Development of Complex Curricula for Molecular Bionics and Infobionics Programs within a consortial* framework**

Consortium leader

PETER PAZMANY CATHOLIC UNIVERSITY

Consortium members

SEMMELWEIS UNIVERSITY, DIALOG CAMPUS PUBLISHER

The Project has been realised with the support of the European Union and has been co-financed by the European Social Fund ***

**Molekuláris bionika és Infobionika Szakok tananyagának komplex fejlesztése konzorciumi keretben

***A projekt az Európai Unió támogatásával, az Európai Szociális Alap társfinanszírozásával valósul meg.

VLSI Design Methodologies

(VLSI tervezési módszerek)

Image sensors and their design

(Képszenzorok és tervezésük)

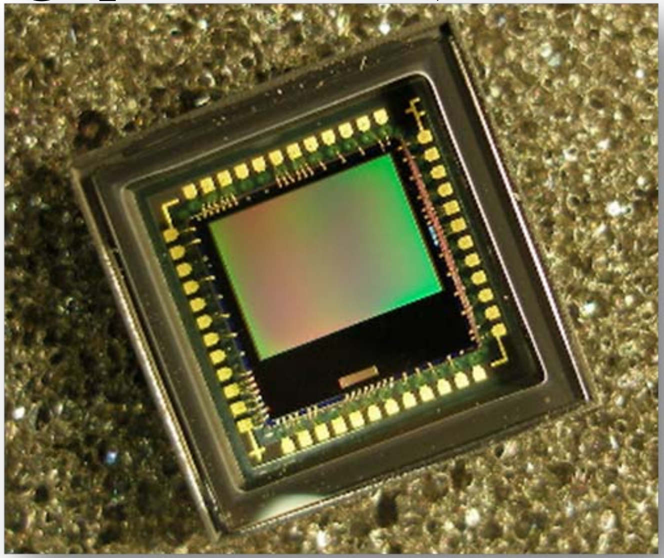
PÉTER FÖLDESY

TÁMOP – 4.1.2-08/2/A/KMR-2009-0006

The topics are covered in this chapter:

- Architecture
- Optical characteristics and materials
- Noise and the dynamic range issues
- CCD v. CMOS sensors
- Architectures
- Conclusions

- Architecture of photosensors
  - Optical focusing
  - Color filtering (usually IR and UV)
  - Photon to charge converter (e.g. photodiode)
  - Array addressing
  - Amplifier and correlated double sampling for noise reduction
  - Converter
  - Digital post processing



Section I

Optical characteristics and materials, physics of light sensing

Optical Characteristics

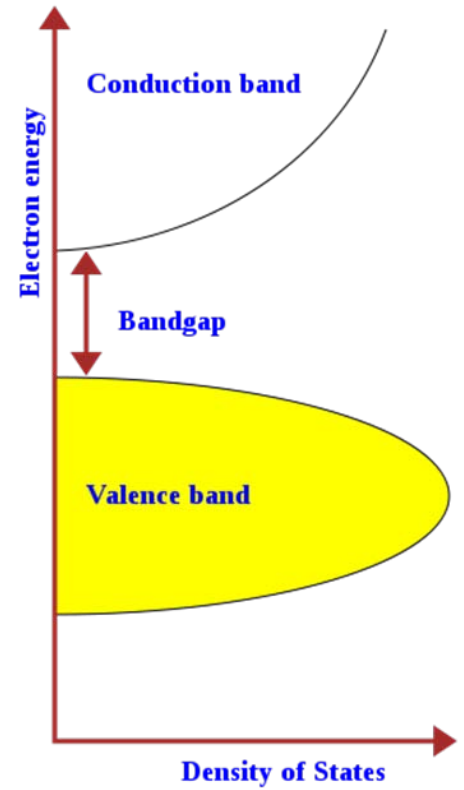
- Absorption of Photons
- Light Sensitivity
- Quantum Efficiency
- Fill Factor, Micro-Lenses
- Dynamic range
- Others
    - Smear, Blooming
    - Electronic Shuttering
    - Sampling, Aliasing, MTF

Absorption of Photons

- Convert optical energy into electrical energy
- Energy-band structure
  - Conduction and valence band
- Direct or indirect bandgap materials
  - Si – indirect
  - GaAs, GaAlAs, InP – direct
  - Nanoscale plasmon enhanced combinations
- The difference is whether phonon generation required in electron state transition or not

Absorption of Photons

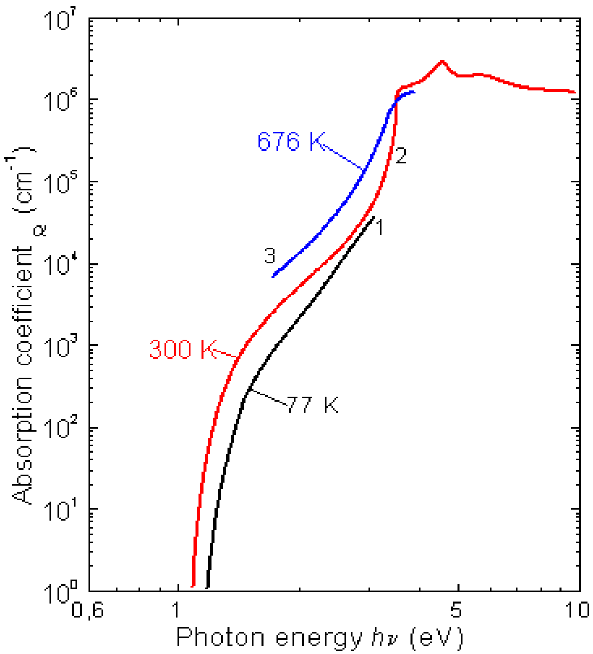
- In order for an electron to jump from a valence band to a conduction band, it requires specific minimum amount of energy.
- The required energy alters with different materials.
- Electrons can gain energy to flip to the conduction band by absorbing either a phonon (heat) or a photon (light).



http://en.wikipedia.org/wiki/File:Bandgap_in_semiconductor.svg

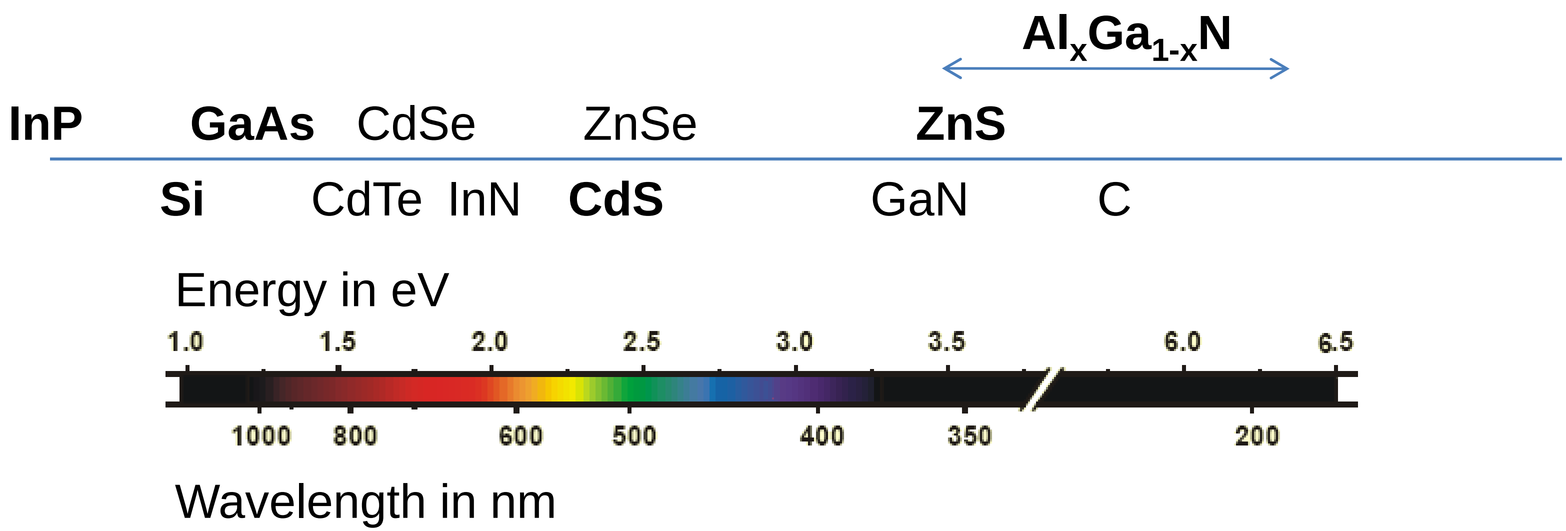
Absorption of Photons

- Energy of the photon ($E = hc/\lambda$) > Eg, electron-hole pair may be generated
- Visible range: 1.7-3.1 eV
- Penetration depth
  ~ exp(-α*depth)
- Note the strong temperature dependence



Silicon absorption curve
http://www.ioffe.rssi.ru/SVA/NSM/Semicond/Si/Figs/145.gif

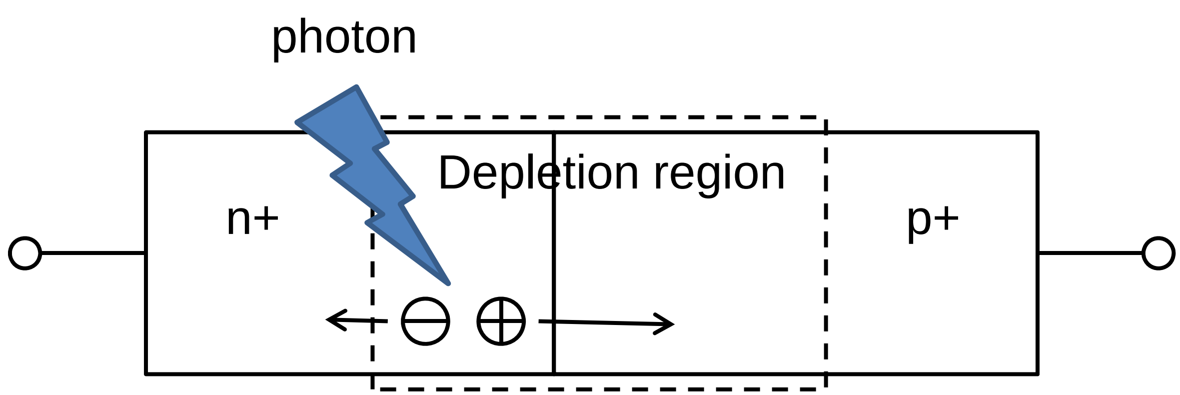
- *Band gaps* of different materials



Separation of electron hole pairs

- Electron-hole pair generation by photons
  - But, electron-hole pair recombination always work
- With a large electric field we can separate the pairs, making the detection.
  - The most simplest form is the photodiode.
- More advanced and better is to collect electrons in potential traps
  - This way works the so called pin photodiodes
  - The CCD image sensors.

- Depletion region with large electric field
  - Quick drift, no recombination.
- Quasineutral region, with no electric field
  - Loss, but drift length is um range, may be detected in a nearby depletion region
- Higher doping level -> smaller drift length



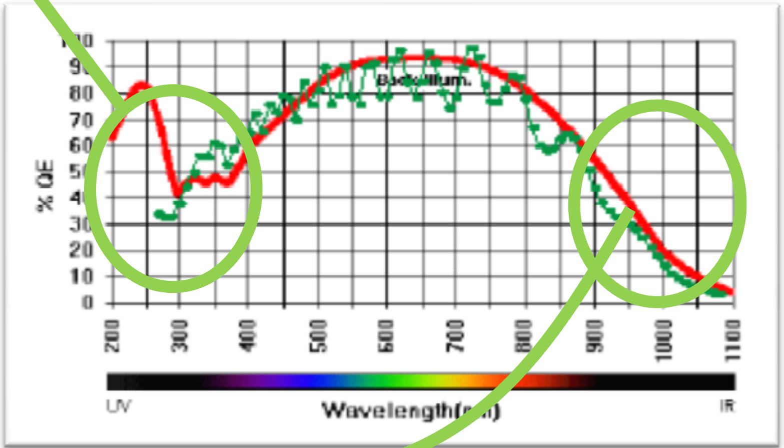
Section II

Light sensing efficiency, measures, and ways to increase

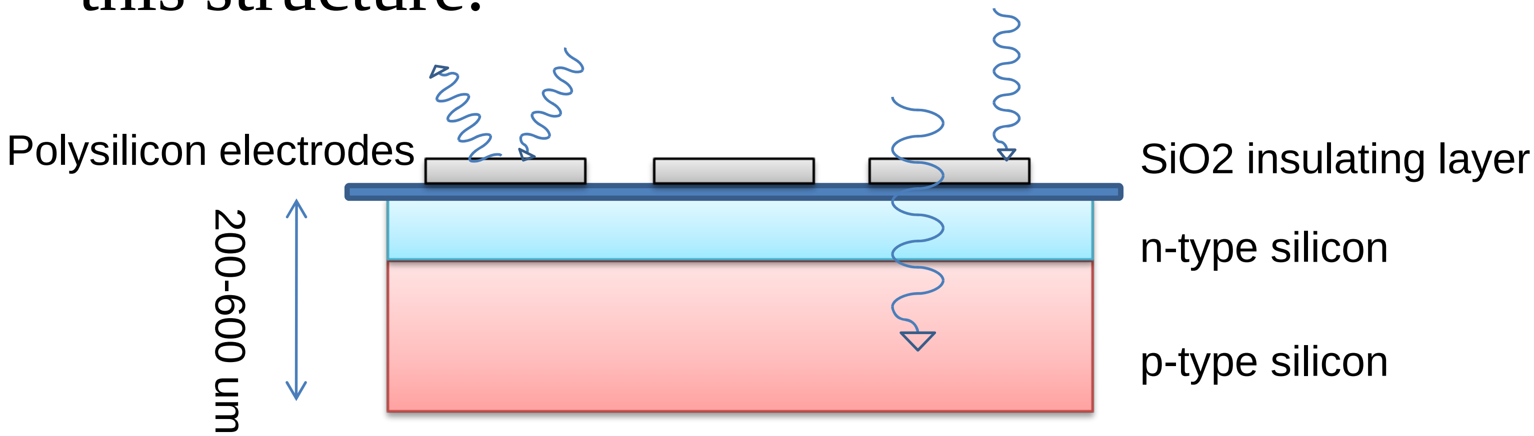
Efficiency measures

- The efficiency can be measured in different ways, depending on what kind of loss we are expressing.
- *Optical efficiency*
  - Defined as *1-R*, where *R* is the reflectivity of the system
- *Quantum efficiency*
  - Describes the efficiency of the photon absorption that becomes useful signal.
  - External: number of the detected electron-hole pairs divided by the incident photons
  - Internal: same as external, but counts the penetrated photons only

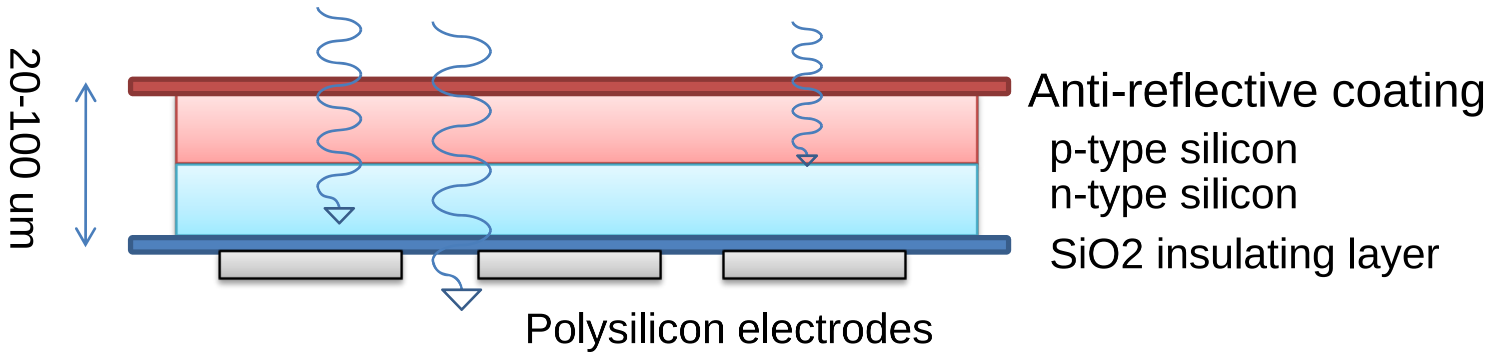
- Efficiency depending on the wavelength.
- High energy photons
  - Swallow penetration depth
  - Highly doped N+ (not depletion region) low drift length, no detection
- Low energy photons
  - Deeper penetration depth
  - Out of the depletion region, drift long, but diffuse
  - Finally does not detected



- Solution for increasing sensitivity of detection of the lower energy photons: *Front side illumination* (poor blue response). Most of the cameras follow this structure.

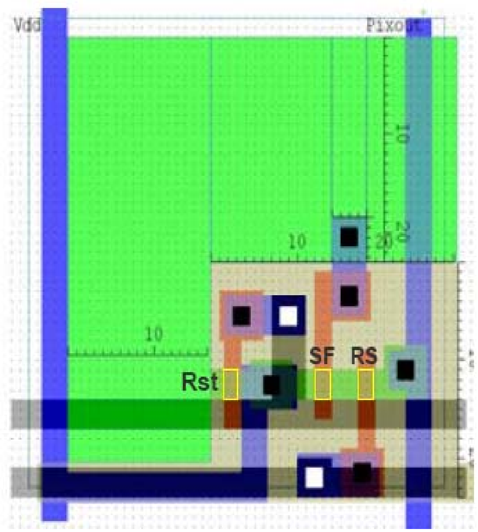


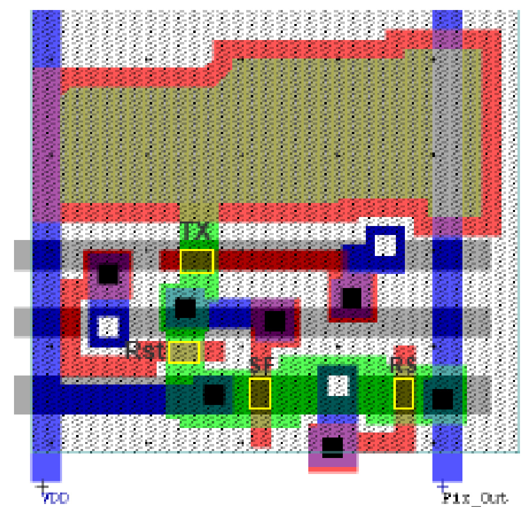
- Solution for increasing sensitivity of detection of the higher energy photons: *Back illumination* (poor red response, astronomical CCDs)



- Internal quantum efficiency
  - *Fill factor*. The photosensitive area divided by the pitch of the sensor array. Note that below the larger portions are the sensitive area, the rest is the readout electronics.

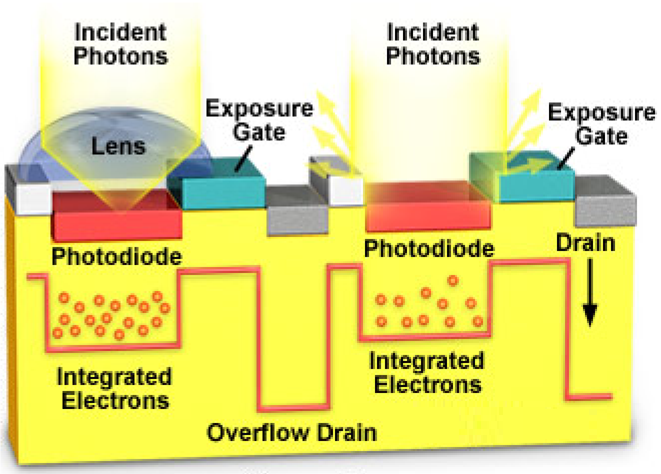
Photodiode

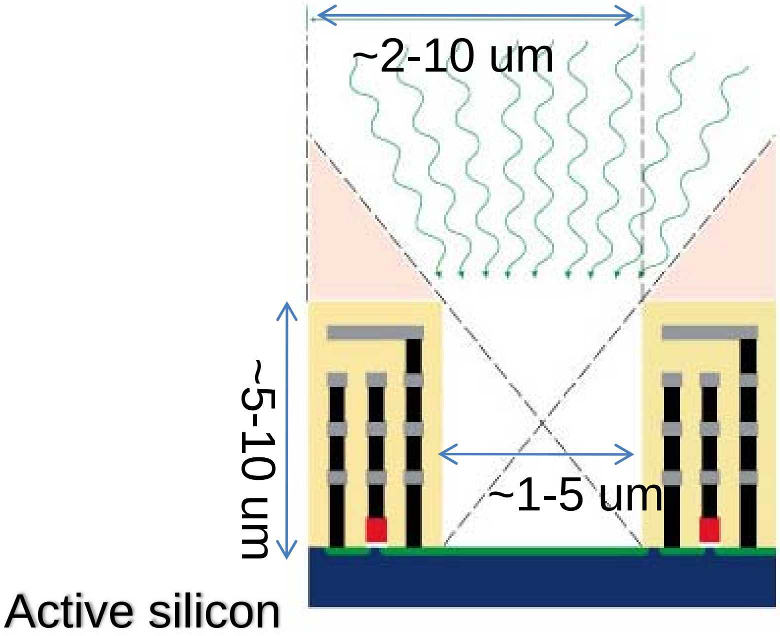




Photogate

- Fill factor can be increased by microlenses (or lenslet). The blooming is also reduced
  - Nowadays a standard method in cameras
- The walls of metalization also degrade quality and view angle

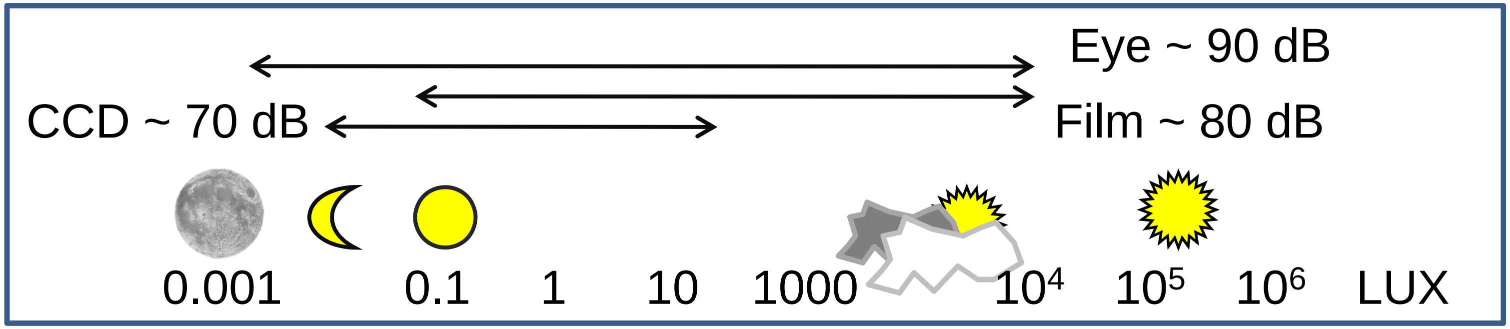




- Color detection
  - Filter Wheel
  - Prism
  - Color Filters
    - Mosaic (e.g Bayer) and in stripe configuration
    - in primary (RGB) and in complementary colors (CMY)
    - matrixing and color de-mosaicing (aliasing: nearest neighbor, linear, cubic, and cubic spline)
  - Different wavelength propagates different depth (see Foveon technologies)

Dynamic range

- Classic integration type diode sensor: restricted by the full well capacity (max electrons in the charge collection area)
- Noise floor (measured in electrons)
- Voltage range allowed on the capacitor (diode)



- Dynamic range:
  - Eye 90 dB, film 80 dB, CMOS/CCD 65-75 dB
- Methods to increase:
  - Companding sensors, such as logarithmic compressed-response photodetectors;
  - Multi-mode sensors, where operation modes are changed;
  - Frequency-based sensors, where the sensor output is converted to pulse frequency;

- Methods to increase:
  - Sensors with external control over integration time
  - global control (where the integration time of the whole sensor can be controlled)
  - local control (where different areas within the sensor can have different exposure times);
  - Sensors with autonomous control over integration time

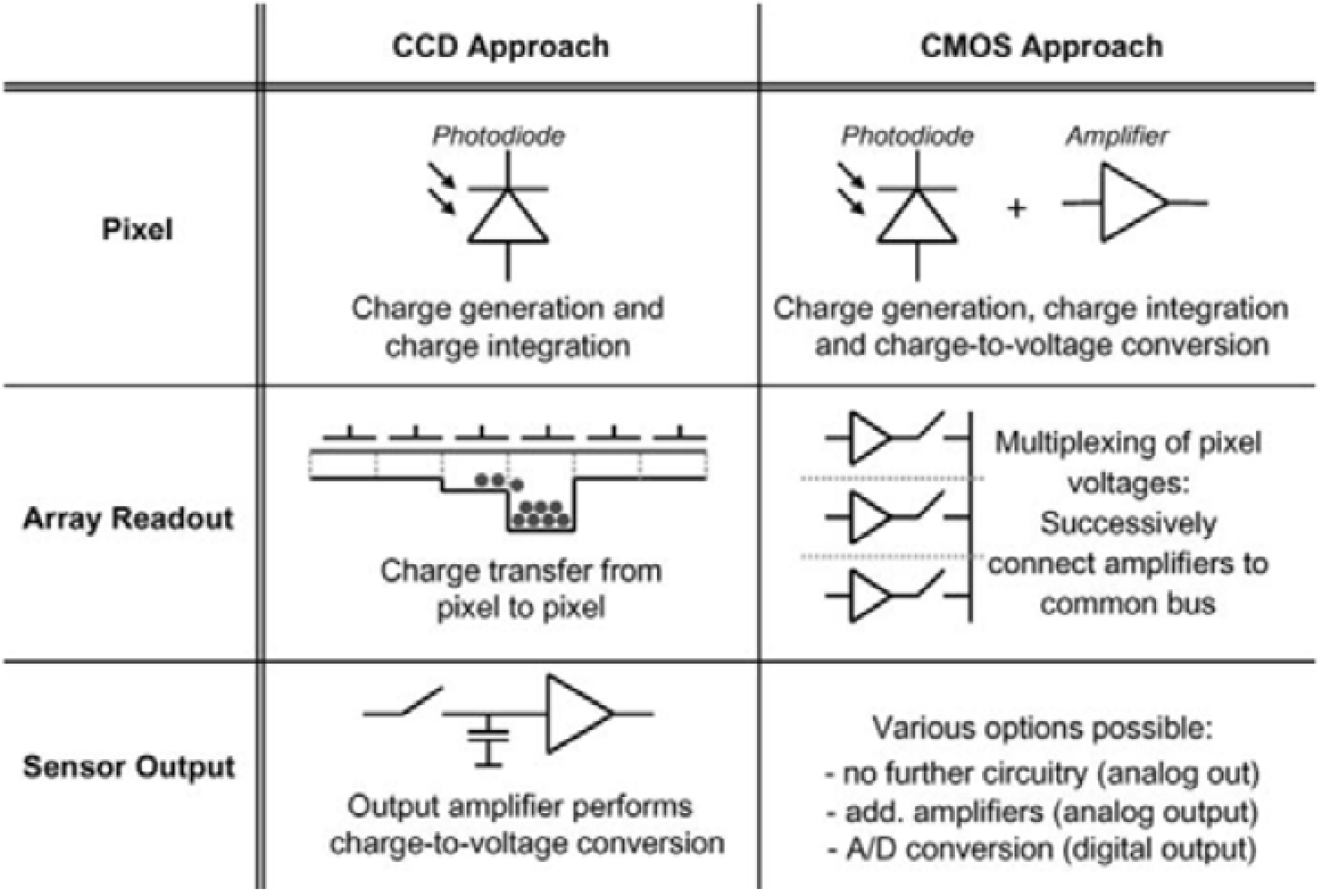
- Noise and The Dynamic Range
  - Reset of Noise
    - Incomplete reset the integration level (blur from previous value)
    - Thermal noise, the moment of switch off the reset switch
  - Shot Noise
    - Statistical fluctuations in the amount of illumination
    - The smaller the sensor, larger the noise
      (10 Mpixel = 2-3 um sensor ~ 10,000 e- capacity)

- Noise and The Dynamic Range
  - 1/f of the electronics
  - Quantization of Noise
    - ADC resolution, 10-12 bit
  - Fixed Pattern Noise
    - Solution: correlated double sampling (CDS)
  - Dark current; readout noise
    - CCD – 1-10 e- (even electron per hour level!)
    - CMOS – 1-15 fAmp; 20-200 e-

Section III

CMOS versus CCD technologies

CCD versus CMOS sensors



CCD versus CMOS sensors

CCD

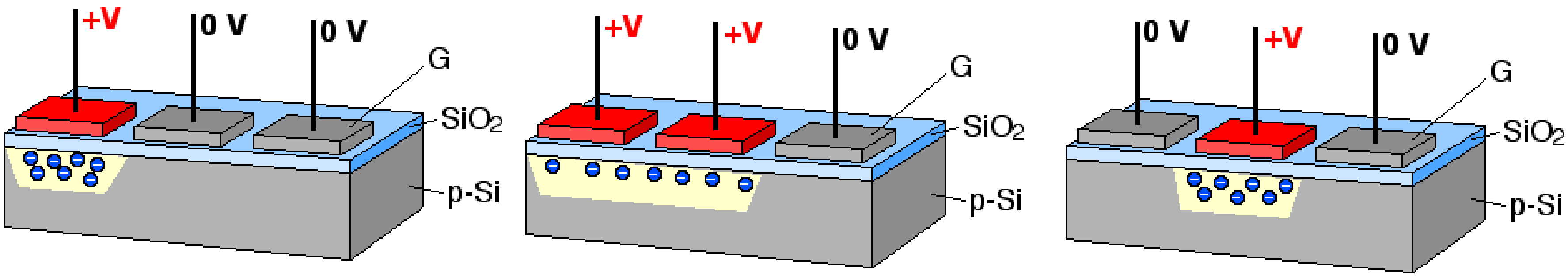
- Expensive in small number (mass product)
- Sensitive, has low noise, hence better dynamic range
- Serial readout
- Special sensors for moving scenes and extremely low light conditions

CCD versus CMOS sensors

CMOS

- Cheap – mass production for cameras, cell phones, web cameras
- Noisy, as the photons are converted to potential and handled as voltage.
- Random access available.
- Integrated camera components (e.g. camera on chip with MPEG coding)

- Architecture and variants for CCD
  - Charge coupled devices. Based on change transfer mechanism (shift register) driven by three phase potential change and separated wells for electrons.



History: first as shift register has been used, but after they identified its light sensitivity, Sony started mass production of CCDs with light sensitivity for camcorders.

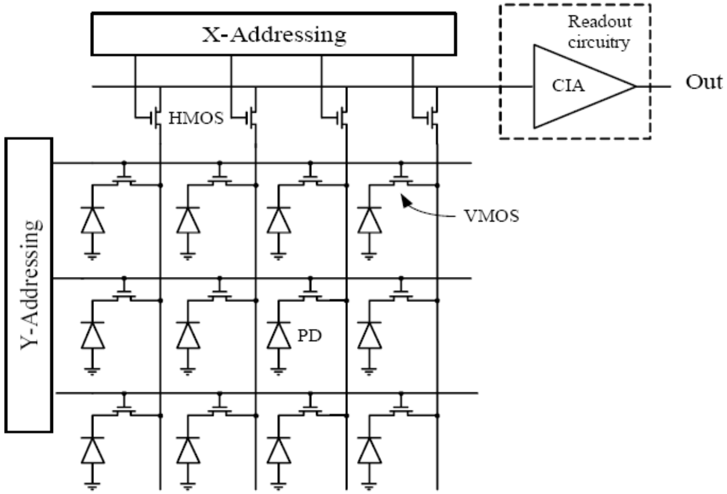
- Architecture and variants for CCD
  - In electron-multiplying CCD (L3Vision CCD) a gain register is placed at the output.
    - The gain register is split up into a number of stages. In a stage the electrons are multiplied by impact ionization (gain > 500). Used in astronomy, its noise is as low as of 0.01 to 1 e-.
  - Time-delay-and-integration CCD (TDI-CCD) for fast objects. The image is transferred and captured again.

- CMOS architectures for pixels and converters
  - *Passive pixel sensor*
  - *Active pixel sensor*
    - Photodiodes
    - Photogates
    - Pinned photodiode
  - Specials
    - Phototransistor
    - Logarithmic
    - Snapshot
  - ADC position relative to the pixel array

Section IV

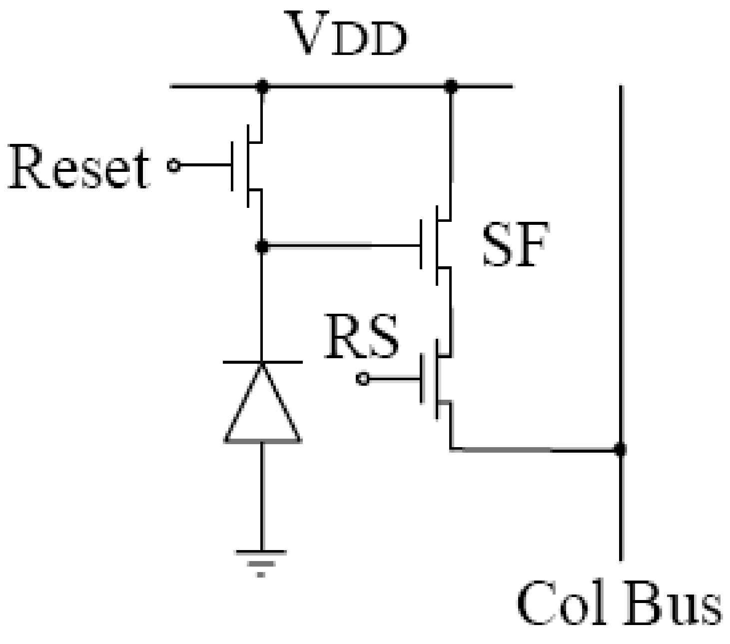
CMOS sensor architectures

- Passive pixel architecture
  - The PPS consists of a photodiode and just one transistor
  - The passive pixel structure has major problems due to its large capacitive loads
  - Readout noise large (250 e-)
  - Fill factor near 100%

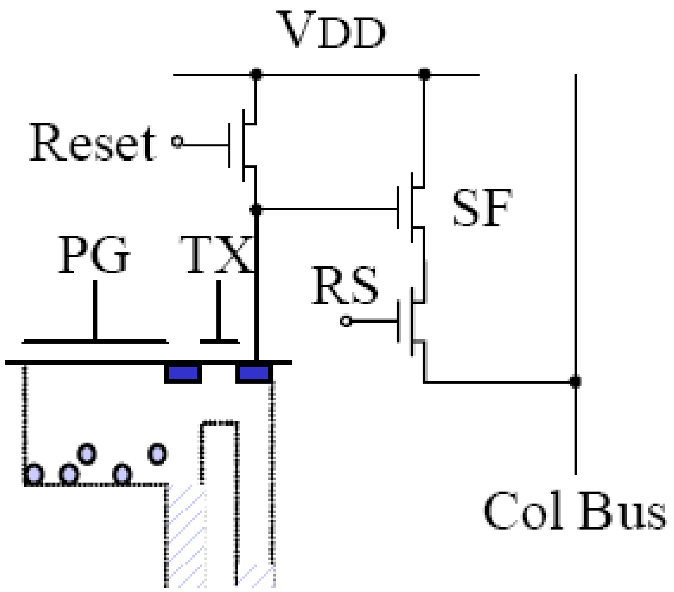


- Active pixel architecture
  - Fill factor 50-70%
  - Lower readout noise (20-100 e-)
  - Faster than PPS and well scalable
  - Types:
    - Photodiodes, Photogates, Pinned
  - Correlated double sampling (CDS) can suppress reset noise, 1/f noise and FPN due to threshold voltage and lithographic variations in the array.

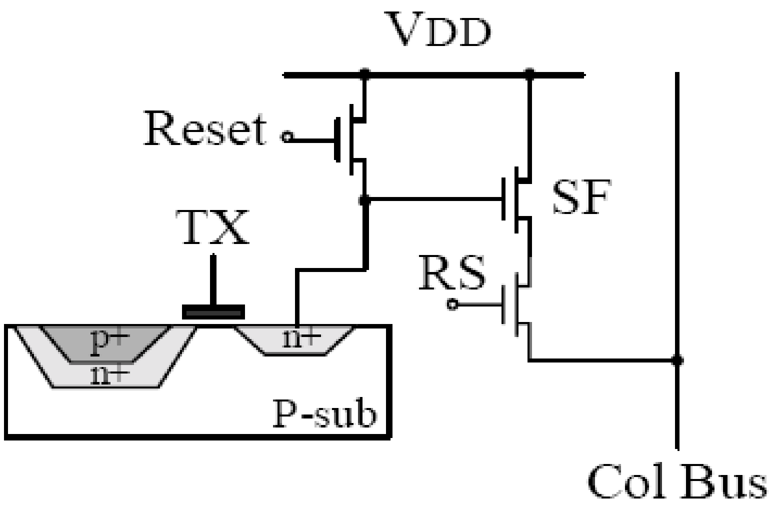
- Photodiodes
  - photodiode and a readout circuit of three transistors: a photodiode reset transistor (Reset), a row select transistor (RS) and a source-follower transistor (SF).
  - Its structure is the most frequent



- Photogate
  - basic concept for the photogate pixel arose from CCD technology
  - photon-generated charge is integrated under a photogate with a high potential well
  - Reduced fill factor, QE
  - Bad blue response



- Pinned photodiodes
  - Similar to photogate, but p+ generates the depletion region
  - Pinned diode (p+-n-p)
  - Small photon collection area (less e-)
  - Many sensor uses it
  - Very tricky layout



- Electronic shutter
  - Non rolling mode, but synchronous operation
  - The pixel includes a sample-and-hold (S/H) switch with analog storage
- Special sensors
  - Logarithmic, Lateral Bipolar Phototransistor
    - Enables logarithmic encoding (LOG) of the photocurrent, thus increasing the dynamic range
    - Significant temperature dependence of the output, low swing of the output, current gain non-uniformity

ADC position

- Off chip:
  - typically CCD
- On chip
  - One fast ADC
    - Typical CMOS sensors (10-50 fps)
  - One per column
    - Fast cameras (up to 1000 fps)
  - One per pixel
    - Pixim HDR sensor (not speed but multisnapshot solution)

Example of a real camera chip:

- Sony ICX285AL Exview HAD
- CCD, Pixel size: 6.45uM x 6.45uM
- Image area: 8.98mm (Horizontal) x 6.7mm (Vertical)
- Spectral Response: QE max at 540nm (~65%), 50% roll-off at 400nm and 750nm.
- Readout Noise: Less than 12 e- RMS.
- Full-well capacity: Greater than 27,000 e-
- Less than 0.02 electrons/second @ + 10C ambient!
- Data format: 16 bits
- Critics: 27,000 e- / 12 e- => 2250 levels clear (11-12 bit usefull)

Conclusions

- There are many pure and compound semiconductors that can react to visible or near visible photons
- The usual digital/analog technologies are not suited for good sensor design
- The sensor's integrated environment in CMOS technology offers a lot advantages over CCD solution

Recommended literature

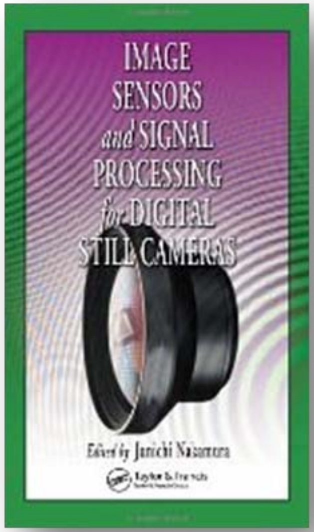


Image Sensors and Signal Processing for Digital Still Cameras
Junichi Nakamura
Publisher: CRC Press (August 5, 2005)

Comprehension questions:

I. What is the physical phenomenon in semiconductors that enables light detection?

II. What is difference between CCD and CMOS sensors?

III. List some detector architectures.