Active Pixel Sensors

EEL 5357 Analog CMOS/VLSI Design

Absorption

The energy of a photon

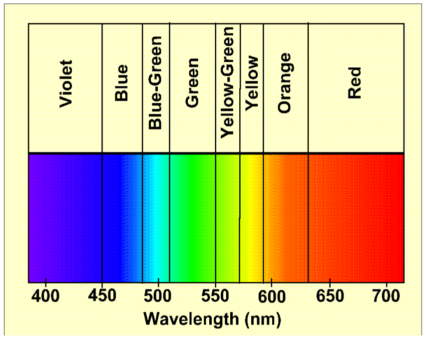
$$E = \frac{1240}{\lambda}$$

Where ëis the wavelength of light in nm

Example

Let ë=450 nm (blue)

$$E = \frac{1240}{450} = 2.75\,eV$$



Visible Spectrum (380-740 nm)

Bandgap of a semiconductor, Eg, is the energy required to raise an electron from the valence to conduction band

If E> Eg, a photon may be converted into an electron-hole(e-h) pair which is known as optical absorption

On the other hand, if E < Eg, the photon will pass through the material.

Cut off wavelength

$$\lambda_c = \frac{1240}{E_g}$$

Example

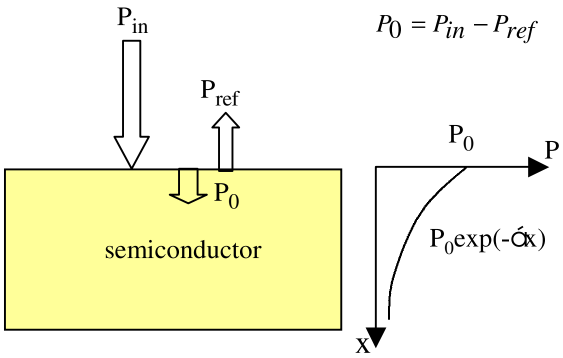
For Si Eg =1.12 eV

$$\lambda_c = \frac{1240}{1.12} = 1107\,nm$$

Wavengths less than 1100 nm generate e-h pairs in Si

Absorption Coefficient(ά)

Defines the depth of penetration of the light in a material for a particular wavelength



$$P_0 = P_{in} - P_{ref}$$

P_{in} is the incident and P_{ref} is the reflected optical power.

From Lambert-Beer law, the optical power at a distance *x* is

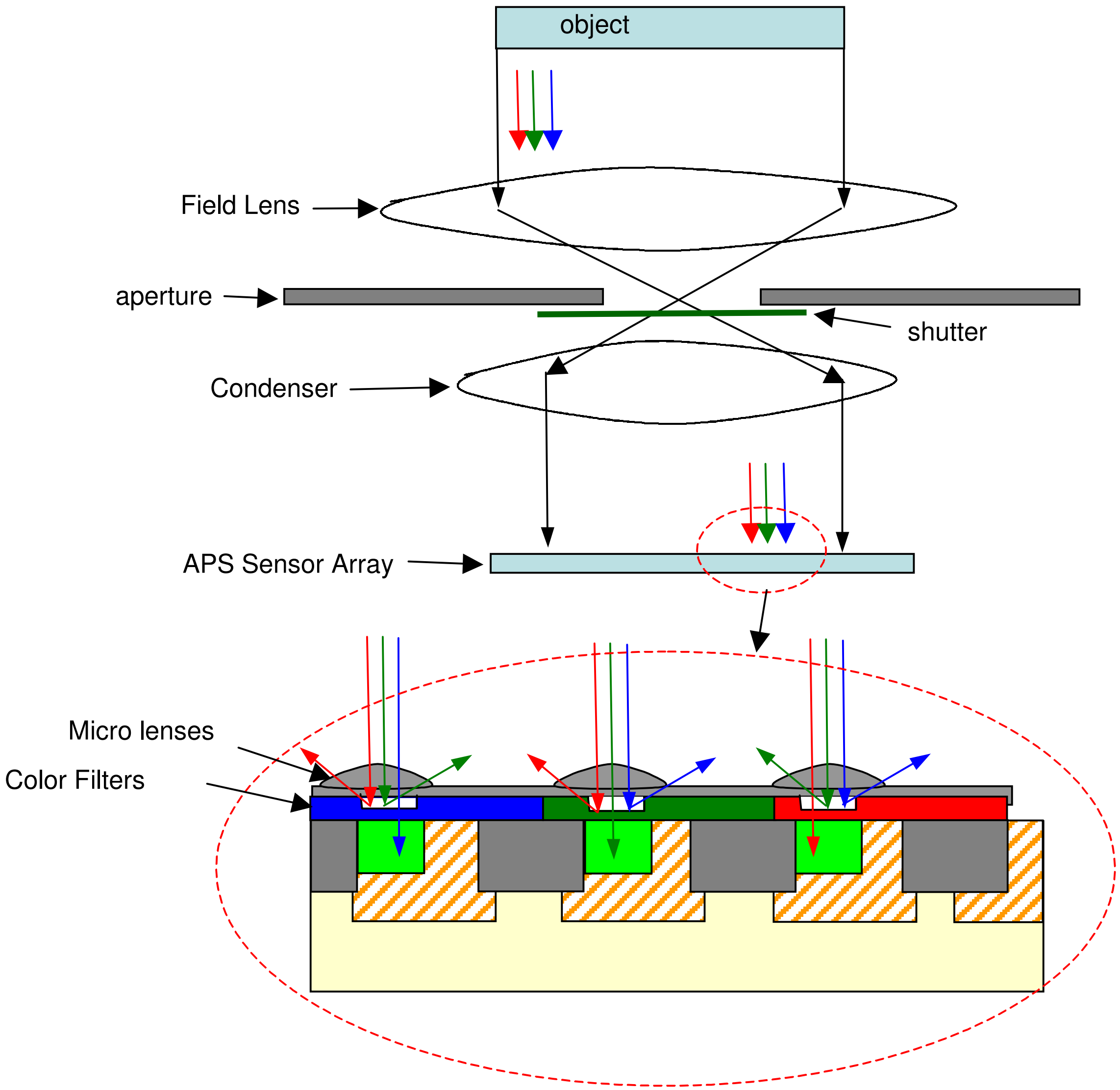
$$P(x) = P_0 e^{-\alpha x}$$

where P_0= $E\ddot{O}_0A$ and

$\ddot{O}_0$ is the photon flux density (photons/s-cm^2)

Prepared by: Ashok Rangaswamy

Digital Camera Configuration

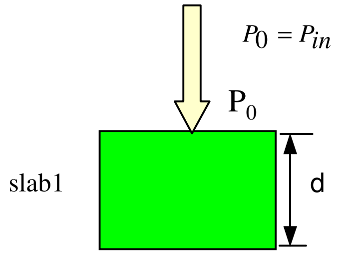


http://www.extremetech.com/article2/0,3973,15466,00.asp

Photodiode Model

Semiconductor Slab

$$P_0 = P_{in} - P_{ref}$$



e-h pair generation rate per unit volume,

$$g(x) = \frac{\alpha}{A}\Phi_0 e^{-\alpha x}$$

Ö$_0$ is the photon flux density (photons/s-cm^2)

$$\Phi_0 = \frac{P_0}{A(h\nu)}$$

e-h pair generation rate per unit area,

$$G = \frac{\Phi_0}{A}[1 - e^{-\alpha d}]$$

The absorption efficiency is

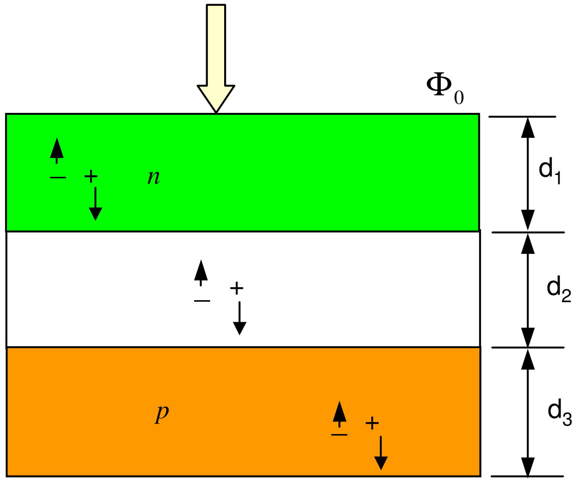
$$\eta_o = \frac{P_{absorbed}}{P_0} = \left(1 - e^{-\alpha d}\right)$$

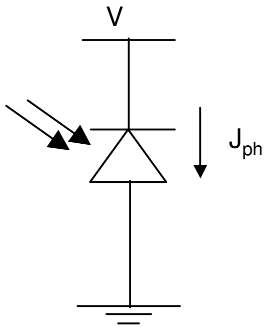
Internal quantum efficiency Ç$_i$ is the number of photogenerated electron-hole pair, that contribute to the photocurrent per incident photon

External quantum efficiency is

$$\eta_{ext} = \eta_o \eta_i$$

Photo current components in photodiode are
Generated carriers in space charge region (SCR) –drift current
Minority carriers generated in quasi neutral n and p regions-diffusion current





Reverse biased

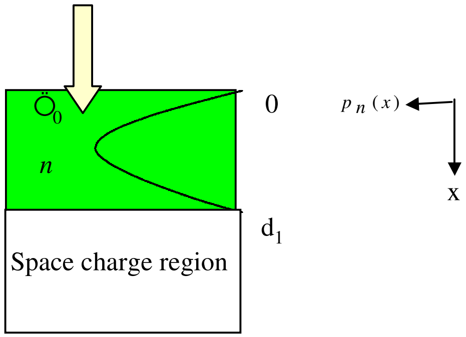
e-h pair generation rate per unit area in SCR

$$G_{SCR} = \Phi_0[e^{-\alpha d_1} - e^{-\alpha d_2}]$$

Current density J_{SCR}, assuming all generated e-h pair are swept away by the junction potential (drift) and collected before they recombine

$$J_{SCR} = q\Phi_0[e^{-\alpha d_1} - e^{-\alpha d_2}]$$

Photodiode Model Contd…



Φ_0 is the photon flux density (photons/s-cm^2) at the semiconductor surface after reflection

$P_n(x)$ is the photo generated minority carrier density (hole) in n-region and D_p is the diffusion constant of holes in cm^2/s

e-h pair generation rate per unit volume,

$$g(x) = \alpha\Phi_0 e^{-\alpha x}$$

Current density due to diffusion in n region,

$$J_{pn} = -qD_p \frac{\partial p_n(x)}{\partial x}\Big|_{x=d_1}$$

To find $P_n(x)$ use continuity equation,

$$\frac{\partial p_n(x)}{\partial t} = D_p \frac{\partial^2 p_n(x)}{\partial x^2} + g_n(x) - R_n(x)$$

By short channel assumption, recombination rate is zero and under steady state the lhs is zero. Therfore

$$D_p \frac{\partial^2 p_n(x)}{\partial x^2} + g_n(x) = 0$$

Integrating twice we get the solution of form,

$$p_n(x) = a + bx - \frac{\Phi_0}{\alpha D_p} e^{-\alpha x}$$

Using the boundary conditions $p_n(0)=p_n(d_1)=0$, we get,

$$a = \frac{\Phi_0}{\alpha D_p} \quad \text{and} \quad b = \frac{-\Phi_0}{\alpha D_p d_1}\left[1 - e^{-\alpha d_1}\right]$$

$$p_n(x) = \frac{\Phi_0}{\alpha D_p}\left(1 - \frac{x}{d_1}\left(1 - e^{-\alpha d_1}\right) - e^{-\alpha x}\right)$$

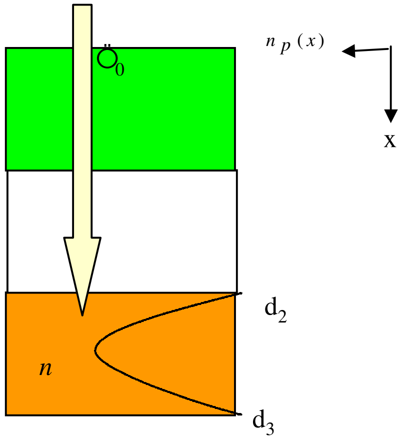
The current density due to the diffusion in the *n*- region,

$$J_{pn} = -qD_p \frac{\partial p_n(x)}{\partial x}\Big|_{x=d_1}$$

$$= \frac{-q\Phi_0}{\alpha}\left(\frac{-\left(1 - e^{-\alpha d_1}\right)}{d_1} + \alpha e^{-\alpha d_1}\right)$$

$$= \frac{q\Phi_0}{\alpha d_1}\left(1 - (\alpha d_1 + 1)e^{-\alpha d_1}\right)$$

Photodiode model –Contd…



$n_p(x)$ is the photo generated minority carrier density (hole) in n-region and D_n is the diffusion constant of electrons in cm^2/s

e-h pair generation rate per unit volume in p region,

$$g_p(x) = \alpha\Phi_0 e^{-\alpha x}$$

Current density due to diffusion in n region,

$$J_{np} = qD_n \frac{\partial n_p(x)}{\partial x}\Big|_{x=d_2}$$

Continuity equation under steady state,

$$D_n \frac{\partial^2 n_p(x)}{\partial x^2} + g_p(x) = 0$$

Using the boundary conditions $p_n(d_3)=p_n(d_2)=0$, we get,

$$a = \frac{\Phi_0}{\alpha D_n (d_3 - d_2)}\left[-e^{-\alpha d_3} + (d_3 - d_2 + 1)e^{-\alpha d_2}\right]$$

$$b = \frac{\Phi_0}{\alpha D_n (d_3 - d_2)}\left[e^{-\alpha d_3} - e^{-\alpha d_2}\right]$$

$$n_p(x) = \frac{\Phi_0}{\alpha D_n}\left(a + \frac{x\left[e^{-\alpha d_3} - e^{-\alpha d_2}\right]}{(d_3 - d_2)} - e^{-\alpha x}\right)$$

Hence the current density due to the diffusion in the *p*- region,

$$J_{np} = qD_n \frac{\partial n_p(x)}{\partial x}\Big|_{x=d_2}$$

$$= \frac{q\Phi_0}{\alpha(d_3 - d_2)}\left([\alpha(d_3 - d_2) - 1]\, e^{-\alpha d_2} + e^{-\alpha d_3}\right)\text{A/cm}^2$$

By adding J_{SCR}, J_{pn}, and J_{np}, we obtain the total photo generated current density as

$$J_{photo} = \frac{q\Phi_0}{\alpha}\left(\frac{1 - e^{-\alpha d_1}}{d_1} + \frac{e^{-\alpha d_3} - e^{-\alpha d_2}}{d_3 - d_2}\right) \text{A/cm}^2$$

Then the internal efficiency (e-h pairs/photon) is given by

$$\eta_i(\lambda) = \frac{1}{\alpha}\left(\frac{1 - e^{-\alpha d_1}}{d_1} + \frac{e^{-\alpha d_3} - e^{-\alpha d_2}}{d_3 - d_2}\right) \text{ electrons / photon}$$

and is a function of the wavelength (through ά(ë)).

We may nominally define $ς_i$ = ς(ë)$_{max}$

Active Pixel Sensors: EEL 5357 Analog CMOS/VLSI Design, Fall 2003

Junction Capacitance and Depletion width

$$x_n = \left\{ \frac{2\varepsilon(V_{bi}+V)}{q} \frac{N_a}{N_d} \left[\frac{1}{N_a+N_d} \right] \right\}^{1/2}$$

$$x_p = \left\{ \frac{2\varepsilon_s(V_{bi}+V)}{q} \frac{N_d}{N_a} \left[\frac{1}{N_a+N_d} \right] \right\}^{1/2}$$

Depletion width

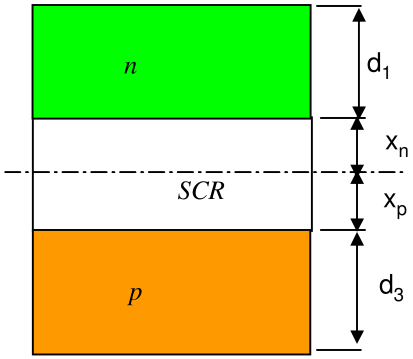
$$W = \left\{ \frac{2\varepsilon(V_{bi}+V)}{q} \left[\frac{N_a+N_d}{N_a N_d} \right] \right\}^{1/2}$$

Junction capacitance

$$C_D = \frac{\varepsilon}{W}$$

Built in Potential,

$$V_{bi} = \frac{kT}{q} \log\left(\frac{N_a N_d}{n_i^2} \right)$$



Example

Consider a *p-n* diode with

$$\mathrm{Na} = 1\times10^{20}\ /\mathrm{cm}^3 (p+)$$

$$\mathrm{Nd} = 1\times10^{16}\ /\mathrm{cm}^3 (n)$$

$$n_i = 1\times10^{10} / cm^3$$

Reverse biased for 2.2V at room temperature(300k),

$$V_{bi} = \frac{1.38\mathrm{E}-23\times300}{1.6\times10^{-19}} \left(\log\left(\frac{1\times10^{20}}{1\times10^{10}} \right) + \log\left(\frac{1\times10^{16}}{1\times10^{10}} \right) \right)$$

$$= 0.9533V$$

$$\varepsilon_{si} = 11.7\times8.85\times10^{14}$$

Therefore

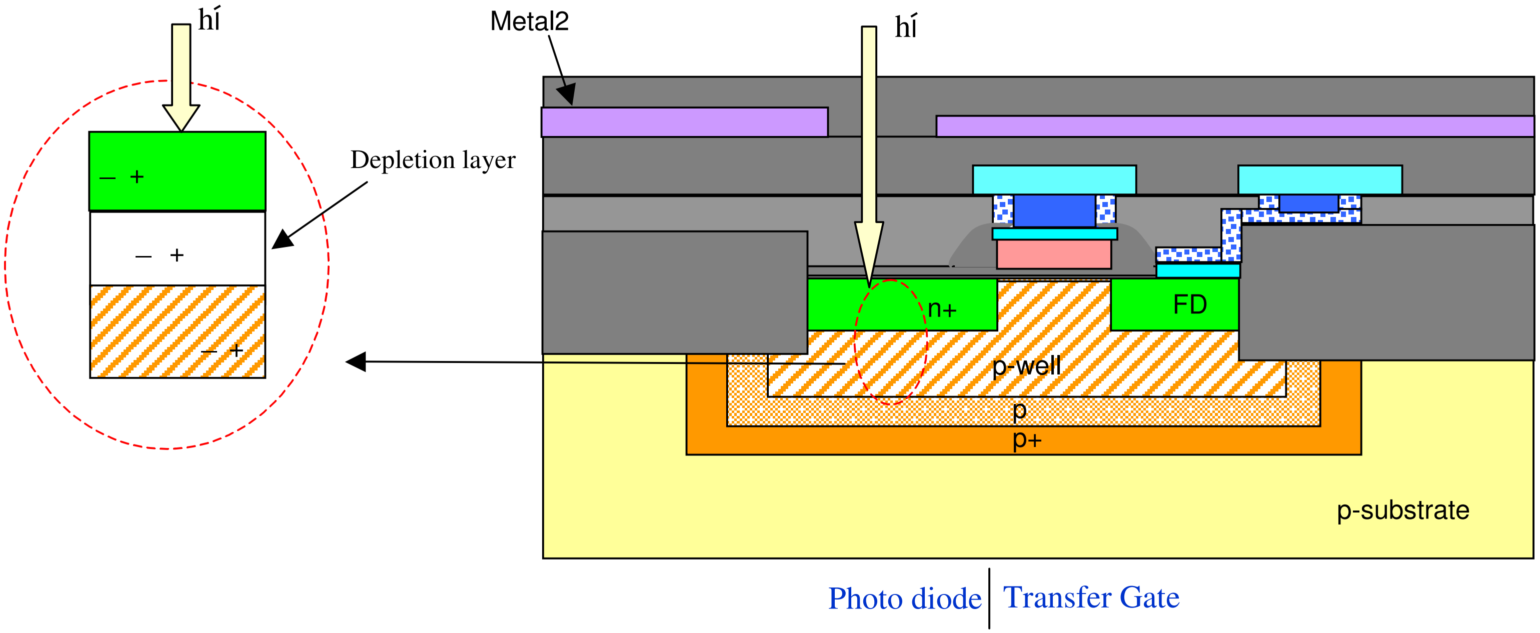
$$\mathrm{X_n} = 0.639 \quad microns$$

$$\mathrm{X_p} = 0.639\times10^{-4} \quad microns$$

$$W = 0.639 \quad microns$$

$$C_D = 16.21 \quad nF$$

Active Pixel



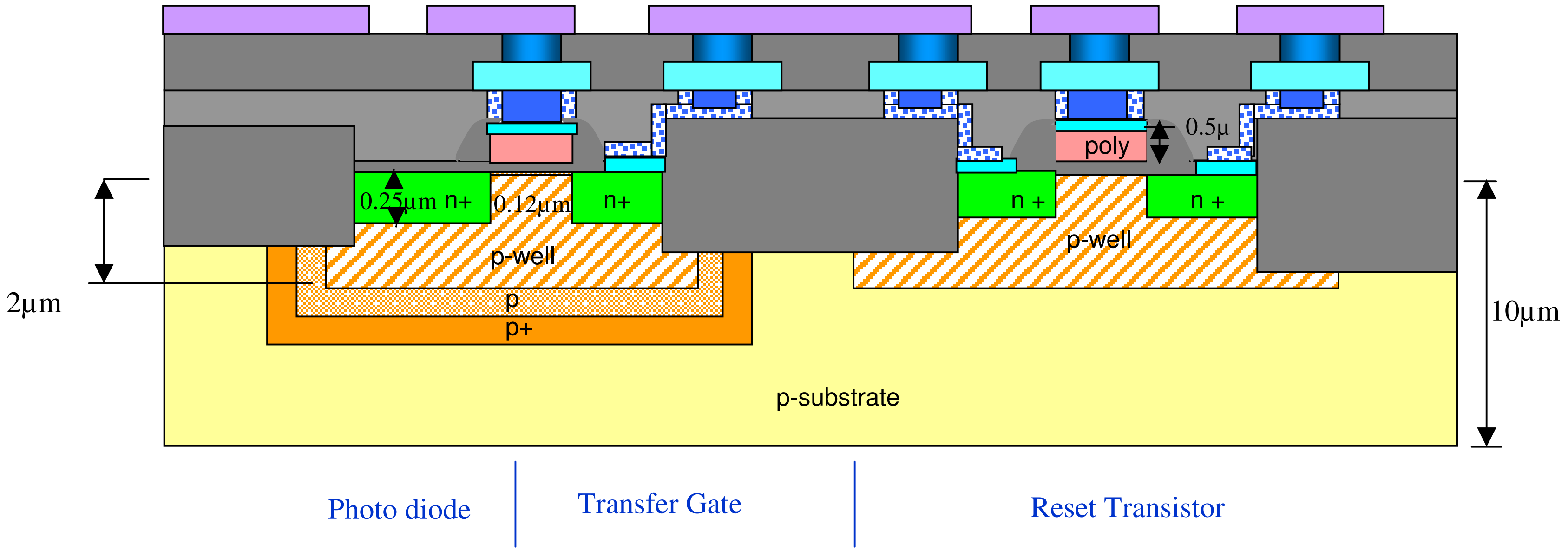
1.Photon Collection

SiO_2-with bandgap of 8 eV allows the visible light spectrum to pass through to the photodiode
Metal 2 acts as a light shield
Si with bandgap 1.12 eV collects the photons in the visible spectrum (400-700 nm)
The amount of photons getting converted into electrons depends on light intensity and transfer rate
This photo generated charge is transferred from the photodiode to the Floating Diffusion (FD) output node, when the transfer gate becomes active
Noise from high-speed circuits is normally coupled to low-level analog circuits via references, substrate, and ground

Triple well formation is one technique to isolate the most sensitive analog cicuits from the digital circuits to avoid such noise

IEEE Tran.Electron Devices, April 1998, p.889
http://www.mosis.org/Technical/Designrules/scmos/scmos-contact.html#6

APS Fabrication



Dimensions:

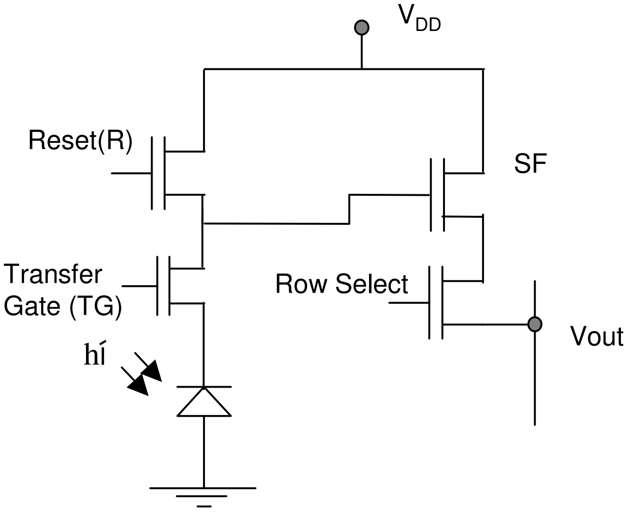
ë of SCMOS Rule	0.25µm
Gate Oxide Thickness	4nm
Poly Thickness	0.5µm
Well Width	10 ë
Metal1 Width	3 ë
Via	2 ë x 2 ë
Metal2 Width	3 ë
Active Contact	2 ë x 2 ë

Impurity Concentrations:

p-substrate	10^{15}/cm^3
p-well	10^{16}/cm^3
n+	10^{20}/cm^3
p+	10^{20}/cm^3

IEEE Tran.Electron Devices, April 1998, p.889
http://www.mosis.org/Technical/Designrules/scmos/scmos-contact.html#6

Active pixel Read out circuit



After charge integration, all pixels in a row are readout simultaneously onto column lines.

Reset **R** is pulsed briefly to HIGH which resets the floating diffusion output node (drain of TG MOSFET)

Row Select is biased briefly at HIGH; this activates the source follower **SF**

TG is then pulsed to HIGH

Thus gate potential of SF changes; output of **SF** depends on the amount of integrated charge

Image Pixel

Instantaneous current is proportional to the incident photon flux

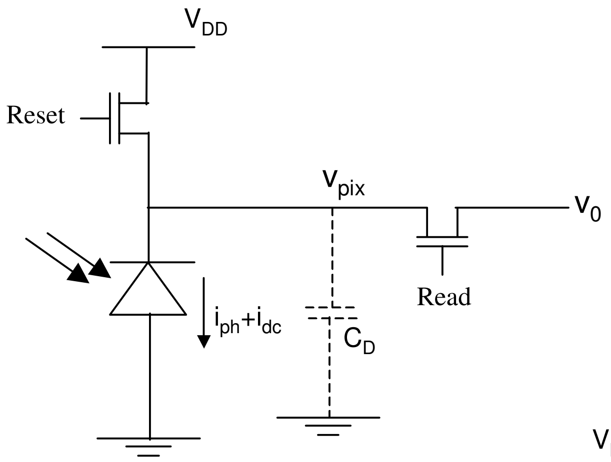
Reverse biased, but only to form a ‘photo-capacitor’ from the junction capacitance

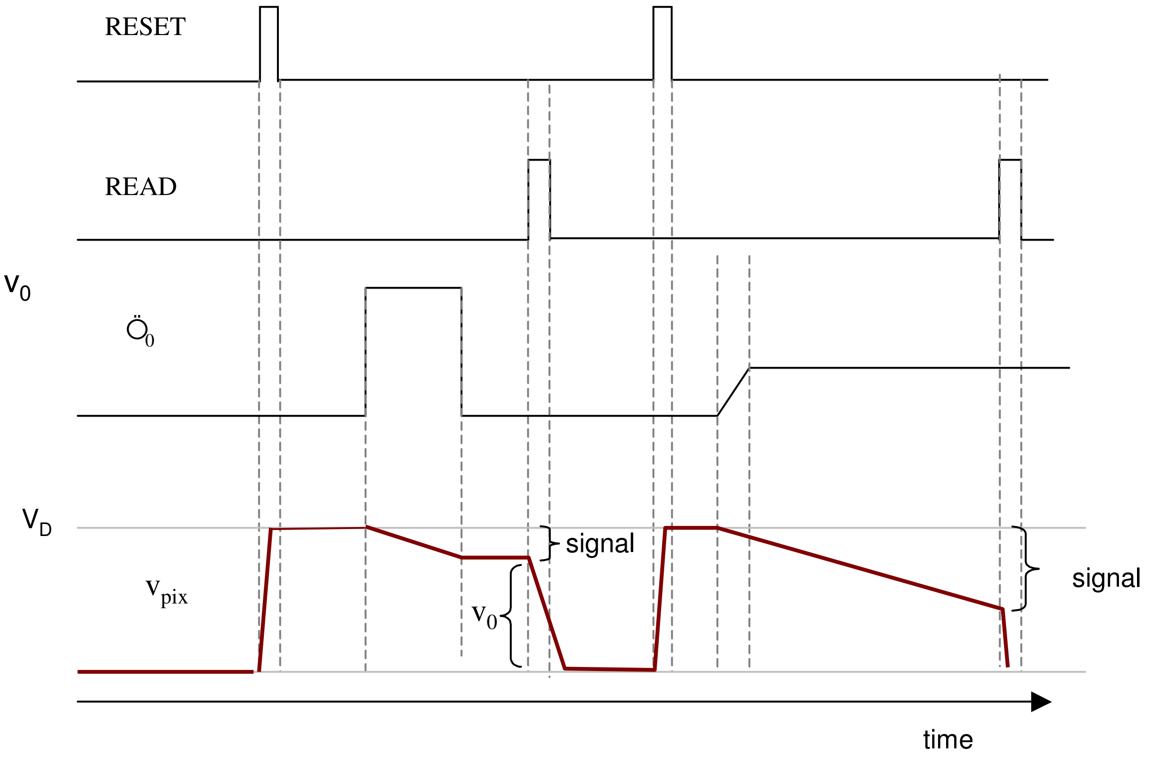
When allowed to float (disconnected from reverse bias), this capacitance holds its charge

With incident light, photogenerated electrons bleed off the charge on the capacitance of the junction at a rate proportional to the incident photon flux

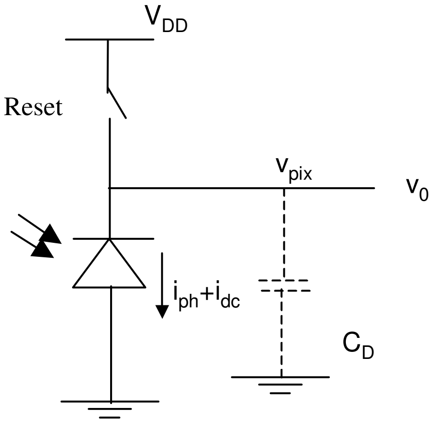
The **charge that bleeds is proportional to the “Exposure”**, time accumulated photon flux

This is then read out by conversion circuit which converts charge to voltage





Direct Integration



Photodiode is reset to reverse bias voltage V_{DD}
Diode current discharges C_D for t_{int} sec (integration time or exposure time)
At the end of integration time, the voltage v_0 is read out
Assume photo (I_{ph}) and dark current (I_{dc}) do not change with reverse bias voltage,

$$Q(t_{\text{int}}) = (i_{ph} + i_{dc})\, t_{\text{int}} \quad \text{Columbs}$$

Dark Current (i_{dc})

It is the photodetector leakage current, i.e., current not induced by photogeneration (under no illumination)

It limits the photodetector dynamic range
reduces signal swing
introduces unavoidable noise
can vary widely over the image sensor array causing fixed pattern noise (FPN)

Assume that C_D does not vary with reverse bias voltage

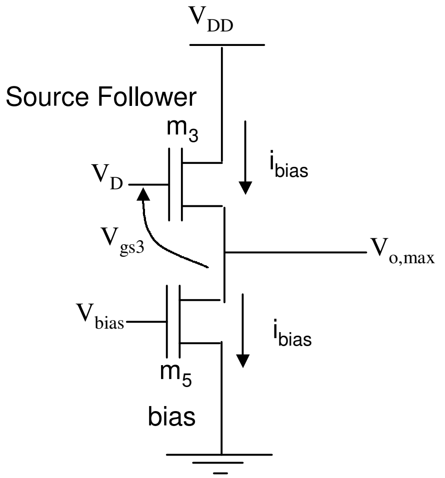
$$v_0(t_{\text{int}}) = V_D - \frac{(i_{ph} + i_{dc})\, t_{\text{int}}}{C_D} \quad \text{Volts}$$

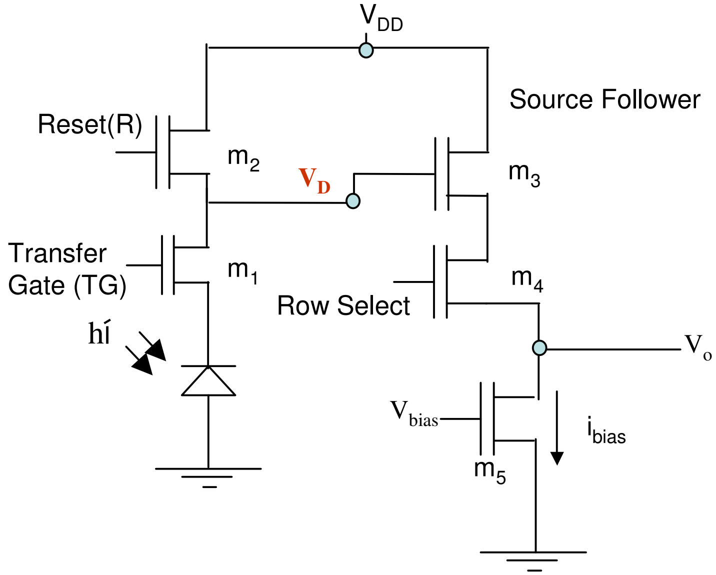
To avoid blooming (overflowing of charges to the neighboring diodes), the diode should be reverse biased before exposure.

Example

$$C_D = 1.55\, fF$$
$$i_{ph} = 167\ \text{fA}$$
$$\text{i}_{\text{dc}} = 2\, fA$$
$$t_{\text{int}} = 20ms$$
$$Q = (167 + 2)\times 10^{-15} \times 20 \times 10^{-3}$$
$$= 3.38\times 10^{-15}\, Columbs$$
$$Vo = V_{DD} - \frac{Q}{C_D}$$
$$= 5 - \frac{3.38}{1.5} = 2.25V$$

Output Swing





I_{bias} is m5 bias current

Assume first order MOS transistor model

$$I_{bias} = \frac{\beta_{n3}}{2}\left(V_{gs3} - V_{t3}\right)^2$$

where β_{n3} is the device transconductance of m_3. Therefore

$$V_{gs3} = V_{t3} + \sqrt{\frac{2\,I_{bias}}{\beta_{n3}}}$$

Let Q be the charge accumulated from PD at the end of integration. Assume that the drop across access transistors is negligible. Then the output is

$$V_o = V_D - V_{gs3}$$

where

$$V_D = V_{DD} - V_{t2}$$

V_{gs3} is the source follower transistor gate to source voltage

V_{t2} is the reset transistor threshold voltage including body effect

V_{t5} is the source follower transistor gate to source voltage

Output swing is given by

$$V_{o,min} = V_{bias} - V_{t5}$$

$$V_{o,\,max} = V_{DD} - V_{t2} - V_{gs3}$$

APS Read Out

Example

Consider a 4 × 4 APS matrix

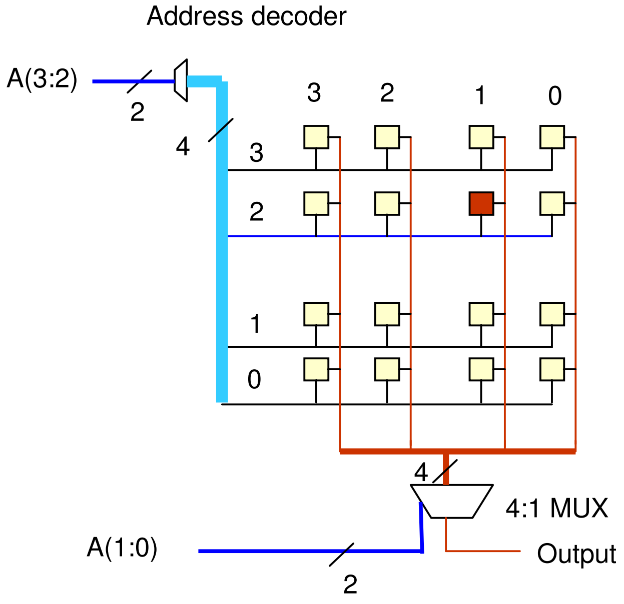
2:4 row decoder

Direct integration of voltage is readout of the pixel, somewhat like a RAM

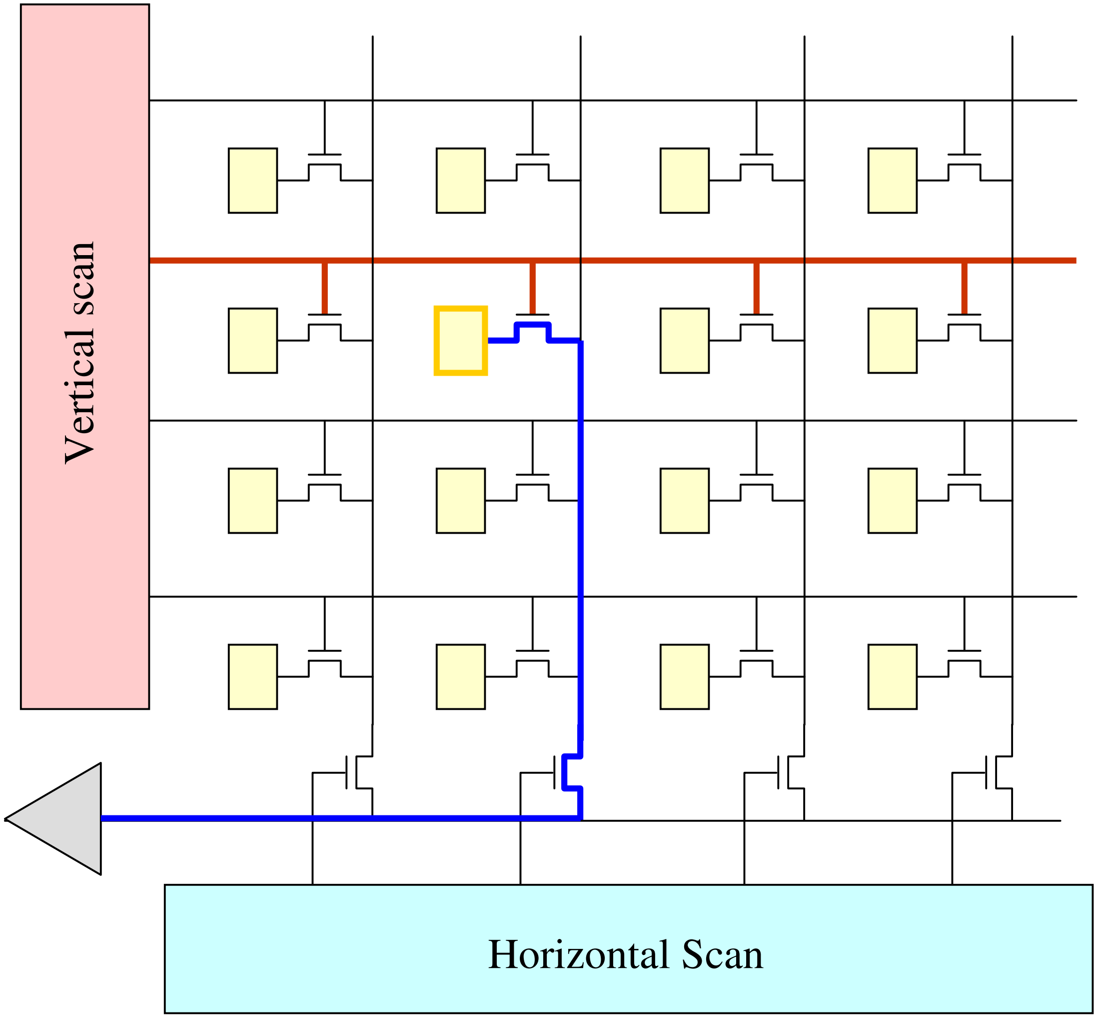
Readout is done in two stages:

Initially, a row is selected using the row decoder the data and transferred to column multiplexer

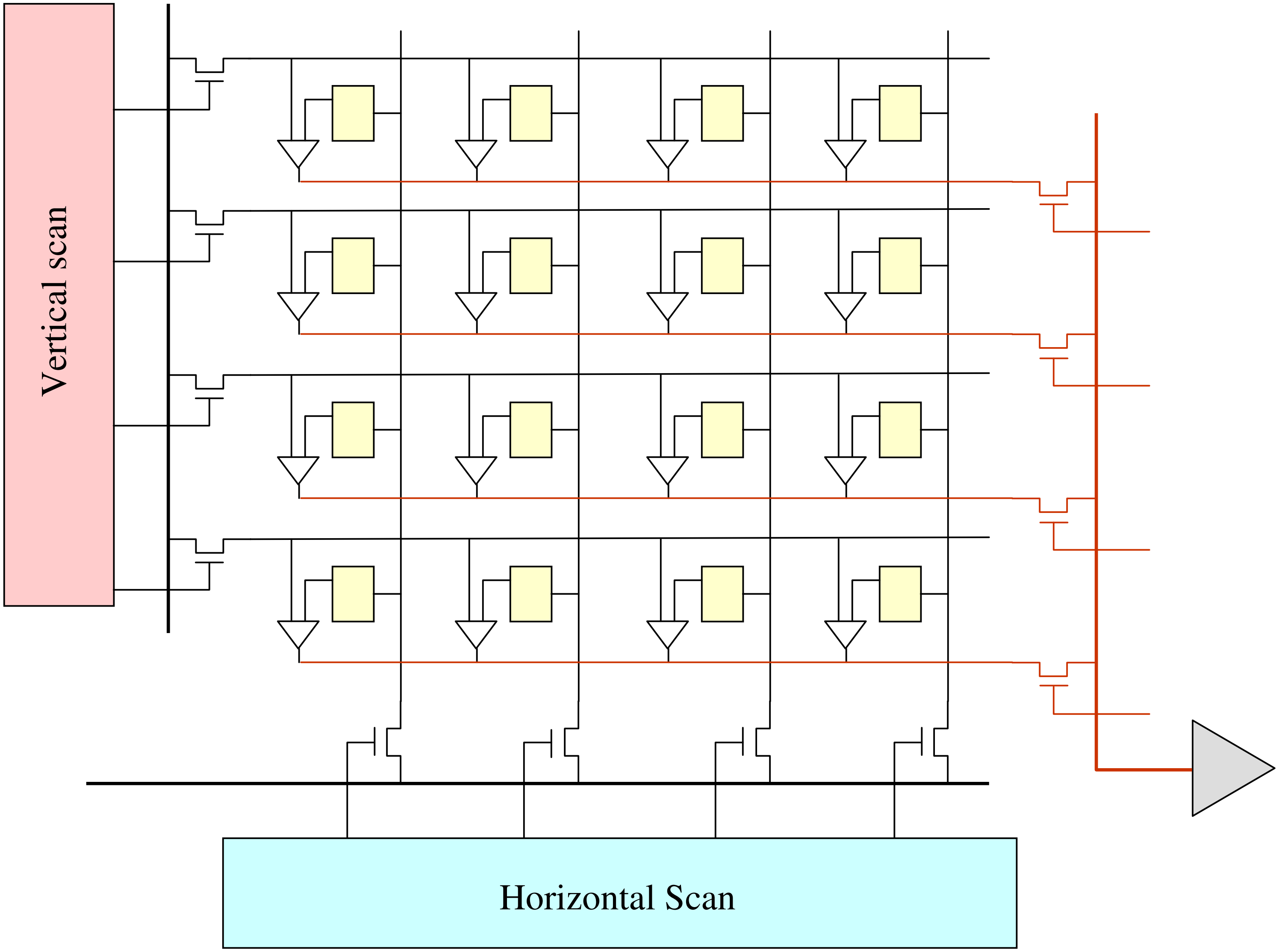
Then the data is transferred to data output, serially, using the column multiplexer.

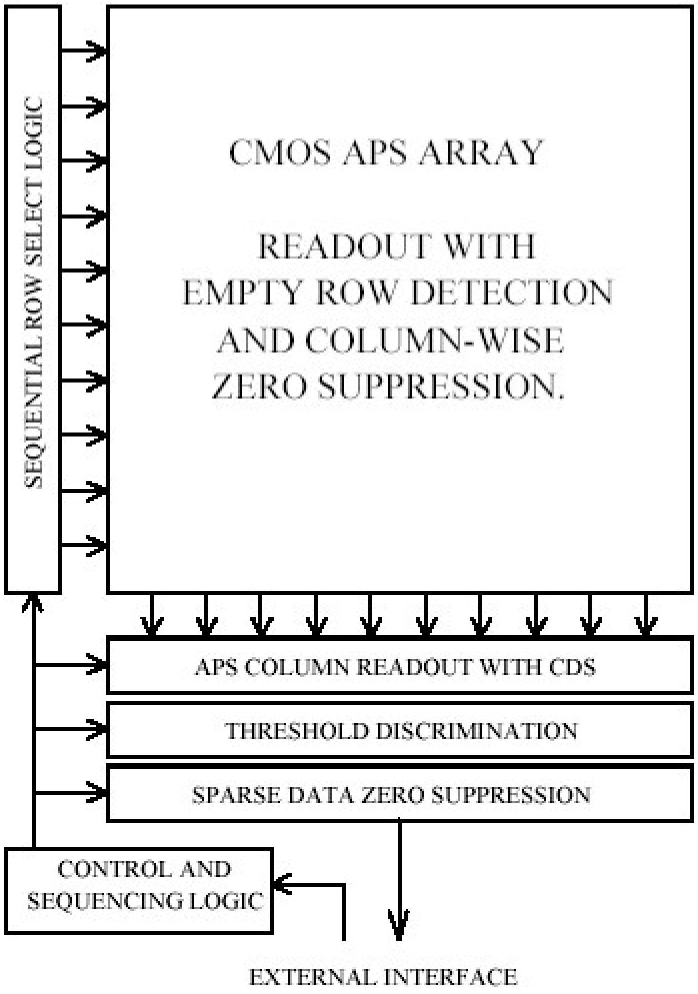


Passive Pixel CMOS



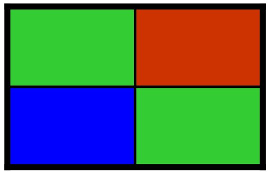
Active Pixel CMOS



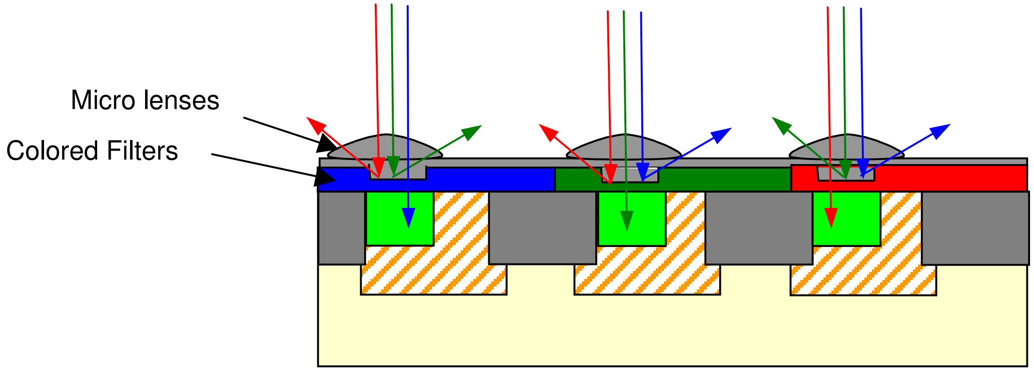

SEQUENTIAL ROW SELECT LOGIC
CMOS APS ARRAY
READOUT WITH
EMPTY ROW DETECTION
AND COLUMN-WISE
ZERO SUPPRESSION.
APS COLUMN READOUT WITH CDS
THRESHOLD DISCRIMINATION
SPARSE DATA ZERO SUPPRESSION
CONTROL AND
SEQUENCING LOGIC
EXTERNAL INTERFACE

Color Filter

- To enable Color imaging, each active pixel can be used to store one color, preferably in bayer’s format



- This can be achieved using color filters for each pixel



Microlens

- Microlens is fabricated over each pixel to focus light to active region of each pixel
- The ratio of the active region area (photodiode area) to the total area of each pixel is called *the Fill Factor*