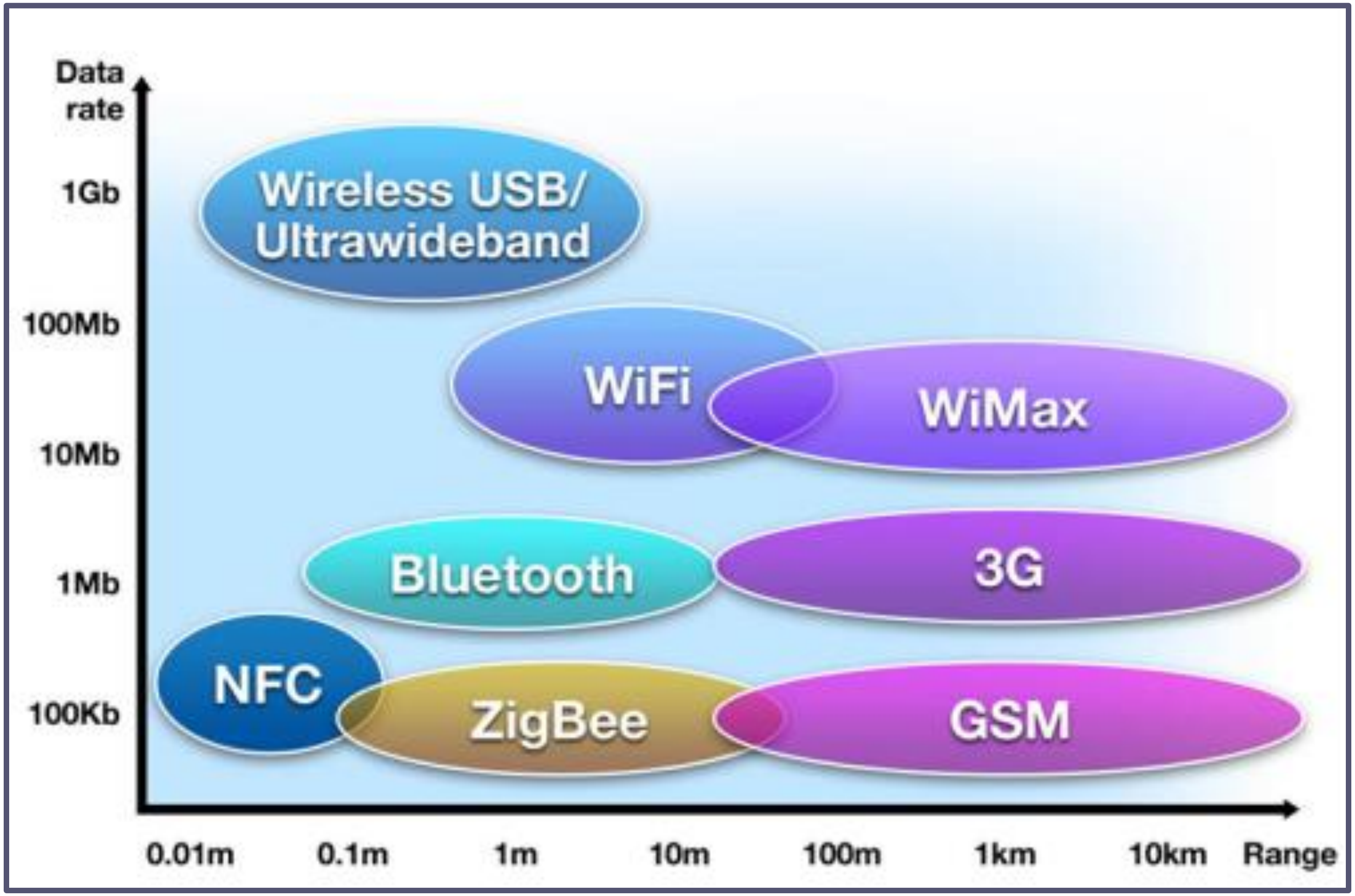
Optical Sensors

Instructor: Ching-Te Chiu

Outline

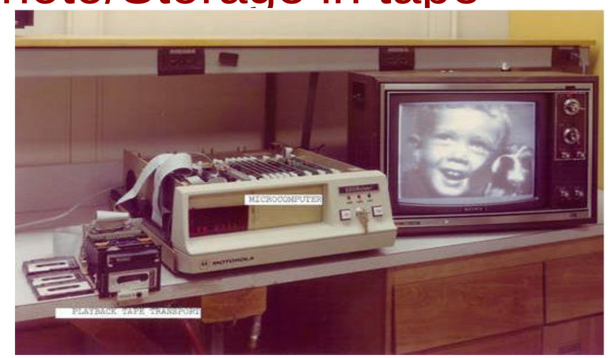
- Introduction
- Technology Analysis
- Applications
- Industry Analysis
- Conclusion
- Reference

Comparison Between Wireless Communication Technologies[3]



Introduction

- 1975 First digital Camera
  - Photograph: An image is taken by light-sensitive material and then made visible
  - 10,000 pixel Charge Couple Device (CCD) sensor with black/white image
  - Taking 23 sec to take a photo/Storage in tape



Current Cameras in Smart Phone

三鏡頭設計模式	三鏡頭作用	代表性手機
RGB/單色(Mono)/望遠(Tele)	強化低光線拍攝	Huawei P20 Pro
廣角RGB/超廣角RGB/望遠(Tele)	支援廣角拍攝	LG V40 ThinQ
廣角RGB/超廣角RGB/景深(DOF)	支援景深拍攝	Galaxy A7
廣角RGB/望遠(Tele)/摺疊望遠(folded Tele)	拍遠景/大景的最佳助手	N/A

Comparison with different phones

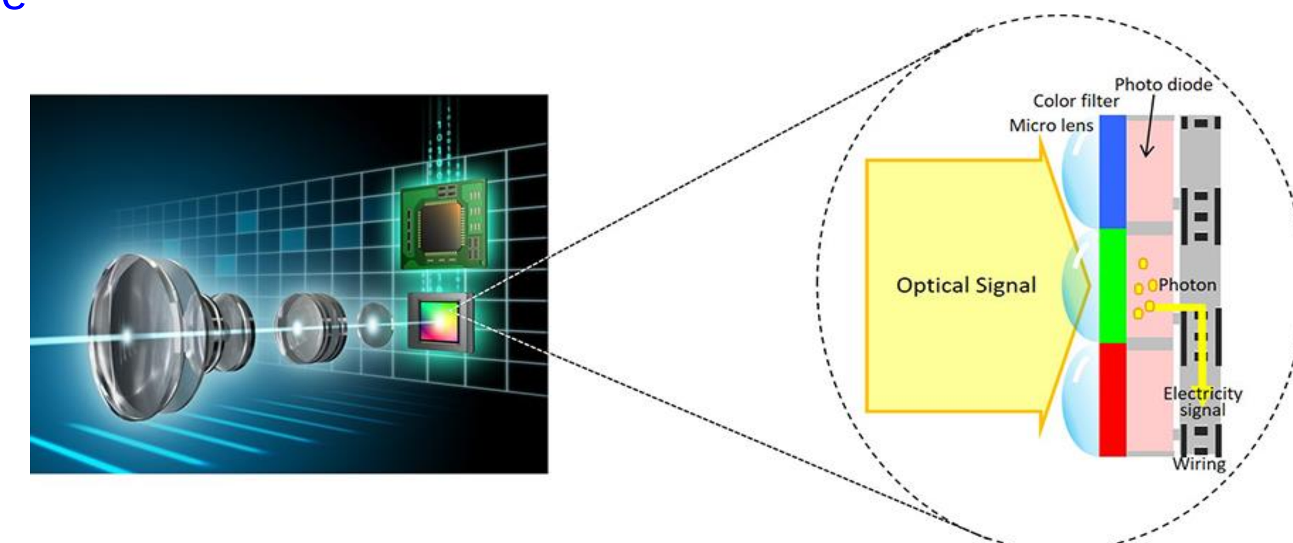
品牌	APPLE	Samsung	Huawei
機型	iPhone 11/11 Pro Max	Note 10	Mate 20 Pro
處理器	A13 Bionic + U11	高通S855八核心	KIRIN 980八核心
第一主鏡頭(標準)	1200萬 f1.8 26mm OIS	1200萬 Dual f1.5/f2.4 77° OIS	4000萬 f1.8 27mm OIS
第二主相機(超廣角)	1200萬 f 2.4 120° 13mm	1600萬 f2.2 123°	2000萬 f2.2 16mm
第三主相機(望遠)	1200萬 f 2.2 52mm OIS	1200萬 f2.1 45° OIS	800萬 f2.4 27-80mm
第一前鏡頭	1200萬 f2.2	1200萬 f2.2	2400萬 f2.0 26mm

Vendor	Part Number	Product Common Name	Product Model Number	Front or Rear Facing?	Reported Resolution (MP)	Pixel Pitch (μm)	Die Size Length (mm) (Die Edge)	Die Size Width (mm) (Die Edge)	Die Area (mm^2)
Sony	<Unknown> iPhone 11 TrueDepth selfie	iPhone 11	A2111	Front	12.0	1.00	4.04	5.53	22.3
STMicroelectronics	56G08A (TrueDepth Infrared Camera)	iPhone 11	A2111	Front	1.4	2.80	4.65	5.65	26.3
Sony	<Unknown> iPhone 11 Pro telephoto	iPhone 11 Pro Max	A2161	Rear	12.0	1.00	5.21	6.28	32.7
Sony	<Unknown> iPhone 11 Pro ultra wide-angle	iPhone 11 Pro Max	A2161	Rear	12.0	1.00	5.22	6.28	32.8
Sony	<Unknown> iPhone 11 Pro wide-angle	iPhone 11	A2161	Rear	12.0	1.40	5.78	7.01	40.5

OIS: Optical Image Stabilizer: capture sharp pictures at shutter speeds three, four, or five times slower than previously possible

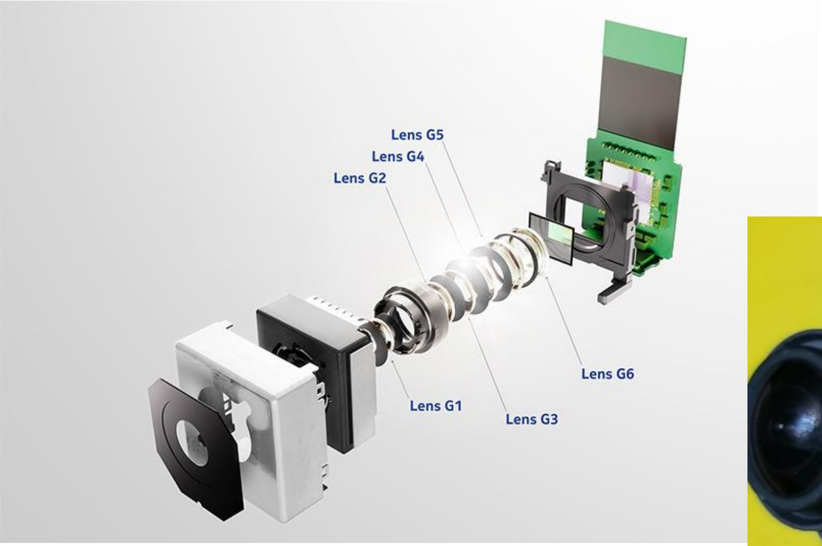
Semiconductor Image Sensors

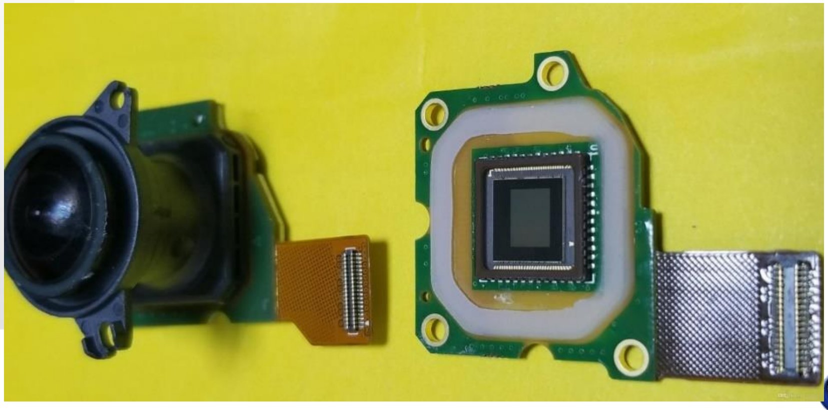
- Image sensors:
  - Convert light into electrical signals
  - Oppositive to LED (Convert electrical signals to light)
  - Main components
    - Micro lens
    - Color filter
    - Photo diode
    - Amplifier



Semiconductor Image Sensors

- Two main types of photo diode
- Both on metal–oxide–**semiconductor** (MOS) technology
  - **Charge-coupled device** (**CCD**)
    - based on store electrons
  - **Active-pixel sensor** (**CMOS sensor**)
    - Amplifier signals by MOSFET (MOS field-effect transistor) amplifiers





CCD Internal Architecture (1)

- Four main components
  - Microlens: light focusing
  - Color filter: R/G/B light
  - Photodiode: convert light into electrical sig
  - Shift register(well) : collect electrons

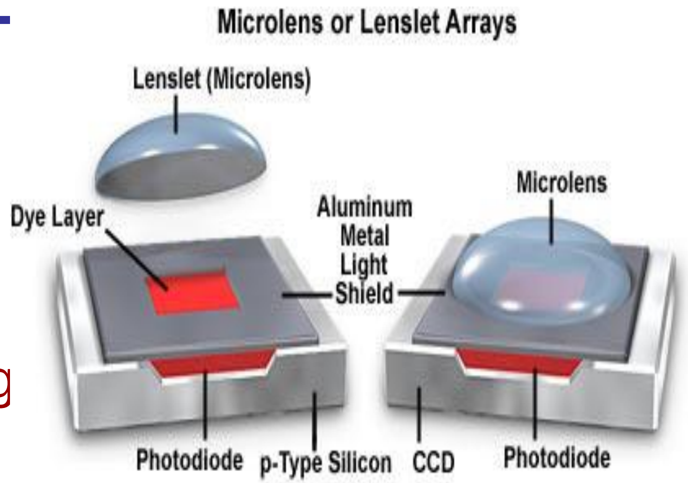
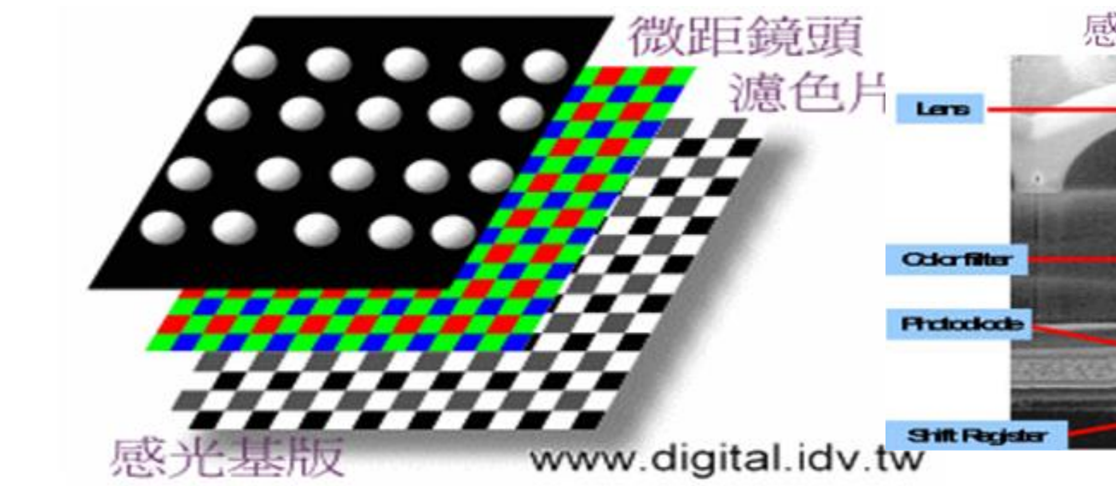
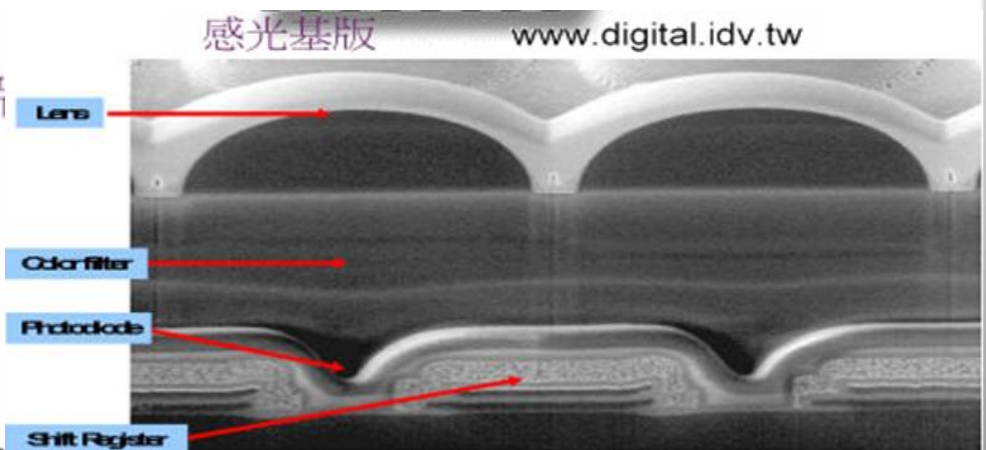


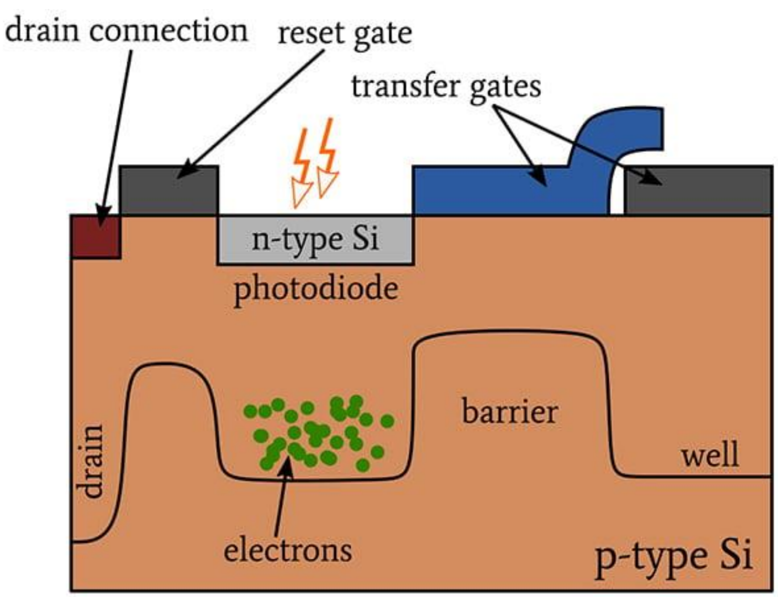
Figure 1





CCD Architecture

- Microlens to increase the fill in factor of electrons
- Photodiode: photon sensitive detector with light-sensitive area (pixel)
    - n-type silicon channel
        - Photo falls into the pixels convers to electrons
        - Number of electrons proportional to intensity of light
- Electrons are stored in a potential well



Microlens Array Architecture

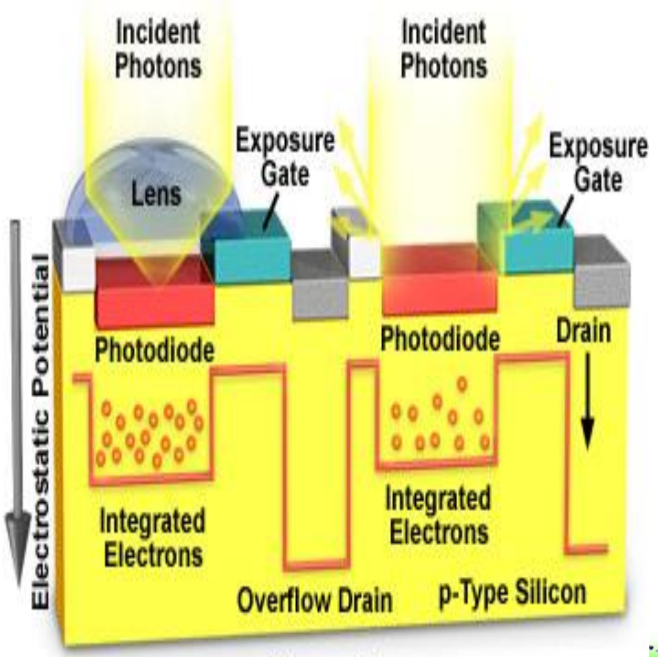
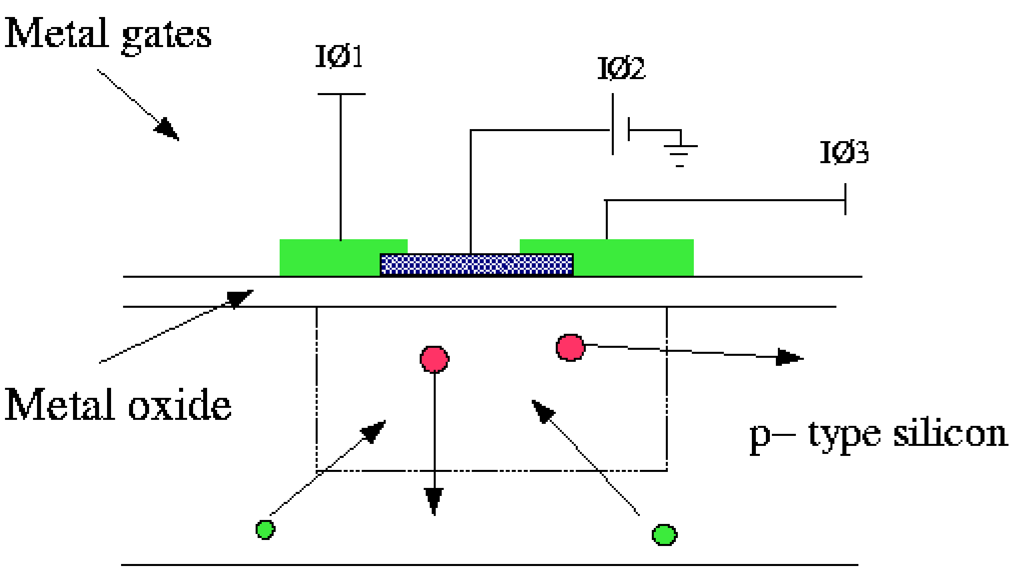


Figure 2

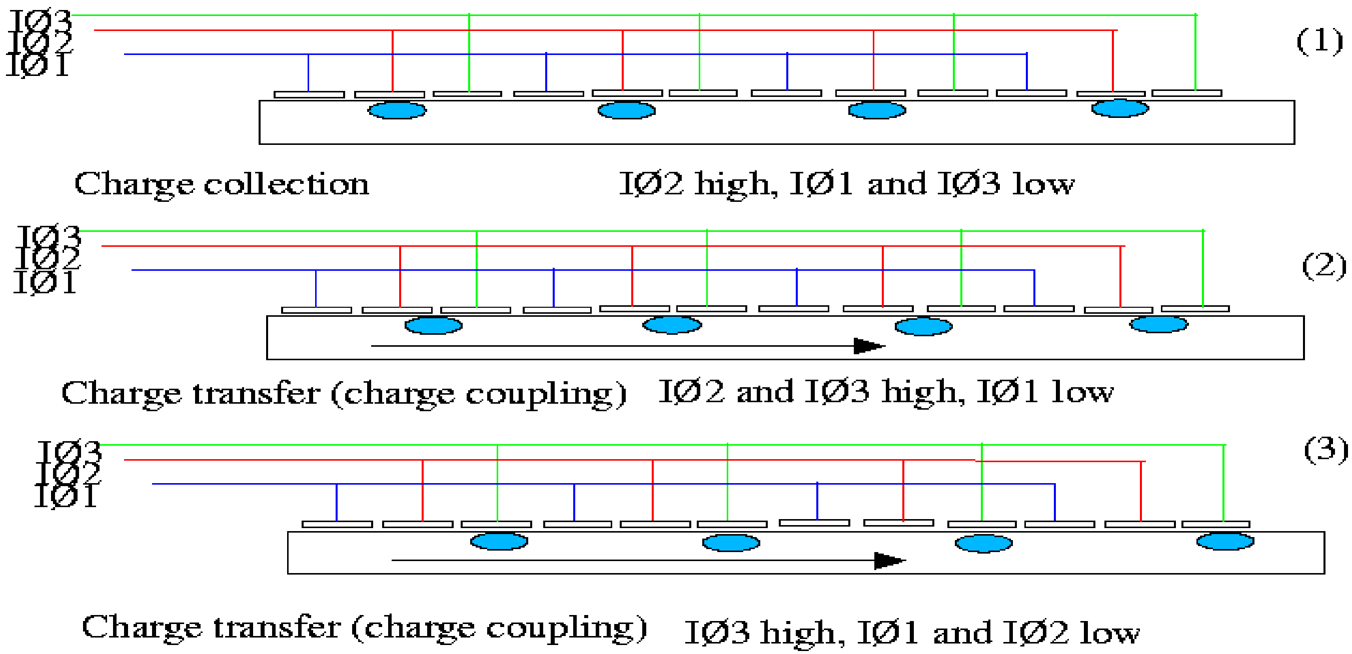
CCD Architecture

- Photodiode
- Electrons are stored in a potential well
- Potential well is defined by the position of electrodes above the CCD
- Positive voltage applied by I02 attracts electrons generated by photons
- Holes will be repulsed
- Potential well is formed in which all electrons produced by incoming photons will be stored



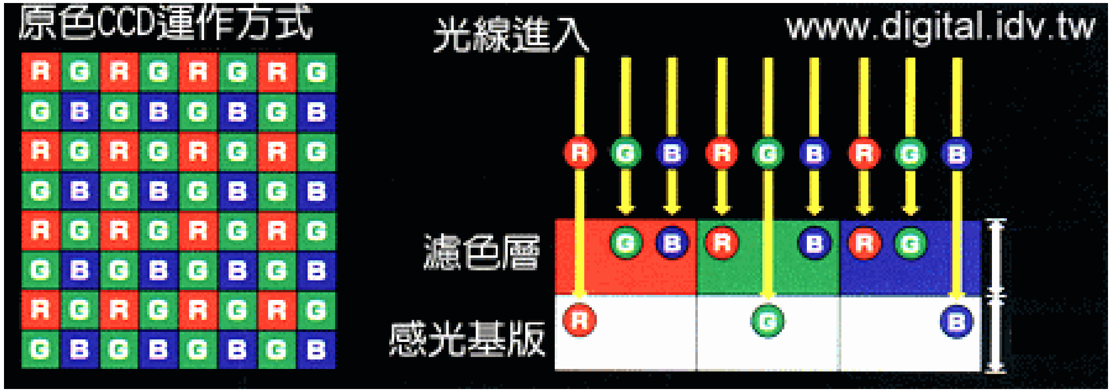
CCD: Charge movement

- Controlled by the gate voltage
- Charge subsequently be transferred across the chip through registers and output to an amplifier



CCD Color Filters

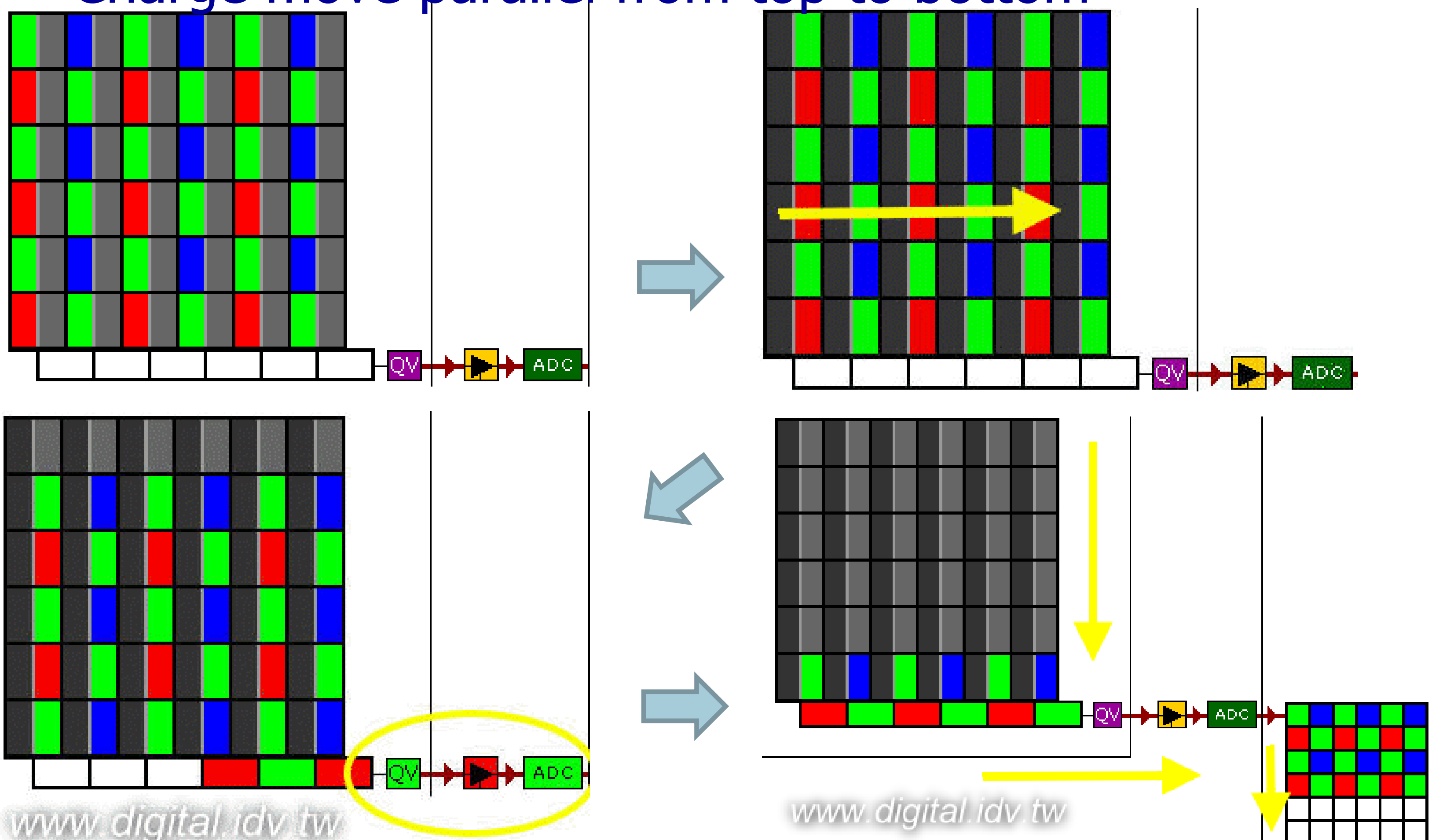
- Color filters is made from photoresists (polymers)
- CCD Primary color separation Method
- One pixel has R/G/B colors



- Advantages:
  - Sharp picture quality
  - The colors are more realistic
- Disadvantages:
  - Noise problem

CCD Working Principle

- Charge moves sequentially from left to right
- Charge move parallel from top to bottom



CCD Overall Architecture

- Electrical Circuit part
  - Serial shift register
  - Parallel shift register
  - Clock controller/Amplifier

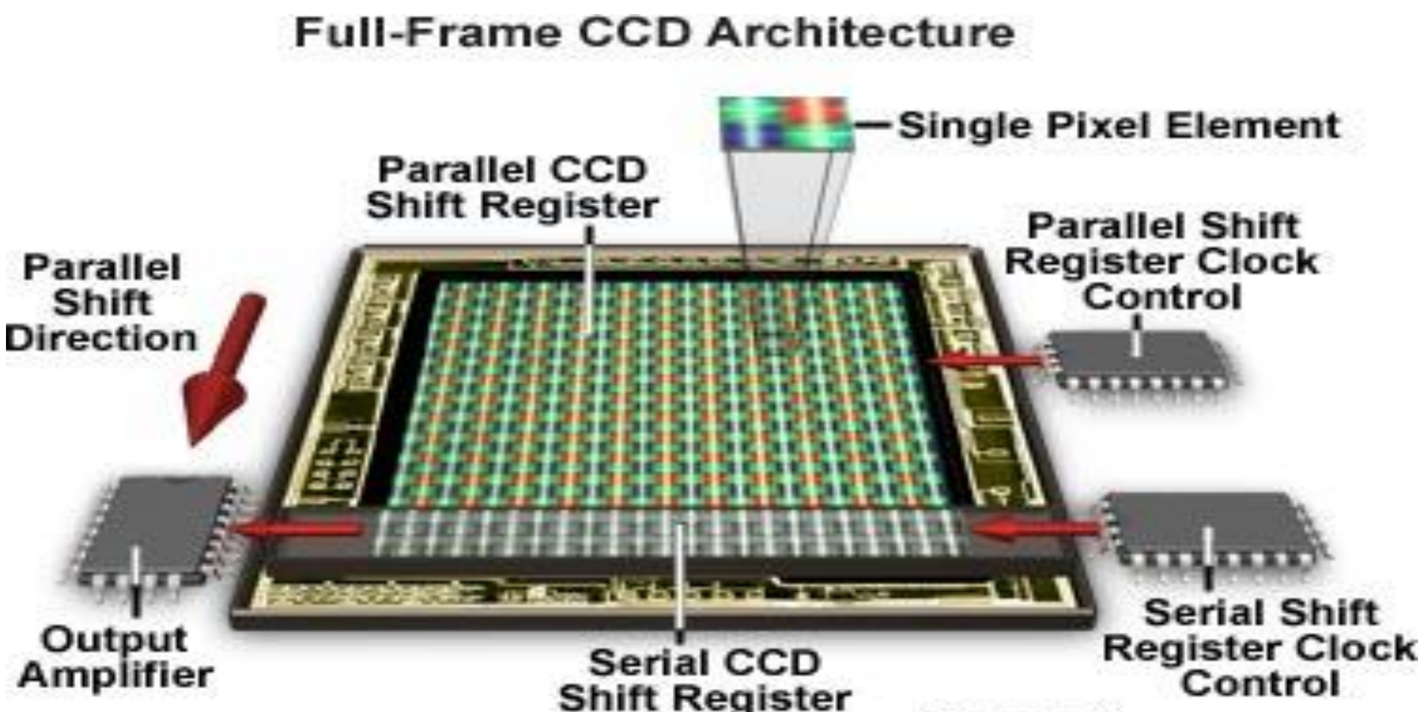
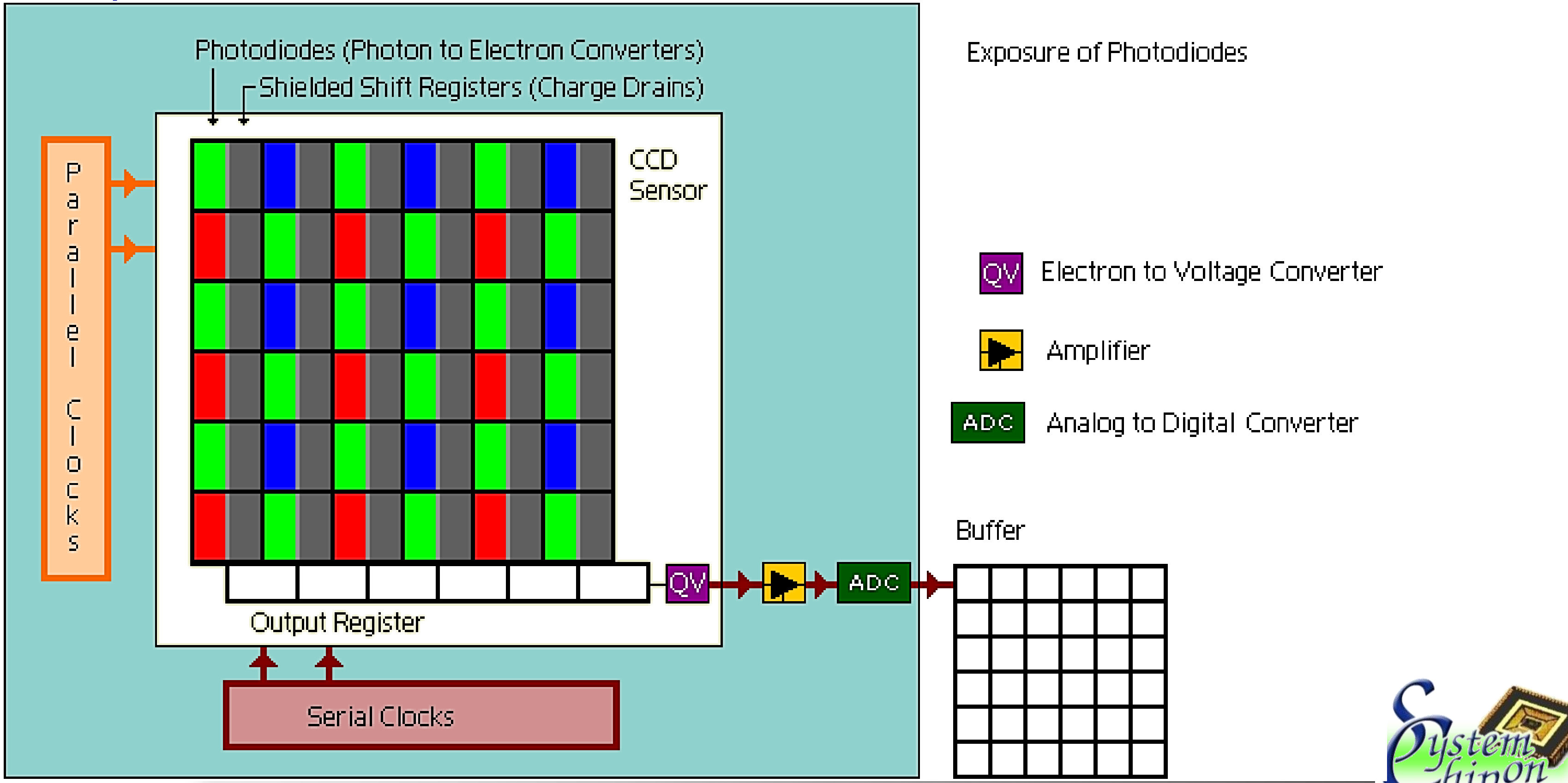


Figure 1

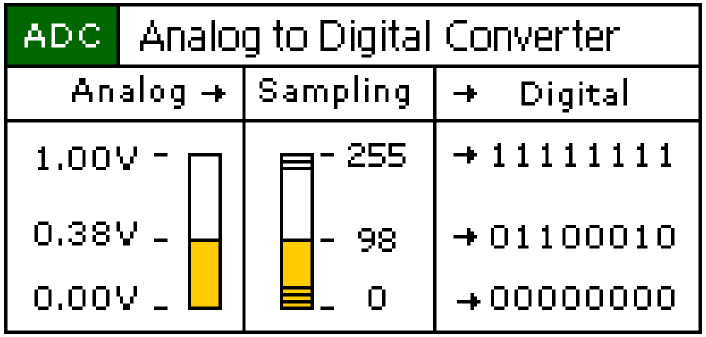
Schematic diagram of CCD image processing core

- Serial shift register/Parallel shift register Clock controller
- Electron to voltage converter
- Amplifier
- ADC/Buffer



CCD ADC conversion

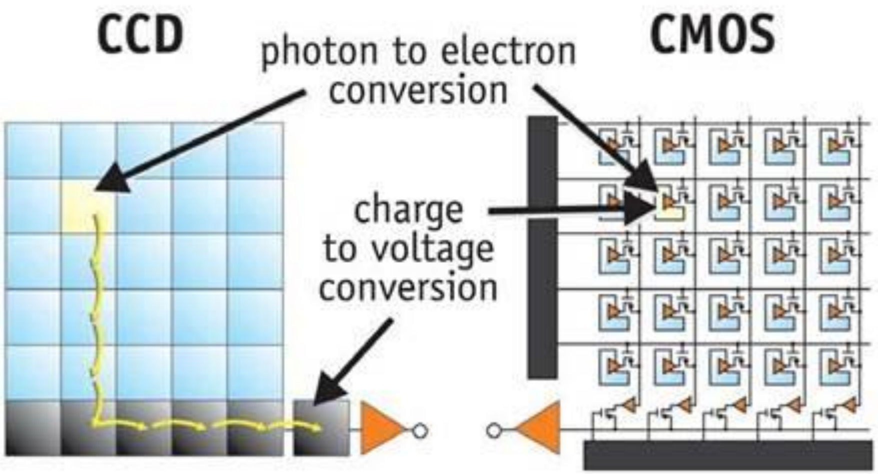
- ADC to convert analog signal to 8 bit digital signal



- Most of the current ADC can achieve 12 bit

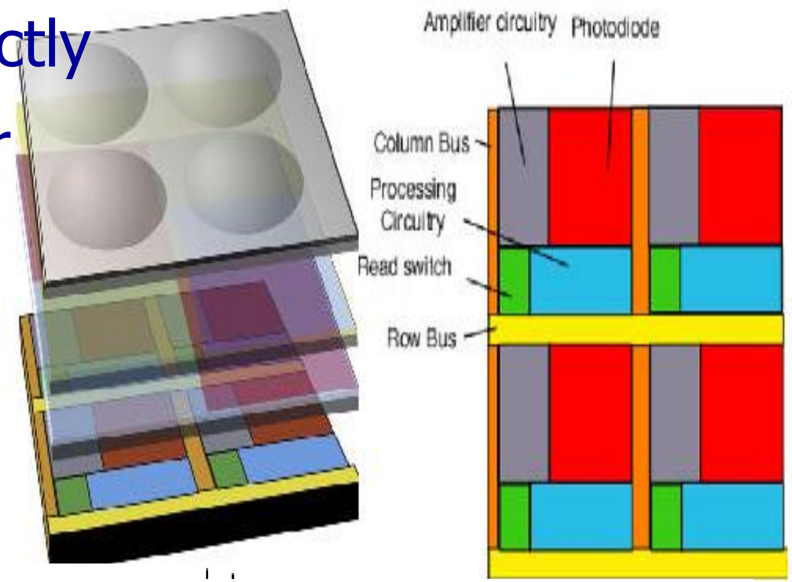
CMOS Image Sensor Structure

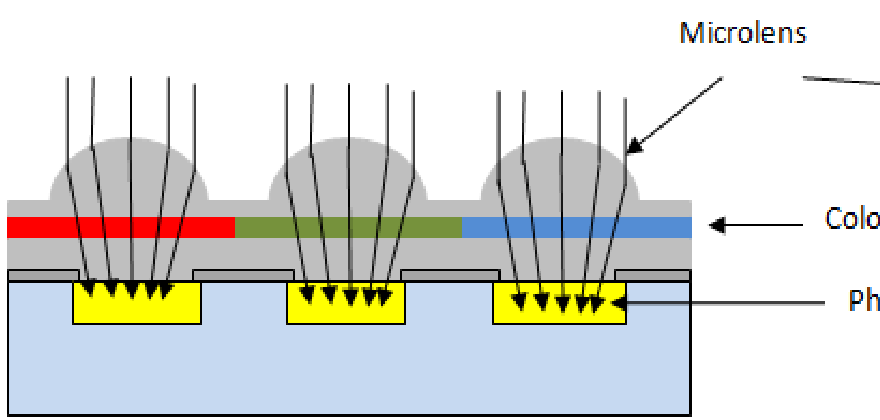
- Definition: A CMOS sensor is **an electronic chip that converts photons to electrons for digital processing**.
- CMOS (complementary metal oxide semiconductor) sensors are used to create images in digital cameras, digital video cameras and digital CCTV cameras.
- The structure of image sensor
  - Microlens
  - RGB filter
  - **photodiode**
  - **Active amplifier**

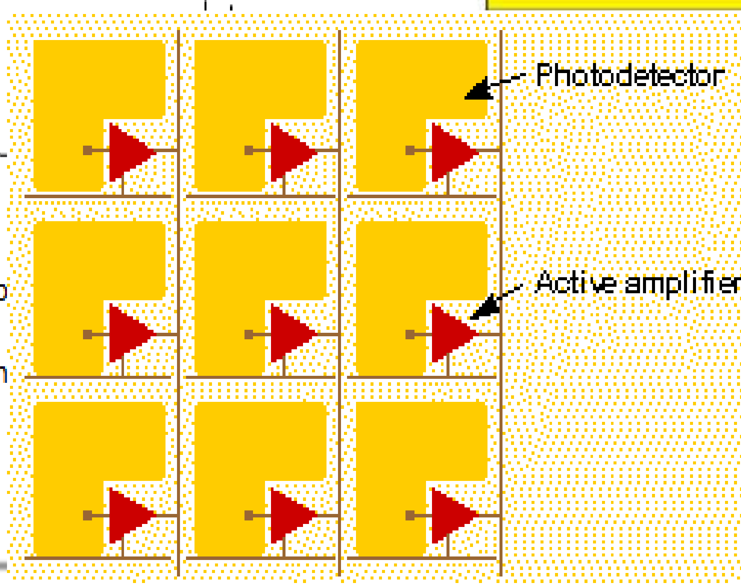


CMOS Image Sensor Principle

- Amplifiers to enlarge signal directly
- Each pixel has its own amplifier
  - CCD store electrons
- Control pixel directly

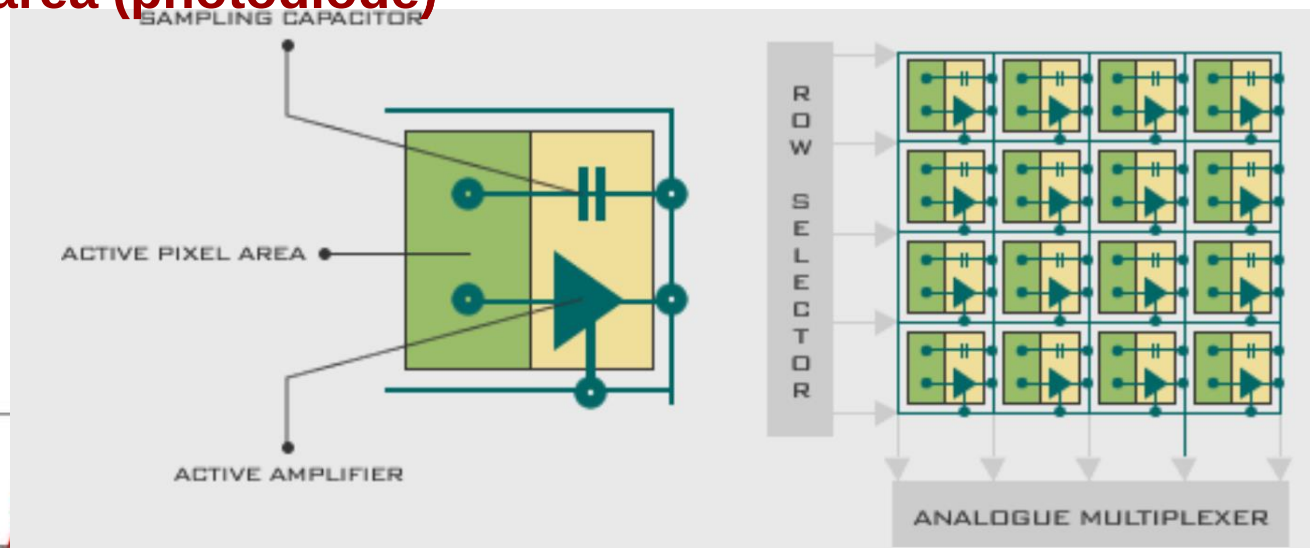


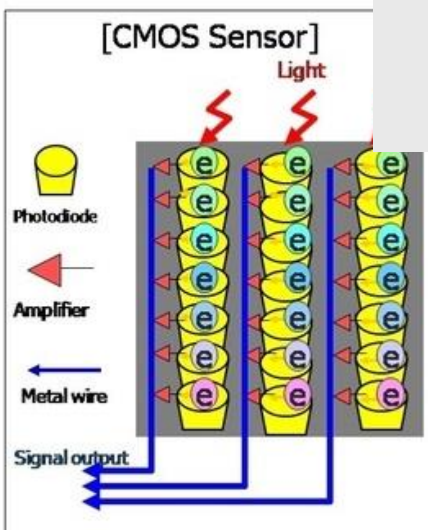


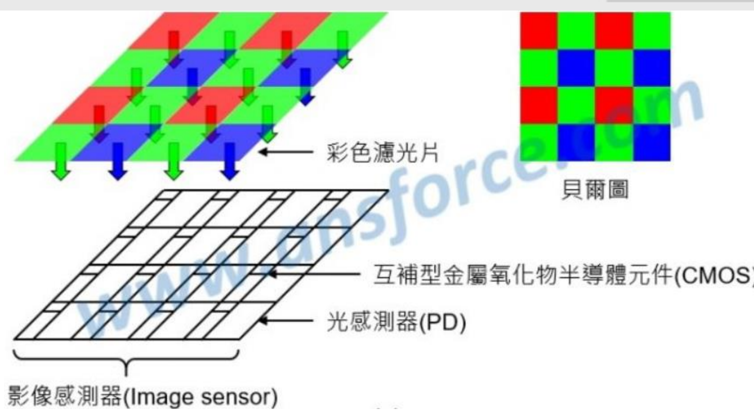


CMOS Active Pixel Sensor

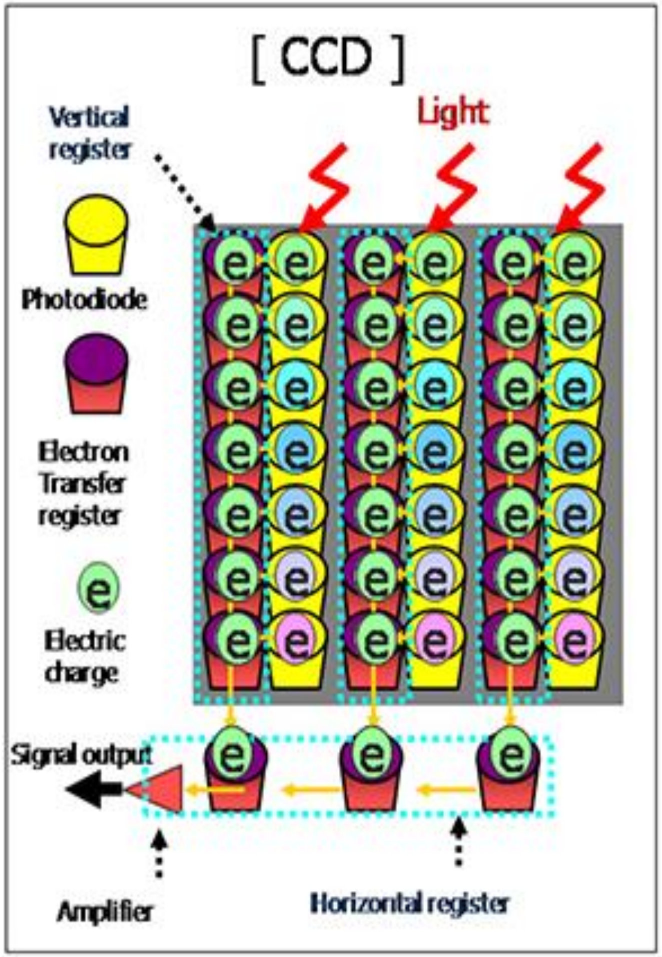
- The structure of pixel sensor
  - **Active pixel area (photodiode)**
  - Capacitor
  - Amplifier

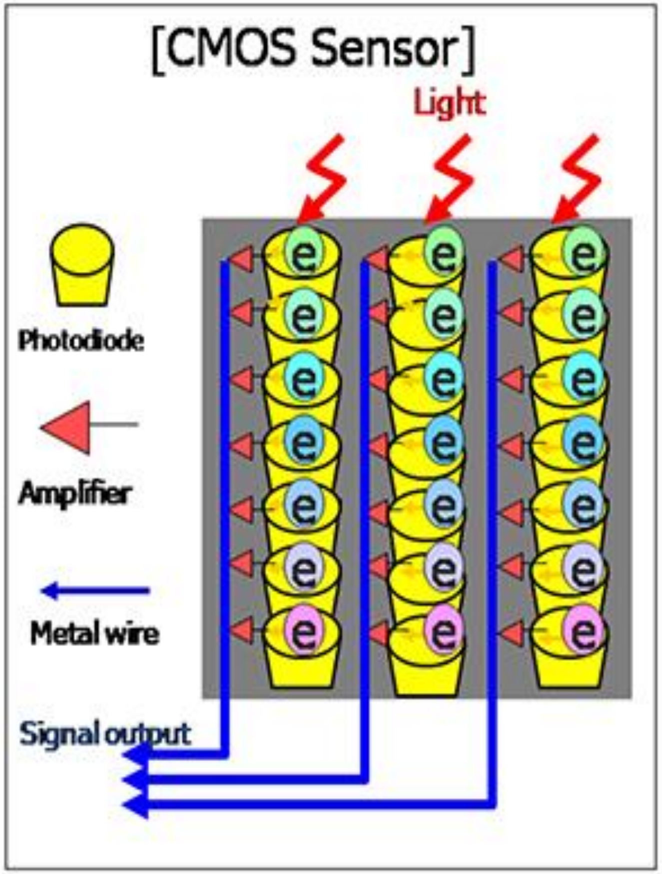






CCD v.s CMOS Principle





CCD v.s CMOS Comparison

Description	CCD	CMOS
Camera components	Sensor+ Optic Support Chips+ Optics	Sensor+ Optic: Support Chips Sometimes
Speed	Moderate to fast	Fast
Sensitivity	High	Low
Noise	Low	Moderate
System complexity	High	Low
Sensor complexity	Low	High
Fill factor	High	Low
Chip output	Voltage (analog)	Bits (digital)
Pixel signal	Electron	Voltage
Uniform shuttering	High to moderate	Low

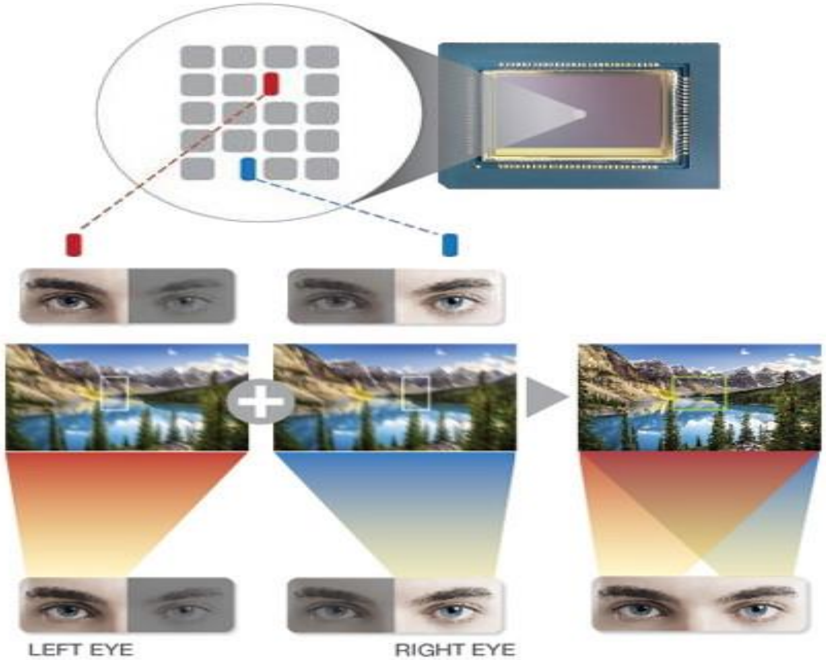
Source: Frost & Sullivan

Iphone 14 Camera System

- The new Photonic Engine improves the cameras, producing more detail in low-light shots.
- The main upgrade is the 48 MP main camera sensor
  - The camera bins pixels together in groups of 4, resulting in 12 MP photos with improved lighting
  - Enable ProRAW to capture full 48 MP photos
  - A new zoom step between wide 1x and telephoto 3x (by cropping into the new larger sensor for a 2x zoom)

PDAF

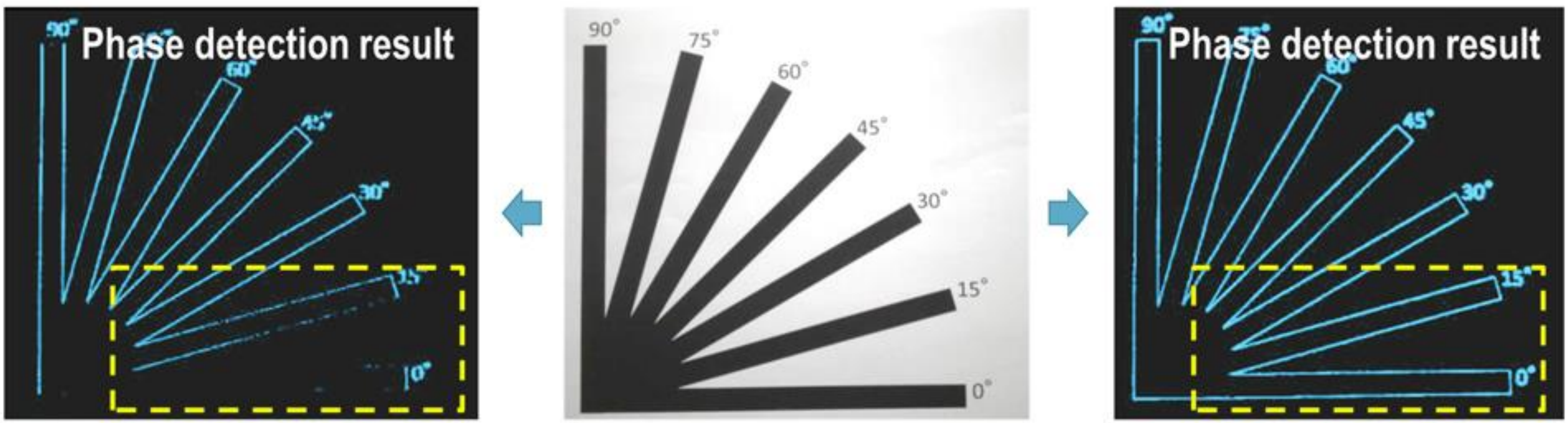
- Masked PDAF (phase different autofocus)
  - Creates dual perspective using dedicated phase detecting photodiodes on the image sensor itself.
  - These photodiodes are physically masked such that light from only one side of the lens reaches it.
  - This produces left-looking and right-looking pixels on a single image sensor, giving two images to compare focus.
  - The phase difference between the two images is calculated to determine the focus point.
  - Dual Pixel PDAF
  - Uses some of the pixels for imaging on the image sensor as pixels for phase detection.



https://www.androidauthority.com/how-pdaf-works-1102272/

PDAF

- Masked PDAF (phase different autofocus)
  - Problem of Dual Pixel PDAF : hard to focus on horizontal line
  - Quad Pixel PDAF: one pixel splits to four photodiodes
  - All Pixel Omni-Directional PDAF is Oppo’s nomenclature for the autofocus afforded by Sony’s **2×2 OCL sensor**. 2×2 OCL is essentially a Quad Pixel Quad Bayer setup with one condenser lens per pixel, covering all four photodiodes.



Left/Right phase detection

Test Object

Left/Right and Top/Bottom combined phase detection

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PDAF

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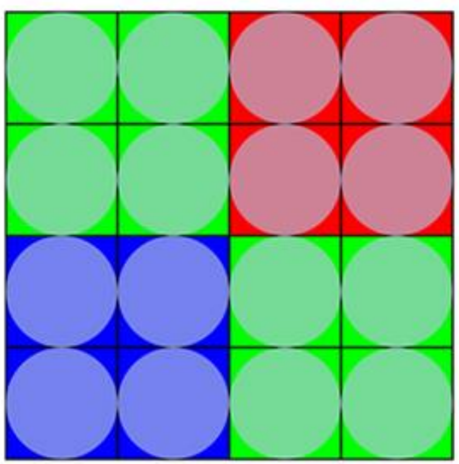
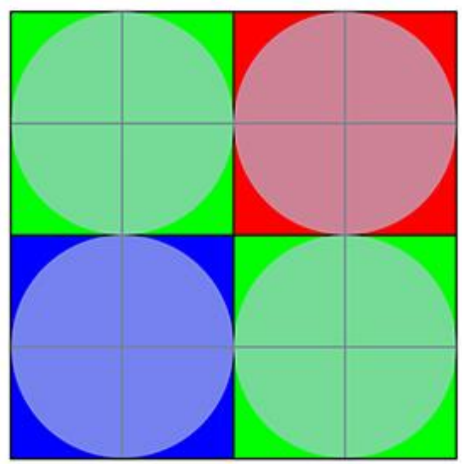
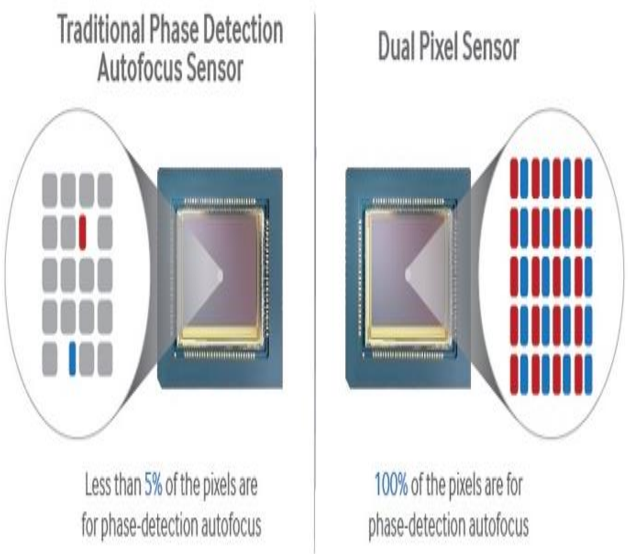


Conventional on-chip lenses



2x2 OCL



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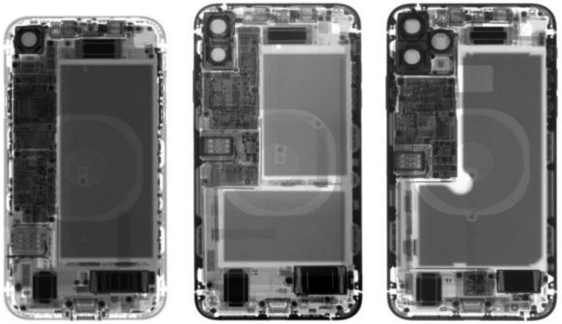
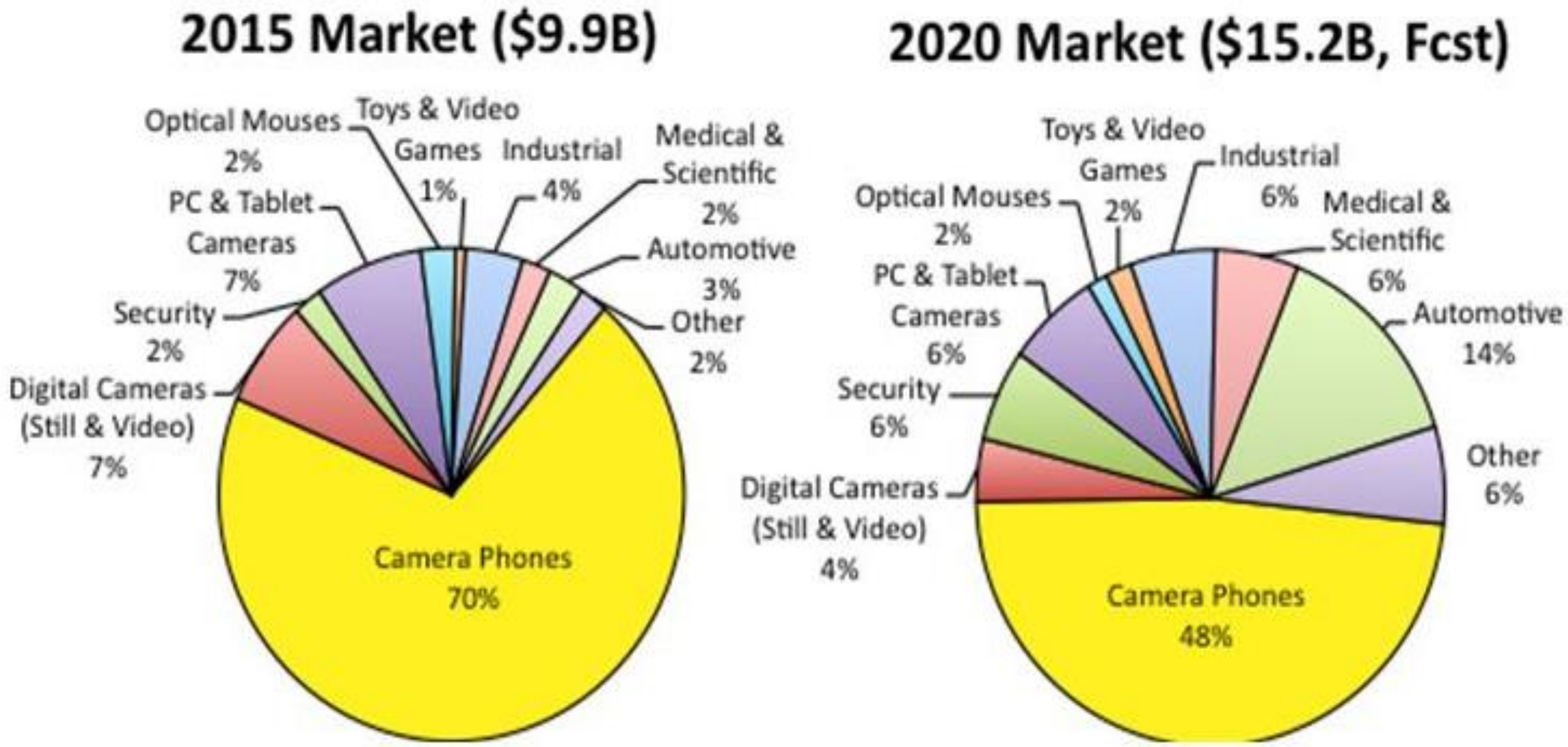
Applications



Application Market



Depth Sensor

- Introduction
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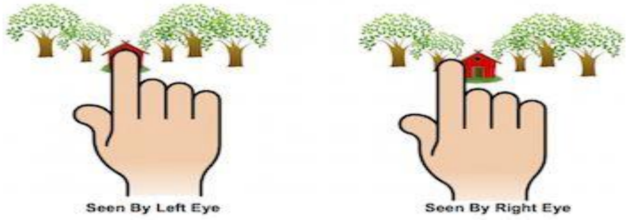
Introduction

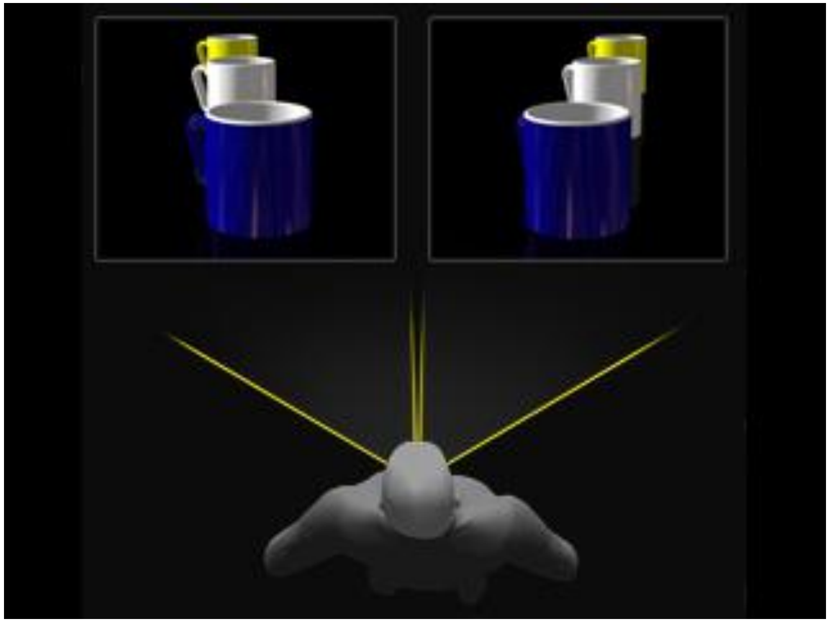
- **Depth Map**
  - A **depth map** is an **image** or image channel that contains information relating to the distance of the surfaces of scene objects from a viewpoint.
- Three methods to make depth map
  - Stereo Vision
  - Structure Light
  - Time of Flight

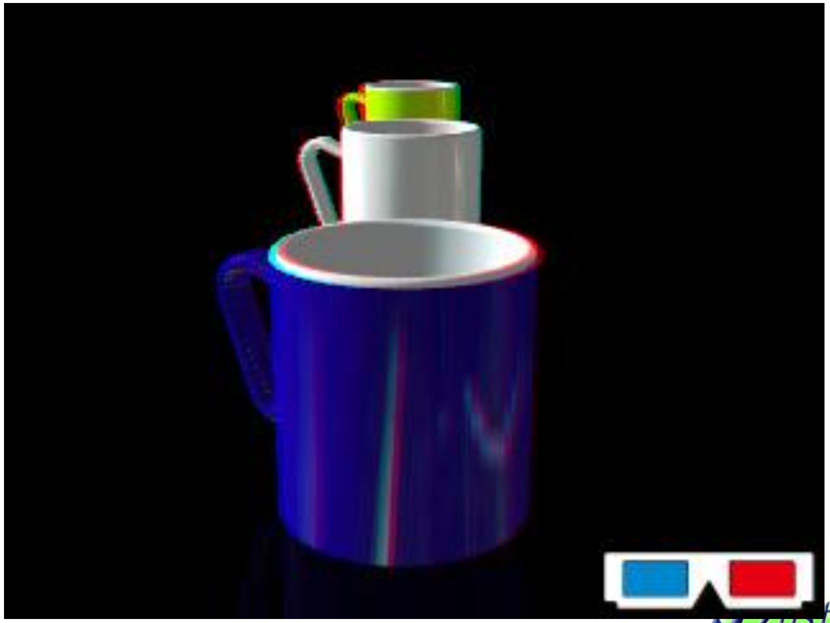
RGB image and Depth map

Stereo Vision



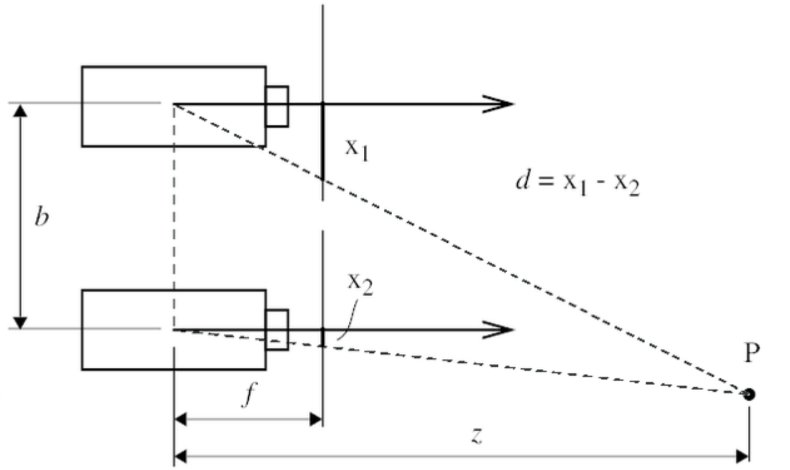
- The difference in view observed by your left and right eye is known as **retina disparity**.
- **Stereopsis:** ability to perceive depth due to 2 different perspectives of the world.
- By comparing images from the retinas in the two eyes, the brain computes distance.
- The greater the disparity, the closer things are to you.





Stereo Vision

- **Stereo Vision**
  - Use **two cameras (photo detectors)** to detect light reflecting from the same object.
  - concept of f **triangulation** and **stereo matching**
  - The two cameras are separated by a baseline distance (*b*)
  - The difference between 2 views as disparity (*d*)
  - Depth z can be obtained from disparity, focal length *(f)* and baseline distance *(b)*



From similar triangles,

$$\frac{d}{b} = \frac{f}{z}$$

Structured Light

- Use **one camera (detect light) and one projector (emitting light)**
- **Project sends out gray-code patterns**

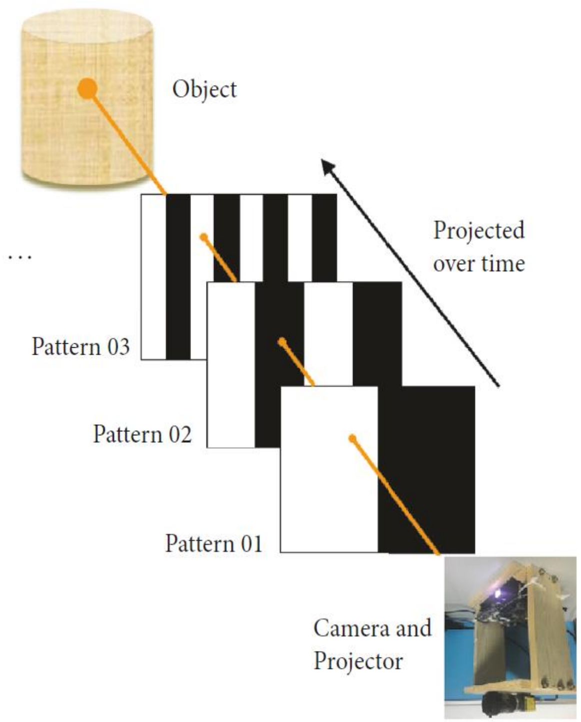
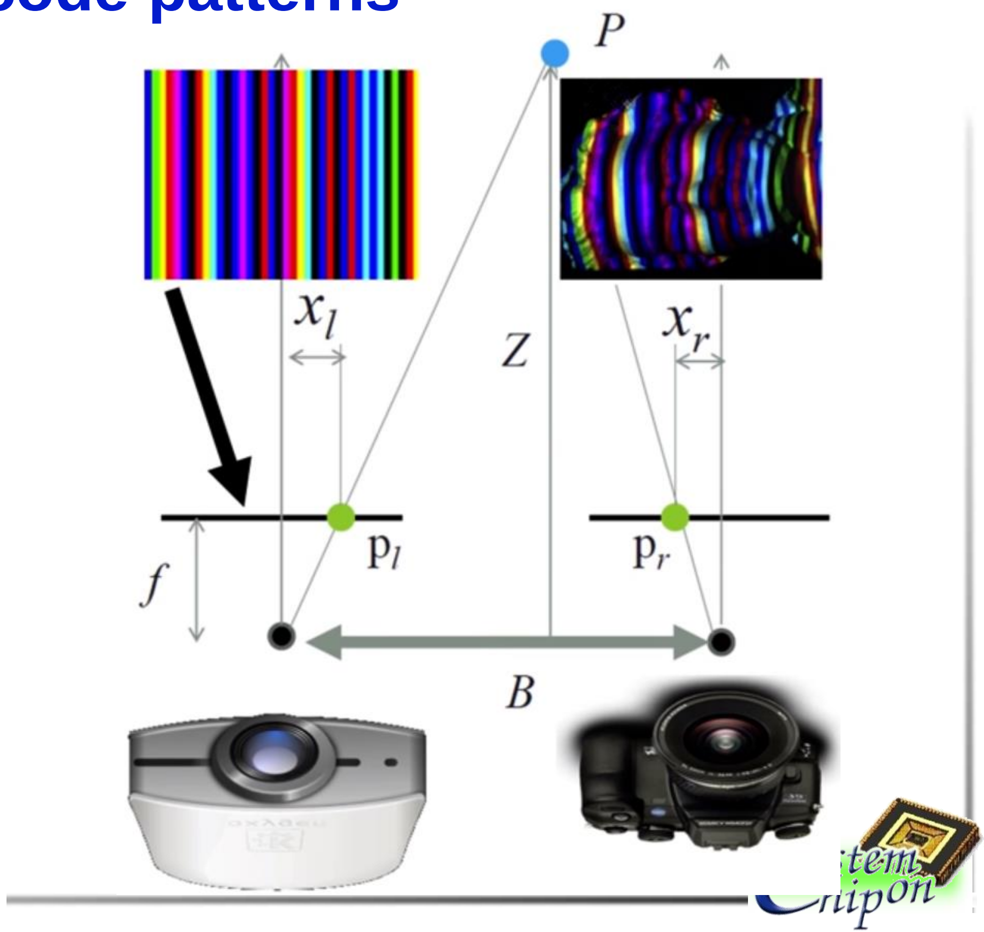
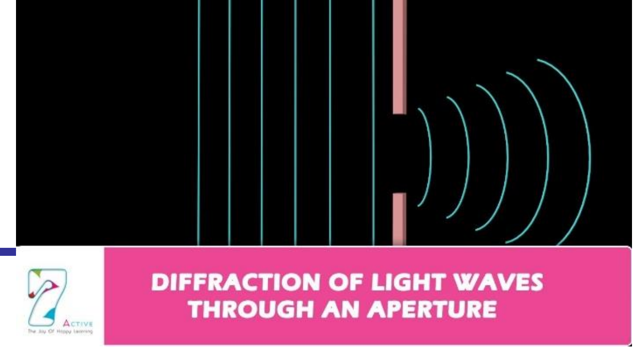


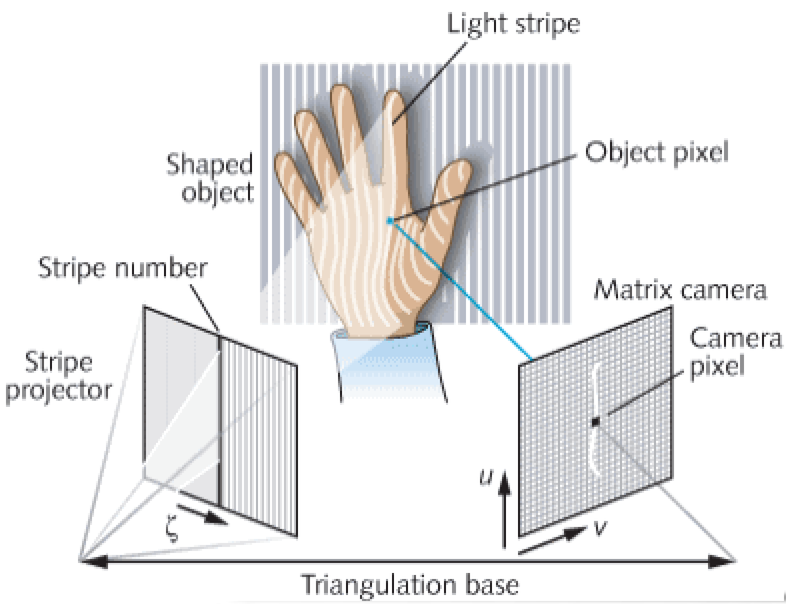
FIGURE 5: The acquisition of the projected patterns on an object. The gray-code pattern is projected by the projector and the scene is captured by the camera [1].

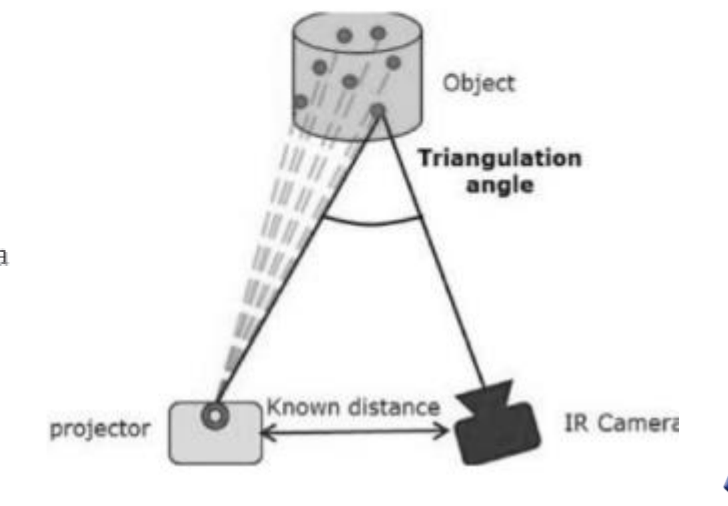


Structured Light



- The principle of structured light
  - the laser beam emitted by an **infrared projector** is diffracted to the surface of the object
  - through **a specific grating** to form a light spot pattern,
  - **near-infrared light camera** receives the light spot pattern code on the surface of the projected object (LightCoding).
- The **spot patterns** are all different depending on **the spatial position** of the object.
- 3D imaging system can analyze the 3D simulation data of the object.





Structured Light System

- The projector sends out gray-code pattern sequentially
- Acquisition by the camera for each pattens in sequence
- Decode from the coded map
- 3D imaging system can analyze the 3D simulation data of the object.

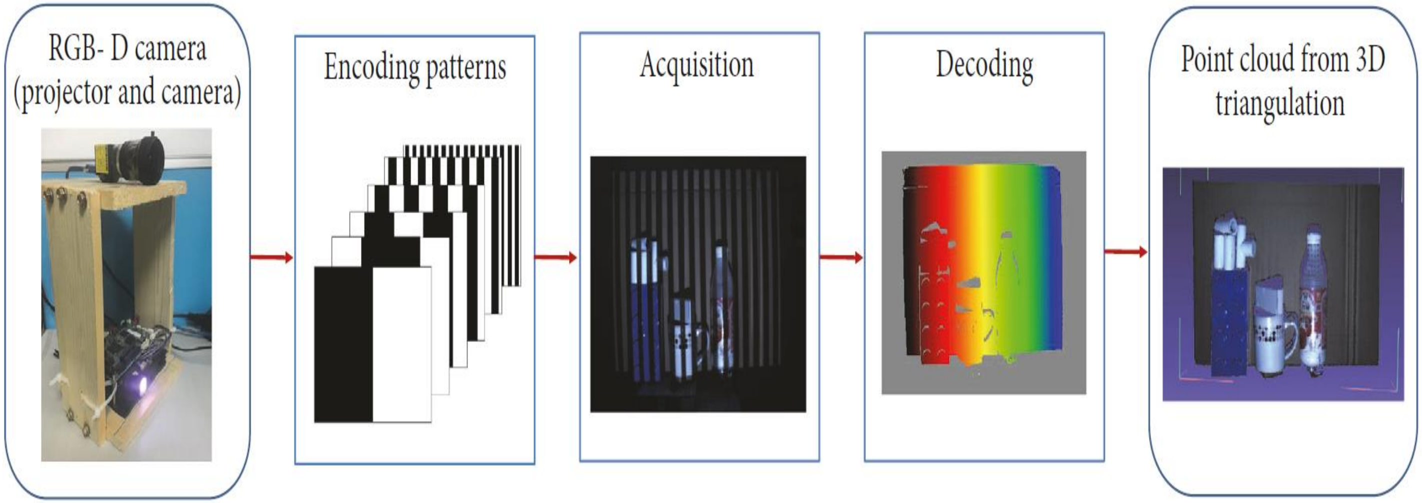
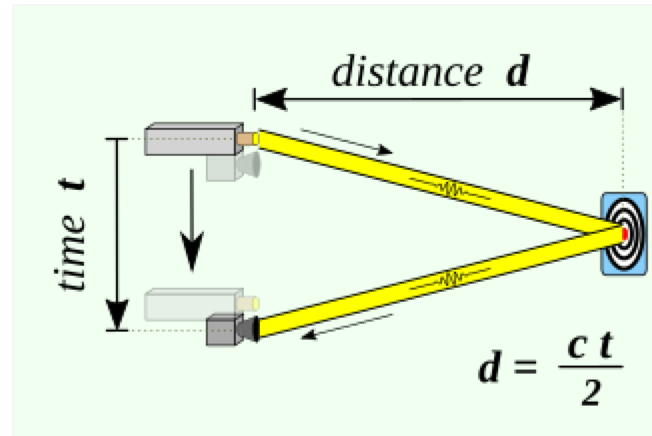
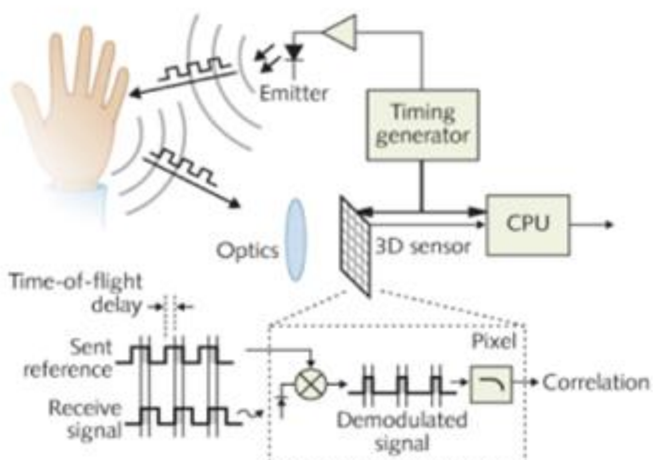


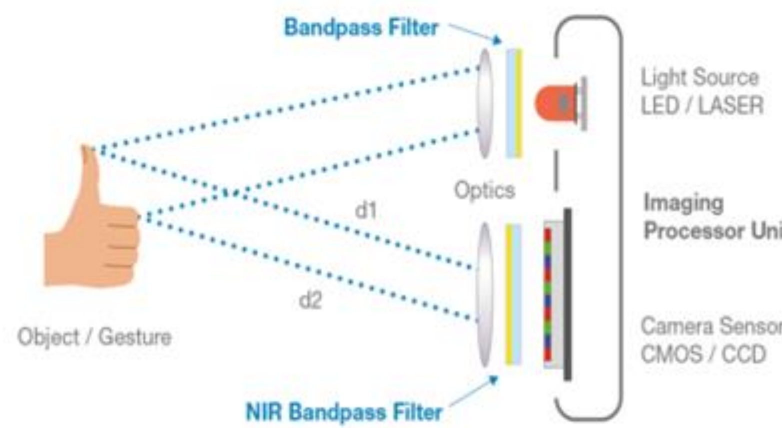
FIGURE 1: The overview of our RGB-D camera system with the structured light technique. The encoding pattern is a gray-code pattern. The acquisition is the images captured by the camera for each pattern in the sequence. The decoding is a coded map.

Time of Flight

- Time of Flight
  - Structure
    - One LED or laser diode
    - One photo detector
  - Principle
    - LED or laser diode emits IR light,
    - photo detectors receives the light
    - calculates the **time** difference between the emitted pulse, and a received signal.



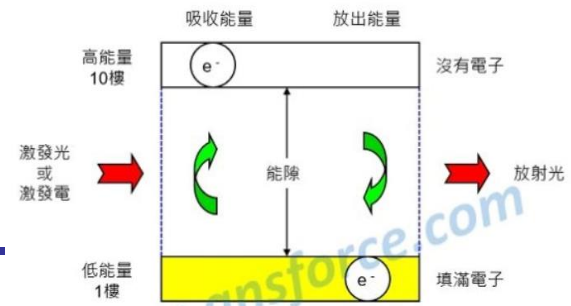




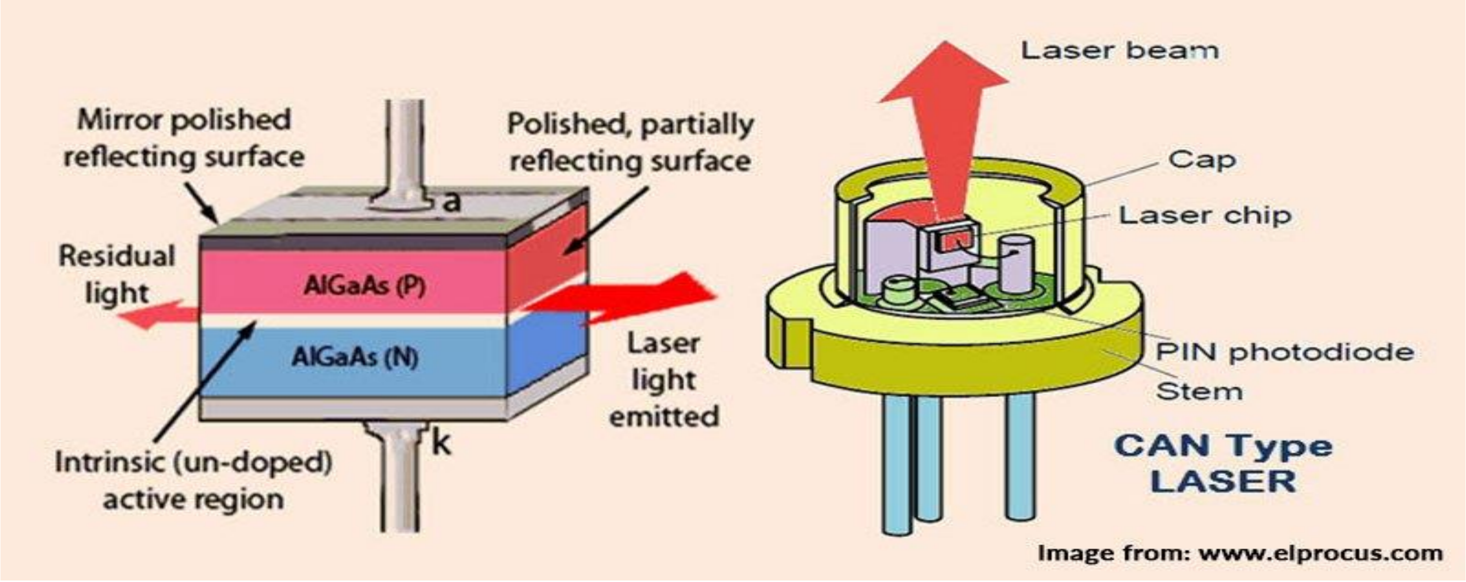
Comparison Table

Characteristic	Stereo Vision	Structured Light	Time- of -flight
Software complexity	High	High	Low
Material cost	Low	High/Middle	Middle
Response time	Middle	Slow	Fast
Low light performance	Weak	Light source (IR or visible)	Good (IR, laser)
Outdoor	Good	Weak	Fair
Depth (“z”) accuracy	Cm	µm – cm	mm – cm
Range	Mid-range	Very short range	Short range
Bright light performance	Good	Weak	Good
Power consumption	Low	Medium	Scalable
代表性廠商	intel, LEAP MOTION, ams	ST, intel, Texas Instruments, Infineon, ams	Texas Instruments, Infineon, SONY, ST, Microsoft, ams

Laser Diode

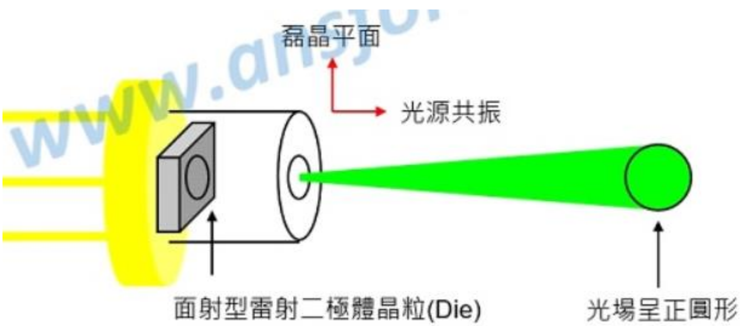


- Light Amplification by Stimulated Emission of Radiation (Laser)
  - **P-N Junction Diode**
  - **A partially reflecting mirror** on either side of the diode
  - spontaneous emission photo are trapped in the p-n junction until their concentration reaches a threshold value
  - Emit **Coherent light** (same frequency and same phase)

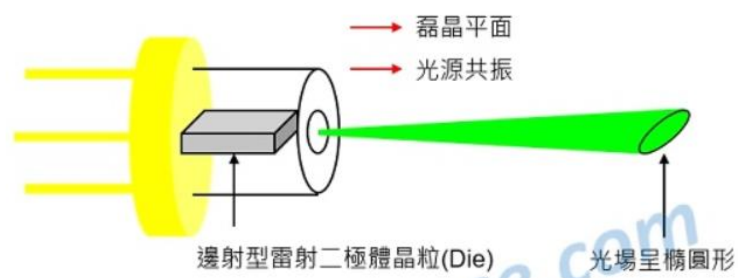


Two Types of Laser Diode

- **Surface Emitting Laser Diode (LD)**
  - light propagates in the direction **perpendicular** to the semiconductor wafer **surface**
- **Edge Emitting Laser Diode (LD):**
  - light propagates in a **direction along** the wafer **surface** of the semiconductor chip



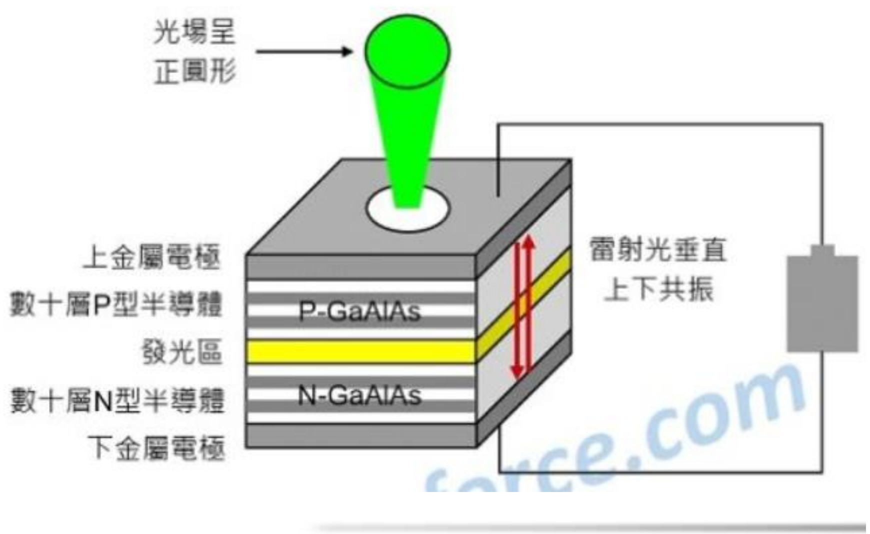
Surface

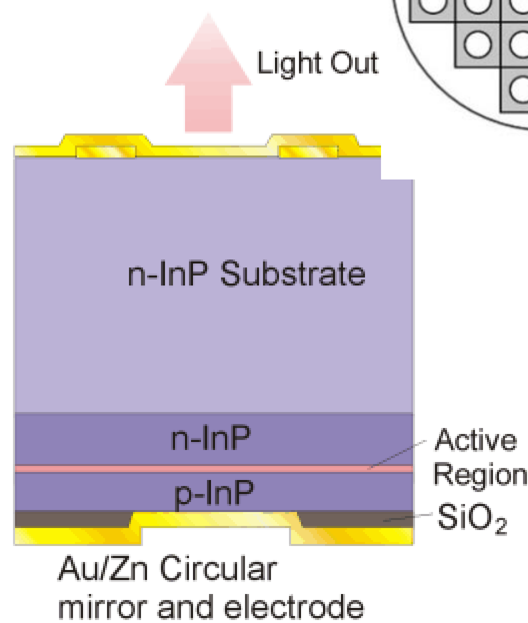


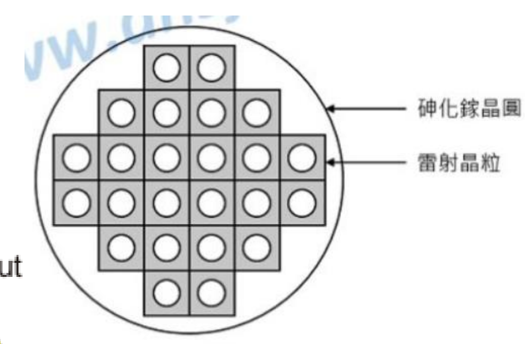
Edge

VCSEL(Vertical Cavity Surface Emitting Laser)

- Vertical Cavity Surface Emitting Laser, VCSEL
- **laser** beam **emission** perpendicular from the top **surface**
- N-InP (N-type semiconductor)
- P-InP (N-type semiconductor)
- Au/Zn circular mirror and electrode
- Pumping/Resonance



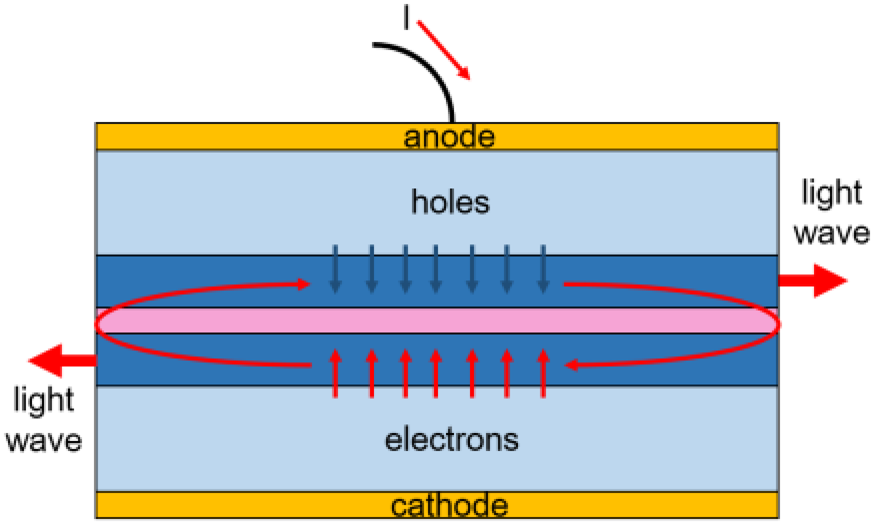




(b)

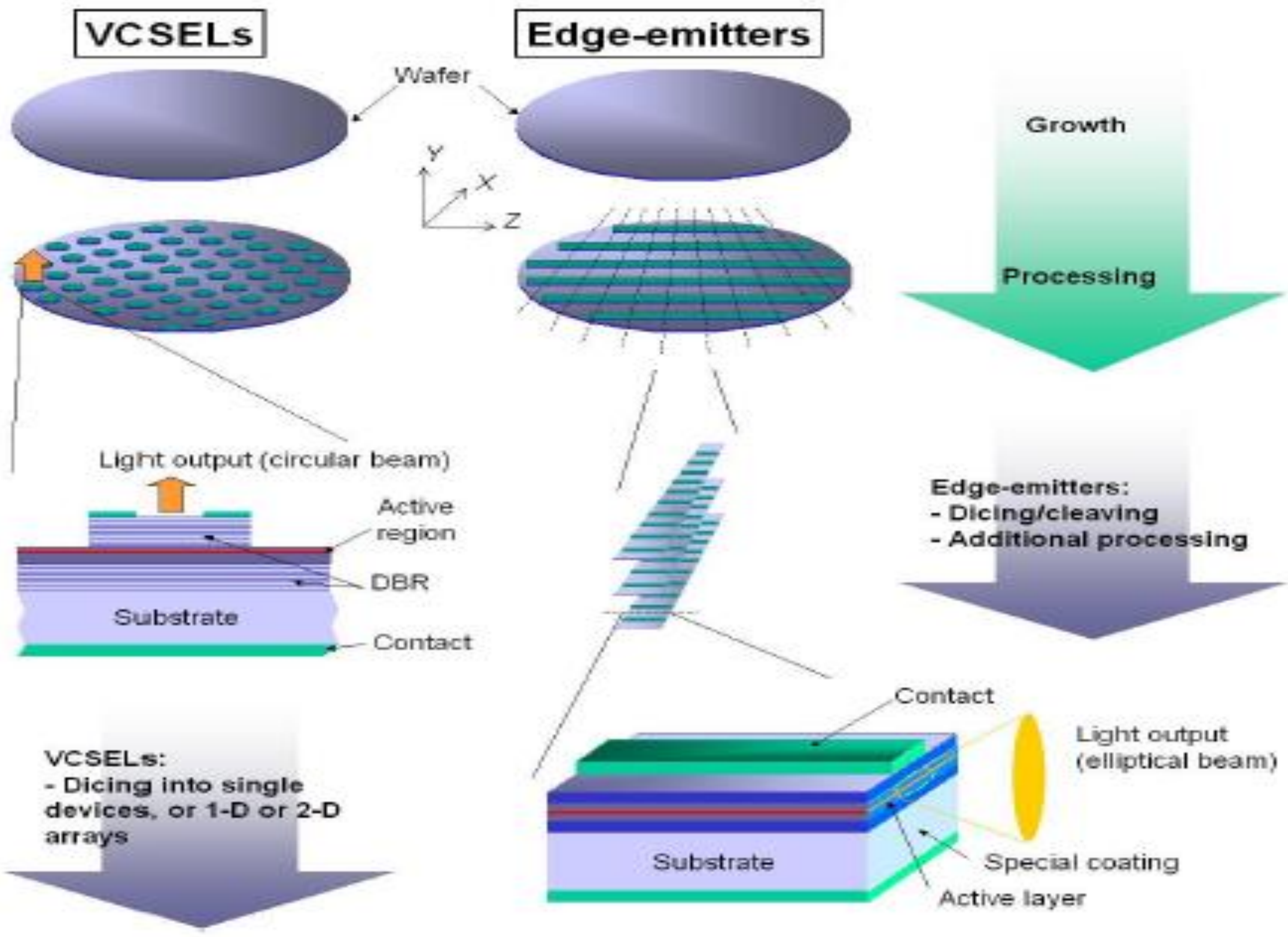
Edge Emitting Laser

- Light bounces back and forth horizontally as shown in the below image
- The optical cavity is a Fabry-Perot cavity with the end facets acting as reflectors.
- The difference in the index of refraction between the air and the gain medium causes reflection at the end facets.
- End facets are created **by cleaving**, a high degree of smoothness is hard to obtain.

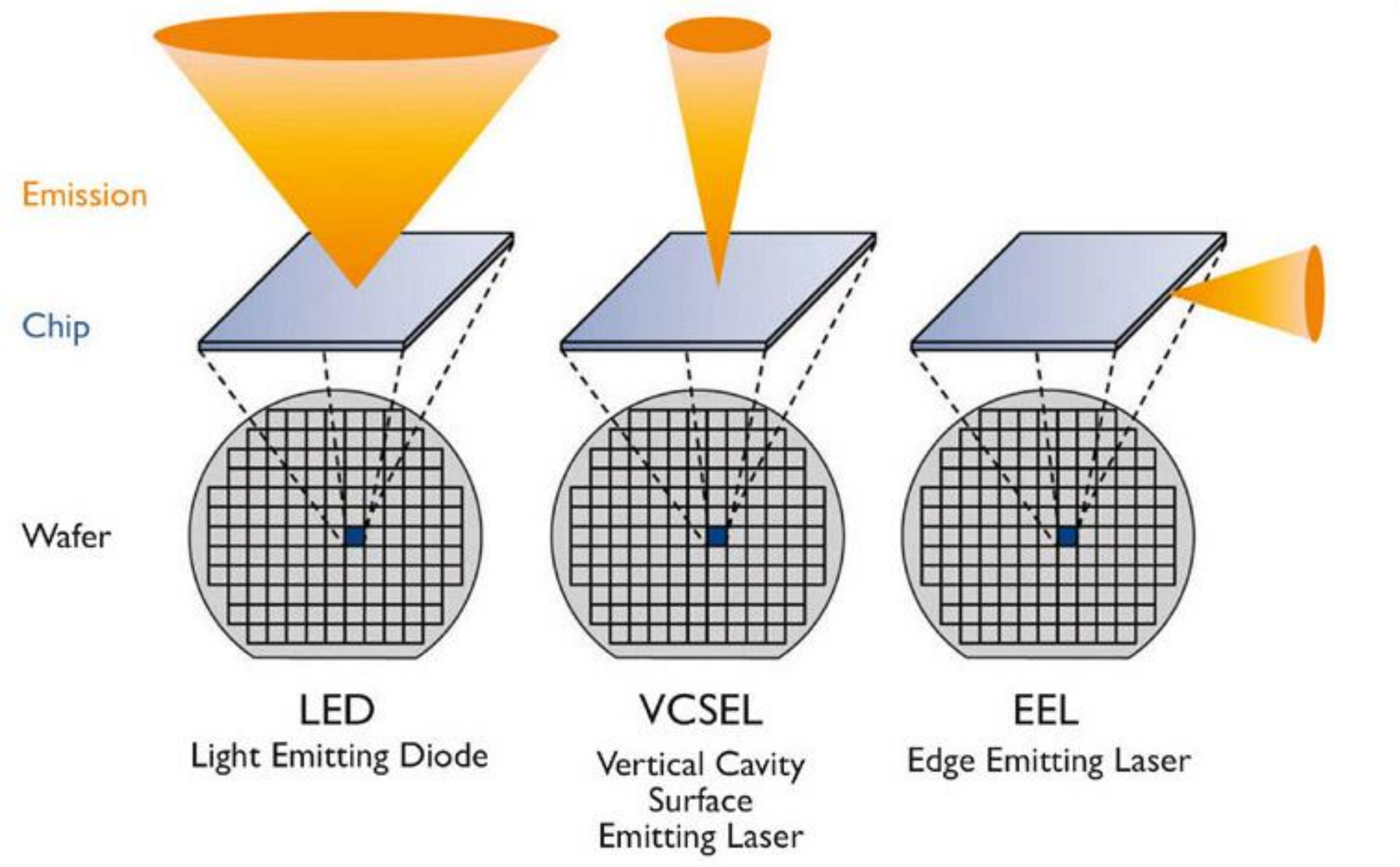


https://www.findlight.net/blog/2019/02/15/edge-emitting-vs-surface-emitting/

VCESL and Edge-emitters Process



Comparison between LED/VCSEL/EED

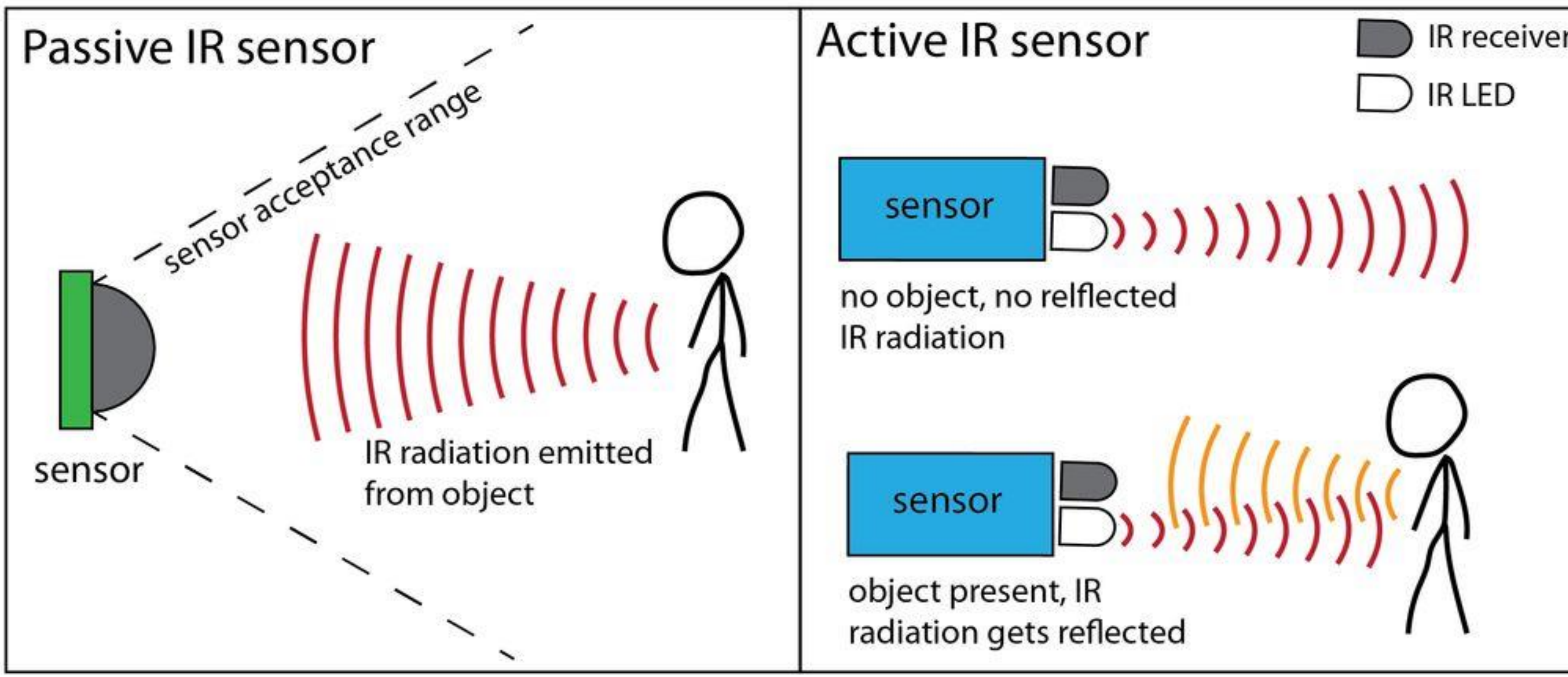


Intel® RealSense™ Depth Camera D435

- Launched date : January, 2018
- Price: US$ 179
- Depth Technology: **Active IR Stereo**
- Camera Dimension: 90 mm x 25 mm x 25 mm
- Depth Stream Output Resolution: Up to 1280 x 720
- Depth Stream Output Frame Rate: Up to 90 fps

Active IR v.s. Passive IR

- Active IR
  - One IR Receiver
  - One LED
- Passive IR
  - One Receiver

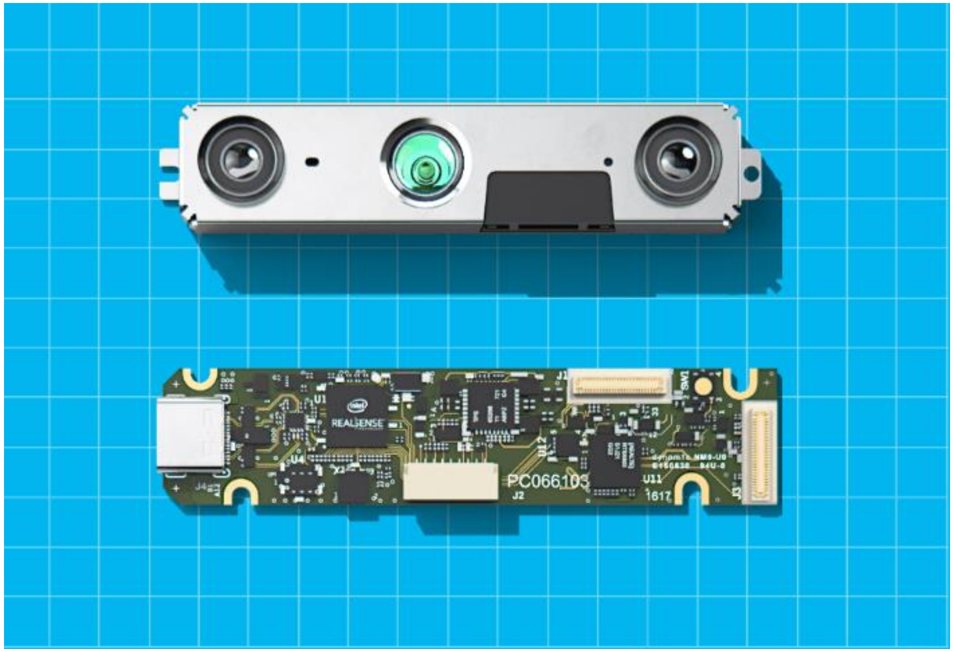


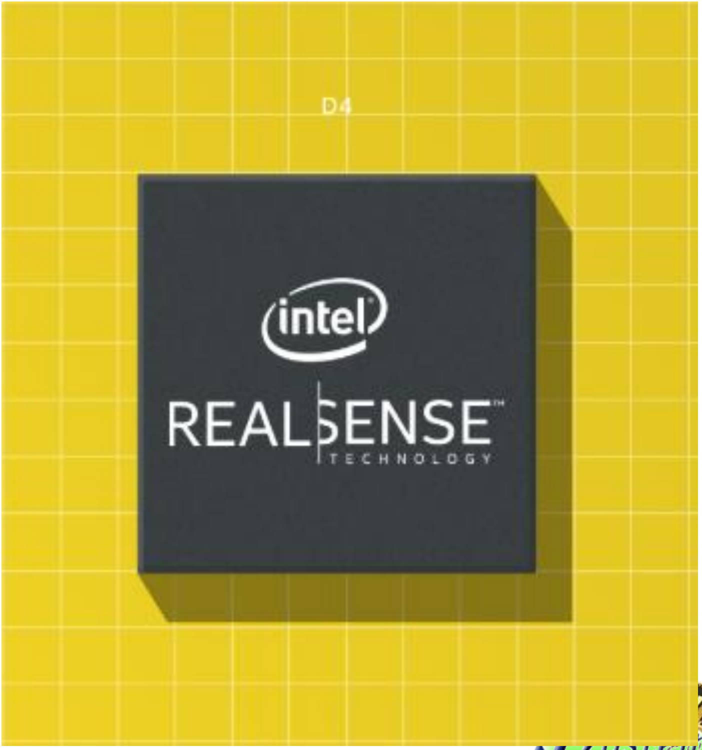
Intel® RealSense™ Depth Camera

- Main component:

  (1) Intel® RealSense™ module D435

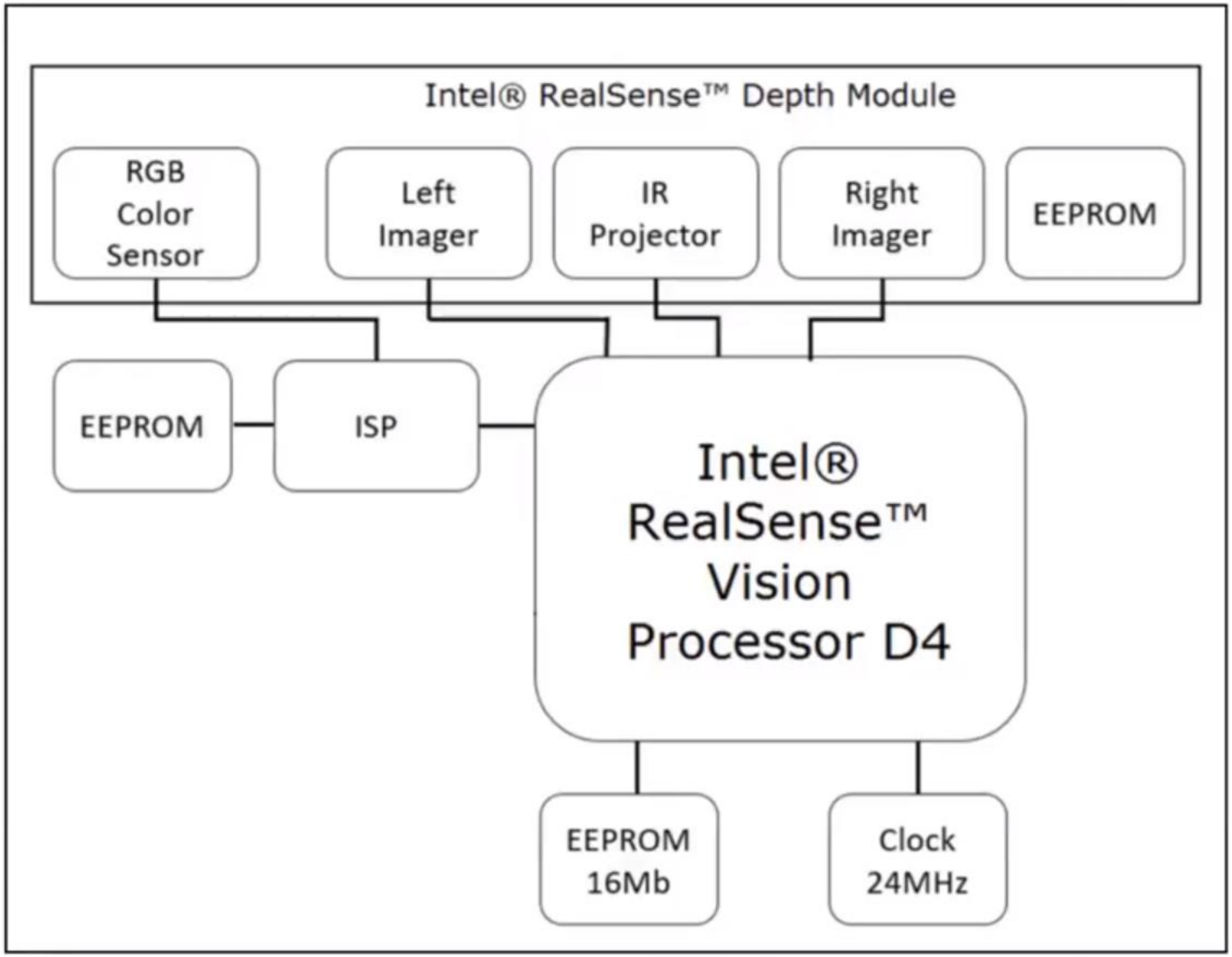
  (2) Intel® RealSense™ Vision Processor D4





System Block Diagram

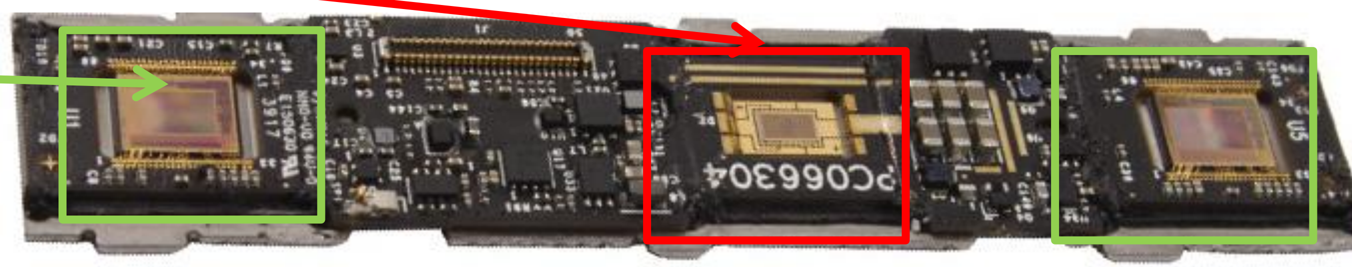
Figure 2-5. D415/D435 System Block Diagram



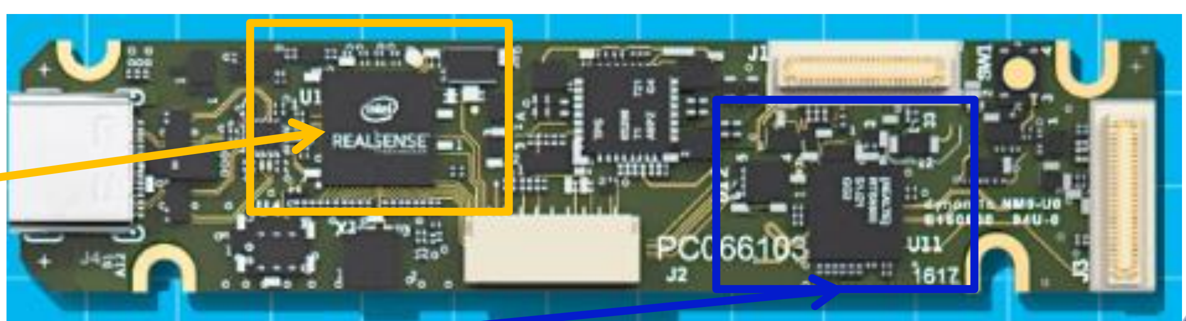
Sensors Board

- **Top Side – Global View – Bottom View**

Infrared Laser Projector



CMOS 1080p RGB
sensor by Omnivision



D4 Vision Processor
by Intel

Color Image Processor
by Realtek

D4 Vision Processor

	D4 Vision Processor
Depth Technology	Stereo
Form Factor	ASIC BGA
Package Size	6.4mm x 6.4mm x 1mm
Process Technology	28 nm
Depth Max Throughput	36.6 MP/sec (848×480@90fps)
Depth Stream Output Resolution	Up to 1280×720
Depth Stream Output Frame Rate	Up to 90fps
RGB Sensor Max Resolution & Max Frame Rate	1920×1080, Up to 60fps
IR Projector Controls	Yes
Host Interface	USB 3.0
Multi Camera Support	Yes, up to 5
I/O	5x MIPI CSI-2, 5x I2C, 1x SPI, GPIO, Timer

Comparison of Depth Camera

Scanning spec	Intel RealSense D415	Intel RealSense D435i	Intel RealSense L515 With RGB Camera	Kinect v2	YUJIN LiDAR	OUSTER OS1
Depth tech.	Stereoscopic	Stereoscopic	LiDAR	Time-of-Flight	LiDAR (ToF)	LiDAR
FOV	50˚ * 40˚ (depth, VGA 4:3) 65˚ * 40˚ (depth, HD 16:9) 69˚ * 42˚ (RGB)	74˚ * 62˚ (depth, VGA 4:3) 86˚ * 57˚ (depth, HD 16:9) 69˚ * 42˚ (RGB)	75˚ * 55˚	70˚ * 50˚(depth) 84˚ * 53˚(RGB)	45˚ * 45˚ (Mechanic Scan)	22.5˚ * 22.5˚ (Mechanic Scan)
Pixels	Up to 1280˚ * 720˚ (depth) Up to 1920 * 1080 (RGB)	Up to 1280˚ * 720˚ (depth) Up to 1920 * 1080 (RGB)	320 * 240 1024 * 768	512*424 1920*1080		512/1024/2048 * 16/64/128
Angular res.	-	-	-	-	0.55˚ * 0.35˚	0.35˚ * 2.8˚
Distance	0.3~over 10m 0.5~3 m (ideal range)	0.2~over 10m 0.3~3 m (ideal range)	0.25~9 m This preset is useful when there is no ambient light in the scene	0.5~4.5m	0.1~20m	12 m
PRF (throughput)	-	-	2.3M(<9m)~23.6M (<6.5m)	-	130 K	655 K
Line rate	-	-	-	-	20 Hz	-
Frame rate	depth:30 Hz(HD), 90 Hz(other) RGB:30 Hz (FHD, HD), 60 Hz(other)	depth:30 Hz(HD), 90 Hz(other) RGB:30 Hz (FHD, HD), 60 Hz(other)	30 Hz	30 Hz	20 Hz (H) 0.57 Hz (V)	10 Hz
Accuracy	< 2% @ 2 m	< 2% @ 2 m	2.5mm @ 1m 15.5mm @ 9m	10mm	<10mm	7-50 mm
Environments	Indoor/Outdoor	Indoor/Outdoor	Indoor	Indoor	Indoor	Indoor/outdoor

Application

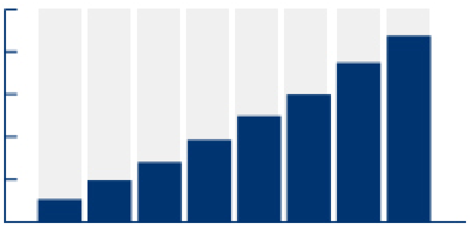
- Face Recognition
- Autonomous driving
- 3D modeling
- 3D scanning
- Person Tracking
- Drone
- AR/VR

Global 3D Camera Market

Segmentation and Forecast, 2013 - 2020

Global 3D Camera Market

Global 3D Camera Market is Expected to reach $7,661.8 million by 2020



Growing at a CAGR of 39.4% (2014-2020)

Global 3D Camera Market by type

Target Camera
Free Camera

The comprehensive view on the % share of Lubricant type segment (2020)

For More Details See Table of Contents

Global 3D Camera Market by application

Professional Camera
Smartphone
Tablets
Computers
Others

The comprehensive view on the % share of Technology segment (2020)

Global 3D Camera Market by Technology

Time of flight
Stereo Vision
Structured light

The comprehensive view on the % share of Technology segment (2020)

Drivers & Restraints

Drivers

- Growing demand of 3D content from entertainment industry
- Enhancement in 3D scanning technology
- Improved user taste & preferences

Restraints

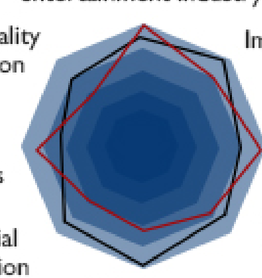
- High prices
- Lack of awareness

Global 3D Camera Market by Geography

North America
Europe
Asia-Pacific
LAMEA

Asia Pacific is expected to be highest revenue generating region by 2020

Top Impacting Factors



Suppliers

Module	Components	Supplier	Foundries
Tx module supply chain	VCSEL	Lumentum、IIVI、Philips Photonics、Finisar	磊晶代工：IQE 全新科 晶片代工：穩懋 光環 宏捷科
	Wafer Level Optical Element Diffraction Optical Element	Heptagon、奇景光電、台積電	
	Sensor package	奧地利微電子（AMS）、台積電、精材	聯均
Rx module supply chain	3D lens	大立光、玉晶光、舜宇光學、新鉅科	
	Infrared image sensor	意法半導體	
	Filter	Viavi	
	Module assembly and active alignment	LG Innotek	致茂 宏捷科
	CIS (CMOS Image Sensor)	Ominivision Sony	

Conclusion

- Major Types of 3D Sensor covered are Stereo Vision, Structured Light and Time of Flight
- 3D sensing applications will also be more available with more third-party applications.
- Growing demand for 3D Sensors in consumer electronics to drive the Market

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