CHAPTER 2

Fundamentals of CMOS Image Sensors

Outline

- Photoelectric Effect
- Photodetectors
- CMOS Image Sensor(CIS) Array Architecture
- CIS Peripherals
- Design Considerations

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Architecture of a CIS

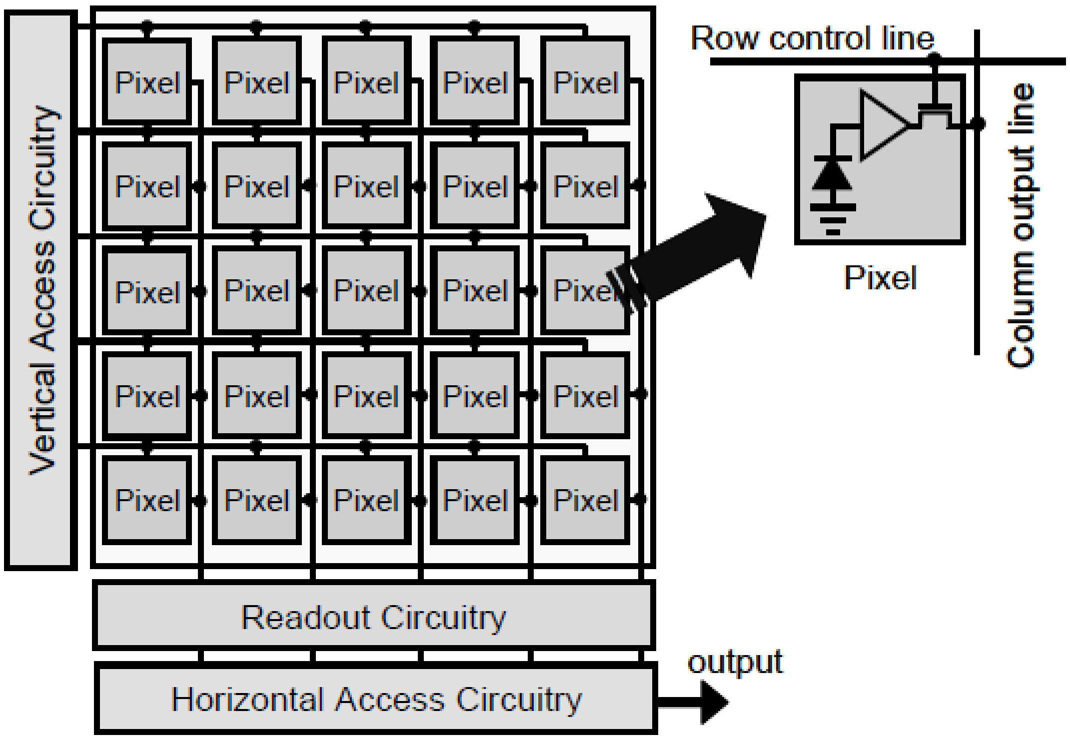
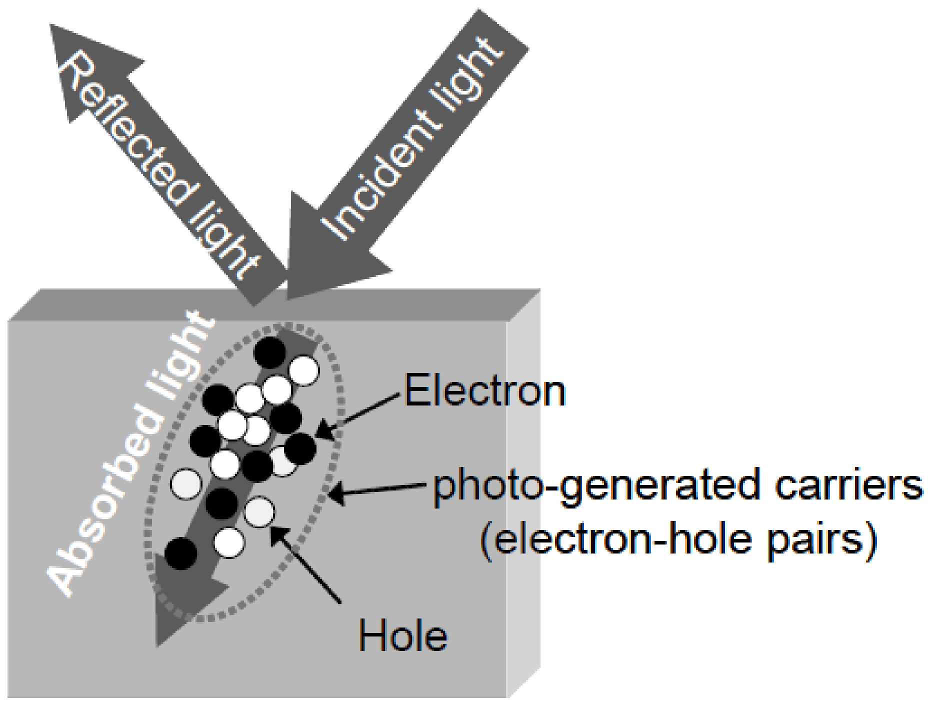


Photo-generated Carriers

- The amount of photo-generated carriers
  - Depends on the semiconductor material
  - Described by the absorption coefficient α



Absorption Coefficient

- Absorption coefficient α

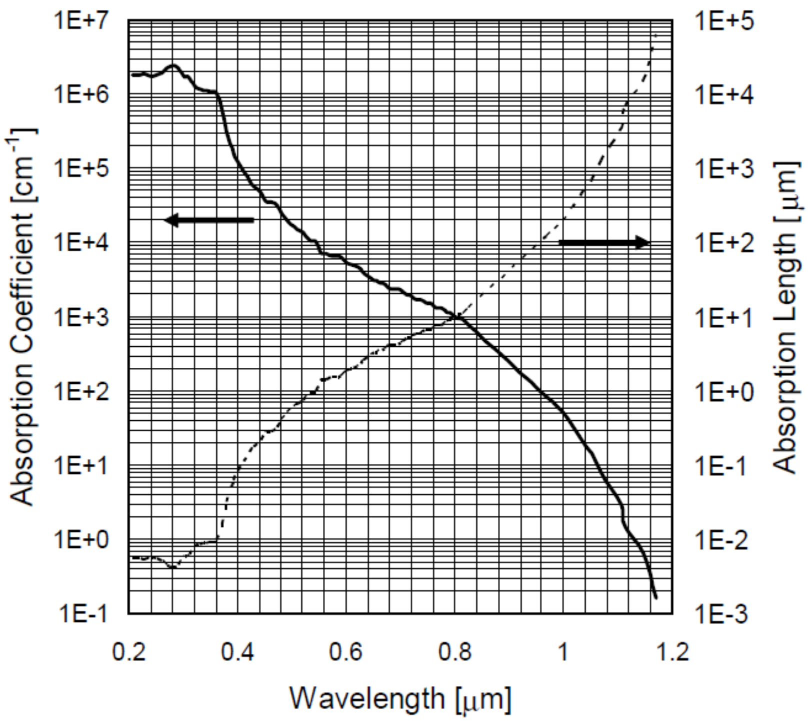
$$\alpha(\lambda) = \frac{1}{\Delta z}\frac{\Delta P}{P}$$

$$P(z) = P_o \exp(-\alpha z)$$

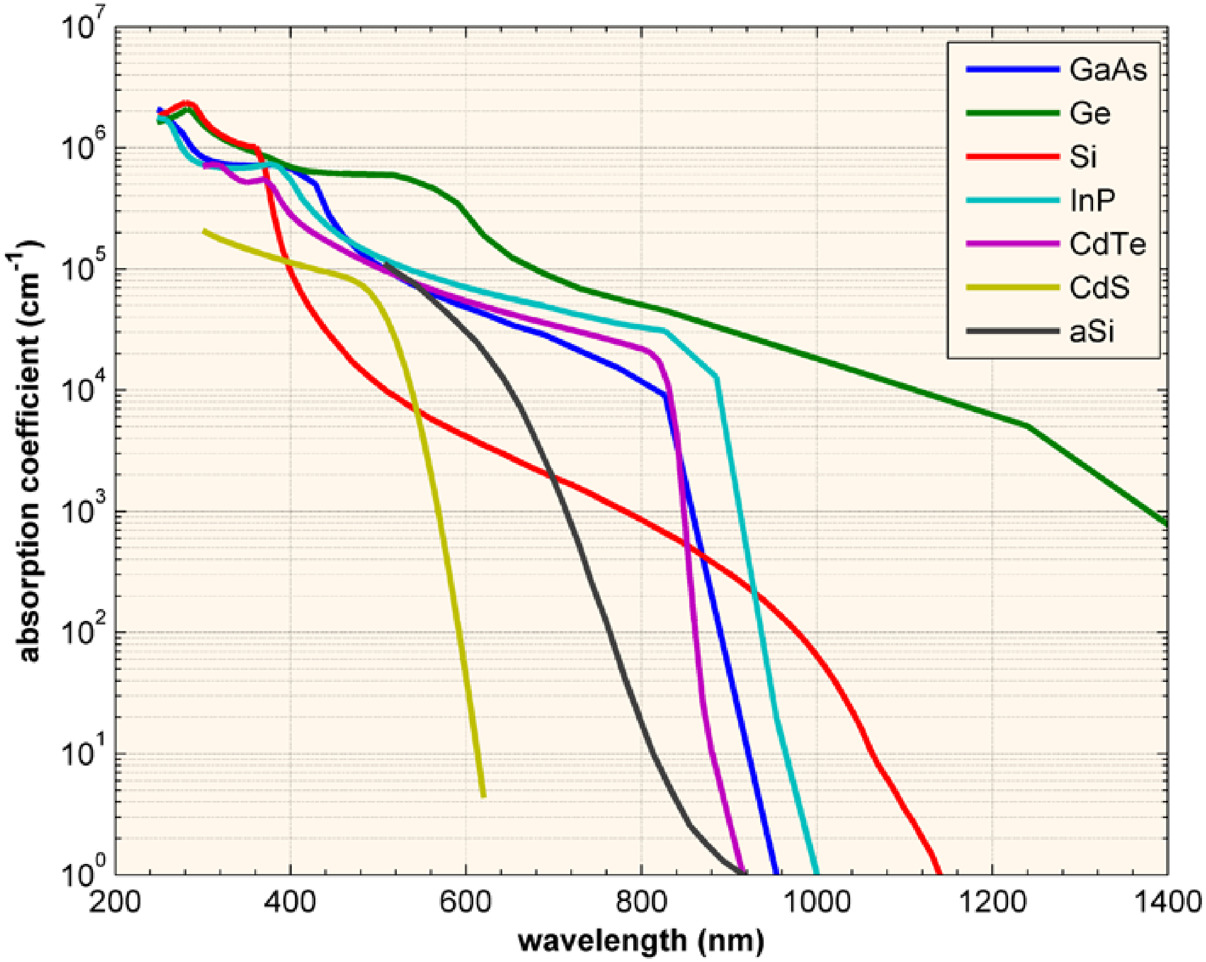
- Absorption length L_{abs}

$$L_{abs} = \alpha^{-1}$$

- Visible light (0.4 ~ 0.6um)
  - $L_{abs} \cong$ 0.1~10um



α : Depends on Material



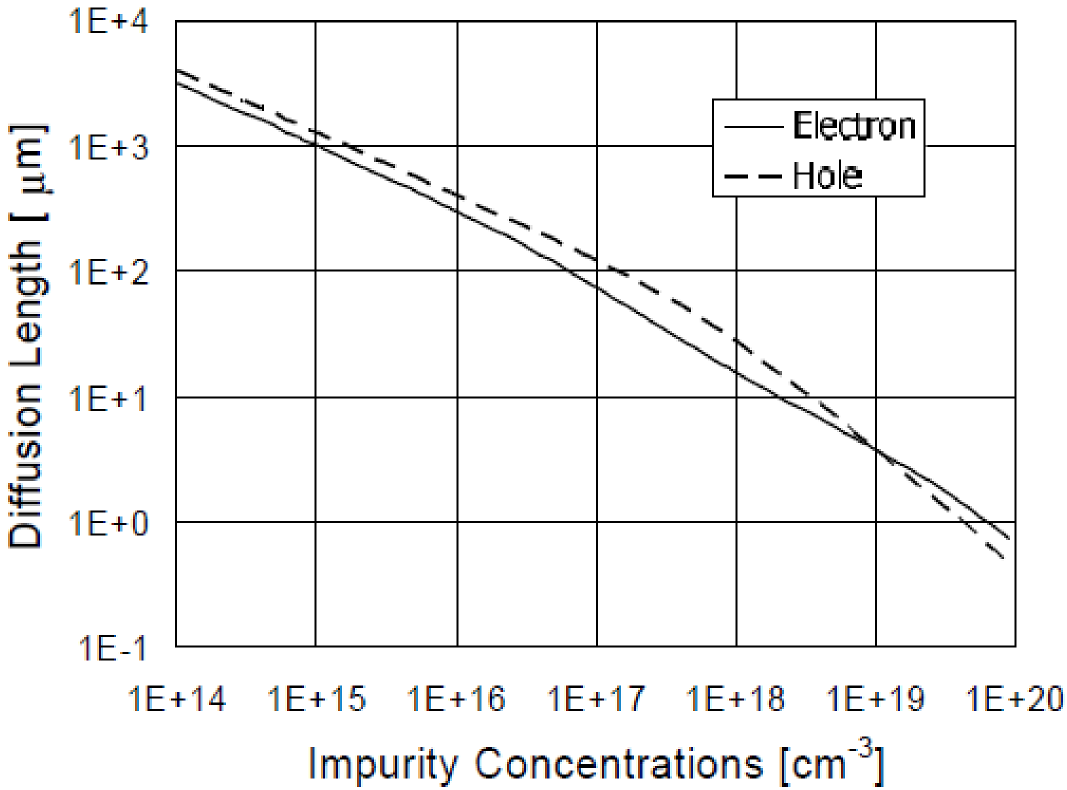
Behavior of Minority Carriers

- Large absorption length of IR
  - Photo-generated minority carrier in substrate
  - Long life time & diffusion
  - Crosstalk
  - Need IR cut filter to suppress blur effect

Diffusion Length vs. Impurity Conc.

- Diffusion lengths
  - > 10um with concentration < 1E18cm^{-3}

$$L_{e,p} = \sqrt{\frac{k_B T \mu_{n,p} \tau_{n,p}}{e}}$$



Sensitivity and Quantum Efficiency

- Sensitivity

$$R_{ph} \equiv \frac{I_L}{P_o}$$

I_L : Photocurrent, P_0: unit light power

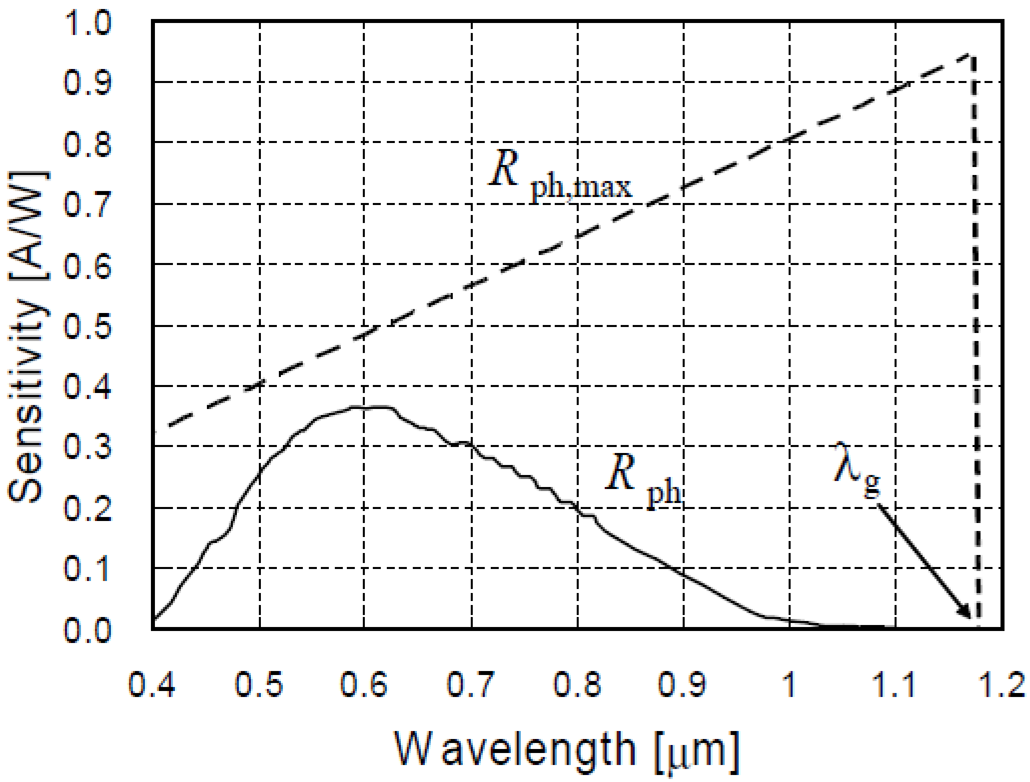
- Quantum efficiency *# of generated carrier / # of input photons*

$$\eta_Q \equiv \frac{I_L/e}{P_o/(h\nu)} = R_{ph}\frac{h\nu}{e}$$

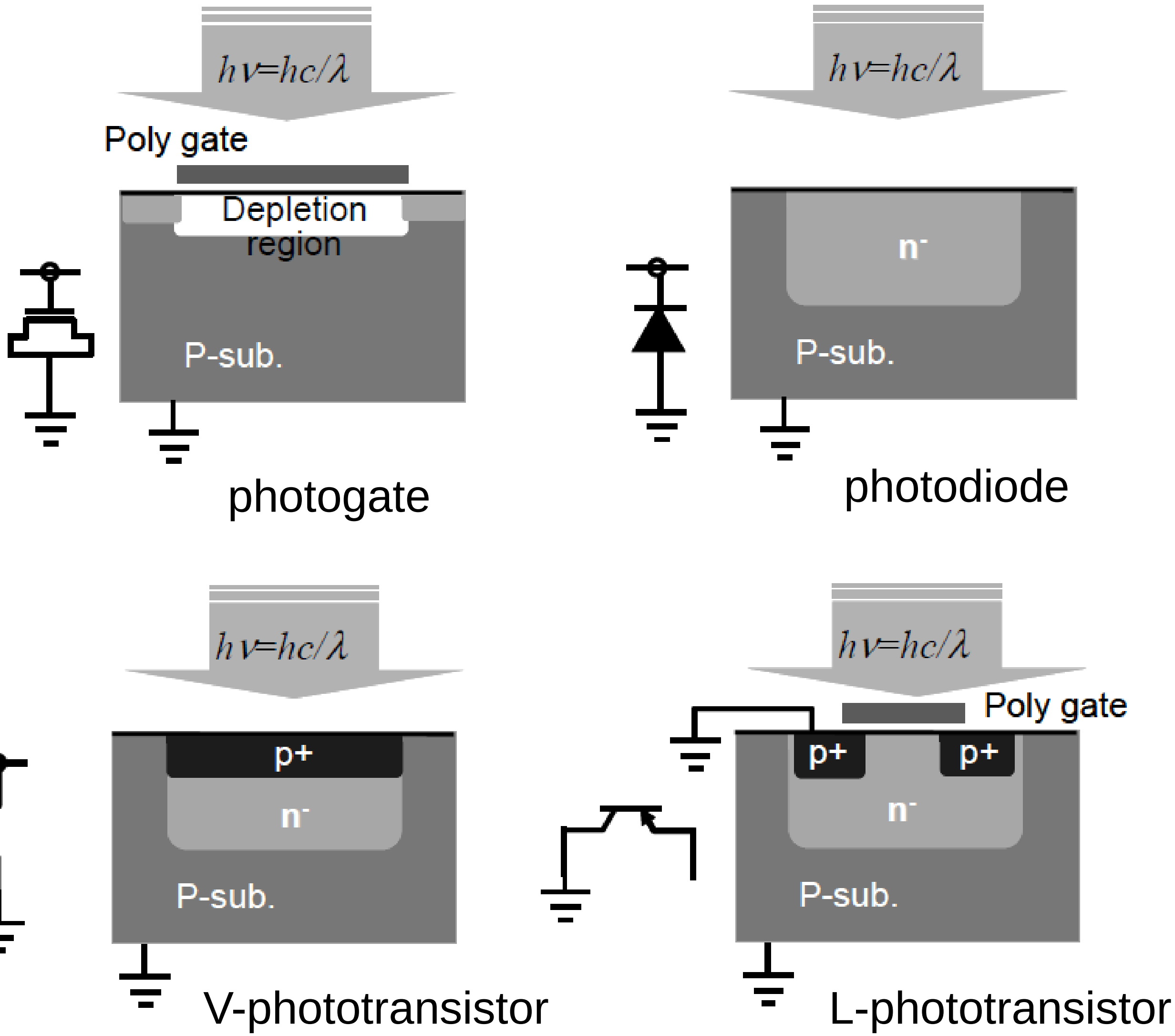
- Maximum sensitivity (at $\eta_Q = 1$)

$$R_{ph,max} = \frac{e}{h\nu} = \frac{e}{hc}\lambda = \frac{\lambda\ [\mu\mathrm{m}]}{1.23}$$

Sensitivity of Silicon



Structures of PDs, PGs, and PTrs.



PN Junction Diode

- Forward current

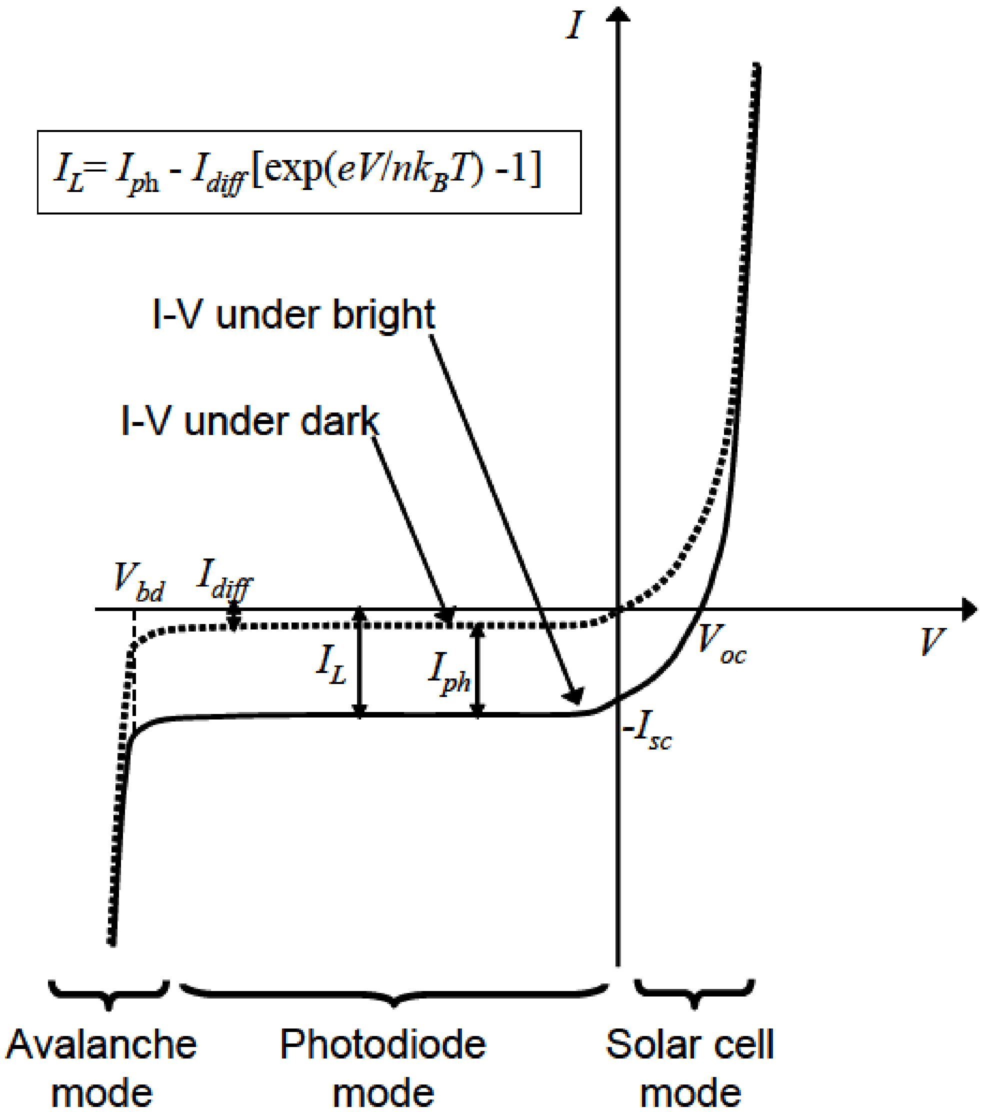
$$I_F = I_{diff}\left[\exp\left(\frac{eV}{nk_BT}\right)-1\right]$$

$$I_{diff} = eA\left(\frac{D_n}{L_n}n_{po}+\frac{D_p}{L_p}p_{no}\right)$$

- Photocurrent of the pn-junction PD

$$\begin{aligned} I_L &= I_{ph} - I_F \\ &= I_{ph} - I_{diff}\left[\exp\left(\frac{eV}{nk_BT}\right)-1\right] \end{aligned}$$

PD I–V Curves



$I_L = I_{ph} - I_{diff}[\exp(eV/nk_BT) - 1]$
I-V under bright
I-V under dark
I
V
V_{bd}
I_{diff}
I_L
I_{ph}
V_{oc}
$-I_{sc}$
Avalanche mode
Photodiode mode
Solar cell mode

- Solar cell mode (get V_{oc} from I_L=0)

$$V_{oc} = \frac{k_B T}{e} \ln\left(\frac{I_{ph}}{I_{diff}} + 1\right)$$

- PD mode (reverse biased)

$$I_L \approx I_{ph} + I_{diff}$$

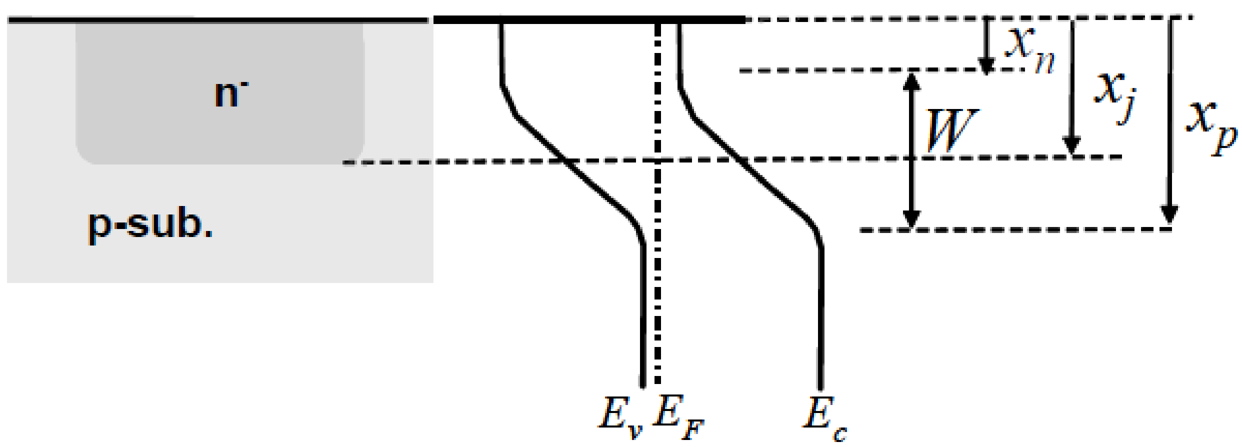
- Avalanche mode
  - Used in an avalanche photodiode (APD) : single photon detection

Quantum Efficiency and Sensitivity

- Light intensity

$$dP(z) = -\alpha(\lambda)P_o \exp[-\alpha(\lambda)z]\,dz$$

- PN-junction structure

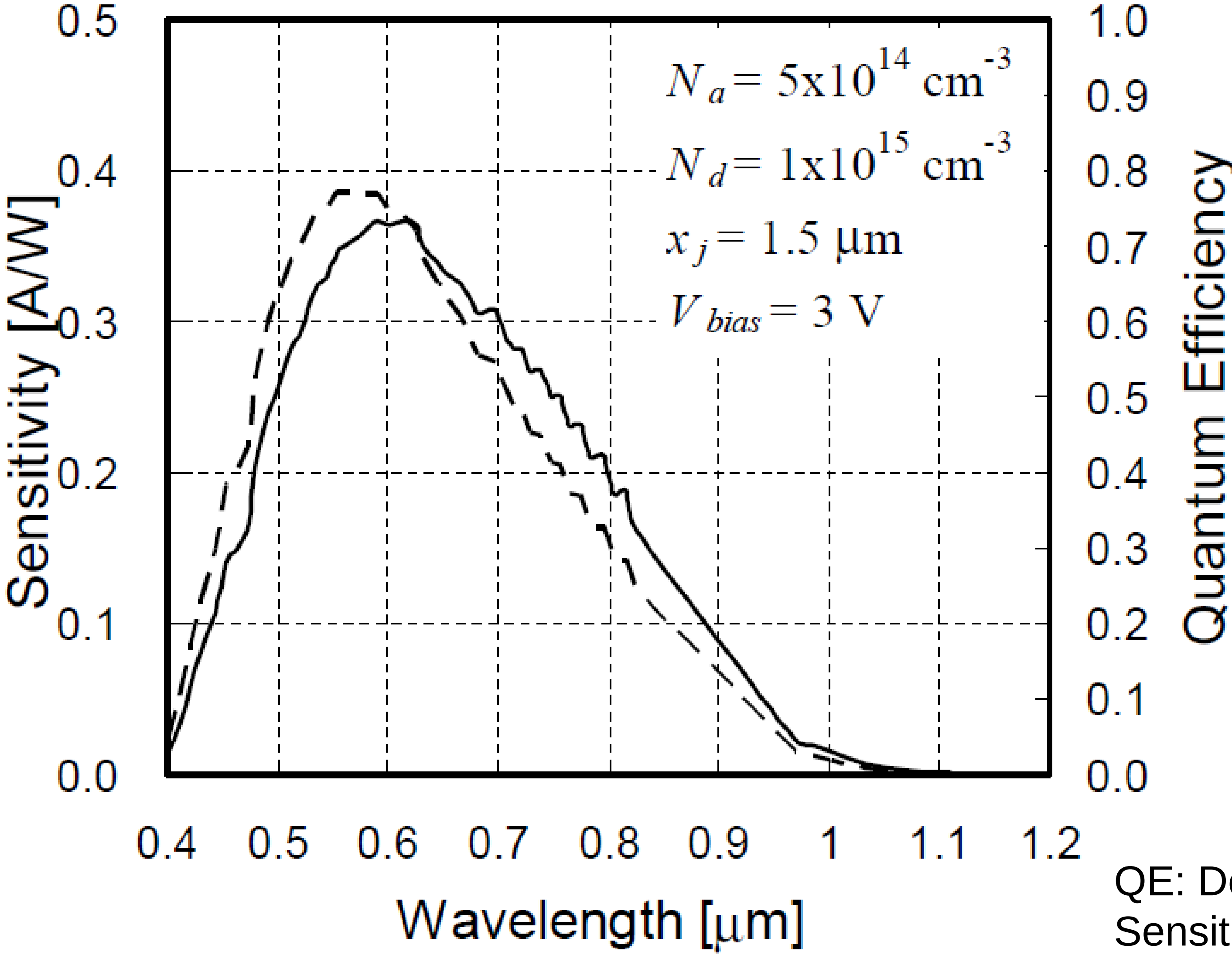


- Quantum efficiency

$$\eta_Q = \frac{\int_{x_n}^{x_p} \alpha(\lambda) P_o \exp[-\alpha(\lambda)x]\,dx}{\int_0^{\infty} \alpha(\lambda) P_o \exp[-\alpha(\lambda)x]\,dx} = (1 - \exp[-\alpha(\lambda)W]) \exp[-\alpha(\lambda)x_n]$$

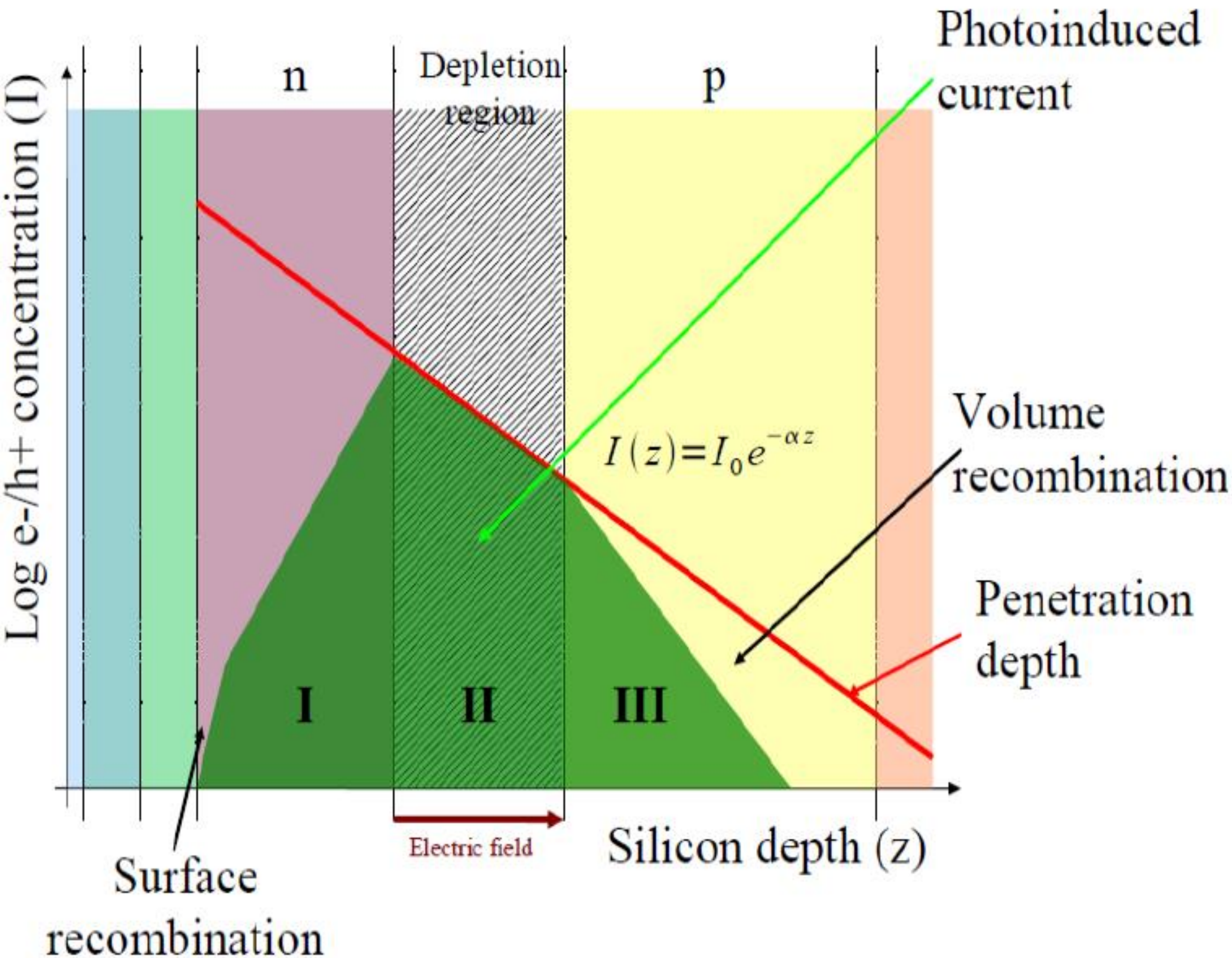
- Sensitivity

$$R_{ph} = \eta_Q \frac{e\lambda}{hc} = \frac{e\lambda}{hc}(1 - \exp[-\alpha(\lambda)W]) \exp[-\alpha(\lambda)x_n]$$

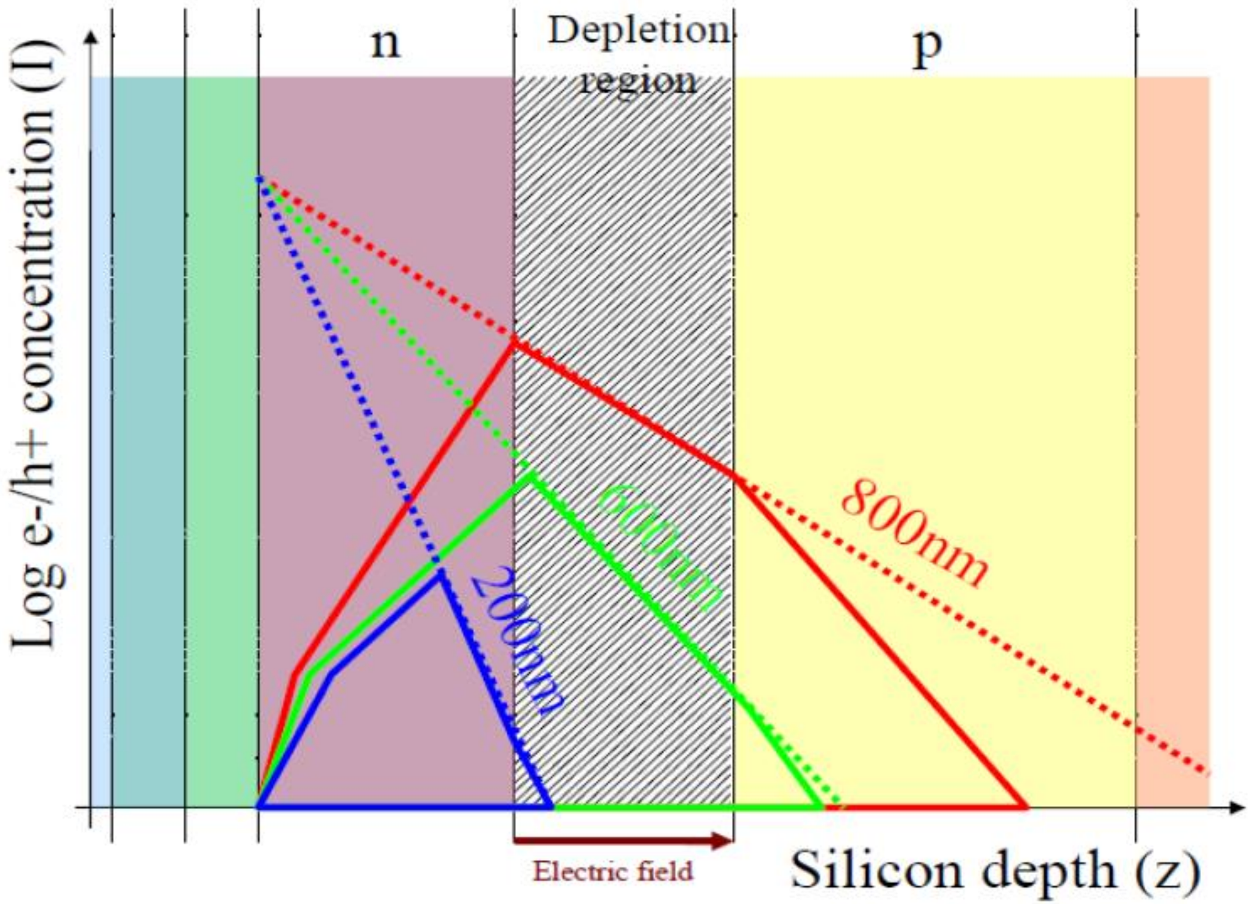


QE: Dotted
Sensitivity : Solid

QE in P-N Junction

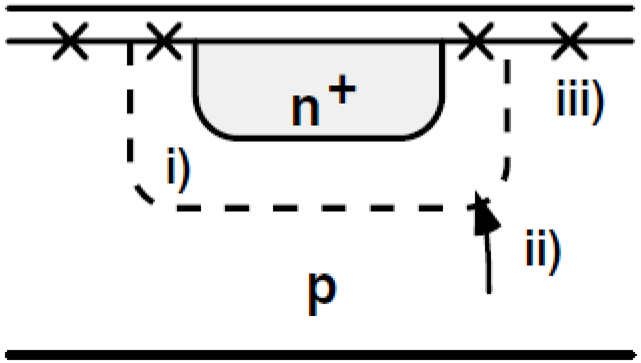


QE in P-N Junction



Dark Current

- G–R current (generation-recombination)
  - Thermal generation
- Diffusion current
  - Minority diffusion
- Surface leak current
  - Si-SiO_2 interface



i) Generation in the depletion region
ii) Diffusion from a neutral bulk
iii) Generation at the surface of Si

Dark Current

- Diffusion current

$$I_{diff} = Ae\left(\frac{D_n n_{po}}{L_n} + \frac{D_p n_{no}}{L_p}\right)$$
$$= Ae\left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right) N_c N_v \exp\left(-\frac{E_g}{k_B T}\right)$$

T↑ I_{diff} ↑

- Tunnel current
  - Band-to-band tunneling (BTBT)
  - Trap-assisted tunneling (TAT)

Dark Current

- G–R current (generation-recombination)
  - Thermal generation

$$I_{gr} = AW\frac{en_i}{\tau_g} = AW\frac{e\sqrt{N_c N_v}}{\tau_g}\exp\left(-\frac{E_g}{2k_B T}\right)$$

- Surface leak current

$$I_{surf} = \frac{1}{2}en_i s_o A_s$$

Surface Recombination

- SiO_2 interfaces the surface of the silicon
  - Produce surface states or interface states
  - Carriers near the surface are trapped
  - Degrade the quantum efficiency or sensitivity (critical for short wavelength light)

Dependence of I_{dark} (T, V)

Process	Dependence
Diffusion	$\propto \exp\left(-\frac{E_g}{k_B T}\right)$
G–R	$\propto \sqrt{V} \exp\left(-\frac{E_g}{2k_B T}\right)$
Band-to-band tunneling	$\propto V^2 \exp\left(\frac{-a}{V}\right)$
Trap-assisted tunneling	$\propto \exp\left(\frac{-a'}{V}\right)^2$
Impact ionization	$\alpha \propto \exp\left(\frac{-b}{V}\right)$
Frankel–Poole	$\propto V \exp\left(\frac{-c}{T}\right)$
Surface leak	$\propto \exp\left(-\frac{E_g}{2k_B T}\right)$

Temporal Noise

- Shot noise

$$i_{sh,\ rms} = \sqrt{2e\bar{I}\Delta f}$$

- Signal-to-noise ratio (SNR) for shot noise

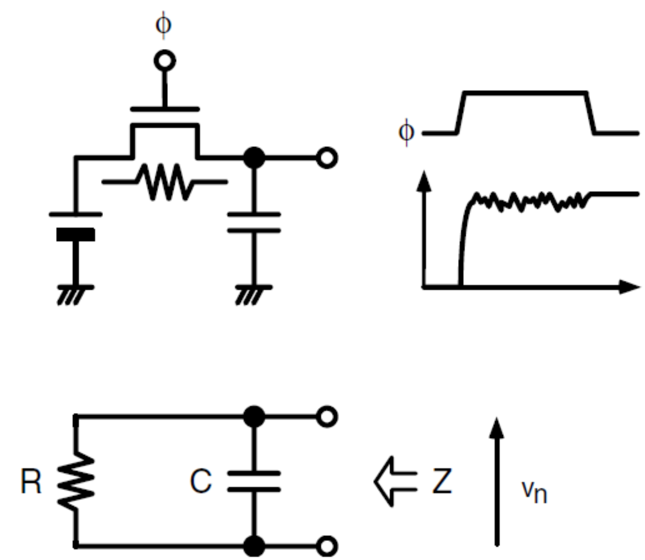
$$\mathrm{SNR} = \frac{\bar{I}}{\sqrt{2e\bar{I}\Delta f}} = \frac{\sqrt{I}}{2e\Delta f}$$

Temporal Noise

- Thermal noise
  - Johnson noise or Nyquist noise
  - Appears as *kTC noise*

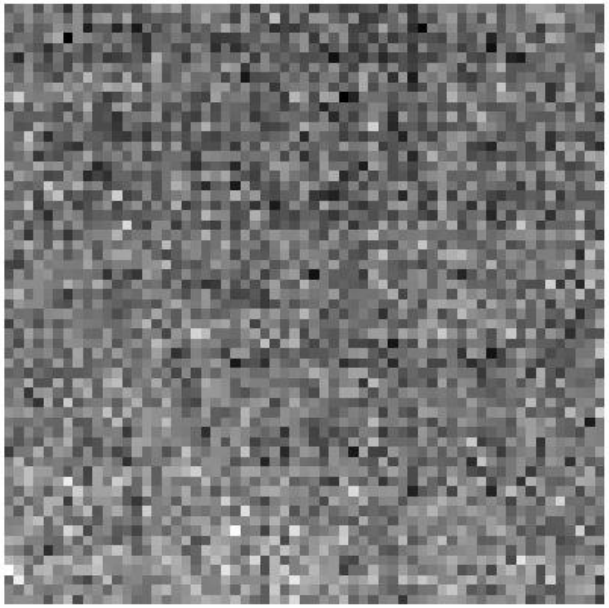
$$v_n{}^2 = \int_0^{\infty} 4kT \cdot \frac{R}{1+(2\pi fRC)^2} \cdot df = \frac{kT}{C}$$

$$q_n{}^2 = C^2 \cdot v_n{}^2 = kTC$$

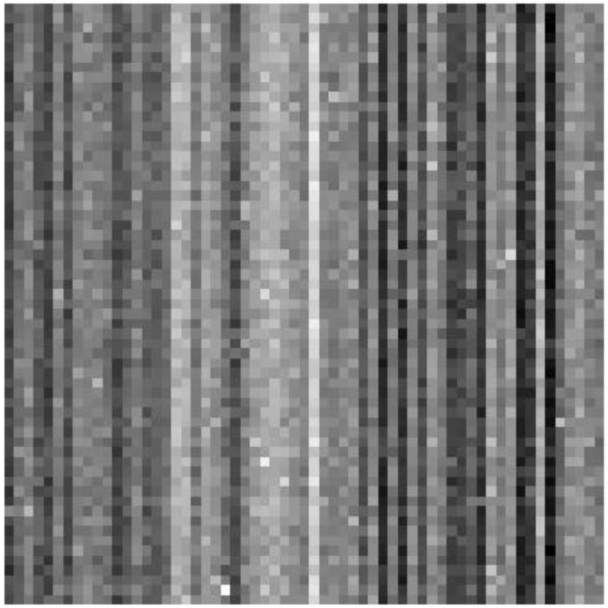


Spatial Noise

- Fixed Pattern Noise (FPN)
  - Pixel uniformity
  - Readout circuit uniformity

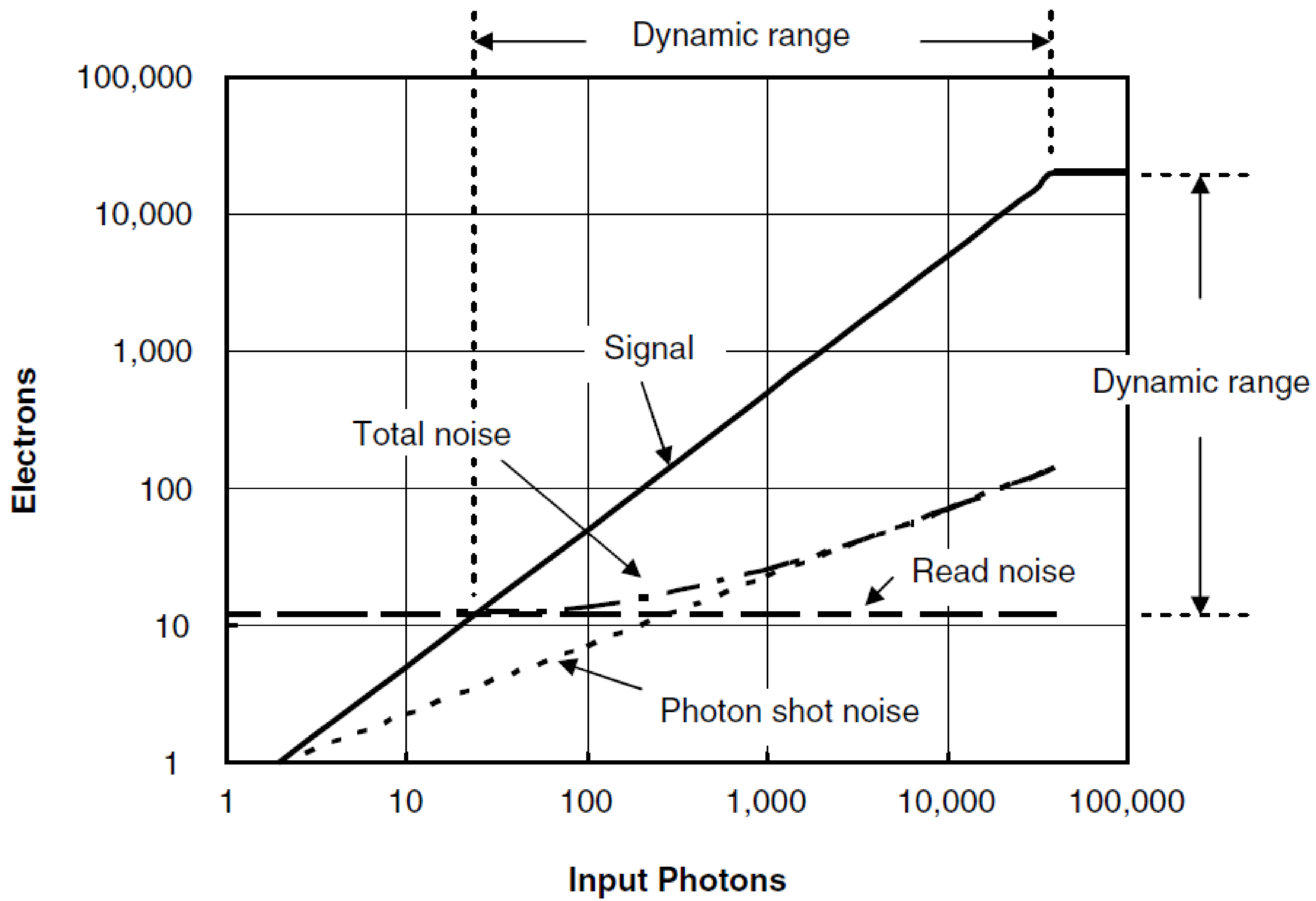


Array FPN



Column FPN

Photon Transfer Curve



Noise

- Shot noise

$$i_{sh,\ rms} = \sqrt{2e\bar{I}\Delta f}$$

- Signal-to-noise ratio (SNR) for shot noise

$$\mathrm{SNR} = \frac{\bar{I}}{\sqrt{2e\bar{I}\Delta f}} = \frac{\sqrt{I}}{2e\Delta f}$$

Noise

- Thermal noise
  - also Johnson noise or Nyquist noise
  - appears as $k_B TC$ *noise*

$$i_{sh,\ rms} = \sqrt{\frac{4k_B T \Delta f}{R}}$$

Speed

- Some kinds of smart image sensors need a PD with a fast response
  - for optical wireless LANs
  - measure time-of-flight (TOF)

- The response of a PD is limited by

(1) CR time constant

$$\tau_{CR} = 2\pi C_D R_L$$

(2) Transit time

$$\tau_{tr} = W / v_s$$

(3) Diffusion time of minority carriers

$$\tau_{n,p} = L_{n,p}^2 / D_{n,p}$$

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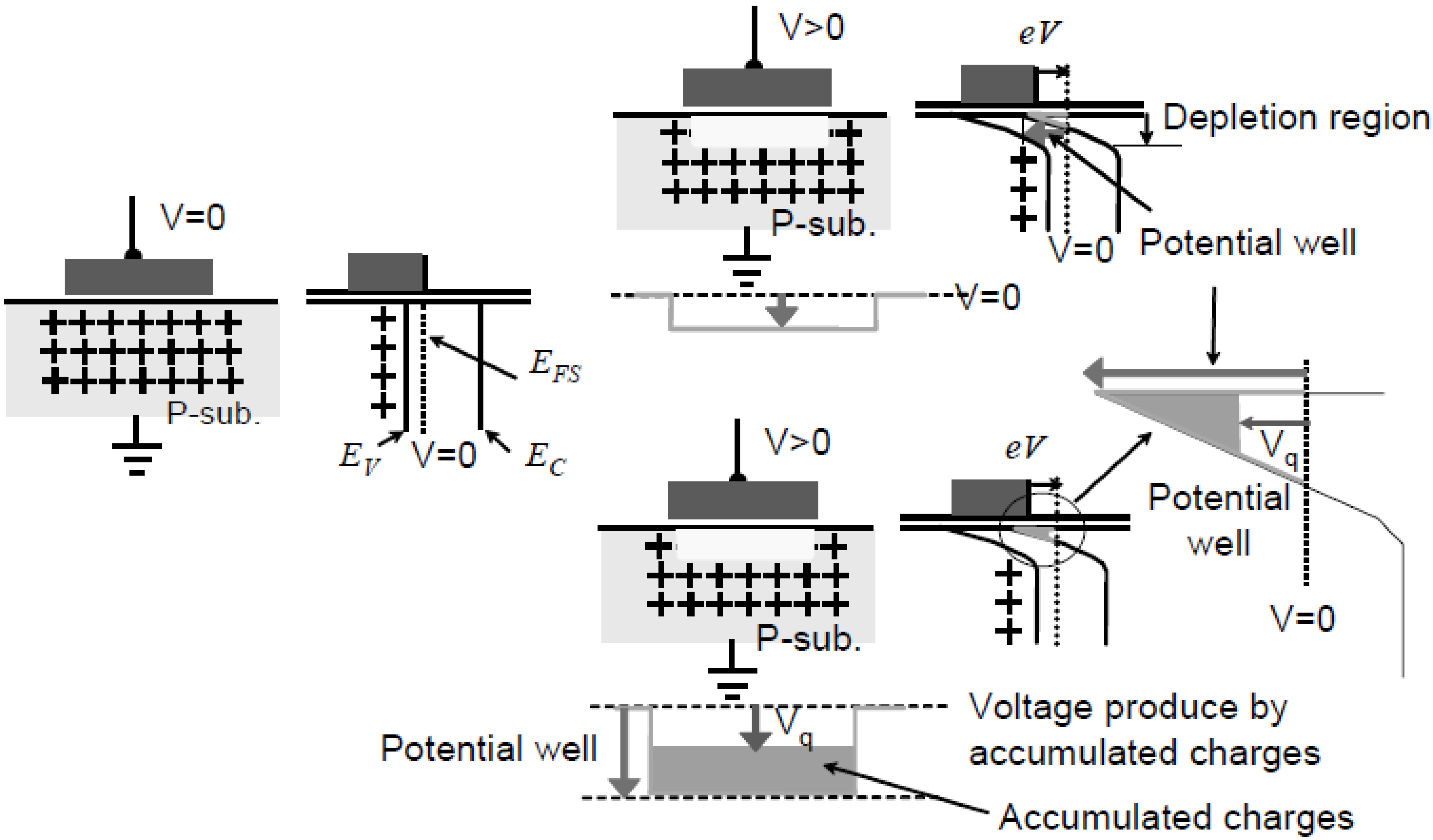
Photogate


V=0
P-sub.
E_{FS}
E_V
V=0
E_C
V>0
P-sub.
eV
Depletion region
V=0
Potential well
V=0
V>0
P-sub.
eV
Potential well
V_q
V=0
Potential well
V_q
Voltage produce by accumulated charges
Accumulated charges

Phototransistor

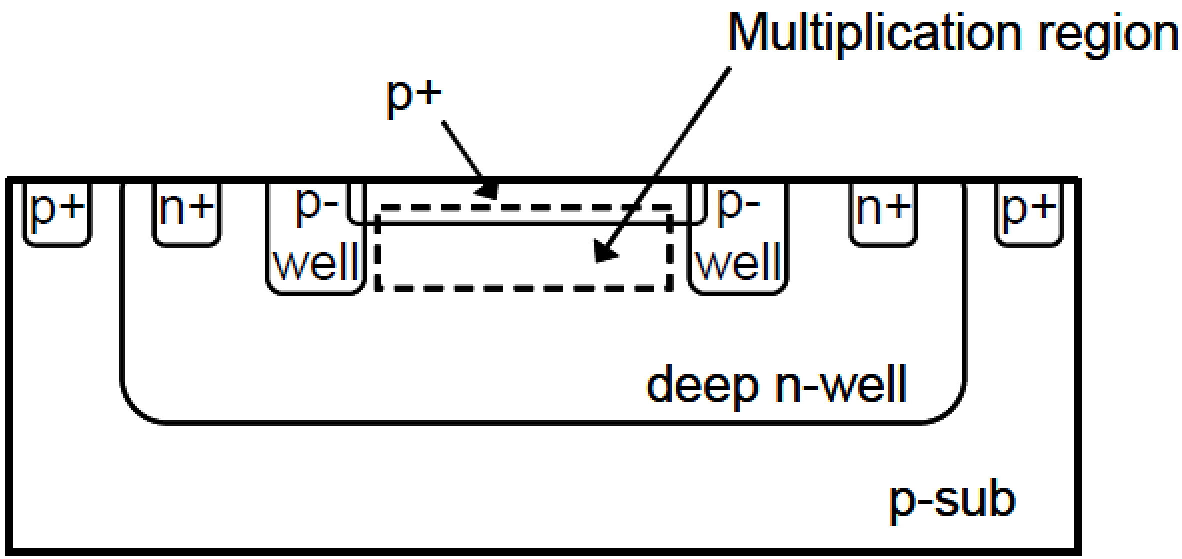
- Amplifies a photocurrent by a factor of the base current gain β
  - Not high, typically about 10–20
  - Large variation (produces FPN)

- When base width increases, the quantum efficiency increases but the gain decreases

Avalanche Photodiode (APD)

- High-speed response
- Optical fiber communication
- Ultra low light detection (single photon)
- Spike-current output (not for imaging)
- Require a high voltage over 100 V
- Low voltage operation possibility at sub-micron technology

Avalanche Photodiode Structure



Photoconductive Detector (PCD)

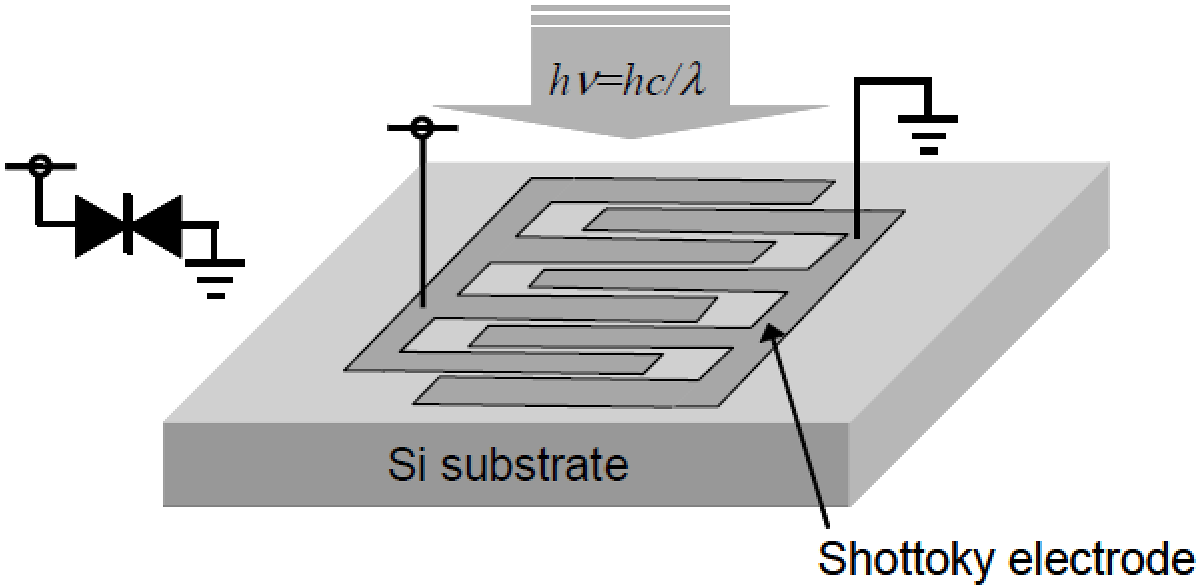
- Typically has a structure of n^+–n^-–n^+
- Gain originates from two parts
  - Long lifetime of holes τ_p
  - Short transit time of electrons t_{tr}

$$G_{PC} = \frac{\tau_p}{t_{tr}}\left(1 + \frac{\mu_p}{\mu_n}\right)$$

MSM Photodetector

- Metal-Semiconductor-Metal (MSM) Photodetector
  - A kind of PCD
- Easy to fabricate
- Ultra-fast photodetectors (GaAs MSM)
- Image sensors with a sensitivity in the UV region (GaN MSM)

Structure of MSM Photodetector



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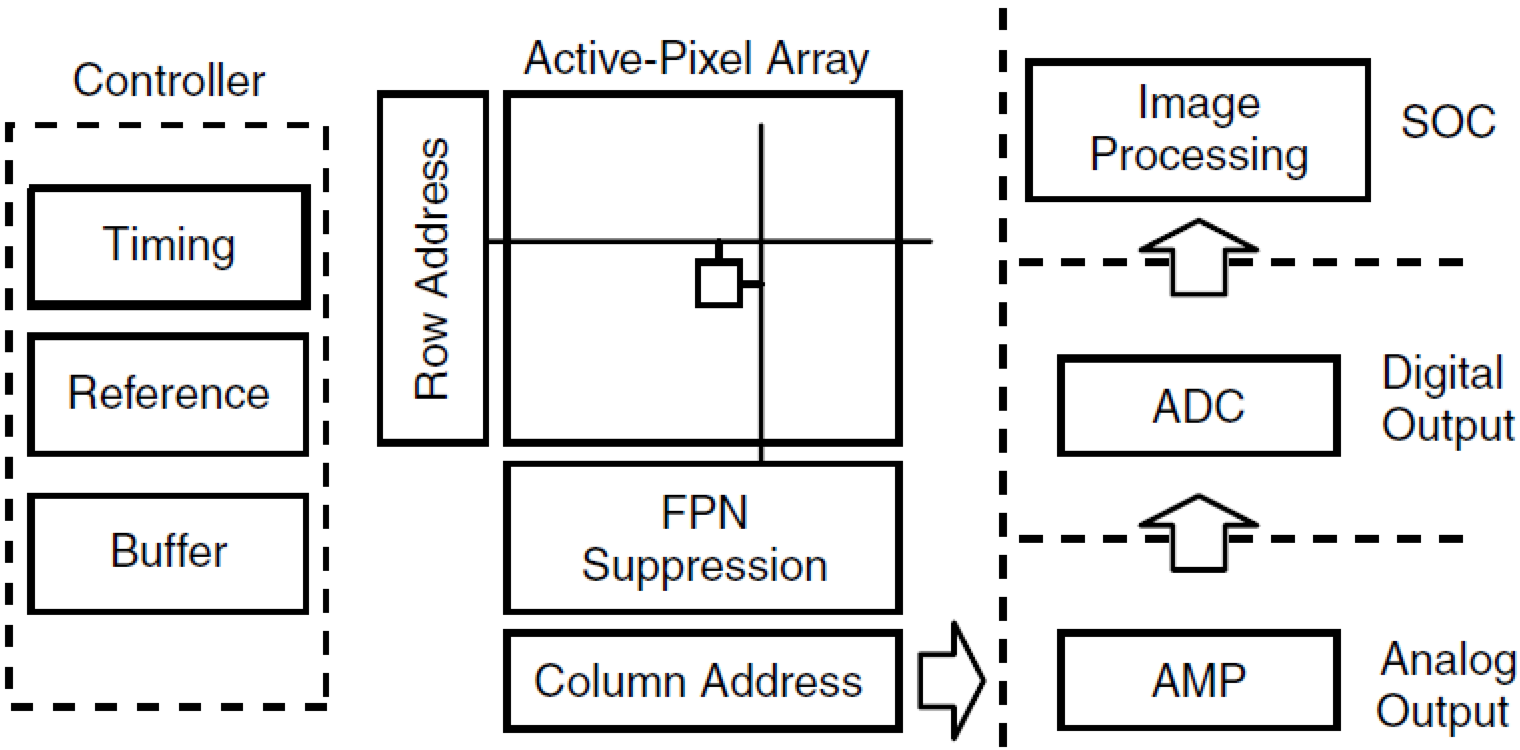
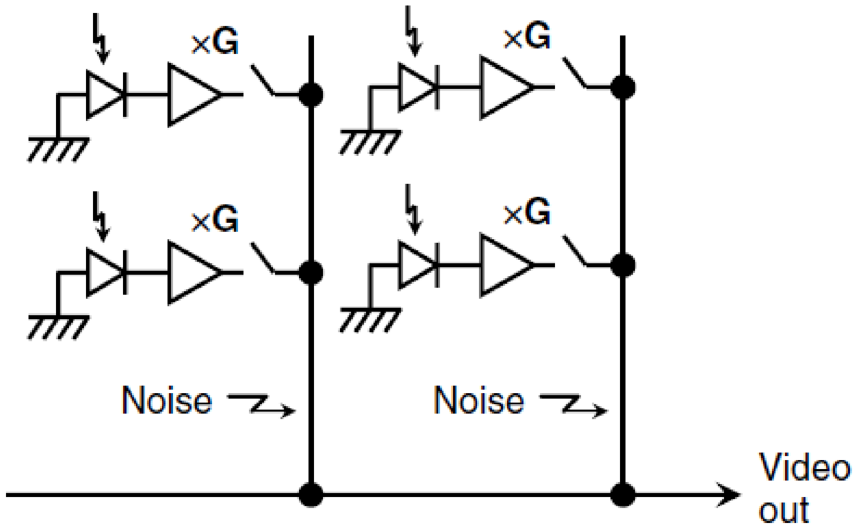
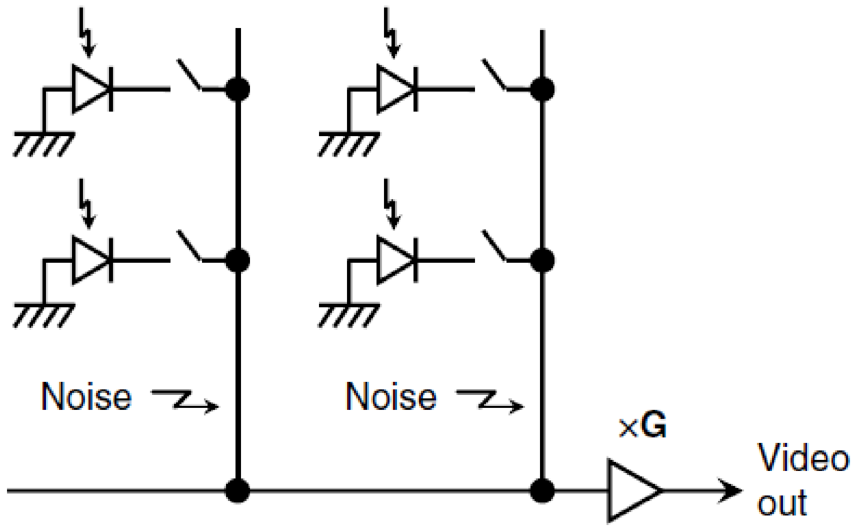
Architecture of a CIS



Active & Passive Pixel

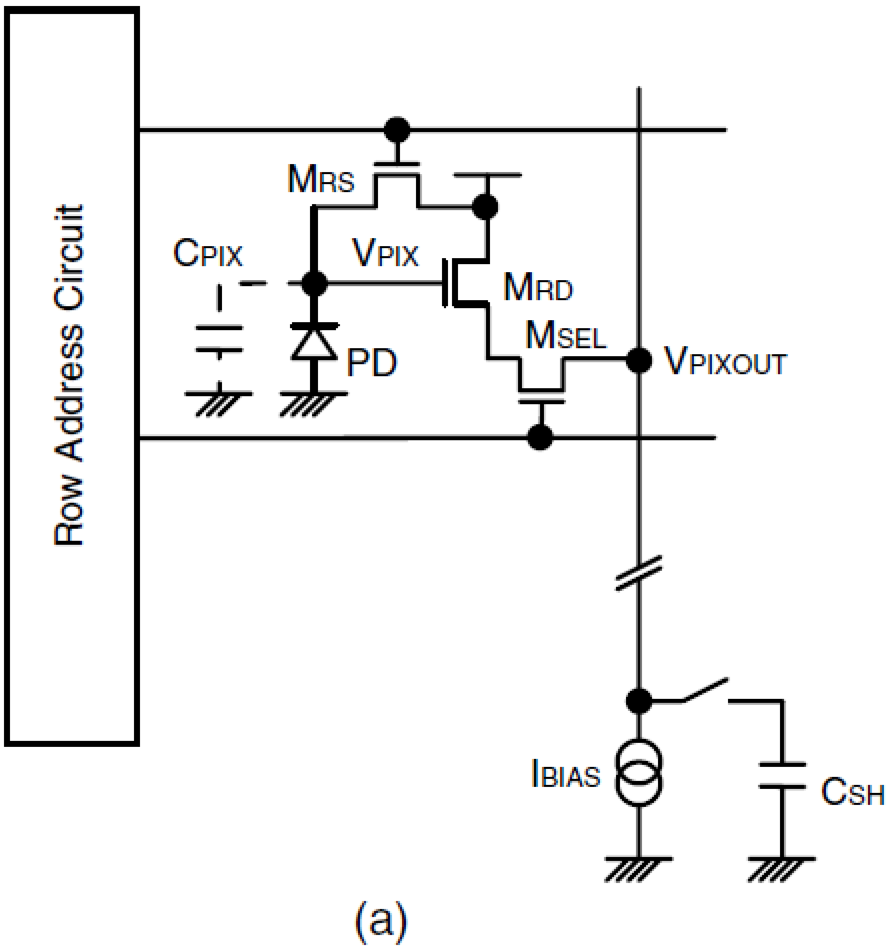


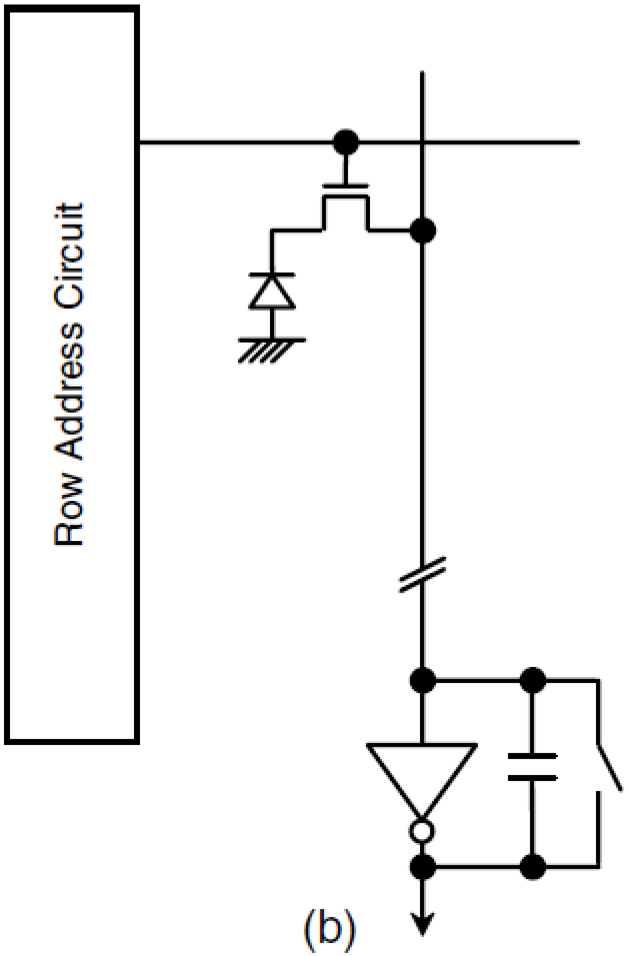
(a) Active



(b) Passive

Active & Passive Pixel





Accumulation Mode

- Electrical floating PD as capacitor
- Accumulation of photo-generated carrier is interpreted as discharge process.
- R_{ph} = 0.3A/W, PD area A = 100um^2, illumination L_o = 100lux, 1lux~= 1.6x10^{-7}W/cm^2

$$
\begin{aligned}
I_{ph} &= R_{ph} \times L_o \times A \\
&= 0.3\,\mathrm{A/W} \times 100 \times 1.6 \times 10^{-7}\,\mathrm{W/cm^{-2}} \times 100\,\mu\mathrm{m}^2 \\
&\approx 10\,\mathrm{pA}.
\end{aligned}
$$

- Accumulation is necessary at video rate

Accumulation Mode

- Junction capacitance (depends on applied bias V)

$$C_{PD}(V) = \frac{\varepsilon_o \varepsilon_{Si}}{W}$$

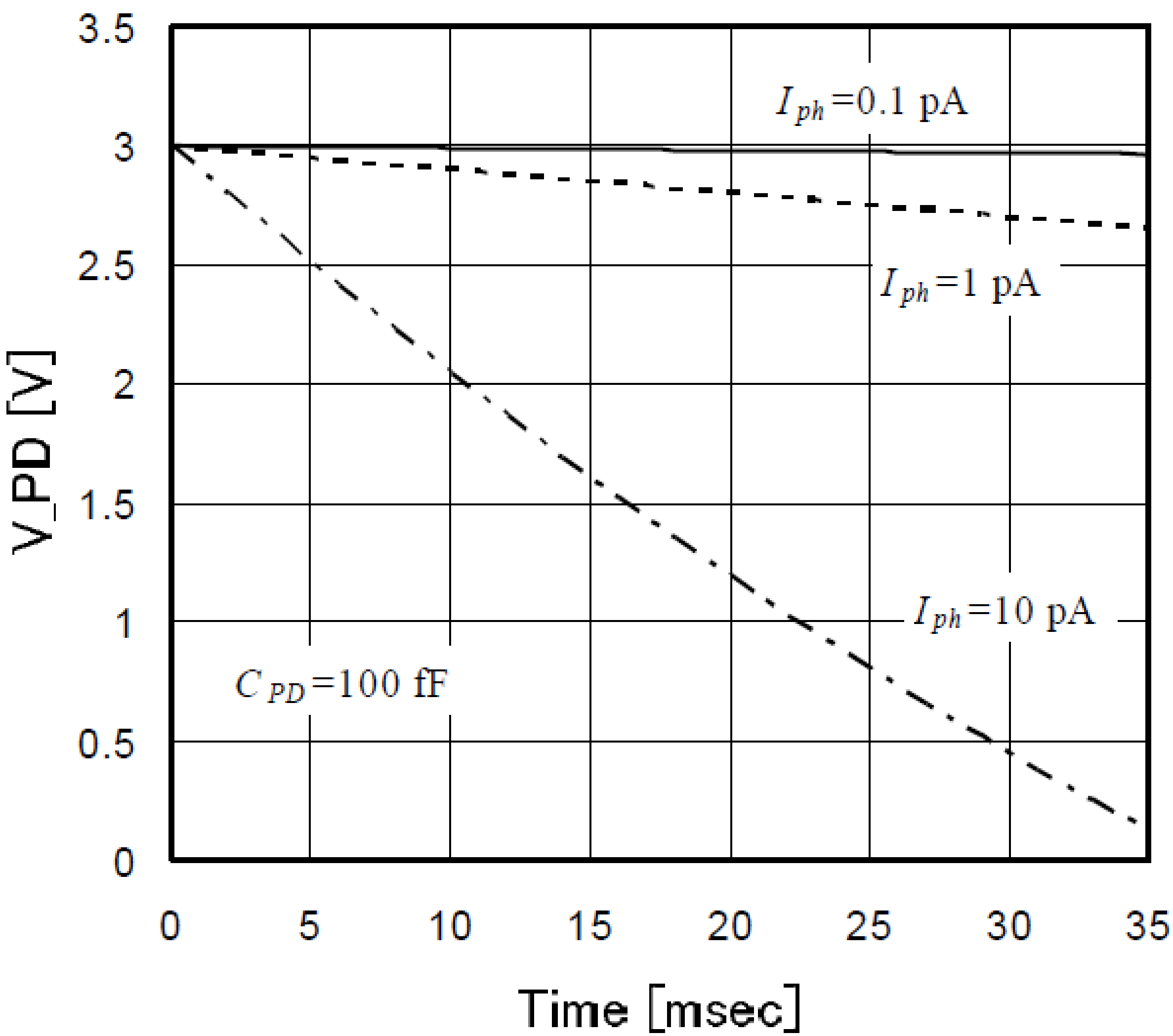
$$W = K(V + V_{bi})^{m_j}$$

- For $C_{PD}(V)$: linearly proportional to $I_{ph} + I_d$

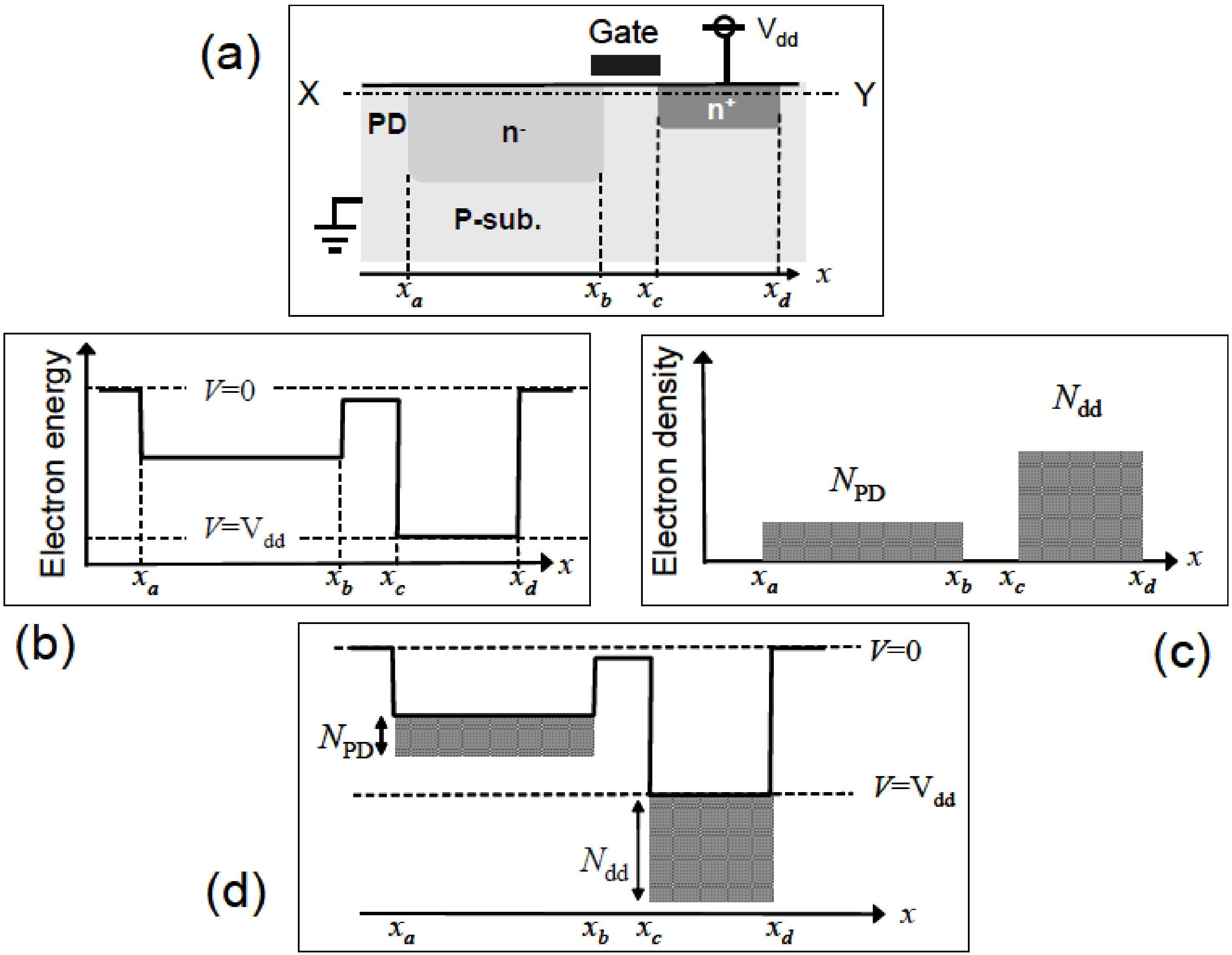
$$C_{PD}(V)\frac{dV}{dt} + I_{ph} + I_d = 0$$

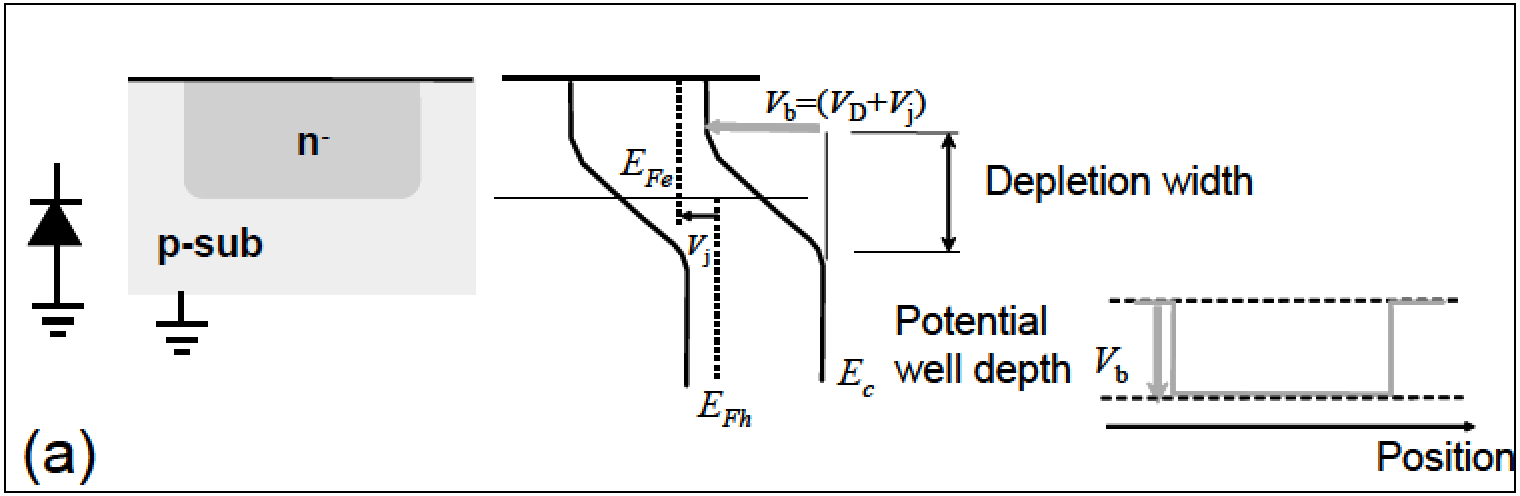
$$V(t) = (V_0 + V_{bi})\left[1 - \frac{(I_{ph} + I_d)(1 - m_j)}{C_0(V_0 + V_{bi})}t\right]^{\frac{1}{1-m_j}} - V_{bi}$$

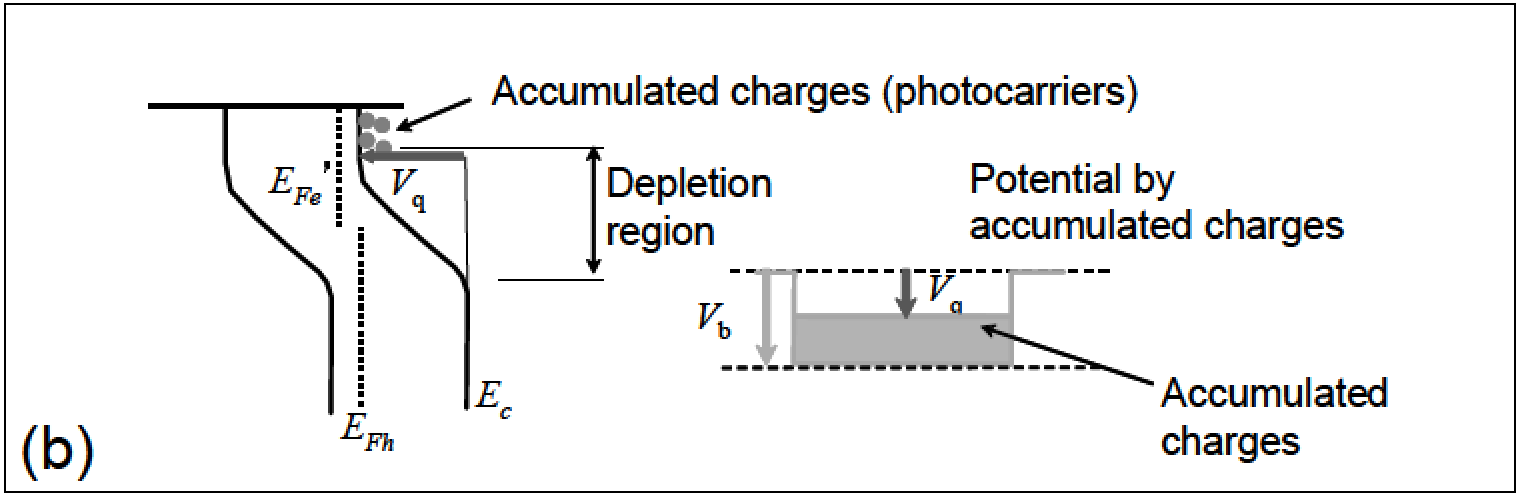
Voltage Drop of a PD



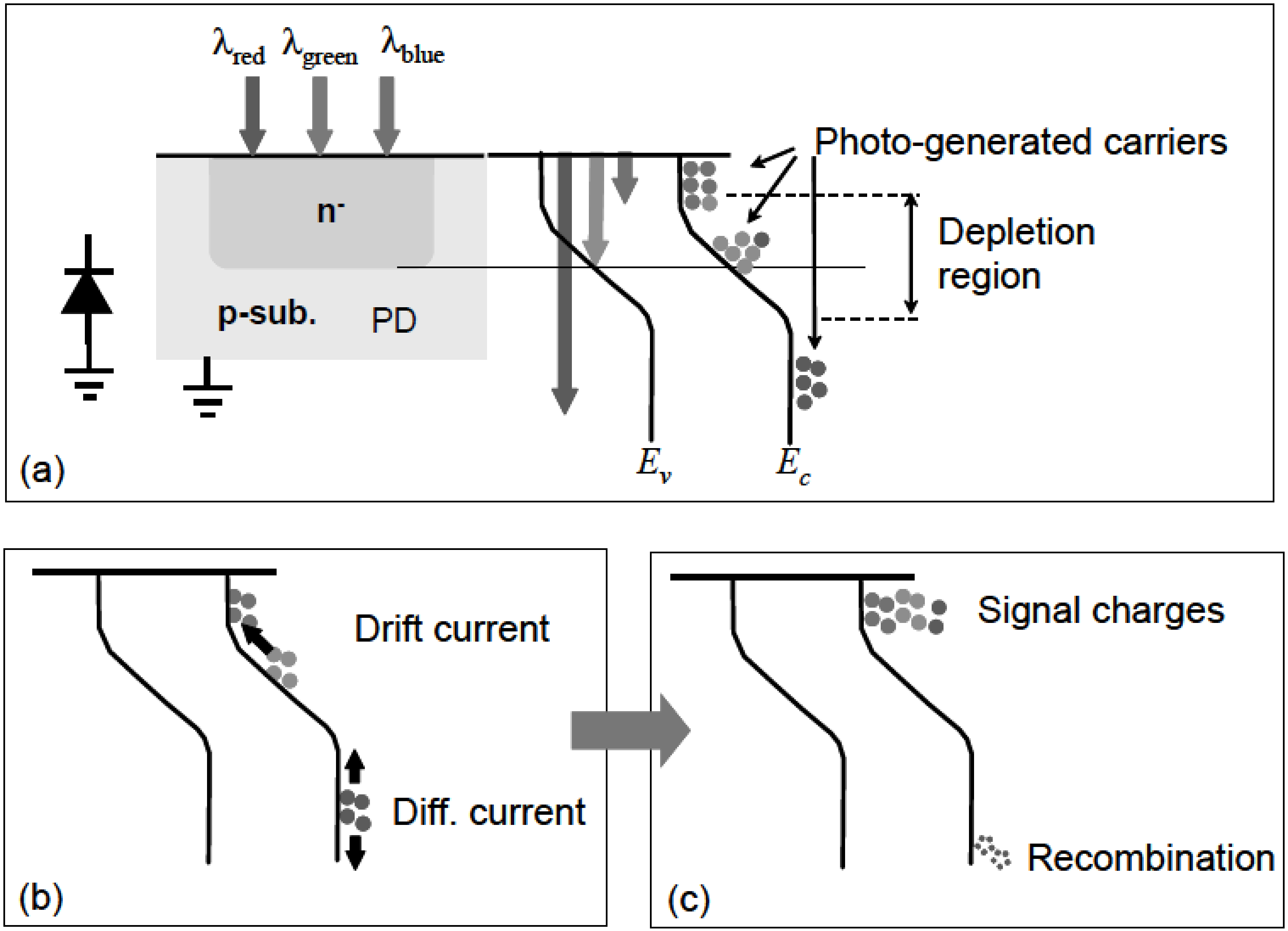
Potential Description




n-
p-sub
$V_b=(V_D+V_j)$
E_{Fe}
V_j
Depletion width
Potential
well depth
E_c
E_{Fh}
V_b
Position
(a)


Accumulated charges (photocarriers)
E_{Fe}'
V_q
Depletion
region
Potential by
accumulated charges
V_q
V_b
Accumulated
charges
E_c
E_{Fh}
(b)

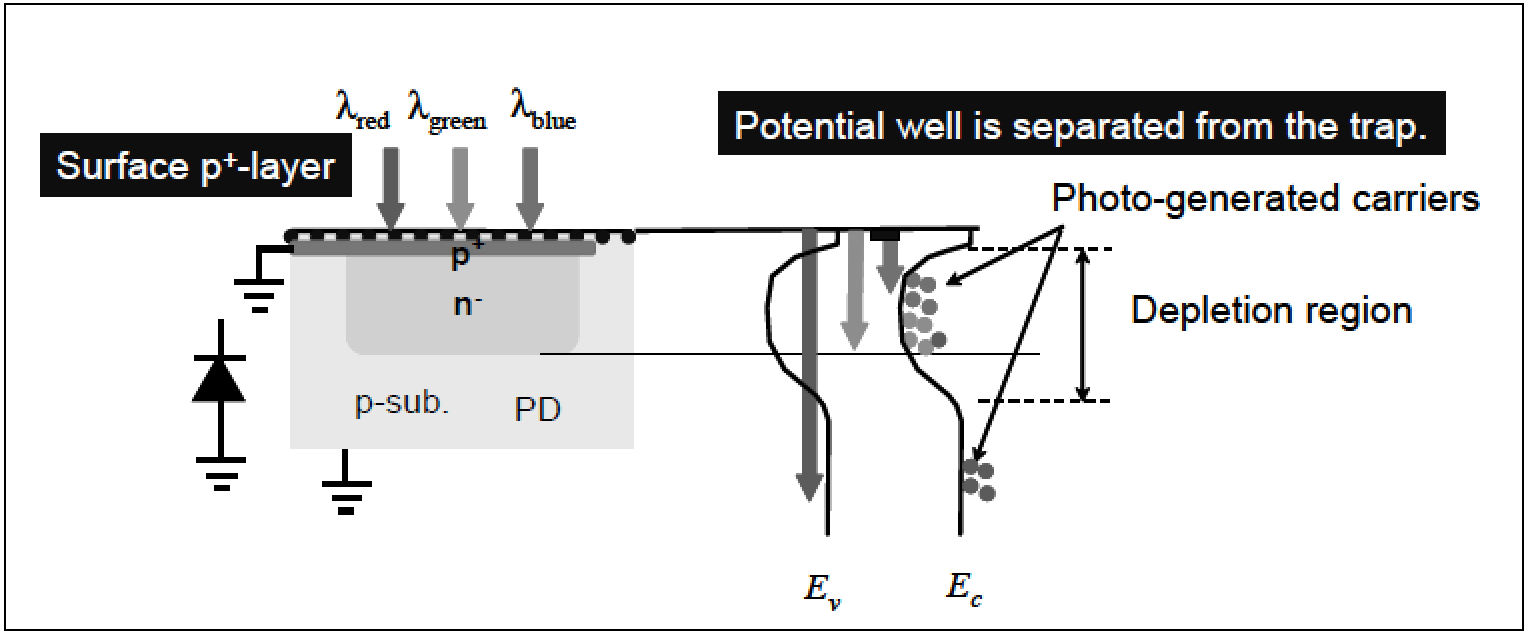
Behavior of Carriers in PD



Pinned Photodiode (PPD)

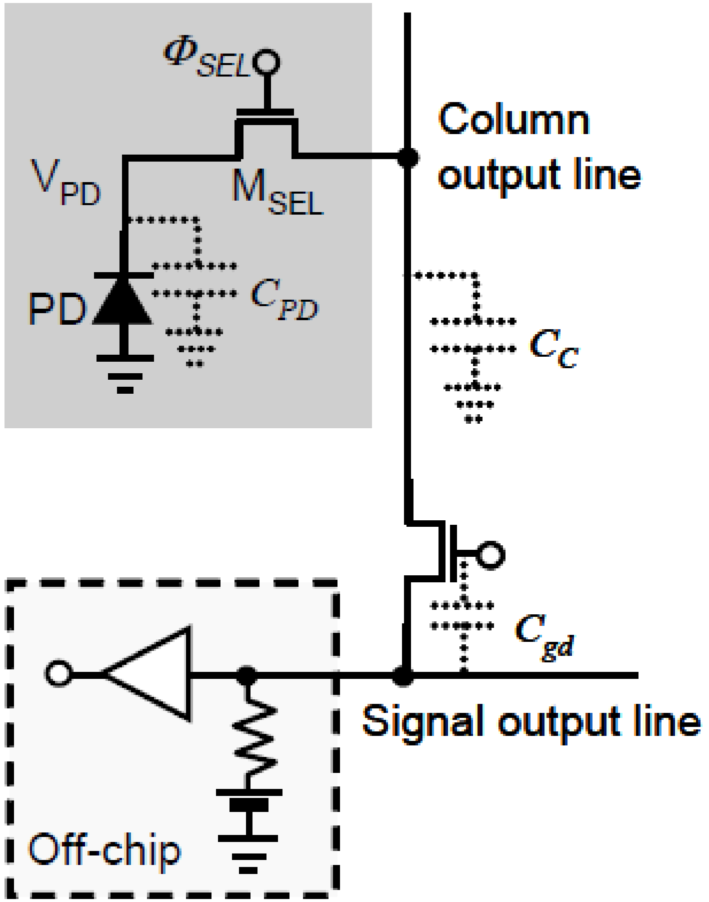
- Also buried photodiode (BPD)
- Has less dark current than a conventional PD
- Has an accumulation region with complete depletion
  - Need precise fabrication process control

Photo-Generated Carriers in PPD



Passive Pixel Sensor

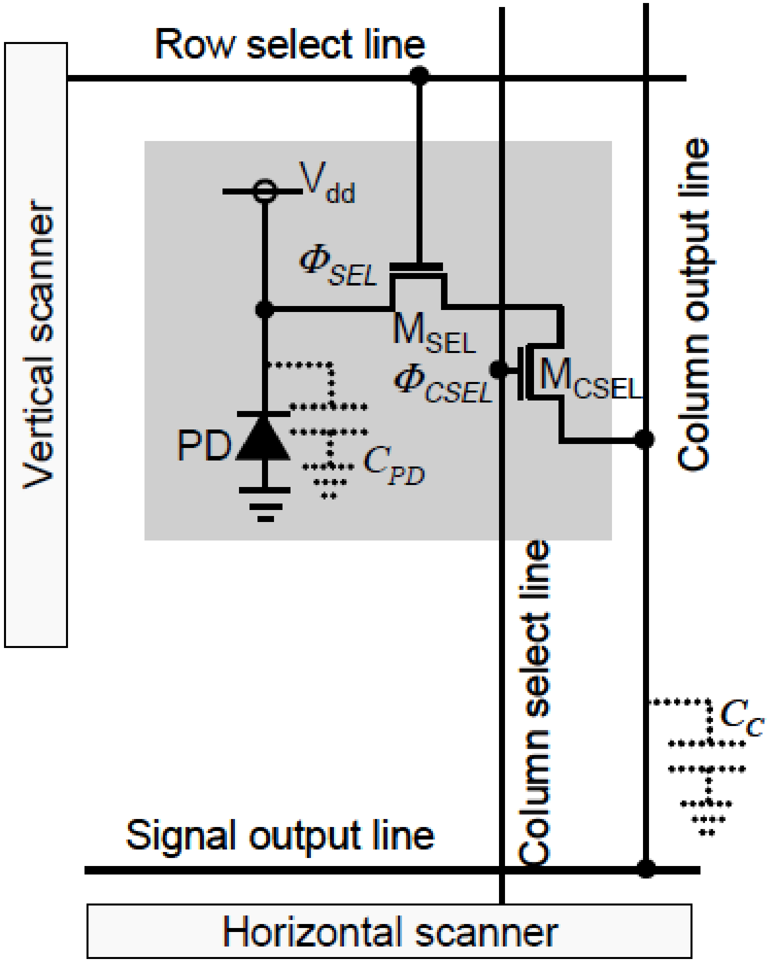
- Advantages
  - very simple
  - large fill factor (FF)
- Disadvantages
  - large smear (?)
  - large $k_B TC$ *noise*
  - large column FPN



http://www.dallmeier.com/fr/produits-electronic/cameras/bon-a-savoir/ccd-vs-cmos.html

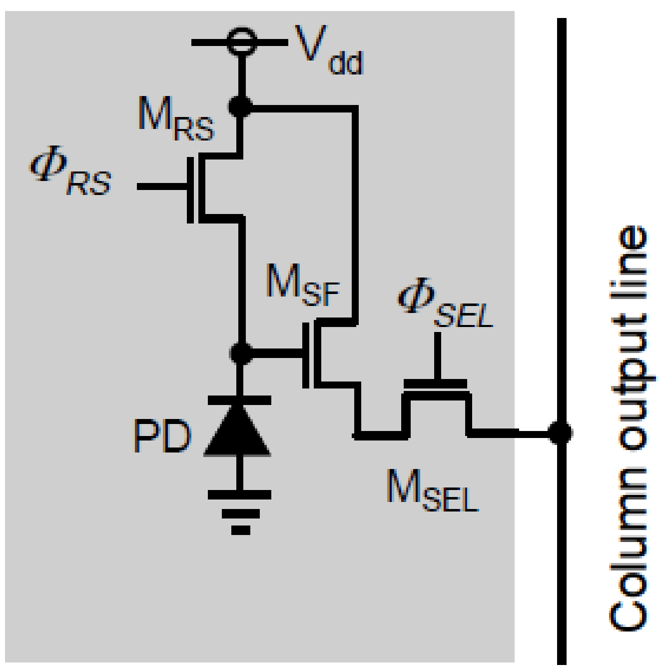
Transversal Signal Line (TSL)

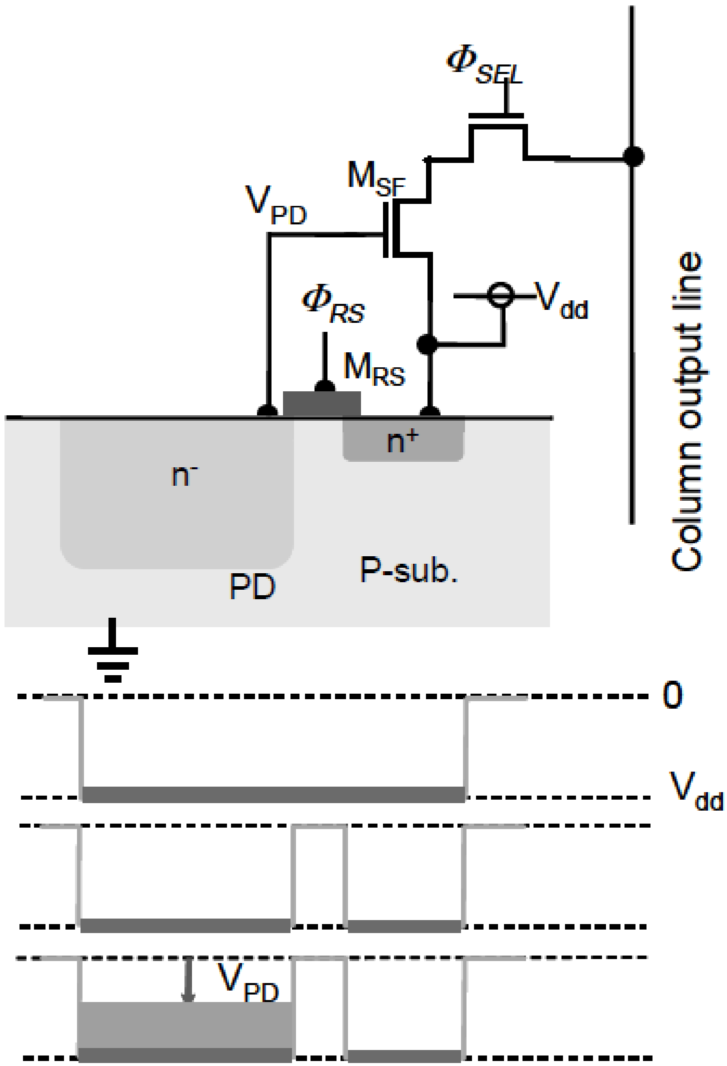
- Drastically reduces smear (?)
- $k_B TC$ noise is reduced
- Little switching noise



Active Pixel Sensor, 3T-APS

- Basic pixel circuits of a 3T-APS



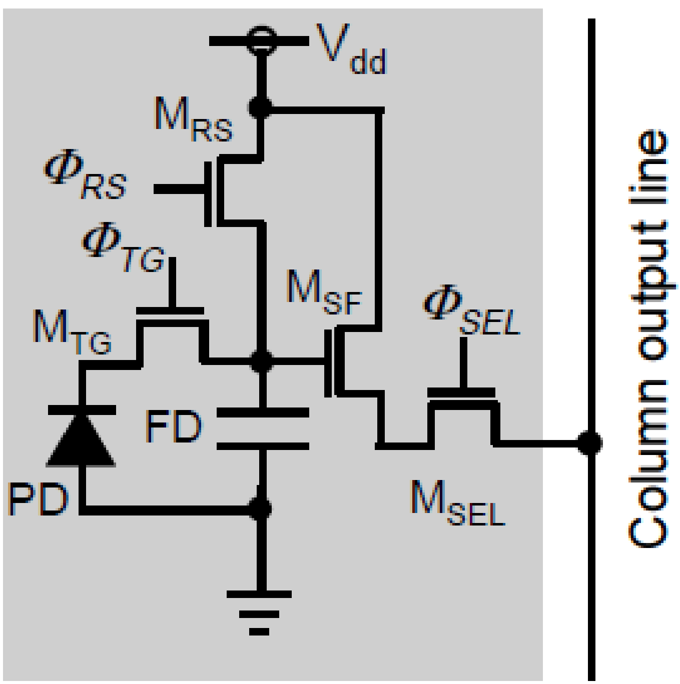


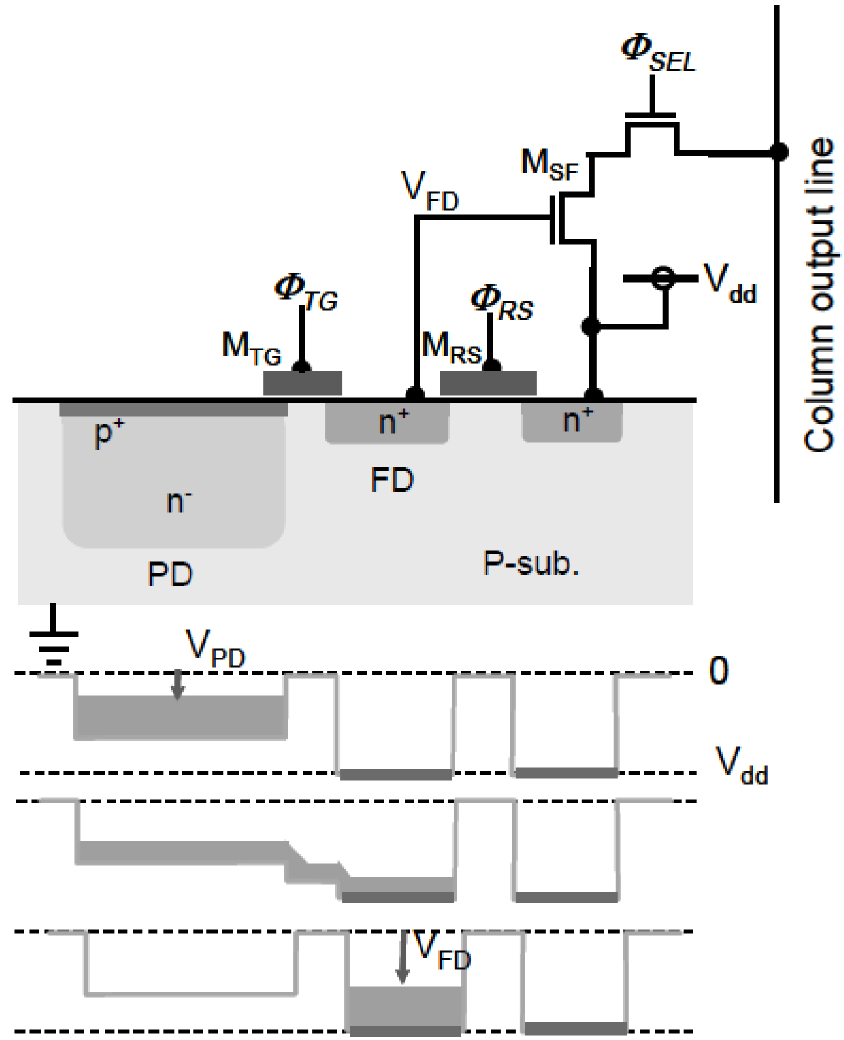
Issues with 3T-APS

- It is difficult to suppress $k_B TC$ noise
- PD simultaneously acts as a photo conversion region. This constrains the PD design
- Full-well capacity and the conversion gain have a trade-off relationship

Active Pixel Sensor, 4T-APS

- Basic pixel circuits of the 4T-APS

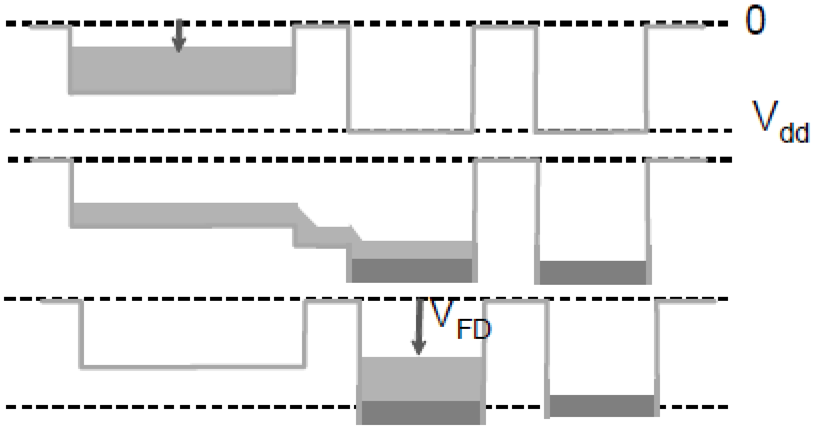




Issues with 4T-APS

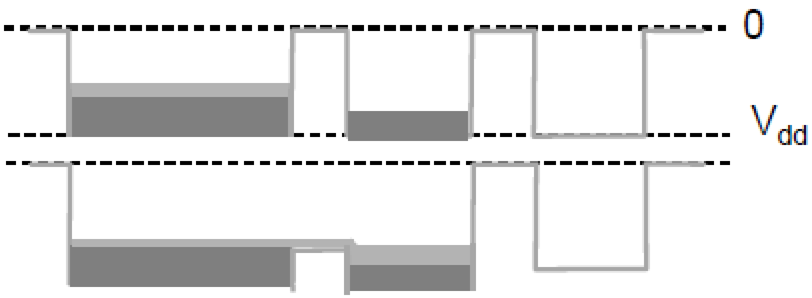
- The additional transistor reduces the FF
- Image lag may occur when the accumulated signal charge is completely transferred into the FD
- It is difficult to establish fabrication process parameters

Incomplete Charge Transfer



Complete transfer ←
PD is depleted completely.

Incomplete transfer →
Causes of image lag and noise



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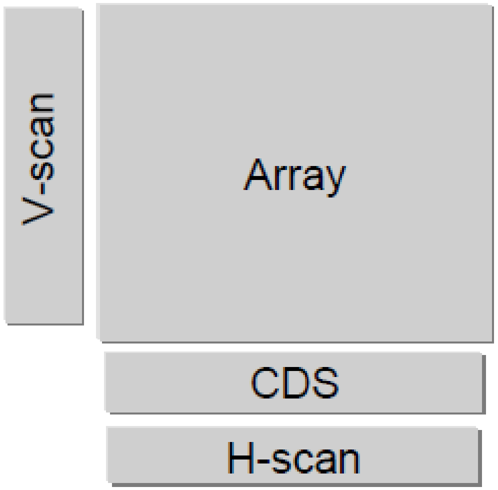
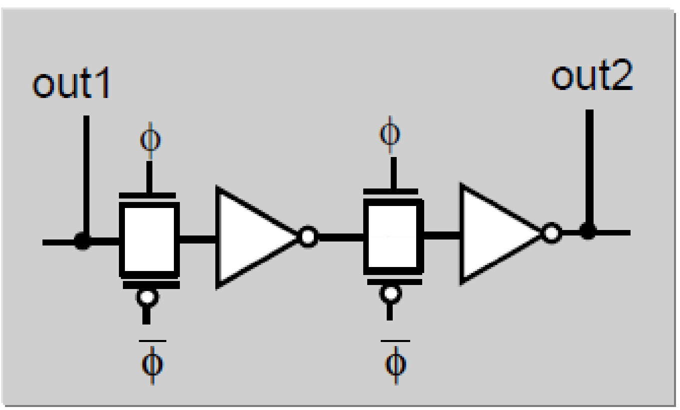
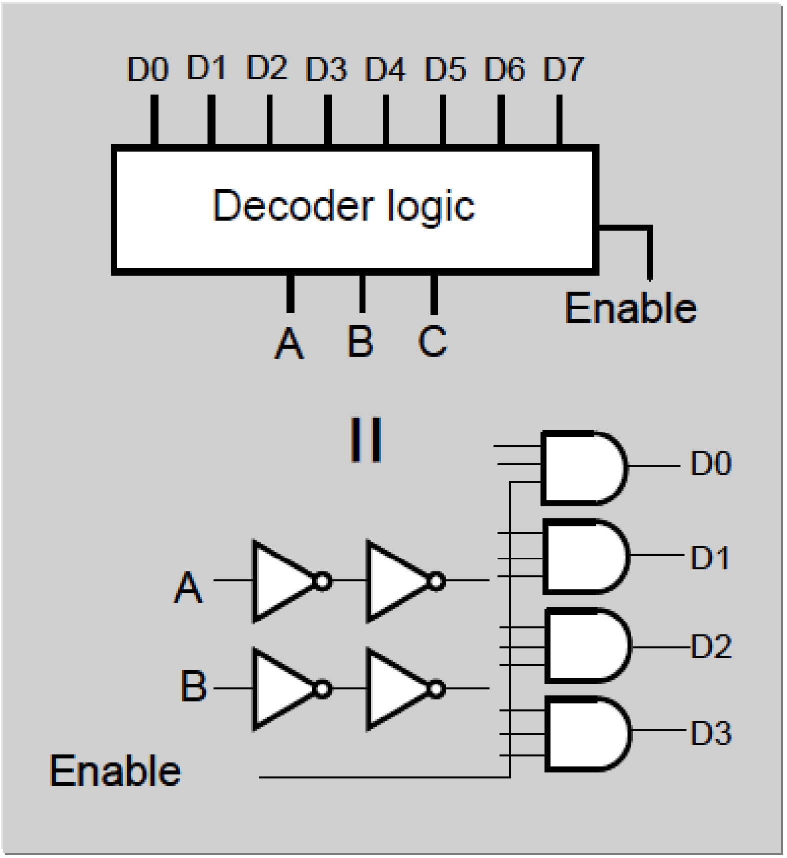
Addressing



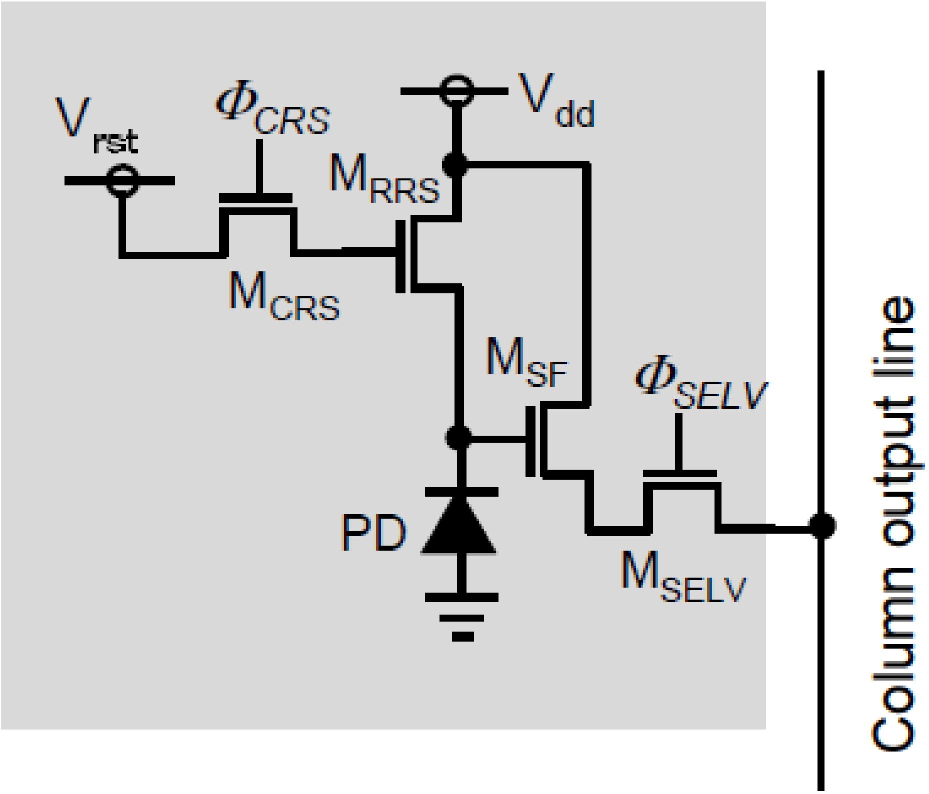




- scanner
- decoder

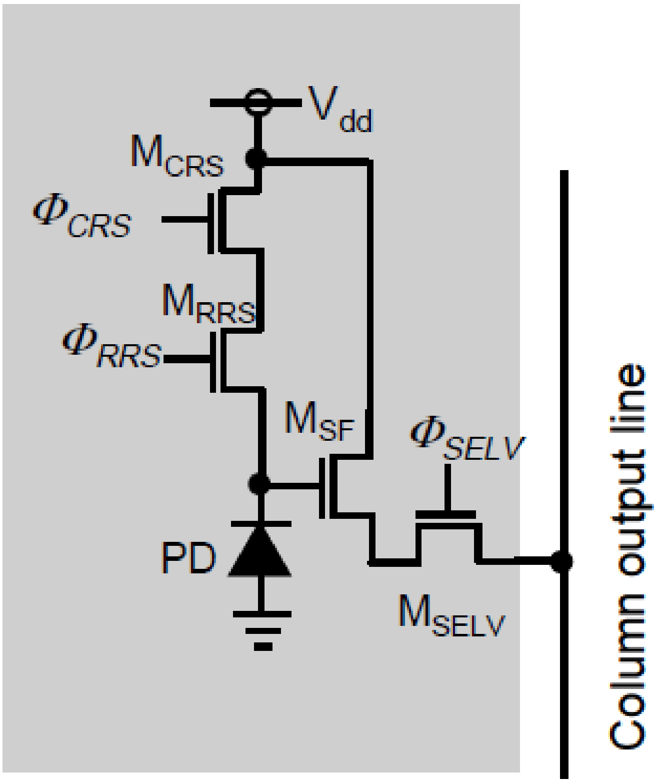
Random Access

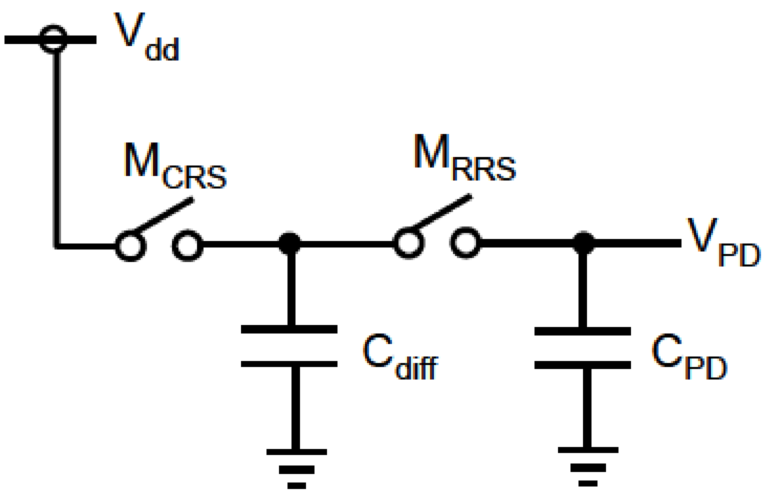
- Typical method



Random Access

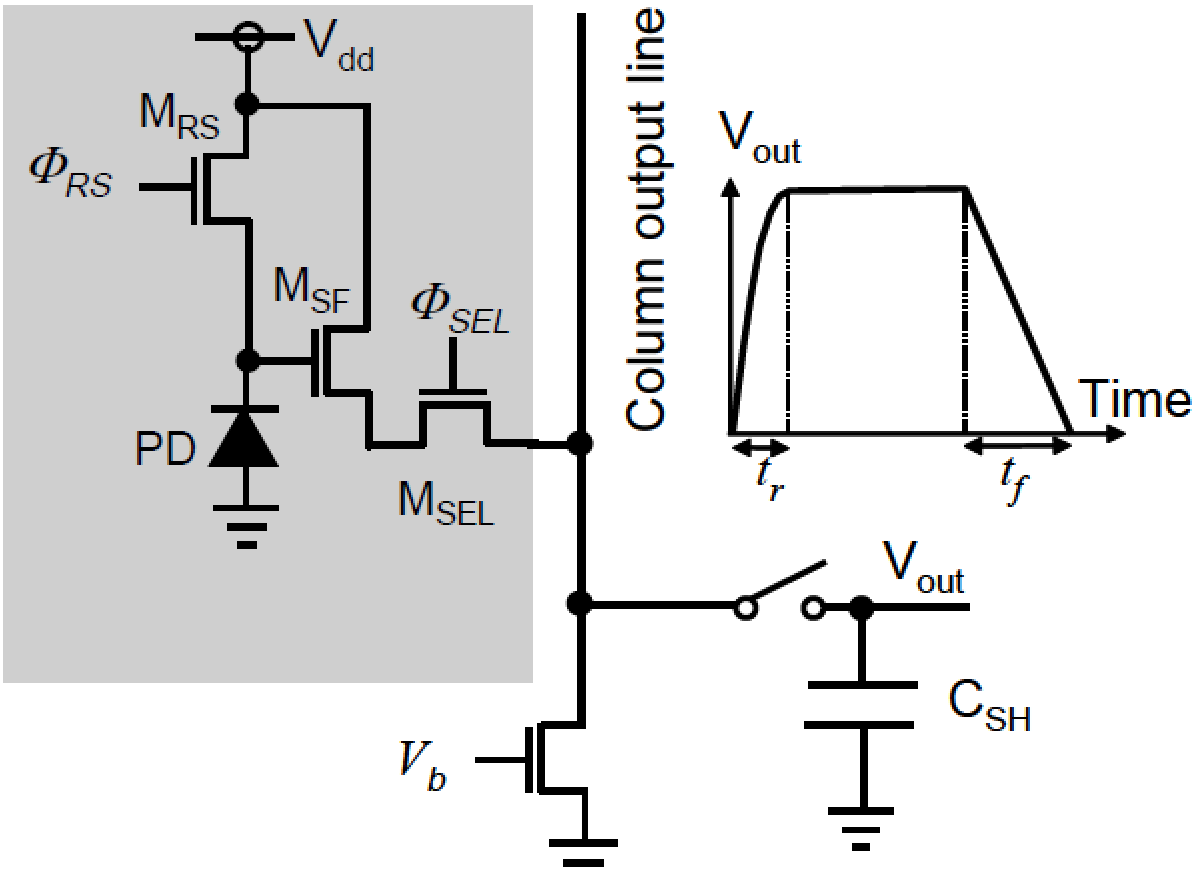
- A different types of random access





Readout Circuits

- Source follower



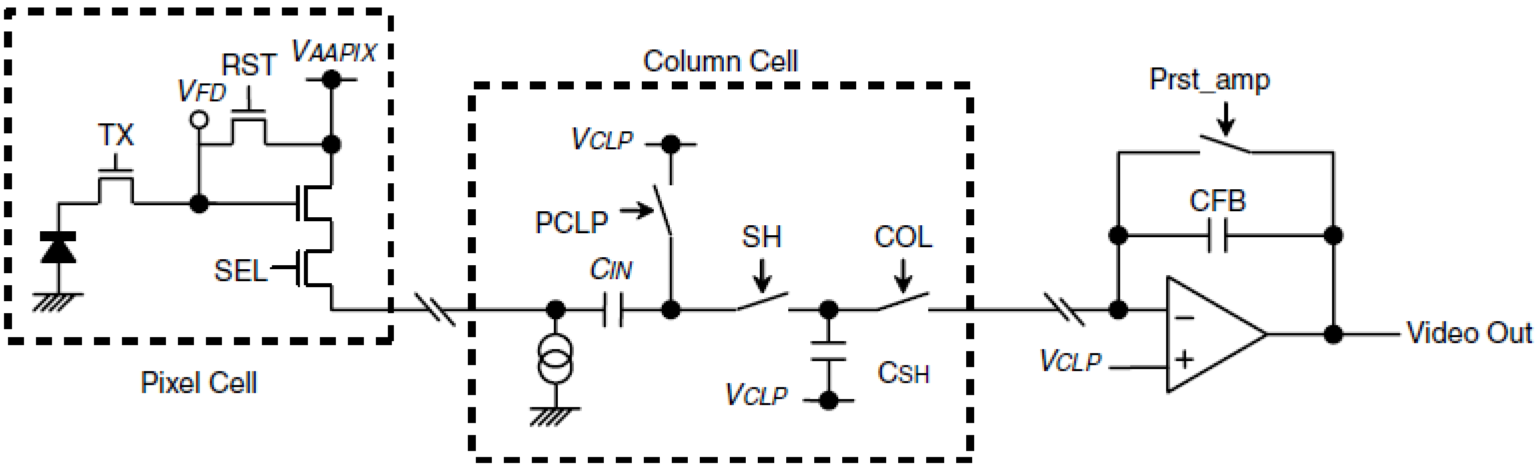
Correlated Double Sampling (CDS)

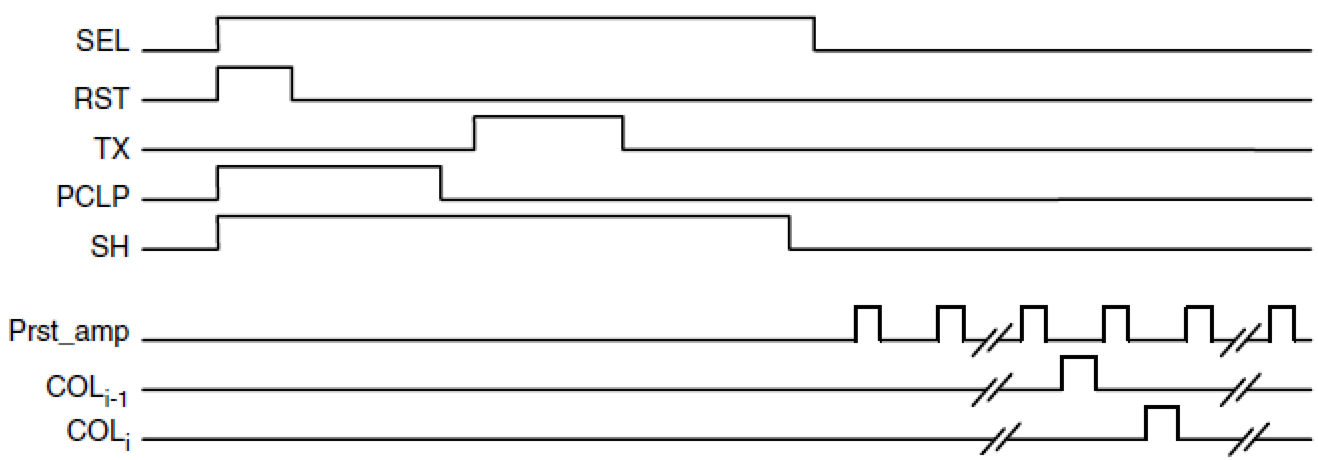
- Eliminate thermal noise from reset transistor
- CDS types for CMOS image sensors

Category	Method	Feature	Ref.
Column CDS 1	One coupling capacitor	Simple structure but suffers from column FPN	[127]
Column CDS 2	Two S/H capacitors	ibid.	[128]
DDS*	DDS following column CDS	Suppression of column FPN	[129]
Chip-level CDS	I–V conv. and CDS in a chip	Suppression of column FPN but needs fast operation	[116]
Column ADC	Single slope ADC	Suppression of column FPN	[130, 131]
	Cyclic ADC	ibid.	[132]

*double delta sampling.

Column CDS

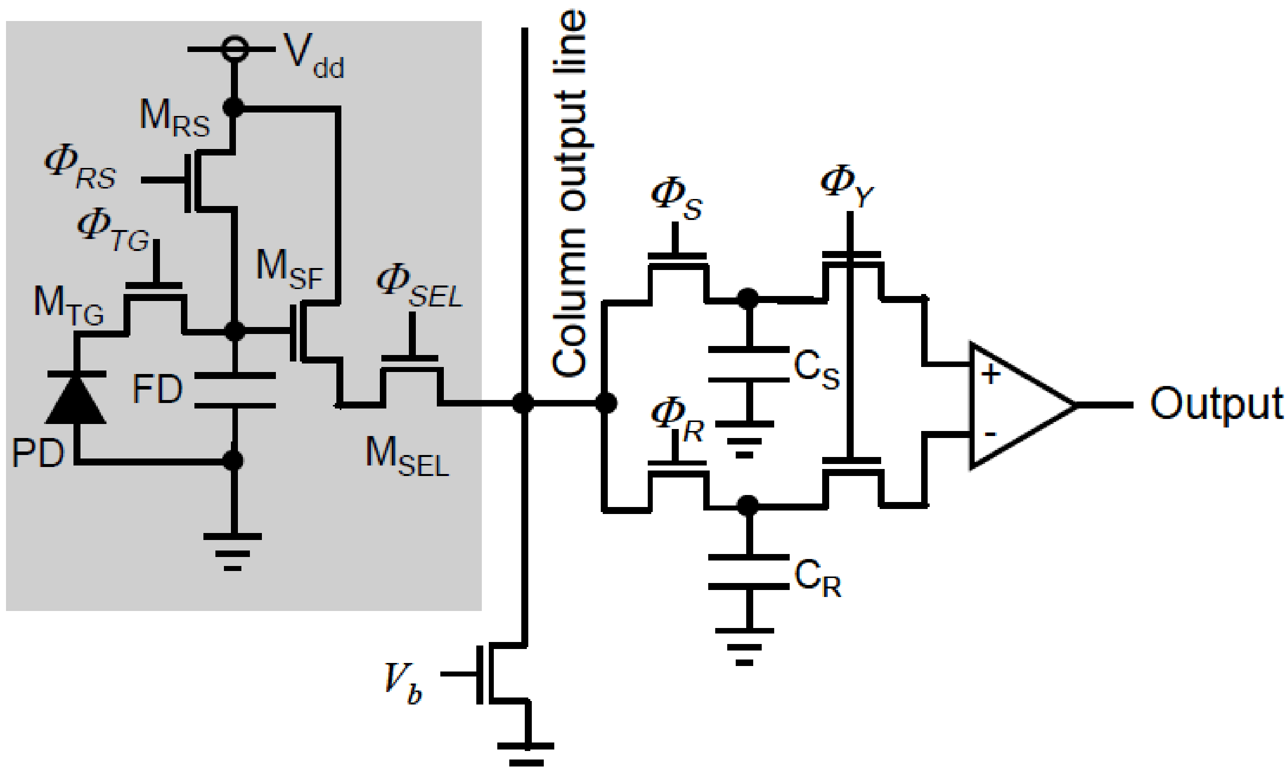




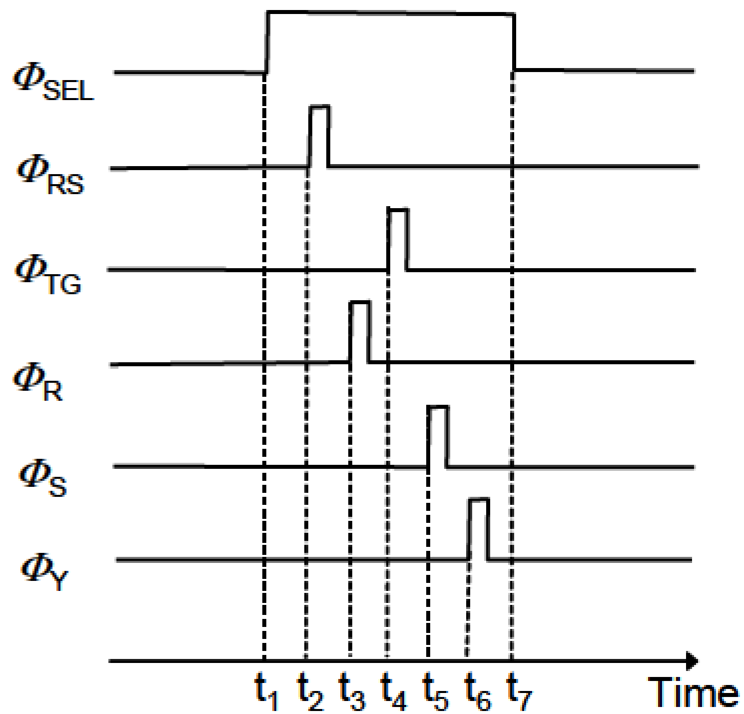
$$V_{SH} = V_{CLP} - A_V \cdot \frac{Q_{PH}}{C_{FD}} \cdot \frac{C_{IN}}{C_{IN} + C_{SH}}$$

CDS with Differential Output

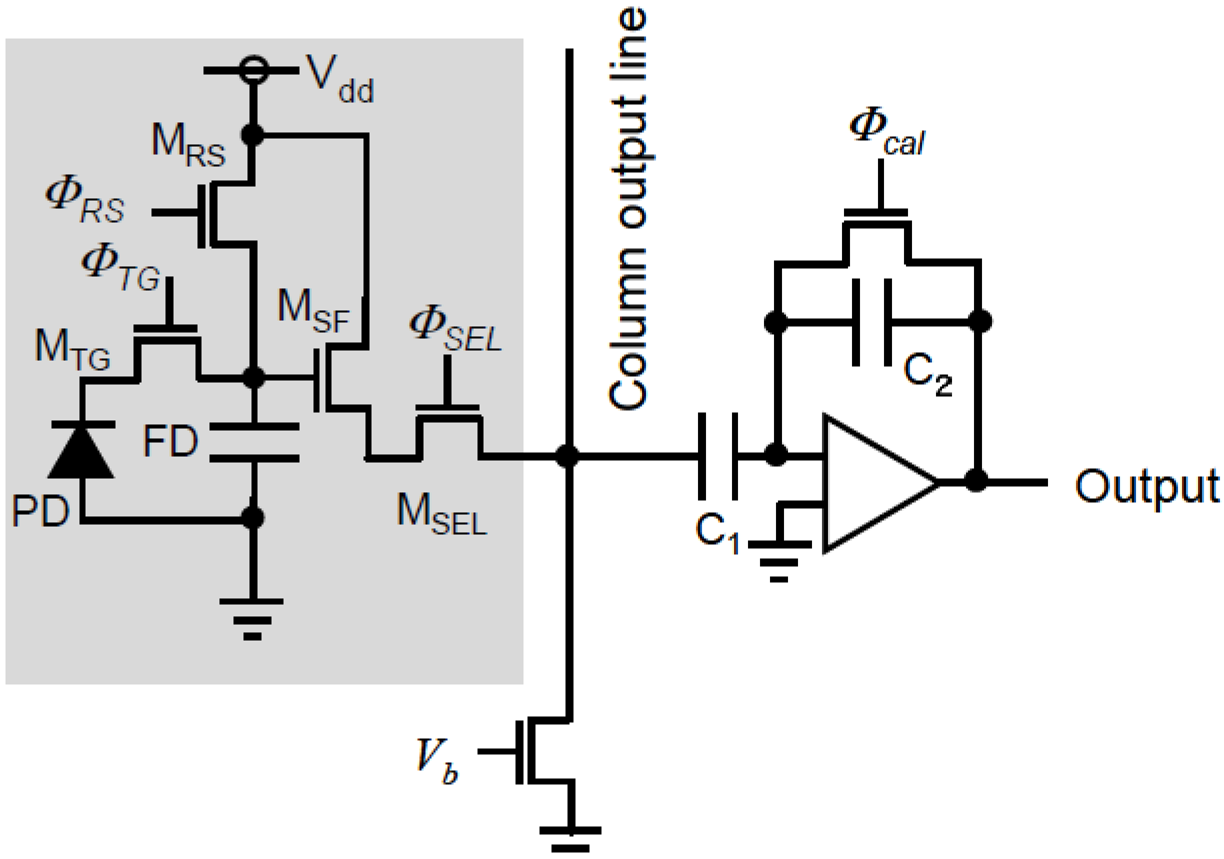
- Typical circuitry for CDS with a 4T-APS pixel circuit



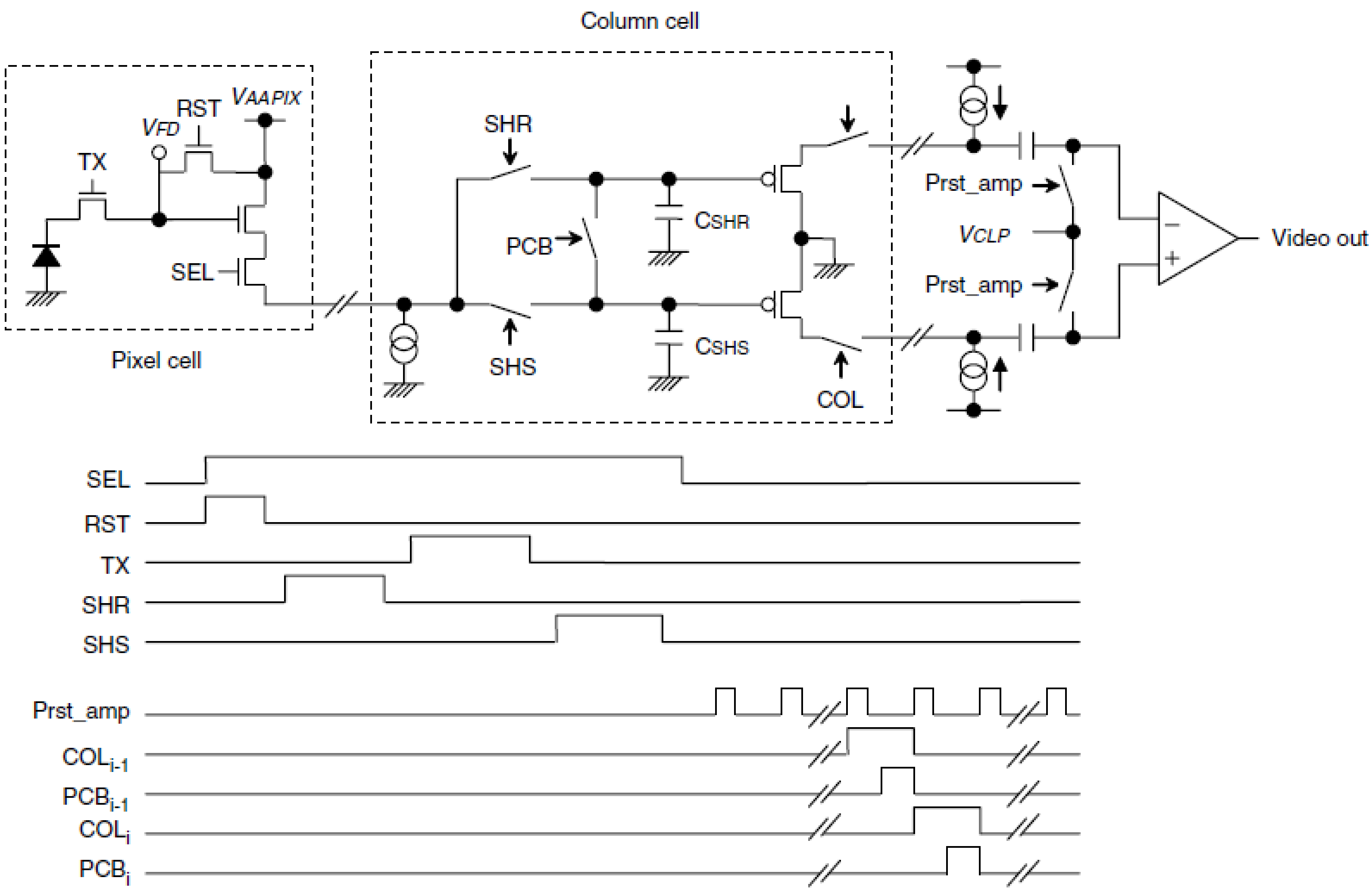
Timing chart of CDS



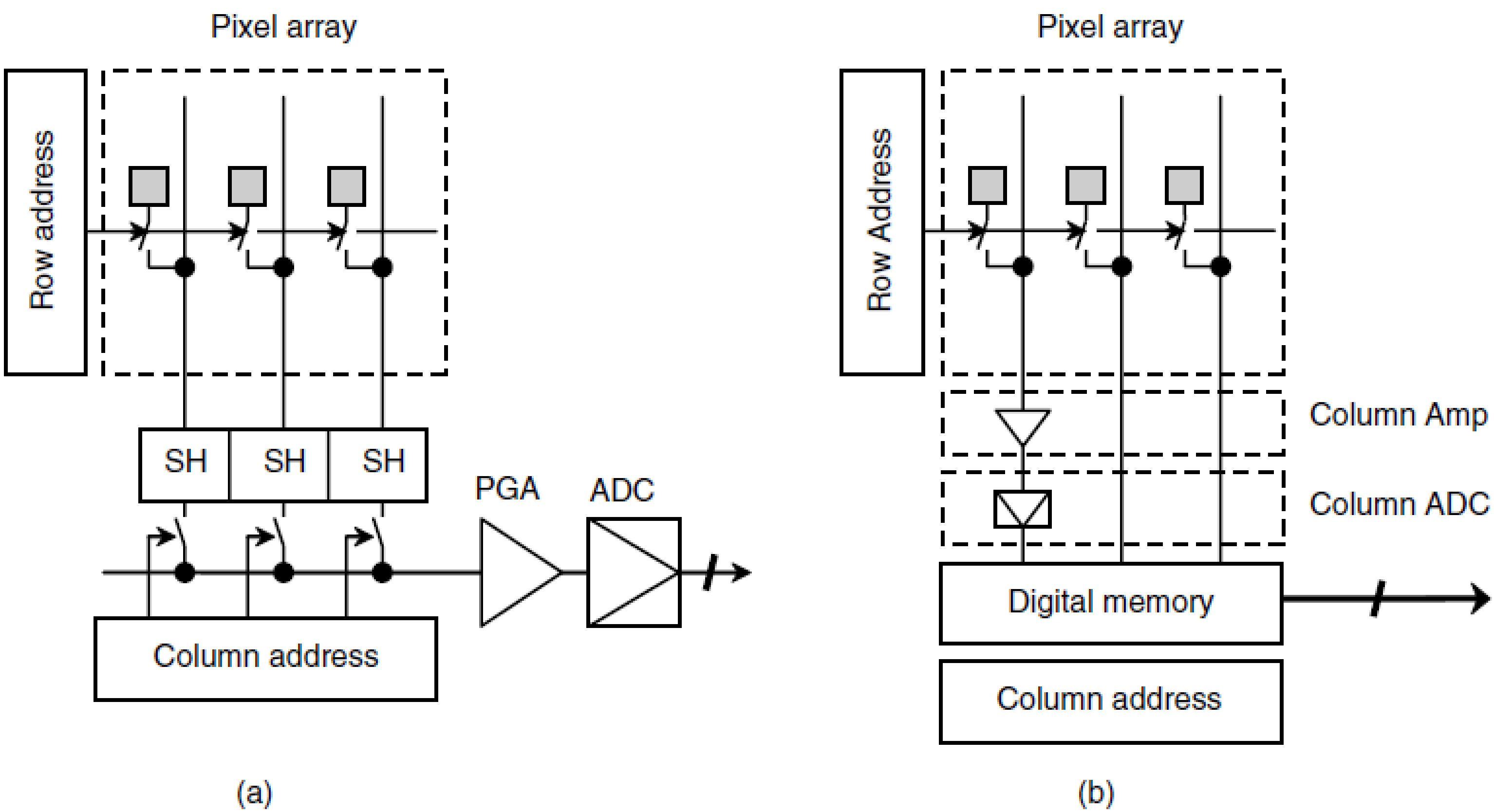
Alternative CDS



Differential Delta Sampling (DDS)



Analog Front End



(a) Serial and (b) column parallel processors

Analog-to-Digital Converters

- When the number of pixels increases, column parallel ADCs are employed
  - successive approximation ADC
  - single slope ADC
  - cyclic ADC

Outline

- Photoelectric Effect
- Photodetectors
- CMOS Image Sensor(CIS) Array Architecture
- CIS Peripherals
- Design Considerations

Reset Noise

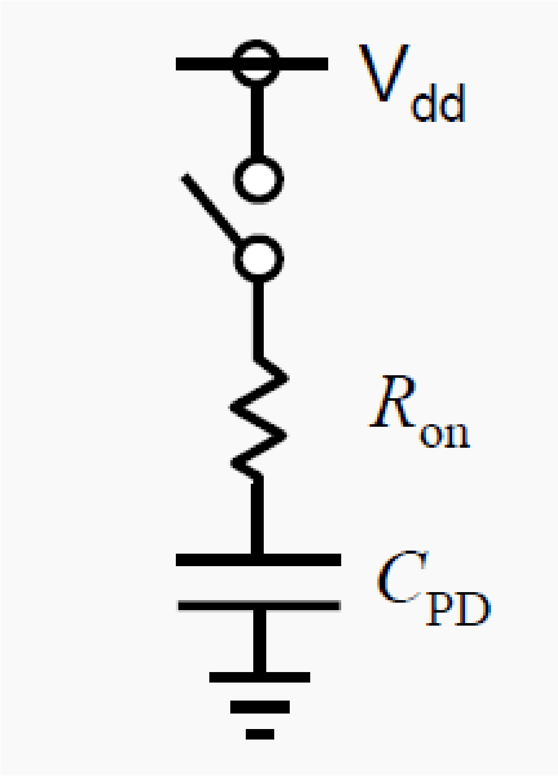
- $k_B TC$ noise

$$\overline{v_n^2} = 4k_B T R_{on} \Delta f$$

$$\frac{v_{out}}{v_n}(s) = \frac{1}{R_{on} C_{PD} s + 1}, \quad s = j\omega.$$

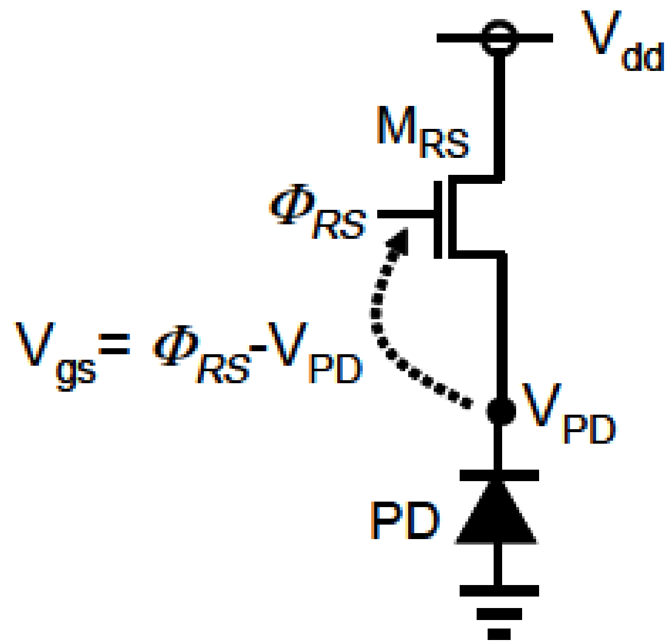
$$\overline{v_{out}^2} = \int_0^\infty \frac{4k_B T R_{on}}{(2\pi R_{on} C f)^2 + 1} df$$
$$= \frac{k_B T}{C}.$$

$$q_{out}^2 = (C v_{out})^2 = k_B TC$$



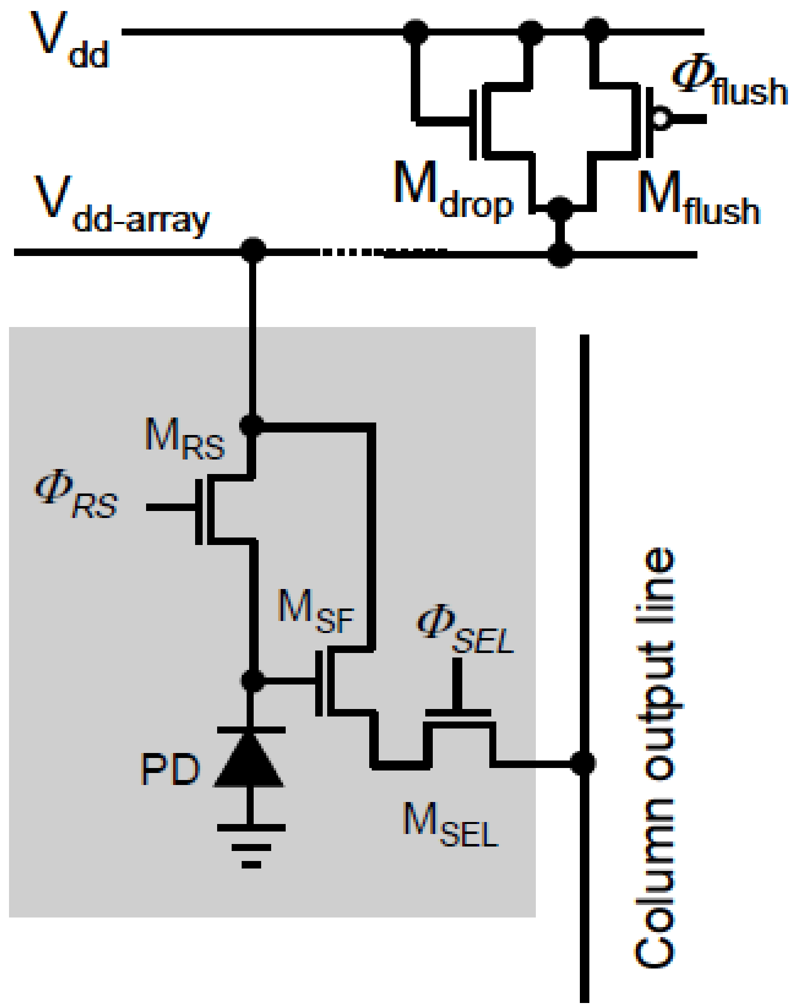
Reset Method

- Soft reset
  - V_{PD} slowly reaches $V_{dd}-V_{th}$
  - *Image lag*
- Hard reset
  - gate voltage is larger than V_{dd}
  - reset action finishes quickly
  - k_BTC *noise*



Flushed Reset

- Hard reset first
- Then soft reset to reduce $k_B TC$ *noise*



Dynamic range

- The ratio of the maximum signal range to the minimum signal range
- Determined by two factors
  - noise floor (min.)
  - well charge capacity (max.)

Color Reproduction

- There are three ways to realize color in a conventional CMOS image sensor
  - On-chip color filter type
  - Three imagers type
  - Three light sources type

On-chip Color Filter Type

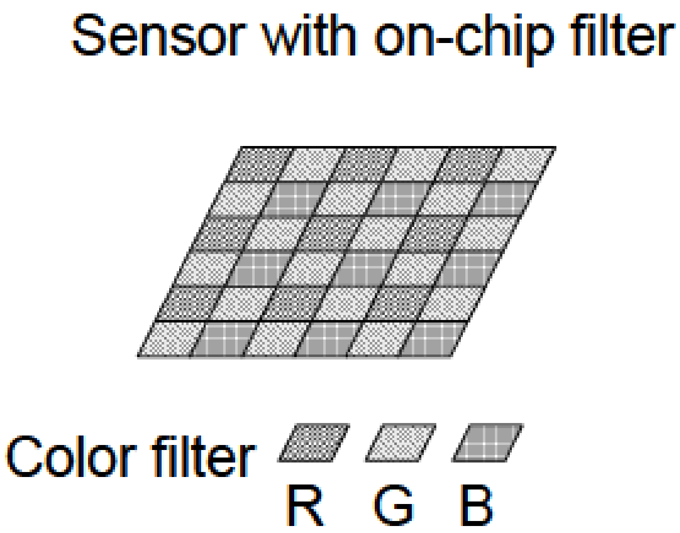
- Three colored filters are directly placed on the pixels
  - RGB or CMY complementary color filters

$$Ye = W - B = R + G$$

$$Mg = W - G = R + B$$

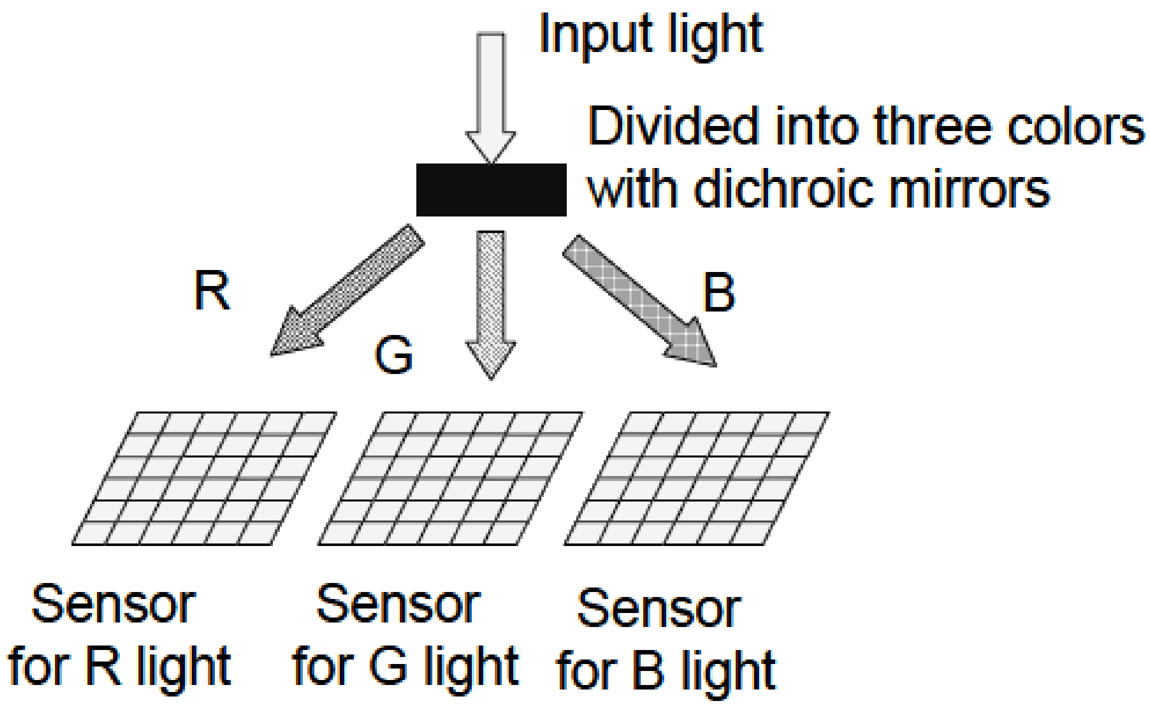
$$Cy = W - R = G + B$$

(W indicates white)



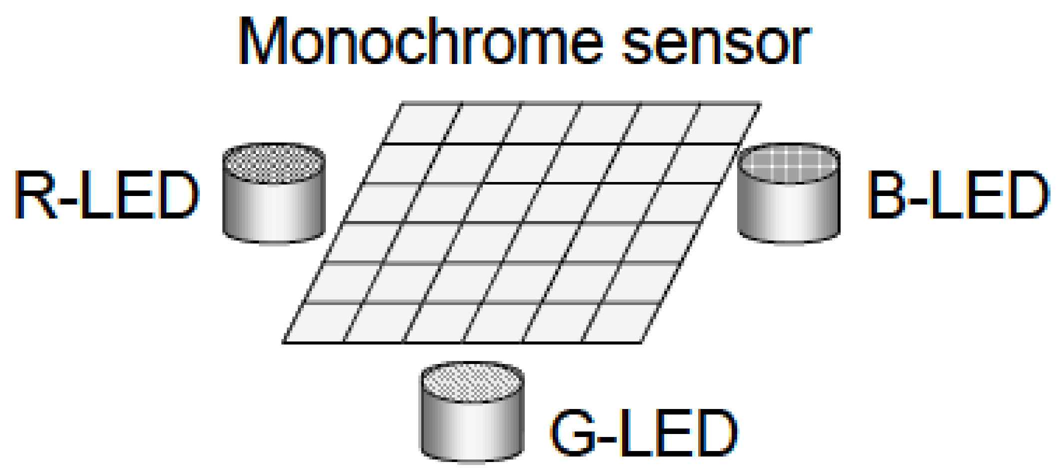
Three Imagers Type

- High color fidelity
- Complicated optics
- Expensive

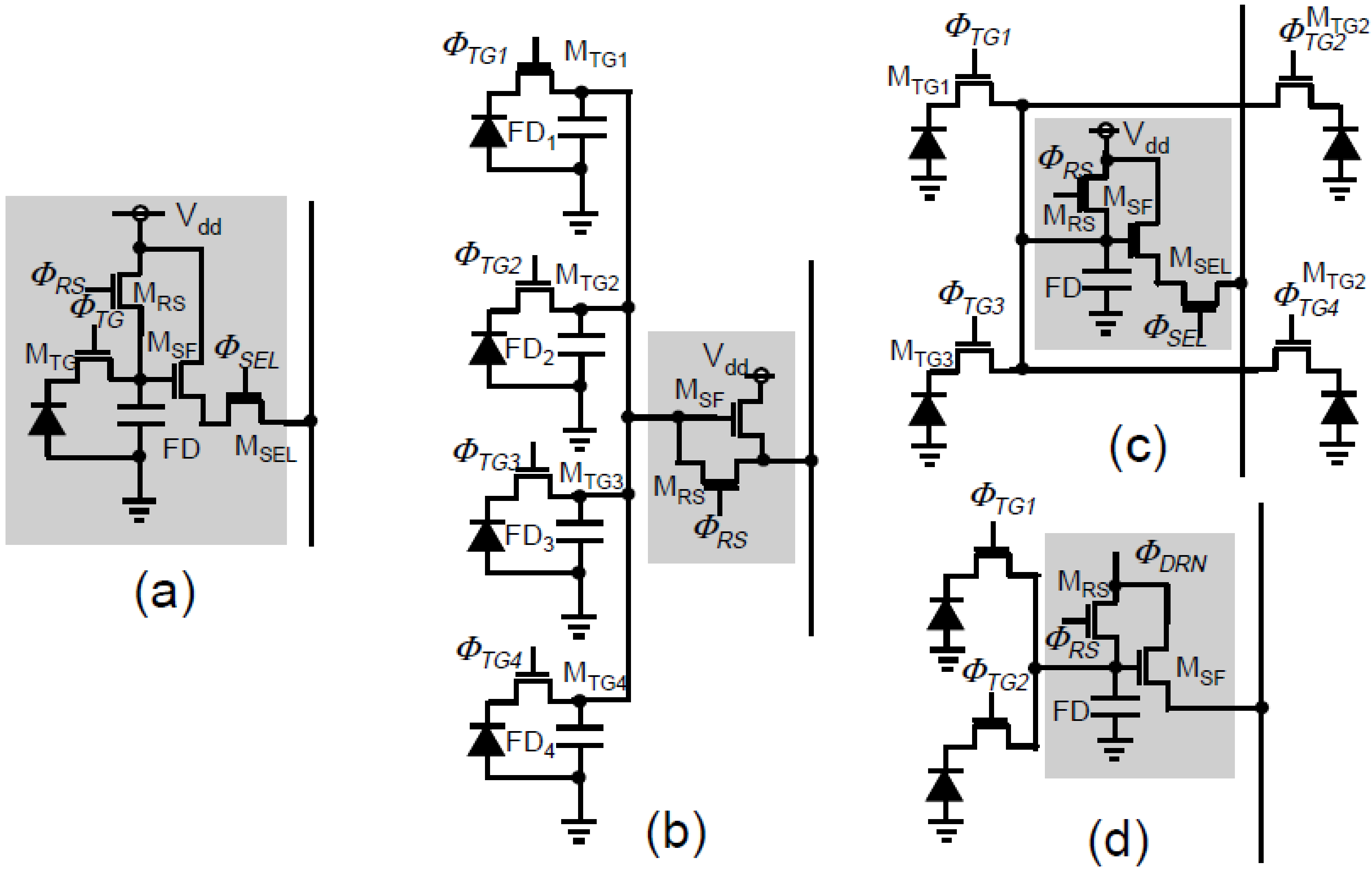


Three Light Sources Type

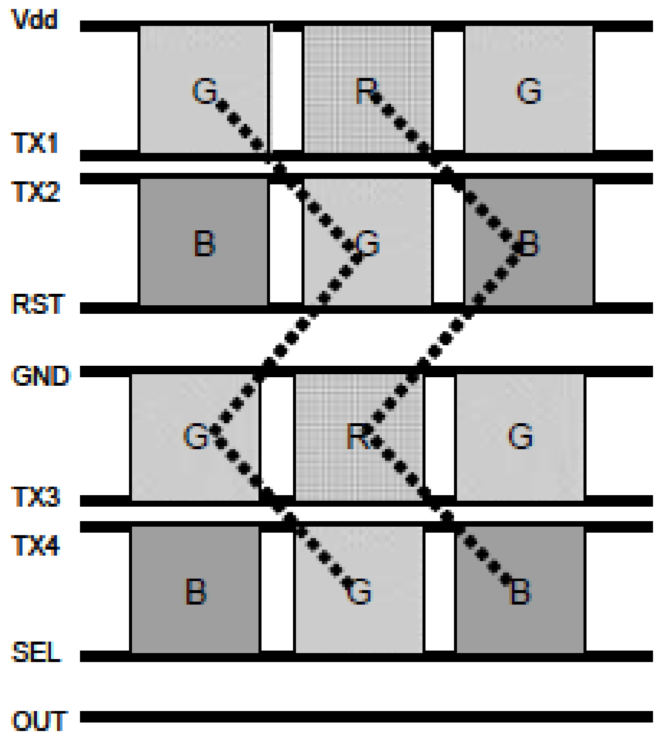
- Mainly used in medical endoscopes
- Color fidelity is excellent
- Time to acquire a whole image is long



Pixel Sharing



Zigzag Placement of RGB Pixels



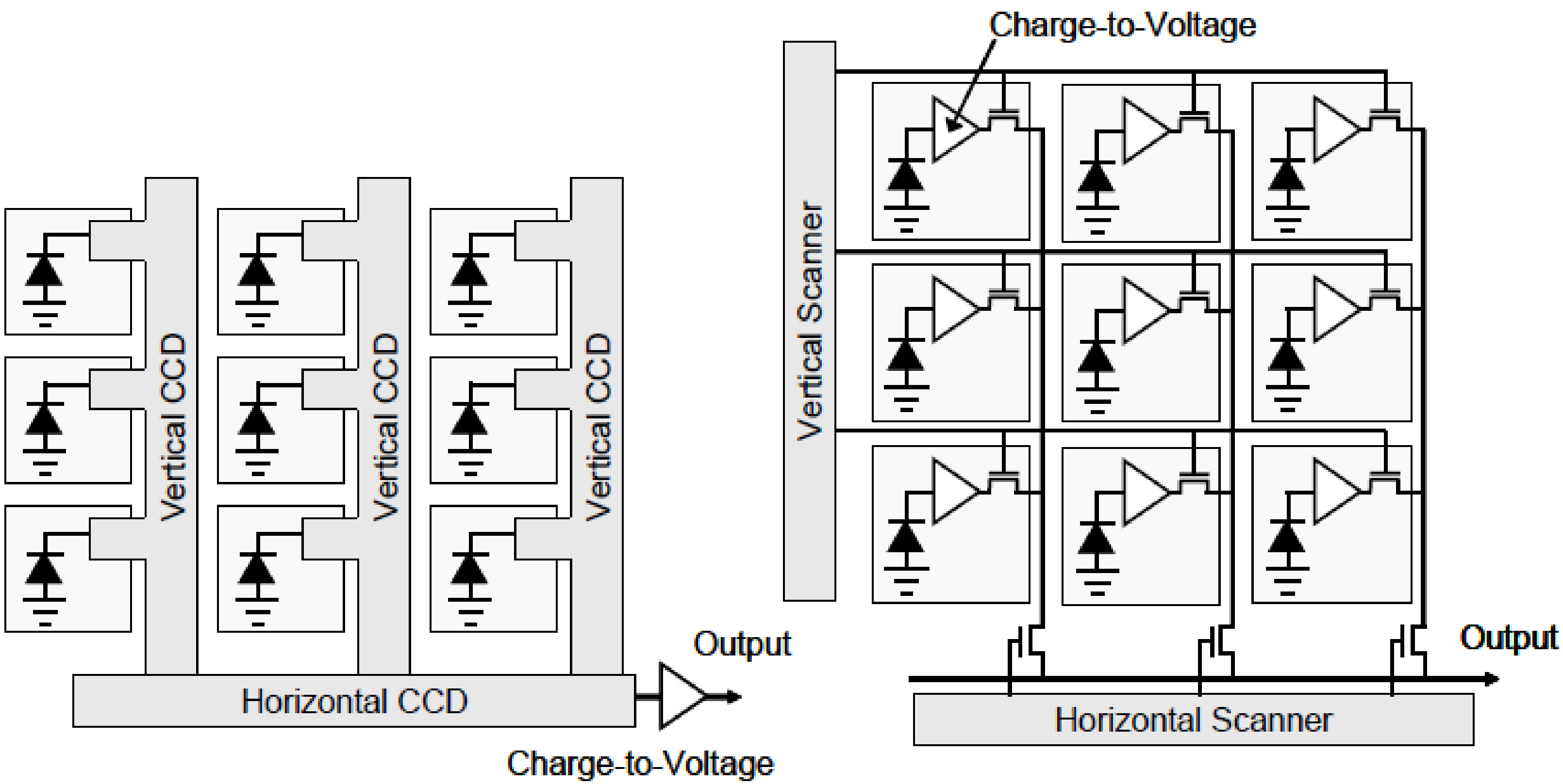
Comparison of Pixels

	PPS	3T-APS	4T-APS (PD)	4T-APS (PG)	Log
Sensitivity	Depends on the performance of a charge amp	Good	Good	Fairly good	Good but poor at low light lev-el
Area consump-tion	Excellent	Good	Fairly good	Fairly good	Poor
Noise	Fairly good	Fairly good (no kTC reduction)	Excellent	Excellent	Poor
Dark current	Good	Good	Excellent	Good	Fairly good
Image lag	Fairly good	Good	Fairly good	Fairly good	Poor
Process	Standard	Standard	Special	Special	Standard
Note	Very few com-mercialized	Widely com-mercialized	Widely com-mercialized	Very few com-mercialized	Recently com-mercialized

Comparison with CCDs

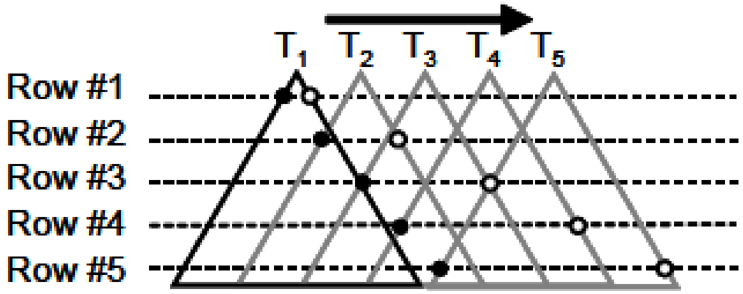
- Main differences between the architecture of CCD and CMOS sensors
  - signal transferring method
  - signal readout method

Chip Structure

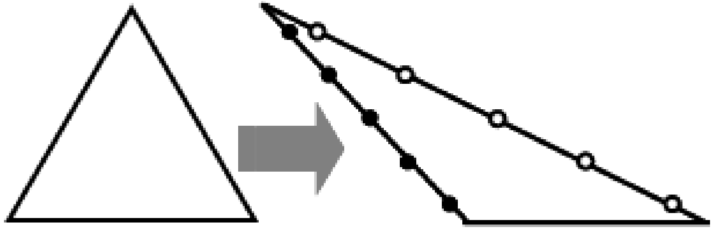


Accumulation Time

- CCD
  - signal transfer gives the same accumulation time for every pixel at any time
- CMOS image sensors
  - rolling shutter



(a)



http://dvxuser.com/jason/CMOS-CCD/

Comparison Table

Item	CCD image sensor	CMOS image sensor
Readout scheme	One on-chip SF; limits speed	SF in every column; may exhibit column FPN
Simultaneity	Simultaneous readout of every pixel	Sequential reset for every row; rolling shutter
Transistor isolation	Reverse biased pn-junction	LOCOS/STI†; may exhibit stress-induced dark currents
Thickness of gate oxide	Thick for complete charge transfer (> 50 nm)	Thin for high speed transistor and low voltage power supply (< 10 nm)
Gate electrode	Overlapped 1st & 2nd poly-Si layers	Polycide poly-Si
Isolation layers	Thin for suppressing light guide	Thick ($\sim 1 \mu$m)
Metal layer	Usually one	Over three layers

†LOCOS: local oxidation of silicon, STI: shallow trench isolation.