CCD vs CMOS Image Sensors

Limitations and Considerations

MAXWELL STONHAM

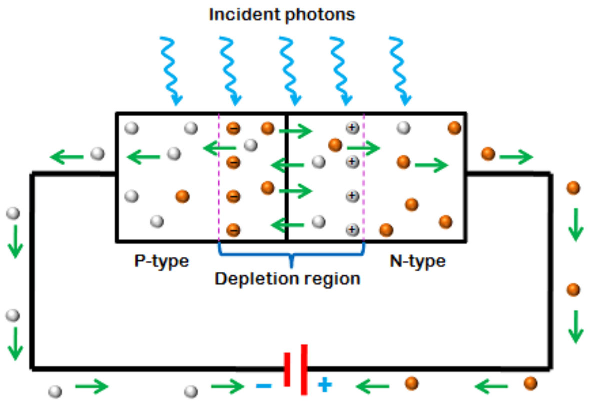
ECG 721

Overview – CCD vs CMOS

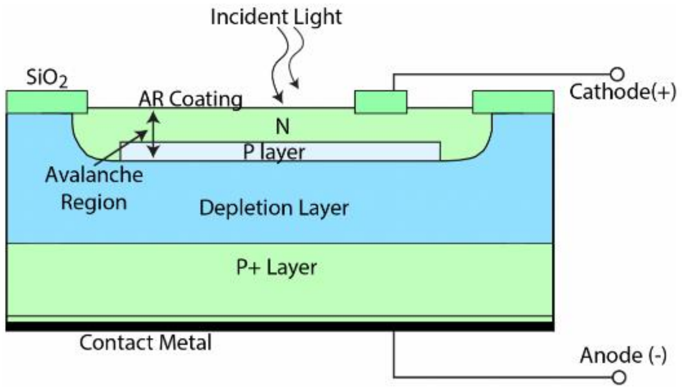
- Charge Coupled Device (CCD) sensors produce high-quality, low-noise images, but use more power (up to 100 times more power than CMOS). Uses MOS capacitors and depleted MOS structure for its photodetectors
- CCDs use thicker epitaxial layers of silicon for its photoactive region (100 microns, CMOS using 5-10 microns), better suited for higher image quality and low noise
- CCDs used to dominate since CMOS used to be difficult to fabricate. Used in higher quality image data for astronomy, healthcare or research
- CCDs are not improving anymore and have peaked, CMOS is continuously developing
- CMOS sensors are more susceptible to noise but have low power consumption, faster speeds, cheaper to produce (now), higher sensitivity to infrared wavelengths (now)
- CMOS sensors started to dominate around late 2010's and is now more commonly used in consumer applications, machine vision, near infrared imagers (increasing epilayer thickness), ultraviolet imagers

Photodiodes

- Photodiode: Semiconductor device with a P-N junction that converts light into electric current which is then quantified to a digital value.
- Reverse biasing increases depletion region and decreases depletion capacitance. When a photon hits, electron hole pair is generated, depletion regions shrinks, output voltage changes depending on the light
- Photodiode only detects light intensity, not color
- PIN PD: Added intrinsic layer between P and N layers, lower capacitance, higher quantum efficiency
- Avalanche PD: adds internal gain through impact ionization causing larger current per photon, more sensitive to low light

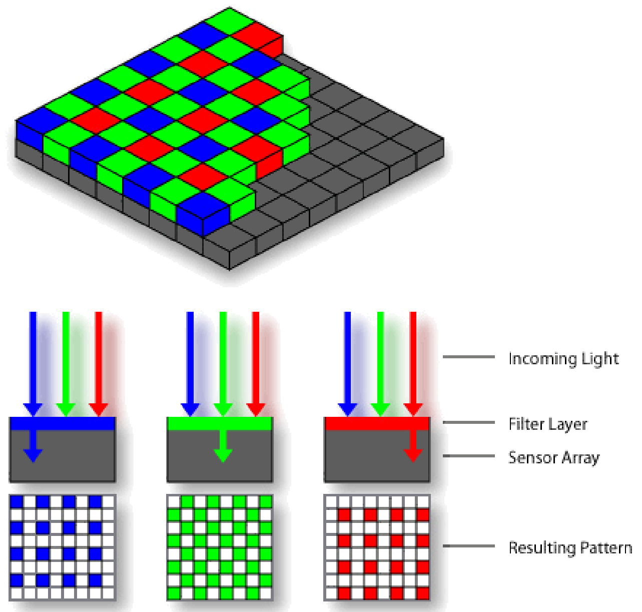


PN Junction photodiode



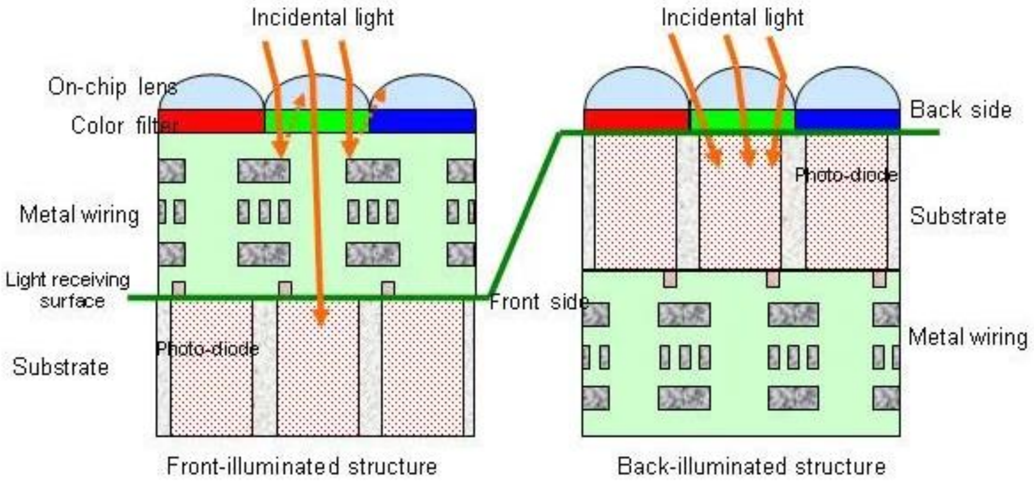
Color Filtering – Bayer Filters

- Bayer Filter used for RGB: mosaic pattern of two parts green, one part blue, one part red. This mimics the physiology of the human eye. Used since image sensors record light intensity, this allows wavelength to be recorded
- Interpolation is used to fill in missing color components



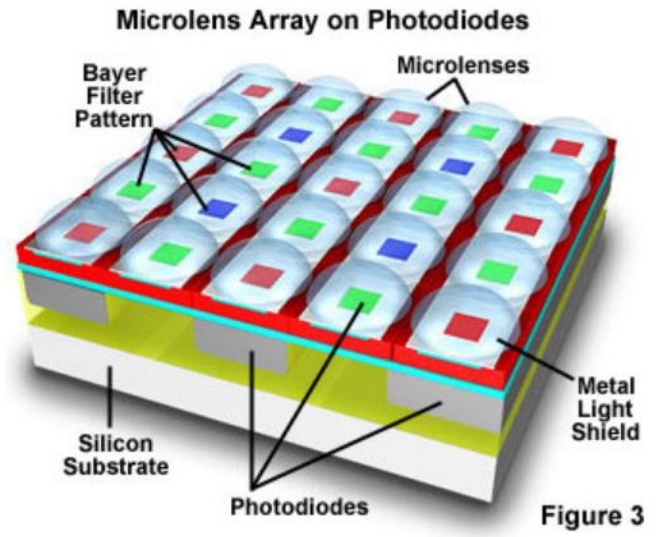
Front & Back-Side Illuminated Sensors

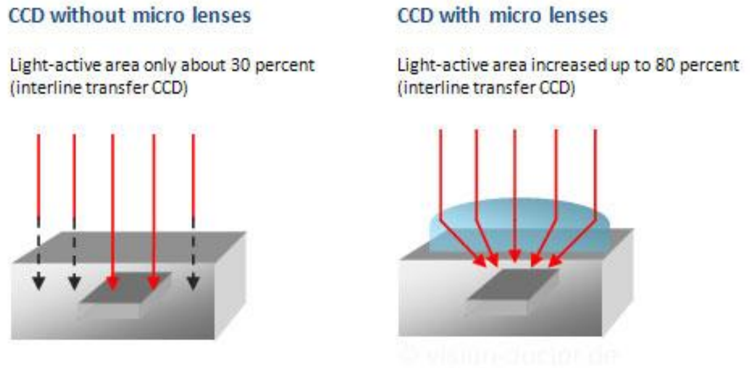
- FSI sensor has the grid of metal wiring as the top layer, while the photodiode resides below it. This reduces fill factor since many layers need to be passed
- Some light bounces of metal wiring, reducing image quality
- BSI is the opposite, increasing fill factor but more expensive and difficult to produce
- BSI reduces noise, captures more light (also better in low light and increases quantum efficiency)



Quantum Efficiency

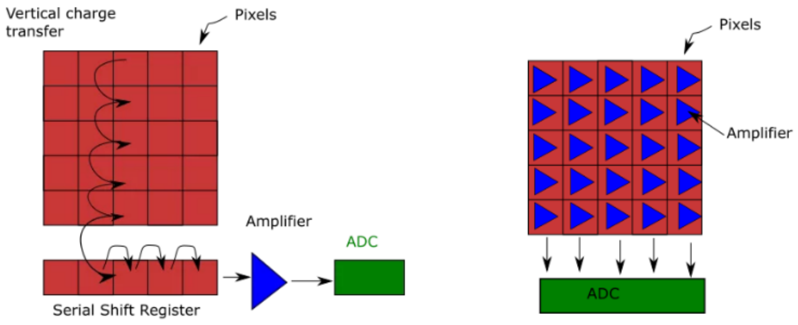
- Quantum efficiency how effective a device converts photons to electrons
- Factors affecting this:
  - Sensor Material and Structure: depth of photosensitive region, near IR vs UV
  - Anti-Reflection (AR) Coating: silicon has a high refractive index causing reflection at detector surface
  - Cover Glass/Micro-lenses: CMOS pixels typically have smaller photosensitive areas than CCDs, smaller fill factor
  - Temperature: dark current affects image quality, can shift dynamic range (range of the maximum and minimum detectable photon energy)



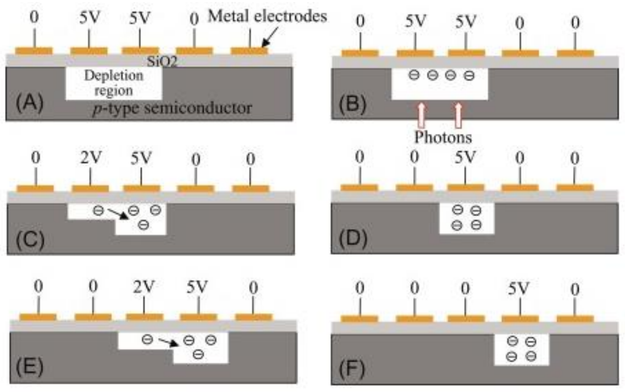


CCD Architecture

- Bucket brigade principle
- Use array of capacitive bins to collect charge in its pixels, then physically shifts the charge on the imager surface to output. Outputs an analog pulse where the charge is proportional to the light intensity.
- Charge to voltage conversion occurs at the end of each readout
- Low noise, generally since only one ADC and amplifier is used

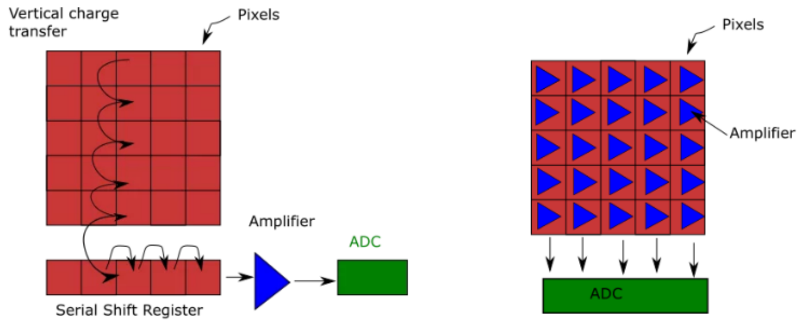


CCD Carrier Transport Process vs. CMOS Reading Process



CCD Architecture - Limitations

- Slow speeds since multiple clock cycles are required to read. More pixels, more cycles, more energy used from charge transferring and serial readout
- Data rates can be increased if more shift registers are used, this limits frame rate
- There is also a maximum number of electrons that can be stored in a single pixel. Charge leakage occurs from one adjacent rows if this limit is reached, and the blooming effect happens (overflowing bucket)
- Prevented by using an anti-blooming drain, limiting the maximum charge per pixel



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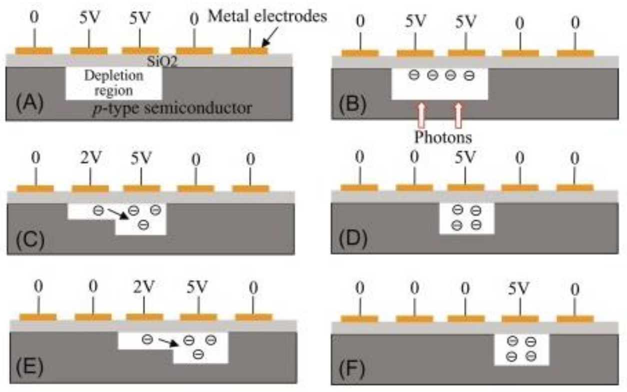
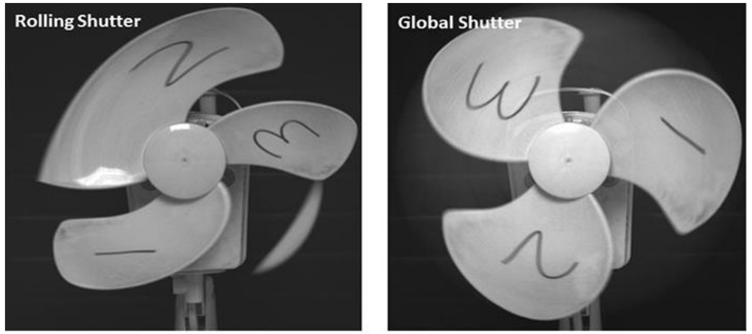
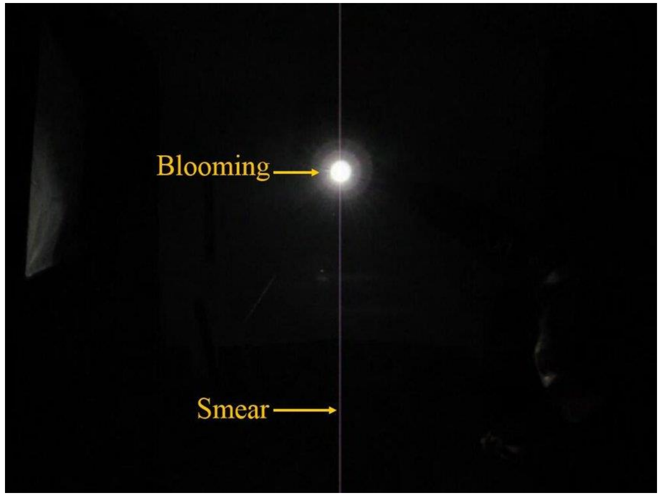
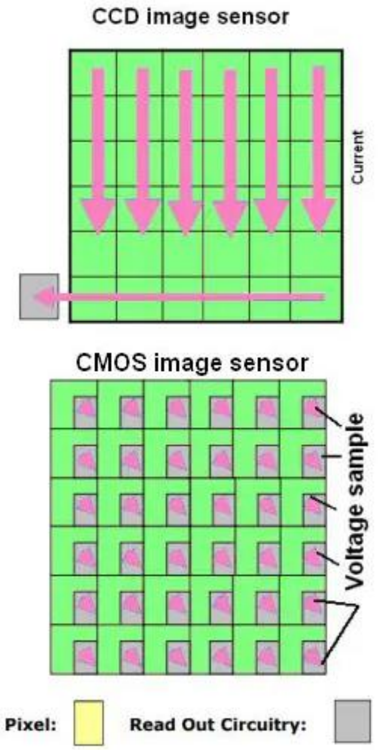


Blooming, Smearing, and Shutter

- Blooming: caused by charge leakage (horizontal shifting)
- Smearing: caused by charge accumulation (vertical shifting). When shifting vertically, light is still being detected onto the sensor as signal is being read out. A mechanical shutter can be used to block light
- CCD: Global Shutter (most)
- CMOS: Rolling Shutter

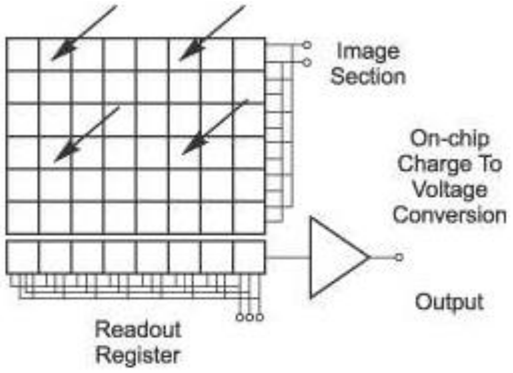




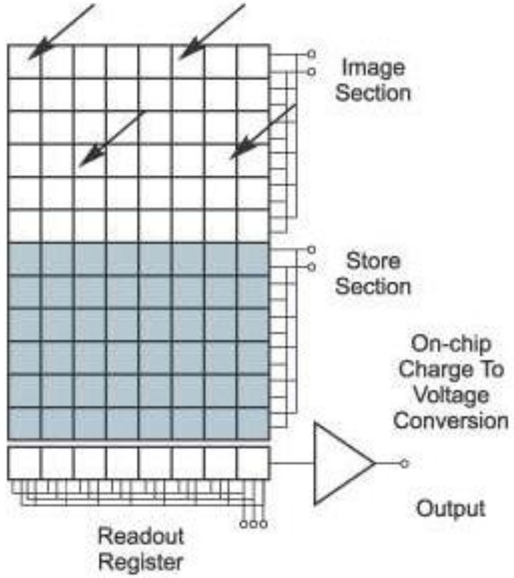


Conceptual diagrams illustrating the difference between CCD and CMOS imaging chip architectures.

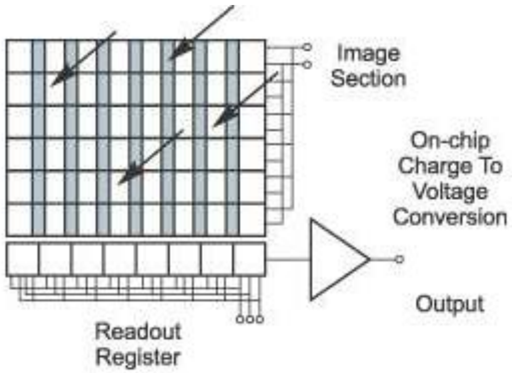
CCD Architecture Types



Full Frame CCD



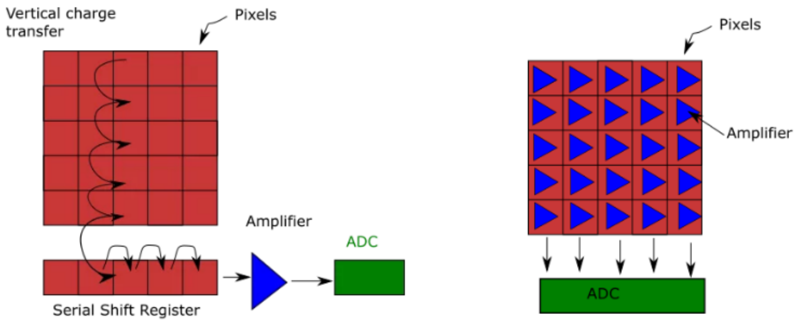
Frame-Transfer CCD



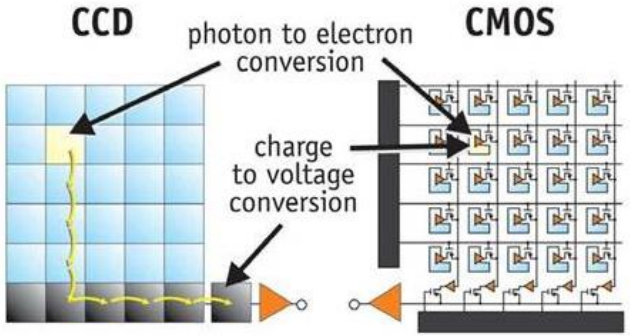
Interline-Transfer CCD

CMOS Architecture

- Each pixel has an amplifier, and each pixel column has an ADC. More ADC's, more pixels read at once, faster speeds
- Uses multiple layers of semiconductor material, allowing a lower charge conversion than CCD. Voltage sampling is much more power efficient than capacitive bins to store charge, and is faster
- More flexible since it works similar to a memory cell, each pixel or region of pixels can be activated specifically to what needs to be read, and can process multiple pixels at once

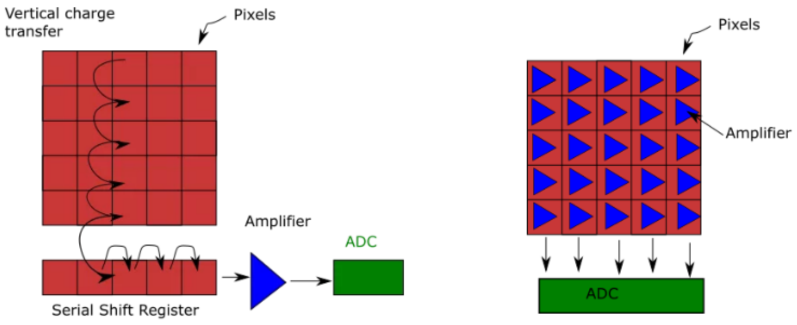


CCD Carrier Transport Process vs. CMOS Reading Process



CMOS Architecture - Limitations

- Limitations: more noise due to more image nonuniformities (temporal noise, fixed pattern noise) that can be caused by mismatches between each pixel and the use of multiple ADC converters
- Nonuniformities and noise caused by multiple levels of amplification (pixel, column, chip)
- Readout is performed one row at a time resulting in faster speeds, but potentially suffering from a rolling shutter effect since integration times are staggered



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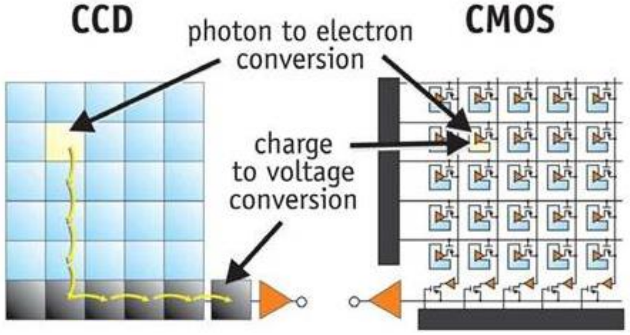
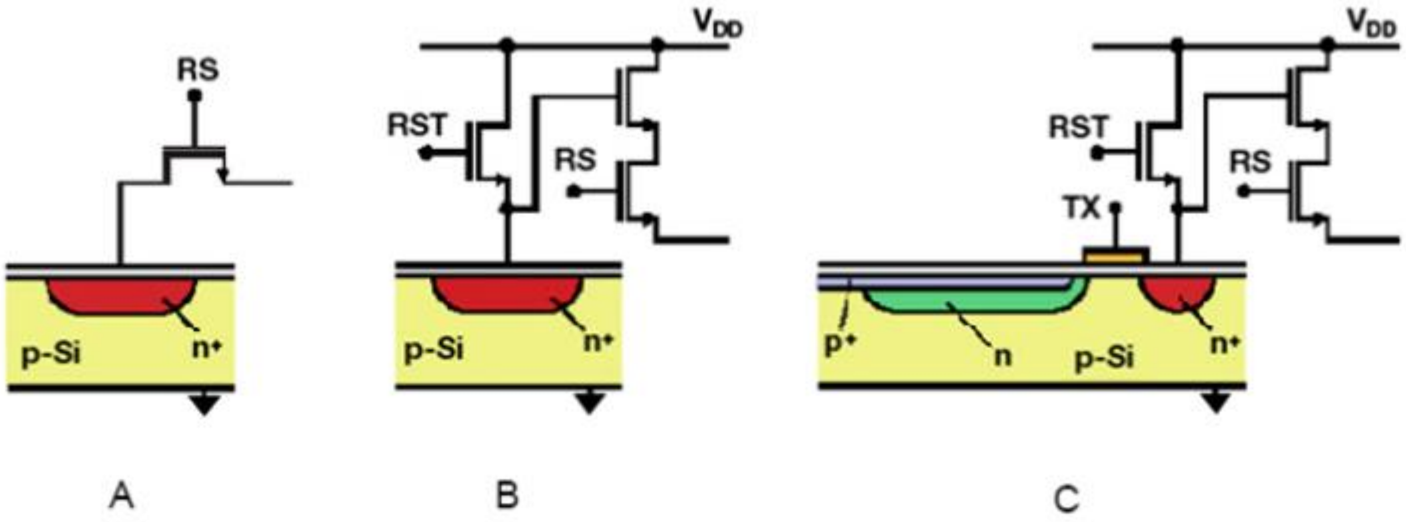


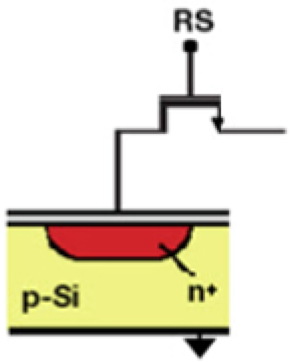
CMOS Image Sensor Topologies

- PPS, APS, Pinned Photodiode APS, DPS
- PMOS generally not used (requires an N-well), else pixel size will be big



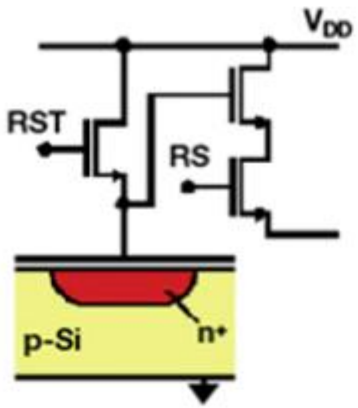
Passive Pixel Sensor

- Passive pixel sensors (PPS) uses a single transistor, similar to a DRAM cell
- How it works: VDD on bitline, turn the cell on to precharge the photodiode to VDD, then turn the NMOS off and let light hit the photodiode (the diode current discharges for a period of time called the integration/exposure time), voltage drops, then read the pixel out after integration time
- Lower the voltage, the brighter the image. Increasing light increases the photogenerated current, so voltage drops even more when discharging
- Limited since we have huge bitline capacitance on the bitline, charge sharing is present, which makes it difficult to read out the signal since it affects the sensitivity
- Not used in main consumer applications due to this limitation, unless large area photodiodes are present



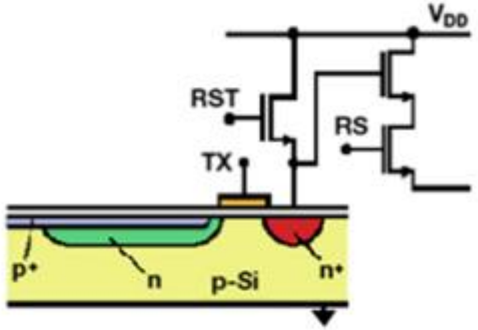
Active Pixel Sensor

- Active pixel sensors (APS) uses a minimum of three transistors
- All NMOS design, as mentioned previously. Use Bayer filter in photodiode
- Voltage that drops is buffered through a source follower which is followed by a row select signal (RS) on the word line so the source follower from every pixel is not driving the bitline. Reset (RST) signal is to precharge the diode



Pinned Photodiode Pixel Sensor

- P-N-P Structure so that the Fermi level/built-in potential within the diode is fixed. Results in no image lag, lower dark current, higher sensitivity
- How it works: turn on TX and RST to precharge our photodiode to VDD. Then turn TX off and let the light hit the photodiode which drops the voltage and turn on RS to read it out through the bitline

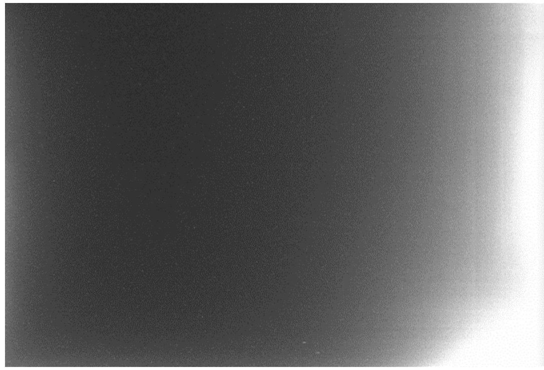


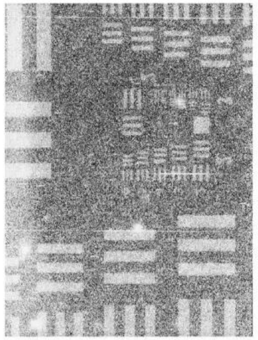
Noise Considerations

- Temporal noise: Thermal noise (kT/C noise) of transistors during readout and amplifying, shot noise of photo and dark currents, flicker noise of photodetector and transistor
- Dark current: leakage current from photodetector causing shot noise and reducing signal swing. This is also called Dark Signal Nonuniformity (DSNU). Caused by thermal generation to be released from the semiconductor material due to defects in the Si/SiO2 interface, imperfections in crystal structure, or metal contamination.
- Fixed Pattern Noise: noise caused by device mismatches (nonlinearity) resulting in offset and gain, or Pixel Response Nonuniformity (PRNU)

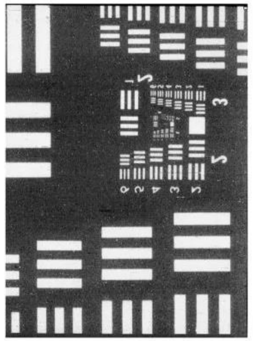
Dark Current

- Charge can be generated from random thermal generation within the silicon regardless of exposure to light/photons
- Dark current increases linearly with exposure time, exponentially with temperature. Specifications are determined by how much electron build up per pixel per second (e-/p/s)
- Photodiodes still hold charge generated by dark current
- If charge is stored in a photodiode, under low-light conditions, this signal is still read since this small bit of charge has been stored from dark current. This causes image degradation
- Dark current can be reduced by reducing exposure time or cooling the image sensors, though not practical in consumer applications





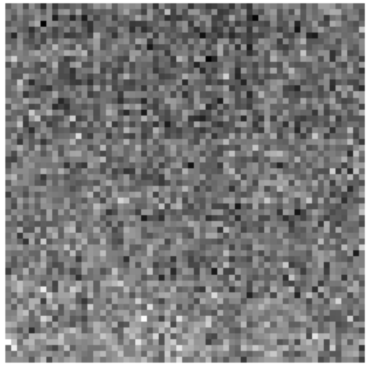
RAW IMAGE



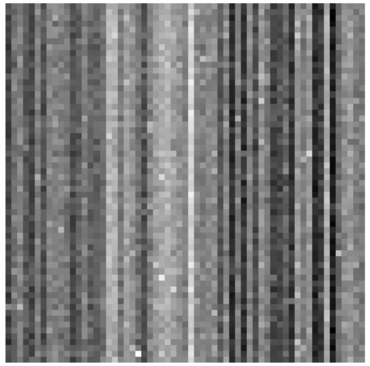
DESPIKED IMAGE
(subtract Dark Frame from Image)

Fixed Pattern Noise

- FPN for CCDs seem random since noise in CCDs are affected by each pixel (due to variations in the photodetector devices) or by the single output amplifier
- FPN in CMOS seem striped due to each column having an individual amplifier causing what's called column FPN, on top of the FPN caused by each pixel having multiple transistors in one
- In PPS, FPN is mainly due to the photodiode and column amplifier parameters (higher column FPN)
- In APS, FPN is also due to variations in the transistors (higher pixel FPN)

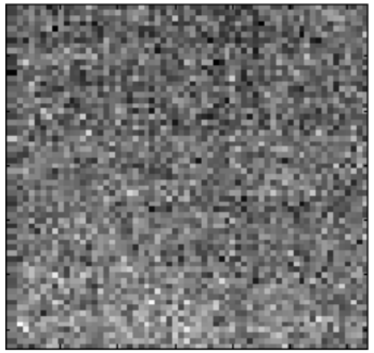


For CCD sensor



For CMOS sensor

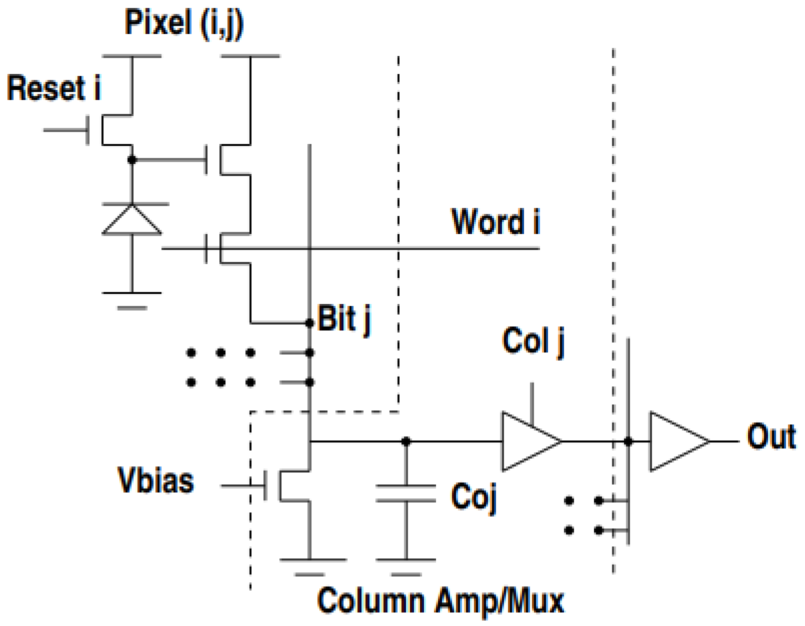
PPS



APS

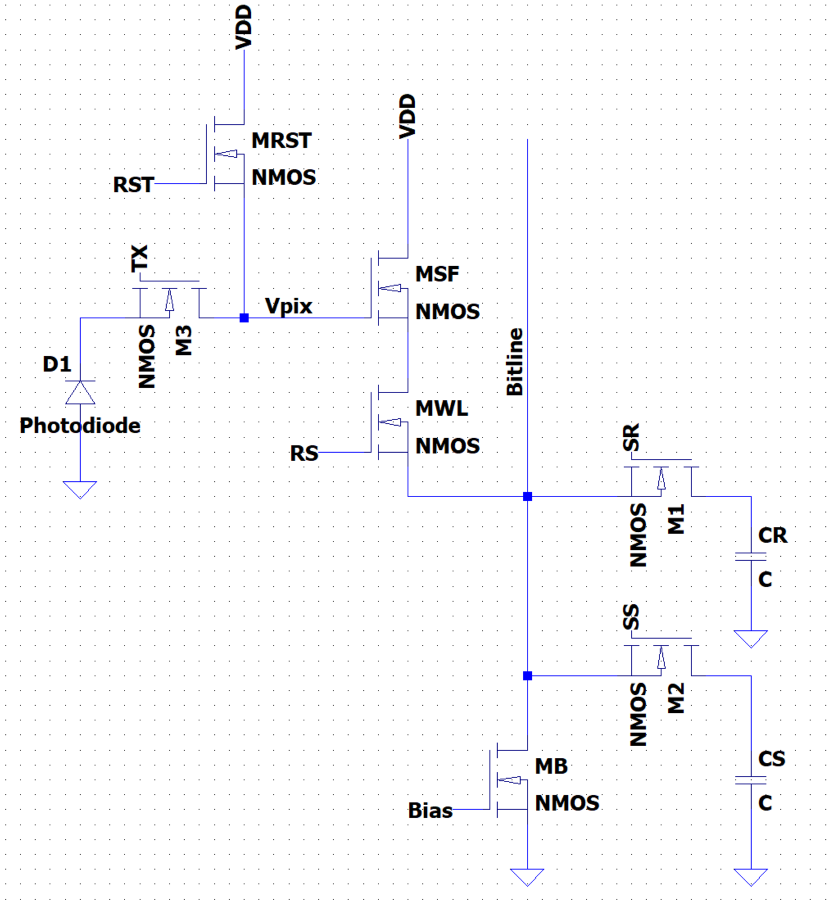
Example of Noise in Active Pixel Sensor

- Shot noise due to photodiode during integration: Current flows through the diode causing random movement of charge across the depletion region
- Thermal noise from reset transistor when resetting: noise caused by thermal effects resulting in random motion of electrons
- Thermal noise from source follower, access and bias transistor during readout
- Noise due to amplifier and ADC
- More noise in CMOS than CCDs since CMOS has more transistors (access transistors, column amplifiers)



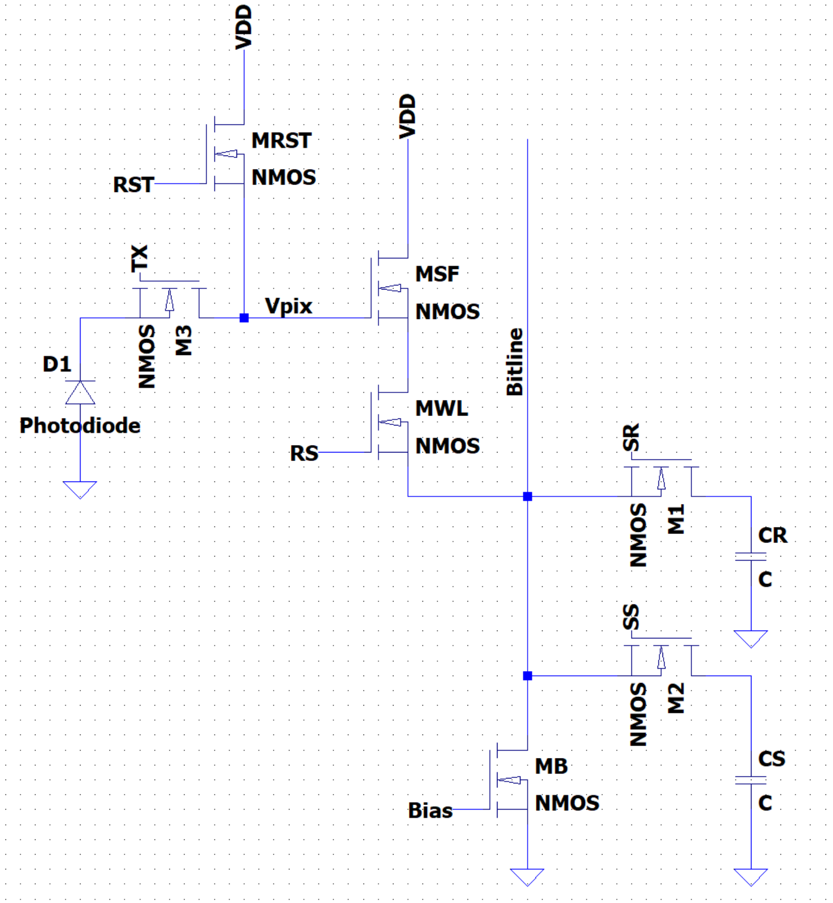
Correlated Double Sampling

- Multiple sampling technique by sampling the output twice, once during the reset stage, once after the signal is read, then take the difference of the two
- How reference is made: When light is hitting the photodiode, TX is off. While this is happening, turn RST on to keep the Vpix node at VDD. Use this VDD as our sample reference using another NMOS and capacitor on the bitline to hold this value. Do the same for our sampling signal. Then we calculate the difference between the two signals to determine the imperfections/noise through the source follower and read out path



Correlated Double Sampling

- Used to reduce FPN, flicker, and shot noise
- Reduces offset, does not reduce gain
- Dark current needs to be considered
- Digitized correlated double sampling



Digital Pixel Sensor

- DPS are a newer kind of pixel sensor that implements an ADC within each pixel as opposed to one ADC at the end of the column
- Can be impractical since having an ADC within each pixel is bulky, but achieve higher speeds (each pixel has an individual ADC instead of one ADC per column) and less noise (instead of analog voltages travelling through the lines, it's now digital so no noise coupling through power lines or substrate)
- Shot and reset noise is still prevalent, but readout noise, column amplifier noise, and source follower noise is eliminated

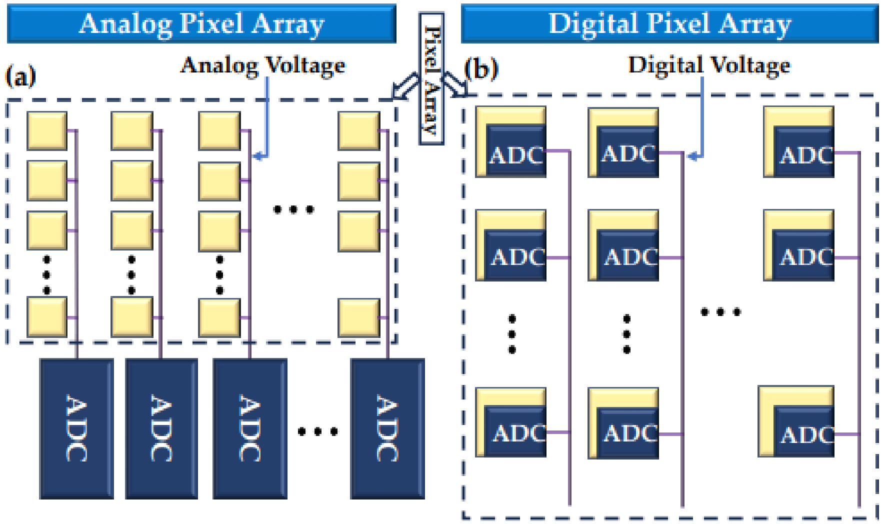


Image Quality

- Affected by temporal noise, such as quantization from ADC conversion, shot/photon noise due to random fluctuations in light, dark current noise from higher temperatures
- Spatial noise/fixed pattern noise: nonuniformities from variations in sensor design or EMI
- Dynamic Range: Range of the maximum and minimum detectable photon energy, affected by noise
- Signal-to-noise ratio affected by quantum efficiency, signal paths, total noise covered

Summary

- Photodiodes, Bayer Filter, Pixel Cross-Section
- CCDs vs CMOS: Types and Topologies
  - Architecture
  - Limitations
- Blooming, smearing, shutter speed
- Noise Considerations
  - Temporal Noise
  - Fixed Pattern Noise
  - Dark Current

References

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