CHAPTER 3

Smart Function and Materials

Outline

3.1 introduction

3.2 Pixel structure

3.3 Analog operation

3.4 Pulse modulation

3.5 Digital Processing

3.6 Materials other than silicon

3.7 Structures other than standard CMOS technologies

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Signal Processing Categories

- Signal processing categories for smart CMOS image sensors

Category	Pros	Cons
Analog	Easy to realize sum and subtraction operation	Difficult to achieve high precision and programmability
Digital	High precision and programmability	Difficult to achieve a good FF*
Pulse	Medium precision, easy to process signals	Difficult to achieve a good FF

*fill factor.

Structures and Materials

- Structures and materials for smart CMOS image sensors

Structure/material	Features
SOI	Small area when using both NMOS and PMOS
SOS	Transparent substrate (sapphire)
3D integration	Large FF
SiGe/Ge	Long wavelength (NIR)

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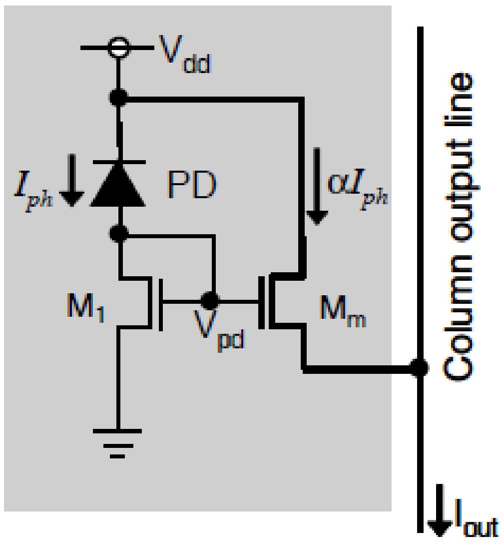
Other Pixel Structures

- Current mode sensor
  - Direct mode
  - Accumulation mode
- Log sensor
- Pulse modulation

Current Mode Sensor

- Direct mode
  - photocurrent is directly output from the detector
  - ratio of the transistor W/L in M_1 to M_m is α, mirror current or output current is equal to αI_{ph}
  - low sensitivity at low light
  - large FPN



Current Mode Sensor

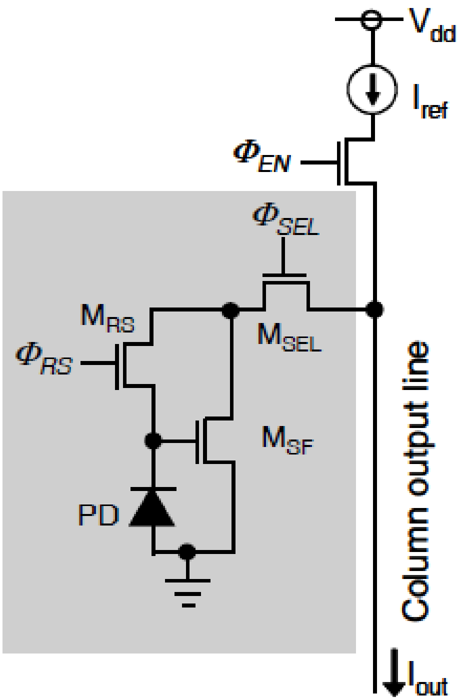
- Accumulation mode
  - by introducing the APS configuration, the image quality is improved compared with the direct mode
  - Vth cancellation

$$V_{reset} = \sqrt{\frac{2L_g}{\mu_n C_{ox} W_g} I_{ref}} + V_{th}.$$

$$I_{pix} = \frac{1}{2}\mu_n C_{ox} \frac{W_g}{L_g} \left(V_{reset} - \Delta V - V_{th}\right)^2.$$

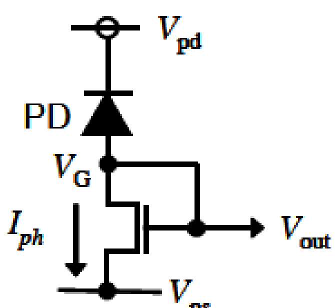
$$I_{diff} = I_{ref} - I_{pix}$$

$$I_{diff} = \sqrt{2\mu_n C_{ox} \frac{W_g}{L_g} I_{ref} \Delta V} - \frac{1}{2}\mu_n C_{ox} \frac{W_g}{L_g} \Delta V^2.$$

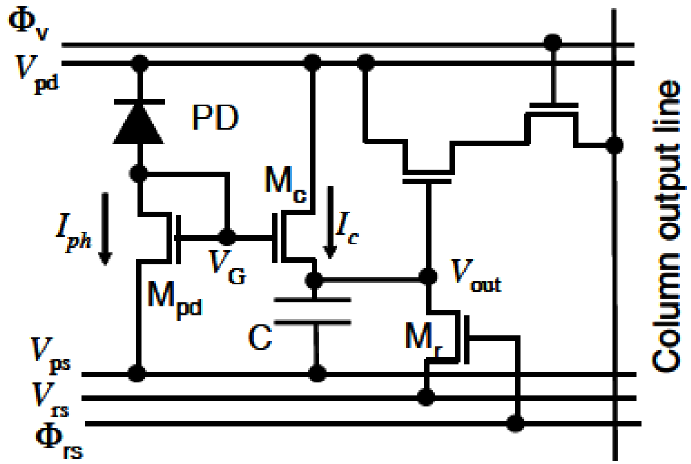


Log Mode Sensor

- Pixel circuit of a log CMOS image sensor.
  - (a) basic pixel circuit
  - (b) circuit including accumulation mode
  - low sensitivity, slow response, large variation



(a)



(b)

$$V_G = \frac{mkT}{e} \ln\left(\frac{I_{ph}}{I_o}\right) + V_{ps} + V_{th}.$$

$$I_c = I_{ph} \exp\left[\frac{e}{mk_B T}(V_{out} - V_{ps})\right]$$

$$V_{out} = \frac{mkT}{e} \ln\left(\frac{e}{mkTC} \int I_{ph} dt\right) + V_{ps}$$

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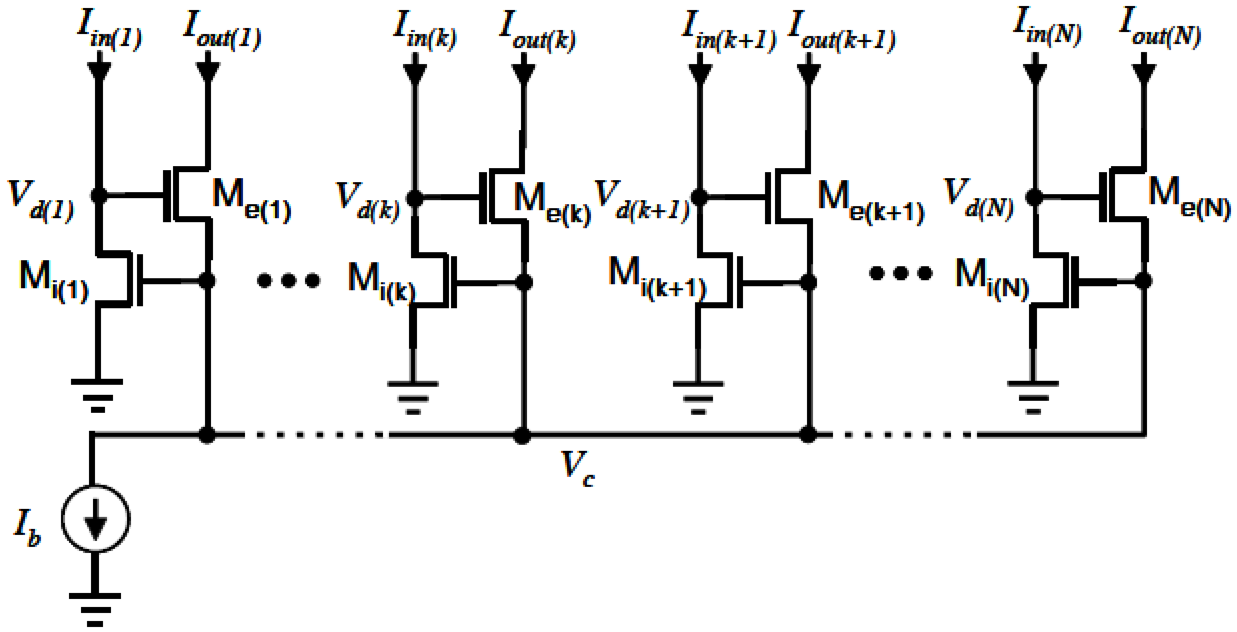
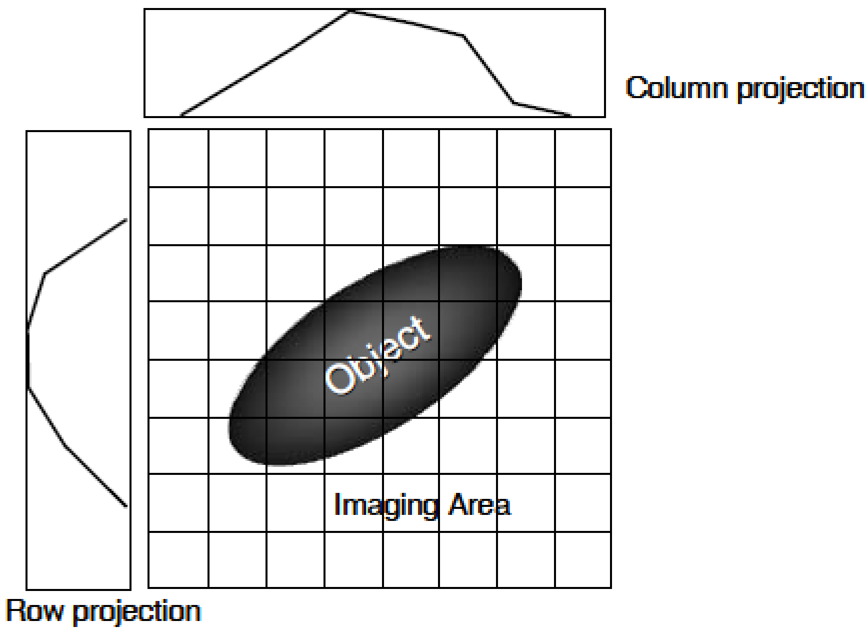
Winner Take All

- Winner take all (WTA) circuits



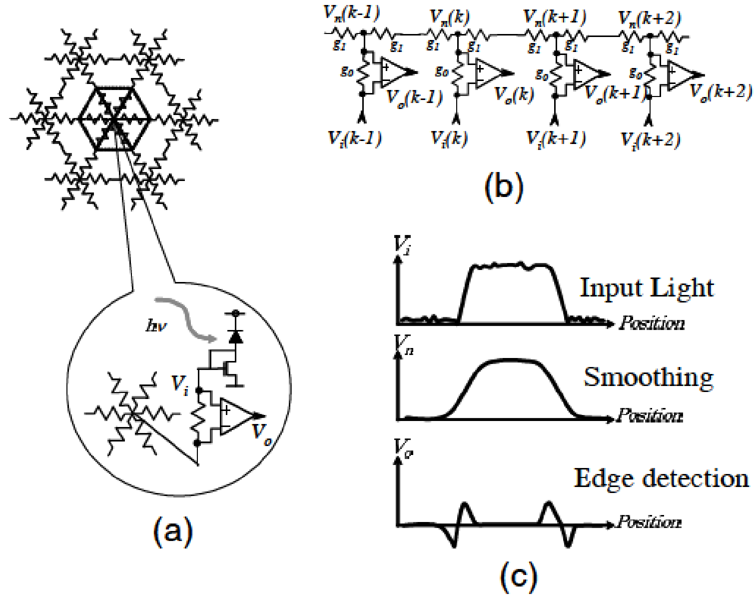
Projection

- Projection of an object in column and row directions



Resistive Network

- Illustration of the concept of the silicon retina using a resistive network
  - (a) Illustration of the circuits
  - (b) one-dimension network
  - (c) input light pattern and its processed patterns



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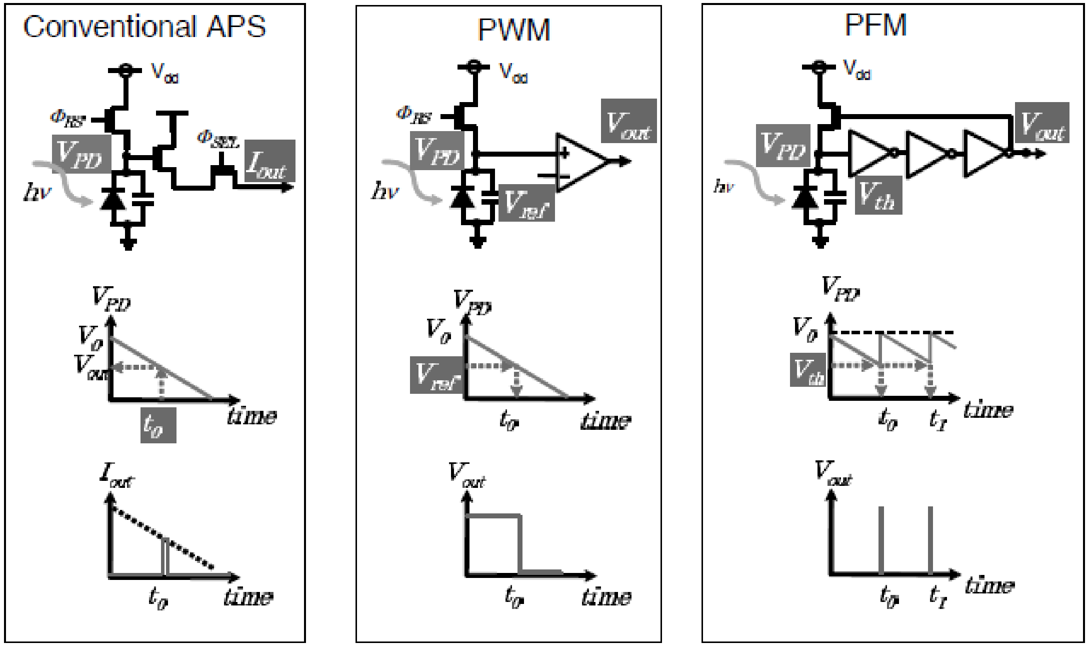
Pulse Modulation Feature

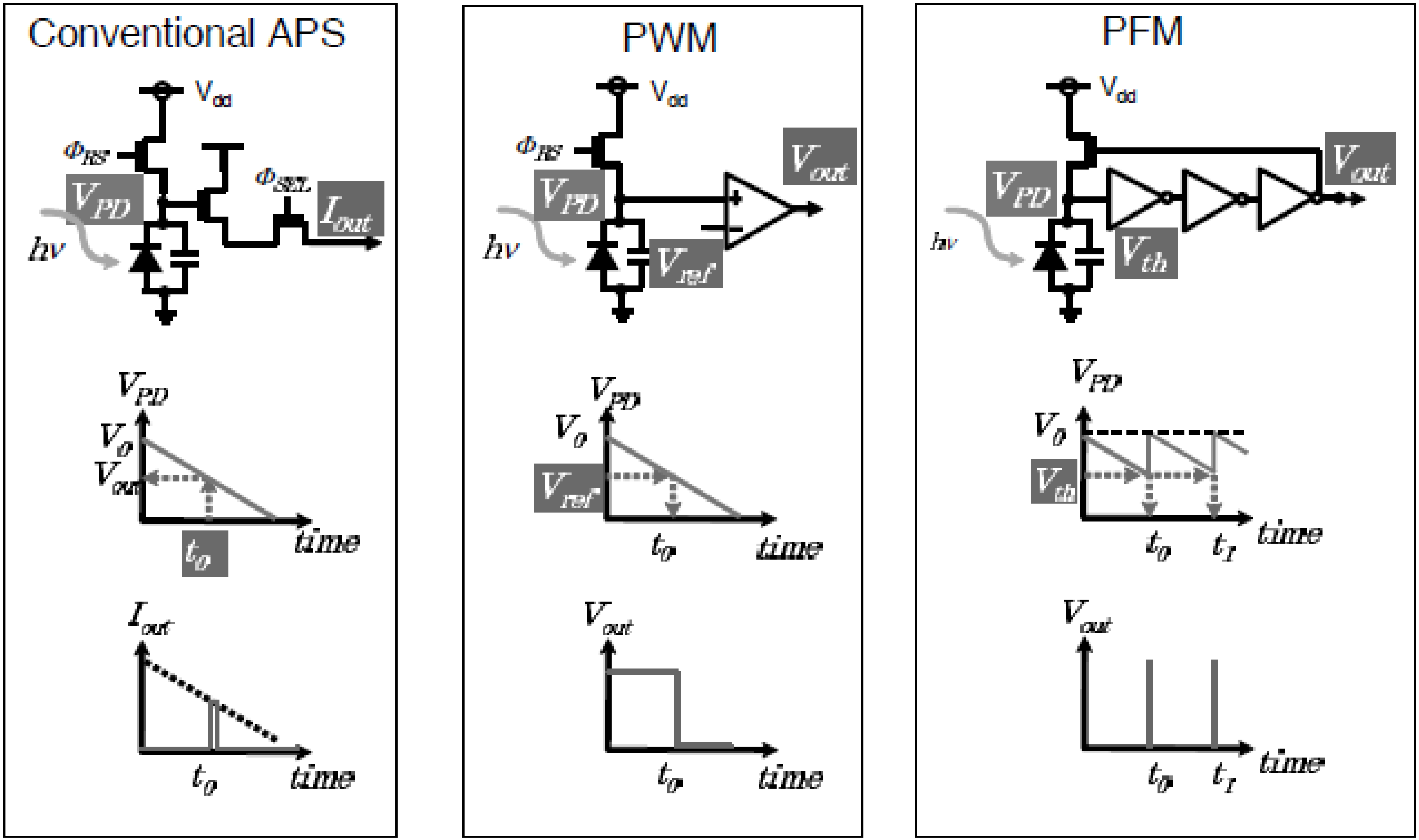
- Asynchronous operation
- Digital output
- Low voltage operation

Pulse Modulation Types

- Basic circuits of pulse modulation.
  - Left : conventional 3T-APS
  - Middle : pulse width modulation(PWM)
  - Right : pulse frequency modulation(PFM)

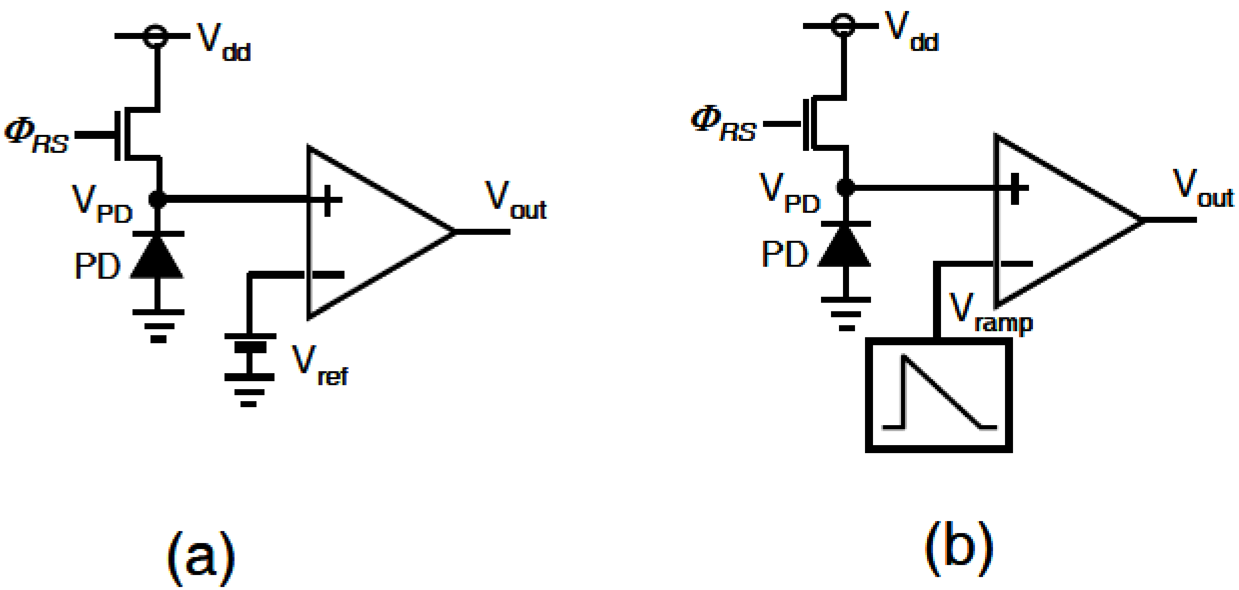


Pulse Modulation Types



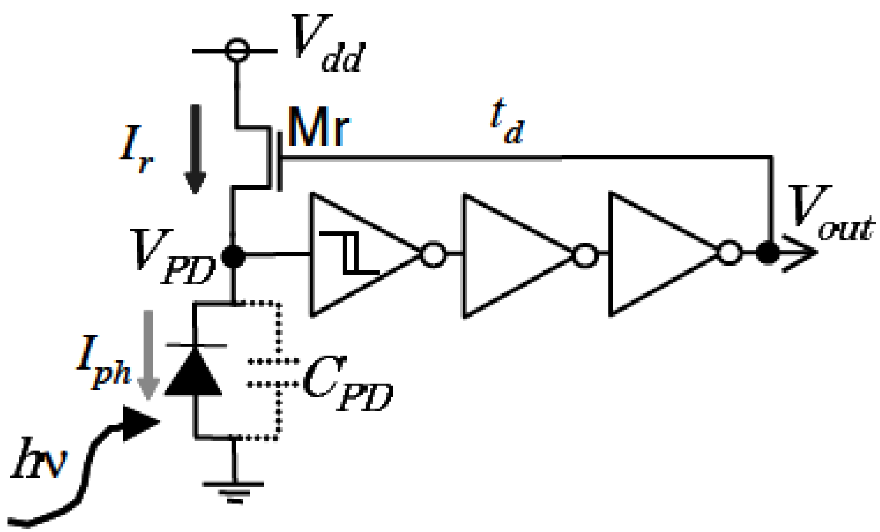
Pulse Width Modulation

- Basic circuits of PWM-based photosensors
  - use a fixed threshold for a comparator
  - use a ramp waveform for a comparator



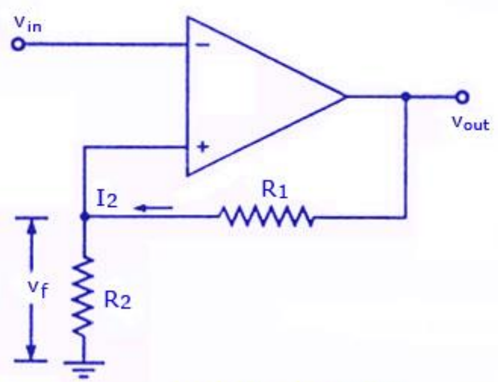
Pulse Frequency Modulation

- Basic circuit of a PFM photosensor

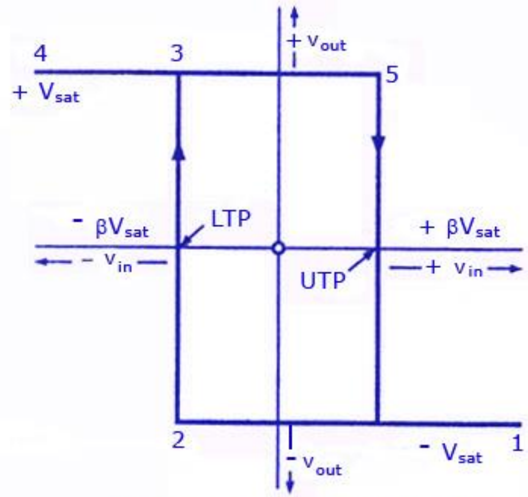


$$f \approx \frac{I_{ph}}{C_{PD}(V_{dd} - V_{th})}.$$

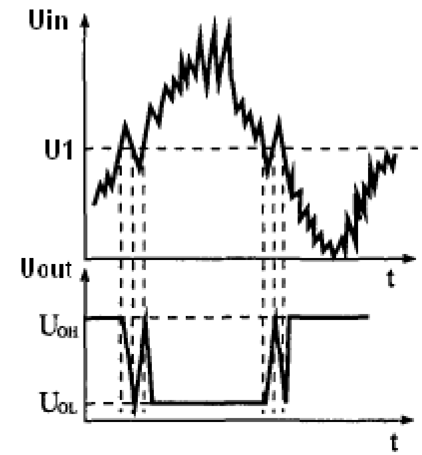
Schmitt Trigger



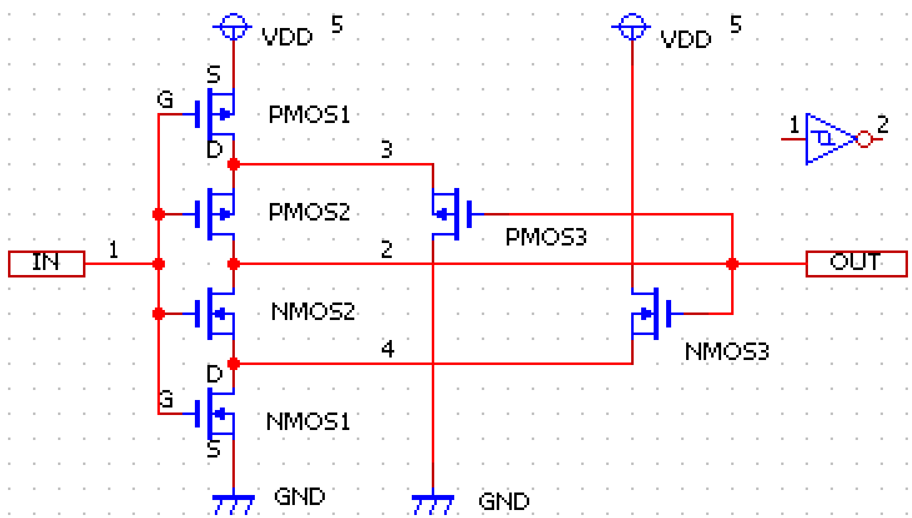
(a) Circuit Diagram

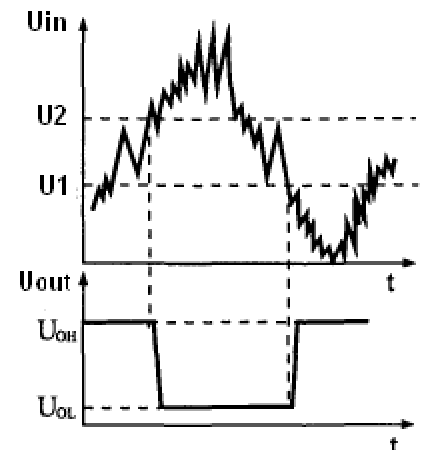


(b) Input Output Characteristics



Regular logics





Schmitt trigger

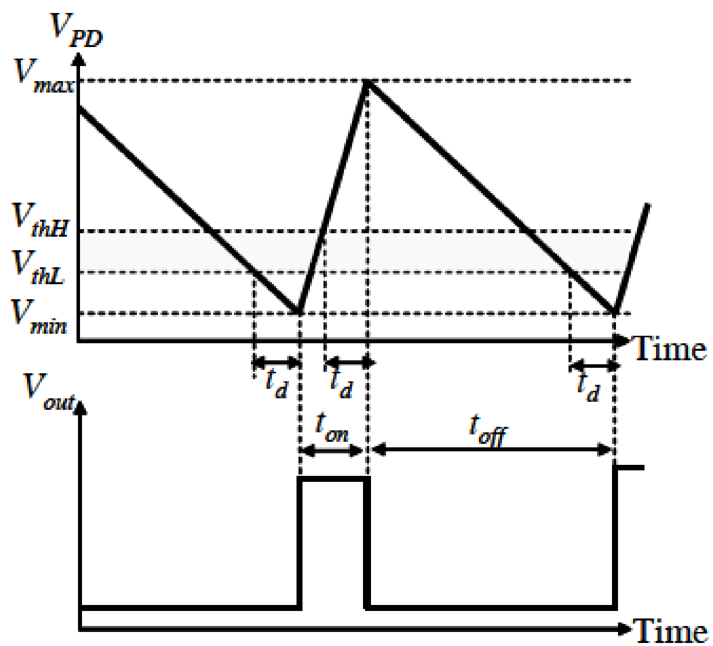
Pulse Frequency Modulation(cont'd)

- Time course of V_{PD}, taking the delay t_d into consideration

$$V_{max} = V_{thH} + \frac{t_d(I_r - I_{ph})}{C_{PD}} \qquad V_{min} = V_{thL} - \frac{t_d I_{ph}}{C_{PD}}. \qquad V_{th} = V_{thH} - V_{thL}$$

$$t_{on} = \frac{C_{PD}(V_{thH} - V_{min})}{I_r - I_{ph}} + t_d = \frac{C_{PD}V_{th} + t_d I_r}{I_r - I_{ph}},$$

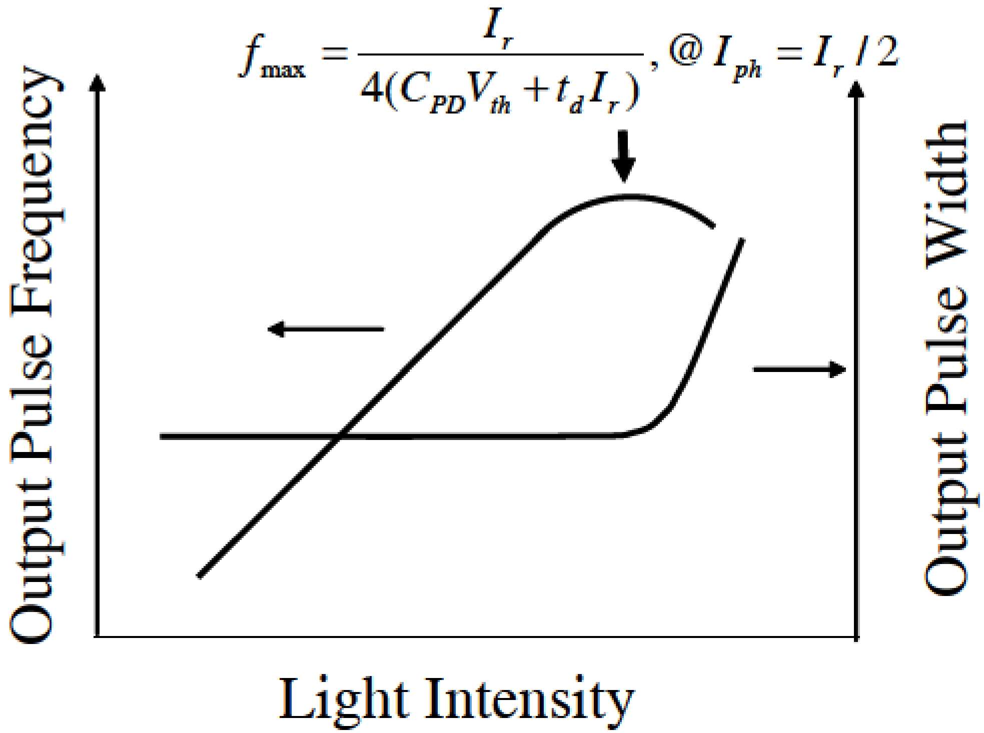
$$t_{off} = \frac{C_{PD}(V_{max} - V_{thL})}{I_{ph}} + t_d = \frac{C_{PD}V_{th} + t_d I_r}{I_{ph}},$$



$$f = \frac{1}{t_{on} + t_{off}} = \frac{I_{ph}(I_r - I_{ph})}{I_r(C_{PD}V_{th} + t_d I_r)} = \frac{I_r^2/4 - \left(I_{ph} - I_r/2\right)^2}{I_r(C_{PD}V_{th} + t_d I_r)}.$$

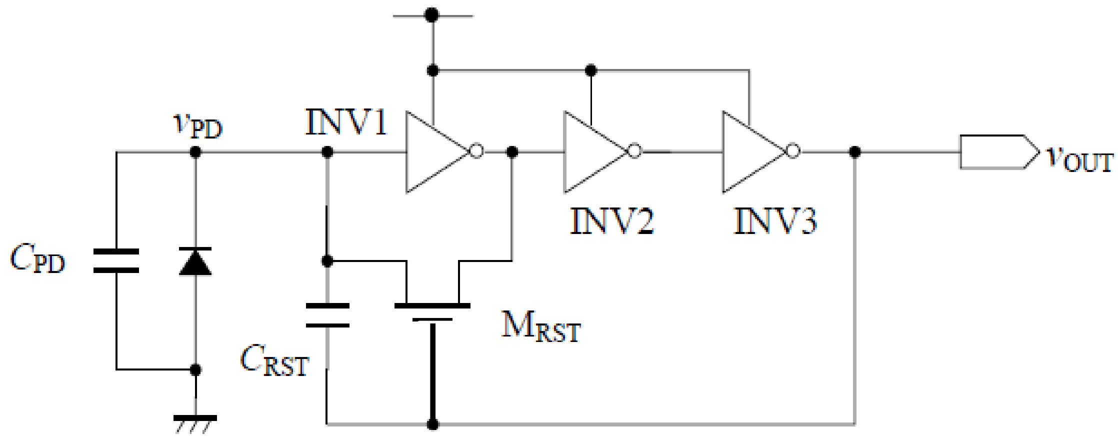
Pulse Frequency Modulation(cont'd)

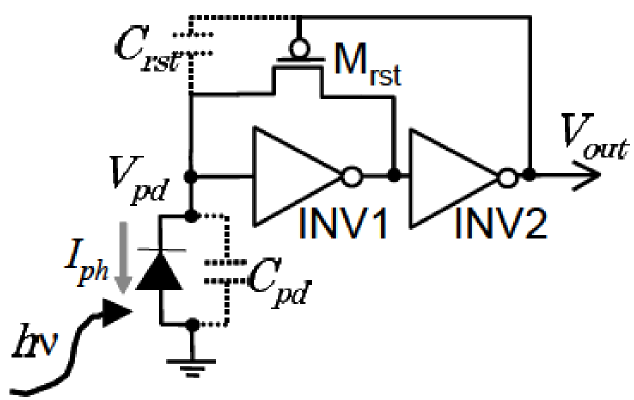
- Pulse frequency and pulse width dependence on input light intensity



Capacitive Feedback PFM

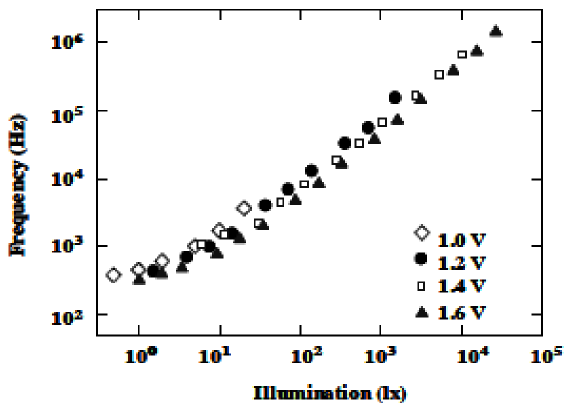
- Schematic of PFM pixel with capacitive feedback reset



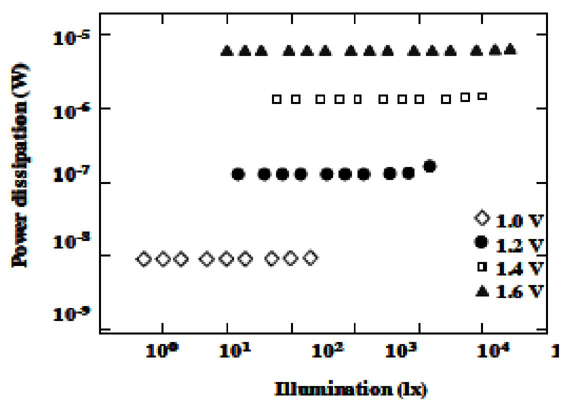


Capacitive Feedback PFM(cont'd)

- Experiment results of the dependence
  - (a) output pulse frequency
  - (b) power dissipation on illumination
  - (c) saturation frequency vs. power supply voltage of a capacitive feedback PFM photosensor



(a)



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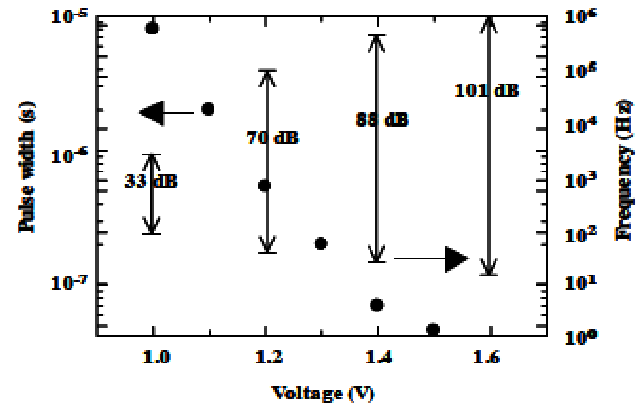
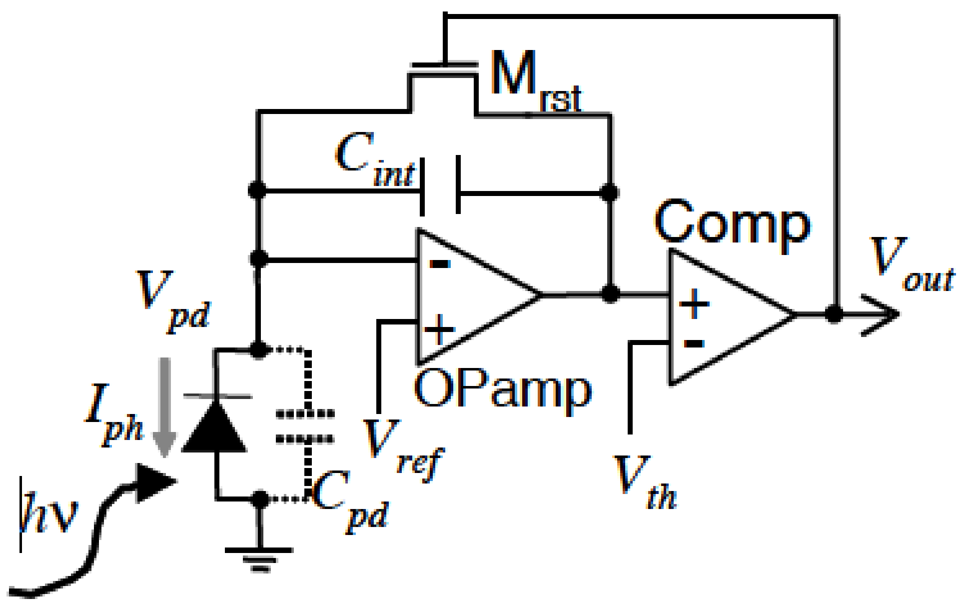


(c)

PFM with Constant PD Bias

- PFM pixel circuit with constant PD bias



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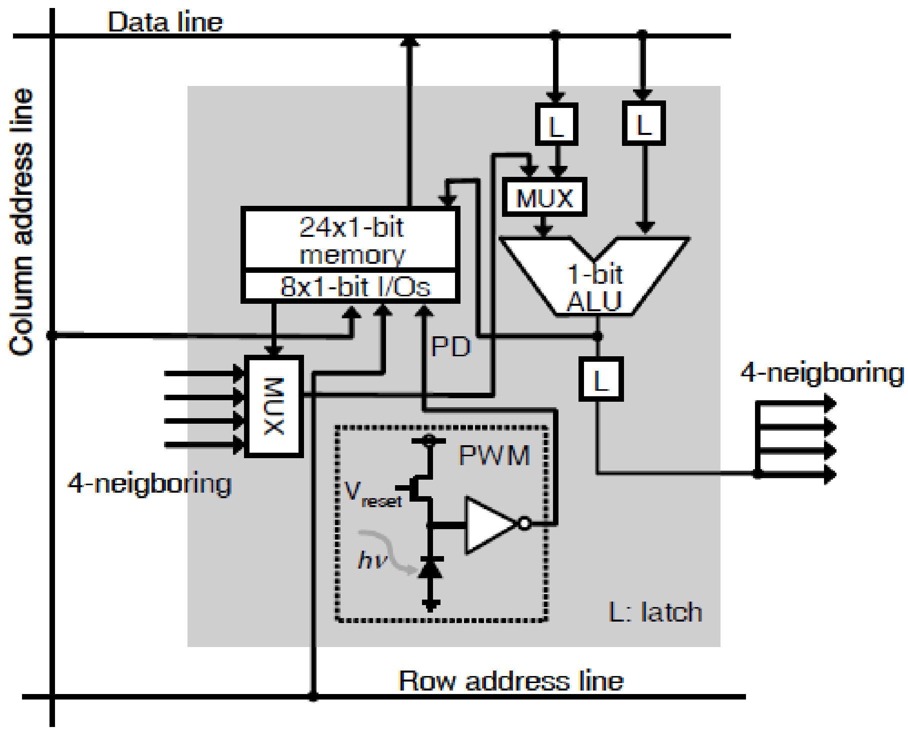
Pixel Circuit Diagram

- Pixel circuit diagram of a smart CMOS image sensor with digital processing architecture



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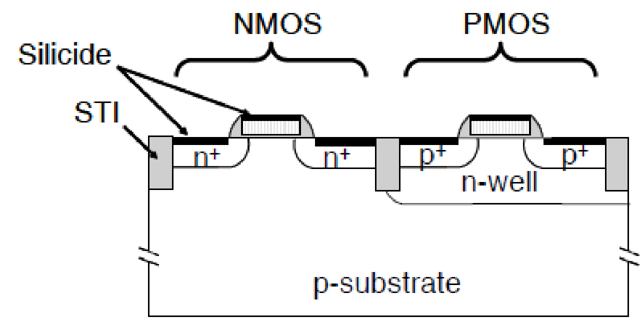
Materials other than Silicon

- Silicon-on-insulator
- Back-illuminated image sensor
- Silicon-on-sapphire
- Extending the detection wavelength

Silicon-on-Insulator

- Cross-section of
  - (a) bulk CMOS devices
  - (b) SOI CMOS devices

(a)



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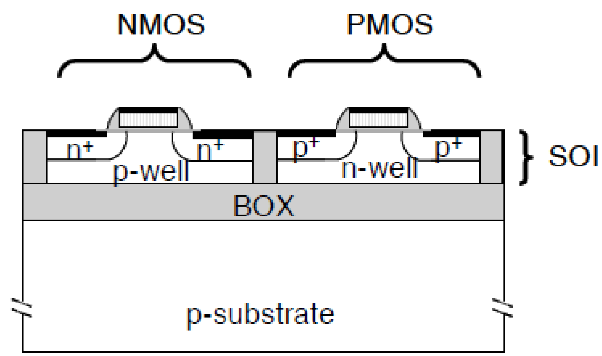
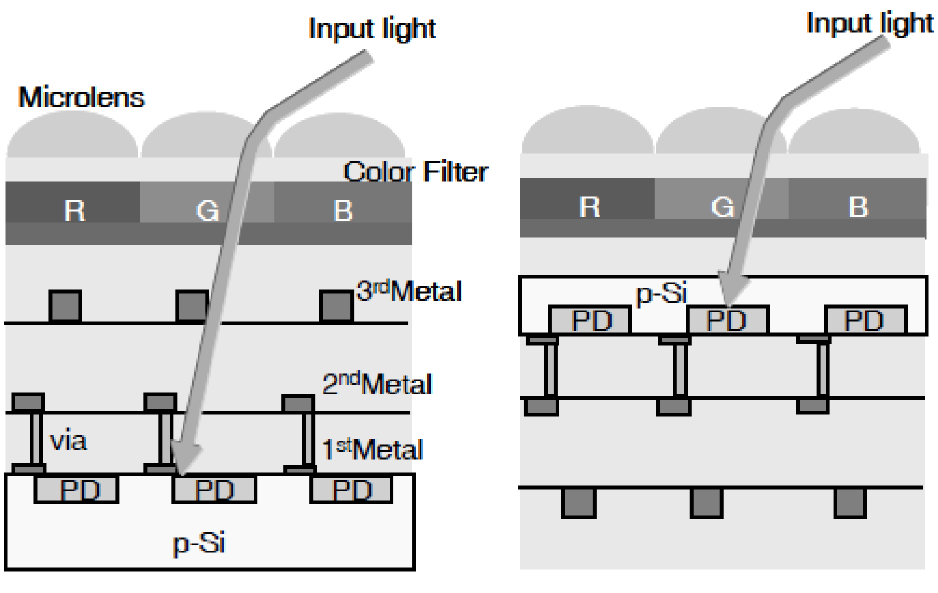


SOI Sensor

- Low voltage / low power operation
- Less crosstalk / latchup
- In-pixel N/PMOS availability
- Back-illuminated sensor implementation
- Perfectly inter-pixel isolation
- Lower QE

Back-illuminated Image Sensor

- Cross-section of
  - (a) a conventional CMOS image sensor
  - (b) a back-illuminated CMOS image sensor



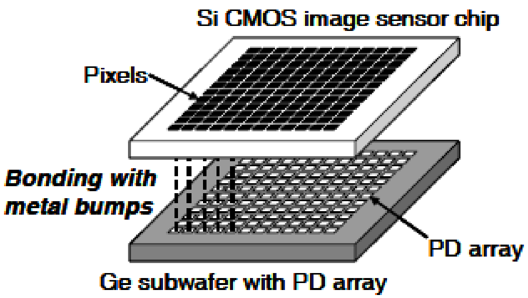
(a) (b)

Silicon-on-Sapphire

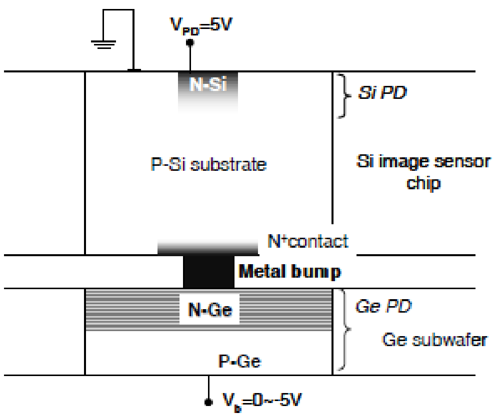
- Silicon crystal layer on Sapphire
- Polishing sapphire is transparent
- BSI solution without thinning down

Extending Detection Wavelength

- Smart CMOS image sensor that can detect in both the visible and eye-safe regions
  - (a) chip structure
  - (b) cross section of the sensor



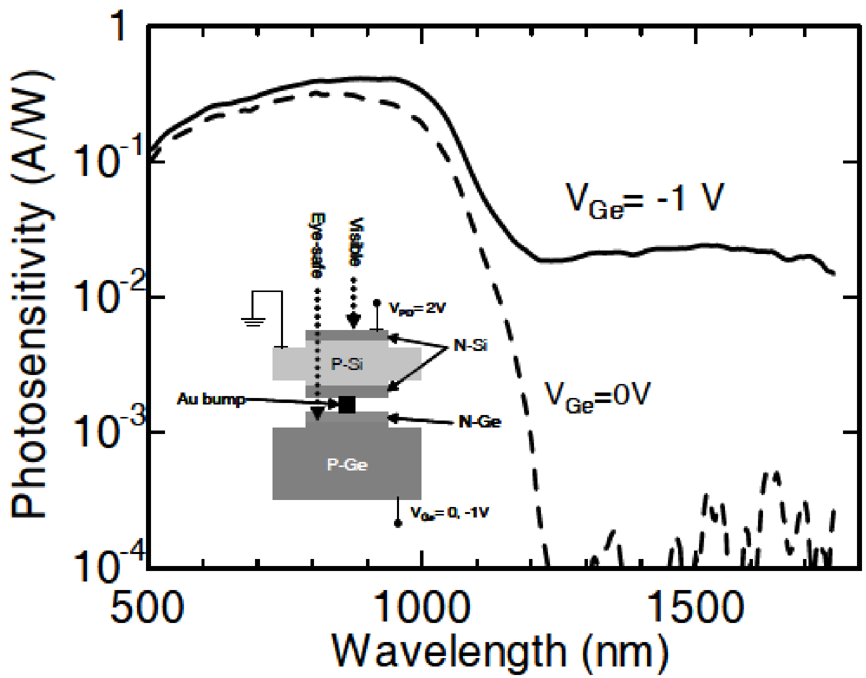
(a)



(b)

Extending Detection Wavelength

- Photosensitivity curve as a function of input light wavelength



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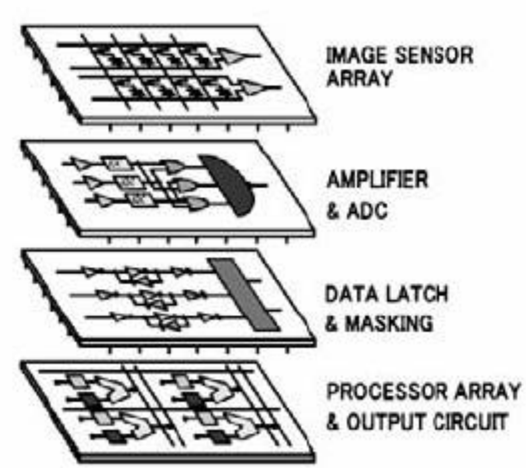
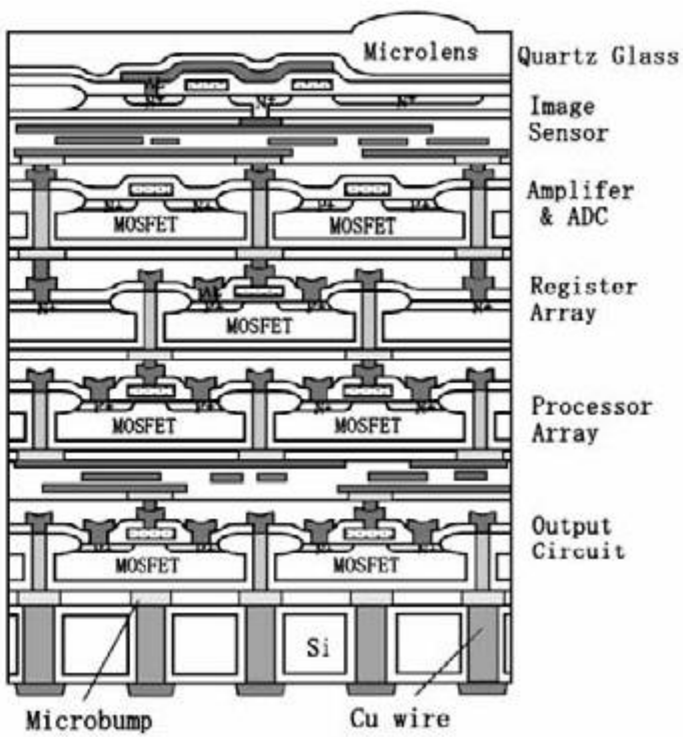
Structures

- 3D integration
- Integration with light emitters
- Color realization using nonstandard structures

3D Integration

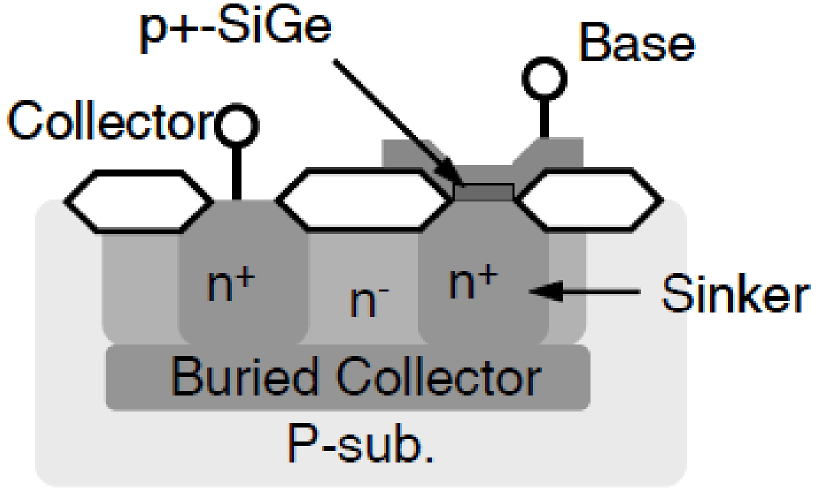
- Three-dimensional image sensor chip
  - Micro bump, Inductive/capacitive/optical coupling
  - Through silicon via (TSV)

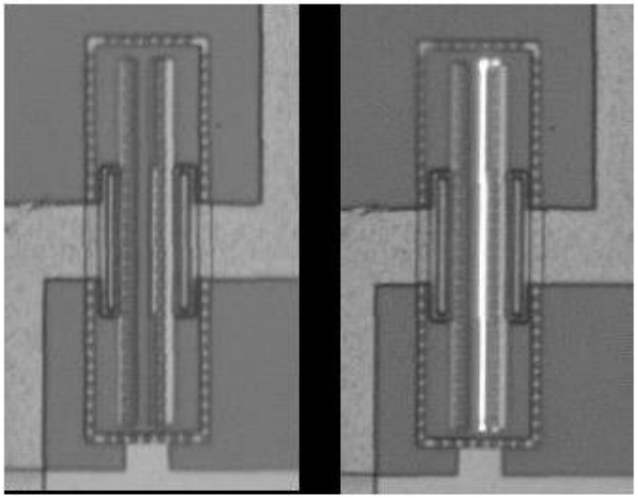




Integration with Light Emitters

- Cross-section of an LED using SiGe-BiCMOS
- Forward bias P/N junction. (band-to-band emission: λ=1.16um)
- Reversed bias P/N junction. (hot-electron of avalanche breakdown: λ=0.7um)



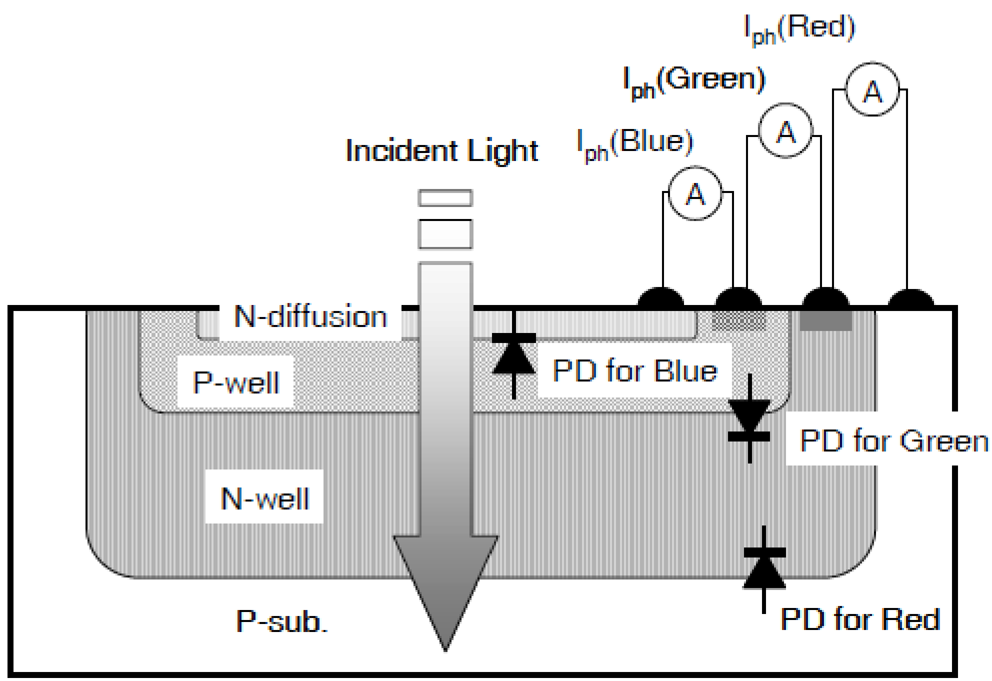


Nonstandard Color Realization

- Stacked organic PC films
  - Separated PC layer for each color
- Multiple junctions
  - Separated junction depth for each color
- Controlling the potential profile
- Sub-wavelength structure

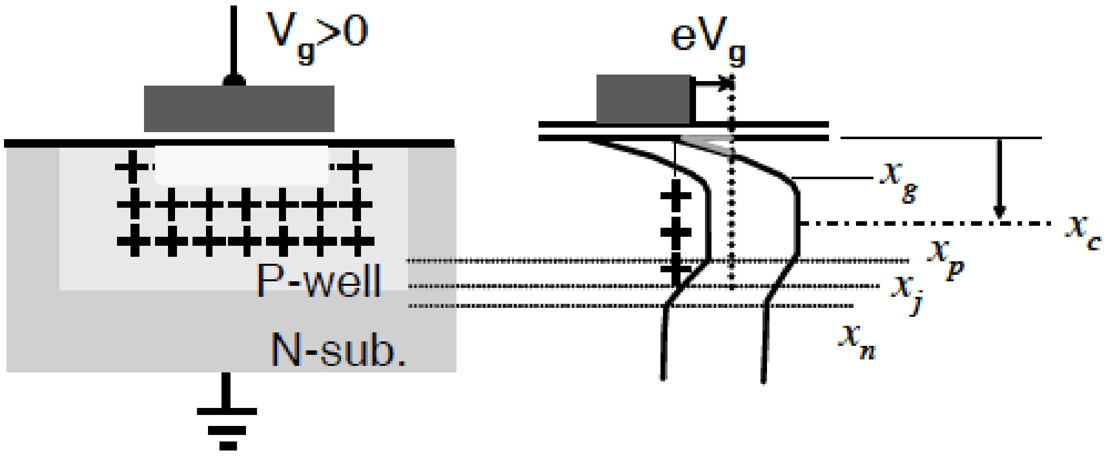
Multiple Junctions

- Device structure of image sensor with a triple junction



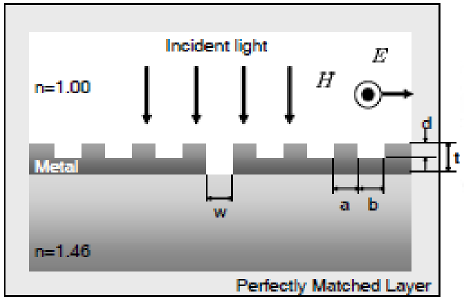
Controlling the Potential Profile

- Device structure and potential profile for filterless fluorescence image sensor

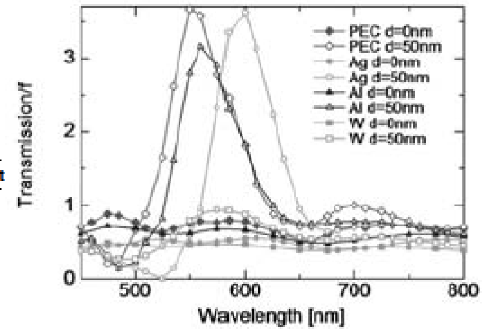


Sub-wavelength Structure

- Metal grid as a sub-wavelength structure and its optical transmission
  - Computer model (a)
  - Optical transmission dependence on the wavelength with the parameters of
    - (b) materials
    - (c) metal thickness
    - (d) period



(a)



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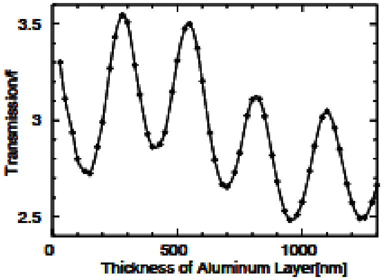

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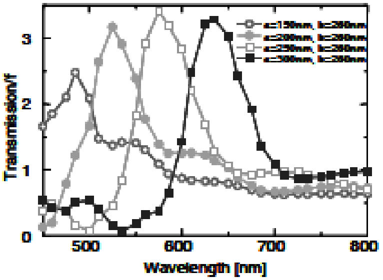
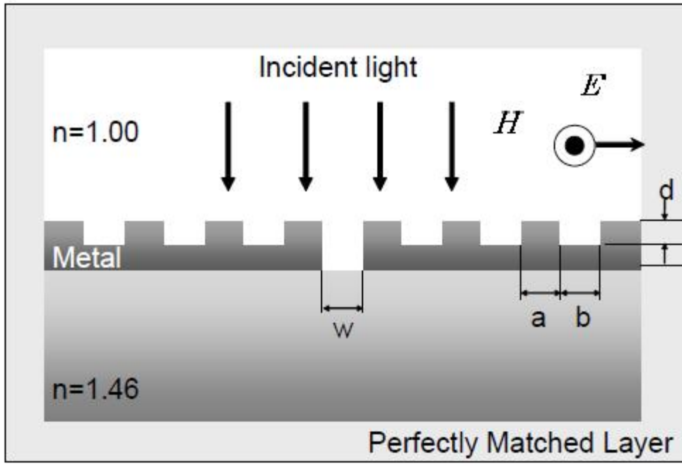


(d)

Sub-wavelength Structure



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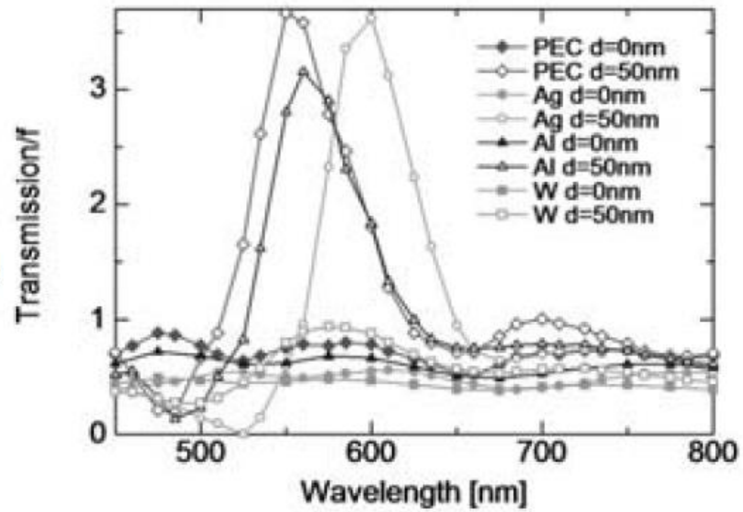

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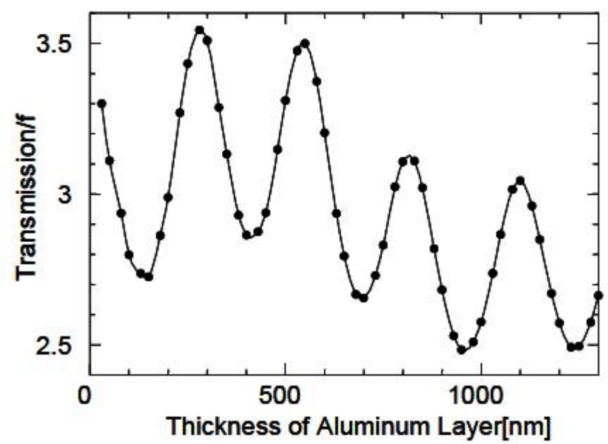

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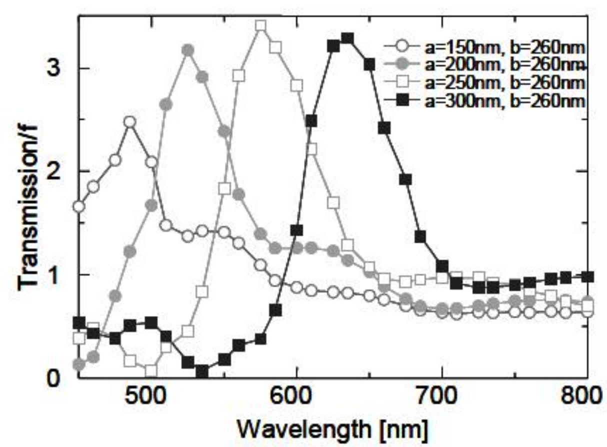

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