Catching Photons

LICN Lecture
October 1, 2014

Dmitriy Yavid, Broad Shoulder Consulting LLC

Introduction

- Photo detectors have become ubiquitous, amazingly good and dirt cheap
- Still, there is an ever-increasing demand from all corners of science and industry
  - Expanded range of wavelengths
  - Wider bandwidth
  - Higher sensitivity
  - Lower noise
- Both new materials and innovative designs are being developed

Summary

- This is just an overview: detailed analysis and comparison of different technologies are beyond the scope of this presentation
- Specifically, we'll talk about photonic detectors, skipping over the subject of thermal radiation detectors
- Furthermore, the focus is on photo-detectors themselves, NOT the systems they are used in
- Both single-pixel and array (imaging detectors) are covered

History

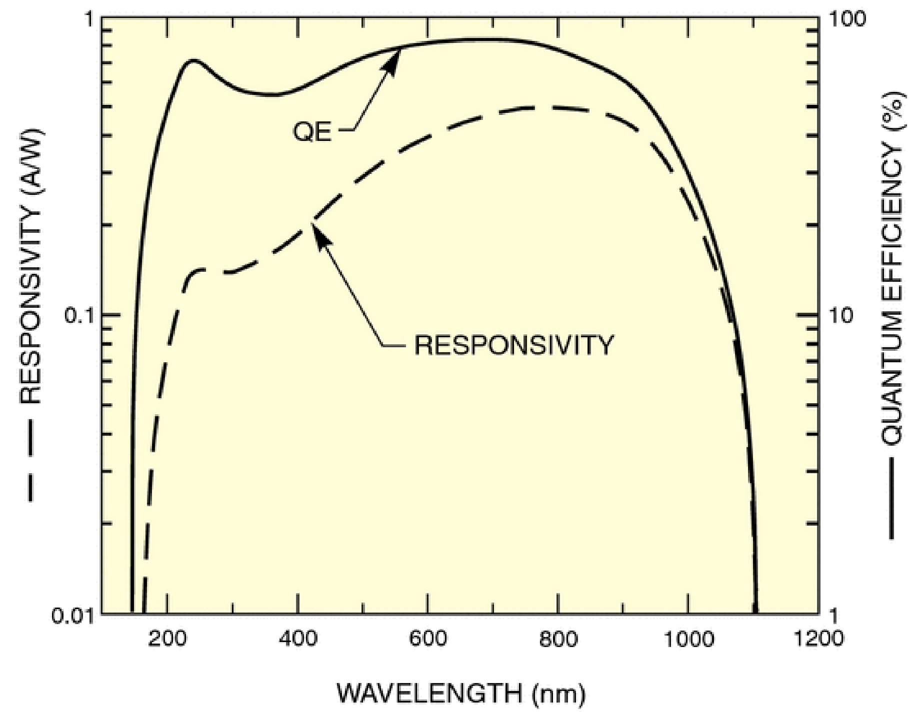
- Curiously, it started with IR detectors at the beginning of 19th century. Back then, human eye was a perfectly fine detector for visible light
- By the end of 19th Century, pretty good thermopile and bolometric detectors were developed
- Roughly at the same time, the effect of light on electrical properties of materials was discovered: a selenium photo-resistor was invented in 1873
- Throughout the first half of the 20th Century, better and better photo-conductive materials were developed, and found limited applications, such as ambient light detectors.
- But the true revolution was brought in by the introduction of the semiconductor photo-diode in the 1940-s.

What is the ideal photo-detector?

- Catch every incident photon
- Of every wavelength
- Infinitely fast
- While producing no noise

Quantum Efficiency

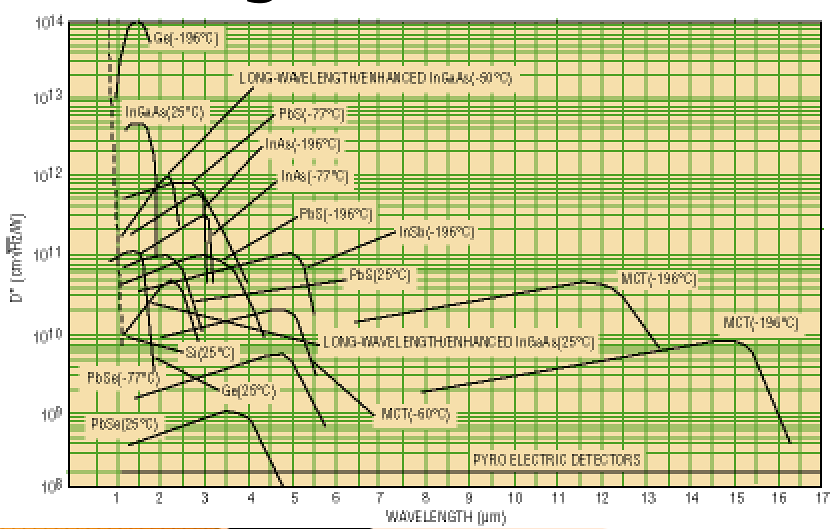
- Photo-detectors are usually characterized by ***responsivity***, i.e. the current produced per unit of incident power.
  - Expressed in A/W
  - Wavelength dependent: different photons carry different power

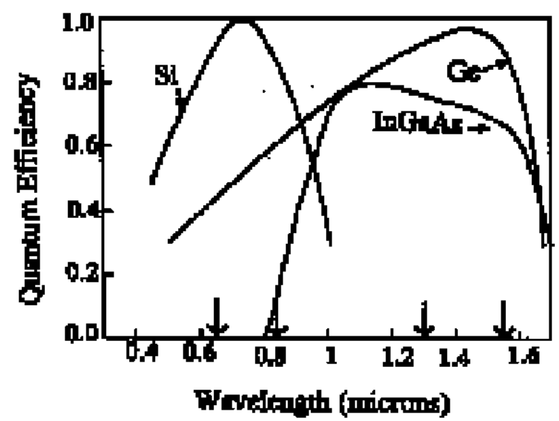


- ***Quantum Efficiency***. i.e. the number of electrons per incident photons is a more "physical" parameter.

Wavelength sensitivity

- Whether expressed as responsivity or QE, the sensitivity of a photo-detector is wavelength dependent
  - Defined by material properties
- Plenty of good materials for visible and NIR light
- Going to longer and shorter wavelengths poses serious challenges



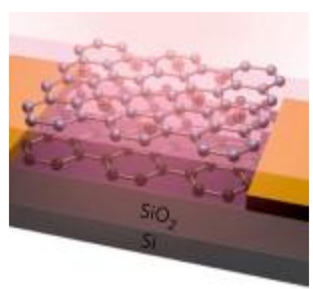


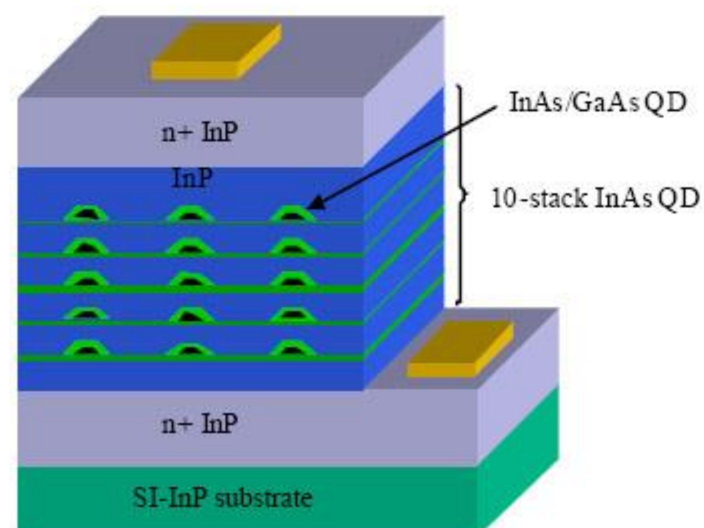
IR Photo-Detectors

- Silicon only detects light up to ~1100 nm
- GaAs can go up to ~1800 nm
  - Much higher dark current
  - Expensive
  - Still, used in great variety of single-pixel and even imaging detectors
- More exotic materials with longer wave response:
  - PbS extends to ~2.4 um
  - PbTe, InSb – up to ~5.5 um
  - HgCdTe – up to ~8 um
- Longer wavelength = lower energy
  - Huge dark currents at normal temperature
  - Need to be cooled

Engineered Photonic Materials

- People are starting to look beyond what Mother Nature gave them for photo-detection
- Quantum Dot (QD) detectors
  - Can be engineered for a given wavelength
  - Promising IR detectors
- Graphene detectors
  - Ultra-wide spectral band
  - High QE, low noise at room temperature



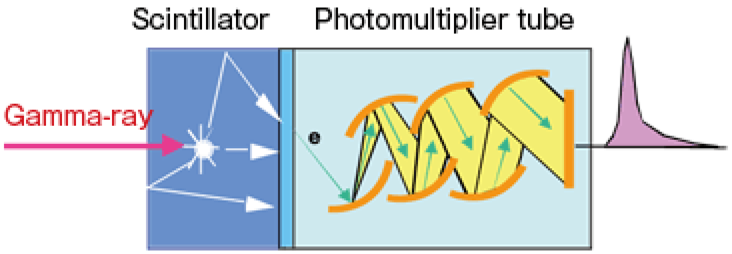


UV Photo-Detectors

- Silicon is widely used down to ~300 nm
- GaP detectors available down to ~150 nm
- A wide range of fluorescent materials are available with absorption down to very short wavelength and emission in visible band
- The problem of UV detection is inherently simpler than IR:
  - lots of ways to rob a high-energy UV photon of excess power
  - Energy cannot be added to a weak IR photon.

Scintillators – going beyond UV

- For X-rays, gamma-rays, and high energy particles, scintillators are used:
  - Crystals, producing lower energy photons when hit by a high energy one or a particle
  - Those lower energy photons are detected by a PMT, or other detectors.
- The efficiency of this process is usually quite low, but is compensated by enormous energy of incident photons
  - Inorganic: CsI(Tl), CsI(Na)
  - Organic: anthracene, stilbene
- Enable PET scanners



Response time

- Two fundamental factors limiting the response time:
  - Internal delays: essentially, time needed for photons to be absorbed and time needed for electrons to reach the connecting electrodes
    - Depends on device size and design, as well as device material
  - Output capacitance:
    - Charge needs to build up to rise the voltage across the device
    - The electronic amplifier to which the detector is coupled plays a roll: low impedance desired

Detector Noise

- Inevitable
- A multitude of different mechanisms
  - Most, but not all, noise mechanisms tied to active area of the detector
  - Obviously, collected light is usually proportional to active area too
  - Hence, SNR is mostly area-independent
- Characterized by normalized detectivity:
  - Ad is detector area
  - NEP is Noise-Equivalent Power (area-dependent)

$$
\begin{aligned}
D^* &= D(A_D^{1/2}\,\Delta f^{1/2}) \\
&= D(A_D\,\Delta f)^{1/2} \\
&= \frac{(A_D\,\Delta f)^{1/2}}{NEP}
\end{aligned}
$$

Dark Current and Shot Noise

- A prevalent source of noise in photo-detectors
- The problem is not the dark current itself, but rather its random variations, known as ***shot noise***:

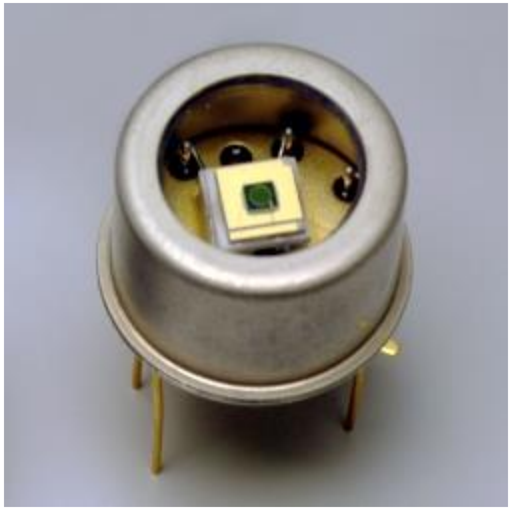
$$Is = SQRT(2*Id*q*B)$$

where: Id is dark current
q – electron charge
B – bandwidth

  - Originates in quantized nature of current, which arrives in single electrons
- Another way to interpret dark current: a number of spontaneously generated electrons per unit of time

Cooled Photo-Detectors

- Dark current is usually due to some electrons being able to free themselves **without** the added energy of a photon, by accumulating disproportionally large thermal energy
  - Probability depends on temperature exponentially
  - Hence, cooling can reduce dark current by orders of magnitude
- Thermo-electric cooling: tens of °C
  - Relatively compact and inexpensive
  - Two-stage up to 100 °C
- Cryogenic: liquid nitrogen or helium cooling



Another Face of Shot Noise

- Not only the current is quantized, light is quantized too
  - If a detector sees 10 photons per micro-second on average, it can be 9 during one and 11 during the other
  - Fundamentally, same as electronic shot noise
- Photonic shot noise is never stronger than the signal
  - In fact, it is proportional to a square root from the signal
  - Doesn’t affect detectability, but does affect the precision of light measurements

The role of the amplifier

- Trans-impedance amplifiers are most prevalent for photo-detectors
  - Provide low input impedance and hence prevent the detector's capacitance from slowing down the response
- Every amplifier has its own voltage noise
  - This voltage noise generates current flowing through the detector's capacitance
  - Indistinguishable from photo-current

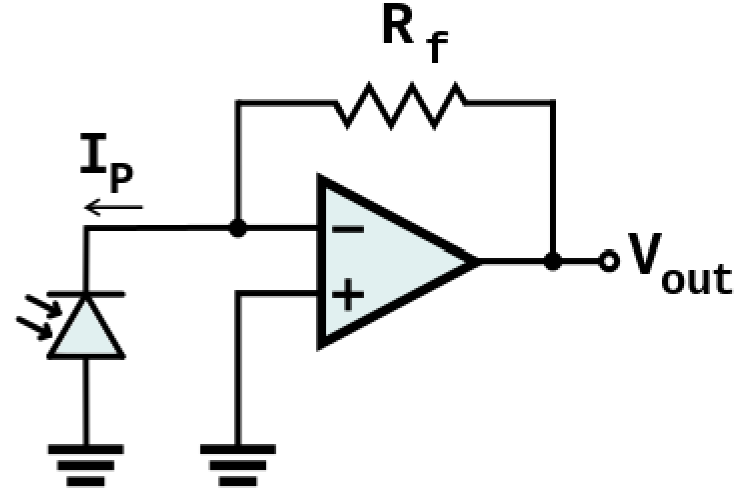
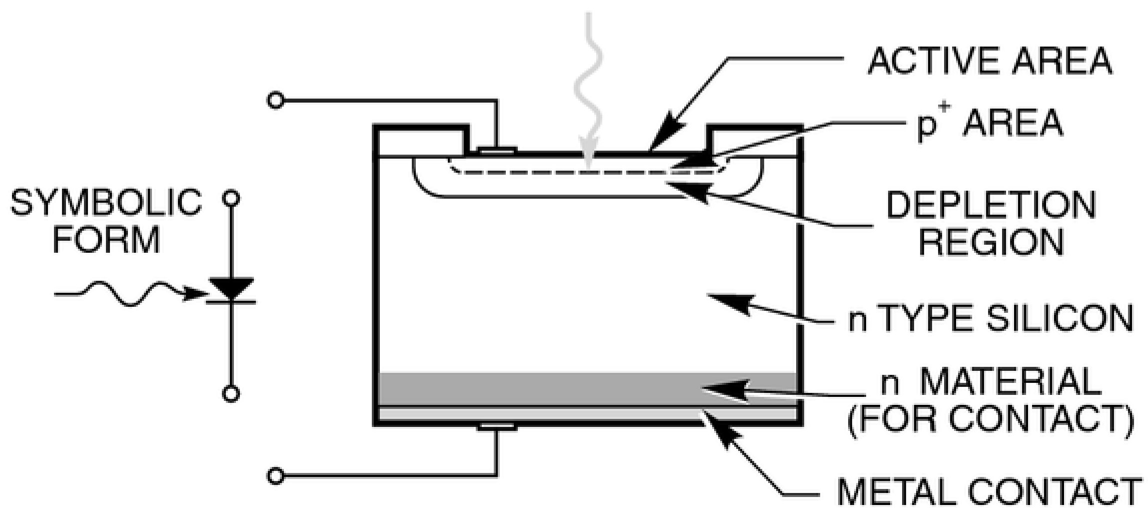


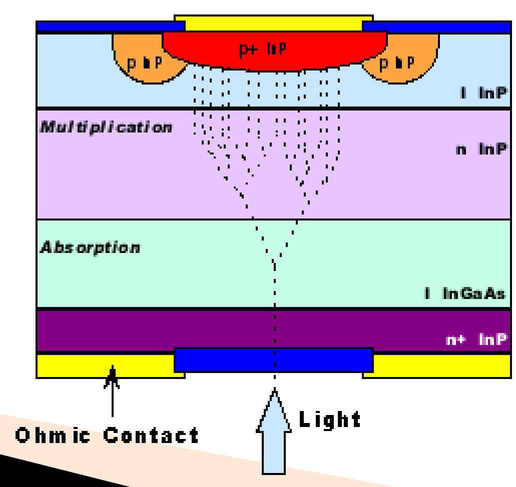
Photo-Diode

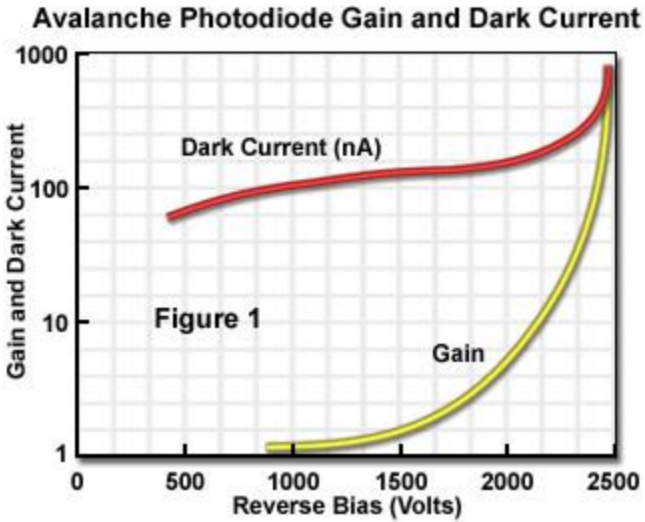
- The most wide-spread photo-detector
- Huge variety of types, sizes and materials
- Silicon is by far the most common material
  - Covers the entire visible band and then some
  - Peak sensitivity in NIR
  - Excellent QE: approach 100%
  - Capacitance in single pF/mm^2 range, dark current in nA/mm^2 range – **not the most sensitive detector**



Avalanche Photo Diode (APD)

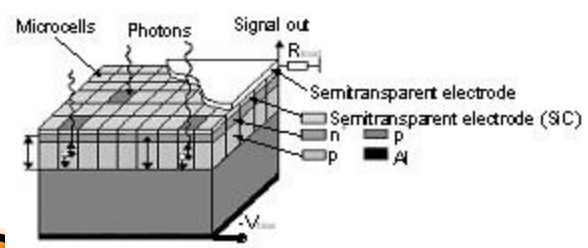
- Basically, a PD near reverse voltage breakdown point
  - Each photo-electron "multiplies", producing more electrons on impact
  - Gain typically in 10…100 range
  - Available in Si and GaAs, other materials problematic
  - Spectral response similar to PD of the same material
- Chiefly, addresses the amplifier-induced noise
  - More current out of roughly same capacitance
- Makes shot noise ***worse***:
  - Avelanche process introduces additional fluctuations

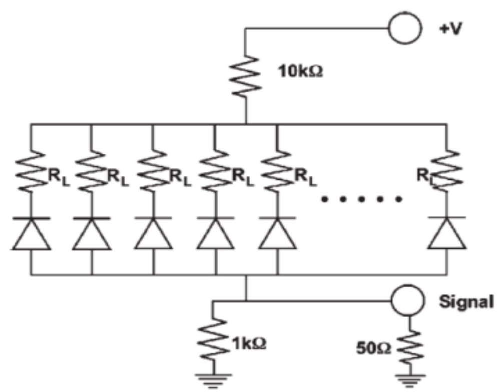




Silicon Photo-Multiplier (SiPM)

- The next step: beyond the breakdown point
  - Each photo-electron "multiplies" hugely
  - Device must be separated into tiny pixels: 10…50 um, each pixel having its own quenching resistor
  - Gain typically in $10^5 \ldots 10^6$ range – capable of single photon detection
  - Spectral response pushed toward UV, because material must be very thin
- Long cell recovery time, narrow bandwidth
- Non-linearity and yet additional shot noise due to finite number of pixels
- Lower QE, because of low fill factor
- Silicon only, other materials pose serious challenges





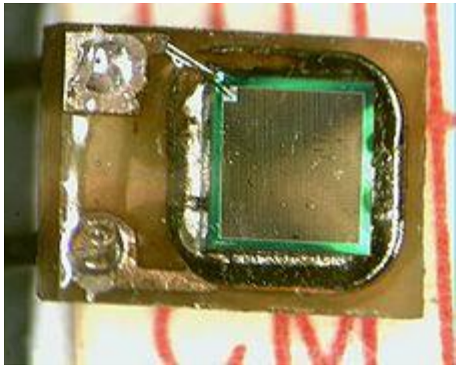
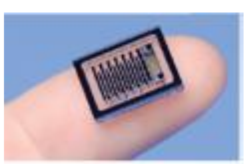
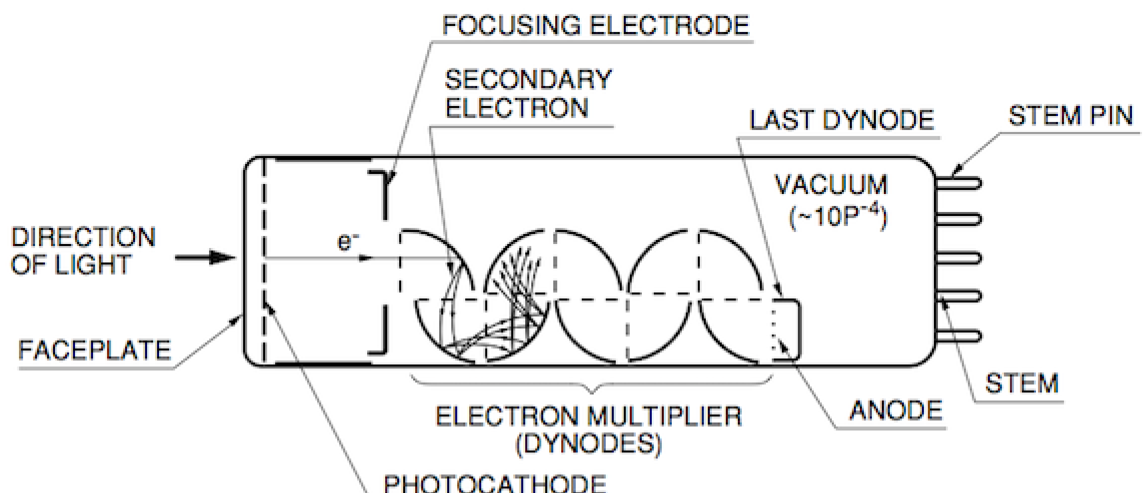


Photo-Multiplying Tube (PMT)

- A photo-emissive device: no semiconductors (almost)
- Electrons are freed from photo-cathode by incident photons, then multiply by hitting successive dynodes
- Gain up to 10^8, often no subsequent amplifier
- Low capacitance and dark current
- Limited to no sensitivity in NIR (except for InGaAs photocathodes, which are very tricky)
- Come in various sizes, but invariably expensive
- Can be damaged by excess light, sensitive to magnetic fields



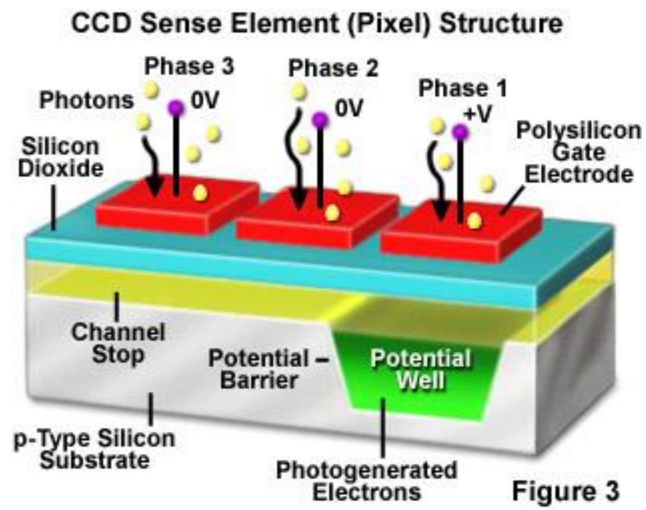


Imaging Photo Detectors

- Generally, any array of photo-detectors capable of sensing and recording spatial distribution of light can be called "imaging"
- Usually, placed near a focal plane of an imaging optical system – hence another common name: "Focal Plane Arrays"
- When the number of pixels surpasses several thousands, parallel reading becomes impractical
  - CCD and CMOS: two most prevalent types of serially-read imagers
- Same active area collects roughly the same number of photons as a single pixel detector
  - Trades time-domain resolution for spatial one

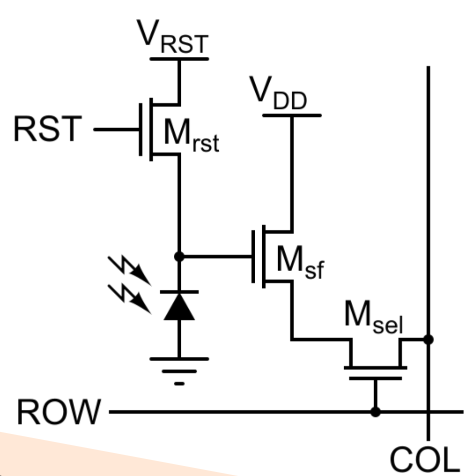
Charge-Coupled Device (CCD)

- Photo-electrons stay in potential wells
- Moved from well to well during read-out process, until reaching the amplifier and ADC
  - Moving is noiseless: electrons are neither added nor lost
  - Amplifier "sees" the capacitance of only one pixel – **big advantage in terms of noise**!
- During exposure, dark current is still present
- Limited well capacity, excess electrons spill over
  - Limited dynamic range



Complementary Metal-Oxide-Semiconductor (CMOS) detectors

- Essentially, an array of PDs, each with its own amplifier/buffer/storage
- Compatible with standard silicon process
- Main advantage over CCD: can be smaller, and hence cheaper
  - Also, don't have dynamic rage limitation
- Typically, more noisy



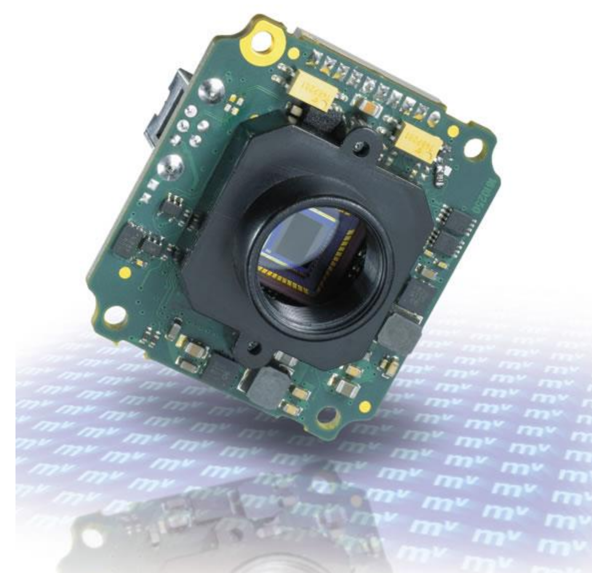
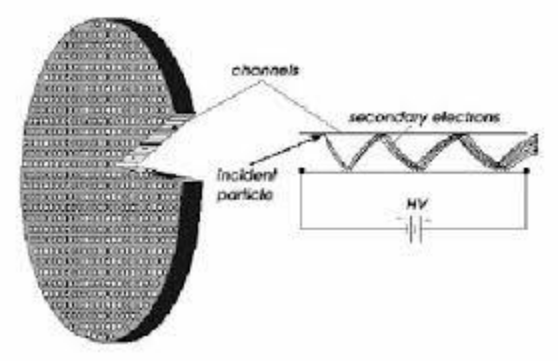
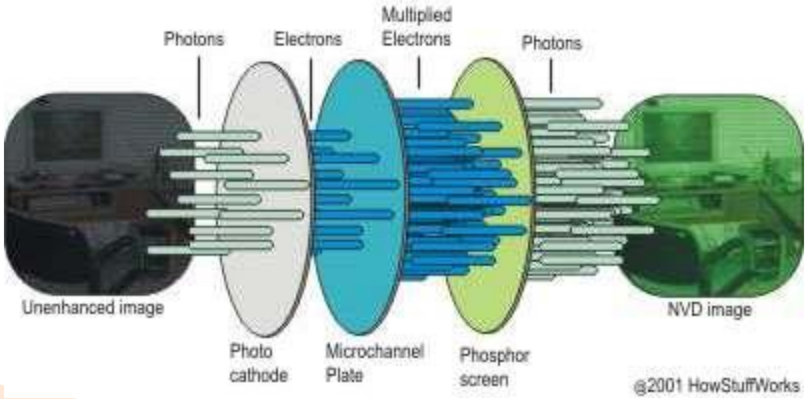


Image Intensifier

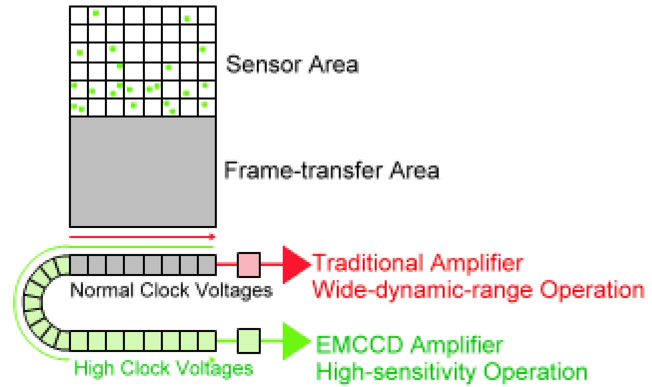
- A photo-emissive device, essentially, a pixelated version of PMT
- Electrons from photo-cathode are accelerated by high electric field, then hit a fluorescent screen, where they free a large number of visible photons
  - Those photons can be seen by naked eye, or by any type of imaging photo-detector
- For greater gain, a so-called Micro-Channel Plate is used, where electrons bounce multiple times between electrodes and multiply too
- Exposure can be very fast, timed by high-voltage on the Intensifier's electrodes





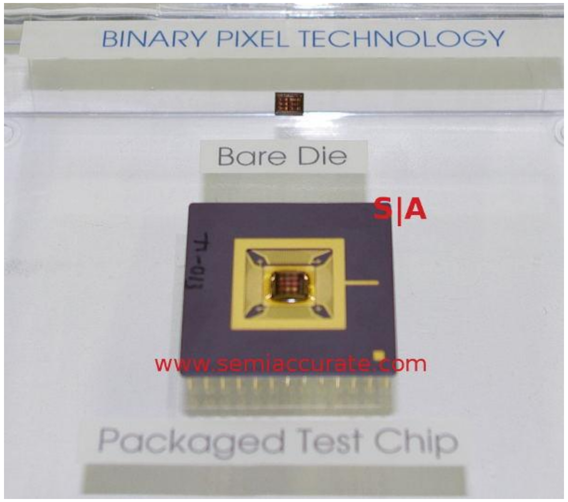
Electron-Multiplying CCD (EMCCD)

- During readout, photo-electrons are passing through a number of special wells, which are kept under voltage near breakdown point
  - Passing electrons multiply (slightly) in each cell, eventually increasing in numbers by a factor of 10…100
  - To some extent, can be viewed as a imaging version of APD
- Negates the readout noise
- Introduces little excess noise, but does nothing to alleviate the shot noise from pixel dark current



Binary Image Sensor

- There are fundamentally different devices hiding behind this name
- One is a combination of a conventional pixelated detector and a binary time-domain sampling mechanism
  - Presumably, better dynamic range and more exposure time flexibility
- Another is a very large array of very small pixels, each of which can either catch a photon, or not.
  - Pixel size way less than a wavelength
  - Emulates traditional film
  - Compatible with very dense silicon processes used in DRAM manufacturing



Conclusions

- The quest for better photo-detectors continue
- A wide variety of approaches are pursued
  - Material sciences
  - Device design and optimization
  - Miniaturization, cost reduction
- An equally wide variety of applications is waiting for better detectors
  - Large economic and social benefits

Thank you for attention!

Questions? Don’t hesitate to contact me.

Broad Shoulder Consulting LLC
Electronics, Mechanics, Optics, Software
www.broshoco.com

Dmitriy Yavid
Founder
(631) 706-4696 Work
dy@broshoco.com