Solid state imaging sensors

Overview

Solid state imaging devices:
- CCD imagers
- CMOS imagers
- Sensor imagers
- 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

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

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

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:

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.
Three-phase clocking system

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

Linear array sensors

(a) Linear imager
(b) Bilinear imager
(c) Quadralinear imager

Full frame CCD

Frame transfer (FT) CCD

Q: What shortcoming(s) does this design have?
Interline transfer (IT) CCD

Frame interline transfer (FIT) CCD’s

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

A closer look...

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:
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.

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.

<table>
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<th>Wavelength (Nanometers)</th>
<th>Penetration Depth (Microns)</th>
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**Example: smear and blooming**

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.

**Source:** Kodak KAI-2000m data sheet
Diffusion

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

Noise

Here is a diagram of a solid state sensing process:

Q: What kind of noise sources might you expect?

Dark current and photon shot noise

Electron-hole pairs are generated according to:

\[ n_{\text{photon}} = I_{\text{INT}} \eta A_p \]

where:
- \( I \) = irradiance of the light
- \( \eta \) = quantum efficiency
- \( A_p \) = area of pixel
- \( t_{\text{INT}} \) = integration time

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

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

where:
- \( T \) = temperature
- \( c \) = constant of proportionality
- \( K \) = Boltzmann’s constant
- \( E_\Delta \) = 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:

\[ \sigma_{\text{photon}} = \sqrt{n_{\text{photon}}} \]
\[ \sigma_{\text{dark}} = \sqrt{n_{\text{dark}}} \]

Q: How should noise vary over an image?
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 $\sigma_{\text{read}}$. 

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**SNR and dynamic range**

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**SNR and dynamic range**

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**Shot noise example**

Original image

Variance (x32)
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

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

Embedded color filters

Color filters can be manufactured directly onto the photodetectors.

Quantum efficiency now depends on embedded filter type:

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.

![Color Filter Arrays Diagram](image)

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.

![Demosaicking CFA’s Diagram](image)

**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

![Foveon Sensor Diagram](image)
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

Bibliography


Marschner, CS448A lecture notes (Stanford, Spring 02).

El Gamal et al., EE392b lecture notes (Spring 01).


