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See Beyond Visible

Short Wavelength Infrared Introduction and Applications

- Short Wave Infrared
- Detectors
- Techniques & Applications
- Conclusion

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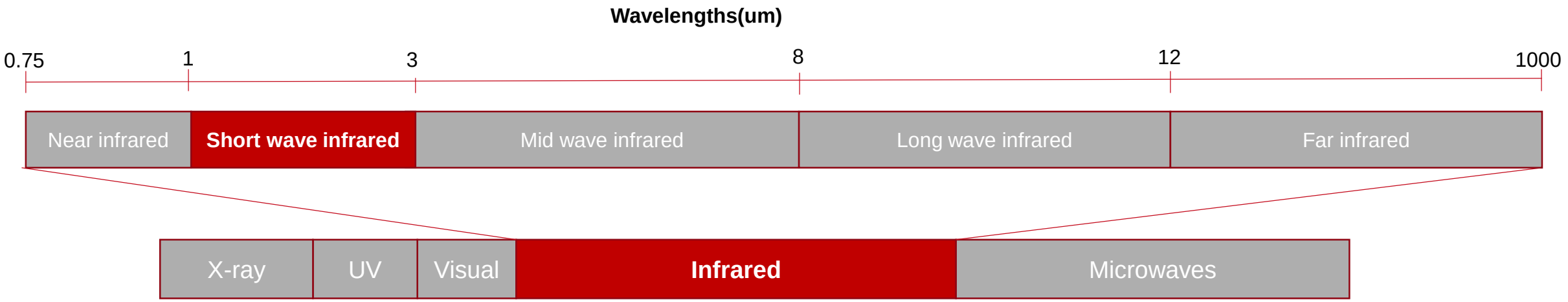
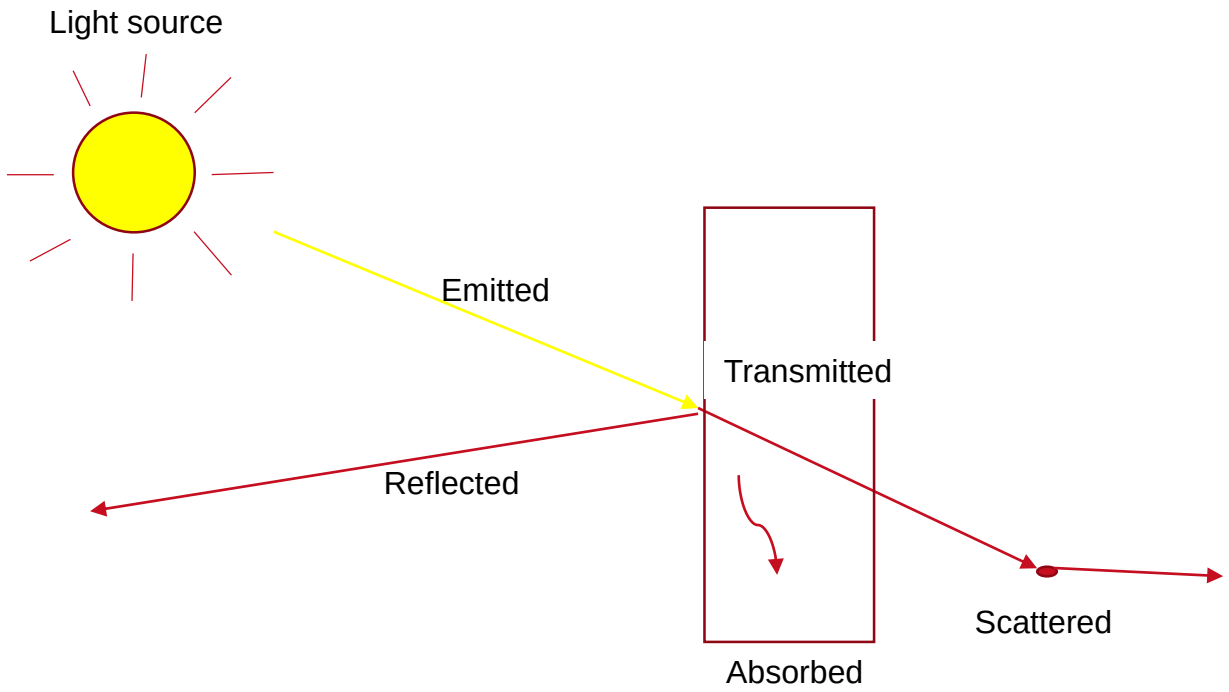
Shortwave Infrared

What is Short Wave Infrared?



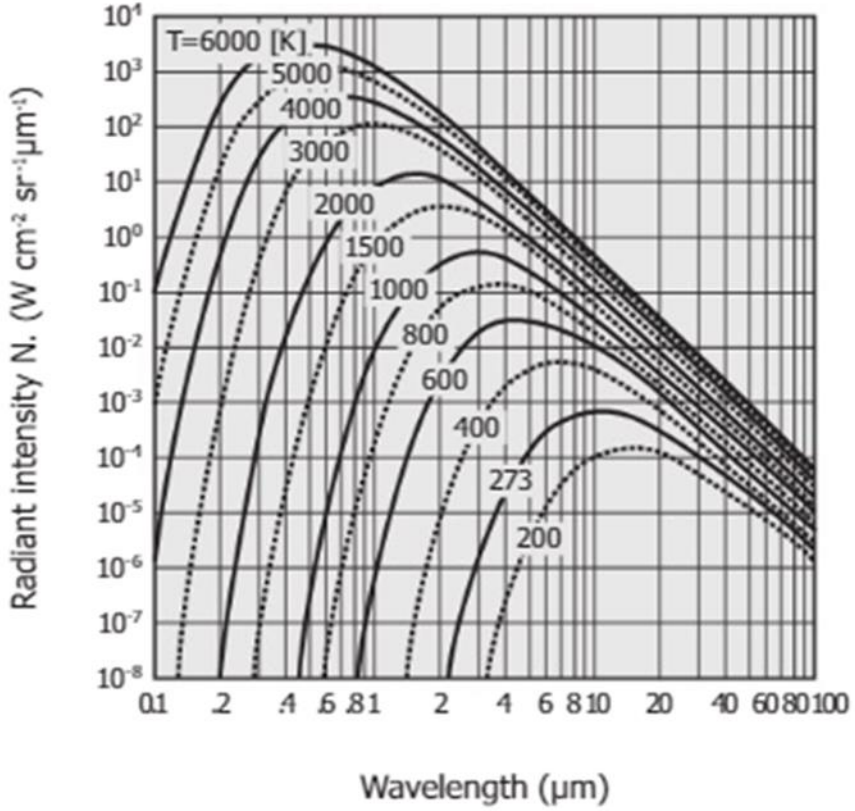
Shortwave infrared is defined from 1um – 3um.

Light



Why Short Wave Infrared?

Heat Detection



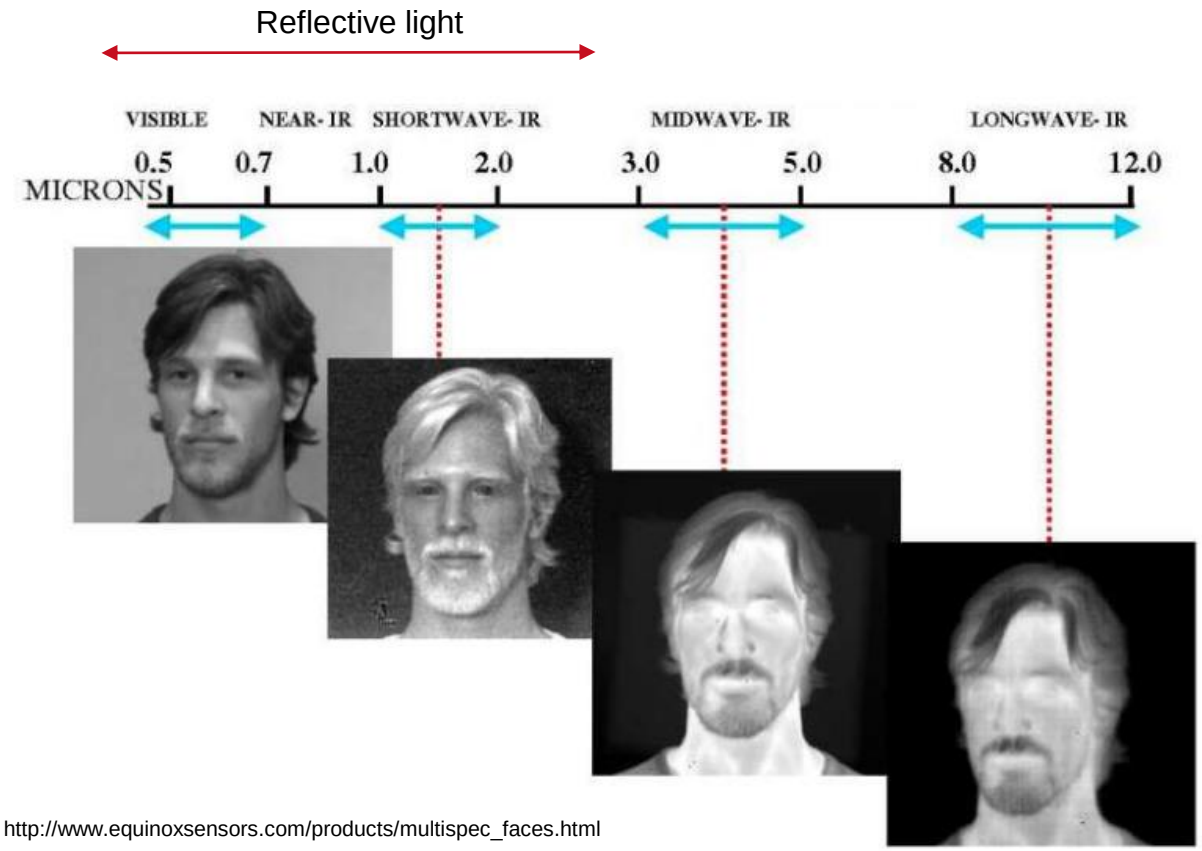
Black body radiation

Thermal radiation could be explained by black body curve calculated by Plank's law

**Radiant intensity - radiant flux emitted, reflected, transmitted or received, per unit*

Why Short Wave Infrared?

Reflective Light Detection



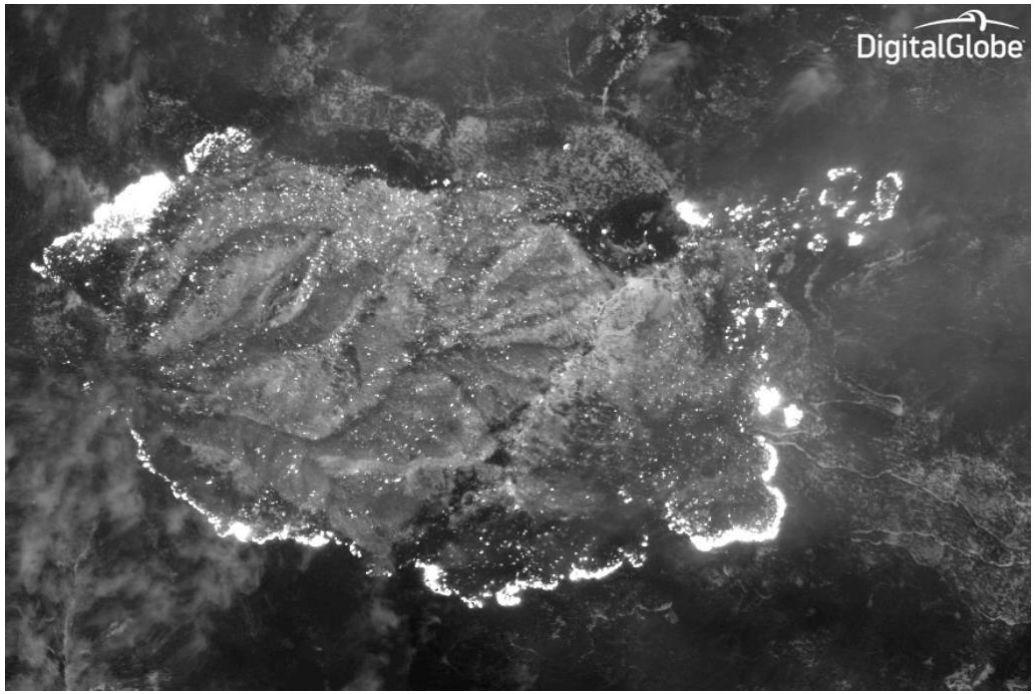
http://www.equinoxsensors.com/products/multispec_faces.html

Unlike MIR and LWIR, SWIR is better in detecting reflective light

Why Short Wave Infrared?

Clear Image with Heat Detection

VIS



SWIR

Compared to VIS

- Better heat detection
- Less scattering

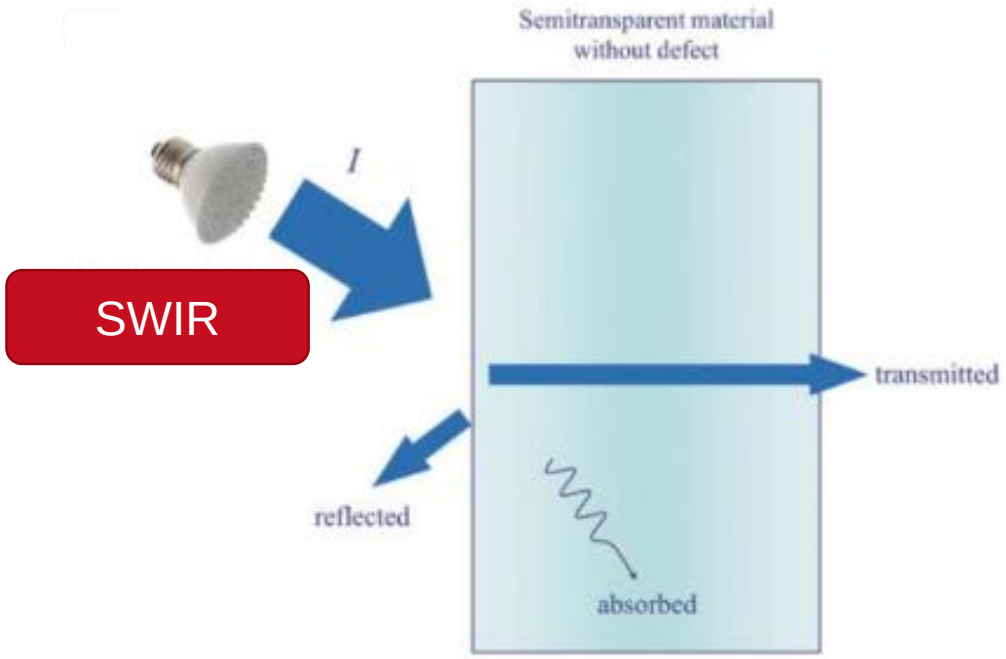
Compared to MIR/LWIR

- Better reflective image

https://blog.maxar.com/earth-intelligence/2014/revealing-the-hidden-world-with-shortwave-infrared-swir-imagery

Why Short Wave Infrared?

See Through The Surface



See through paint

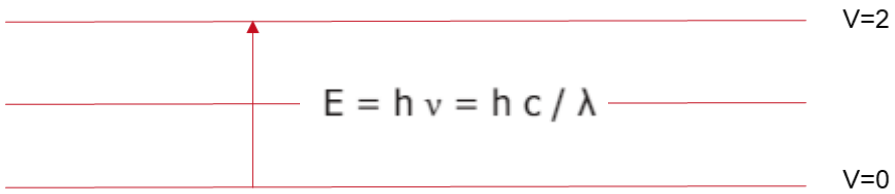
See through plastic

- Short wave infrared could transmit through surfaces such as silicon, plastic and paint.

*Integrated Imaging and Vision Techniques for Industrial Inspection: Advances and Applications (Advances in Computer Vision and Pattern Recognition)
by Zheng Liu, Hiroyuki Ukida, et al.

Why Short Wave Infrared?

Water Absorption



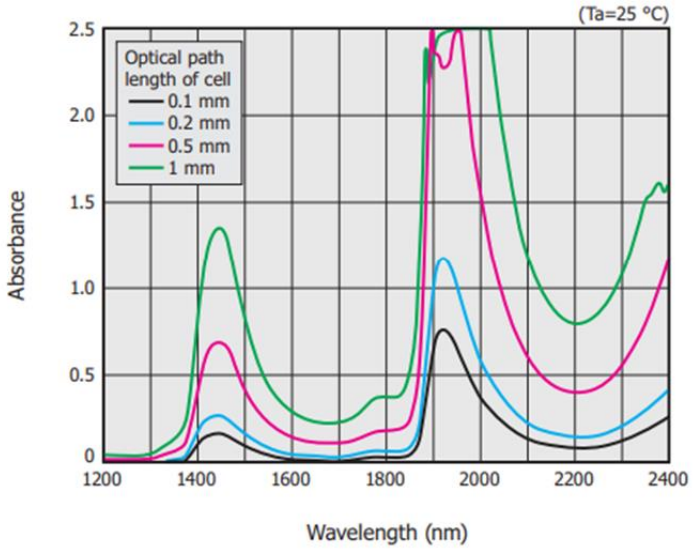
Light comes in as an energy excites the water molecule

Molecule absorbs and vibrates

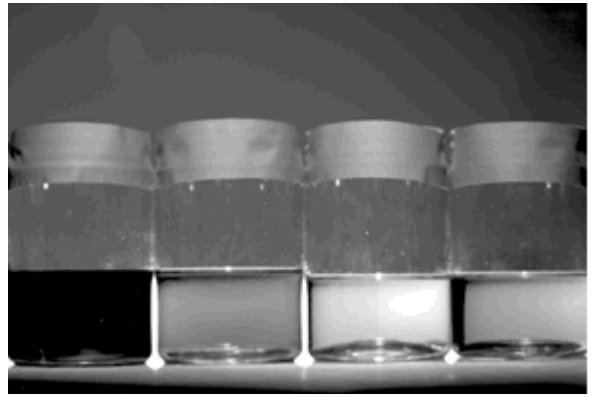
https://en.wikipedia.org/wiki/Electromagnetic_absorption_by_water

Why Short Wave Infrared?

Water Absorption



Water, Ethanol, Mineral oil, and Isohexane @ VIS



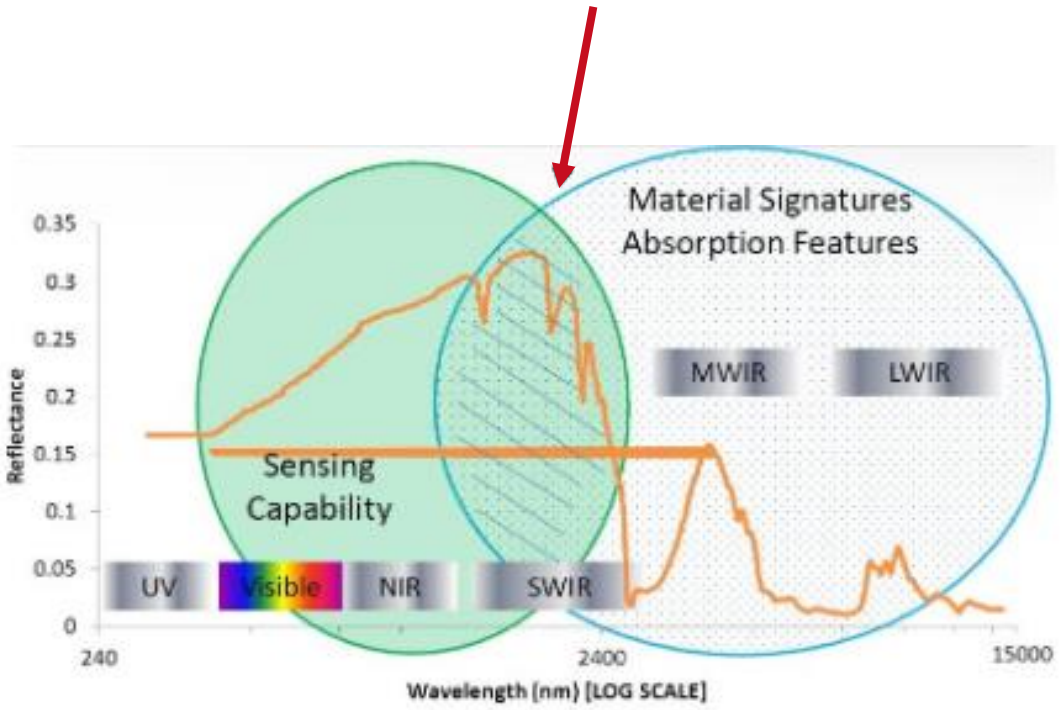
Water, Ethanol, Mineral oil, and Isohexane @ SWIR (1450nm)

In Shortwave infrared water absorbs the light at 1100nm, 1450nm, 1700nm and 2700nm

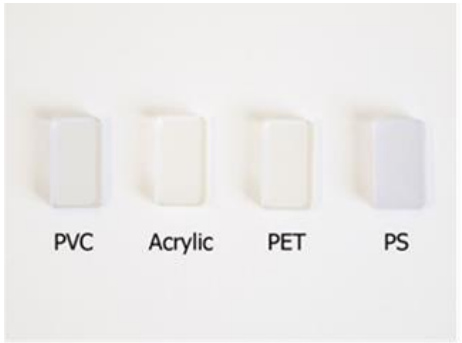
Why Short Wave Infrared?

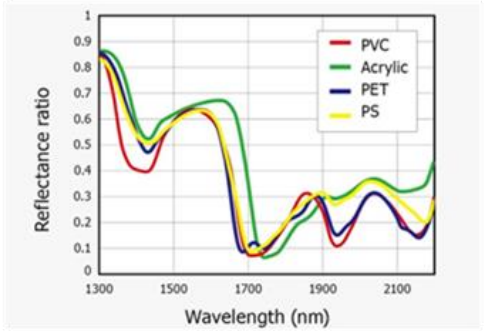
Compound identification

SWIR is a Sweet spot to identify materials



https://www.geoimage.com.au/SWIR%20Series/what-is-swir

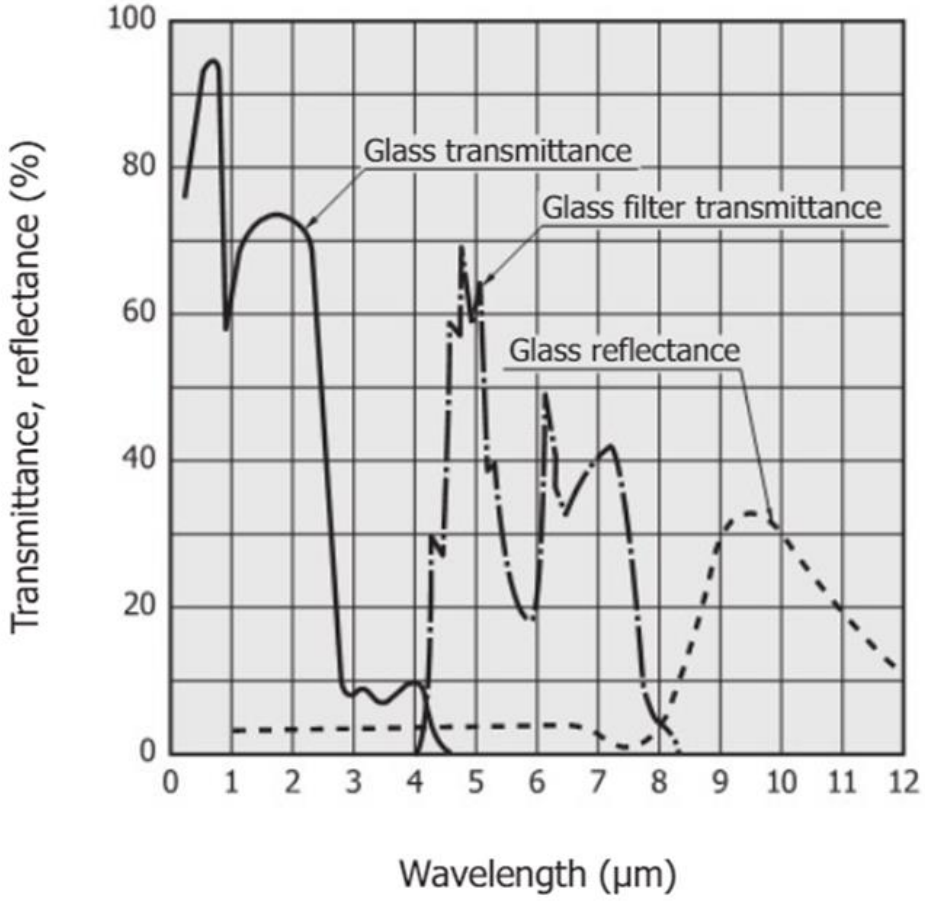




Easy to identify different materials, such as plastic

Why Short Wave Infrared?

Glass is Transmissive



Unlike MIR/LWIR, SWIR could still use glass without special coating

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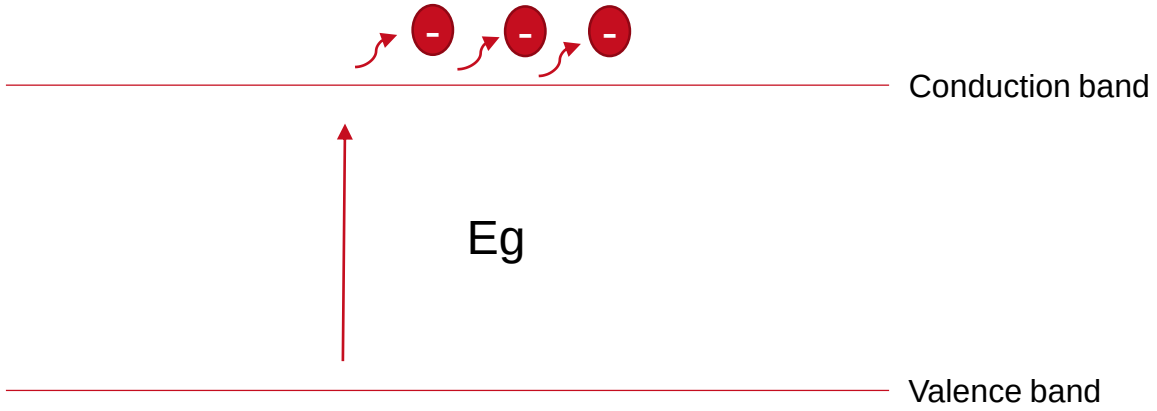
Detectors

How Do We Detect Shortwave Infrared?

Why Can't We Use Silicon?



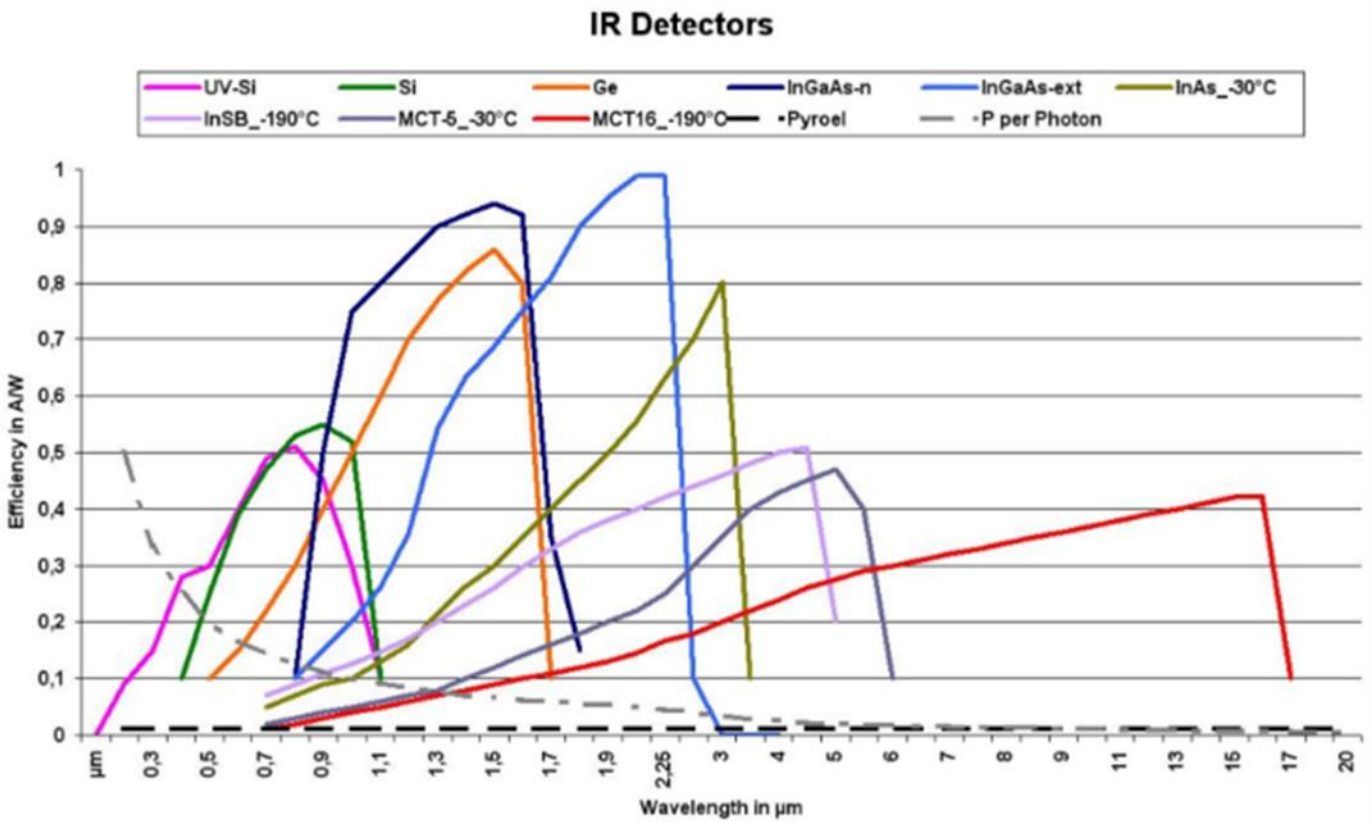
For detectors to excite the electrons, the incident light energy (E=hv) must be higher than the energy gap.

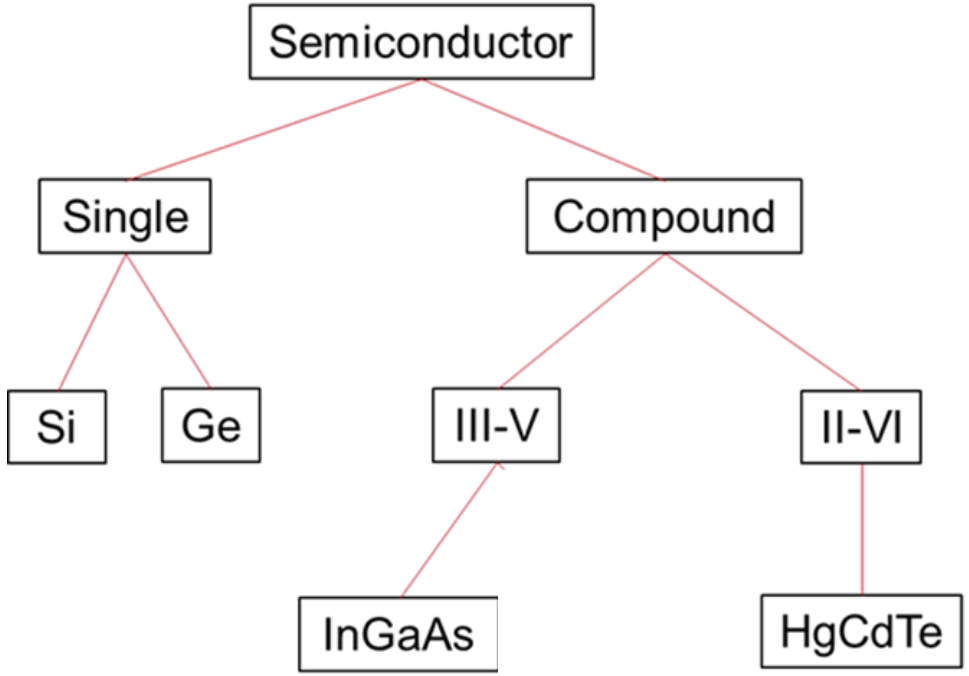
Silicon's energy gap
Eg = 1.11 (eV)

Silicon
λ = 1.1 (um)

How Do We Detect Shortwave Infrared?

Compound Semiconductor Photosensors

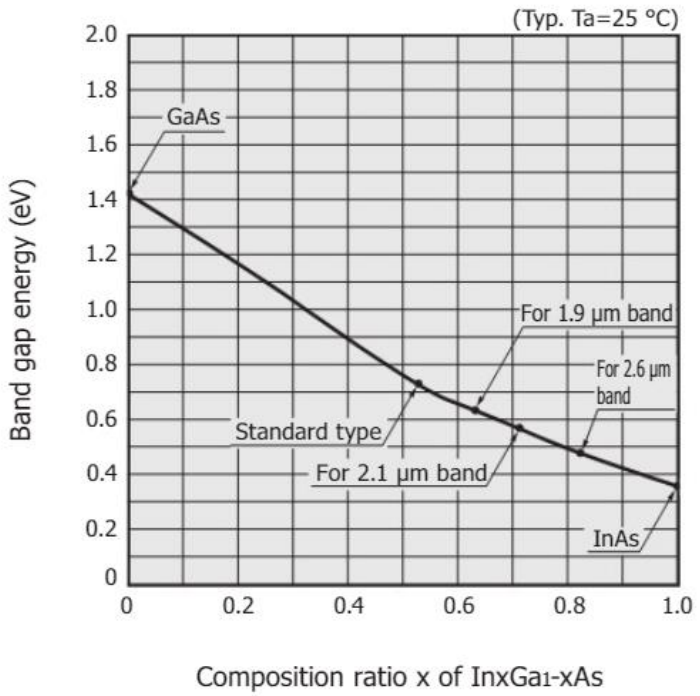


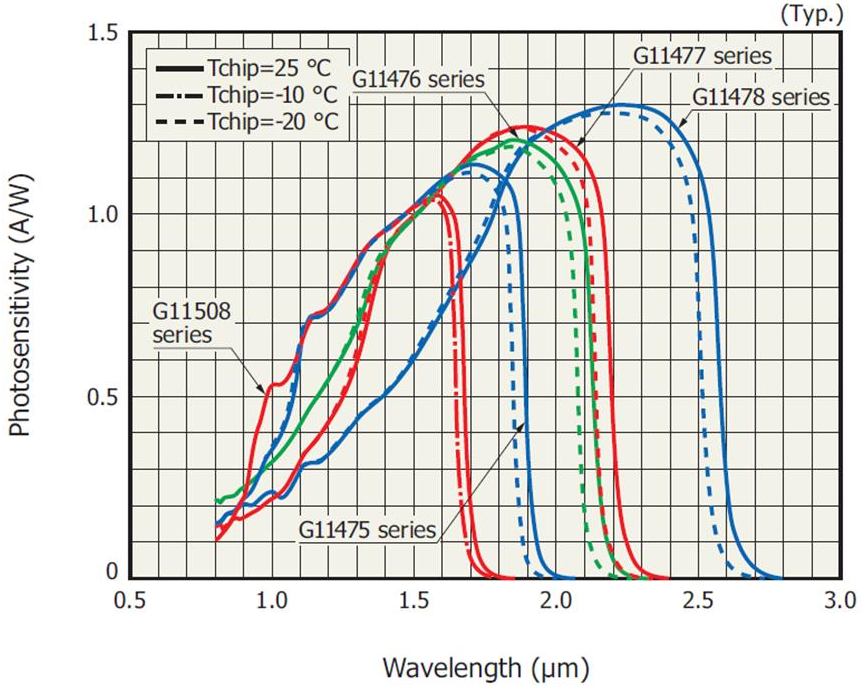


InGaAs and HgCdTe are the most commonly used photosensors for Shortwave infrared detection

How Do We Detect Shortwave Infrared?

InGaAs (0.9um – 2.6um)





Example of InGaAs QE chart with different cutoff wavelength

InGaAs is the most common compound semiconductor photosensor used in shortwave infrared.

How Do We Detect Shortwave Infrared?

Standard InGaAs v.s. Extended InGaAs

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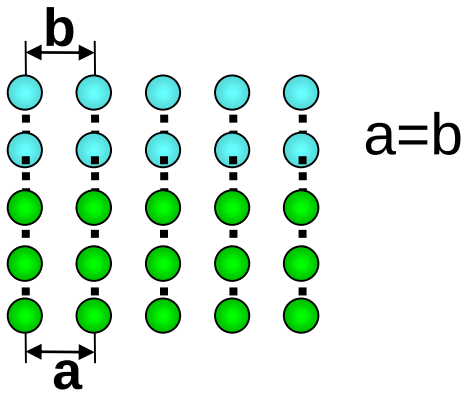
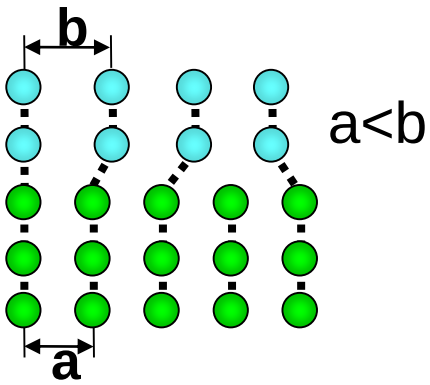
Standard InGaAs



Matched lattice

Extended InGaAs



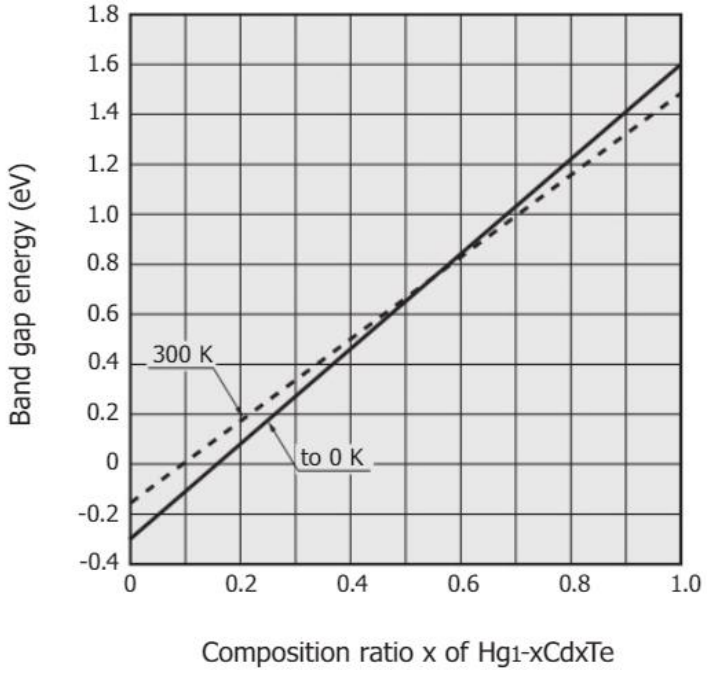
Unmatched lattice

	$In_xGa_{1-x}As$ (x=0.53)	$In_xGa_{1-x}As$ (x=0.82)
Band gap energy	0.73eV	0.48eV
Cutoff wavelength	1.7um	2.6um

- **Standard InGaAs has a cutoff wavelength of 1.7um, extended InGaAs cutoff wavelength could be up to 2.6um.**
- **Extended InGaAs requires high quality wafer with reduce of thin film quality for production.**
- **Due to the improvement of the fabrication process, more extended InGaAs products are showing up in the market.**

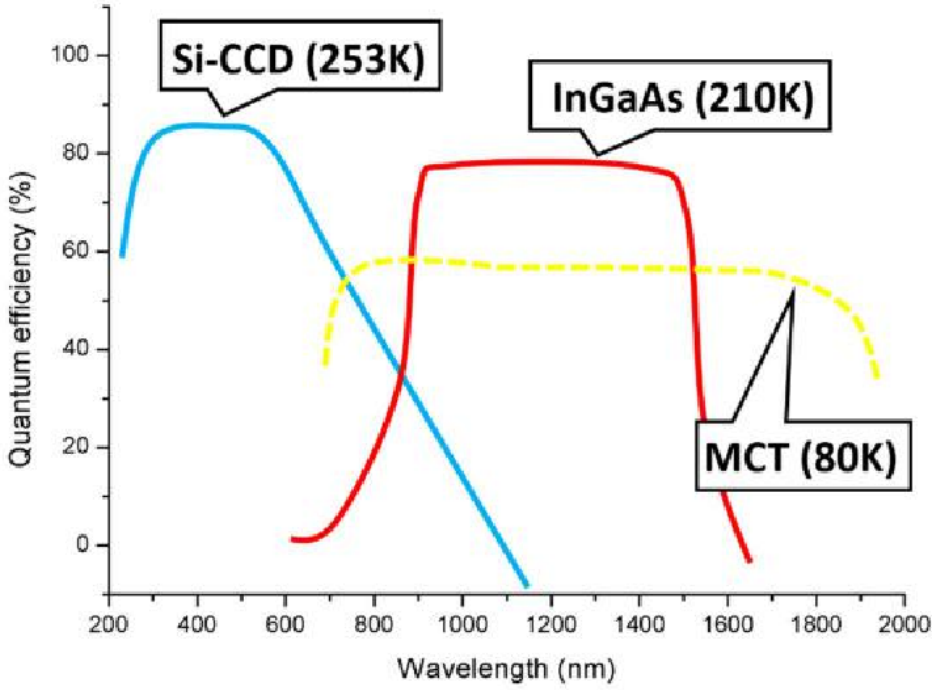
How Do We Detect Shortwave Infrared?

HgCdTe/ MCT (1um – 2.5um)



$$Eg = 1.59x - 0.25 + 5.23 \times 10^{-4} T (1 - 2.08x) + 0.327x^3$$

x: composition ratio of $Hg_{1-x}CdxTe$
T: absolute temperature



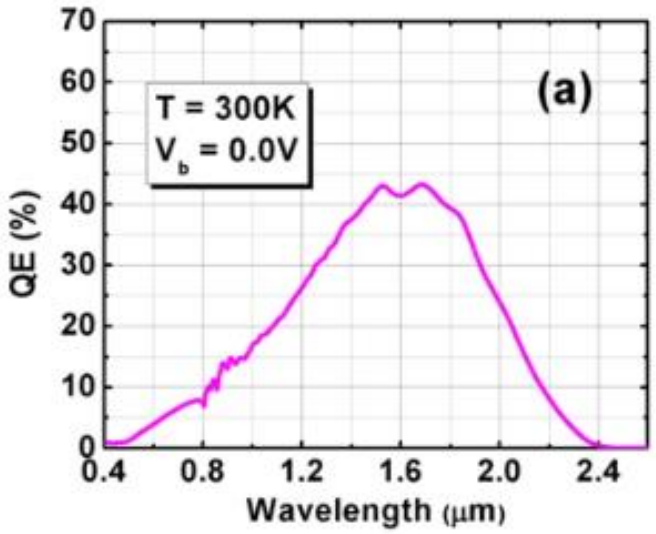
**Example of MCT spectral response range compared to standard InGaAs*

- HgCdTe provides continuously adjustable cutoff wavelength coverage from **SWIR to LWIR and further.**
- Slower frequency response than InGaAs.
- Extremely brittle

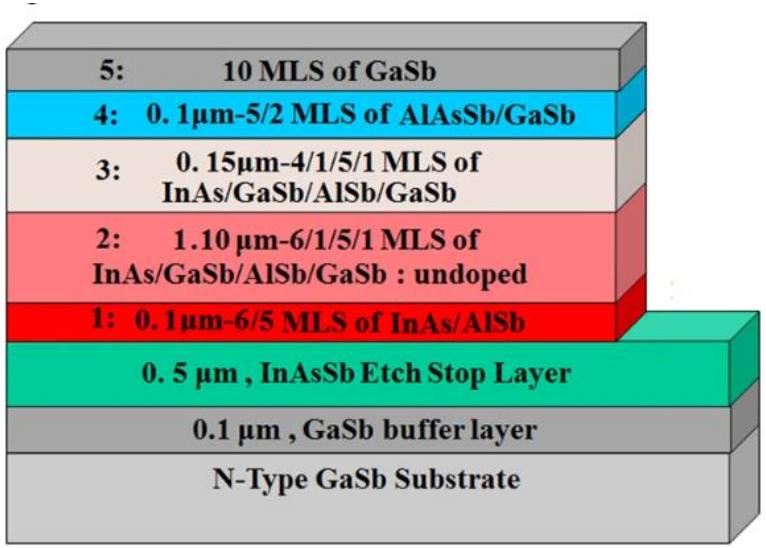
Reference
https://ieeexplore.ieee.org/document/8452497/;jsessionid=Y5cL7--OiouVmXkVT8Sh21P1pHVMfPughV_eWGg2vp2zpbBUecwf!-1086414555

How Do We Detect Shortwave Infrared?

Type 2 Super Lattice (0.4um – 2.4um)



Example of T2SL quantum efficiency curve



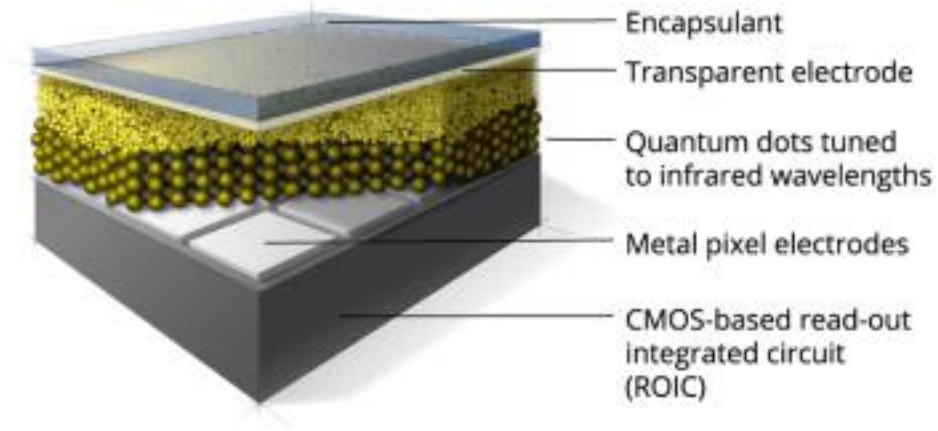
Example of Schematic diagram of the e–SWIR photodetector with a bandstructure–engineered photo–generated carrier extractor and an etch stop layer on GaSb substrate.

- Broad bandwidth
- Lower quantum efficiency compared to InGaAs and MCT.

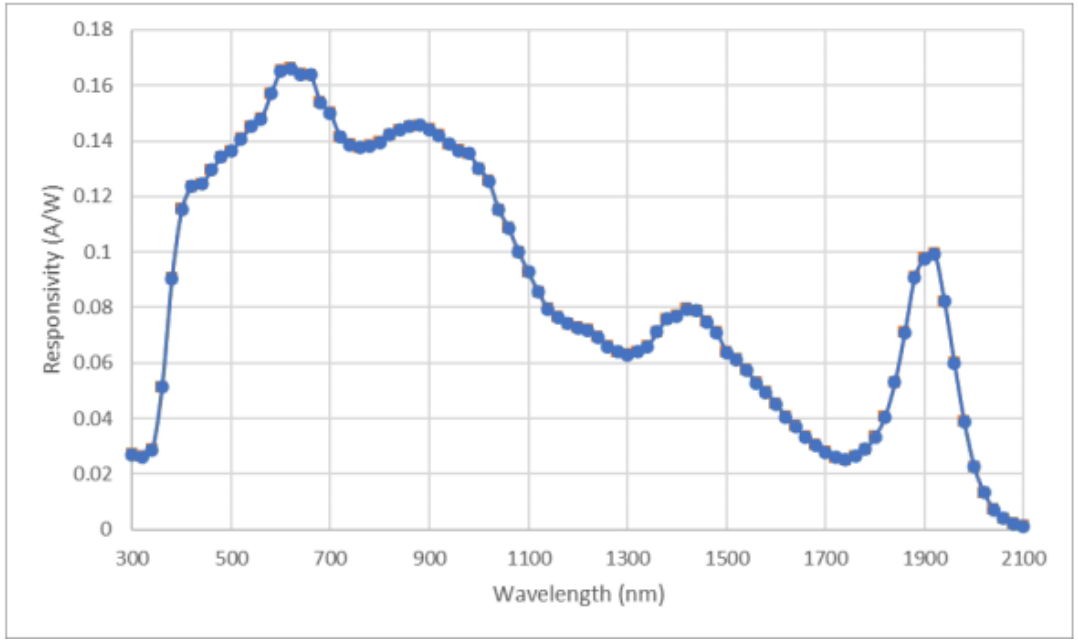
Reference -
https://www.nature.com/articles/s41598-019-41494-6
http://minerva-project.eu/wp-content/uploads/2013/07/MINERVA_IRN_008_A_WP6-T2SL-white-paper.pdf

How Do We Detect Shortwave Infrared?

Quantum Dot Infrared Photodetectors (0.3um – 2.1um)



Simplified conceptual schematic of colloidal quantum dot imager technology directly deposited on CMOS readout circuit



Quantum efficiency curve of QDIP

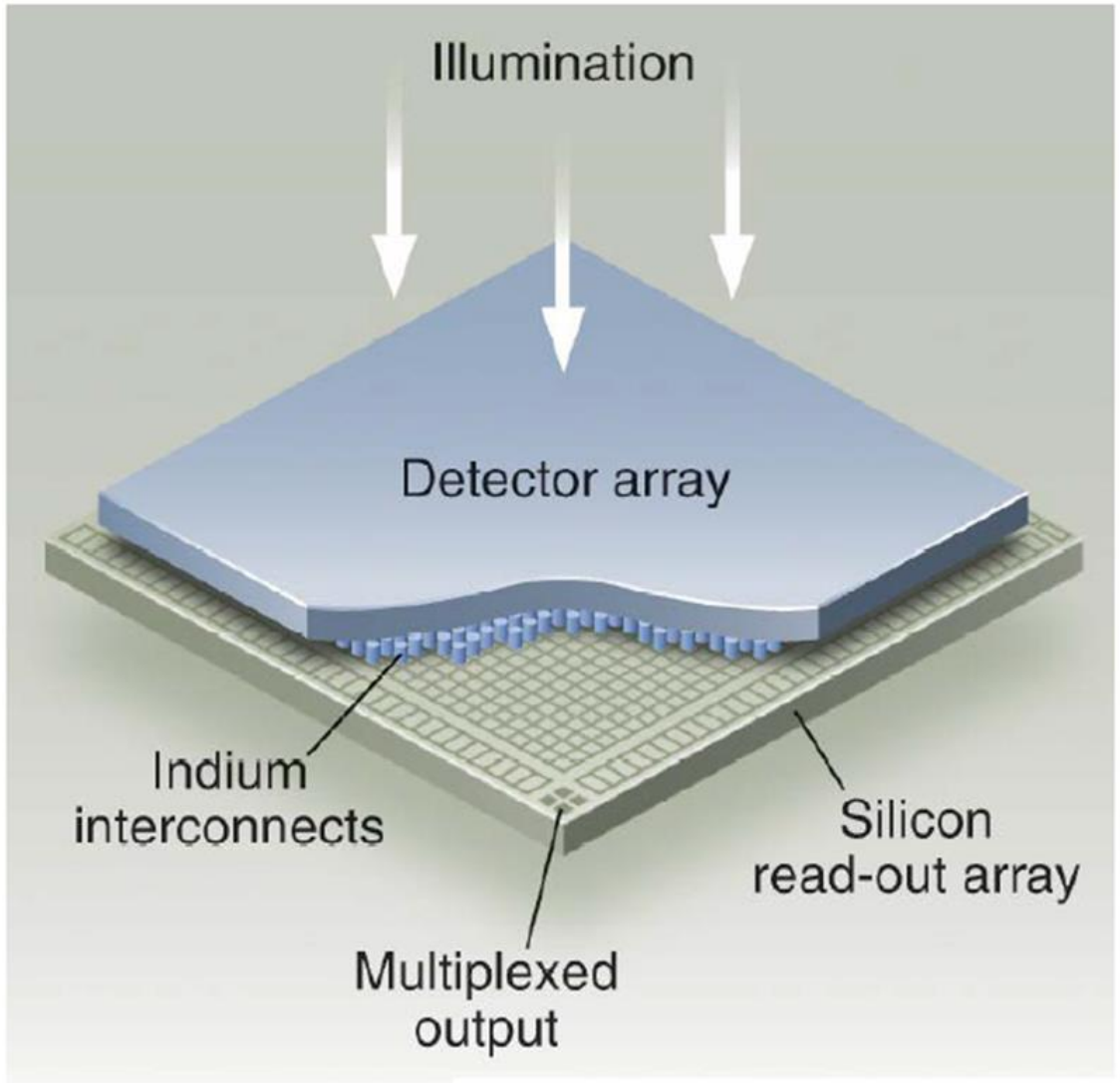
- Lower effected by temperature
- Scalable fabrication process.
- Lower quantum efficiency compared to compound semiconductors.

Reference

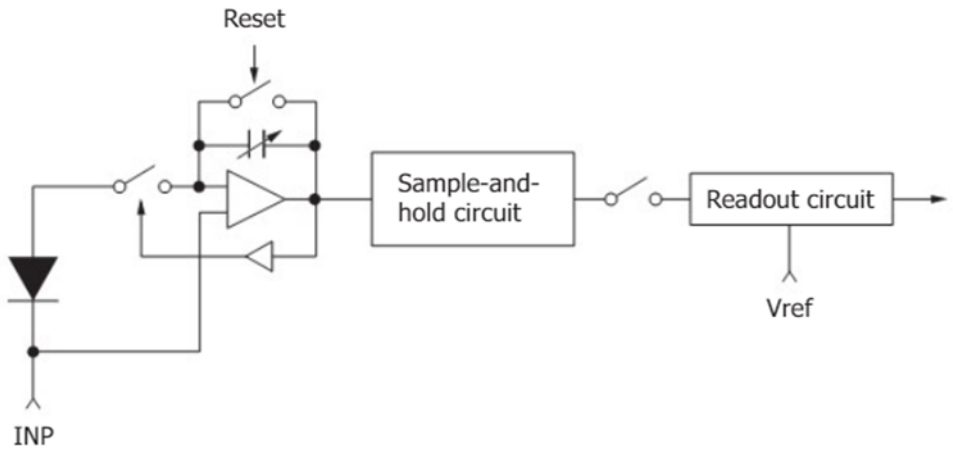
https://www.spiedigitallibrary.org/conference-proceedings-of-spie/11407/1140707/Extended-SWIR-high-performance-and-high-definition-colloidal-quantum-dot/10.1117/12.2559115.full

Compound Image Sensors

Compound Semiconductor Image Sensors



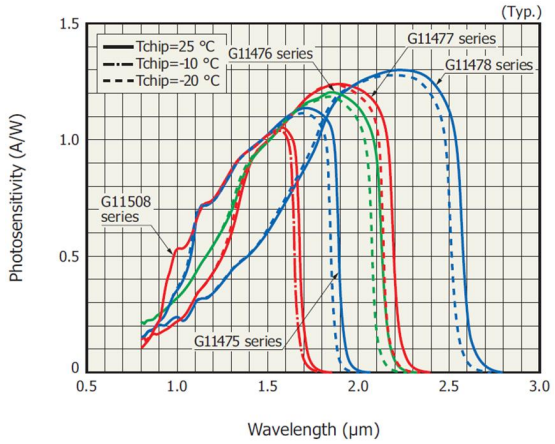
Example - InGaAs image sensor



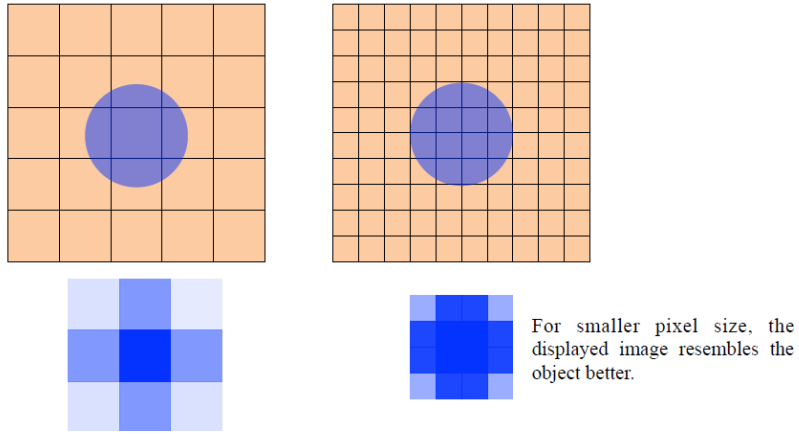
Equivalent circuit (For one pixel)

Compound Image Sensors

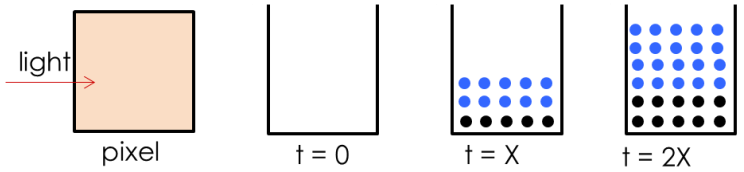
Compound Semiconductor Image Sensors Parameters



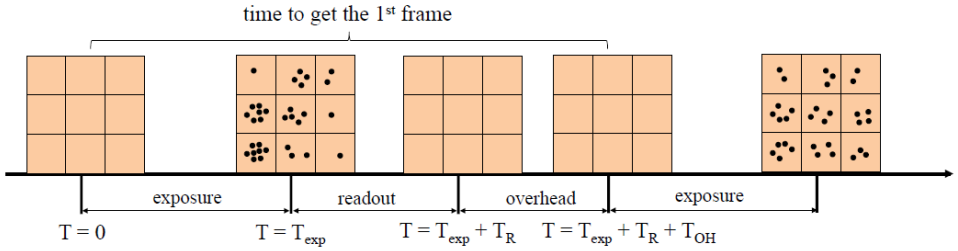
Photosensitivity



Resolution

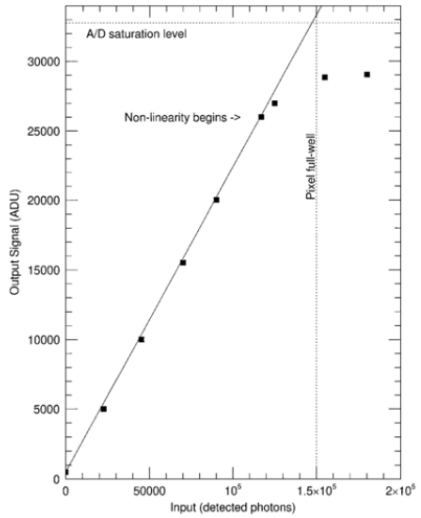


Dark current

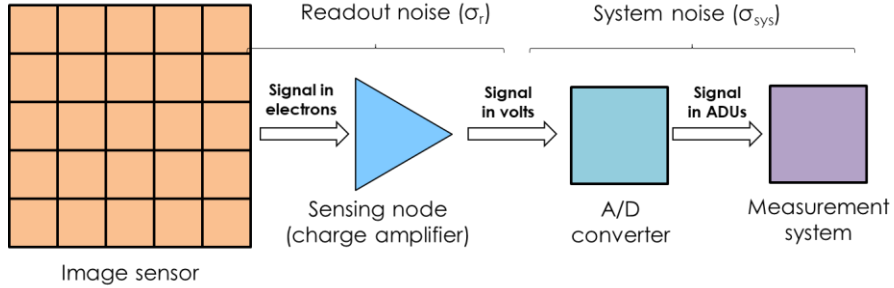


$$\text{frame rate [frames/s]} = 1(T_{exp} + T_R + T_{OH})$$

Frame rate/ Line scan rate



Linearity



Readout noise

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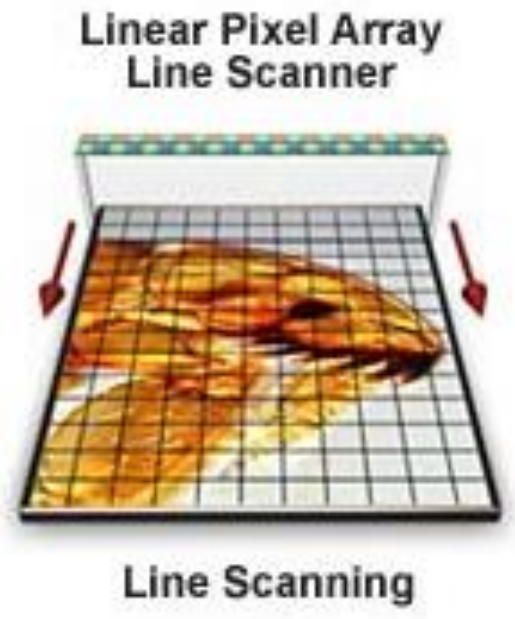
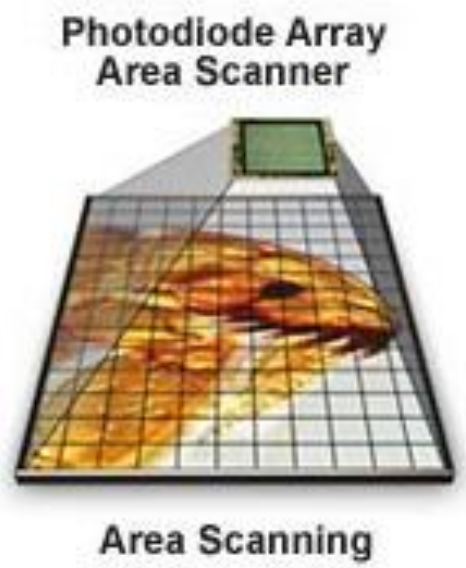
Techniques & Applications

SWIR Imaging



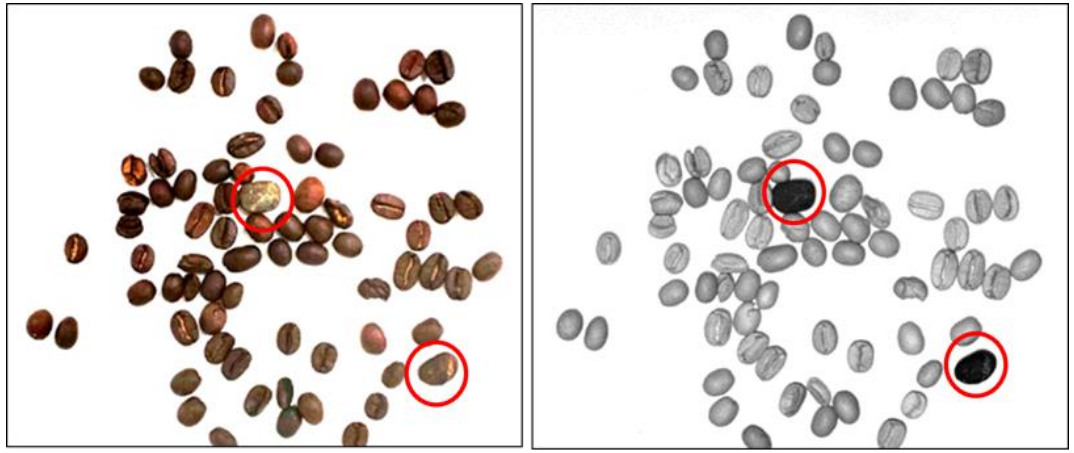


Benefits –

- Heat detection
- Moisture content spatial information
- Pass through hazard
- Pass through materials such as plastic or silicon surfaces

SWIR Line Scanning

Example – Agriculture Sorting



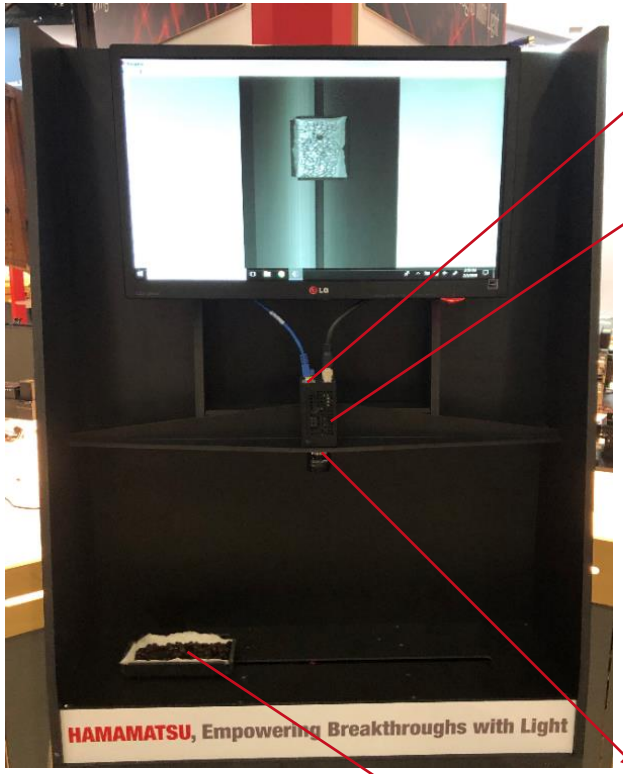
Rocks in Coffee Beans

Bruise apple

Agriculture sorting could benefit out of SWIR line scanning

SWIR Line Scanning

Example – Agriculture Sorting

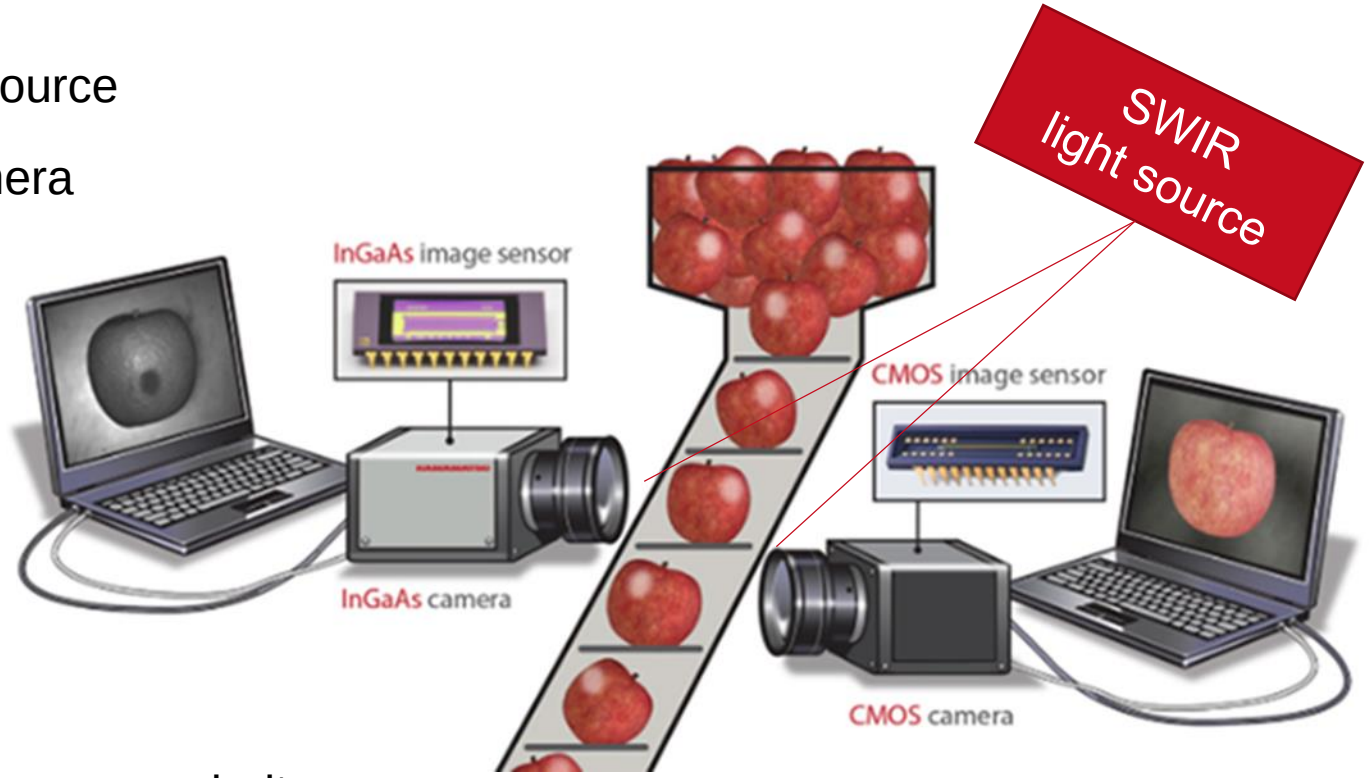


Light source

Camera

Running conveyor belt

Sample



Advantages –

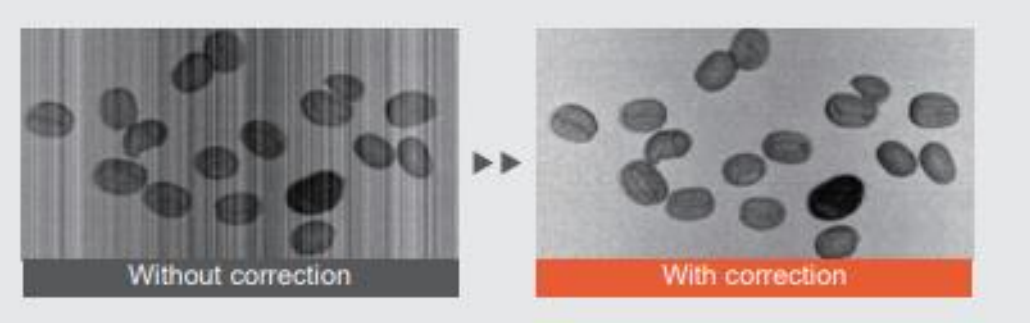
- Non destructive inspection
- High throughput operation
- Cost efficient

SWIR Line Scanning

Example – Agriculture Sorting

System Operation -

- High speed scanning



Cameras with correction functions could help image quality

Linear InGaAs image sensor

Linear InGaAs camera

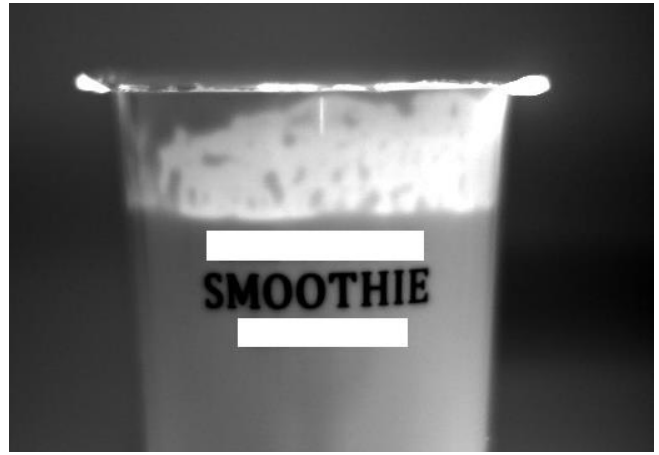
Sensor Parameters -

- Line scan rate
- Sensitivity
- Resolution

SWIR Line Scanning

Other Applications – Food Packaging

Liquid leakage (Moisture detection)

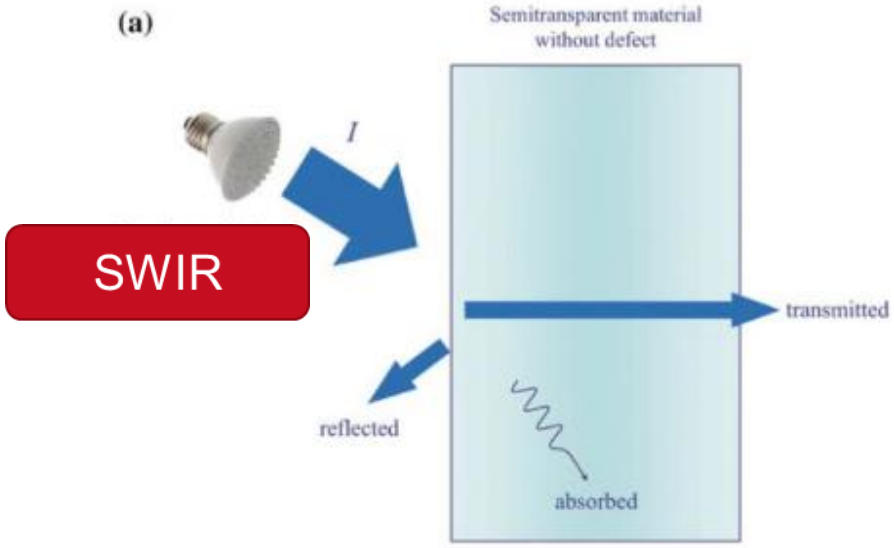


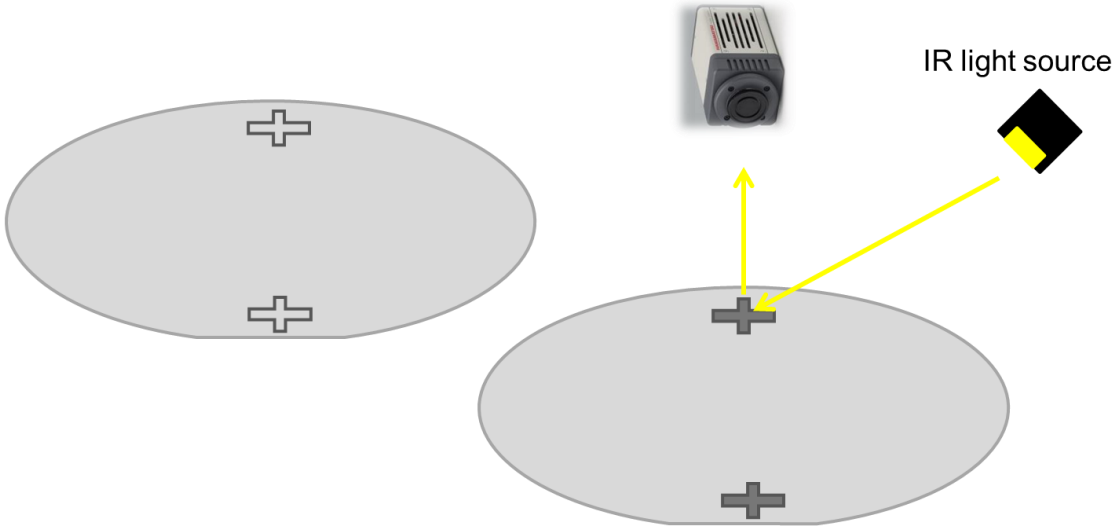
Drilling filling (See through plastic)

SWIR imaging could be used for packaging non-destructive testing.

SWIR Area Scanning

Example – Semiconductor Inspection





Checking the mark when 2 wafers are bonded.

Advantages -

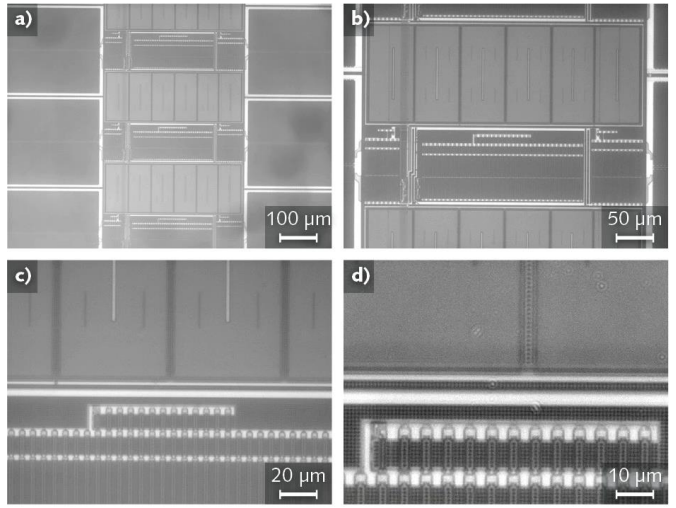
- Non destructive testing
- See through silicon to detect void defects
- Area image with one exposure

SWIR Area Scanning

Example – Semiconductor Inspection

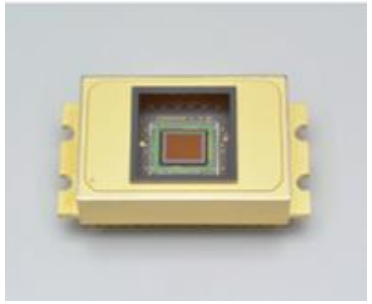
System Operation -

- Spatial information



**Semiconductor Wafer Inspection Under Microscope*

Area InGaAs camera



Area InGaAs image sensor

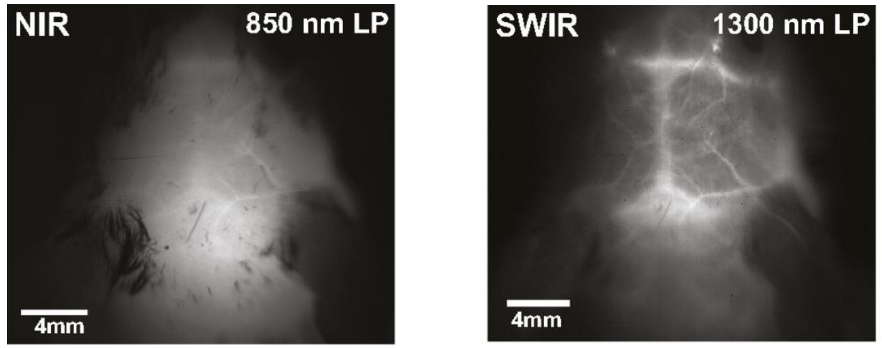
Parameters -

- Resolution
- Sensitivity
- Dark current
- Readout noise

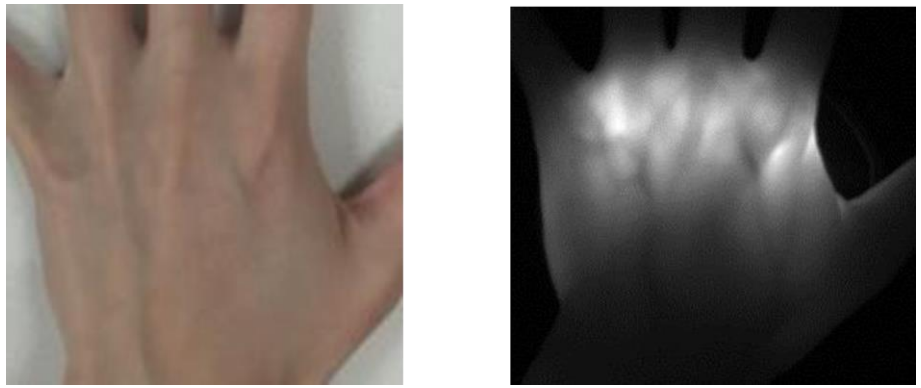
*https://www.laserfocusworld.com/optics/article/16548175/scientific-imaging-nearir-microscopes-image-through-silicon-without-damaging-the-finished-product

SWIR Area Scanning

Other Applications – Life Science



Brain vasculature



Palm vessel

Hamamatsu deep cooled camera
C12741-11

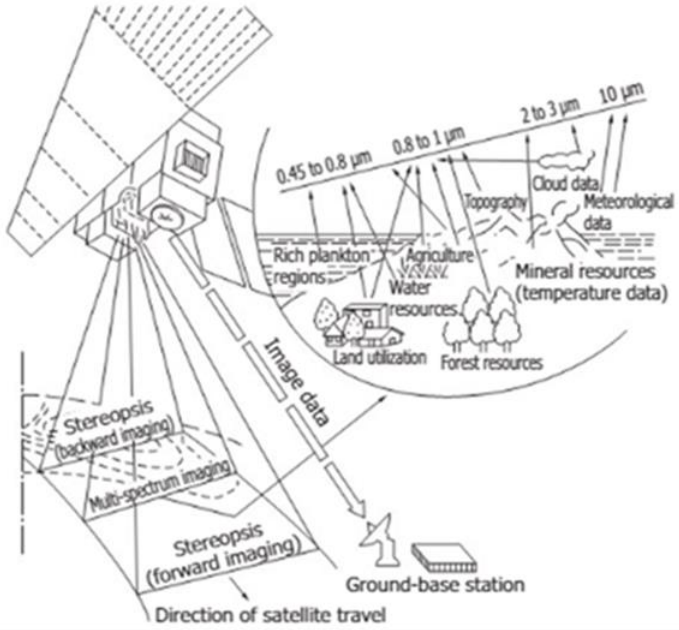
Low light imaging requirements

- High sensitivity
- Low dark current
- Low readout noise
- Deep cooled

https://www.biorxiv.org/content/10.1101/100768v1.full.pdf

Imaging Applications

Markets



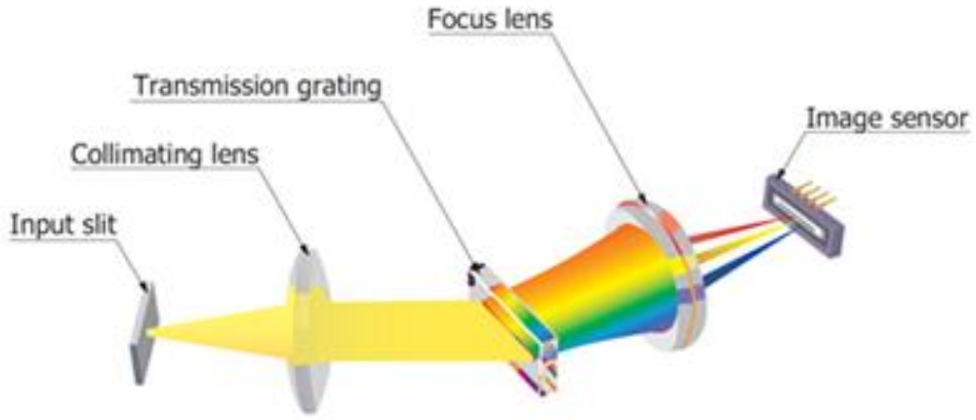
Optical system for resource survey

Remote sensing could be expected with extended wavelength

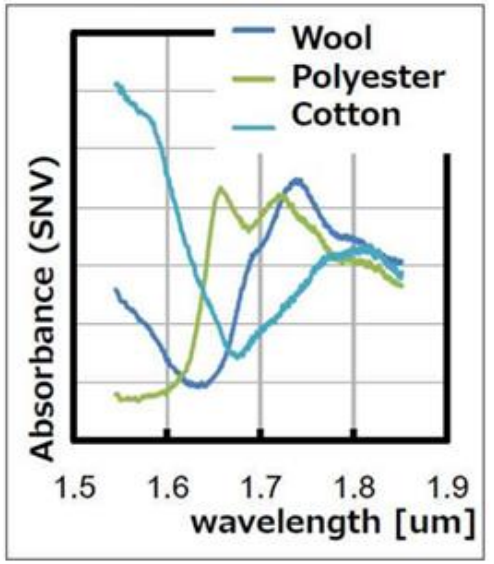
- Surveillance and security (1.0um – 1.7um)
- Food and packaging quality control (1.0um – 1.7um)
- Semiconductor quality control (1.0um – 1.7um)
- Cultural heritage (1.0um – 1.7um)
- Bio science (1.0um – **2.6**um)
- Mineral inspection (2.0um – **2.6**um)

Spectroscopy

Spectroscopy



Example of spectrometer



Spectroscopy is good at identifying man-made materials

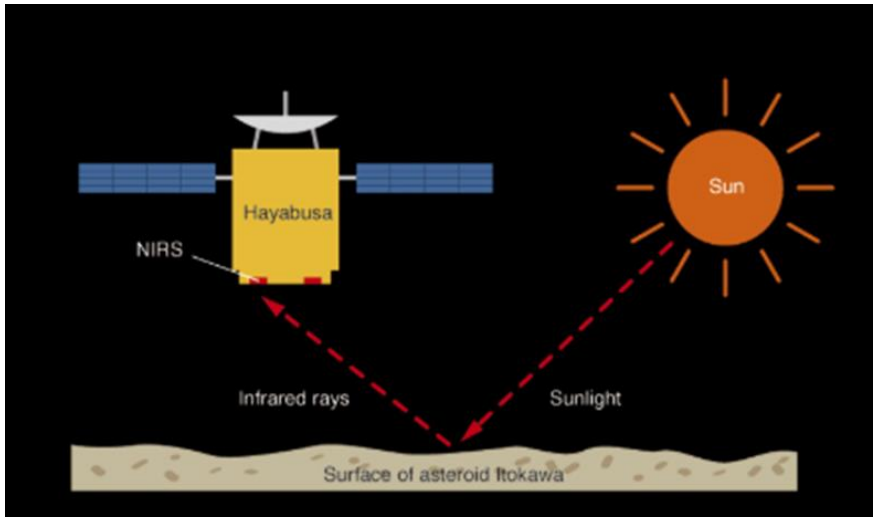
Benefits –

- Compound identification
- Capable to detect reflective light

Shortwave Infrared Spectroscopy

Example - Low Light Operation for Mineral Identification

Asteroid explorer Hayabusa



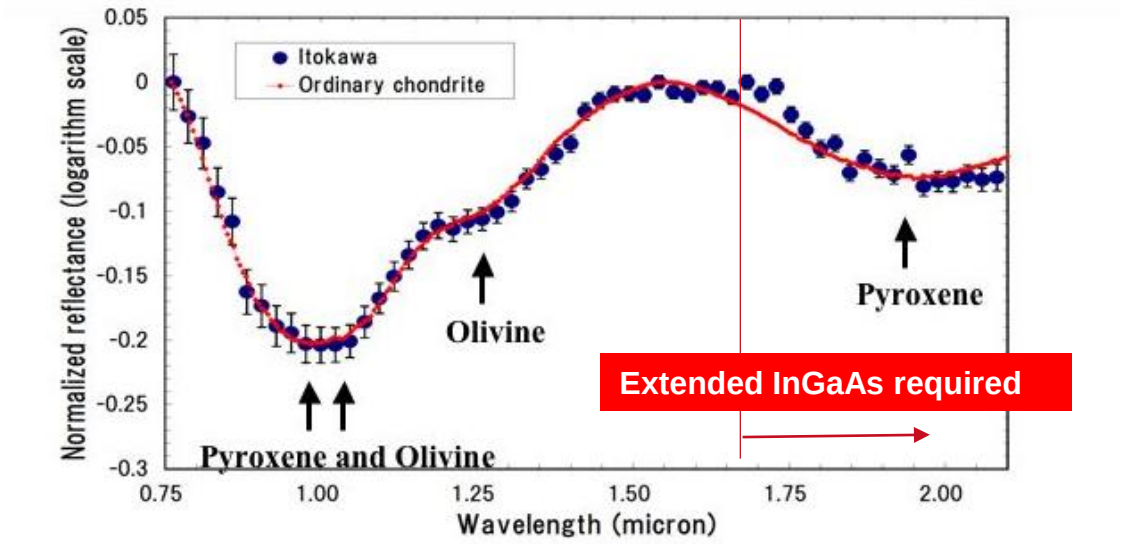
Spectrometer using sunlight to identify the surface

Operation

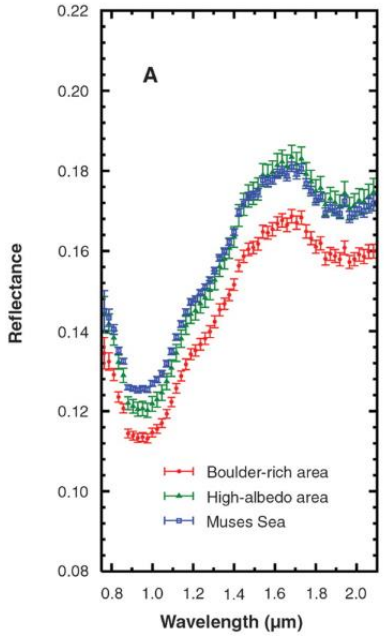
- Identify different minerals
- Low light detection

Shortwave Infrared Spectroscopy

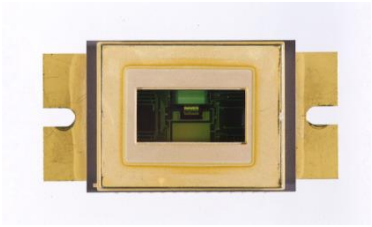
Example - Low Light Operation for Mineral Identification



Mineral identification



Minerals contained in different areas



Extended InGaAs image sensor used on the satellite

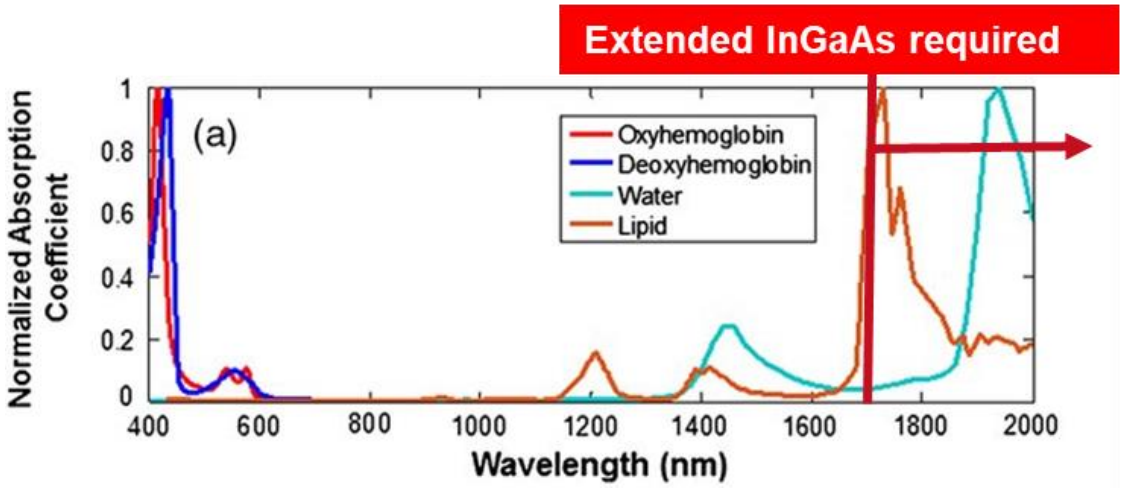
http://www.isas.jaxa.jp/e/snews/2006/0602.shtml

Parameters

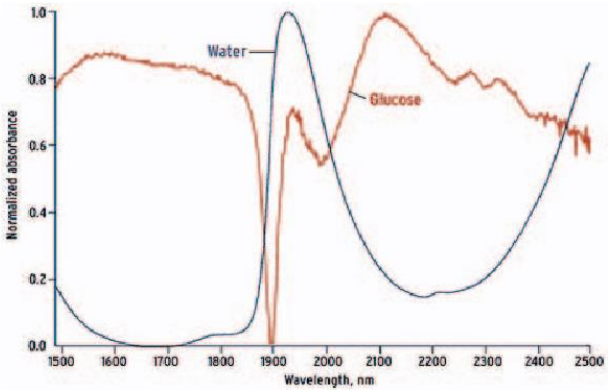
- Spectral response range
- Sensitivity
- Dark current
- Readout noise
- Dynamic range
- Linearity

Shortwave Infrared Spectroscopy

Other Applications – Life Science



Example of biological tissue absorbance spectrum



Example of Glucose absorbance spectrum

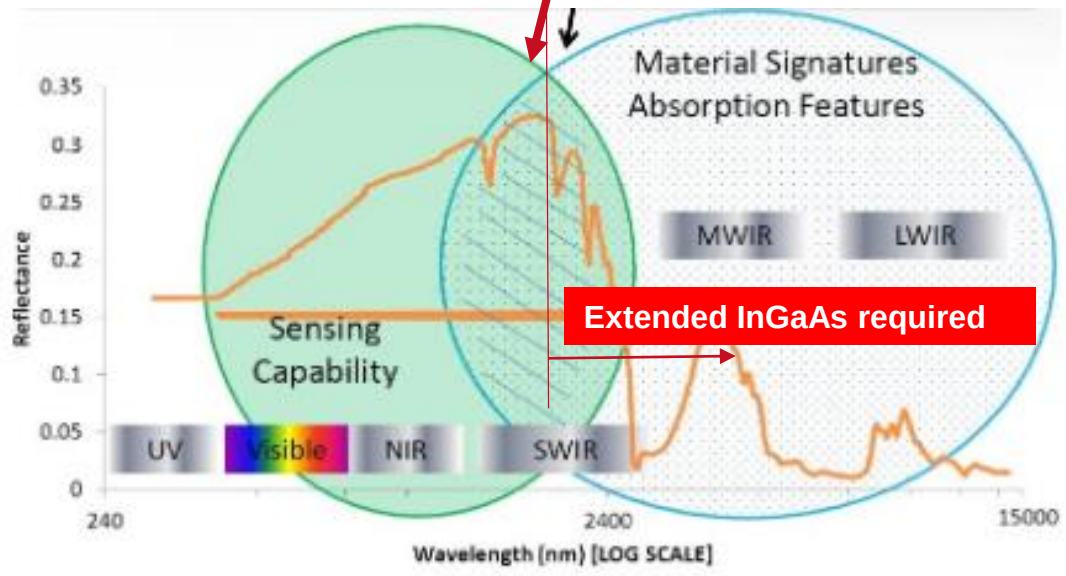
Non-invasive testing could benefit from SWIR range spectroscopy.

Reference 1 -
https://www.spiedigitallibrary.org/journals/Journal-of-Biomedical-Optics/volume-20/issue-03/030901/Review-of-short-wave-infrared-spectroscopy-and-imaging-methods-for/10.1117/1.JBO.20.3.030901.full?SSO=1
Reference 2 -
https://ieeexplore.ieee.org/document/7352586

Shortwave Infrared Spectroscopy

Markets

SWIR is a Sweet spot to identify materials



- Mineral identification (1.0um – **2.6**um)
- Material differentiation (1.0um – **2.6**um)
- Process control (1.5um – **2.6**um)
- Water content (1.0um – **1.9**um)
- Food quality control (1.0um – **2.6**um)
- Life science (1.0um – **2.6**um)

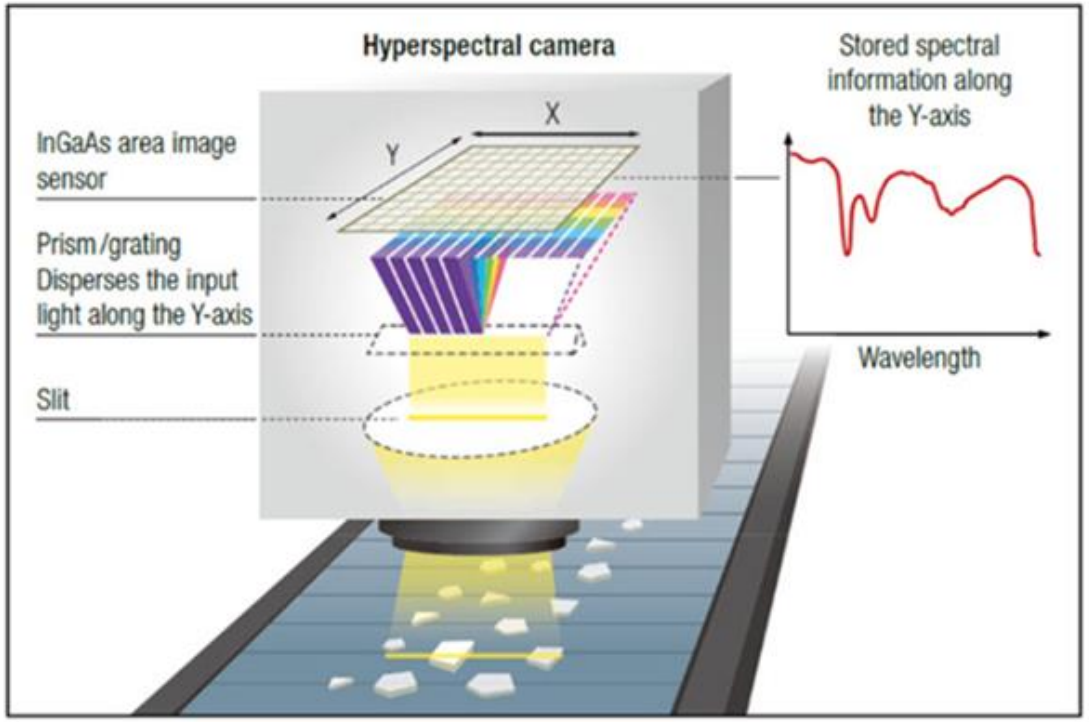
Reference
https://www.geoimage.com.au/SWIR%20Series/what-is-swir

Hyperspectral/ Multispectral Imaging

Technique

Spatial + Spectrum = Hyperspectral/ Multispectral Imaging

Hyperspectral Imaging >100 spectrum
Multispectral Imaging <100 spectrum



Example of pushbroom method

Operation

- Constant speed
- Collecting spatial information
- Collecting spectral information

SWIR Hyperspectral/ Multispectral Imaging

Example – Plastic Sorting

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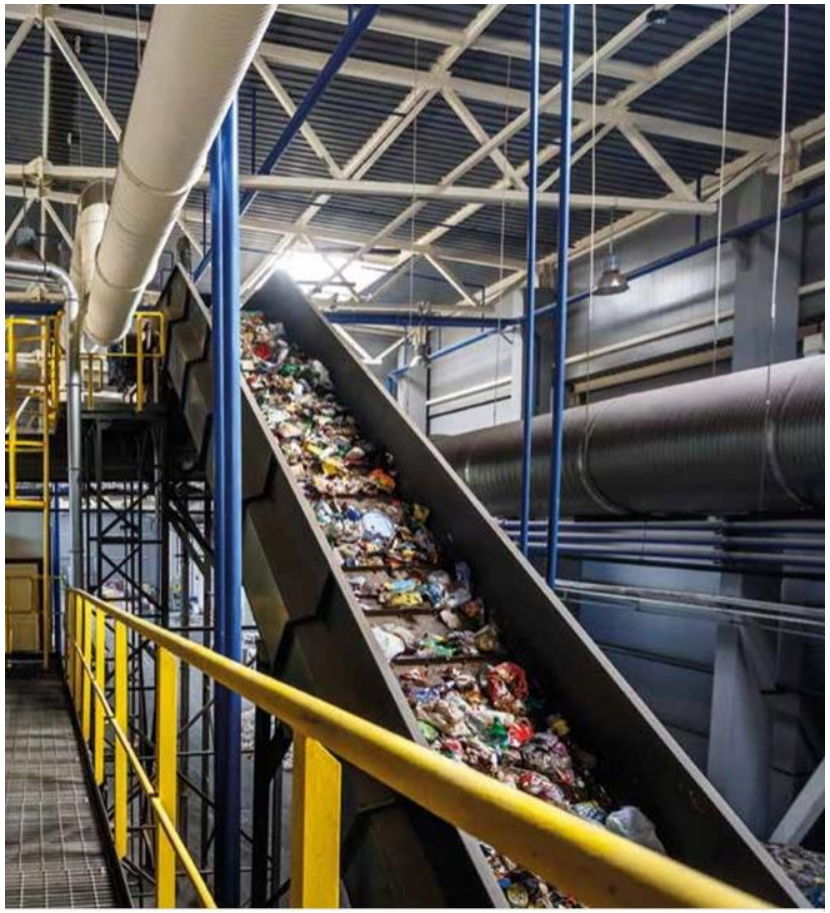
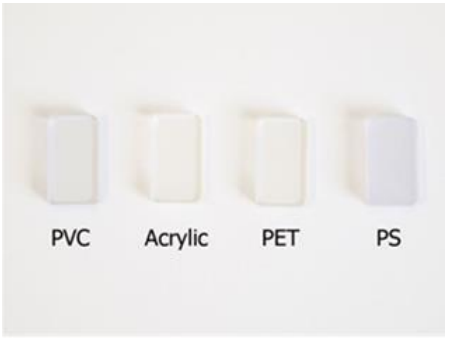
6.7% but still 3 million tons of plastic per year in the US



Different plastic needs different processing

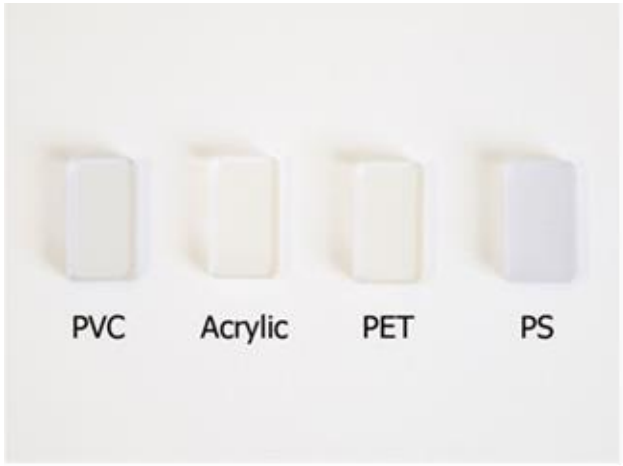
No differentiate → More pollution to the earth.



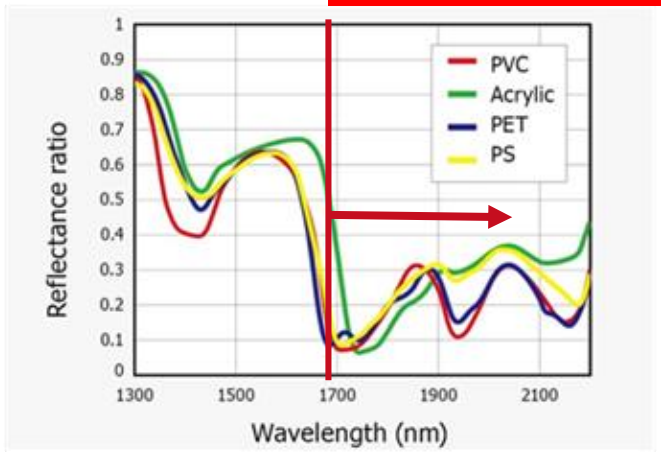
How to differentiate **plastic type** regardless of the colors?
How to find it in the production line?

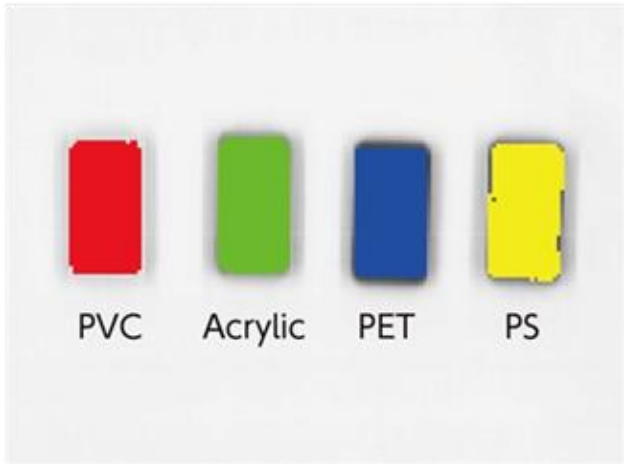
SWIR Hyperspectral/ Multispectral Imaging

Example – Plastic Sorting

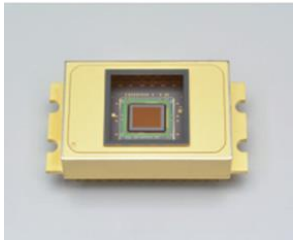


Extended InGaAs required





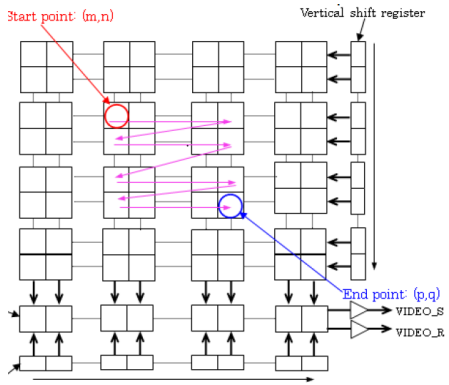
*PVC, Acrylic, PET and PS could be easily identified from **1.7um – 2.2um***



Extended InGaAs image sensor
λc = 2.6

Parameters

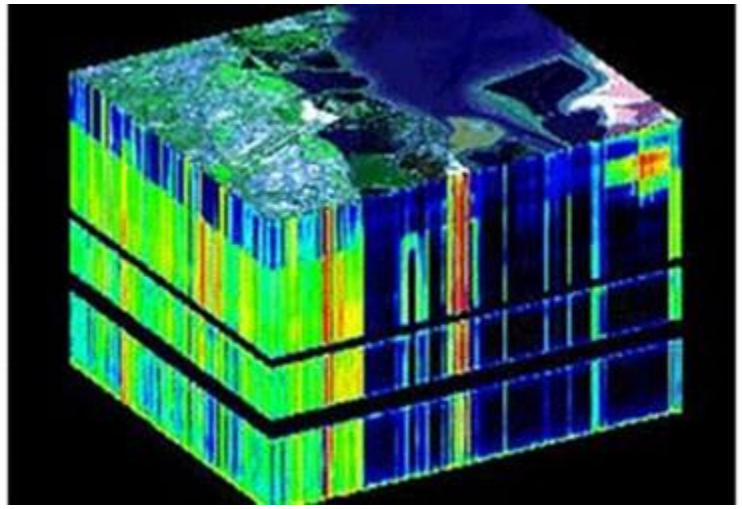
- Spectral response range
- Resolution
- Frame rate
- Dynamic range.



Partial readout is always a good to have feature

SWIR Hyperspectral/ Multispectral Imaging

Market



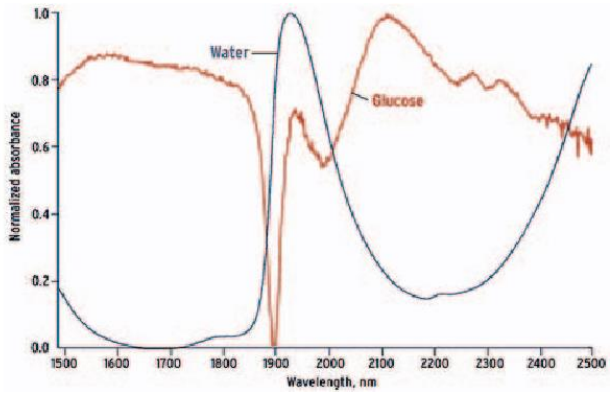
Hyperspectral imaging using for geographic

Market

- Plastic sorting (1.0um – **2.6**um)
- Geological survey (1.0um – **2.6**um)
- Pharmaceutical (1.0um – **2.6**um)
- Food quality sorting (1.0um – 1.7um)

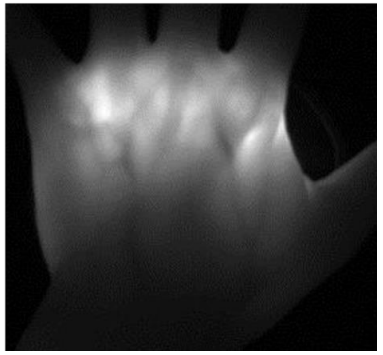
https://www.photonicsonline.com/doc/short-wave-infrared-swir-imaging-for-hyperspectral-and-surveillance-systems-0001

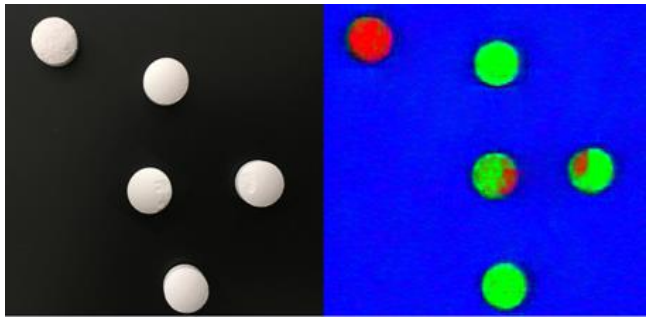
Growing Applications for SWIR



Glucose monitoring could be expected

Image of vessel



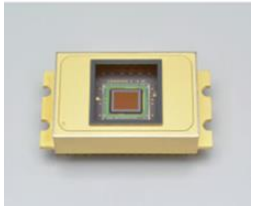


Pharmaceutical process control

Spectroscopy
- Non-invasive testing
- Food safety

Imaging
- In vivo imaging
- Sorting
- Quality control

Hyperspectral Imaging
- Process control
- Bio science
- Remote sensing



Improved Extended InGaAs fabrication will benefit more SWIR applications.

Reference
https://ieeexplore.ieee.org/document/7352586

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Conclusion

Conclusion

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Short wave infrared main benefits

- Water absorption
- Compound identification
- Clear image with heat detection
- Glass transmittance
- See through low energy surfaces

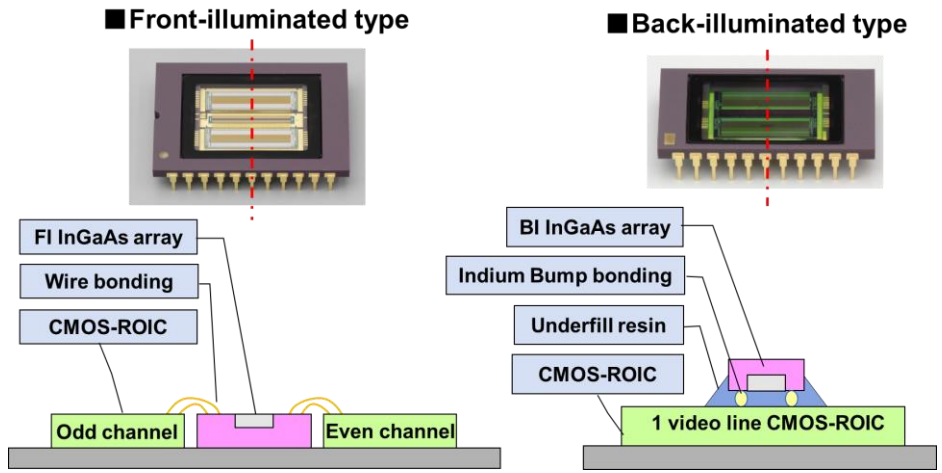
Common Detectors

- InGaAs
- HgCdTe/MCT
- Quantum dot infrared photosensor
- Type 2 super lattice

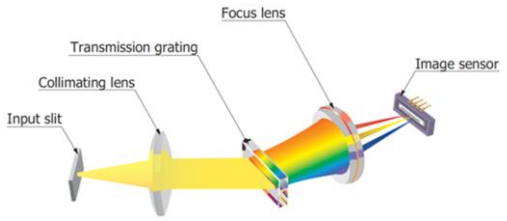
- **Short wave infrared is a growing market with the broad applications and techniques.**
- **Different techniques and applications have different requirements for image sensors.**
- **Camera is a good for plug and play solutions.**
- **Improved Extended InGaAs fabrication will benefit more SWIR applications from 1.7um to 2.6um.**

Hamamatsu Options

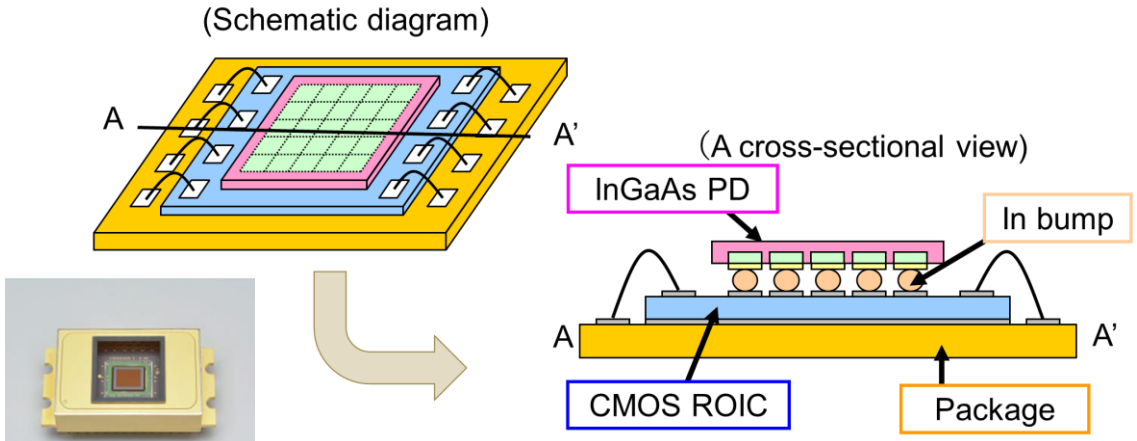
Linear InGaAs Image Sensor



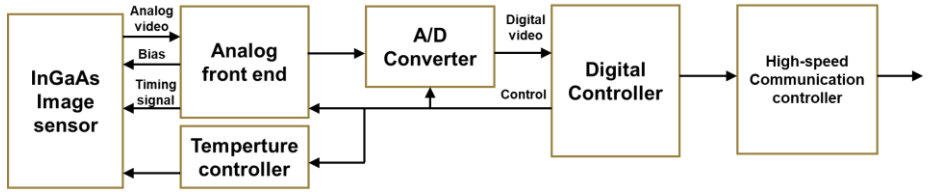
InGaAs Spectrometers



Area InGaAs Image Sensor



InGaAs Cameras



Linear InGaAs Camera

Area InGaAs Camera

Join Us for 10 Weeks of FREE Photonics Webinars (17 Topics)

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Week #	Weekly Topics	# of Talks	Talk #1 Date	Talk #2 Date
1	Introduction to Photodetectors	2	26-May-20	28-May-20
2	Emerging Applications - LiDAR & Flow Cytometry	2	2-Jun-20	4-Jun-20
3	Understanding Spectrometer	2	9-Jun-20	11-Jun-20
1 Weeks Break				
4	Specialty Products – Introduction to Light Sources & X-Ray	2	23-Jun-20	25-Jun-20
5	Introduction to Image Sensors	2	30-Jun-20	02-Jul-20
1 Weeks Break				
6	Specialty Products – Laser Driven Light Sources	2	14-Jul-20	16-Jul-20
7	Image Sensor Circuits and Scientific Camera	2	21-Jul-20	23-Jul-20
8	Mid-Infrared (MIR) Technologies & Applications	2	28-Jul-20	30-Jul-20
1 Weeks Break				
9	Photon Counting Detectors – SiPM and SPAD	1	11-Aug-20	
10	Using SNR Simulation to Select a Photodetector	1	18-Aug-20	

To register and attend other webinar series, please visit link below:

https://www.hamamatsu.com/us/en/news/event/2020/20200526220000.html

Stay safe, stay healthy, see you soon!

https://nypost.com/2020/06/22/fireworks-spark-new-yorkers-to-flee-with-their-panicked-pups/

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