IMAGE SENSOR TECHNOLOGY UPDATE

CMOS Sensor Technology

FEBRUARY 26, 2018

What is next in CMOS Sensor Technology?

- On-Sensor Polarization
- Curved CMOS Sensors
- Stacked CMOS Sensors
- QuantumFilm™
- Organic Photoconductive Film sensors
- 3rd Generation Sony Pregius

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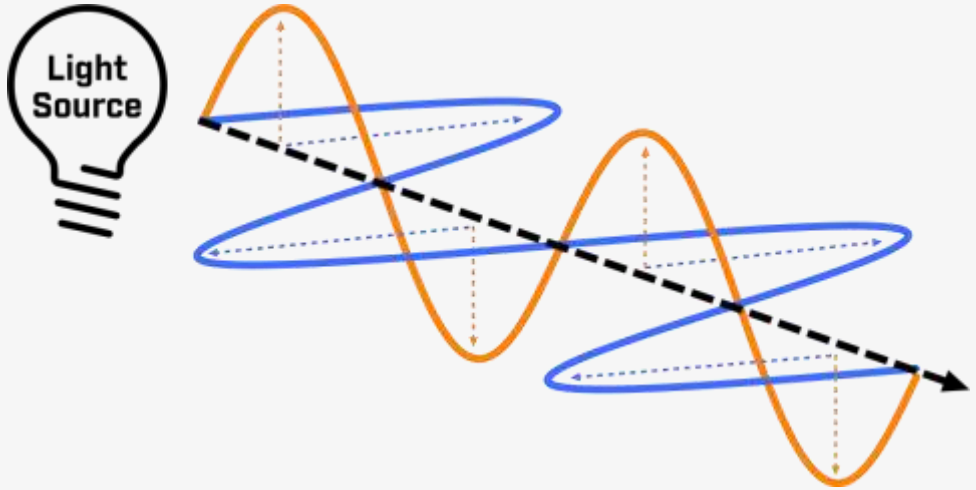
Polarization of Light

- Light is an electromagnetic wave with oscillating electric and magnetic fields.
- Unpolarized light : light waves whose electric field vectors are randomly oriented w.r.t the direction of propagation
- Polarized light : light waves whose electric field vectors are restricted to a single plane w.r.t the direction of propagation
- Most light sources emit unpolarized light

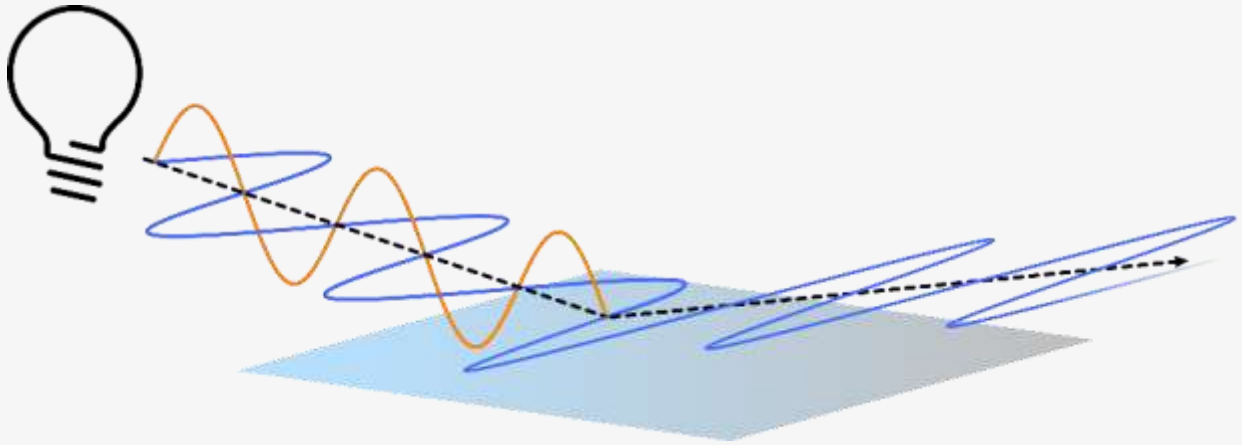


Polarization in Nature - Navigating

- Bees use the sun to navigate
- Sensing polarized light enables bees to sense the position of the sun on cloudy days

Light can be polarized by reflection

- Reflection is one way of polarizing light waves
- The magnitude of this effect depends on the material and angle of incidence of light
- Metals reflect the polarization of the light falling on them and hence there is minimal polarization.
- Non-metallic materials tend to reflect most vibrations on a single plane parallel to the plane of incidence.

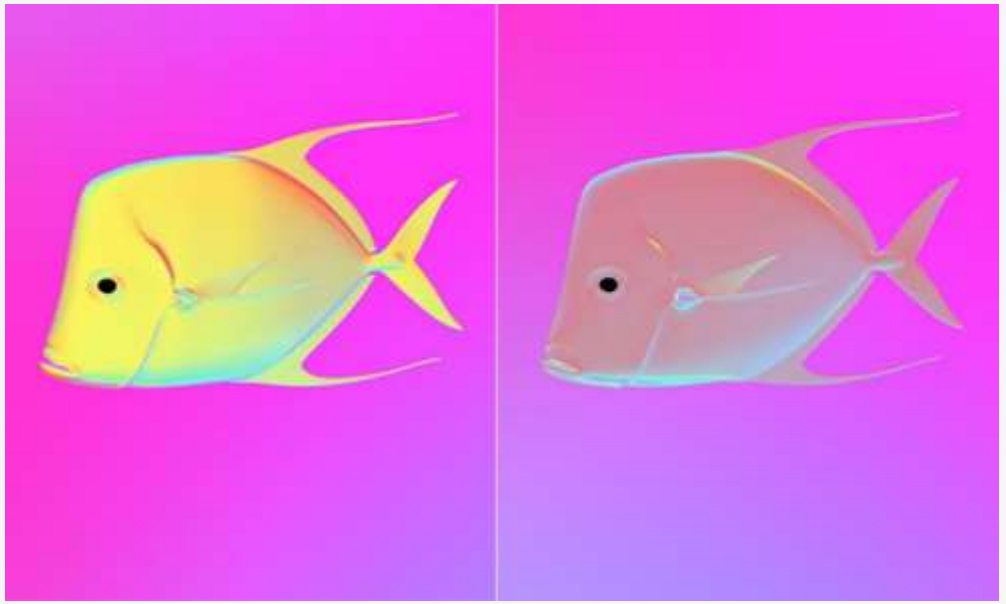


Polarization in Nature - Hunting

- Predators use polarized light in different ways to help them hunt
- Cuttlefish and mantis shrimps are sensitive to polarized light which helps them hunt silvery fish
- Diving birds' eyes block polarized light reflecting off water, enabling them to see below surface of the water more clearly

Polarization in Nature - Hiding

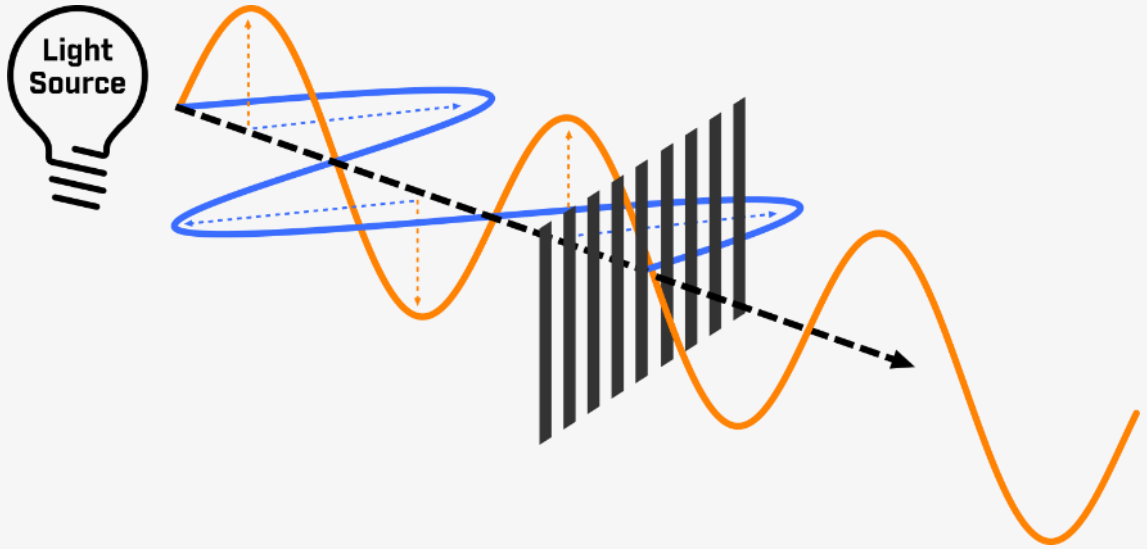
- Some fish have evolved scales capable of reflecting unpolarized light helping them avoid detection by predators using polarized light



Simulation from Cummings Lab

Light can be polarized with filters

- Polarizing filters pass light which is aligned with their angle of polarization
- Polarizing filters block light which is not aligned with their angle of polarization

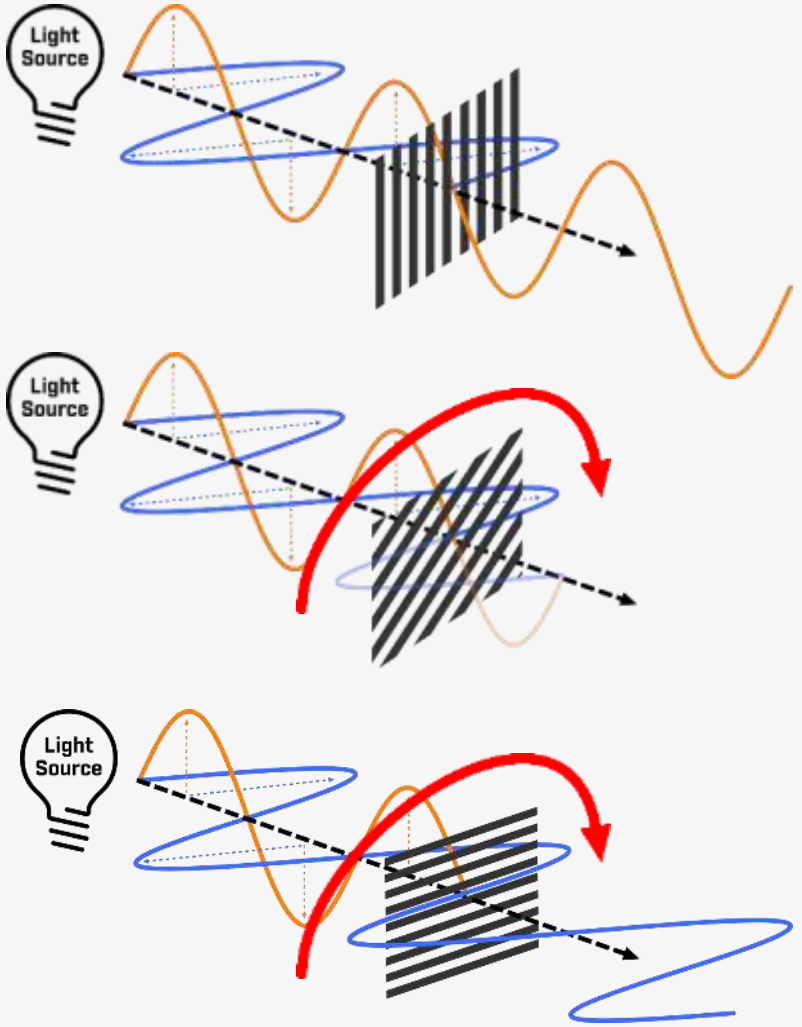


Common applications of polarized light

- Sunglasses are common use of polarizing filters
  - Their polarizers are aligned to block polarized light reflecting off horizontal surfaces
  - Passing or blocking different angles requires the filters to be rotated

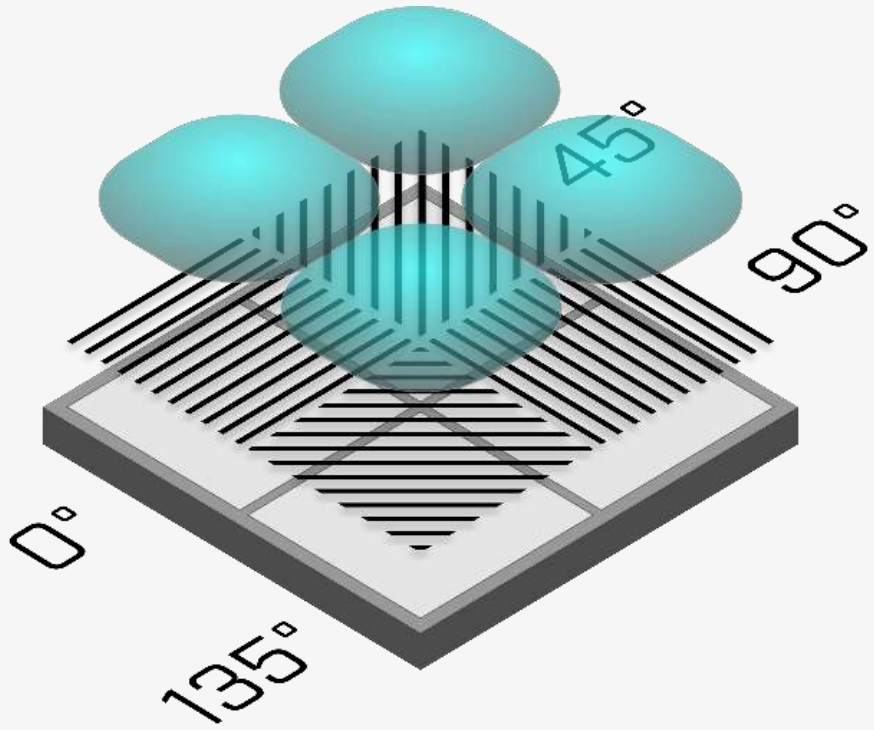
Rotating polarizing filters

- Rotating a polarized filter changes the amount of plane polarized light the filter blocks or passes
- The transition is smooth and predictable
- The relationship between the maximum and minimum amount of polarized light is called the *extinction ratio*

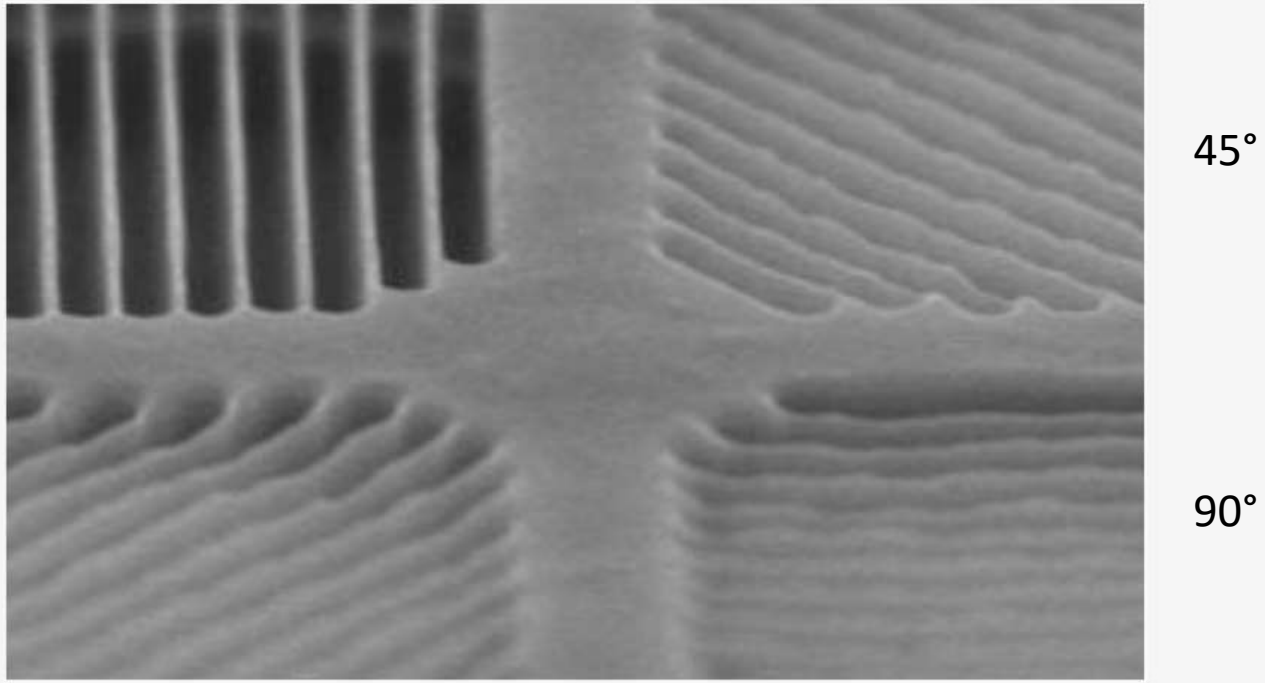


IMX250MZR has on-sensor filters

- Sensor based on the popular IMX250
  - 3.45µm pixel
  - Global shutter
  - Low read noise
- Each pixel has its own polarizing filter/array placed on-chip

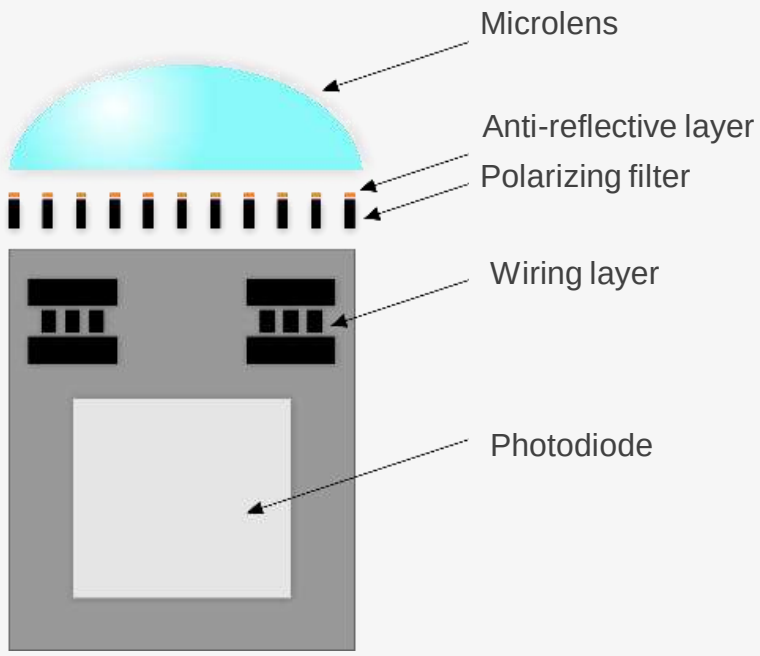


Micrograph of polarization grid



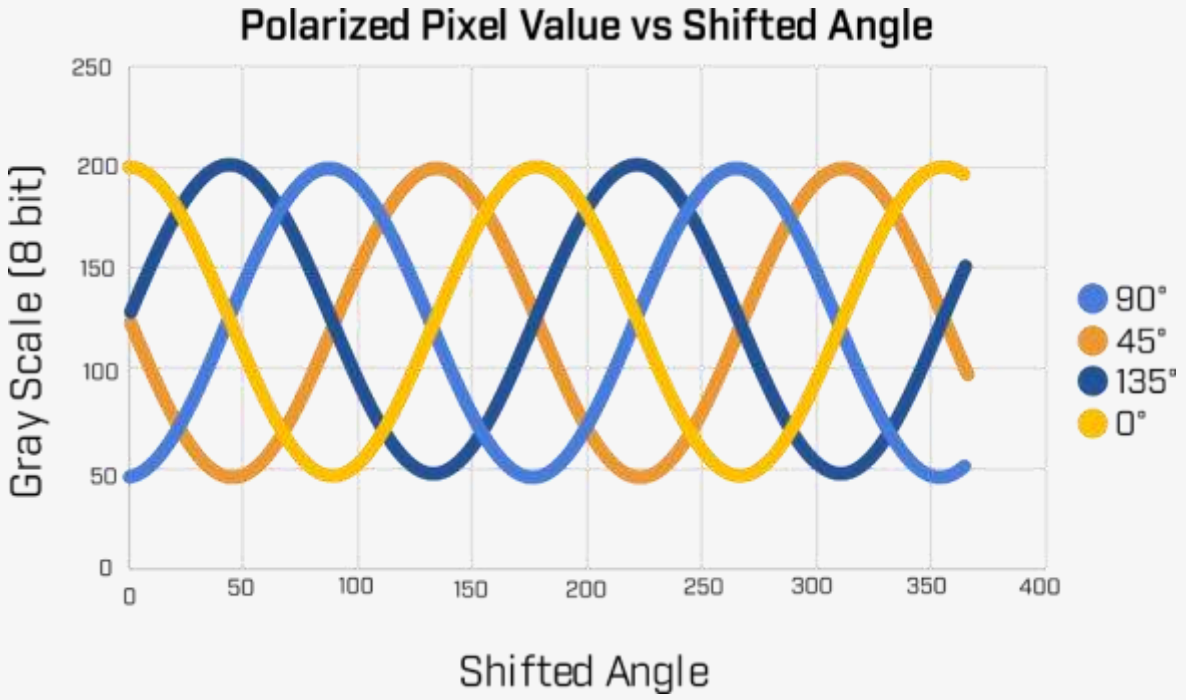
Effect on imaging performance

- Placing a polarizer in-front of the photodiode reduces the quantum efficiency of the sensor
- Sony Pregius sensors feature low read noise enabling high gain without a significant noise penalty



Greyscale values are tightly correlated to angle of polarization

- Rotating a plane polarized light source results in a predictable change in pixel gray values

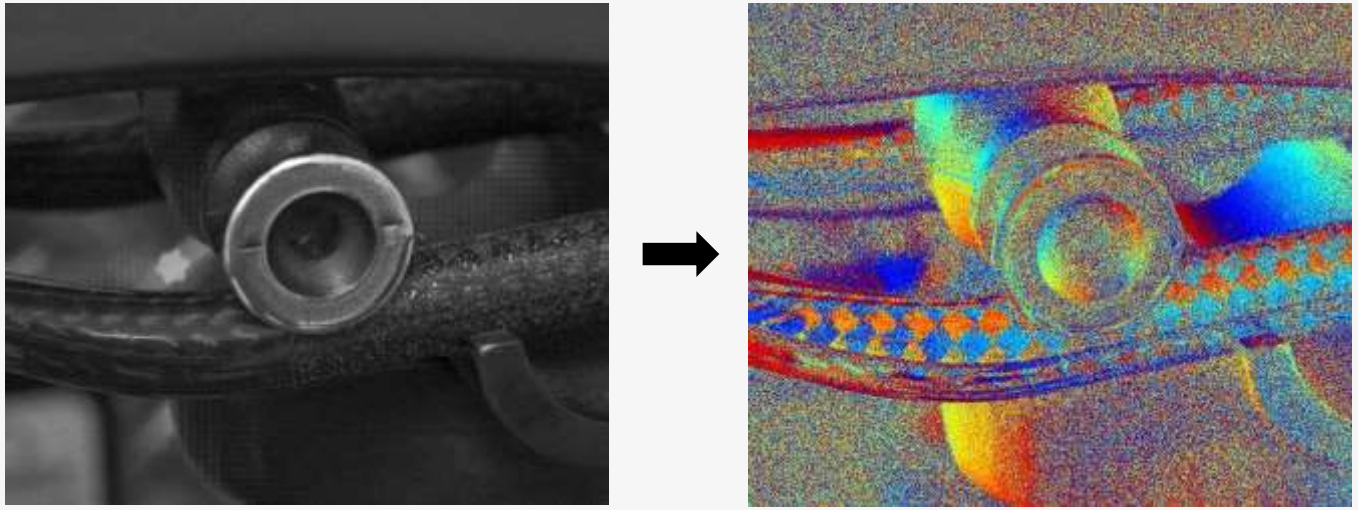


Degree of Linear Polarization

- The Degree of Linear Polarization (DoLP) is the amount of light which is polarized at a particular point in the image.
- This information can be used to identify reflections by identifying regions with a high degree of linear polarization

Angle of Linear Polarization

- The Angle of Linear Polarization (AoLP) is the average polarization angle at a given pixel in the image

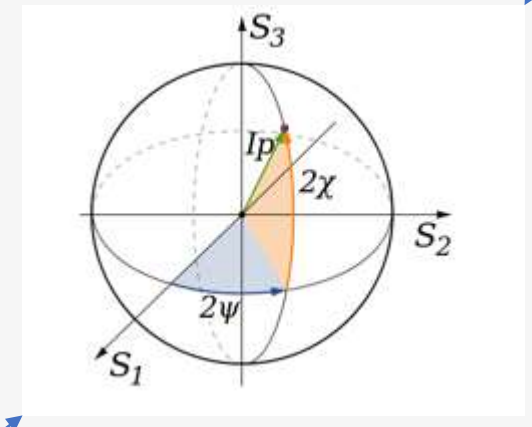


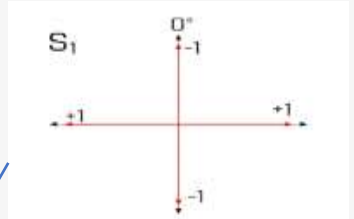
Stokes Parameter

$S_0 = I_0 + I_{90}$

$0 <= S0 <= 512$

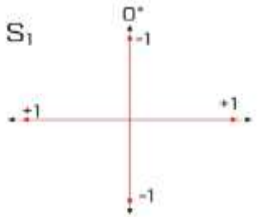
Poincaré sphere





$S_1 = I_0 - I_{90}$

$-255 <= S1 <= 255$



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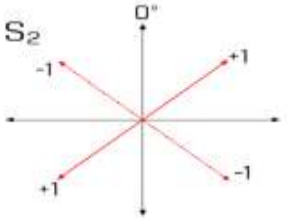
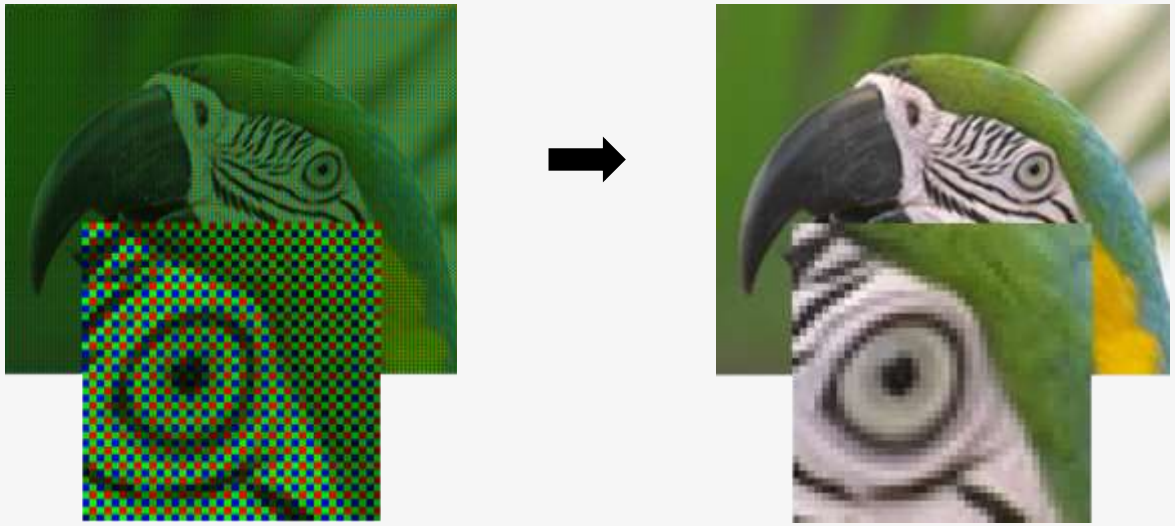


$S_2 = I_{45} - I_{135}$

$-255 <= S2 <= 255$

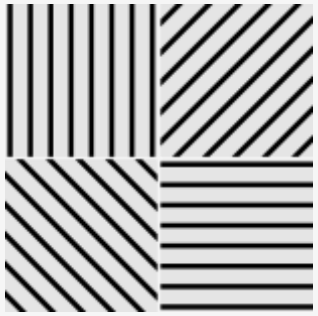
Interpolation of Polarized images

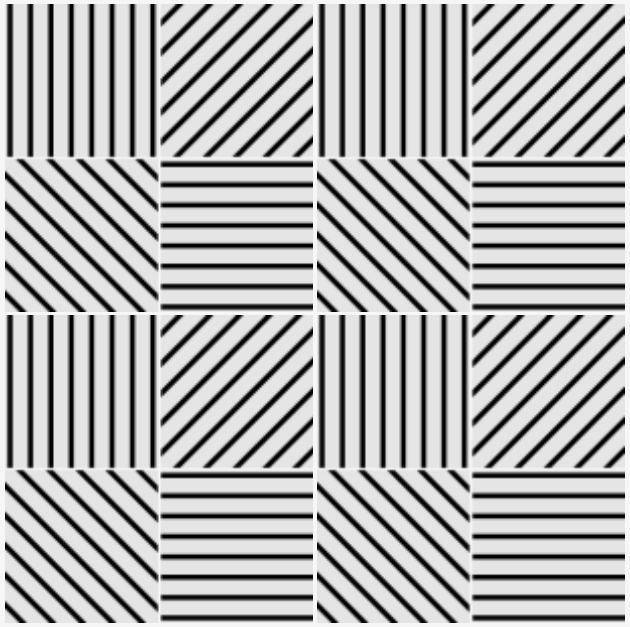
- When the sensitives of adjacent pixels to wavelengths or polarization angles differs, demosaicing is used to generate a full resolution image
- The goal is to preserve the highest spatial resolution and minimize artifacts of the interpolation process



Interpolation of monochrome images

- Interpolation between the four pixels of different polarization angles is very similar to RGB demosaicing

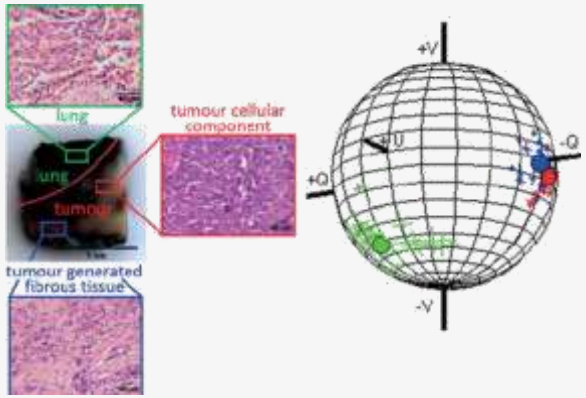


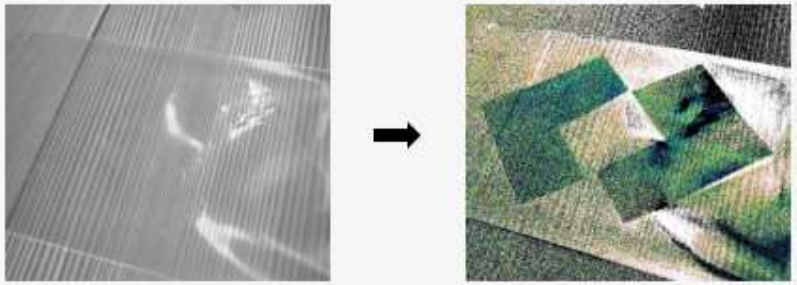


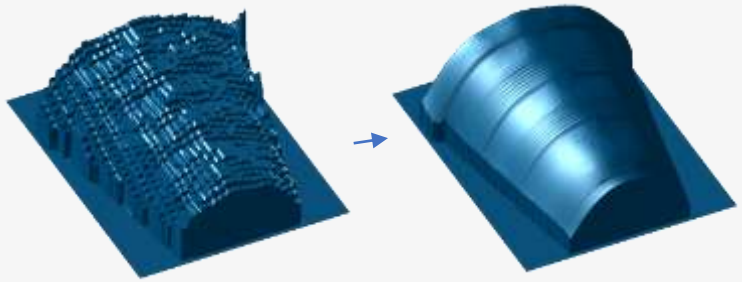
On-sensor polarization replaces mechanical solutions

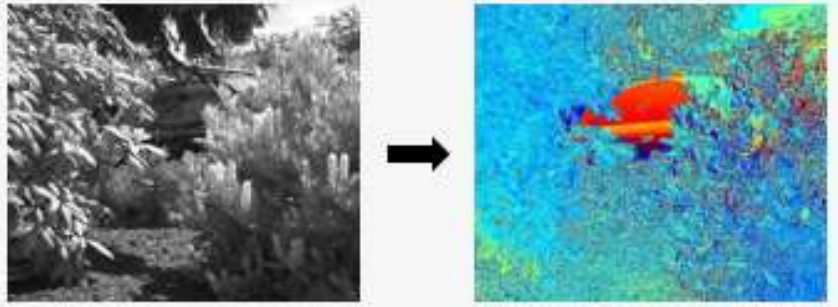
- Capturing multiple angles of polarization in a single image eliminates the mechanical and software complexity of working with filter wheels
  - Reduce mass
  - Reduce power consumption
  - Reduce system complexity
  - Reduce development time
  - Increase system throughput

Applications









FLIR Blackfly S with IMX250MZ

- BFS-U3-51S5P coming Q3, 2018
- 29 mm x 29 mm footprint with an “ice cube” form factor
- 3.5W
- 75FPS on USB 3.1 Gen 1 Interface
- Spinnaker SDK supports demosaicing, and DoLP and AoLP measurements

References

- Brady, Parrish C., et al. "Open-ocean fish reveal an omnidirectional solution to camouflage in polarized environments." *Science* 350.6263 (2015): 965-969.
- Kunnen, Britt, et al. "Application of circularly polarized light for non-invasive diagnosis of cancerous tissues and turbid tissue-like scattering media." *Journal of biophotonics* 8.4 (2015): 317-323.
- Kadambi, Achuta, et al. "Polarized 3d: High-quality depth sensing with polarization cues." *Proceedings of the IEEE International Conference on Computer Vision*. 2015.

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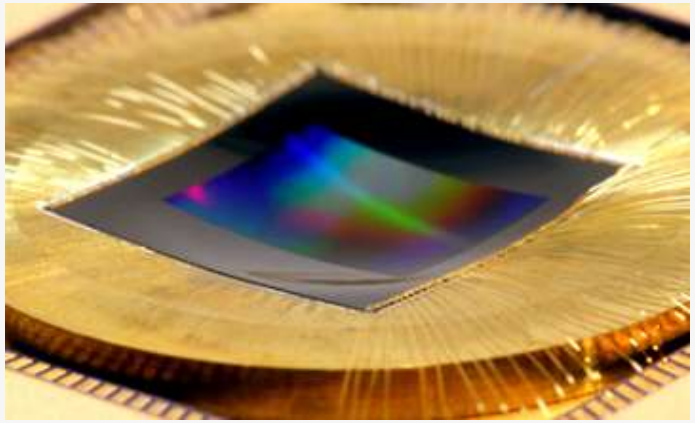
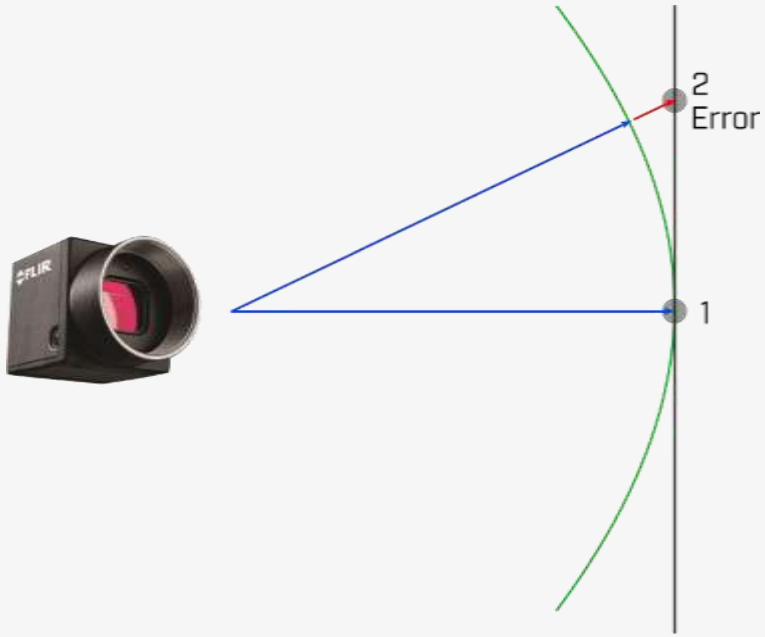
Curved CMOS sensors

- Curved sensors enable more compact and less expensive optics
- Eliminating the need to lens elements to flatten the image
- Fabrication is difficult the process requires thin silicon wafers to be bent without cracking
- Microsoft, Nikon, Canon and Sony all have curved sensor patents and have demonstrated devices



Curved CMOS reduces Chief Ray Angles

- Improve performance of sensor towards the edges by minimizing falloff caused by high Chief Ray Angles (CRA)



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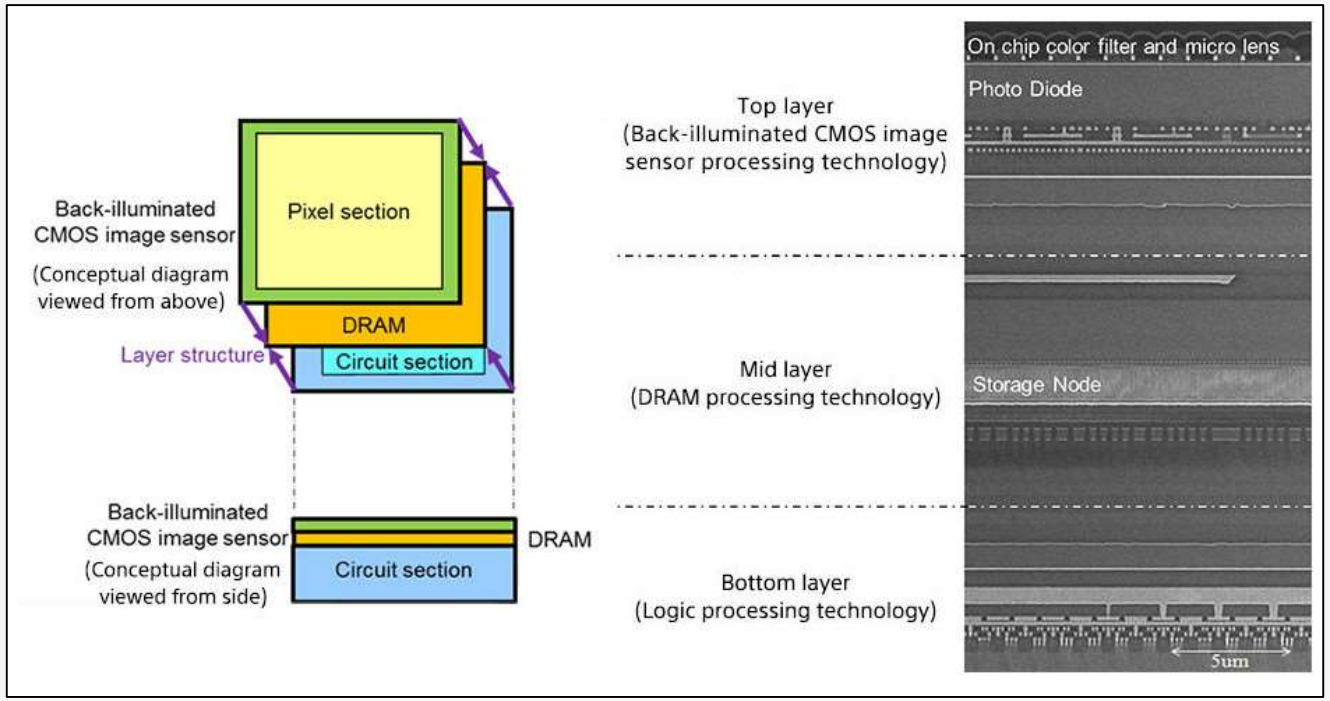
Stacked CMOS

- Stacked CMOS adds layer of DRAM between the sensor and the output circuitry

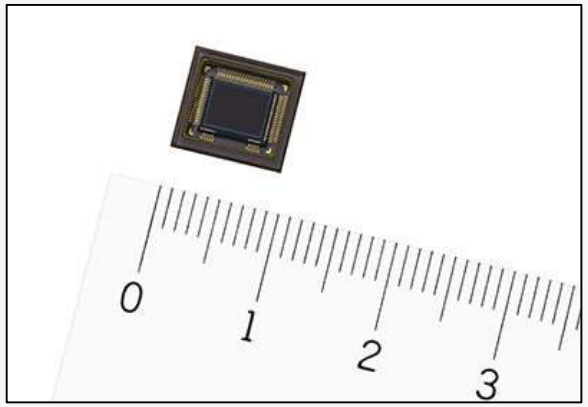


Stacked CMOS

- Building an image sensor directly on top of DRAM memory enables high speed readout
- Image data can be transferred to on-senor memory
- Image data can be transferred off the sensor at a slower rate
- This enables very high speed buffered bursts
- High speed rolling shutter readout can greatly reduce rolling shutter distortion

Advanced on-sensor functions

- Building on the stacked CMOS technology, Sony have demonstrated a sensor with separate sensing and output streams
- On-sensor image processing can do basic object detection and motion vector at 1000fps
- Low speed VGA output stream for monitoring



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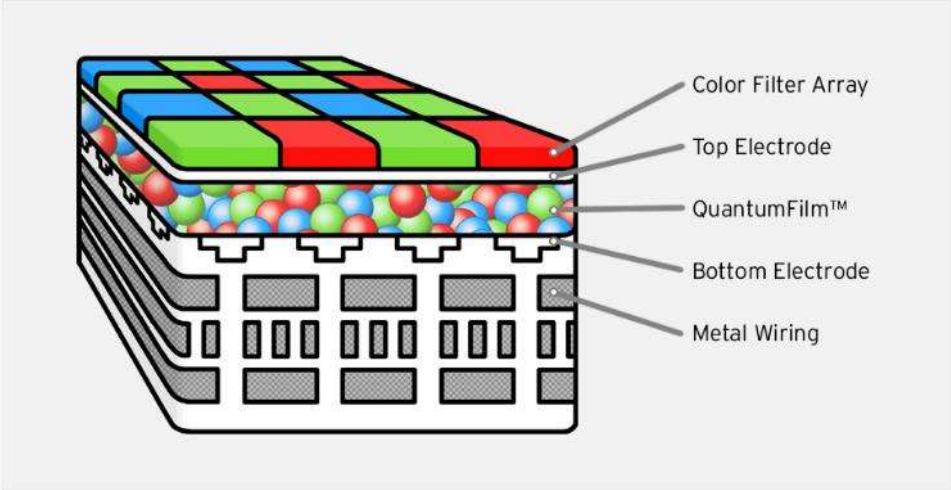
Quantum Dots

- QuantumFilm™ is based on quantum dot technology
- Can be tuned to wavelength by changing the size of the quantum dots
- The current version of this sensor uses a film sensitive to visible light covered by color filters in a Bayer pattern



Quantum Film

- Bayer pattern enables the use of existing color processing pipelines
- Sampling a 13 MP 1.1µm color sensor in 2015
- Targeted at the mobile phone industry, but no adoption
- In late 2016 InVisage started promoting a 13MP, 1.1µm NIR sensor for use with IR structured light
- Acquired by Apple in November 2017

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Organic Photoconductive Film Sensors

- Sensor technology developed by Panasonic
- Novel pixel structure replaces silicon photodiode with photoconductive film
- Sensitivity is dependent on voltage applied to photoconductive film

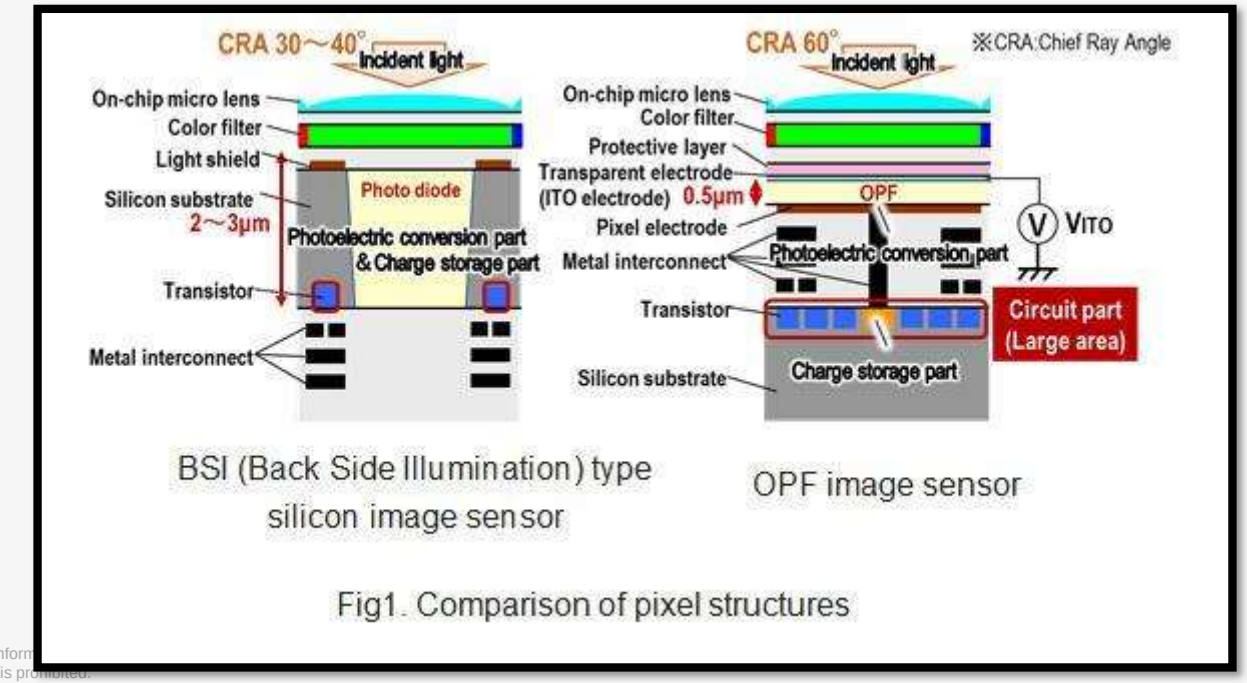

Fig1. Comparison of pixel structures

Advantages of OPF sensors

- Greater fill factor relative to traditional CMOS enables higher resolutions in smaller sensor sizes
- Varying the voltage applied to the OPF can act as an ND filter enabling a high saturation mode
- Global shutter can be realized by switching the sensitivity to zero at the end of the exposure across the entire array

High Saturation Mode Off

High Saturation Mode On

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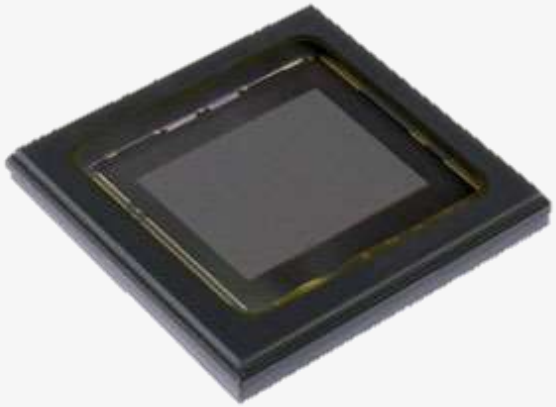
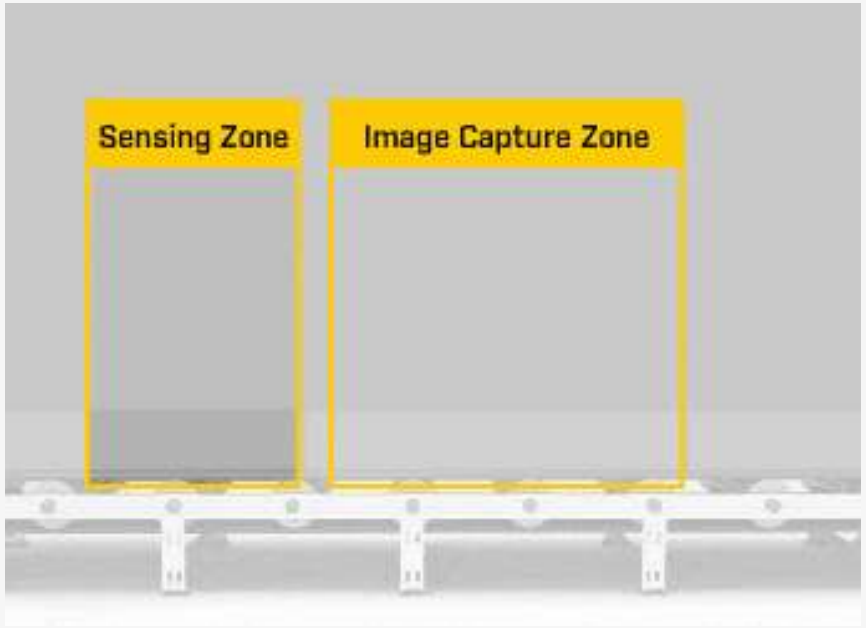
Third generation Sony Pregius

- Sony’s third generation of high-performance global shutter machine vision image sensors introduces exciting new features
- Maintains the low read noise characteristic of Pregius sensors
- Improved dynamic range - 79dB
- Transition from LVDS to SLVS-EC interface delivers 18 Gbit/sec throughput



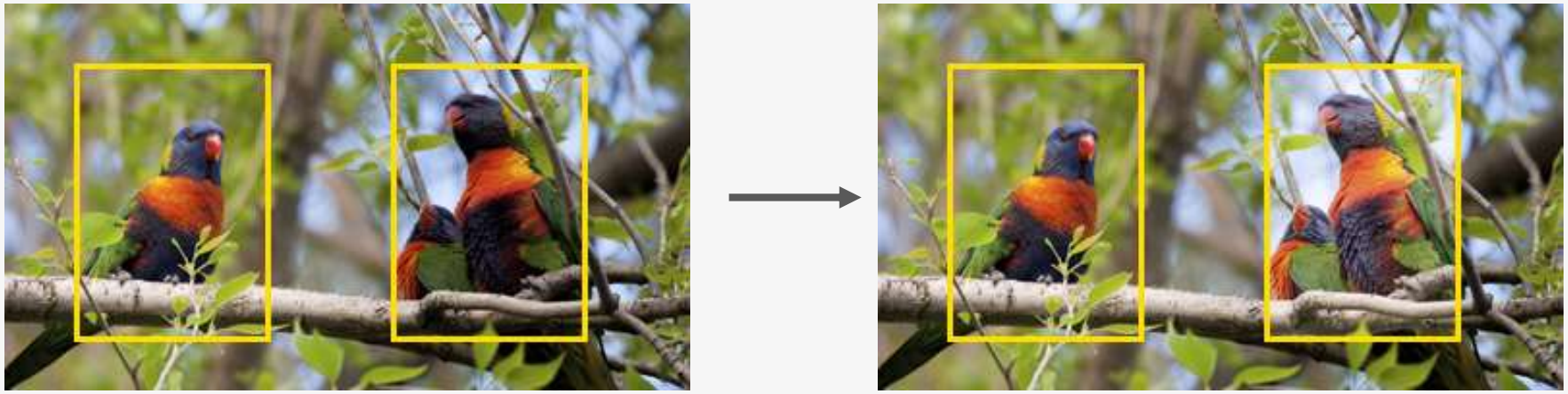
Self Trigger Mode

- A region of interest can be defined as a sensing zone
- The sensing zone can automatically trigger image acquisition in the capture zone
- Simplify systems by eliminating the need for external triggering



Dual trigger mode

- Capture two regions of interest at different exposure times with a single trigger input
- Eliminate the need for multi-exposure HDR imaging



New Pixel Size

- 3rd generation Pregius introduces a 4.5µm pixel
- Intermediate pixel size between 1st generation 5.86µm and 2nd Generation 3.45µm
- The fist sensor in this line will the be 7.1 MP, 1” IMX420
- Greater saturation capacity than 2nd generation Pregius sensors
- Greater resolution than 1st generation Pregius sensors