End to End: Part 2

Earl Wong

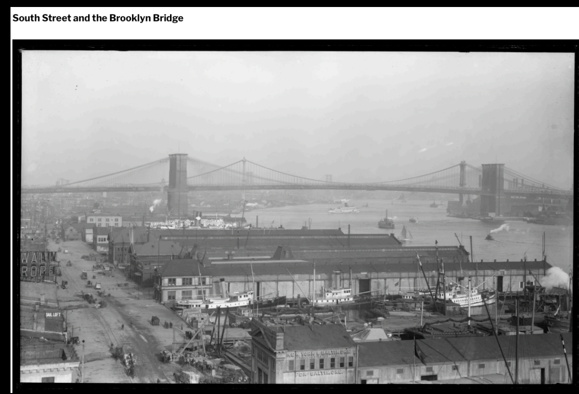
Subjects

- Optics
- **Sensor**
- ISP
- GPU
- NPU

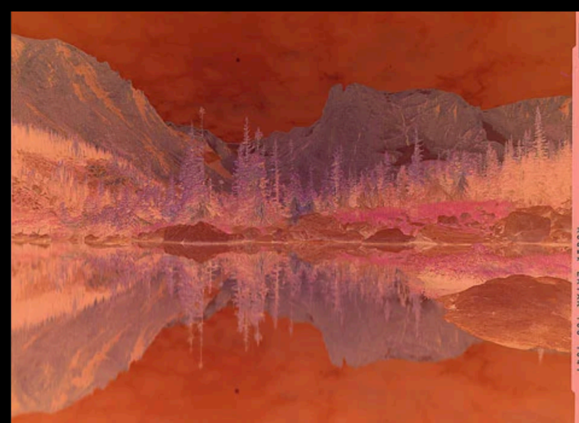
Glass Plate

Sensor Evolution

Glass Plate



Color Film

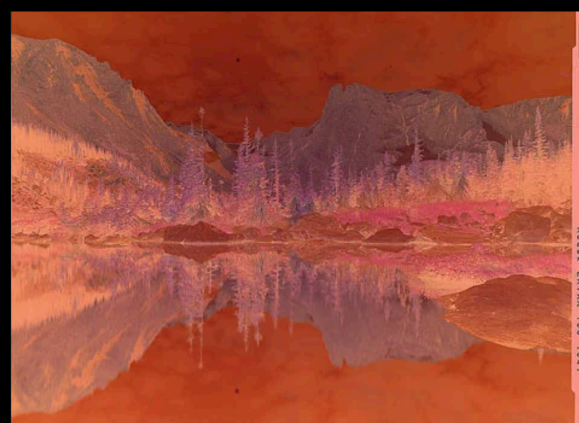


Sensor Evolution

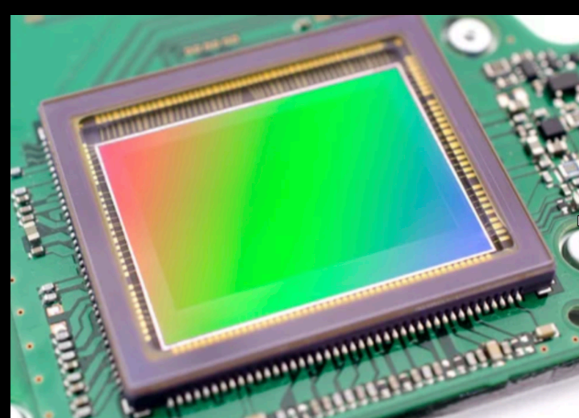
Sensor Evolution

Glass Plate

Color Film



CCD Sensor

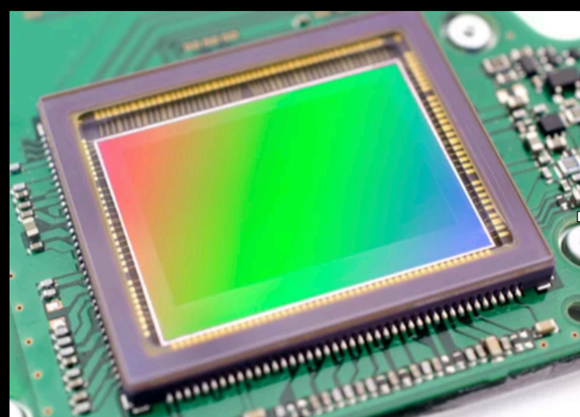


Sensor Evolution

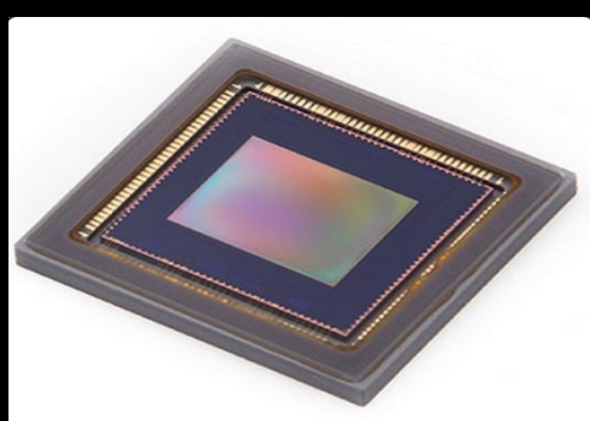
Glass Plate

Color Film

CCD Sensor



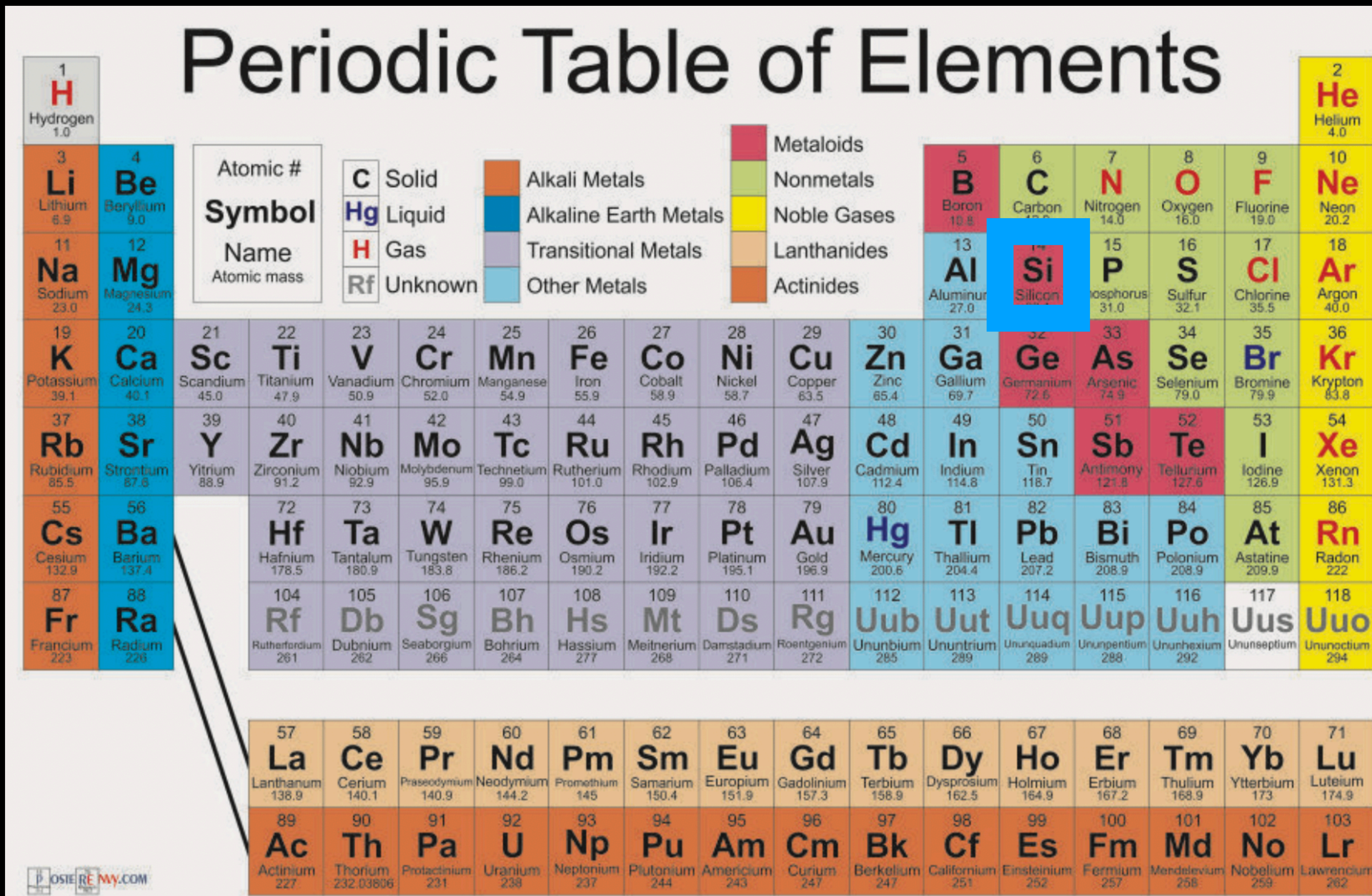
CMOS Sensor



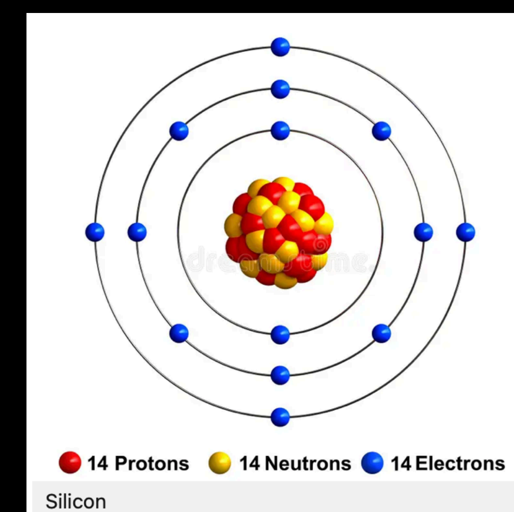
Sensor

- Sensors are light sensitive medium.
- Sensors - up to and including film - involved various wet chemical processes.
- However, this changed, with the introduction of the CCD sensor.
- CCD and CMOS sensors are silicon based photo diodes.

Photo Diode Background



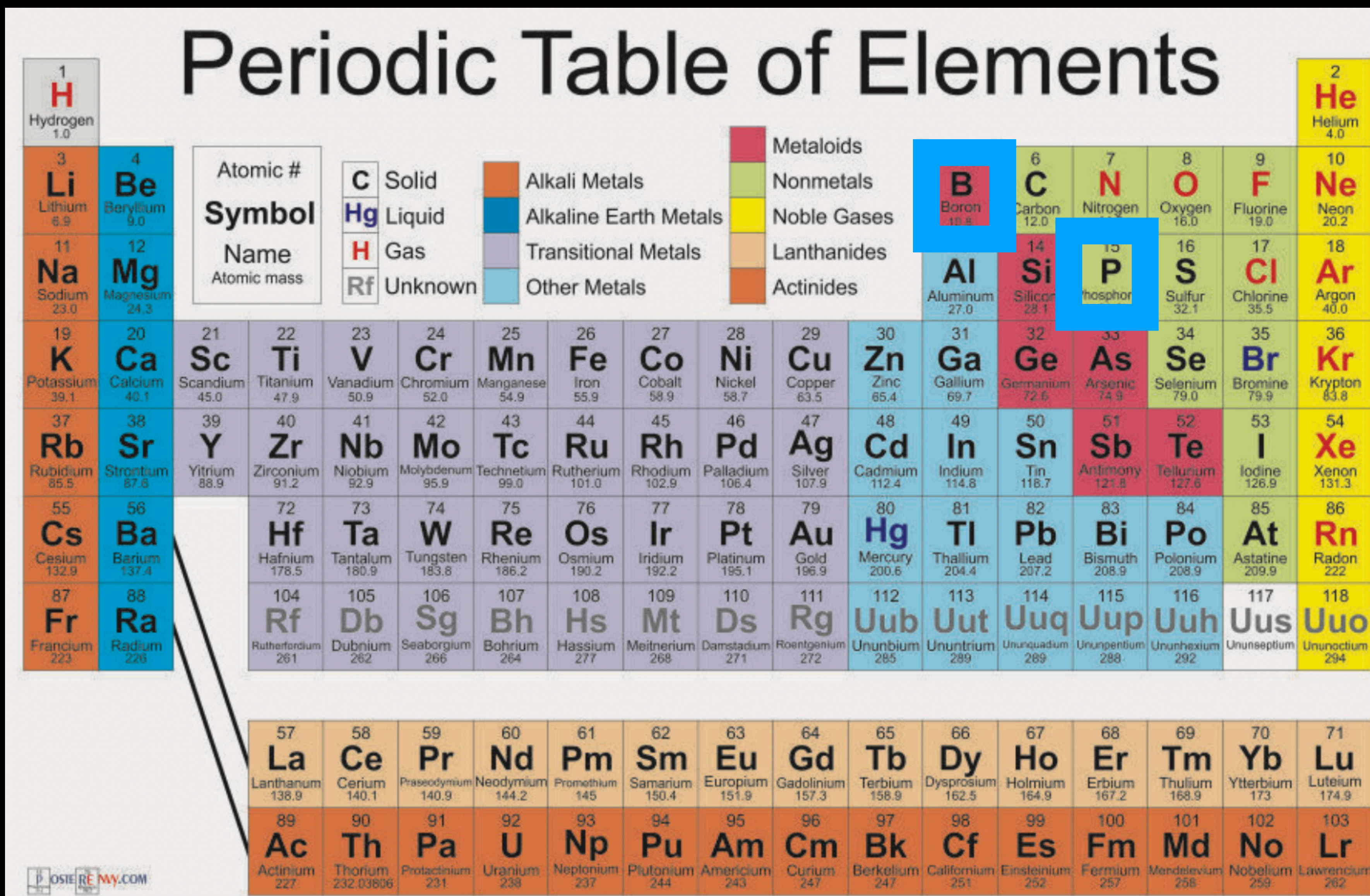
Si

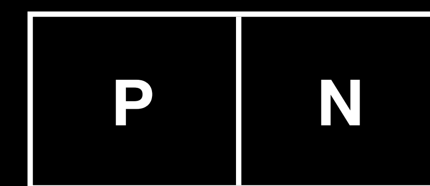


Silicon has 4 valence electrons in its outer orbit.

These valence electrons can break free, when struck by photons with energy exceeding their band gap energy (1.12 eV).

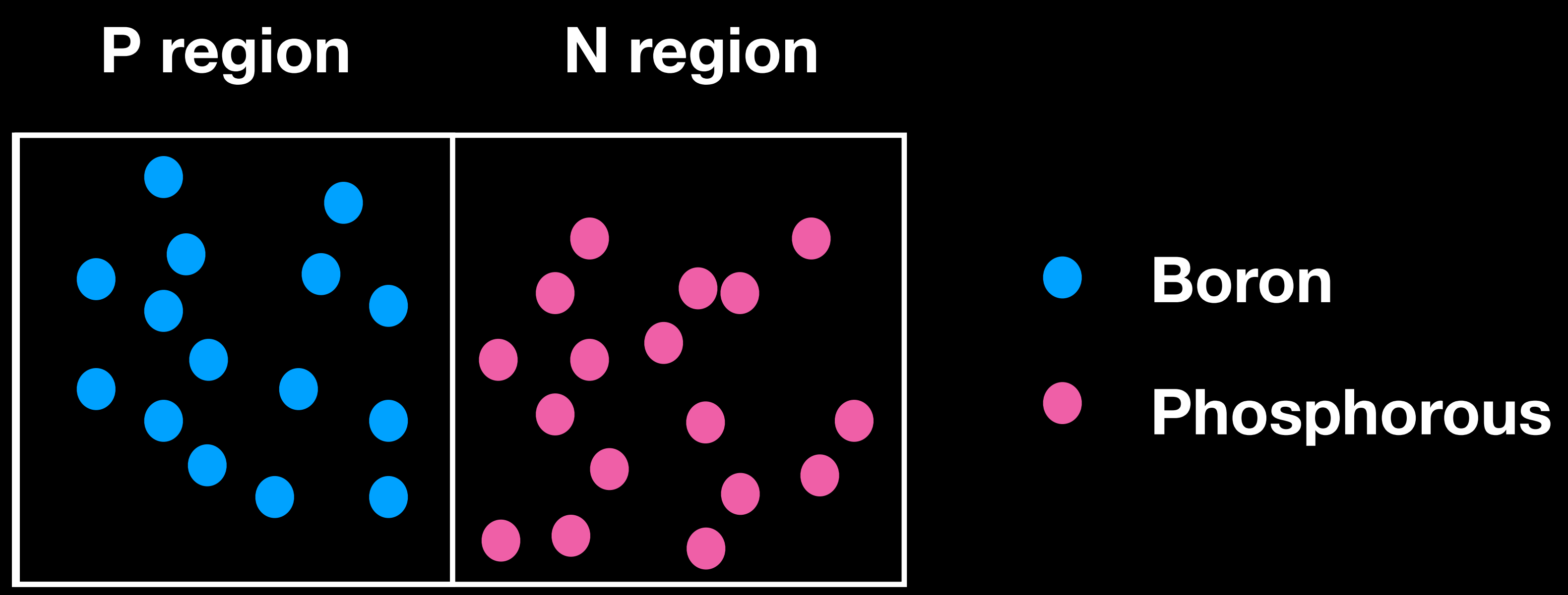
Photo Diode Background



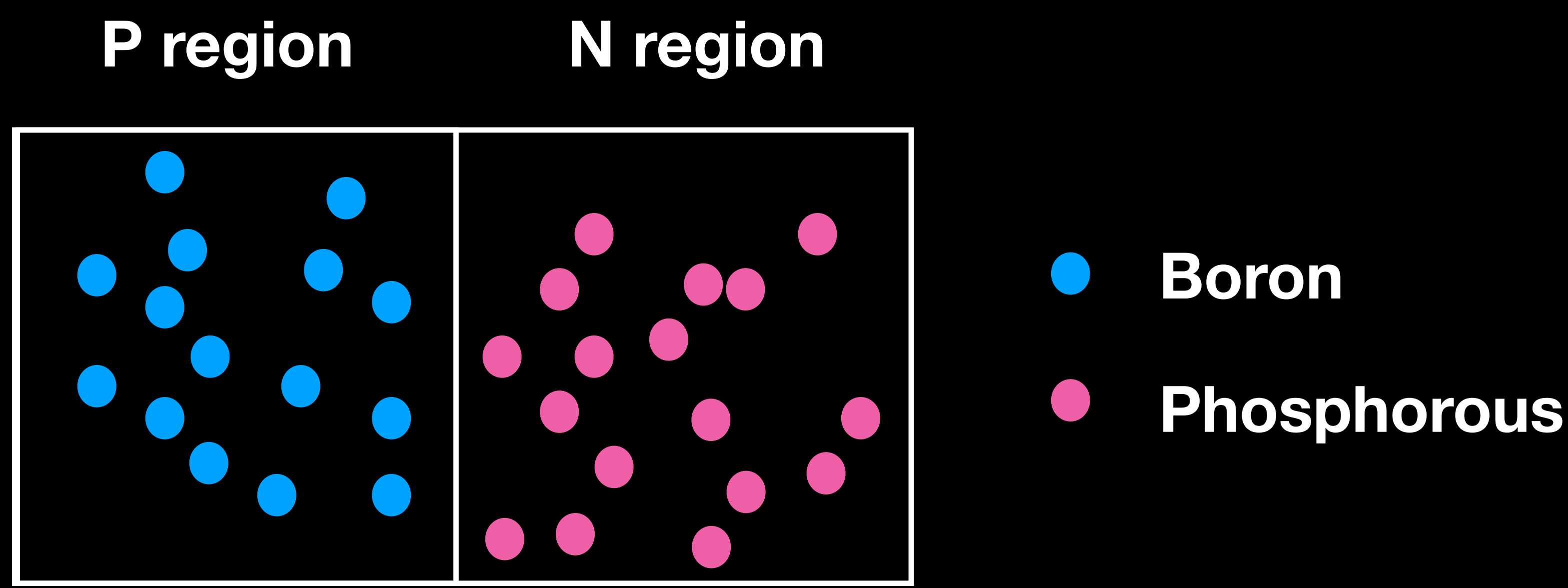


A pn junction can be formed in the silicon, by doping the silicon with different impurities.

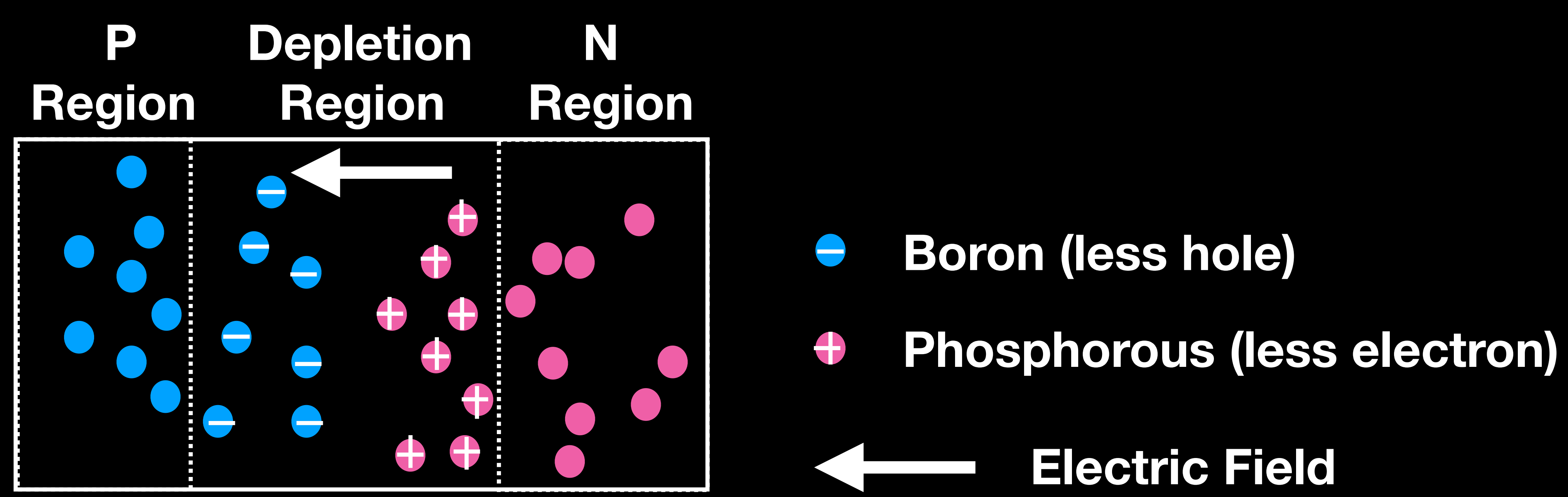
Boron (p dopant - 5 valence electrons) and phosphorous (n dopant - 3 valence electrons) are two such impurities.

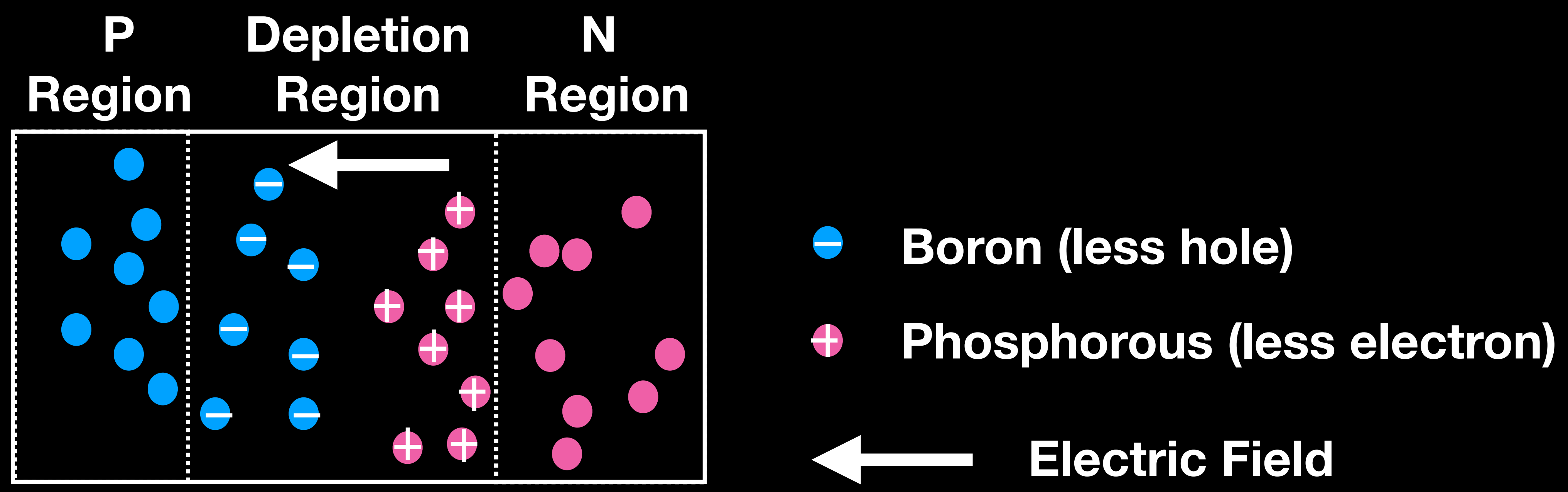


1) Holes in Boron are attracted to the n region.
2) Electrons in Phosphorous are attracted to the p region.
3) Migration of electrons and holes occur, producing a depletion region.
4) An electric field is created in the depletion region.

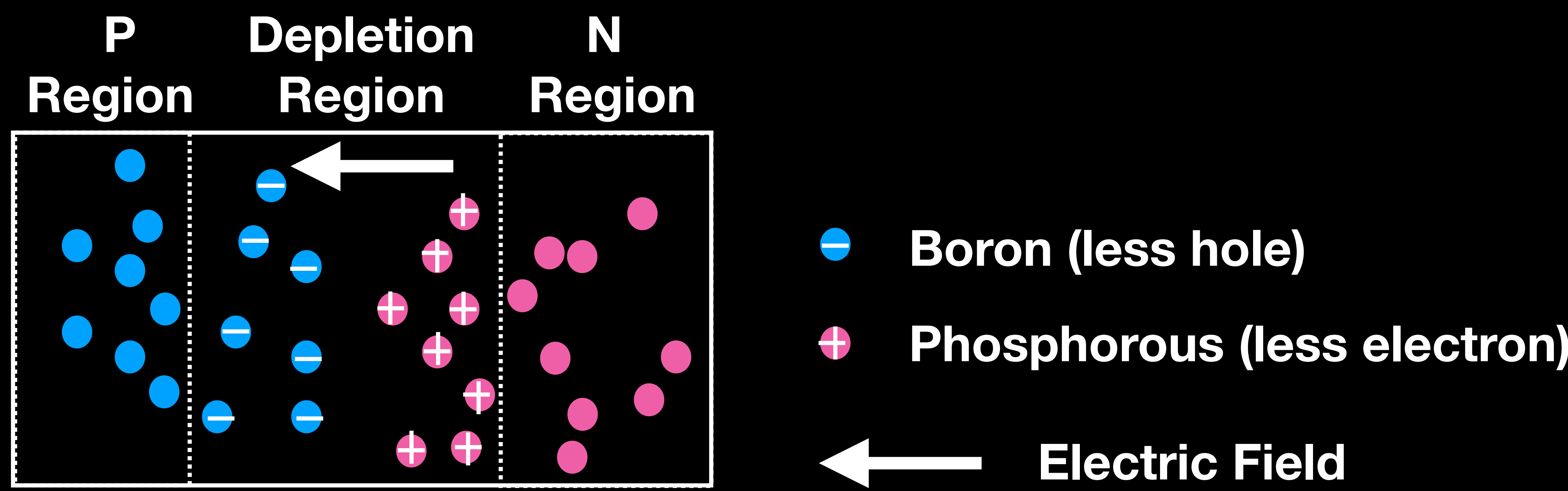


1) Holes in Boron are attracted to the n region.
2) Electrons in Phosphorous are attracted to the p region.
3) Migration of electrons and holes occur, producing a depletion region.
4) An electric field is created in the depletion region.

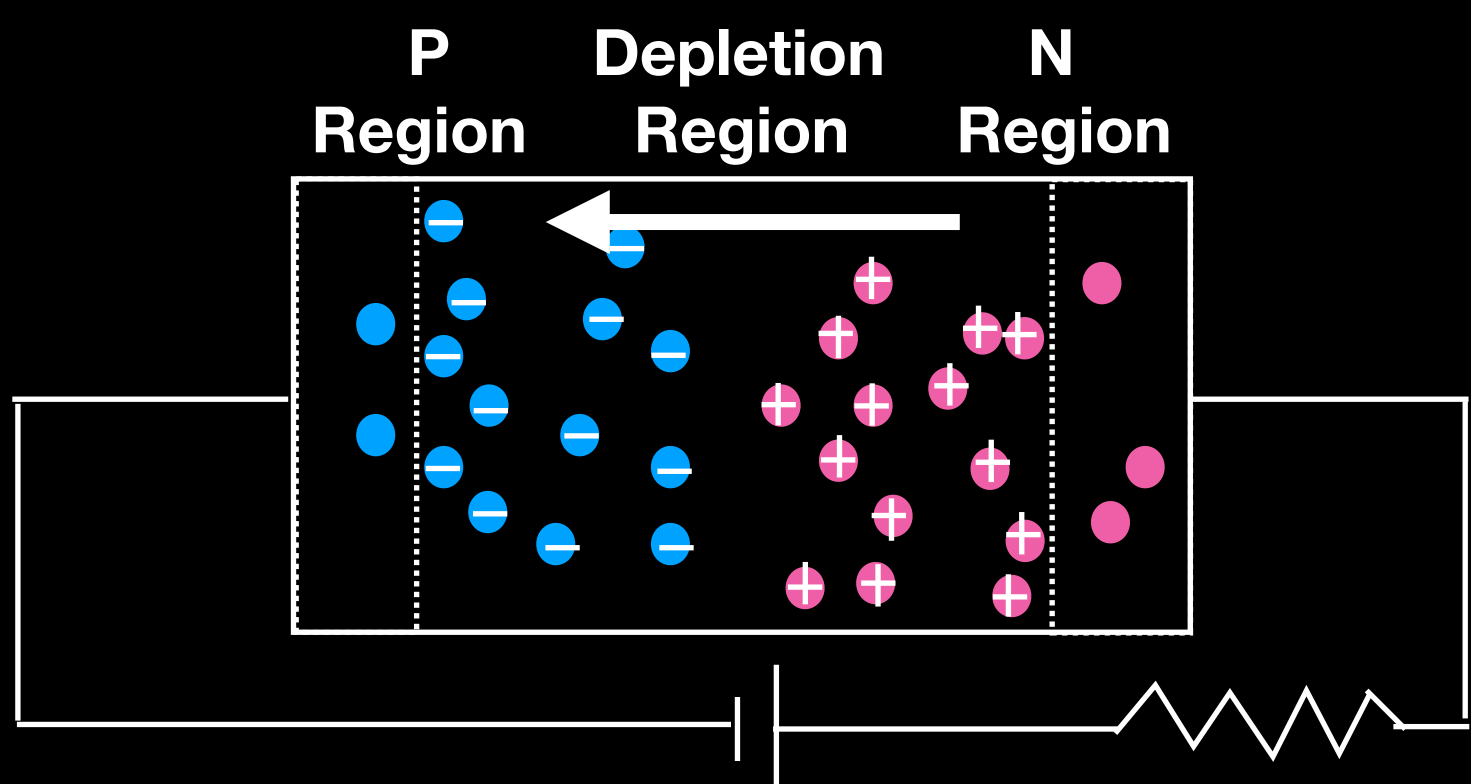


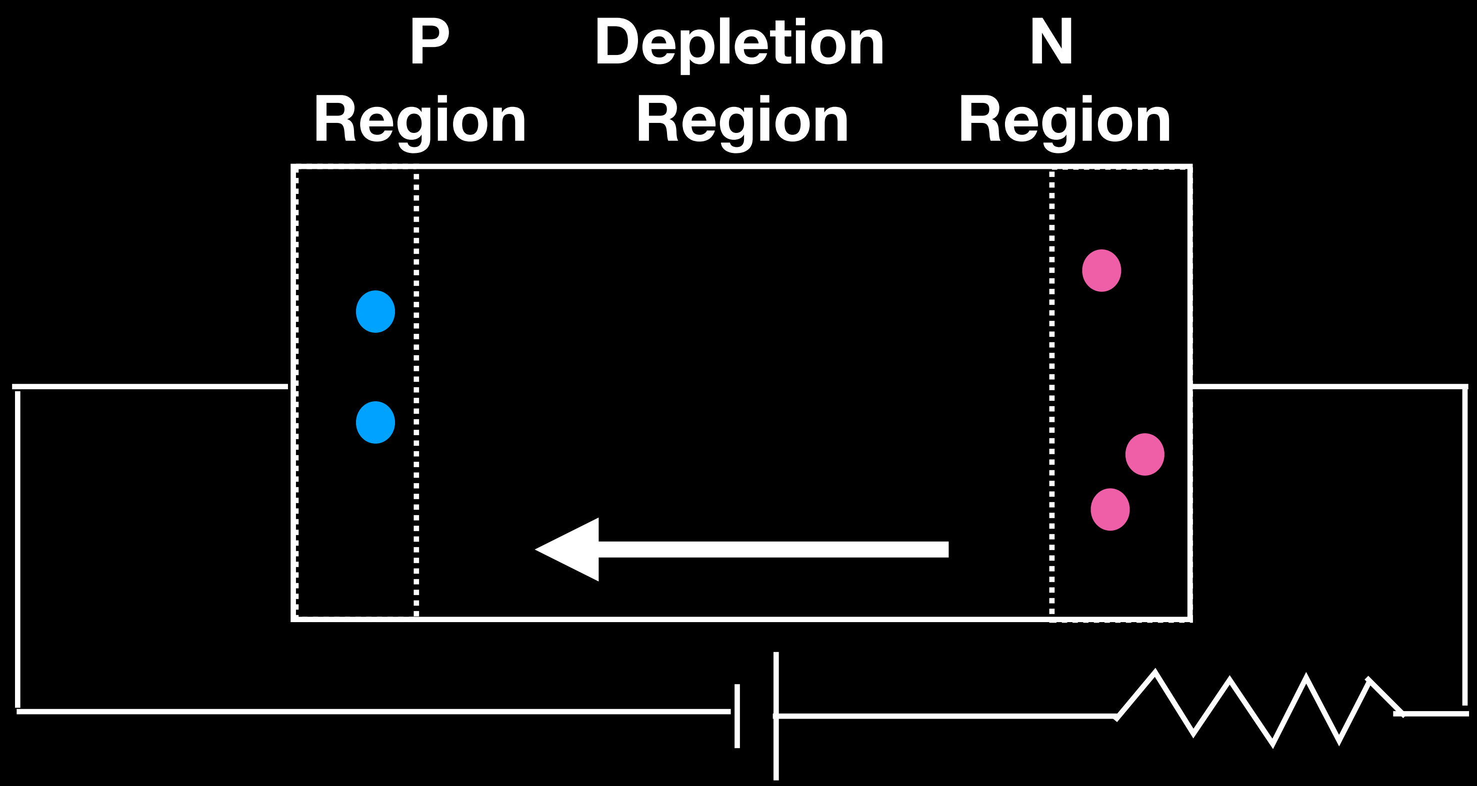


Reverse bias voltage is added, to increase the size of the depletion region.

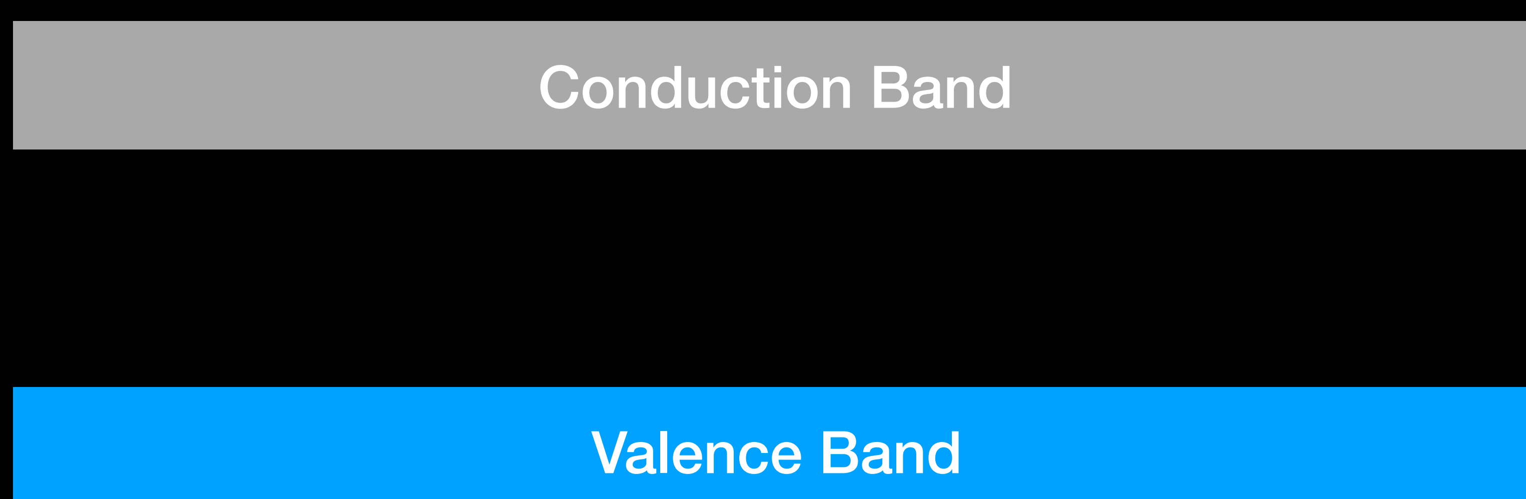


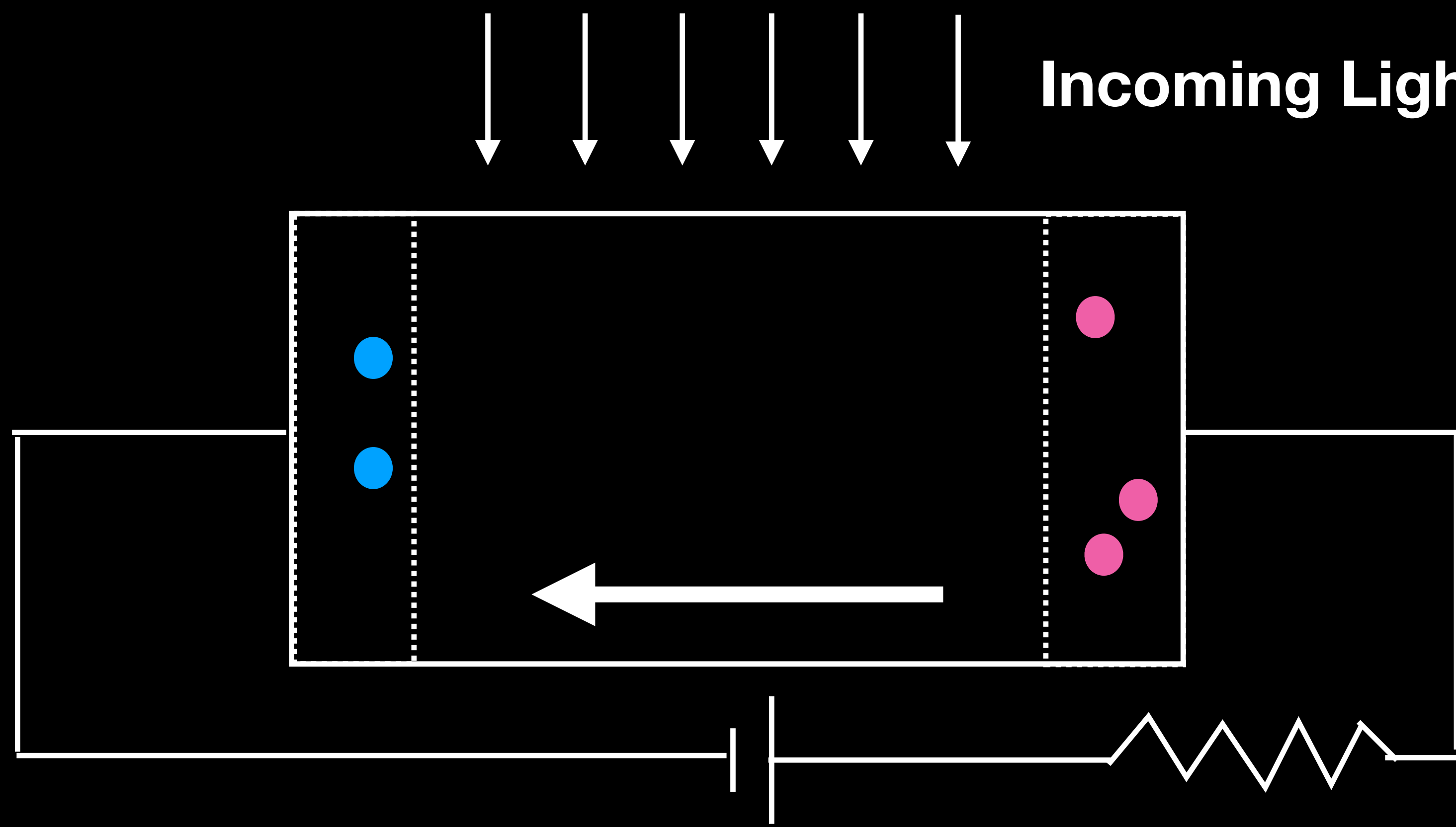
Reverse bias voltage is added, to increase the size of the depletion region.



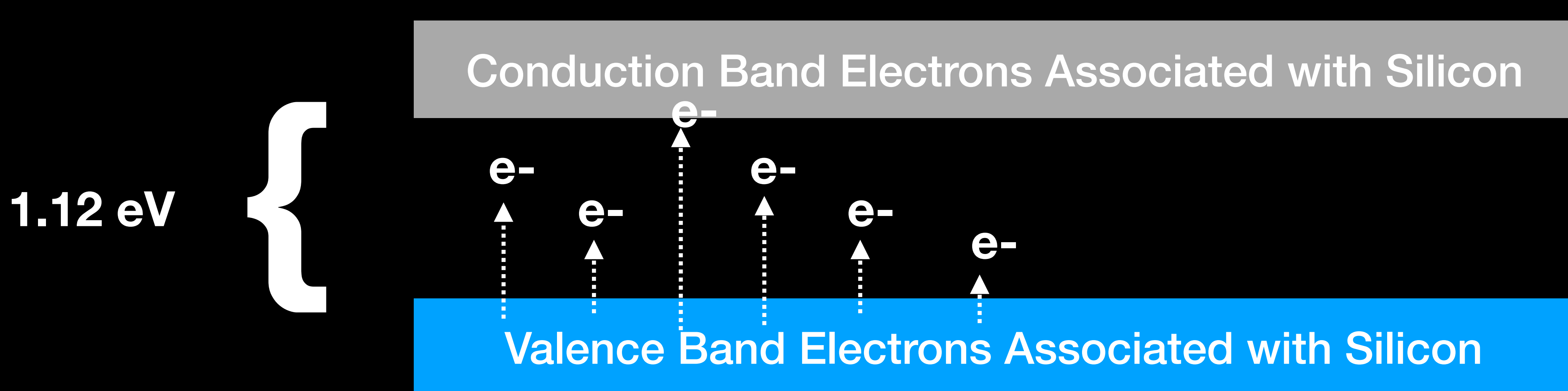


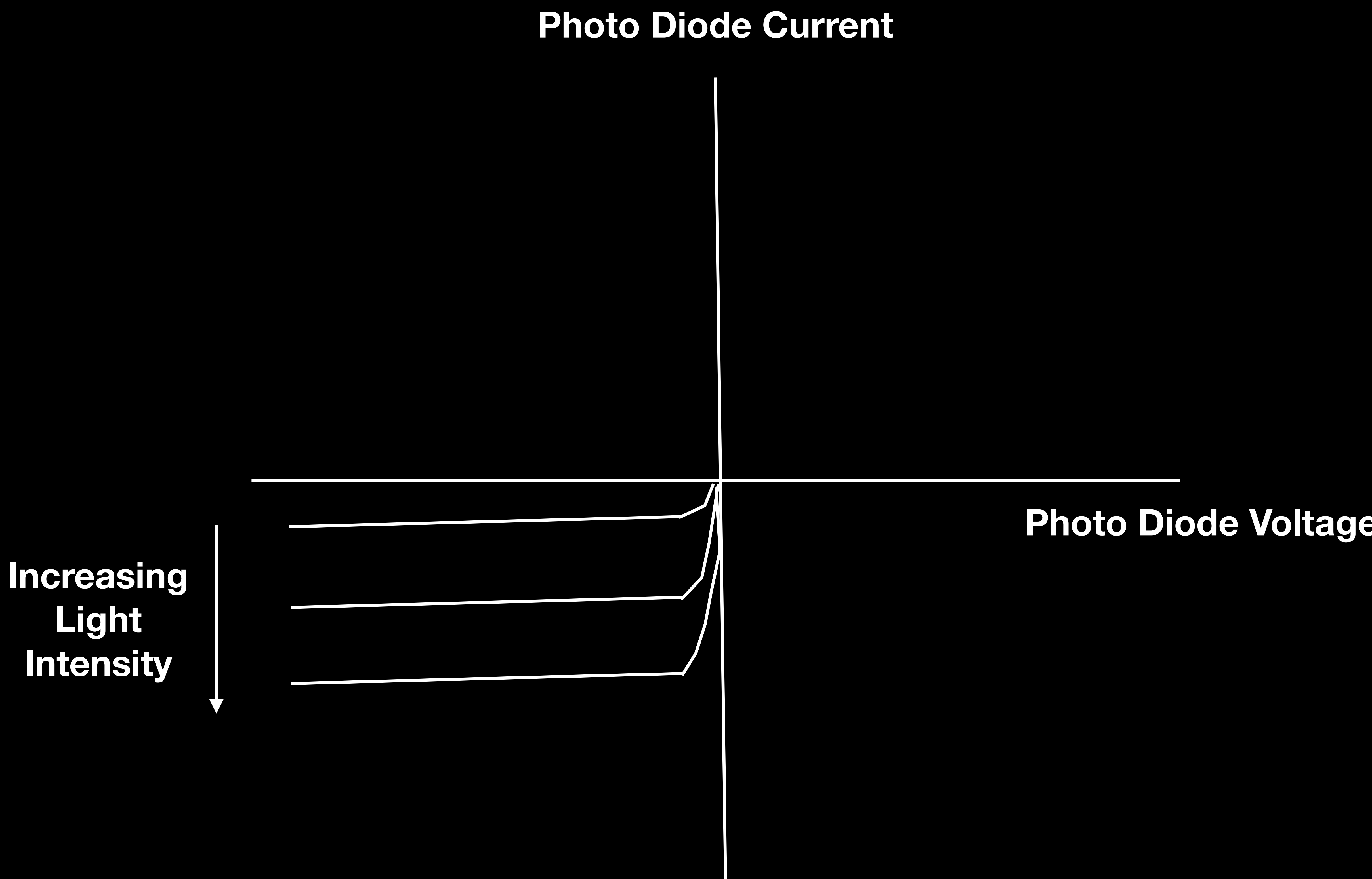
1) A small current flows.
2) The depletion region is heavily populated by silicon atoms.
3) Each silicon atom has 4 valence electrons.





1) If the photons from the incoming light have energy greater than the band gap energy (1.12eV), the valence band electrons are dislodged from the silicon atom …
2) … becoming conduction band electrons.
3) Conductance band electrons are swept out of the depletion region by the electric field, increasing the reverse bias current.





The greater the light intensity, the stronger the reverse bias current.

Sensor

- A CCD or CMOS sensor “collects” incoming photons (light), converts them to photo electrons (conduction band electrons), integrates the charge, and reads out the charge as an electrical signal.

- Quantum efficiency describes the efficiency of this process.

- A quantum efficiency of 100% says that every incoming photon creates a conduction band electron / photo electron.

CCD vs CMOS

- CCD and CMOS sensors differ primarily in how pixel information is read out.
- Early CCD sensors transferred charge across the array in a “bucket brigade” fashion to a single output amplifier.
- In contrast, CMOS sensors contained their own readout transistor circuitry, allowing parallel readout.
- This architecture made CMOS sensors inherently faster than CCDs because they avoided serial charge transfer.

CCD vs CMOS

- One of the main advantages of CMOS sensors, was that they could be fabricated using standard integrated circuit fabrication processes.
- This significantly lowered cost, relative to their CCD counterparts.
- Early CMOS sensors were more noisy than their CCD counterparts, due to fixed pattern noise and amplifier variations at each pixel.
- However, this changed with the pinned photo diode.

Sensor

Desirable CMOS sensor characteristics include:

- High resolution
- High sensitivity
- High dynamic range
- Good linearity
- Low power
- Low noise

Sensor

- The relationship between many of these characteristics is strong, involving different tradeoffs.
- For example: assume a fixed size sensor.
- => Increasing resolution leads to smaller pixel dimensions, resulting in reduced sensitivity and increased noise.
- For example: assume the sensor size can increase.
- => larger pixel dimensions (usually) follow, leading to improved image quality (lower noise and higher dynamic range).
- i.e. the larger pixel dimensions increase the light gathering capabilities and result in larger well capacities.

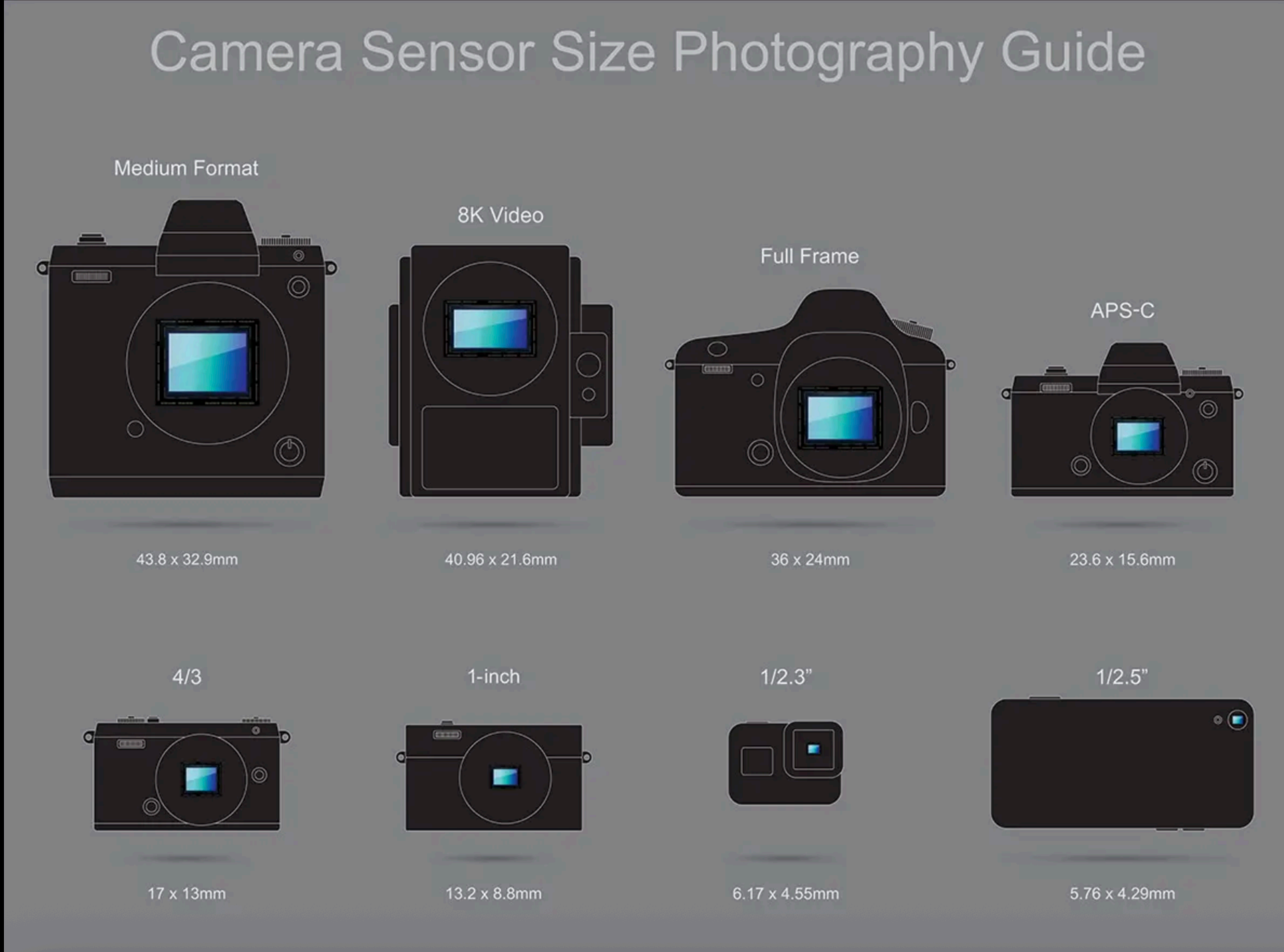


Image courtesy of Adorama

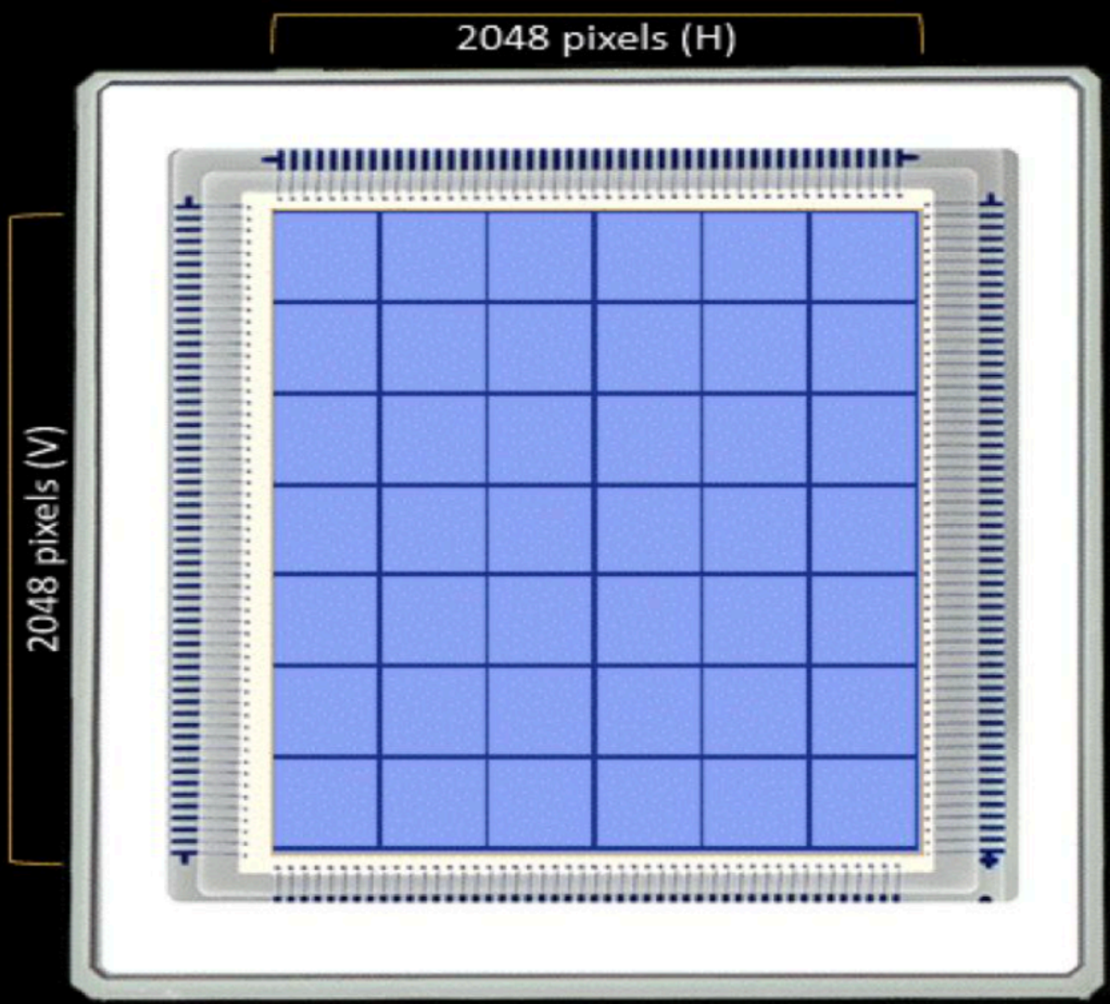
Cell Phone Sensors

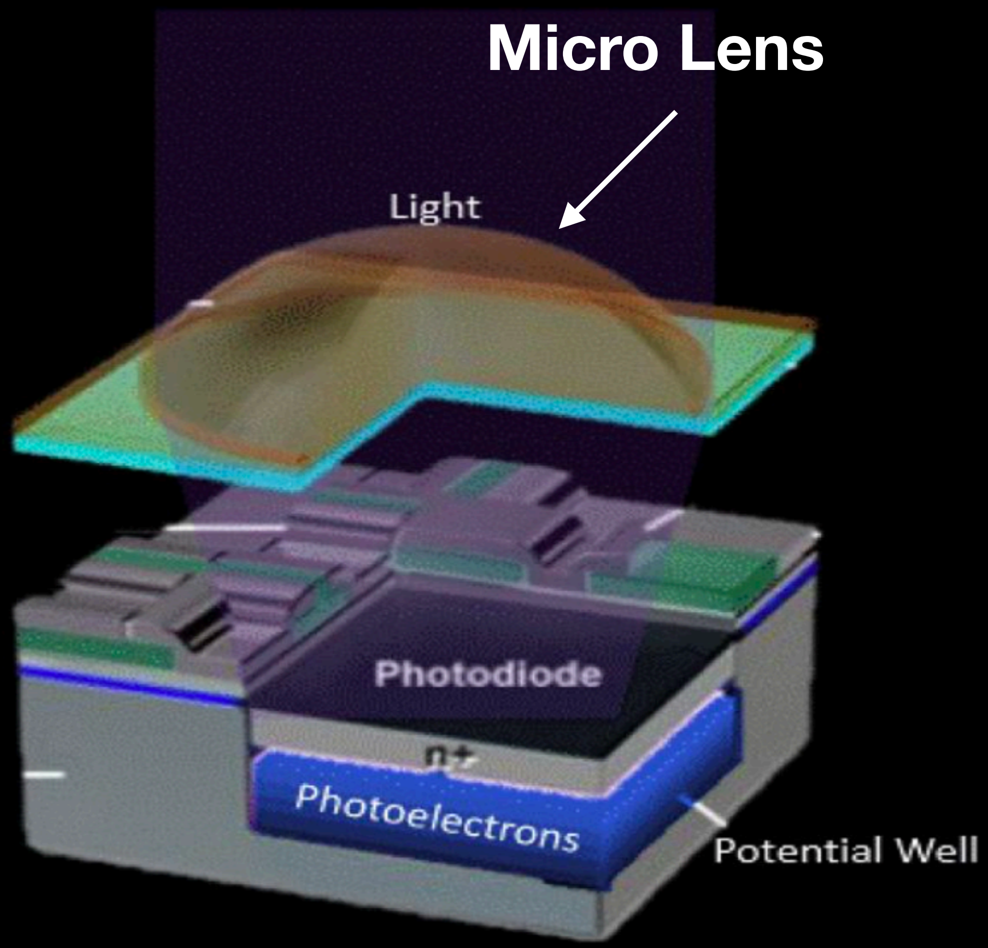
- Given the small sensors found in cell phone cameras and their high pixel count, noise, sensitivity and dynamic range all become problematic.
- Noise and dynamic range can be increased using computational photography.
- We first examine how to improve sensitivity, then noise and then dynamic range.

Sensor Sensitivity

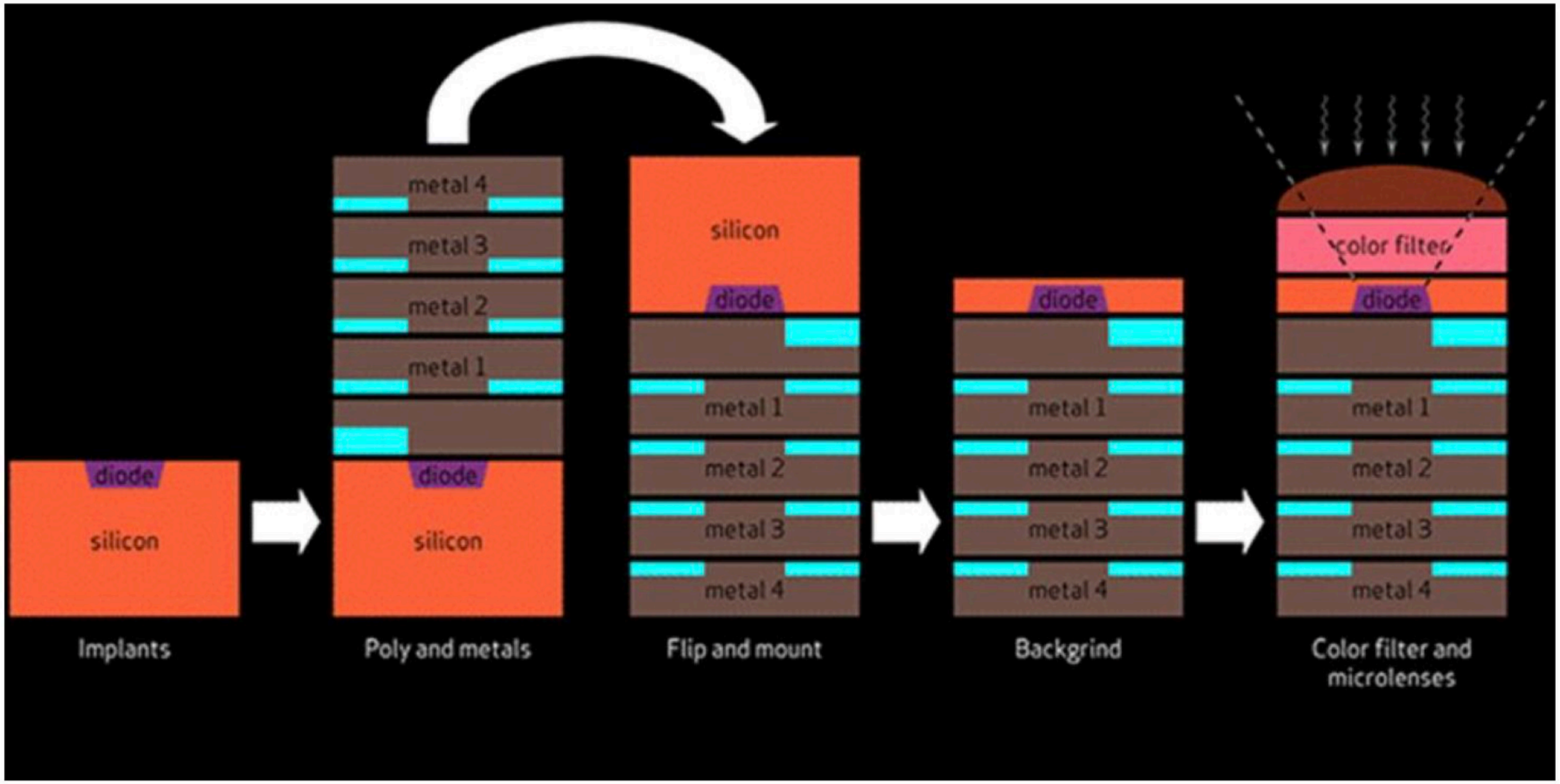
- To increase sensor sensitivity, we need to improve the light gathering capabilities.
- This can be accomplished, by increasing the pixel dimension, enabling a larger light gathering region.
- In a similar spirit, a micro lens can be added, on top of each pixel location. (See next slide.)
- Finally, a back side illuminated (BSI) fabrication process can be used. (See next, next slide.)

Sensor Noise





Sensor Sensitivity



A schematic of the process steps in producing a BSI imager

In traditional front side illuminated sensors, important sensor circuitry is fabricated on top of the photo diode, thereby blocking incoming light.

In back side illuminated sensors, the fabrication process is flipped, moving the important circuitry to the back side.

Sensor Noise

Sensors are subject to various types of noise:

- Shot noise
- Dark current noise
- kTC reset noise
- 1/f noise

Sensor Noise

However, not all sensor noise depends on scene brightness:

- Shot noise (dependent)
- Dark current noise (independent)
- kTC reset noise (independent)
- 1/f noise (independent)

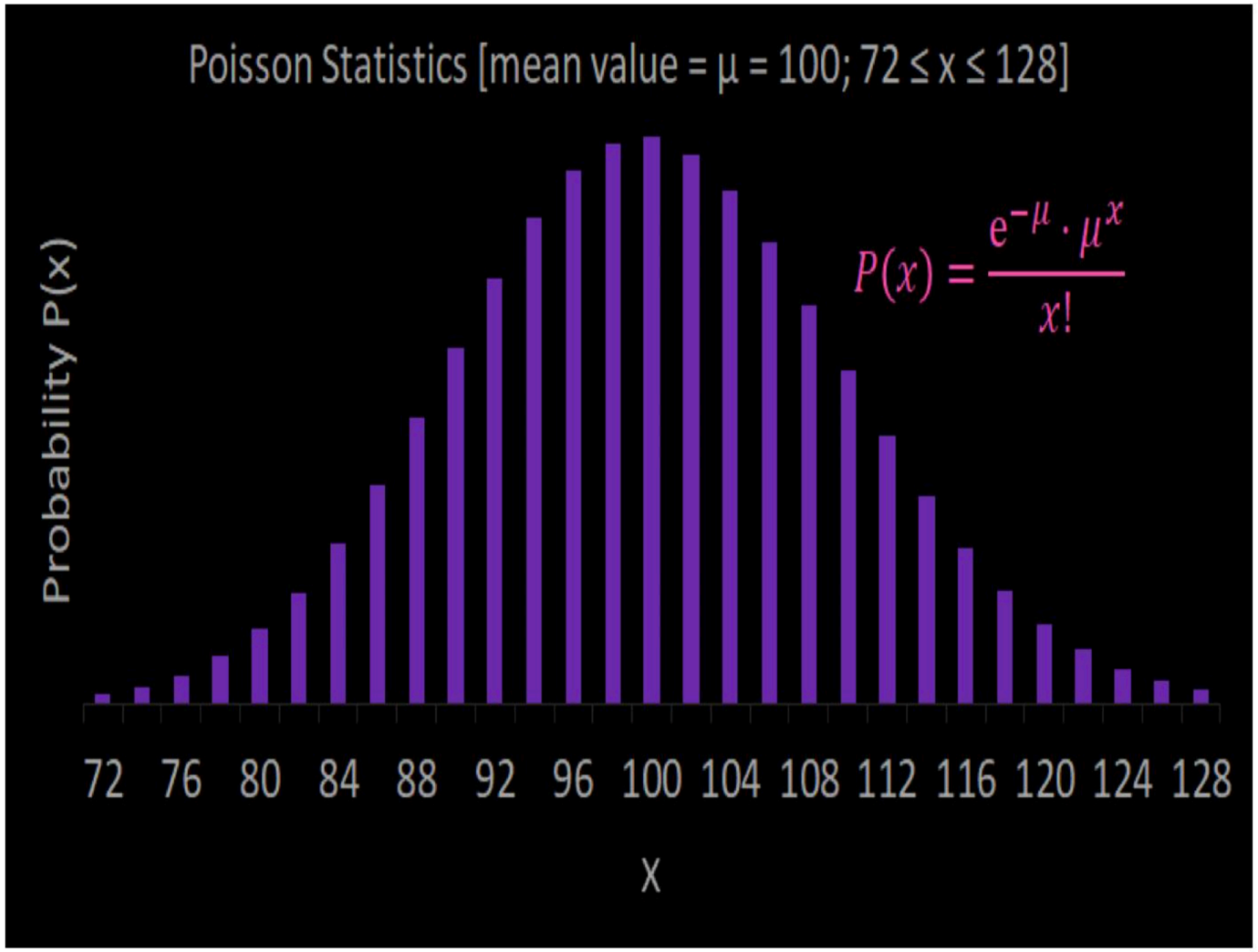
Sensor Noise

- Pinned photo diodes greatly reduces dark current noise.
- Correlated double sampling (CDS) greatly reduces kTC and 1/f noise.
- This leaves shot noise.
- Shot noise increases with increasing brightness.
- Are all of the techniques described under “Sensor Sensitivity” making shot noise worse?

Sensor Noise

In a poisson distribution, the mean of the distribution is equal to the variance of the distribution.

Shot noise is modeled as the standard deviation of the poisson distribution.



Sensor Noise

- Yes, BUT …
- … shot noise is increasing, but ONLY increasing as the square root of the signal.
- For example, if the signal brightness increases by 2x, shot noise increases by sqrt(2).
- Hence, from a signal to noise standpoint (SNR), the SNR increases as 2/sqrt(2) = sqrt(2) with respect to brightness.
- As a result, shot noise is only problematic under low light conditions.

Sensor Dynamic Range

- To improve dynamic range, lower dark current noise and larger well capacity is needed.
- Dark current noise can be reduced by using a pinned photo diode and by improving the sensor cooling / heat sinking.
- Larger well capacity can be achieved by increasing the pixel dimensions on the sensor.
- When this is not possible, computational photography can be used.

Sensor Dynamic Range

- Staggered HDR employs the capture of multiple frames at different exposure levels.
- These fixed frames (with fixed dynamic ranges), are then fused - producing a new image with an increased dynamic range.

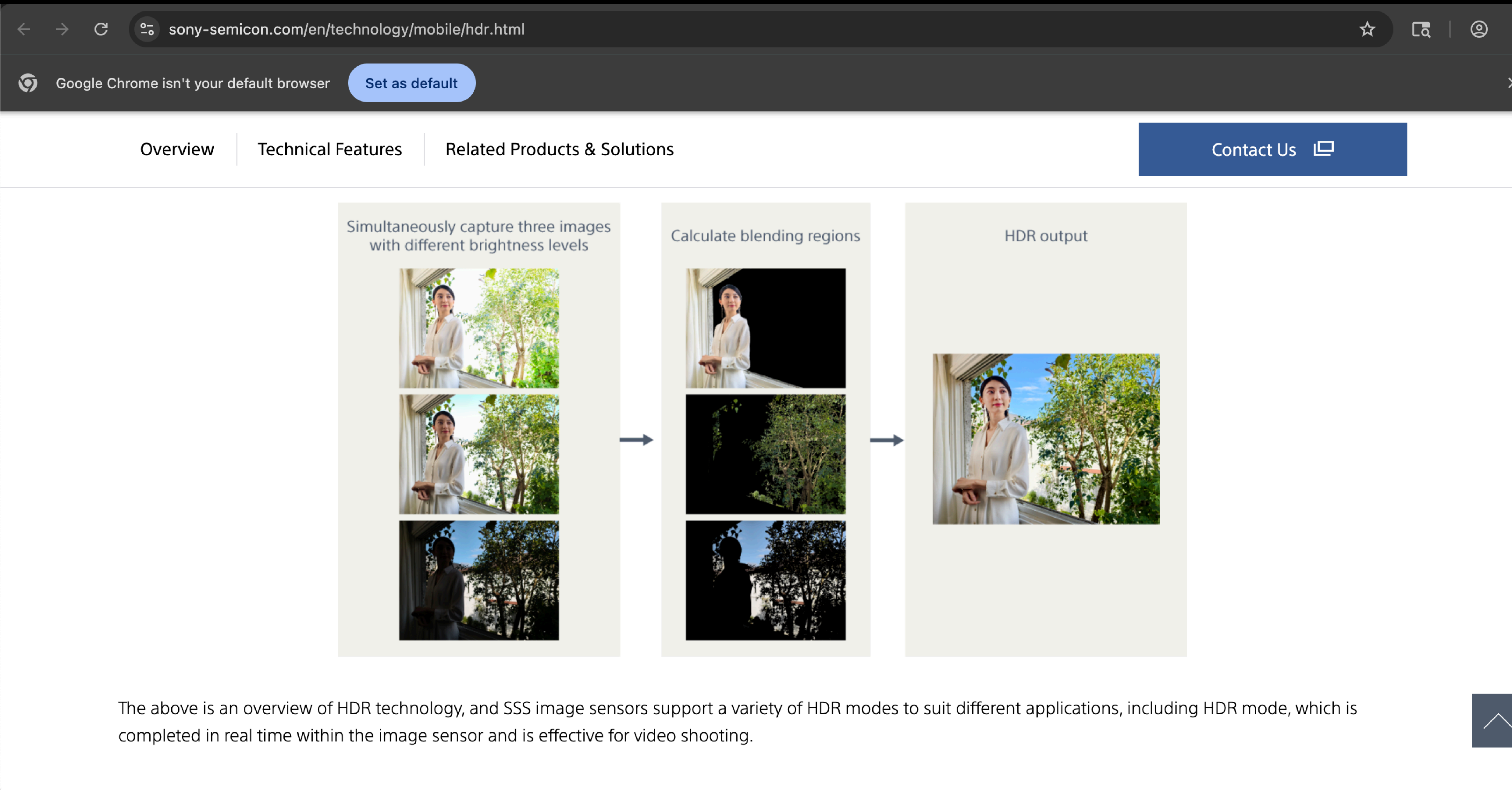
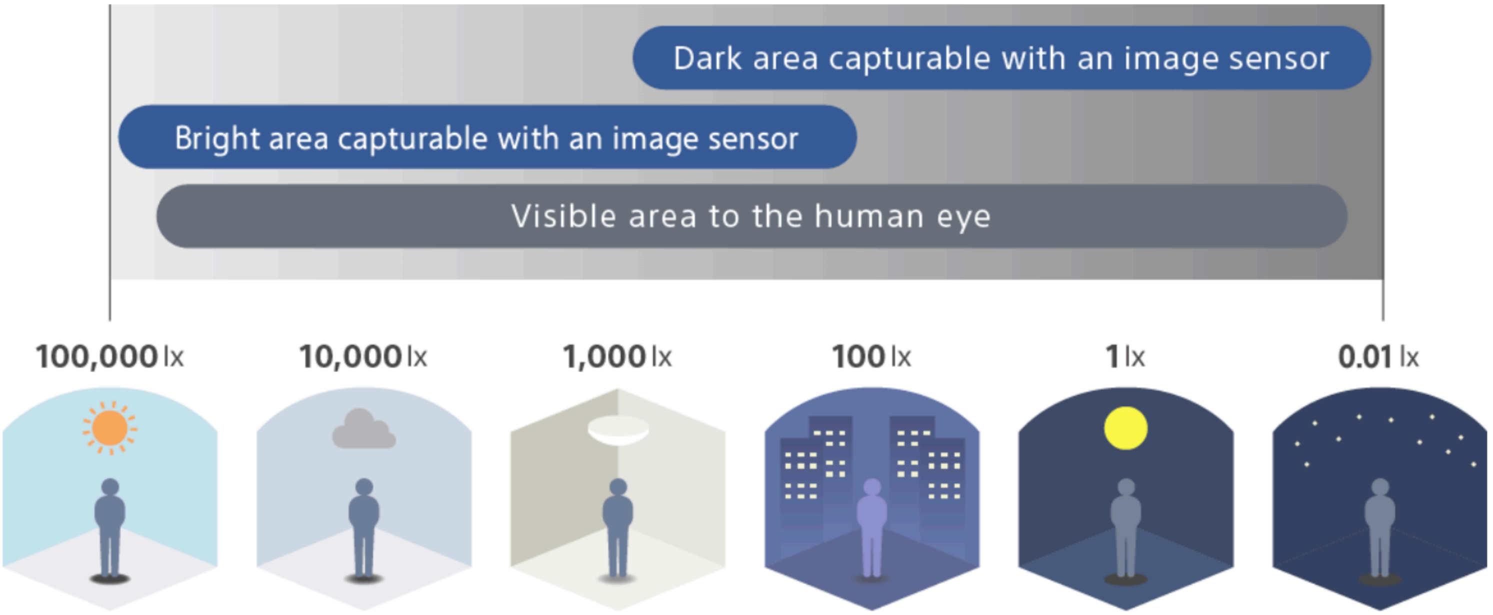


Image courtesy of Sony Semiconductor

Our surroundings are subject to a significant variance of luminous intensity (dynamic range), from the bright sunshine to dim light of stars.



Since the image sensor has a narrow dynamic range of photography, it cannot photograph the range that can be seen by the human eye. If you are going to capture a bright subject, the dark areas will be blacked out, and if you are going to capture a dark subject, the bright areas will become blowout. In addition, because the image sensor for smartphones, which needs to be reduced in size, has a reduced ability to capture light, the range of brightness that can be photographed will be further narrowed. This is the reason why the photographing result may differ from that of the naked eye when photographing a scene with a large difference in brightness such as backlight with a smartphone .

HDR (High Dynamic Range) is a function for capturing scenes with such a large difference in brightness (dynamic range). In HDR mode, the brightness is automatically adjusted by changing the operation of the image sensor, enabling you to photograph with blowout and blackout suppressed, which are close to what you see with the naked eye.

Image courtesy of Sony Semiconductor

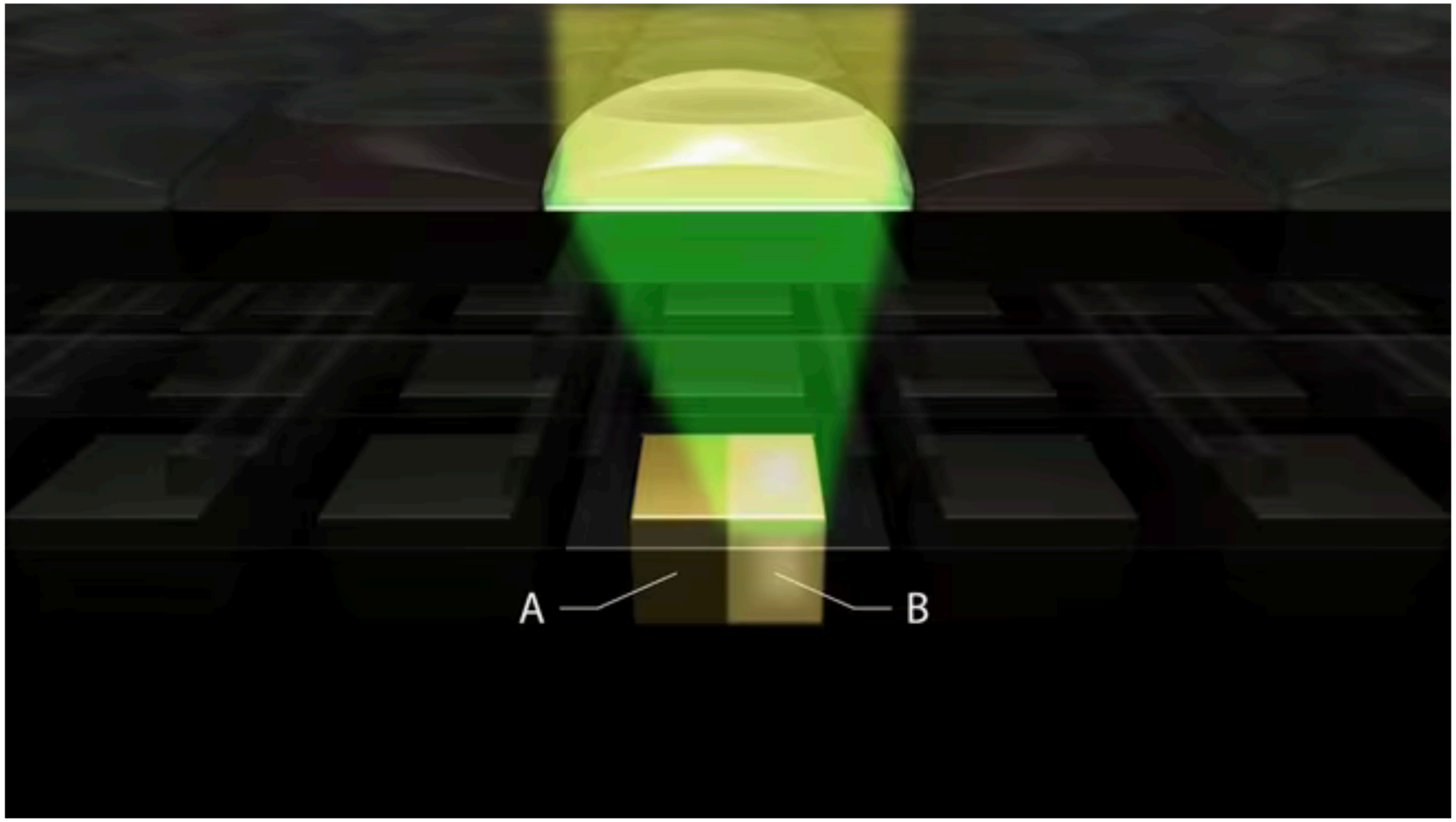
	Optical Format	Pixel Size	Effective Resolution	2-Layer Pixel	Frame Rate @ 4 K	Hybrid Frame-HDR	Single Frame HDR	Multi Frame HDR	UHCG	Auto Focus
LYTIA 901	1/1.12”	0.7μm	200MP		120 fps *1	HF-HDR	DCG-HDR	LBMF		All-pixel AF
LYTIA 900	1/0.98”	1.6μm	50MP		120 fps *1		DCG-HDR	LBMF		All-pixel AF
LYTIA 828	1/1.28”	1.22μm	50MP		120 fps *1	HF-HDR	DCG-HDR	LBMF	UHCG	All-pixel AF
LYTIA 818	1/1.28”	1.22μm	50MP		120 fps *1		DCG-HDR	LBMF	UHCG	All-pixel AF
LYTIA T808	1/1.43”	1.12μm	52MP	2-Layer Pixel	120 fps *1		DCG-HDR	LBMF		All-pixel AF
LYTIA 808	1/1.4”	1.12μm	50MP		60 fps *1		DCG-HDR	LBMF		All-pixel AF
LYTIA 700	1/1.56”	1.0μm	50MP		60 fps *1		DAG-HDR	LBMF		All-pixel AF
LYTIA 700C	1/1.56”	1.0μm	50MP		30 fps *1		DAG-HDR	LBMF		All-pixel AF
LYTIA 600	1/1.95”	0.8μm	50MP		30 fps *1			LBMF		All-pixel AF
LYTIA 500	1/2.93”	0.6μm	50MP		30 fps *2			LBMF		Partial PD
LYTIA 505	1/2.93”	0.6μm	50MP		30 fps *2			LBMF		Partial PD
LYTIA 501	1/2.93”	0.6μm	12.5MP		30 fps *2			LBMF		Partial PD

*1 All-pixel AF and non-HDR mode *2

Image courtesy of Sony Semiconductor

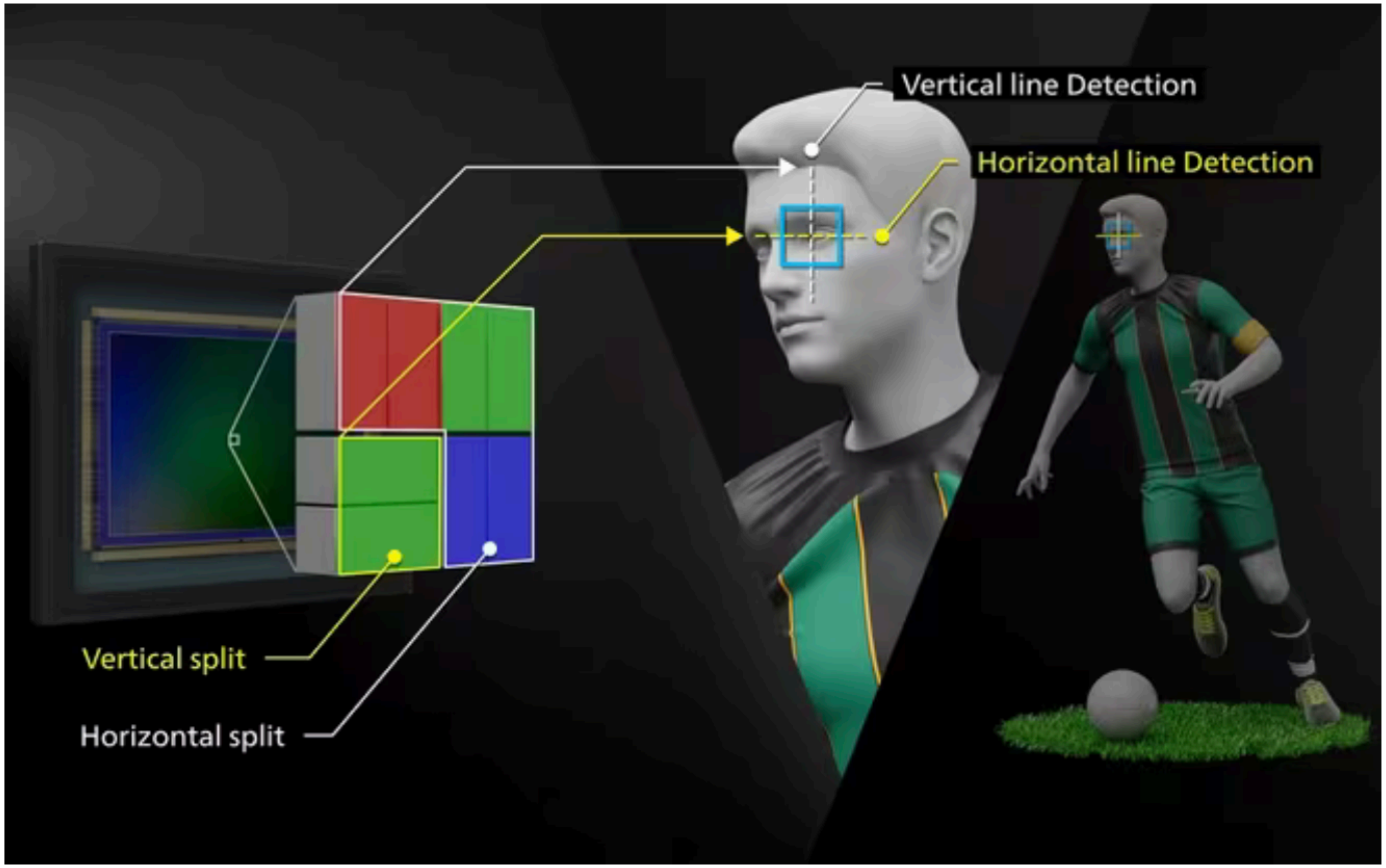
An Additional Sensor Feature for Auto Focus

- Dual pixel autofocus (DPAF) splits the standard photo diode at a pixel site into two separate photo diodes.
- This split can be in the horizontal or vertical direction.
- More recently, a quad split sensor was released by Canon, yielding AF information in both the horizontal and vertical directions.
- https://www.eos-magazine.com/articles/eospedia/what-is/dual-pixel-cmos-af.html



In Canon's unique Dual Pixel CMOS AF system and its updated versions, every pixel in the sensor is capable of both imaging and phase-detection autofocus. Each pixel has two independent photodiodes, labelled A and B here, and if there is any deviation between the two signals, the camera knows that this point of the image is not in sharp focus. By looking at pairs of photodiodes across a group of pixels, it can determine how much adjustment is required to achieve sharp focus and in which direction.

Image courtesy of Canon Imaging



The **EOS R1**'s Dual Pixel Intelligent AF features Cross-type AF points, which are sensitive to both horizontal and vertical detail. It required a new Dual Pixel CMOS AF sensor arrangement with photodiodes sensitive to contrast along both the vertical and horizontal axes of the sensor. The result is AF that excels in locking onto details that can be challenging for autofocus to pick out, such as subjects with low contrast or when shooting in low light.

Image courtesy of Canon Imaging

An Additional Sensor Feature for Auto Focus

Marketing boilerplate:

- “Local ray angle error is measured.”
- Unlike traditional stereo which operates in “scene space”, DPAF operates in “ray space”.
- When the signal from the two photo diodes do not match (due to ray angle error), 1) defocus is detected and 2) defocus direction can be determined.
- DPAF measure phase shift resulting from defocused induced wavefront tilt.

Physical Origins

- In 1992, Adelson and Wang published: Single Lens Stereo With a Plenoptic Camera
- In the paper, the authors describe a novel camera, where a lenticular array (micro lens) array is placed at the sensor plane.
- Unlike the standard micro lens setup used to improve light gathering capabilities (for individual pixels), large micro lenses are NOW placed above a spatial region extending over multiple pixels.

Physical Origins

- The authors demonstrate that directional information results from the captured output.
- The following slides are “cut and paste” from their paper, illustrating this principle.

Core Physical Concept

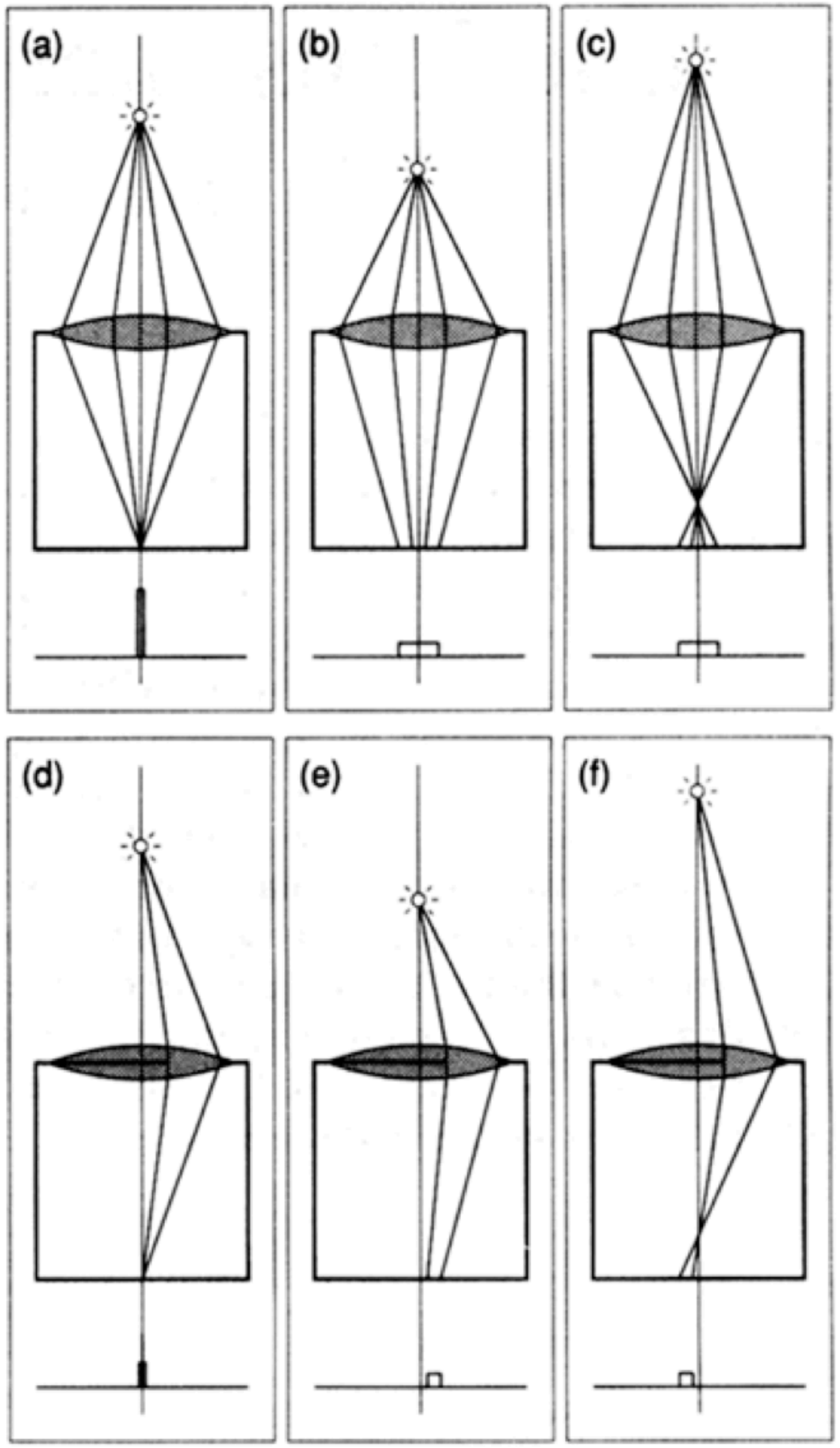


Fig. 3. Principle of single lens stereo: (a) In-focus point object forms a point image; (b) near object; (c) far object forms a blurred image; (d) with an eccentric aperture, the image of the in-focus object retains its position, but the images of the near or far objects (e) and (f), are displaced to the right or left.

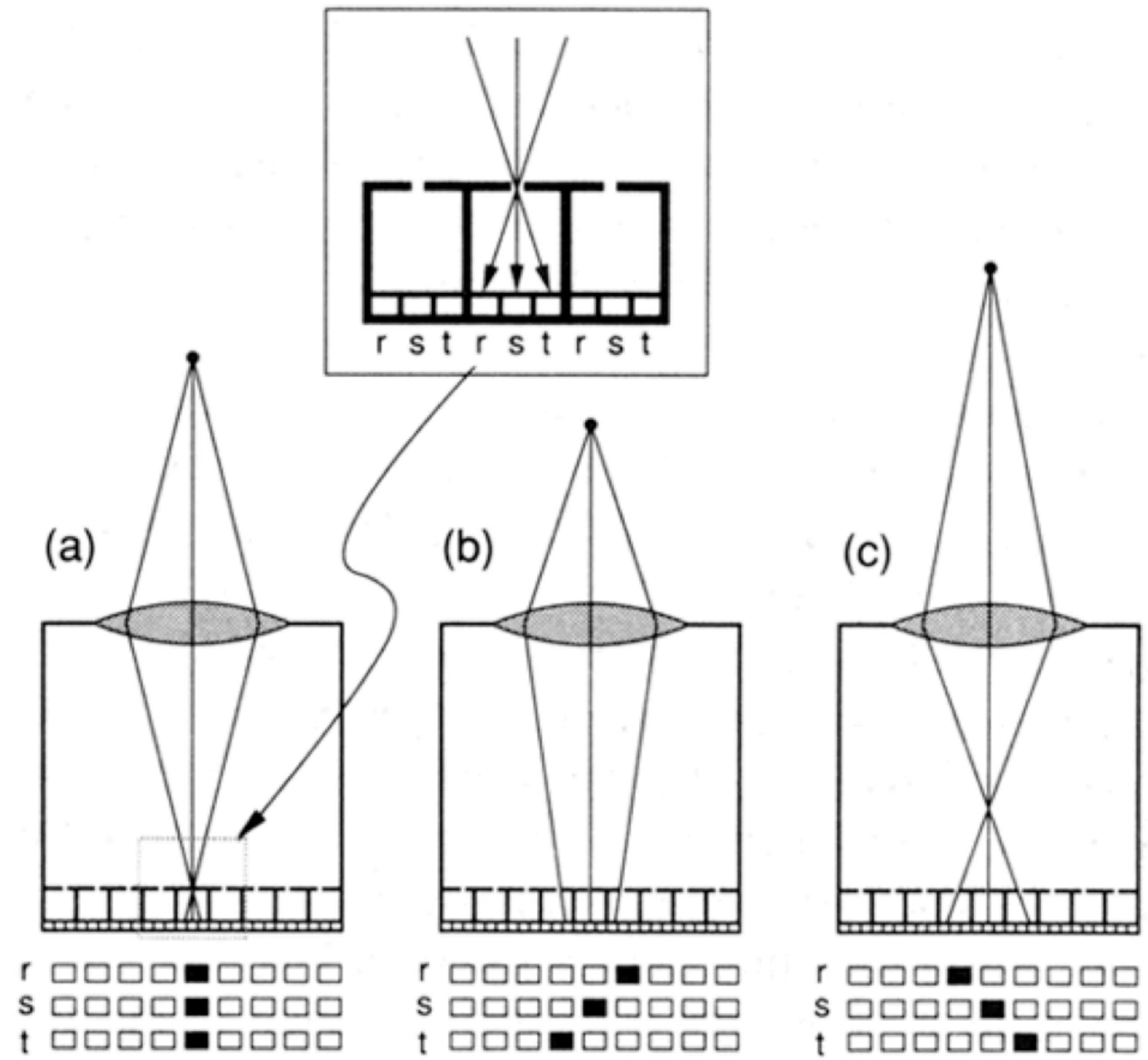


Fig. 5. Array of miniature pinhole cameras placed at the image plane can be used to analyze the structure of the light striking each macropixel.

The resulting shift that is captured by the underlying array of pixels, under the micro lens. (In the diagram, a pinhole camera / aperture is shown.)

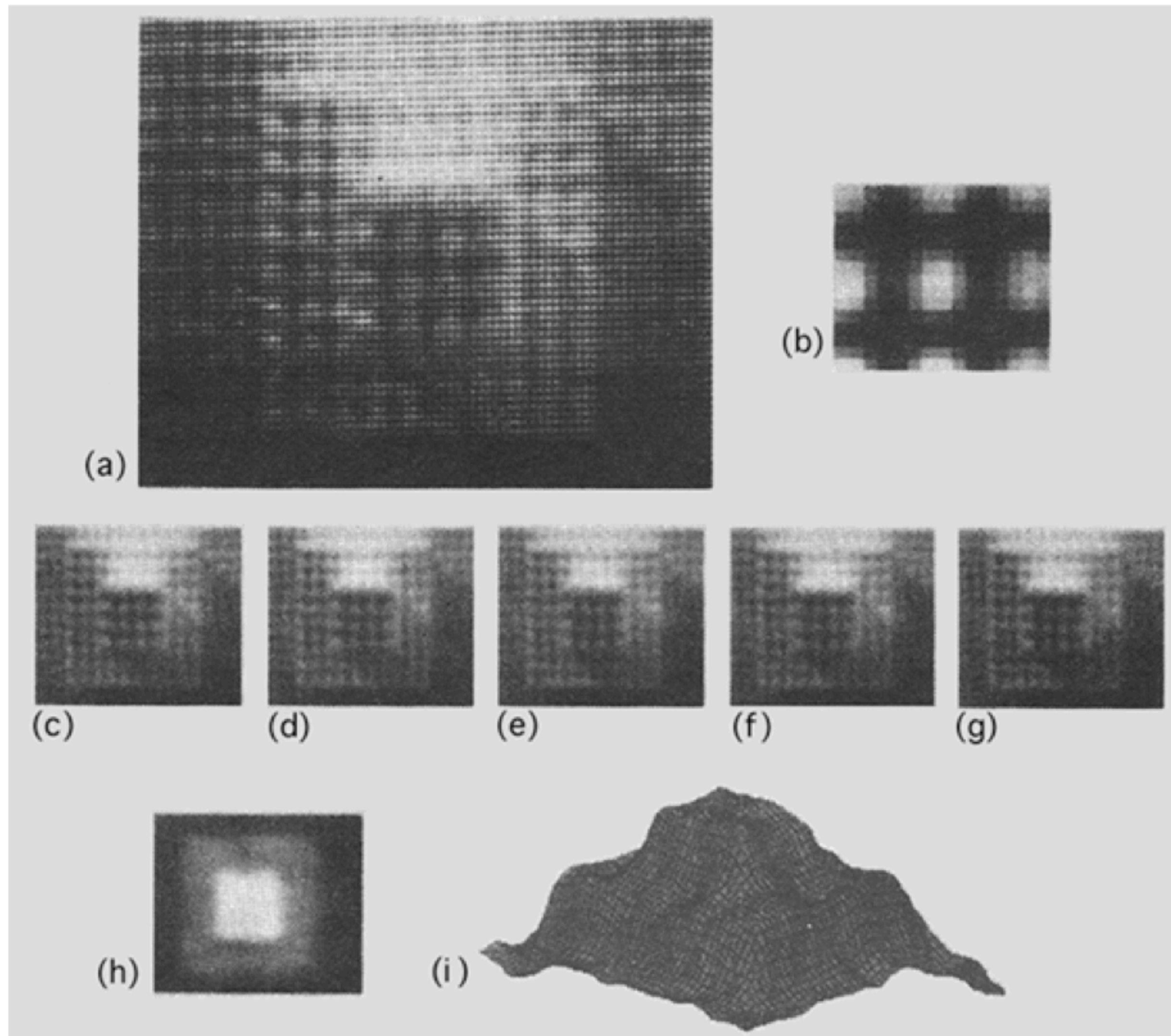


Fig. 7. (a) Digitized image of a lego pyramid, taken with the plenoptic camera. (b) enlarged section of the image, showing the macropixels. (c)-(g) set of subimages taken from virtual viewpoints traversing the lens aperture horizontally; (h) depth map; (i) wire-frame surface plot of the depth map.

The captured output image, consisting of multiple sub images underneath each micro lens.

Summary

- The era of the digital light sensor (for digital imaging and video) began with the introduction of the photo diode.
- A detailed description (regarding the operation of a photo diode) was given, at the device physics level.
- Because of architectural reasons, the commonality of manufacturing with silicon circuits, and the introduction of the pinned photo diode, CMOS became the dominant sensor, vs CCD.

Summary

- Sensor noise, sensitivity and dynamic range are key parameters of concern.
- Making a larger sensor with larger pixels, can greatly improve these performance parameters.
- In lieu of this solution, computational photography can also be used to improve performance.
- A significant performance boost resulted from changing the fabrication process from front side illuminated (FSI) sensors to back side illuminated sensors (BSI).
- Finally, camera auto focus has received an upgrade, with introduction of dual pixel / quad pixel auto focus.