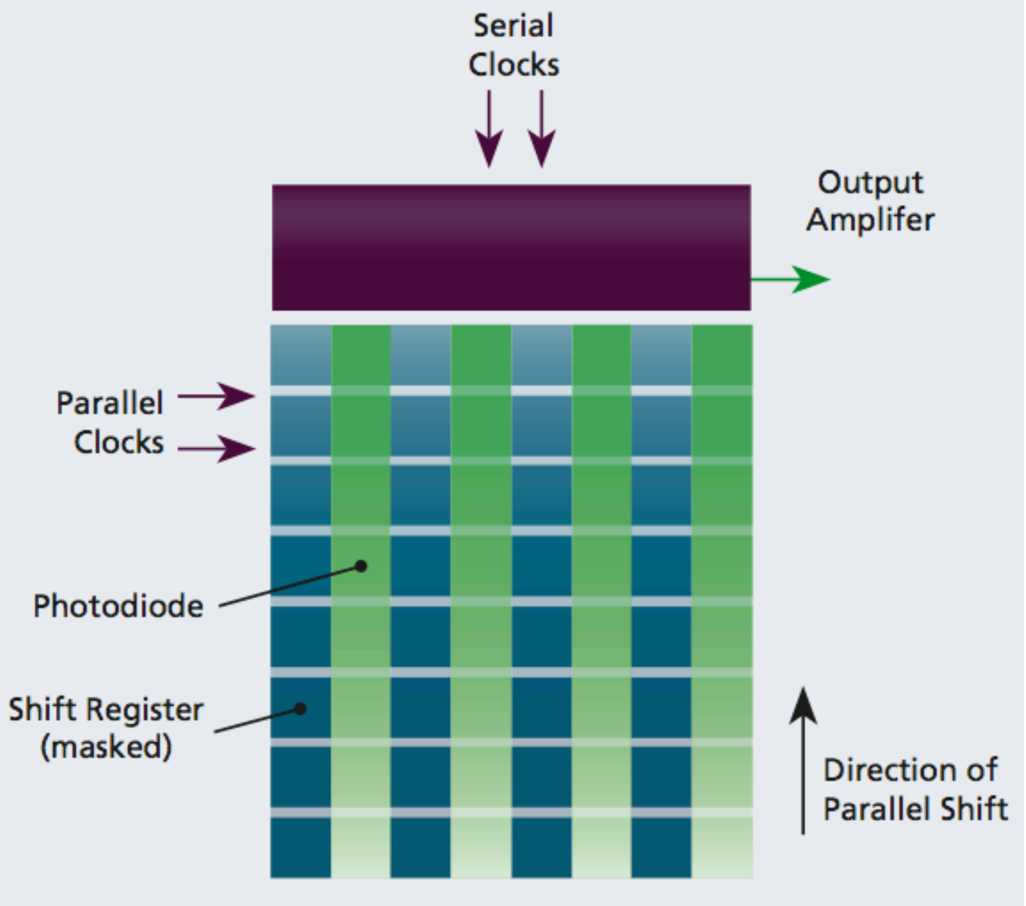


CMOS and CCD sensor architectures

(from Micron Semiconductor)



CMOS pixel arrays are fabricated with standard silicon processes, enabling peripheral electronics to be included on the chip.



CCD pixel arrays are optimized to lower noise and improve image quality. Because of their architecture, they require additional clock signals, converters, and controls off of the chip.

Kodak KAI-11000 pixel cross-section

Cross Section Showing Lenslet

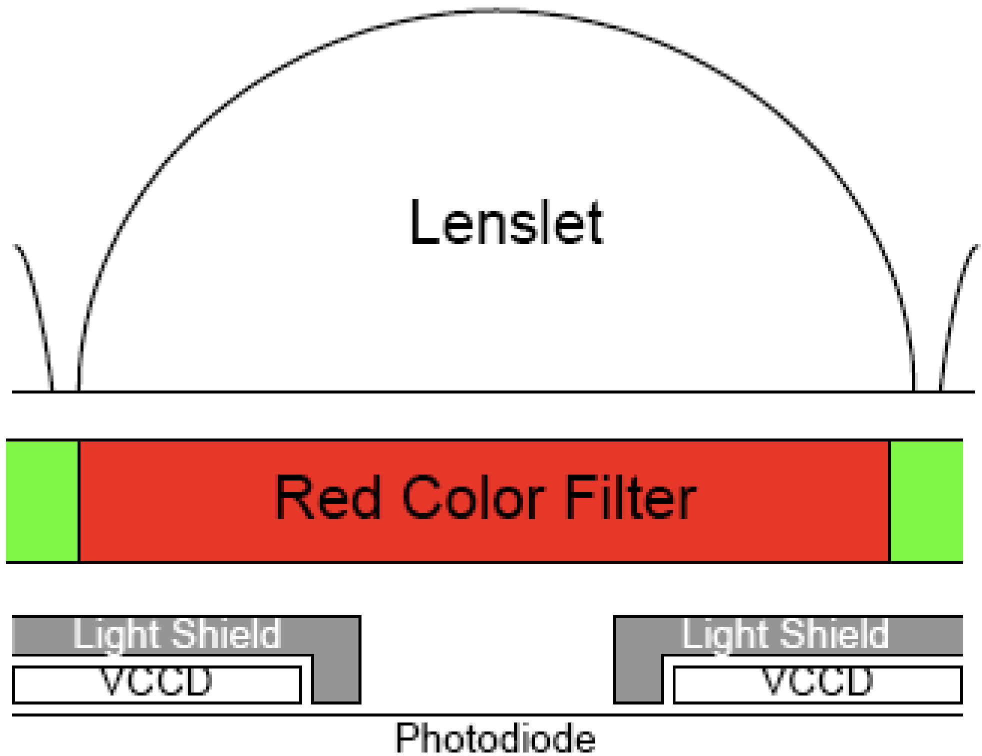


Figure 2: Pixel Architecture

"Not to scale"

Quantum Efficiency: electrons per photon

Quantum Efficiency

Color with Microlens Quantum Efficiency

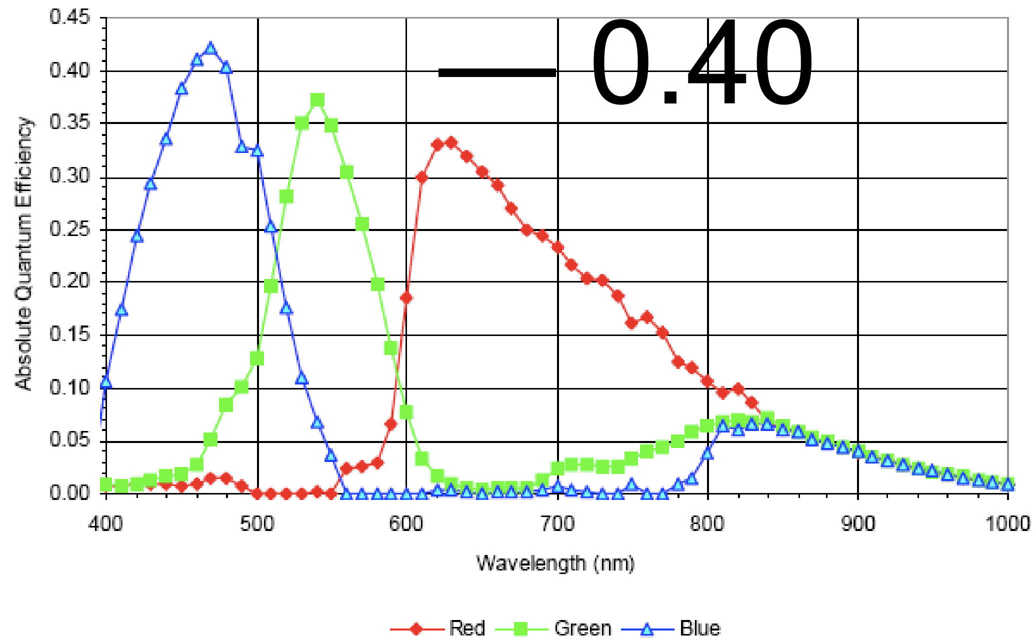
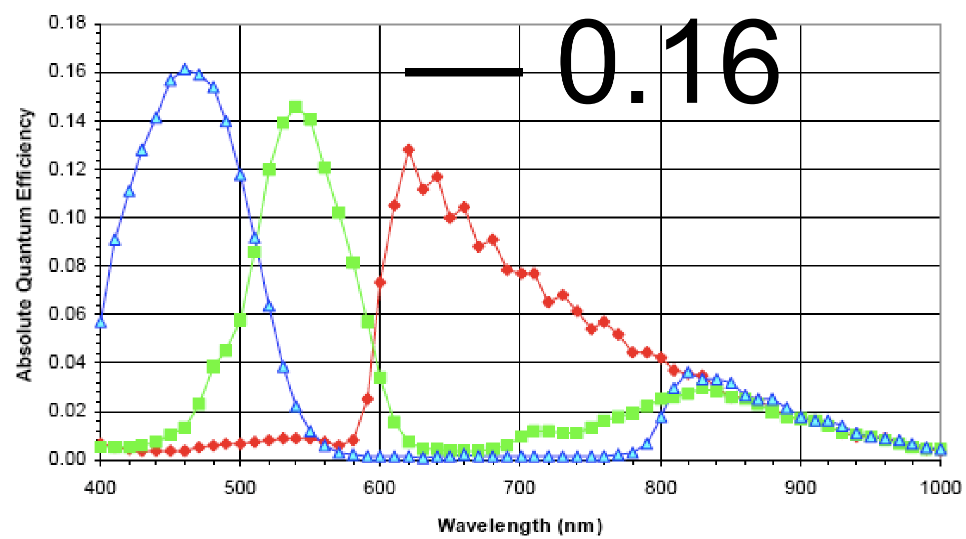


Figure 10: Color with Microlens Quantum Efficiency Using AR Glass

QE

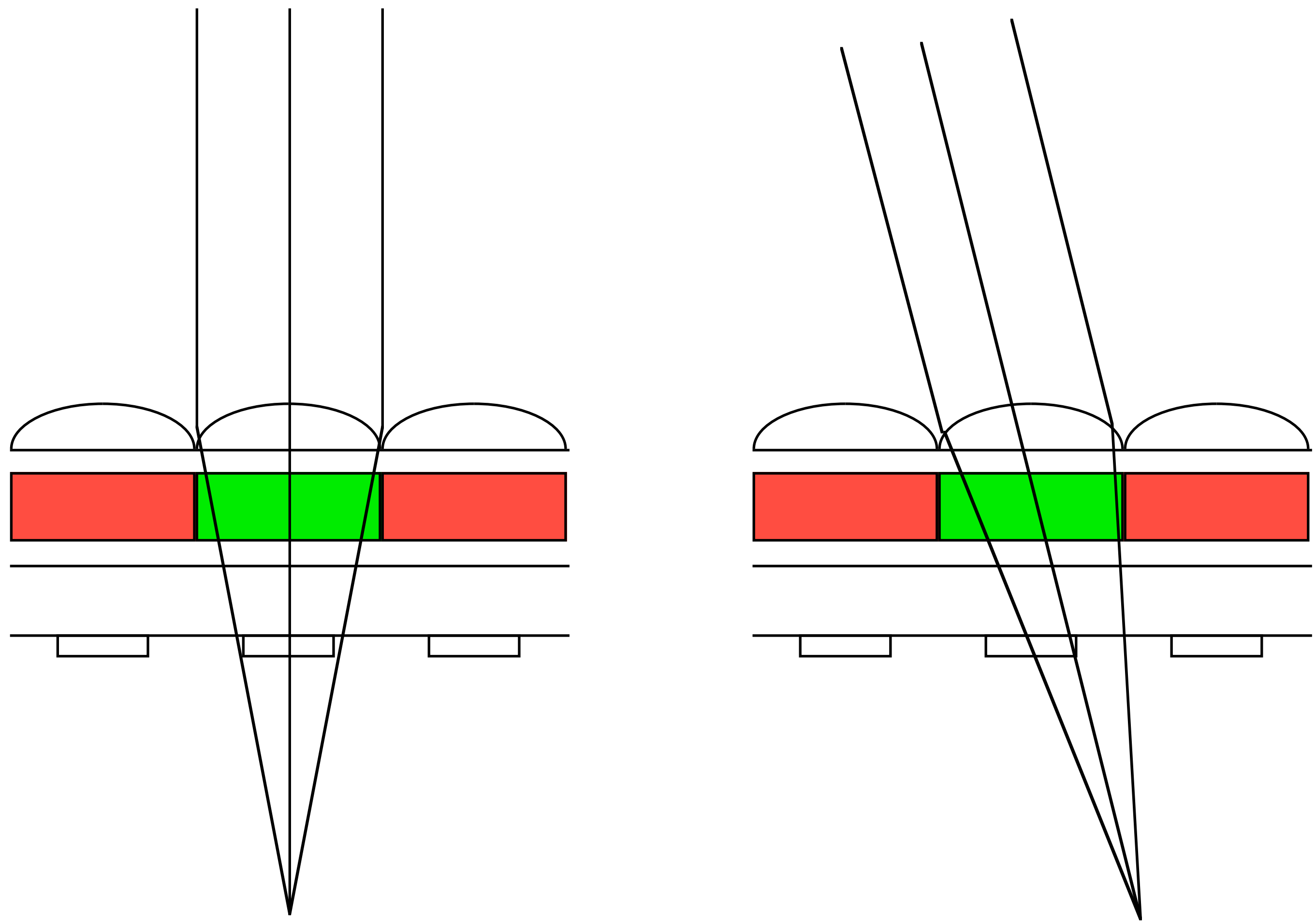
shows 2.5X microlens gain (implies about 40% fill factor)

Color without Microlens Quantum Efficiency



CCD Angle of Incidence Problem:

loss of quantum efficiency at high angles due to light missing the photodiode active area



Angle QE– Rectangular photodiode leads to different X and Y sensitivity

Angular Quantum Efficiency

For the curves marked "Horizontal", the incident light angle is varied in a plane parallel to the HCCD.
For the curves marked "Vertical", the incident light angle is varied in a plane parallel to the VCCD.

Monochrome with Lenslets

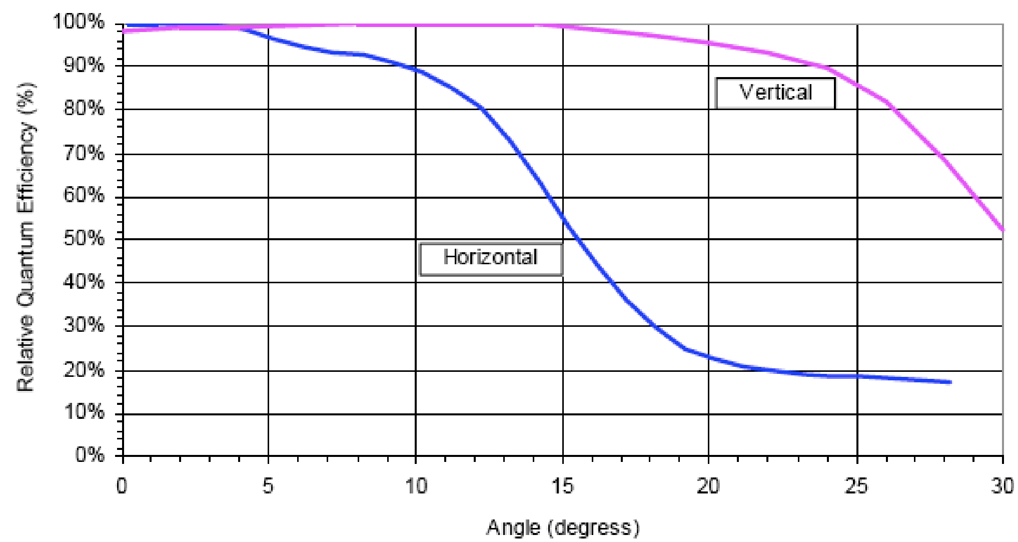
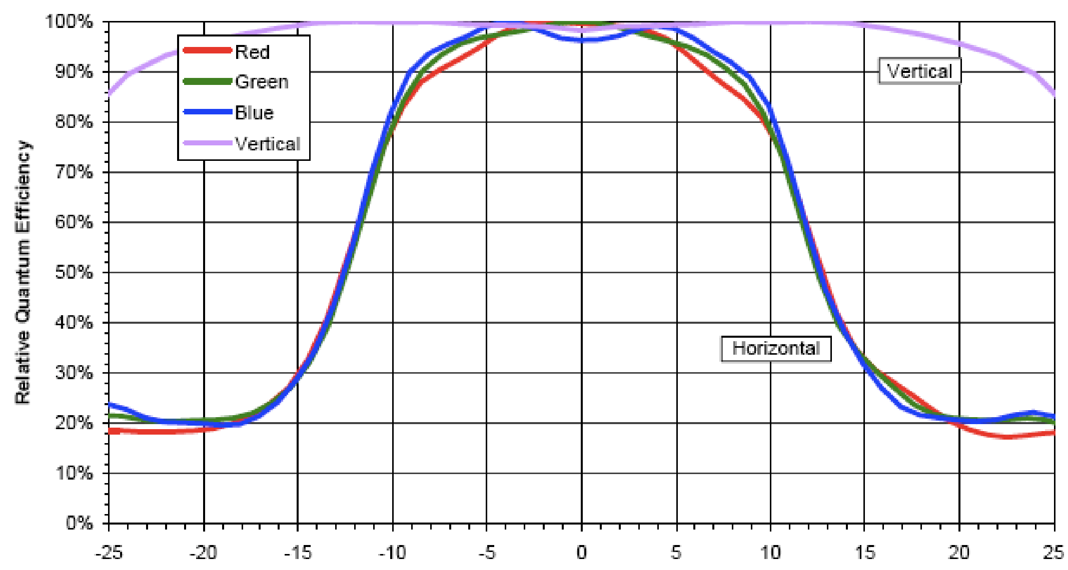
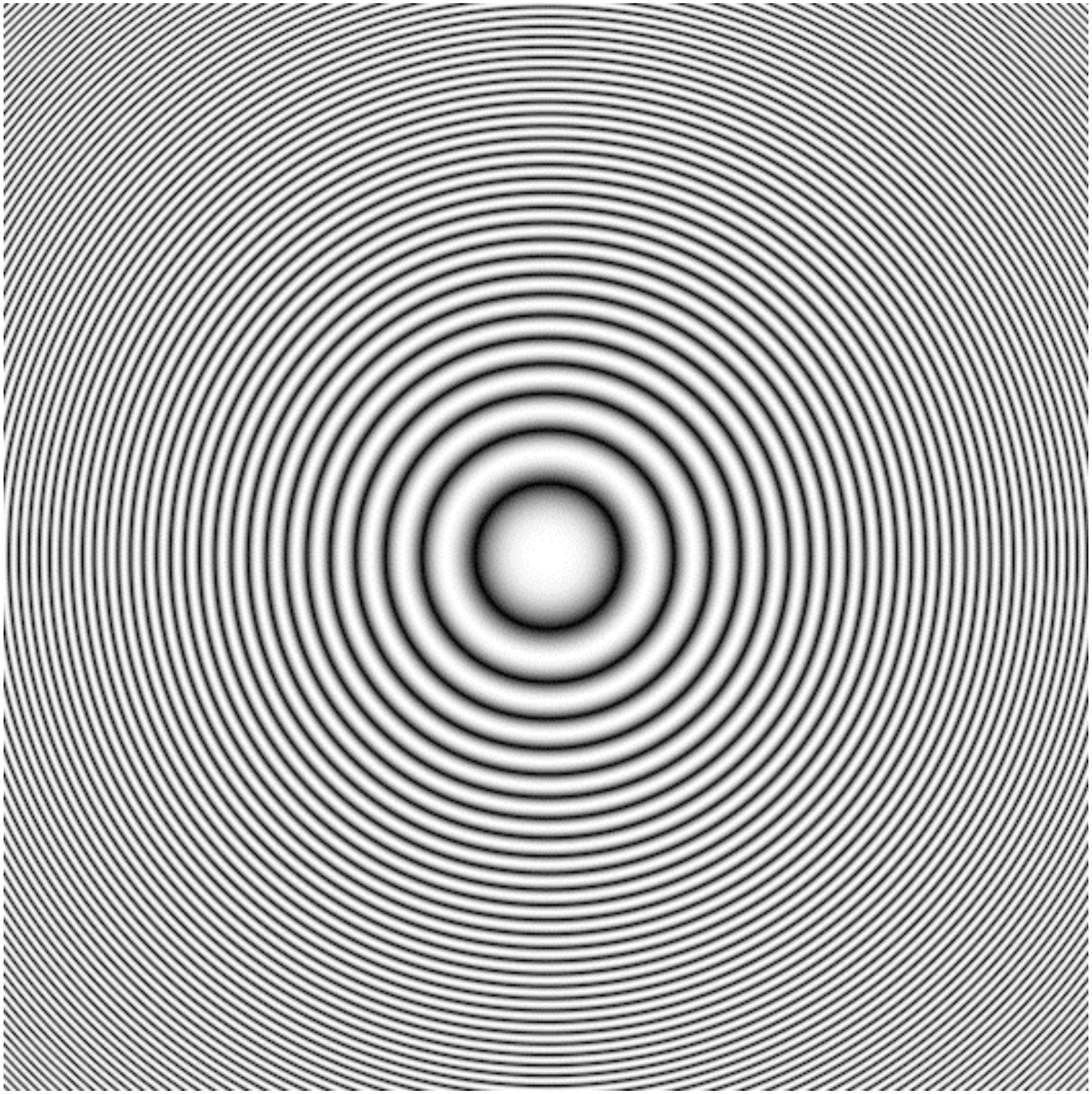


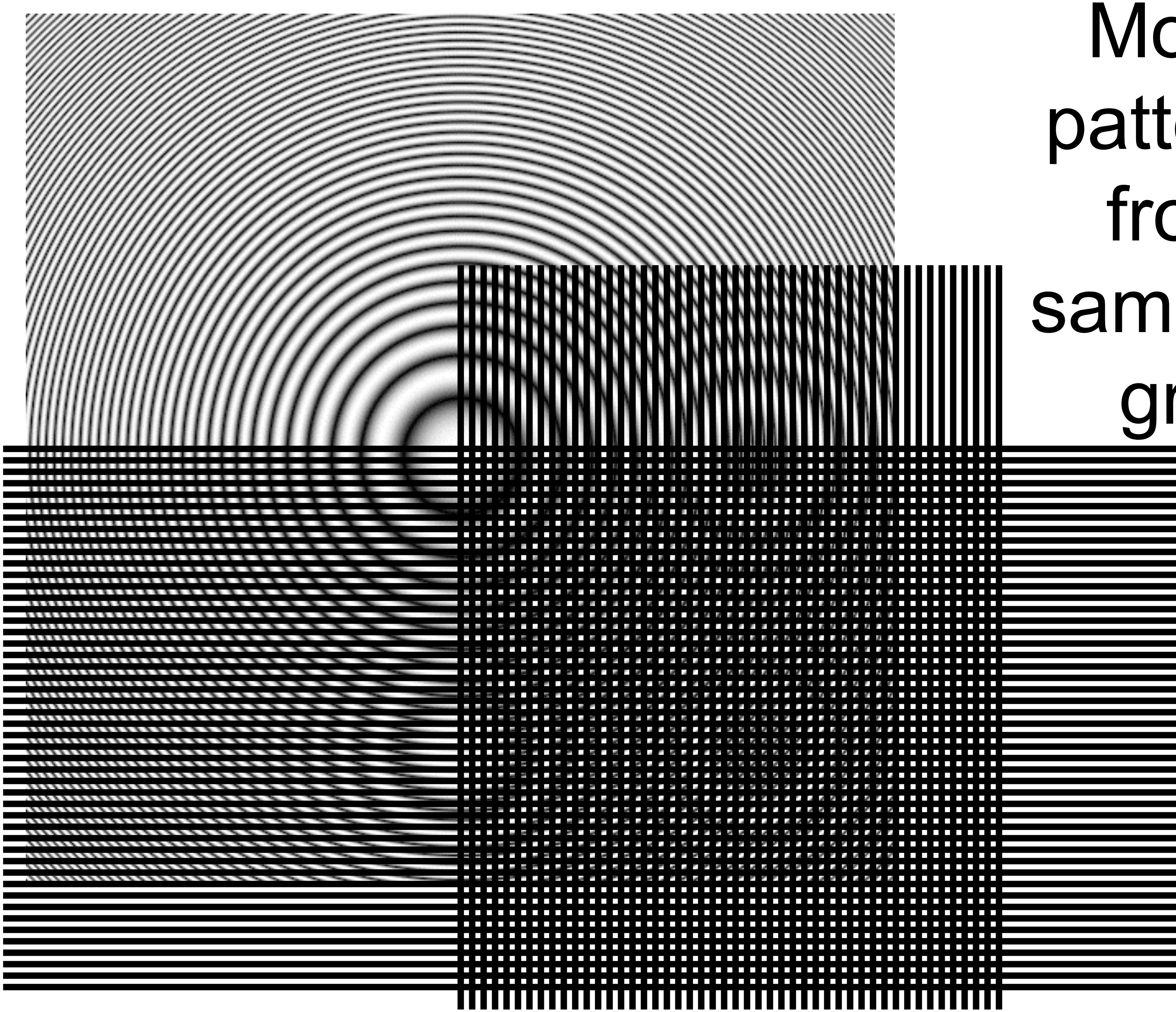
Figure 14: Monochrome with Lenslets Angular Quantum Efficiency

Color with Lenslets

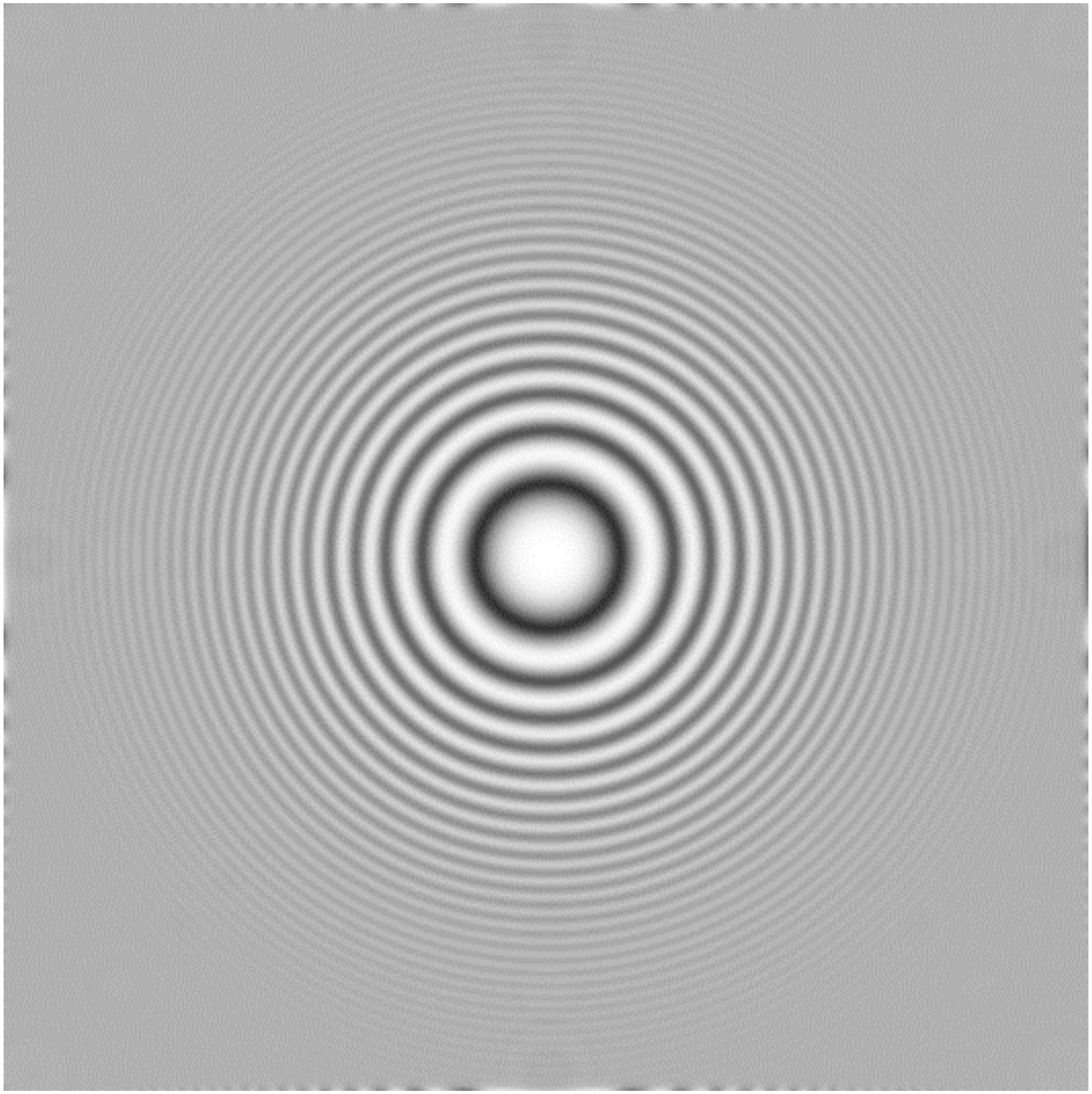




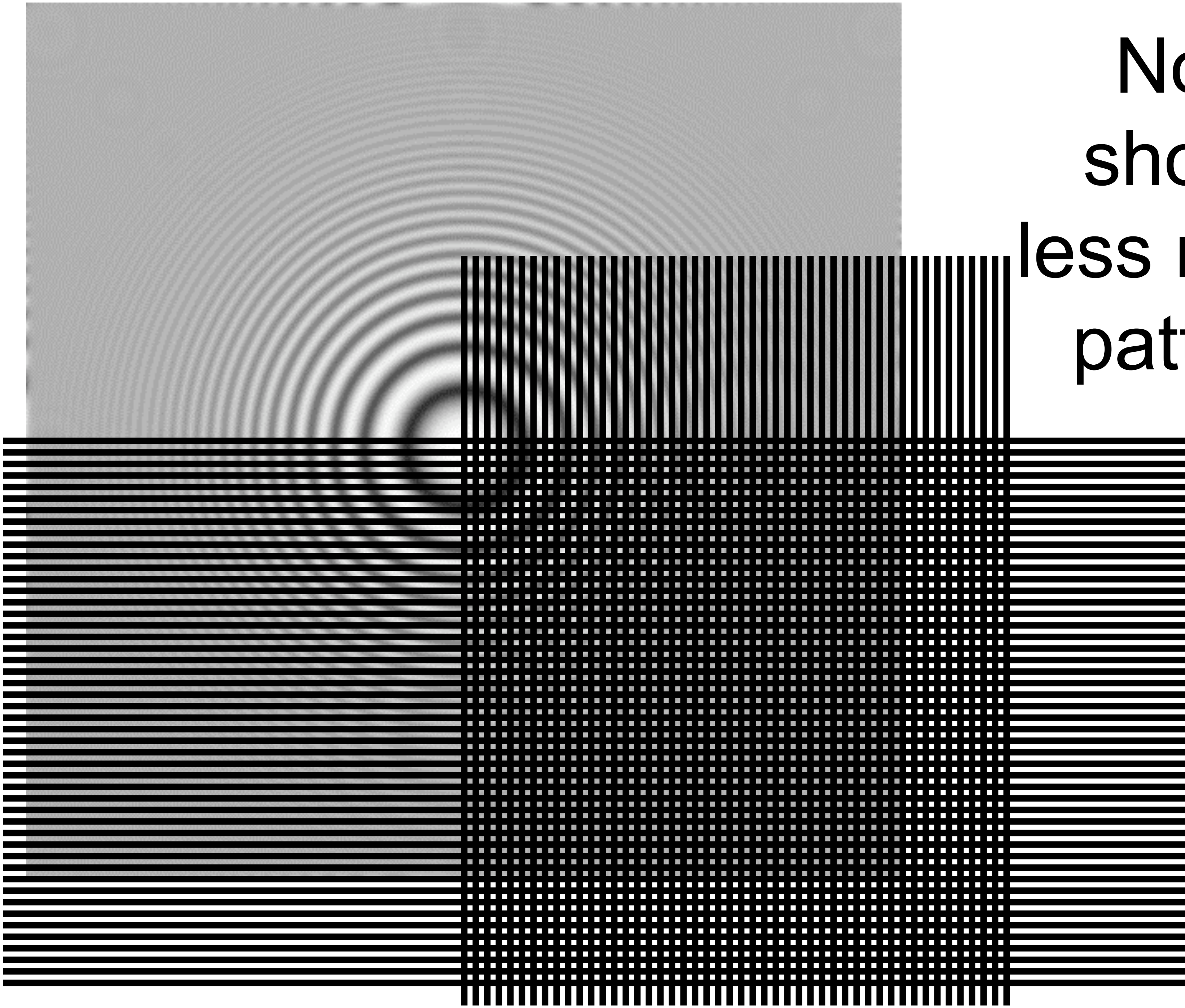
Sampling and aliasing: a test image with lots of frequencies



Moiré patterns from sampling grid



Same test image, but blurred



Now
shows
less moiré
pattern

Optical low-pass (AA) filter attenuates high frequencies before they can alias

(from *Image Sensors and Signal Processing for Digital Still Cameras*)

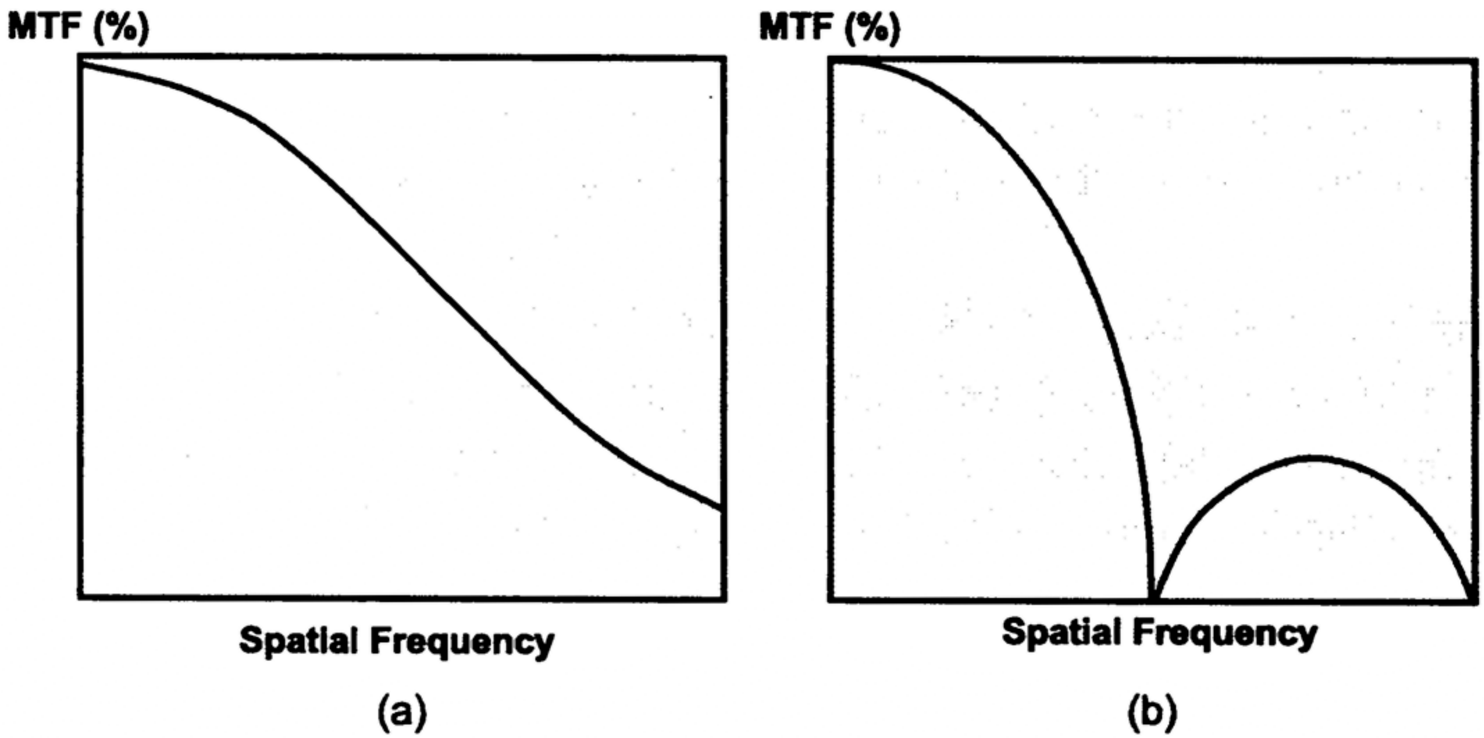
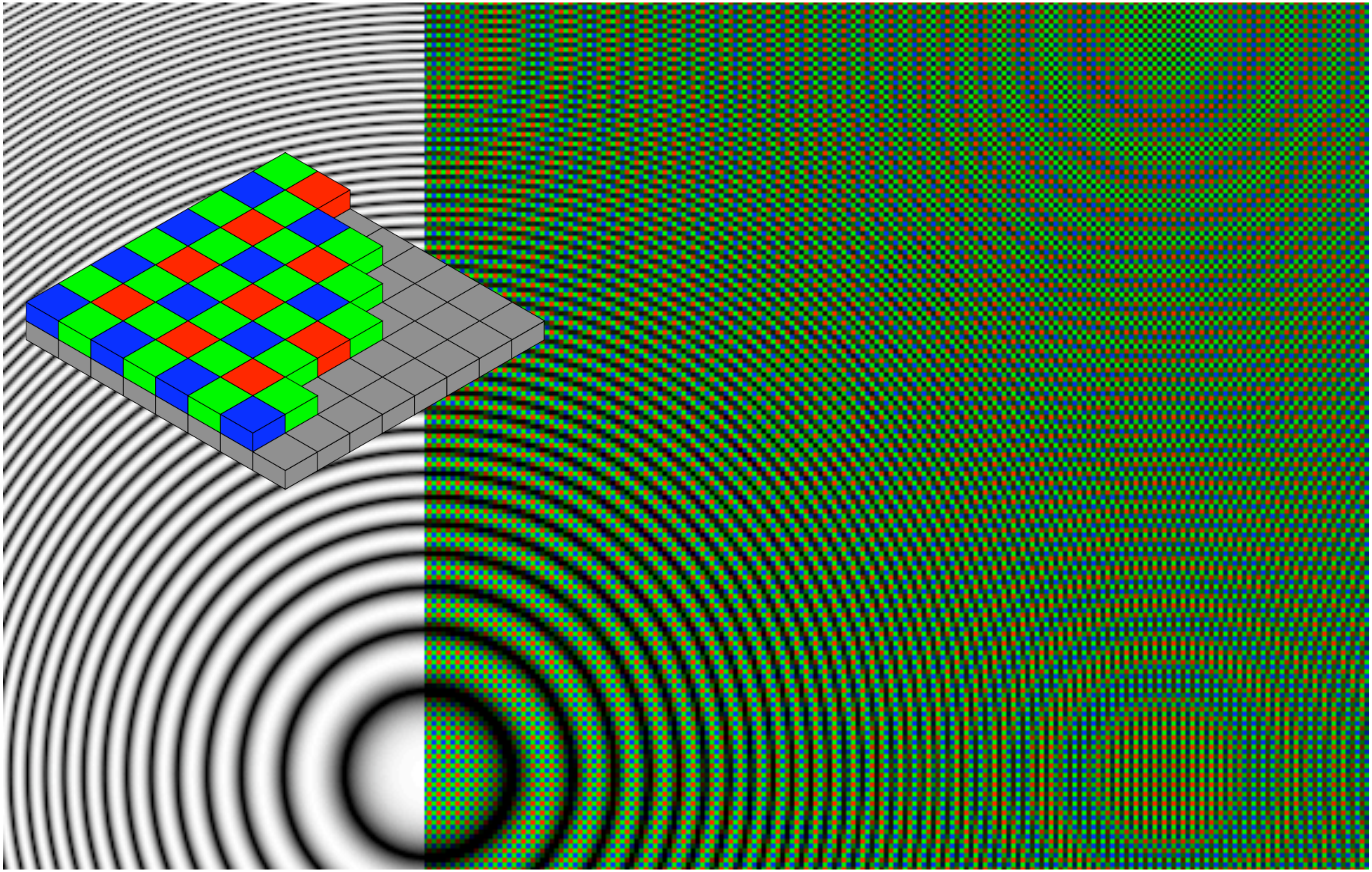
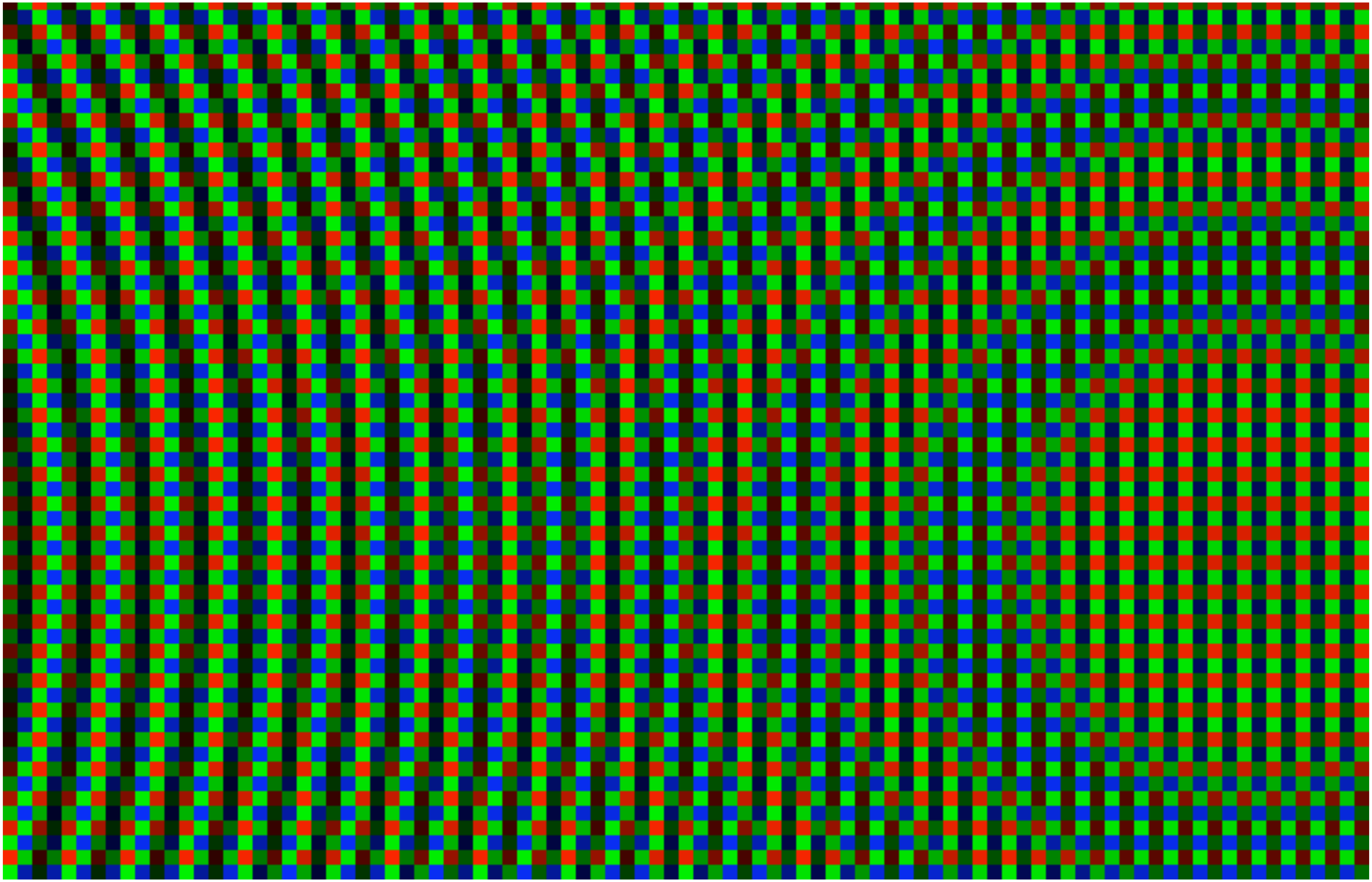


FIGURE 2.10 Example of the MTF for (a) an imaging lens and (b) a typical OLPF.

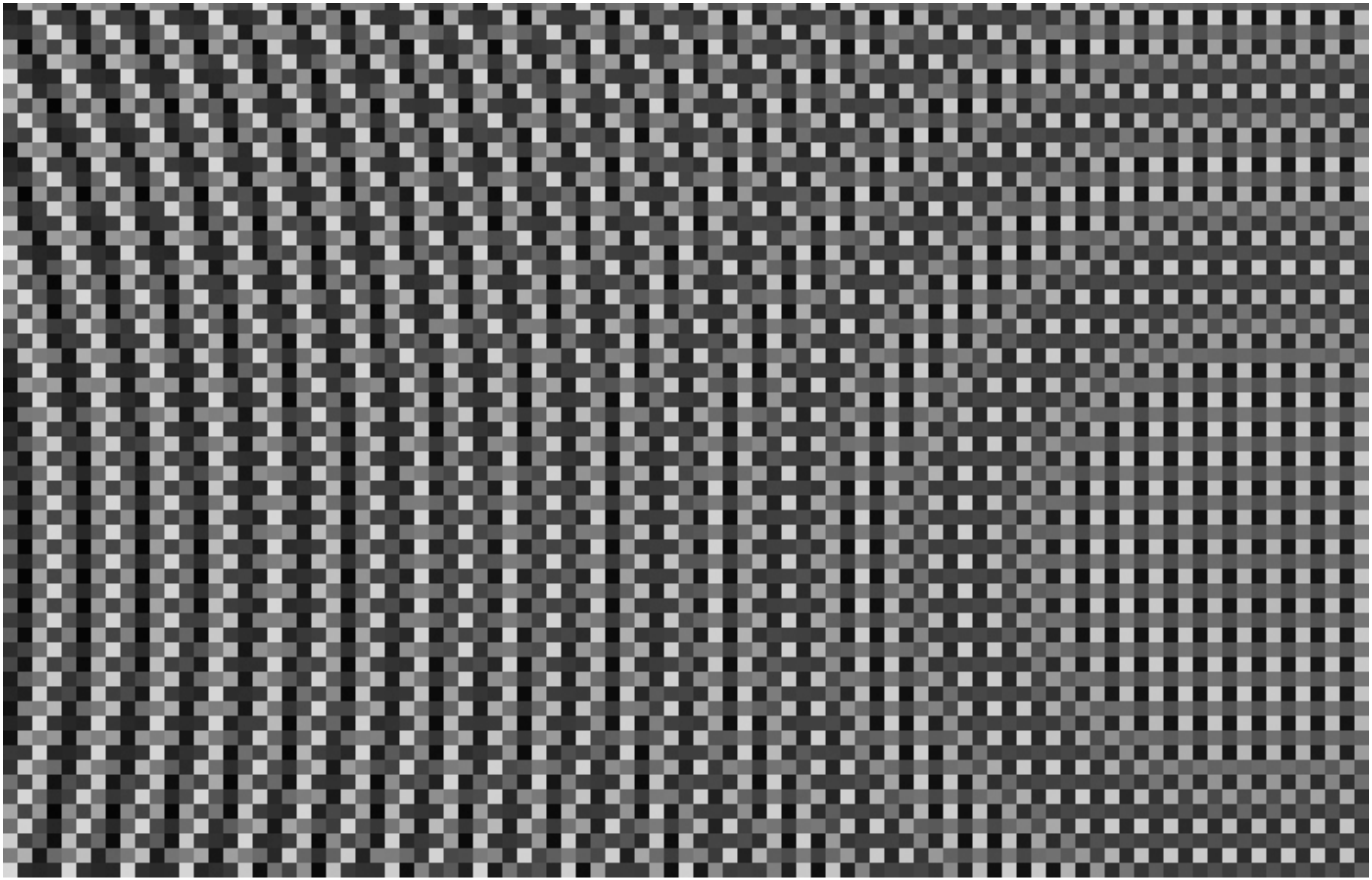
CFA can lead to color moiré



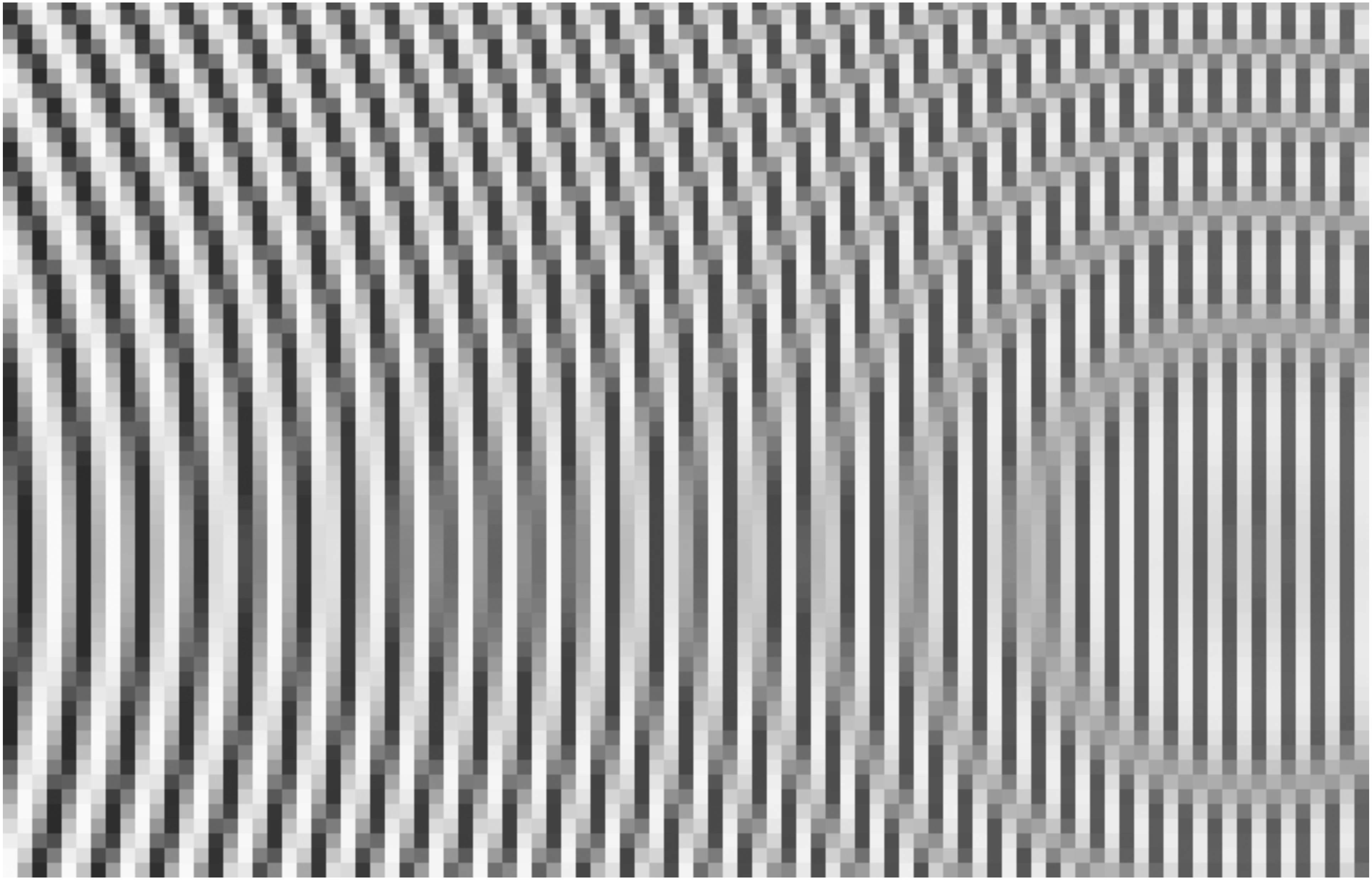
Bayer CFA moiré detail



Luminance artifacts tend to be fine, grid-like



Luma is recoverable when chroma is known



The "-els" according to Holst

Table 1-4
THE "-ELS"

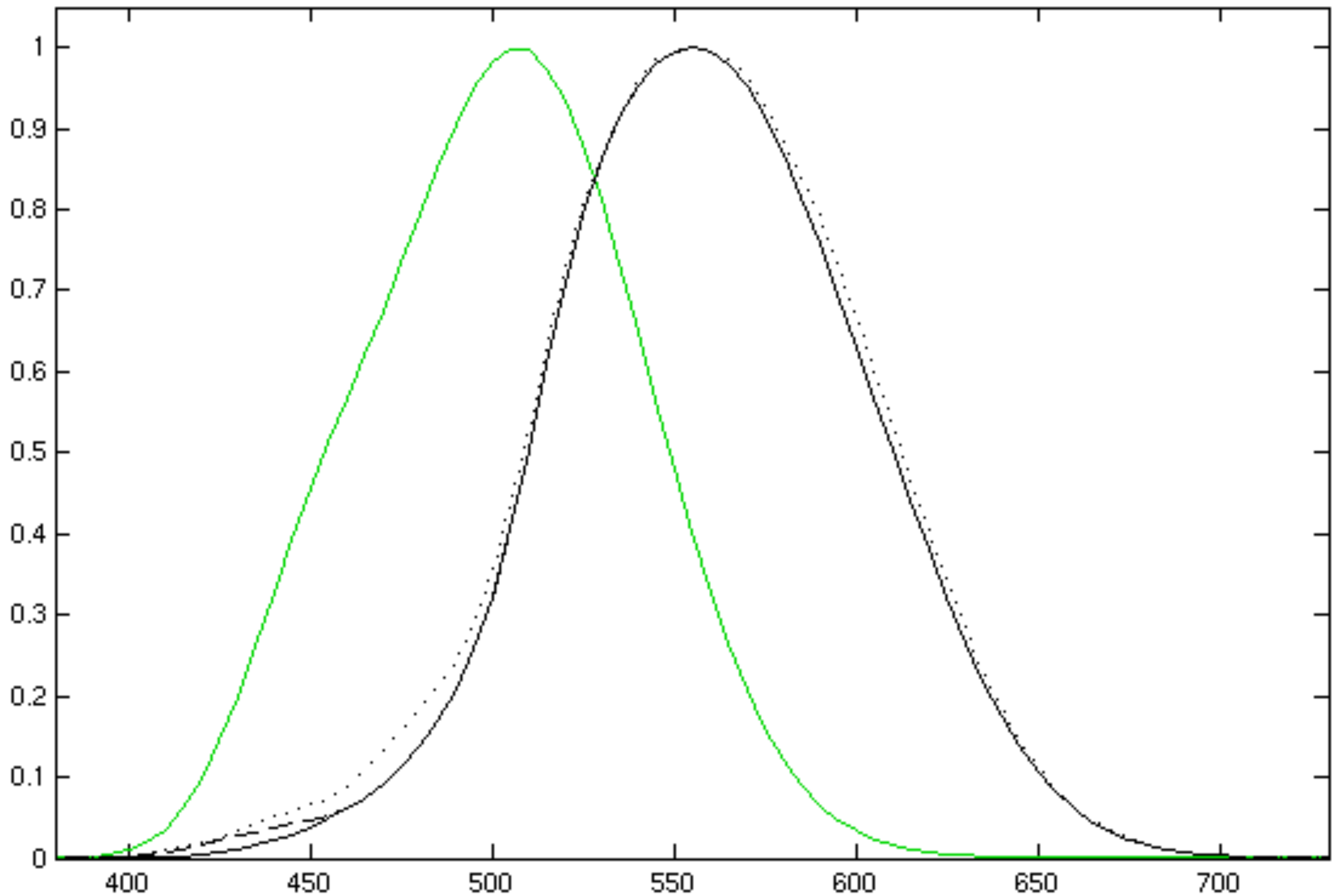
ELEMENT	DESCRIPTION
Scenel (Scene element)	A sample created by a scene simulator. Because the data resides in a computer memory, the array size is equal to the number of scenels.
Pixel or pel (picture element)	A sample created by a detector.
Datel (data element)	Each datum is a datel. Datels reside in a computer memory.
Disel (display element)	The smallest element (sample) that a display medium can access.
Resel (resolution element)	The smallest signal supported by an analog system.

Radiometry: light power

SI radiometry units

Quantity	Symbol	SI unit	Abbr.	Notes
Radiant energy	Q	joule	J	energy
Radiant flux	Φ	watt	W	radiant energy per unit time, also called *radiant power*
Radiant intensity	I	watt per steradian	$W \cdot sr^{-1}$	power per unit solid angle
Radiance	L	watt per steradian per square metre	$W \cdot sr^{-1} \cdot m^{-2}$	power per unit solid angle per unit *projected* source area. Sometimes confusingly called "intensity".
Irradiance	E	watt per square metre	$W \cdot m^{-2}$	power incident on a surface. Sometimes confusingly called "intensity".
Radiant exitance / Radiant emittance	M	watt per square metre	$W \cdot m^{-2}$	power emitted from a surface. Sometimes confusingly called "intensity".
Spectral radiance	L_λ or L_ν	watt per steradian per metre^3 *or* watt per steradian per square metre per hertz	$W \cdot sr^{-1} \cdot m^{-3}$ *or* $W \cdot sr^{-1} \cdot m^{-2} \cdot Hz^{-1}$	commonly measured in $W \cdot sr^{-1} \cdot m^{-2} \cdot nm^{-1}$
Spectral irradiance	E_λ or E_ν	watt per metre^3 *or* watt per square metre per hertz	$W \cdot m^{-3}$ *or* $W \cdot m^{-2} \cdot Hz^{-1}$	commonly measured in $W \cdot m^{-2} \cdot nm^{-1}$

Photometry and Radiometry:
Luminosity function, scotopic and photopic



Photometry: light visibility

SI photometry units

Quantity	Symbol	SI unit	Abbr.	Notes
Luminous energy	Q_v	lumen second	lm·s	units are sometimes called Talbots
Luminous flux	F	lumen (= cd·sr)	lm	also called *luminous power*
Luminous intensity	I_v	candela (= lm/sr)	cd	an SI base unit
Luminance	L_v	candela per square metre	cd/m^2	units are sometimes called nits
Illuminance	E_v	lux (= lm/m^2)	lx	Used for light incident on a surface
Luminous emittance	M_v	lux (= lm/m^2)	lx	Used for light emitted from a surface
Luminous efficacy		lumen per watt	lm/W	ratio of luminous flux to radiant flux; maximum possible is 683.002