TSBB21

Image Sensing - Part 1

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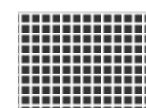
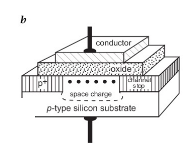
Image sensing

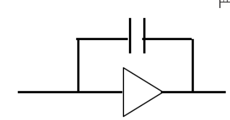
- In the previous lecture we saw how light reflected (or emitted) from objects in a 3D scene is projected onto the image plane of a camera
- In this lecture we will see how this image is sensed to produce a digital image
- Main method
  - The image is spatially sampled and truncated



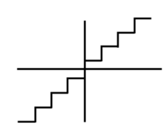
  - Photons are converted to electric charge/voltage



  - The charges are converted to voltage



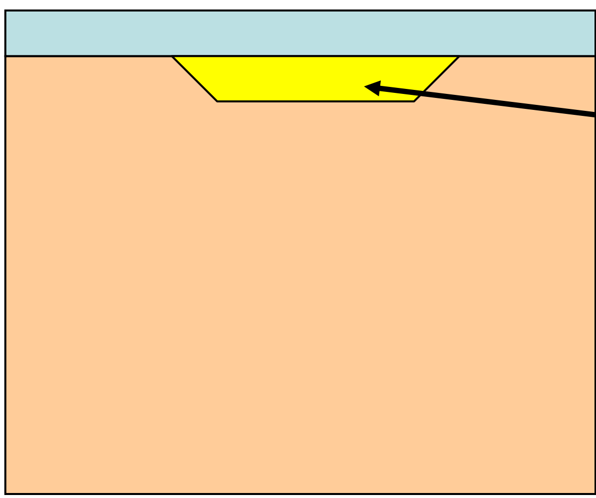
  - The voltage is quantized (A/D-converted)



Light interacts with matter

- The main or wanted interaction in a photo-detector is **absorption**
  - a photon is converted to an electron/hole pair
- Electrons bond to atoms with a certain energy Q_g
  - Photon absorption occurs with a certain probability when the photon energy $E = h\nu \geq Q_g$
- When a photon is absorbed: the electron is released from the atom and becomes "free"
- Leaves a "hole", a missing electron, in the atom. The hole is also "free" to move around
- This is called the "photovoltaic effect" or "photoelectric effect".

Basic layers of an image sensor



transparent coating and conductors, a few μm

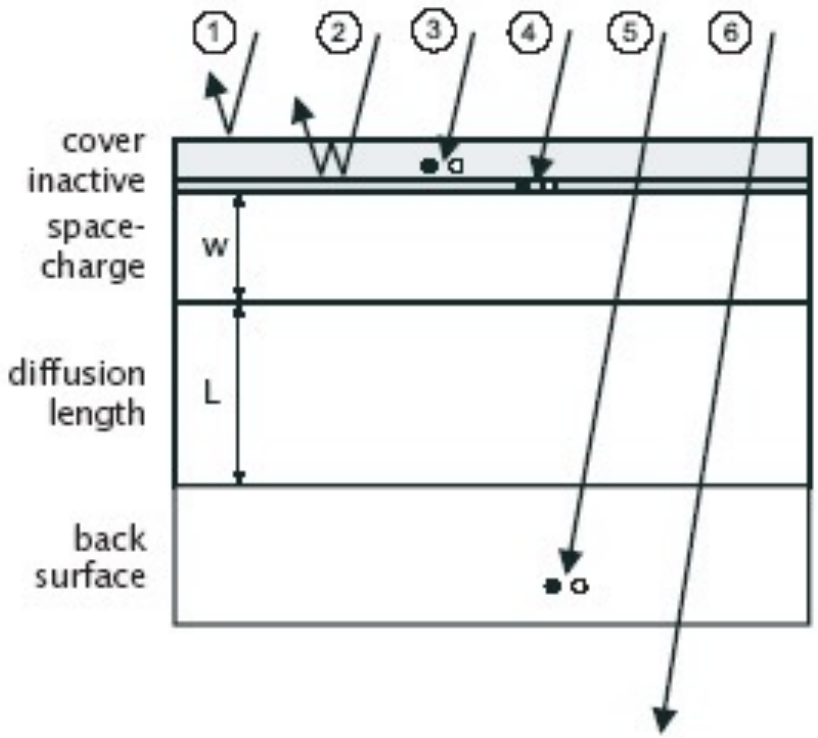
Space charge region, a few μm. Contains an electric field which effectively collects electrons.

Is localized: only deals with electrons in a specific area

Semiconductor bulk, this is where the photon-matter interaction is designed to happen. 2-100 μm

Losses

- When a photon enters the semiconductor material, it may not interact as intended



1+2: reflection before entering the active material

3+4: absorption before entering the active material

5: absorption too deep in the material

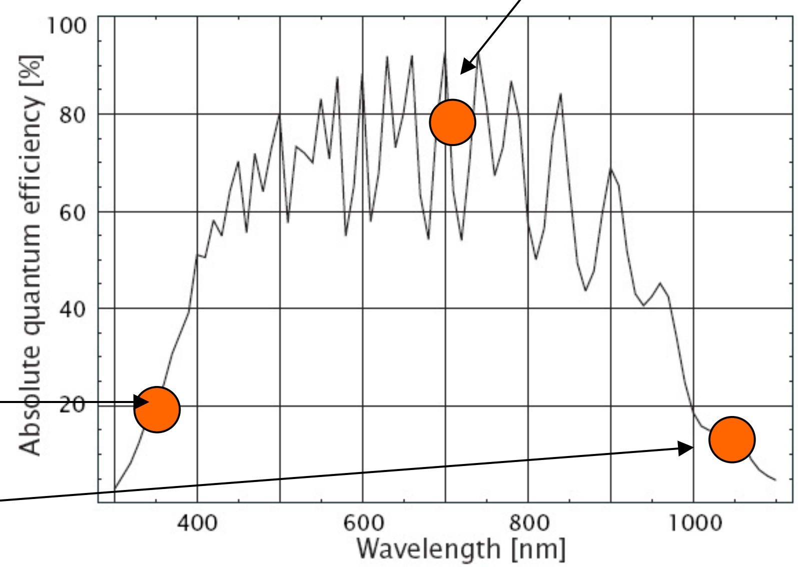
6: the photon doesn't interact with the material and exits at the back

Quantum efficiency

- All these effects are wavelength dependent!
- The <u>mean</u> number of electron/hole pairs created per photon is the *quantum efficiency*

Effect 2

Quantum efficiency for a particular photo device as a function of wavelength



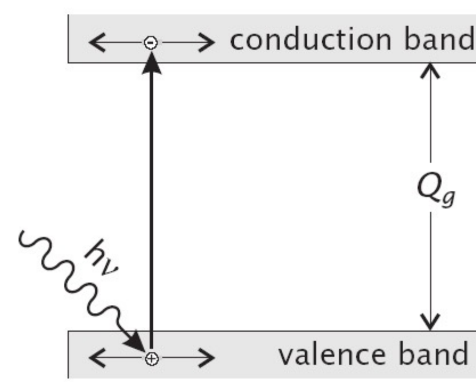
Typically: Effect 1+6 here

Typically: Effect 6 here

From light to electricity

- Pure semiconductors can produce an electric current I_{photo} through the material if
  - It is embedded in an electric field $\mathcal{E}$
  - The material absorbs a photon with an energy $E=h\nu$ which is larger than Q_g, the gap between the material's valence and conduction bands

Requires $$\boxed{\lambda < \frac{h\,c}{Q_g}}$$



intrinsic (pure)

Intrinsic absorption

- This is called *intrinsic absorption*
  - *No doping of the semiconductor is needed*
- Can be made in large arrays
- Can be silicon based
- Have high quantum efficiency
- Basic effect in CCD-arrays
- Different types of materials can be used for $\lambda < 1.5\ \mu m$ (shorter than IR) which are sensitive to
  - Near IR
  - Visible light
  - UV
  - X-ray

Photovoltaic detectors

- Absorption of photons can also generate *photovoltaic current* from the light energy
  - Photo-induced electrons can be made to generate a current by combining n- and p-doped materials into a *photodiode.*
  - Solar cells
    - Photovoltaic or zero-bias mode
  - Image sensors in the range near IR – UV
    - Photo-conductive or reverse-biased mode

Thermal excitation

- Because of heat in the material:
  - Electrons are always excited (moved from the valence band to the conduction band) due to thermal energy in the material
- This induces an electric current I_{thermo}

$$I_{thermo} \propto \mathcal{E} e^{-\frac{Q_g}{kT}}$$

T: absolute temperature
k: Boltzmanns constant

Thermal noise

- I_{thermo} is not a constant current, it is rather a noisy signal with a mean given by the last expression.
- We have to treat it as a random signal added onto the wanted signal I_{photo}
- We will return to the noise issue later

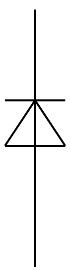
Two main types of photo detectors

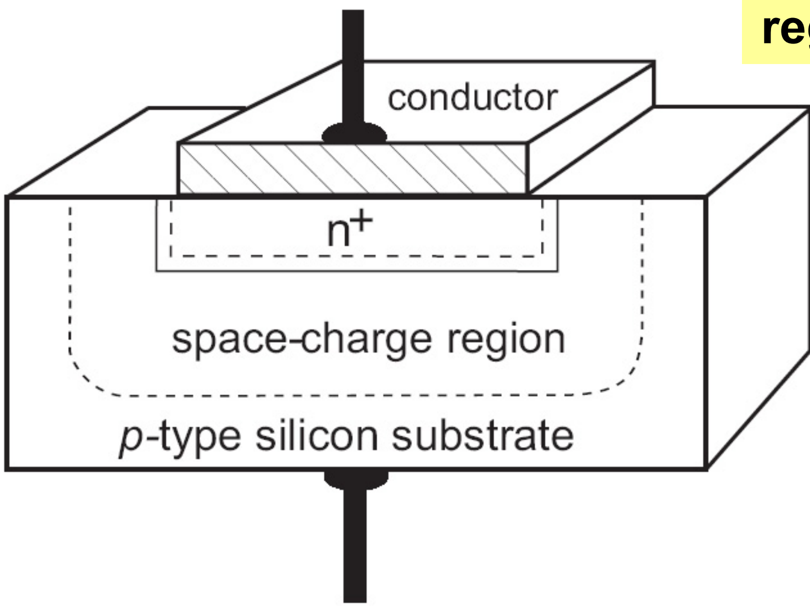
- Most image sensors are based on either of two distinct types of photo detectors
  - The **photo diode** (photo-conductive mode)
  - The **MOS capacitance** (intrinsic absorption)
- Both can be manufactured using standard semiconductor processes
- Both are used as capacitors which are discharged/charged by means of I_{photo} (and I_{thermo} !)

The photo diode

Electrons move from the n+ region to fill the holes in the p-region

Holes from the p-region “move” to the n+ region to be filled with free electrons

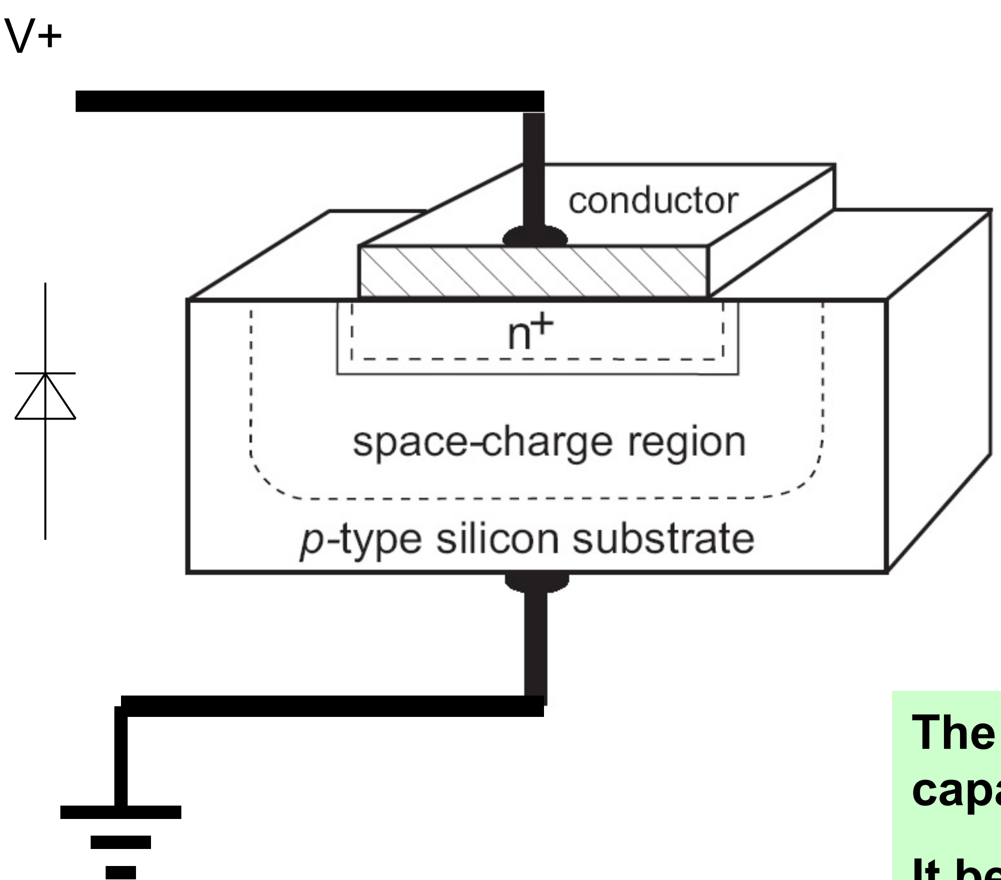




The net result is that

- **A “space-charge region” develops, depleted of free electrons or holes**
- **The space-charge region is an electric insulator**
- **An electric field is established in the space-charge region, (from n+ to p)**

The photo diode



Apply a "bias" voltage of the same polarity as the internal field

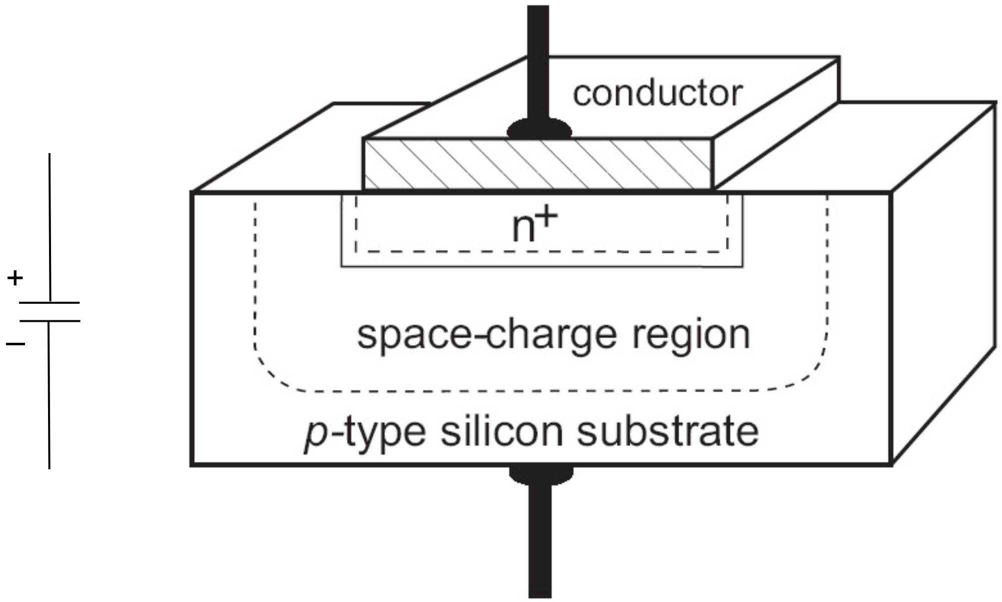
The space-charge region increases

Since the space-charge region is an insulator, no current runs through the junction

The diode acts as an electric capacitor:

It becomes electrically charged

The photo diode

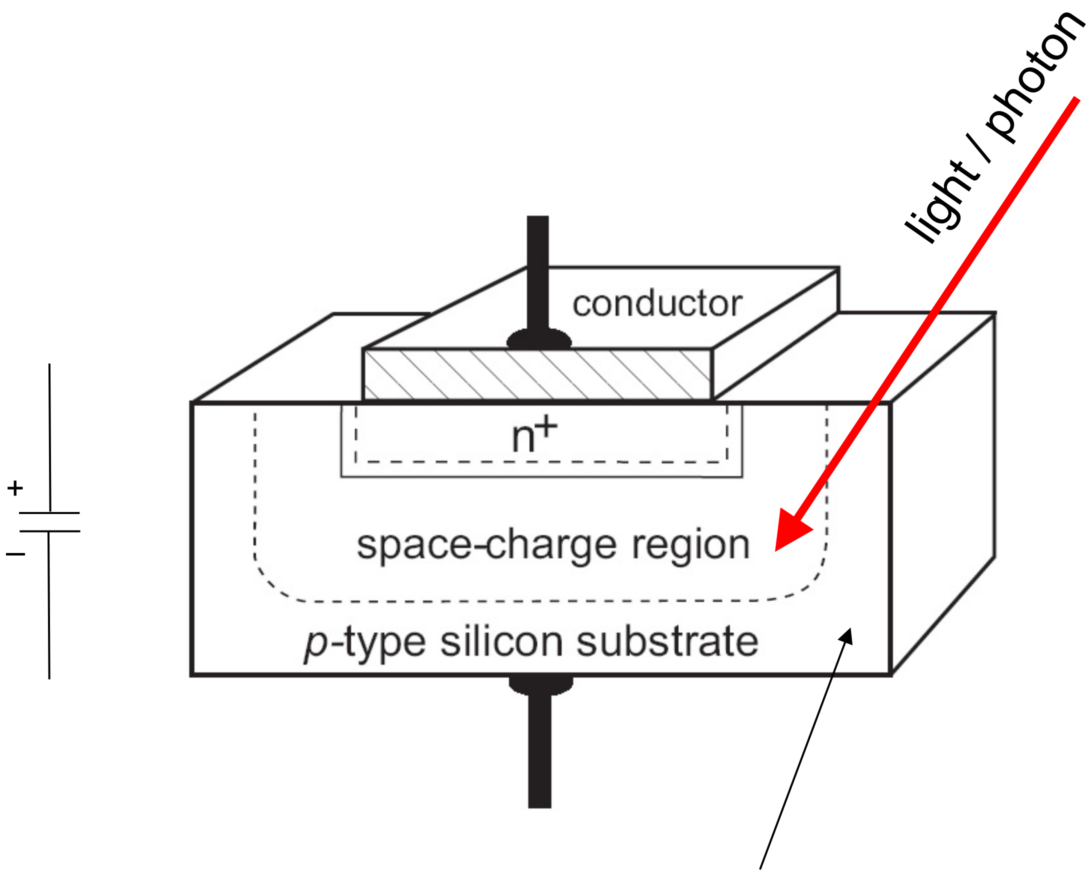


Remove the voltage

The charge remains

It acts as a charged electric capacitor which holds a certain charge

The photo diode



lightly p-doped =
mainly intrinsic absorption

If absorbed: a photon creates a free electron/hole pair

Due to the electric field:

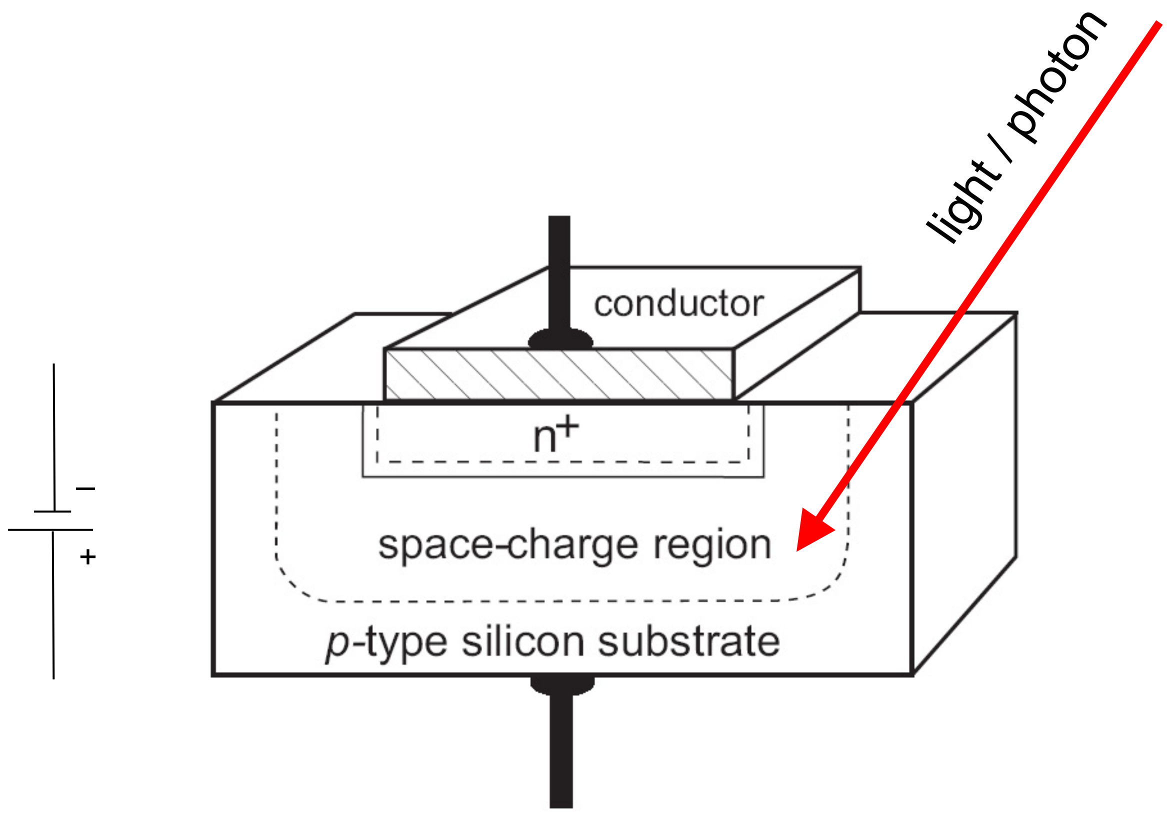
- **The electron sweeps to the n+ region and cancels a hole**
- **The hole sweeps to the p- region and cancels an electron**

This builds up a negative voltage across the junction

The electric field reduces linearly to the number of absorbed photons

This voltage difference can be measured. Alternatively, the *reduction in stored charge* of the photo diode capacitor is measured

The photo diode



The voltage difference generated by the photons occurs even if the diode had not have been pre-charged

Caused by the photo-voltaic effect

The diode can in principle be used as a solar cell

The pre-charging makes the photovoltaic effect stronger since it increases the space-charge region

The photo diode, summary

Basic mode of operation

1. Pre-charge to a specific voltage (typically a few volts)
2. Let the photovoltaic effect discharge the diode a specific time period (the exposure time)
3. The voltage drop over the diode is proportional to the flux density incident on the sensor area
4. Measure the voltage drop, or the lost charge to get the pixel value.

We need to measure **voltage** or **charge**

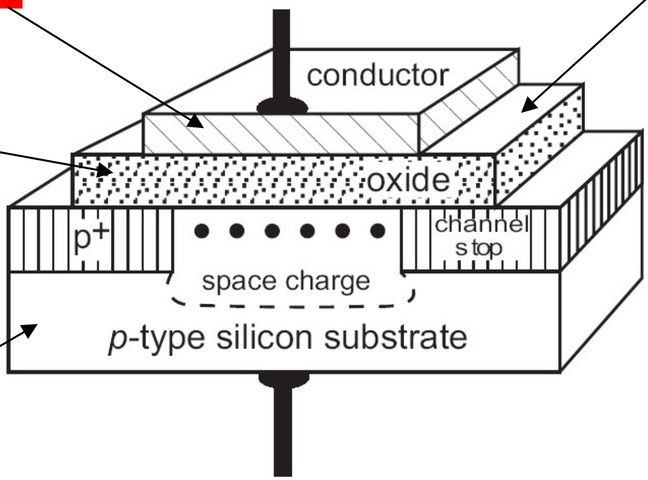
The MOS capacitor

Acts as an electrical capacitor

The oxide layer is a perfect insulator, no current passes through this layer

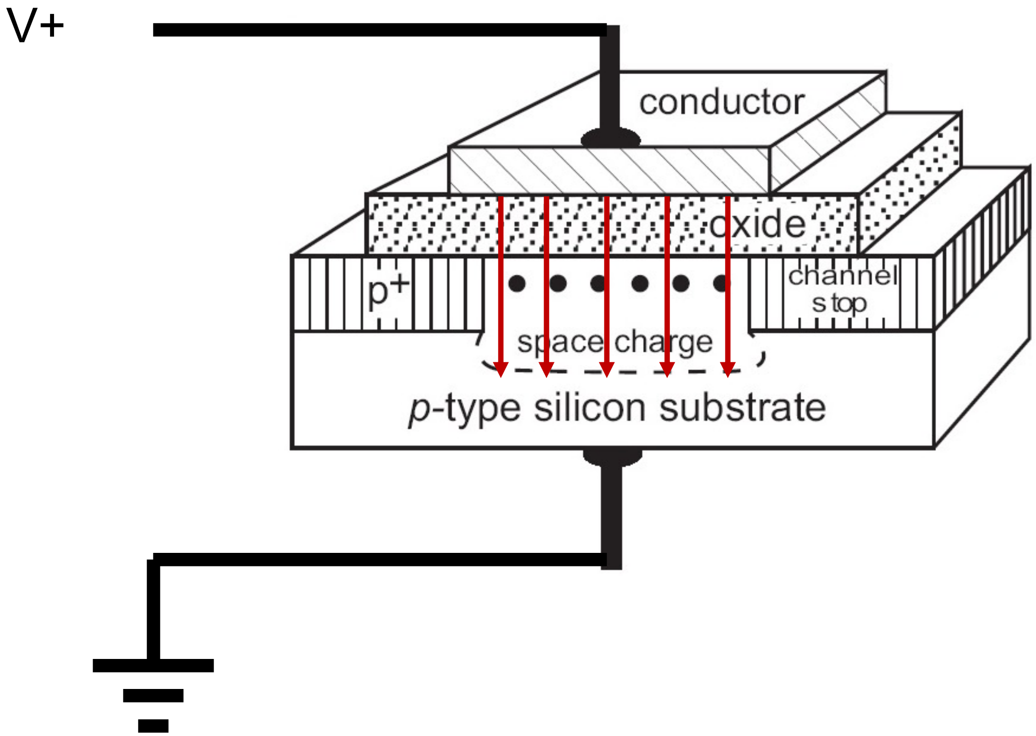
M Metal

O Oxide



S Semiconductor

The MOS capacitor

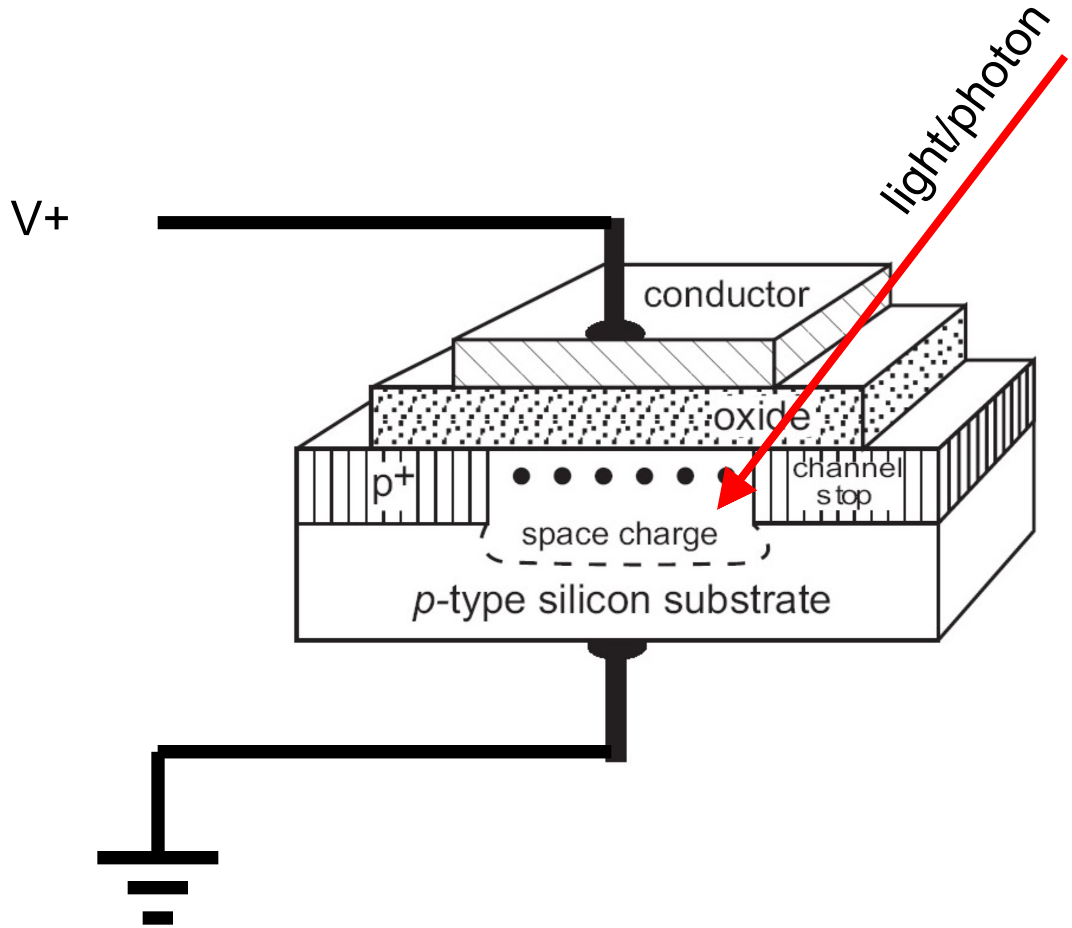


Apply a voltage across the capacitor

Holes in the region under the oxide will move into the substrate and create a space-charge region

An electric field is created across the oxide barrier and through the space-charge region

The MOS capacitor



An absorbed photon creates an electron/hole pair

- The hole is swept into the substrate
- The electron is drawn by the electric field toward the oxide barrier
- Due to the oxide insulation, the electrons accumulate below the oxide barrier, no current flows through the capacitor
- The amount of accumulated electrons is proportional to the number of absorbed photons

The MOS capacitor, summary

Basic mode of operation

1. Apply a voltage across the capacitor
2. Photon absorption creates electrons to deposit under the oxide layer
3. Allow this deposit to accumulate over a certain time period (the exposure time)
4. The corresponding electron charge is proportional to the incident flux density of the sensor
5. Move the deposited charge to somewhere where it can be measured (typically CCD transport)

We need to measure **electric charge**

Blooming

- Both the photodiode and the MOS capacitor “collect” electric charge in a small region corresponding to the conductor region
- When this region becomes saturated, the charge spills over to neighboring elements
- This is called *blooming*
- Barriers between the detectors can reduce this effect, but not eliminate it entirely

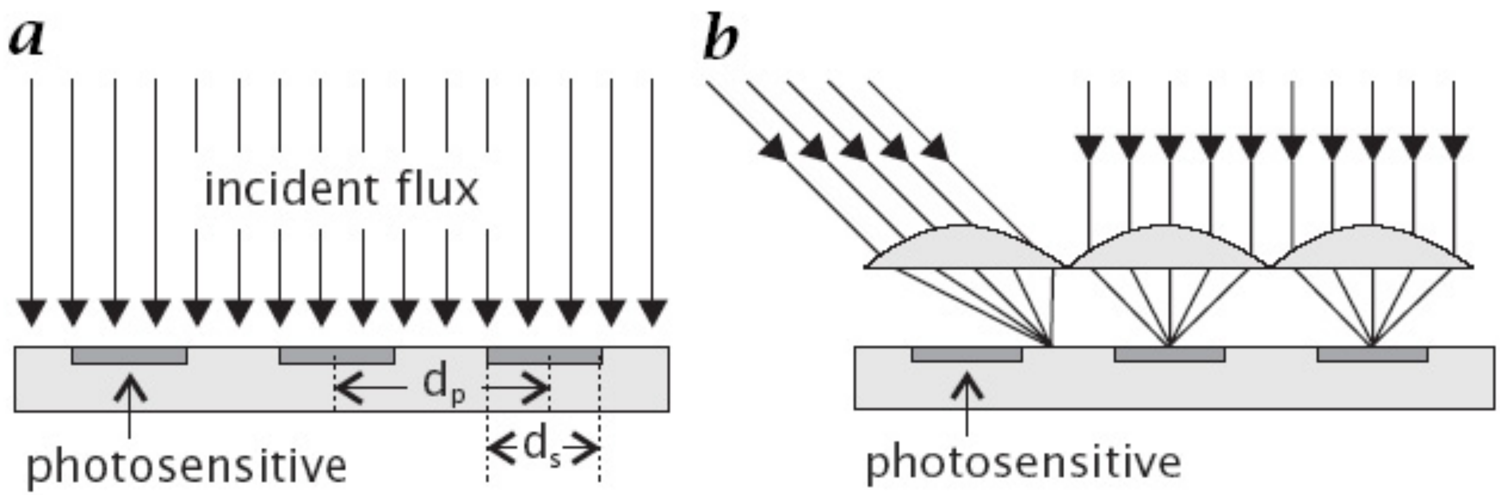
Image illustrating blooming found on the Internet

Fill factor

- In practice, the light sensitive area of an image sensor cannot fill the entire detector area.
- Electronic components and wiring reduce the light sensitive area
- The *fill factor* is the percentage of the total area which is light sensitive

Micro-lenses

- To overcome low fill factors, an array of micro-lenses in front of the sensor array can be used



Micro-lenses

- Micro-lenses enhance the fill factor
- But
  - Due to the manufacturing process, the detector area can often have an inhomogeneous sensitivity
  - When light is focused onto a smaller spot in the sensor, the inhomogeneities become more noticeable as measurement noise
  - At high incident angles, this spot may miss the detector area, see previous illustration

End of Image Sensing - Part 1