Image Sensors

• Super important part of the microscope

• Three major properties:
  • Size (Sampling Resolution)
  • Sensitivity
  • Speed
Image Sensors

- Historically, there was film.
- Now, almost everything is digital.
  - CCD
  - CMOS
  - PMTs and other fast, high-efficiency devices
- Also, some new really cool technology with nanowire etc. is being developed for extreme sensitivity and temporal resolution on every pixel
Photographic Film

The Basic Structure Of Film

- Gelatin binder
- Silver halide crystals in suspension
- Celluloid base
  - Physical Handling protective back coat

\[ 2\text{AgBr} + h\nu \rightarrow 2\text{Ag} + \text{Br}_2 \]
Photon energy

\[ E = h \nu \]

Quantum energy of a photon.

\[ h = \text{Planck's constant} = 6.626 \times 10^{-34} \text{ Joule \cdot sec} \]

\[ = 4.136 \times 10^{-15} \text{ eV \cdot s} \]
Silver grain size

SEM image from RPI project
Color film

BEFORE PROCESSING

Inter layer
Yellow filter layer
Inter layer
Green sensitive layer
Inter layer
Red sensitive layer
Inter layer
Anti-halation layer
Film base
Back layer

AFTER PROCESSING

Protective layer
Blue sensitive layer
Inter layer
Yellow dye negative image
Magenta dye negative image and residual colored coupler
Cyan dye negative image and residual colored coupler
Digital Sensors

• Much more sensitive

• View and manipulate digitally
Matrix of gray-level values

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Bit depth

- Binary: 0 and 1
- 8 bit: 0 up to \((2^8 =)\) 256
- 16 bit: 0 up to \((16^2 =)\) 65,536
- 32 bit: 0 up to \((32^2 =)\) 4,294,967,296
8-bit vs. Binary
Digital Color Image
Digital Color Image

R

G

B
Bayer pattern
We lose light
Dichroic Mirrors, Multiple Cameras
Digital Cameras
Break Time
Recording a Digital Image
The Pixel

Figure 1

Metal Oxide Semiconductor (MOS) Capacitor

Silicon Dioxide

Photons

Polysilicon Gate

n-Channel

Potential Well

Potential Barrier

Photogenerated Electrons

p-Type Silicon
Doped Silicon

Donors, Group V impurities: Phosphorous, Arsenic and Antimony

Acceptors, Group III impurities: (e.g. Boron, Gallium and Indium)
Photogate

Photon creates electron/hole pair. The charges are separated by the electric field.

Outside the depletion volume no electric field exists. Electron/hole pairs created here will recombine because they are not separated.
Holes move

The free electron moves to the left in the electric field. The hole is filled with a bound electron which only jumps between two bound states. Therefore the energy required is small. As this process is repeated the hole continues to move towards the right. The moving hole corresponds to a positive charge.
Energy required to knock it:
\[\sim 1.2 \text{ eV} \sim 1 \text{ µm wavelength}\]

- Infrared
- Now commercially available
- Different material lenses (e.g. Gallium Arsenide)
CCD read-out

2 x 2 Pixel Binning Read-Out Stages

(a) Serial Shift Register
(b) Summed Pixel
(c) Parallel Shift Register

Figure 1
CCD vs CMOS

CCD

- Photon to electron conversion

CMOS

- Charge to voltage conversion
Increase effective fill factor

**Microlens**
These light-collecting microlenses focus the light from the lens onto individual photodiode cells.

**Color filter**
Divides light into RGB (red, green and blue) or CMY (cyan, magenta and yellow) color components.

**Photodiode**
When photodiodes receive light, a photoelectric conversion produces electrical charges (electrons). These electrons are then sent in vertical and horizontal directions, and the amount sent is determined by the intensity of the light received by each pixel. Next, in the CCD’s output layer, the accumulated electrons are converted to a voltage, which creates each pixel’s image output.

**Each pixel is a single-unit cell.**
Flow of electrical charge (electrons) varies according to light intensity. Light is converted into an electrical charge.
Other imaging modes (PMTs)

https://www.olympus-lifescience.com/de/microscope-resource/primer/techniques/confocal/detectorsintro/
Digital X-ray

A. Indirect AMFPI: X-rays to light to charge

B. Direct AMFPI: X-rays to charge
SPEED

Temporal Sampling
Rolling Shutter/Global Shutter and Artifacts
Stopping Time

Harold Edgerton's Kodatron strobe (1/3,000s)
Shadow Photography

http://edgerton-digital-collections.org/techniques/shadow-photography
Spatial Sampling
Sampling density 1 corresponds to “many” sample points per period of the sine wave. Density 2 corresponds to exactly two sample points per period, and density 3 to less than two sample points per period. Let us make simple image reconstructions (linear interpolation) from the sampled values for the three sampling densities:
Recap from last week

The Microscope:

Objective

Tube Lens
Resolution
Abbe Limit of Resolution

$d = \frac{\lambda}{2 \times \text{NA}}$

Lateral resolution is classically limited by diffraction to ~200nm (determined by Numerical Aperture NA and wavelength)

Example for green light with high NA objective: $d = \frac{(550 \text{ nm})}{(2 \times 1.4)} \approx 200 \text{ nm}$
Resolution and Magnification

• Example:

  • We have a CCD camera with 512x512 pixels of 16x16 microns size

  • We have a 100x objective with NA = 1.5

    • Resolution: \((0.5)/(2*1.5) \approx 166 \text{ nm}\)

    • 100X mag => \(\approx 16.6 \text{ microns in image space}\)

    • => We need to sample at twice this \(\approx 8 \text{ microns}\)

    • => This camera will not work well for us