Smartphone-based Spectrometer

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Professional Career Summary

Physics (Prof. Young Cheol Kim)

Pusan National University

B.S., M.S. (1993.3~1997.2)/ (1997.3~1999.2)

Physics (Prof. Peter C Eklund)

The Pennsylvania State University

Ph.D (2000.8~2006.5)

Frontier Research Lab. / Imaging Device Lab.

Samsung Advanced Institute of Technology

Principal Researcher (2006.2~2024.2)

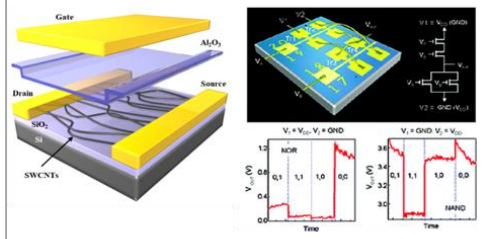
Physics Department/ Assistant Professor

Dongguk University

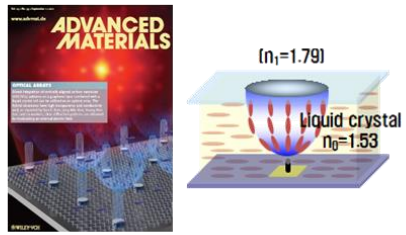
Assistant Professor (2024.4~)

Brief history of Research at SAIT (I)

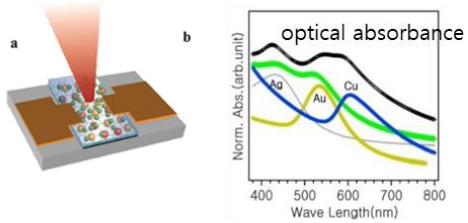
TND 사업단



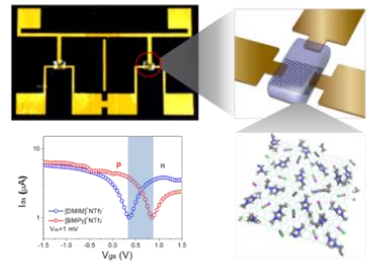
Nano Lett. (2009) – 1st Author



Adv. Mat. (2011) – 1st Author



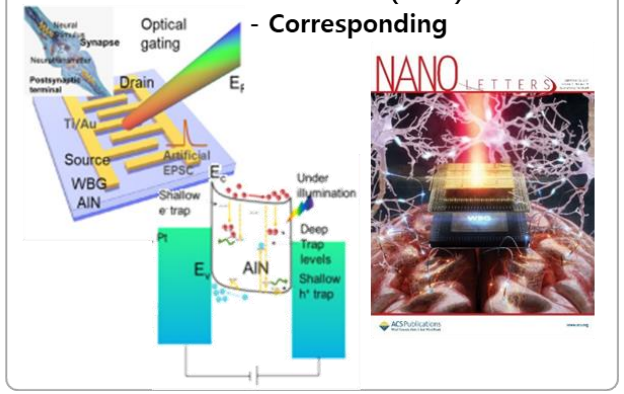
ACS photonics (2015) - 1st Author



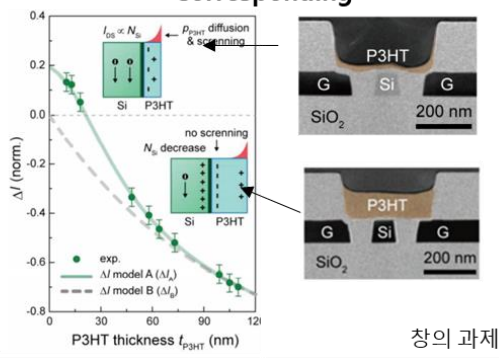
ACS nano (2015) – 1st Author

Device Fabrications & Characterizations

Nano Lett. (2021)
- Corresponding



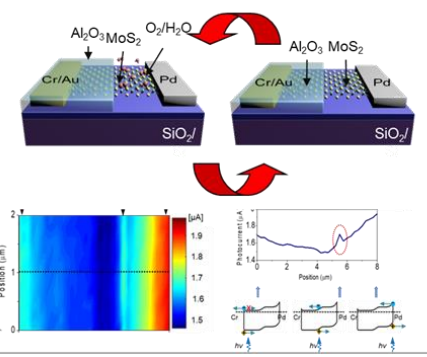
Adv. Mater. Inter. (2018)
- Corresponding



창의 과제

ACS Nano(2016) – 1st Author/Corresponding

Reversible



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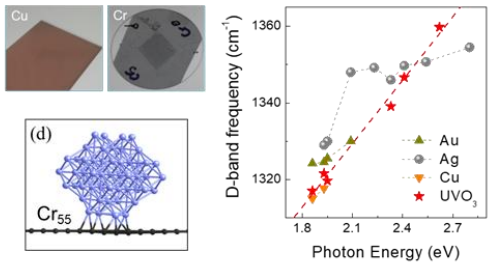
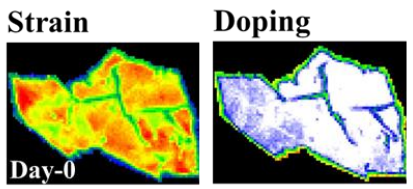
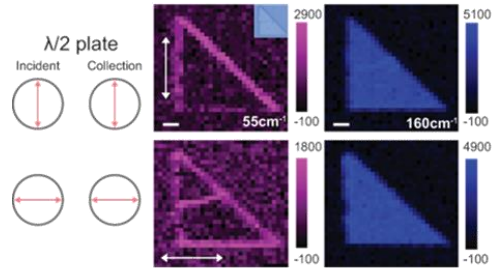
Brief history of Research at SAIT(II)



ACS nano (2018) – 1st author

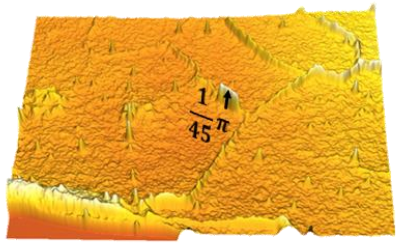


ACS Nano(2019) - Corresponding

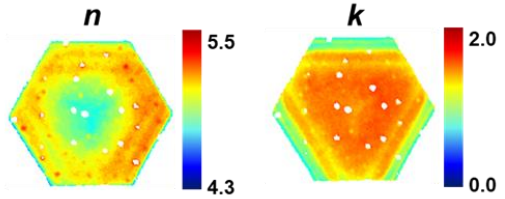


ACS Nano(2022) – 1st Author

Metrology & Inspection (MI)

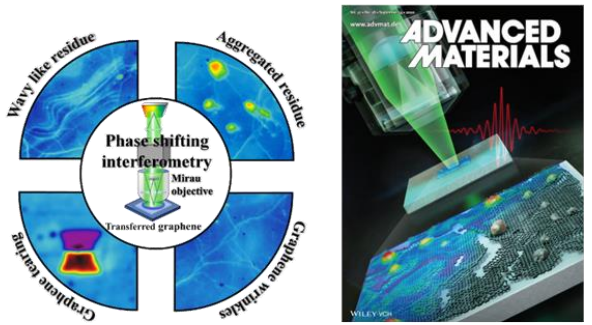


Nano today (under revision)
- 1st author



Nano today (under revision)
- 1st author

"Hyperspectral Phase Microscopy"



Adv. Mater. (2020) - Corresponding

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About SAIT

Founded in 1987

' 2014 Moved to Suwon campus from Giheung campus

Global SAIT

HumanTech Paper Award

https://humantech.samsung.com/saitext/index.jsp

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Contents

- Introduction
  - History of Spectrometer
  - Spectroscopy
  - Applications on Spectrometer

- Smartphone Based Spectrometer
  - Motivation
  - Image sensor based spectrometer
  - Smartphone based Raman Spectrometer
    (Nature Comm. 2023)
  - Machine Vision with Hyperspectral Sensor for Food Inspection
    (to be submitted)
  - Polychromatic Vision for Smart Farming
    (to be submitted)

- Conclusion

Introduction-Spectrum

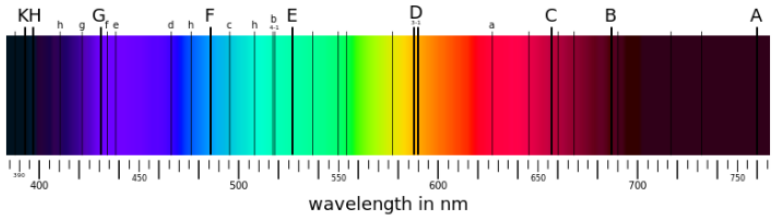
Issac Newton: Founder of Spectroscopy

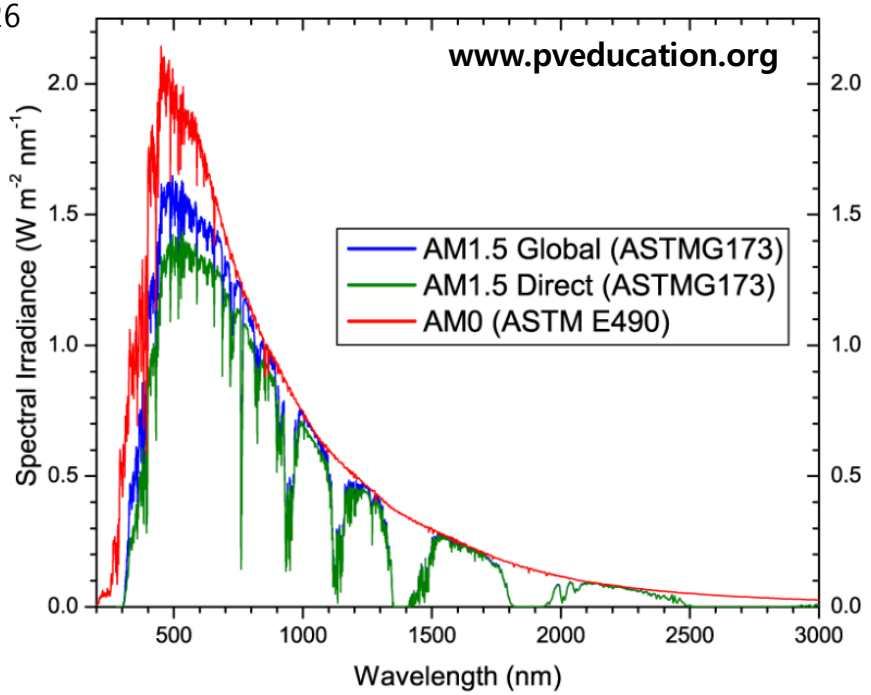
White light from the sun could be dispersed into a continuous series of colors using prism.

Spectrometer

Fraunhofer: 1787-1826

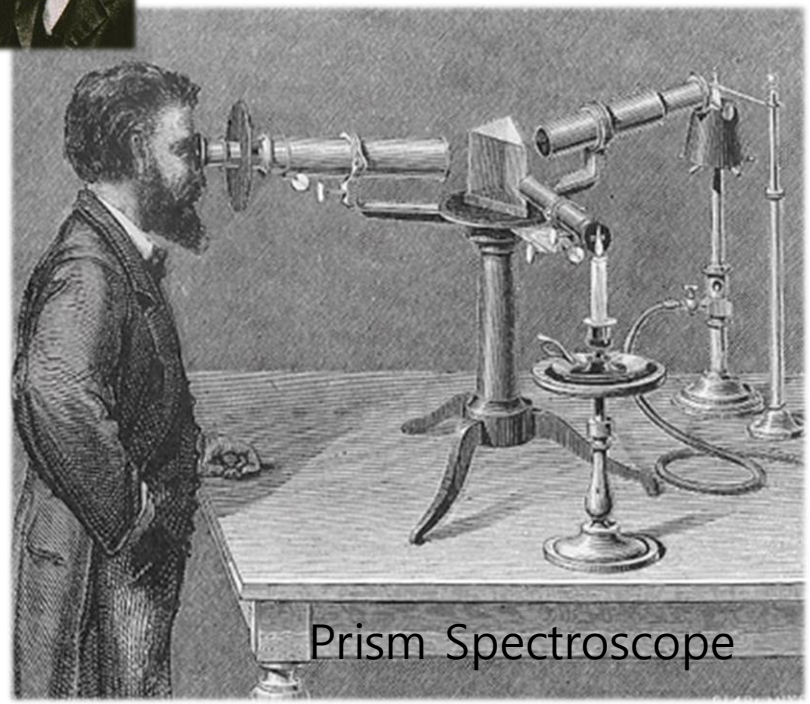
Solar spectrum: Fraunhofer line





https://www.kruess.com/en/campus/spectroscopy/history-of-spectroscopy/

Kirchhoff (1824-1887) and Bunsen (1811-1899)



Spectrometer has been a fundamental exploratory tool in chemistry, physics and astronomy.

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Introduction-Types of spectroscopy

based on many perspectives from Light-matter interaction

Acoustic resonance
Time-resolved
Photoemission
X-ray photoelectron
Circular Dichroism
Infrared spectroscopy
Raman spectroscopy

Absorption spectroscopy
Emission spectroscopy
Elastic scattering
Reflection spectroscopy
Impedance spectroscopy
Inelastic scattering
Coherent or resonance spectroscopy

Introduction- Optical spectrometer

Optical spectrometer

shows the intensity of light as a function of wavelength or frequency

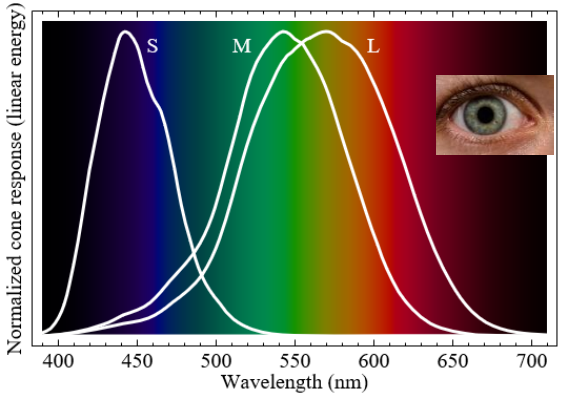
→ Basic tool to analyze remotely & non-destructively

Goal of spectrometer
: identifying materials, monitoring environment, calibration colors… etc..

[Newport Spectromter]

https://en.yna.co.kr/view/AEN20210311010100315

https://www.innovationnewsnetwork.com/portable-measurement-device-food-quality/430/



https://en.wikipedia.org/wiki/Color_vision#/media/File:Eye sensitivity.svg

Introduction-Hyperspectral imaging

Image & spectrum can be measured simultaneously

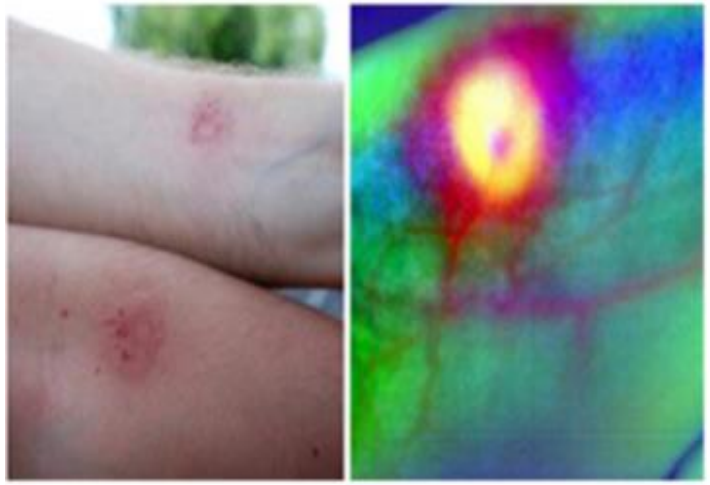
Useful information beyond human sight, typical RGB imaging

: Food inspection, environment/health monitoring, and etc.

[Food Inspection]

https://hippocratesmedreview.org/applications-of-hyperspectral-imaging-for-food-quality-analysis/

[Skin Analysis/Diagnosis]



http://hyperstory.co.kr/

[Materials sorting]

https://www.novuslight.com/spectral-imaging-ready-for-on-field-and-industrial-applications_N7527.html

Introduction- Portable Spectrometer

127 x 89 x 56 mm

handheld Raman spectrometer
https://www.smithsdetection.com/products/ace-id/

257 x 127 x 60 mm
830 nm laser

VAYA – Agilent Handheld Raman Spectrometer
https://overtech.com.sa/vaya-agilent/

250 x 280 x 90 mm

Bruker handheld Raman Spectrometer
https://www.bruker.com/

114 x 23.9 mm

LinkSquare – Agilent Handheld Raman Spectrometer
https://stratiotechnology.com/

89.1 mm x 63.3 mm x 34.4 mm

Miniature Leaf Spectrometer
http://www.lightwindcorp.com/

F-750 Produce Quality Meter
http://www.lightwindcorp.com/

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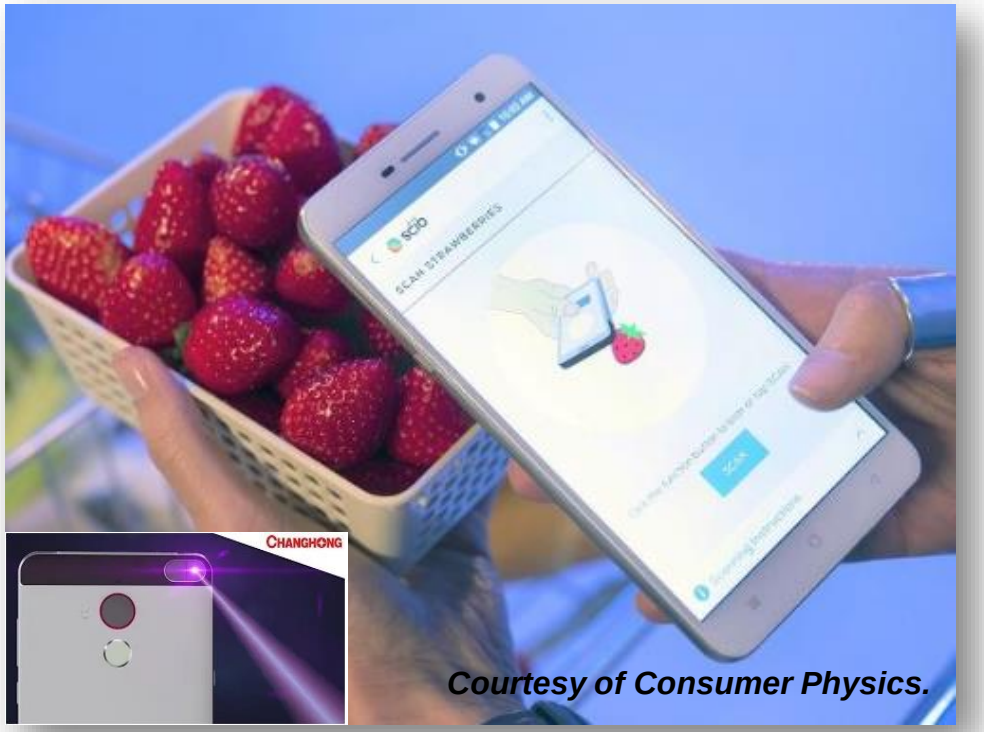
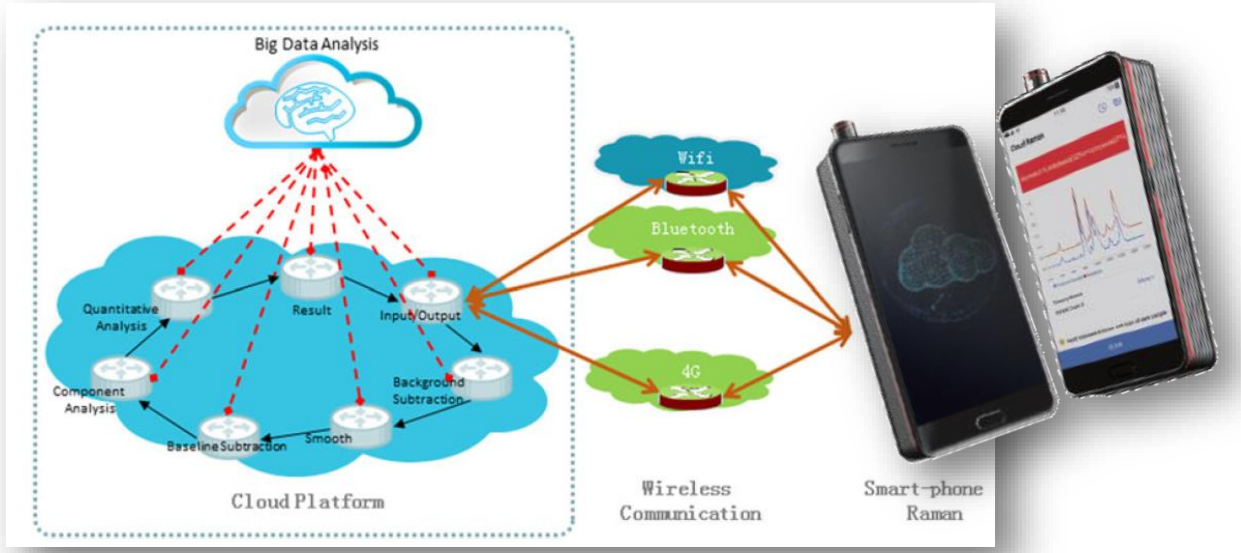
Smartphone Spectrometer



'17 CES
Changhong, Analog Devices, and Consumer Physics



Cloudminds XI™

world's 1st cloud-based handheld Raman spectrometer

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS (2019)

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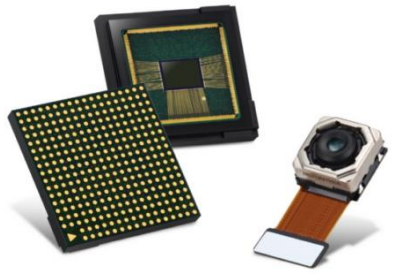
Motivation

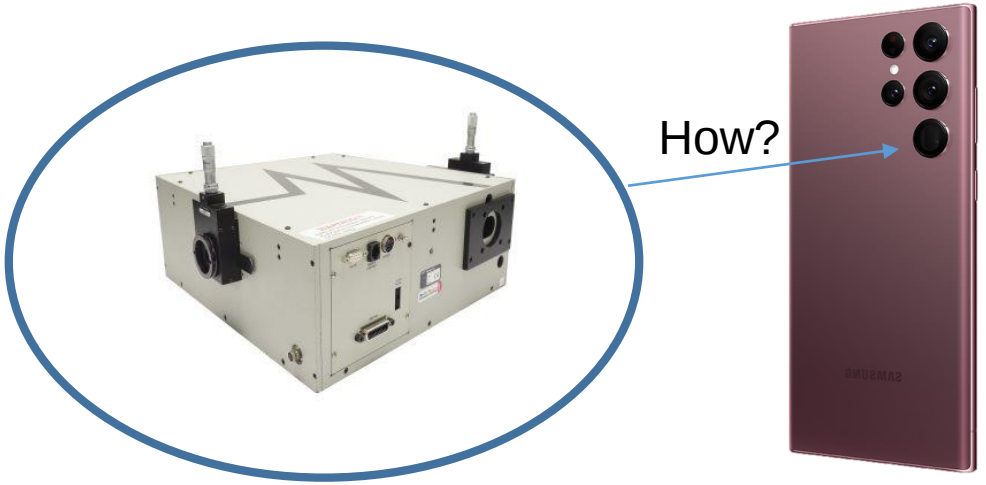
- Smartphone and CMOS Image Sensor : Samsung's Big Biz
- Smartphone user experiences require outstanding sensor platform

1) Image Sensor is full array of photodetector
2) Spectrometer is strong candidate to provide superior sensor platform for smartphone

Is there any way to utilize image sensors to spectrometer ?



[Samsung's Precise and Sensitive Image Sensor]

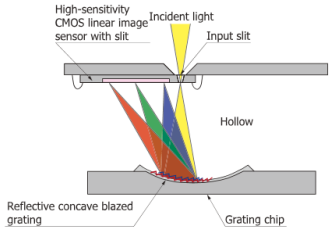


How Can We Make Spectrometer Compact ?

We should reduce its dimensions as small as possible → Miniaturization!

Diffraction of light from limited space

Diffraction by grating

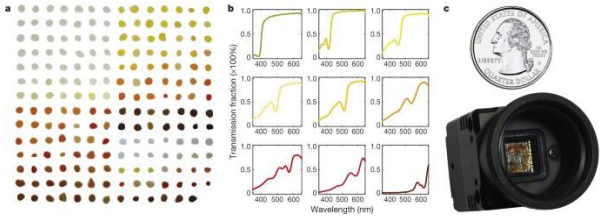


https://www.hamamatsu.com/jp/en/product/type/C12666MA/index.html

Still Large to embed smartphone

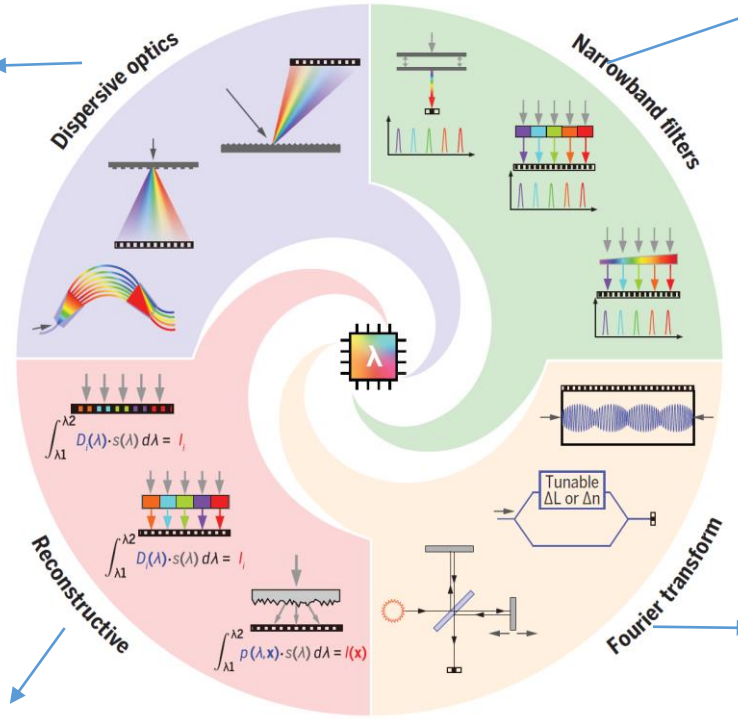
Absorption to remove unwanted wavelengths of light

Absorption by QD



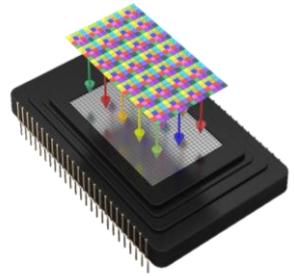
https://www.nature.com/articles/nature14576

Not CMOS-Compatible & heavy algorithm

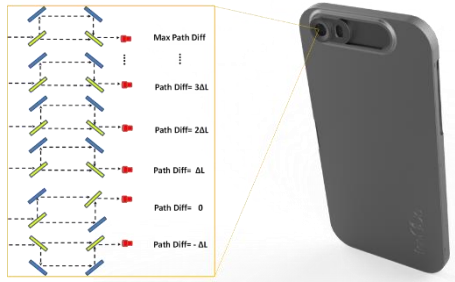


J.Y, T A-O, W.C, T.H, Science, 371(6528), ebae0722 (2021)

Our Approach



Variable light path- interference



https://www.fringe.com

Moving, Varing component needed to control actively

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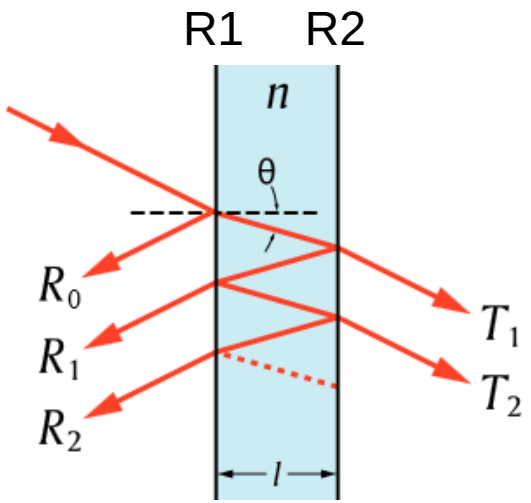
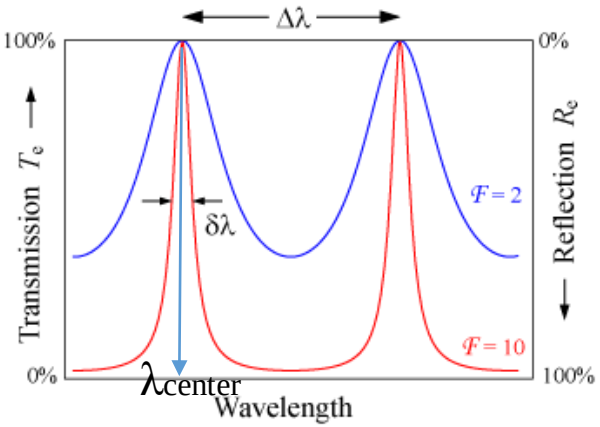
Key Technology : Fabry-Perot Resonator

- Interference of light : superposition of waves
  - controllability of light in a particular range of wavelengths
  - Constructive interference determines

- Fabry-Perot resonator (optical cavity with two parallel reflecting surfaces)
  - Optical bandpass filter with controlling Q(δλ) and λcenter



https://en.wikipedia.org/wiki/Fabry%E2%80%93P%C3%A9rot_interferometer#/media/File:Fabry–Pérot_etalon.svg



https://en.wikipedia.org/wiki/Fabry%E2%80%93P%C3%A9rot_interferometer#/media/File:Etalon-2.png

What determines δλ and λ?

δλ	Reflectivity Cavity Loss	R1,R2
λ	Optical path length	n*L

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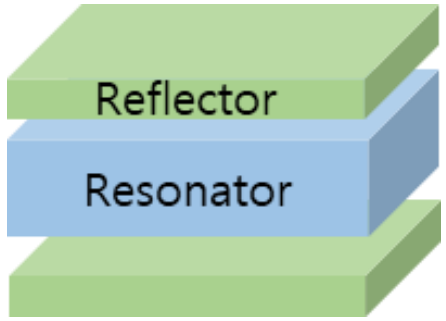
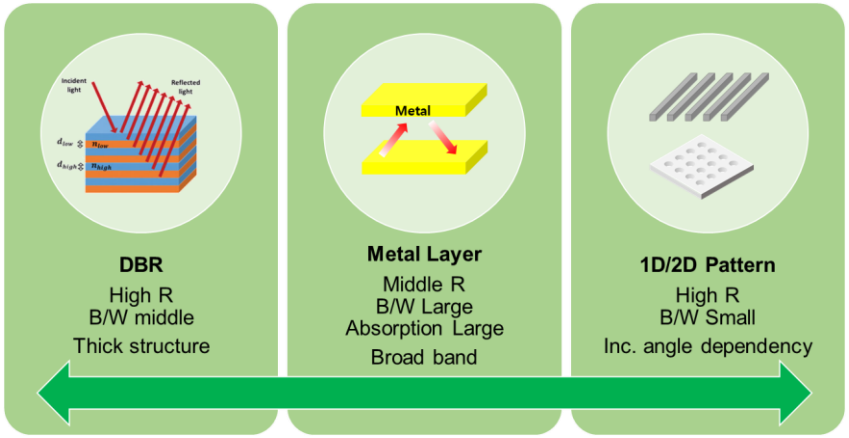
Device Design

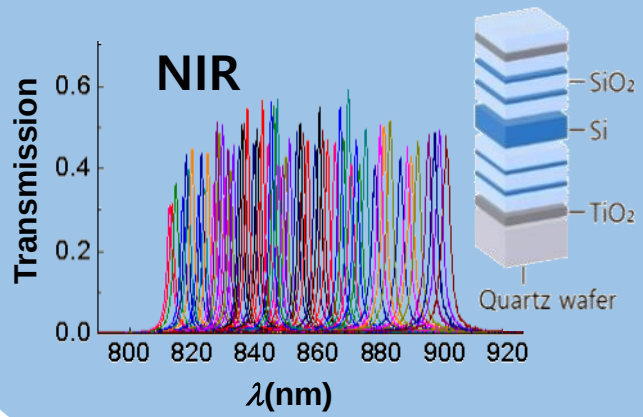
Fabry-Perot resonator

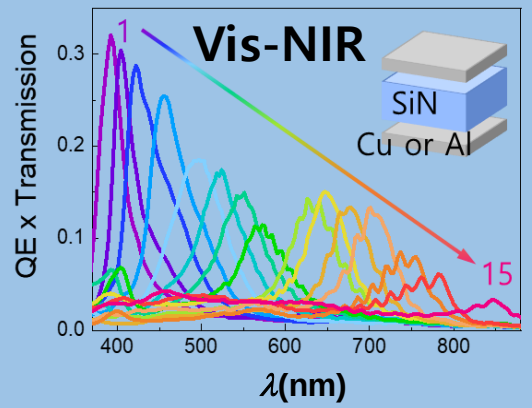


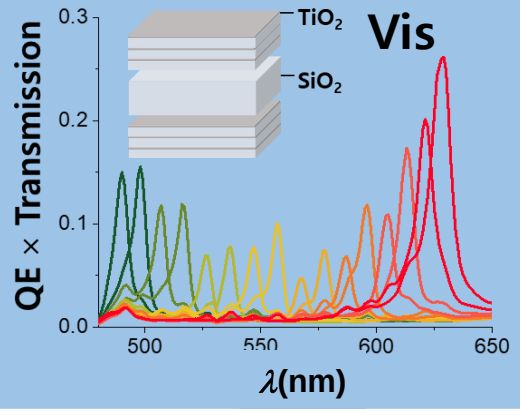
Reflector



Resonator







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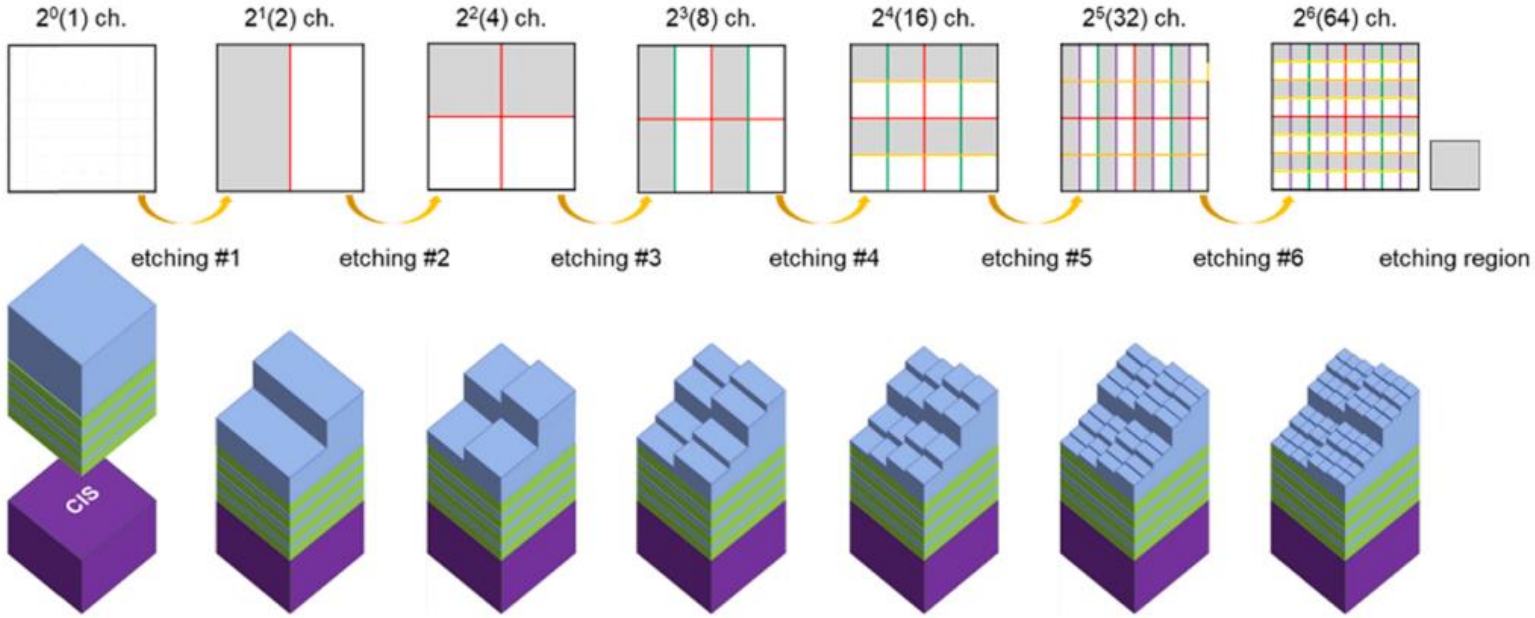
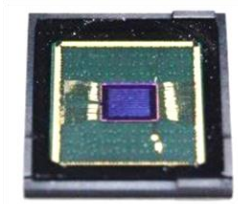
Device Fabrication

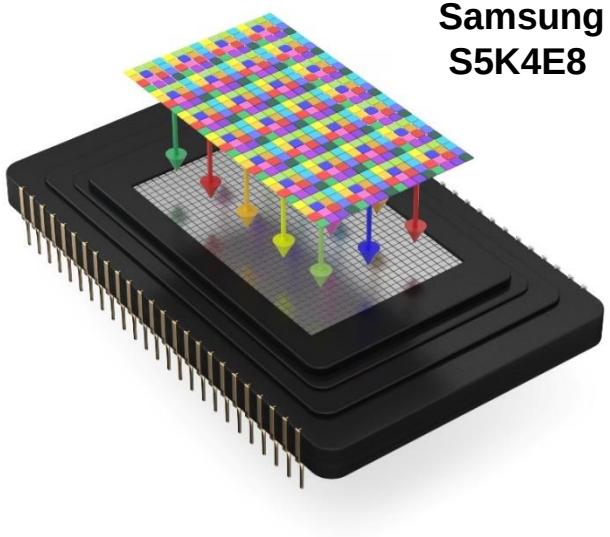
Binary photo/Etching Repetition by 2^N, N=integer



From Device to Analysis

Image Sensor + Nanophotonic Filter

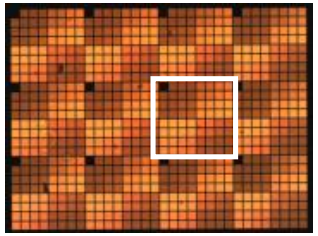


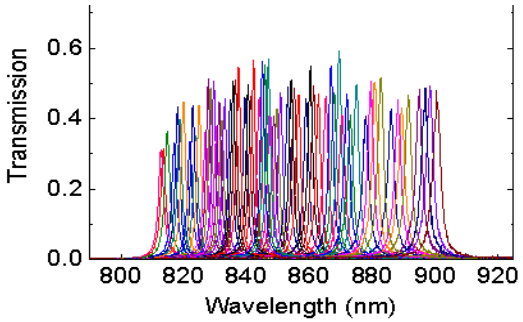


Samsung S5K4E8

Low Spatial resolution
High Spectral resolution

40px X 40px : 64CH

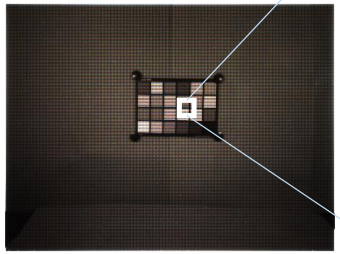


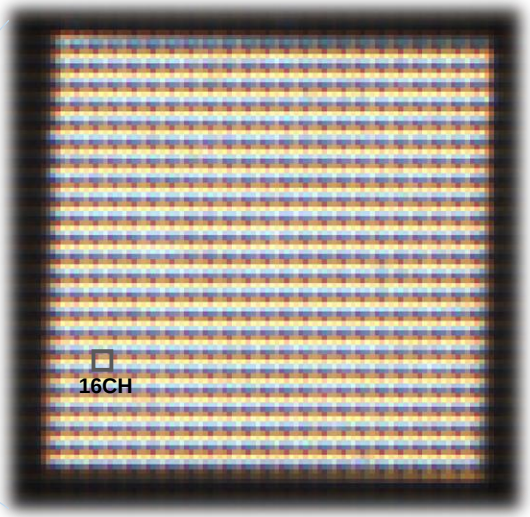


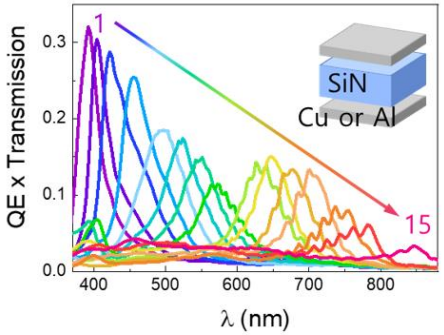
On-Chip spectrometer
: Raman spectrometer

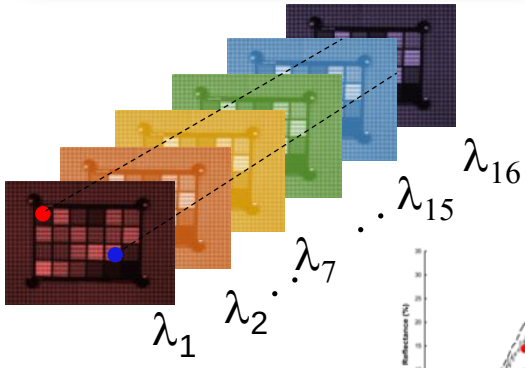
High Spatial resolution
Low Spectral resolution

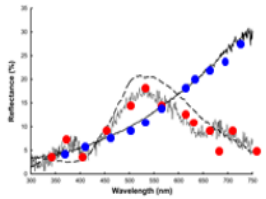
2px X 2px : 16CH











Hyperspectral Image sensor

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Smartphone based Raman Spectrometer

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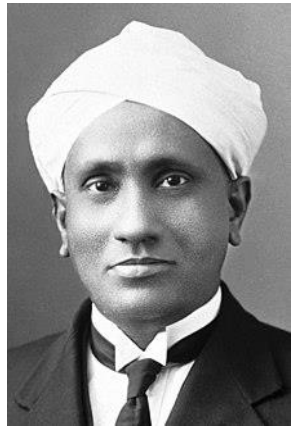
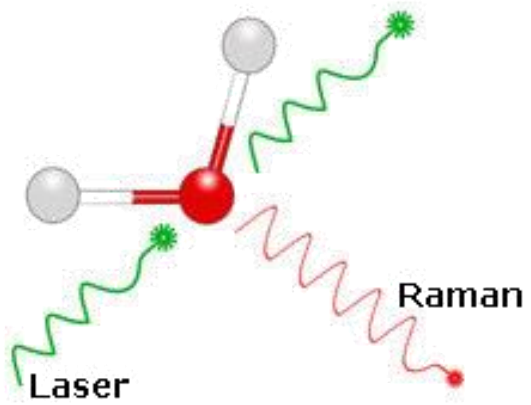
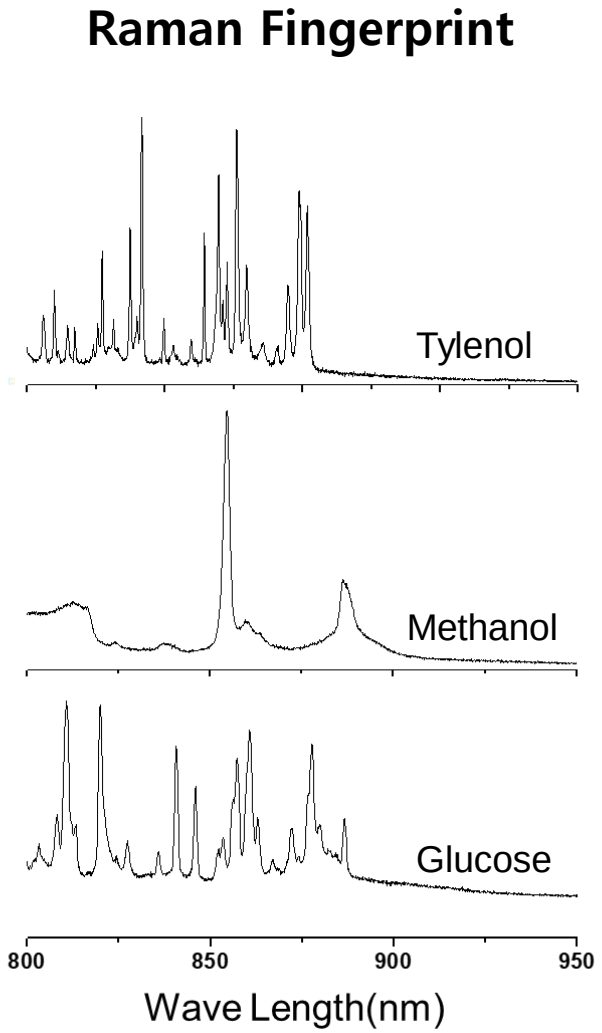
Raman Scattering and Fingerprint



Sir Chandrasekhara Venkata Raman
(1888–1970)





- Raman scattering
  - Discovered by C.V. Raman in 1928. (Nobel prize in 1930)
  - **Inelastic scattering** of photons by matter
    - **Energy change** of incident light,
    - **~ 10^{-5} %** of incident light
  - Involves with vibrational energy of molecules → **Fingerprint of materials**

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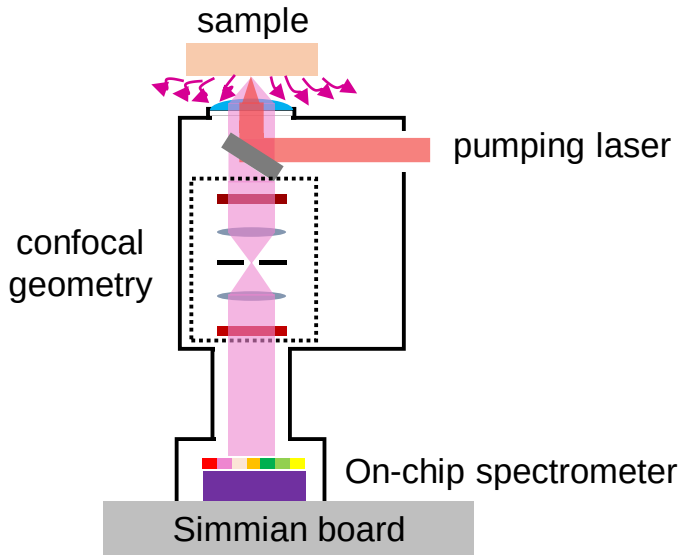
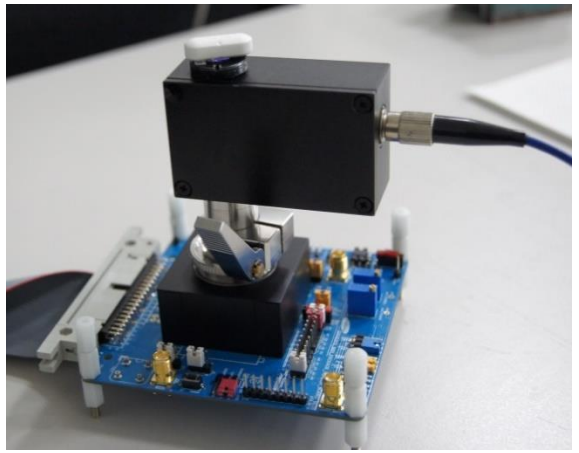
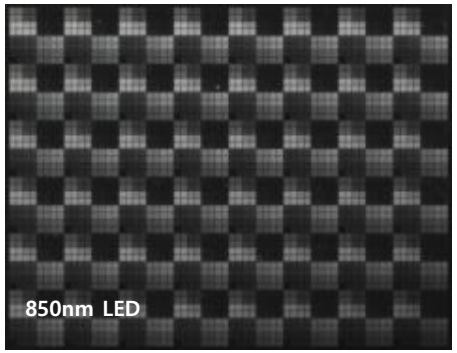
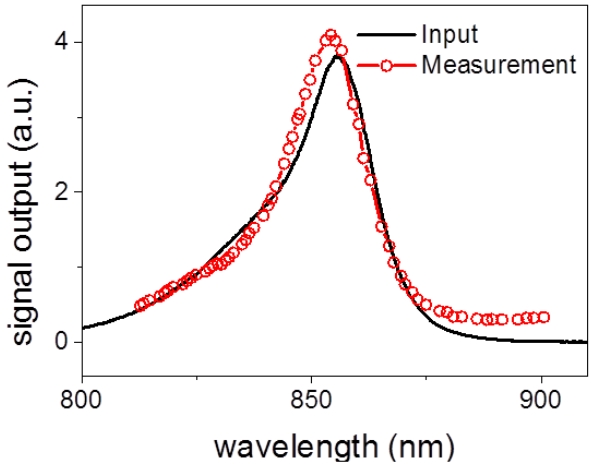
Spectrum Measurement in Chip scale



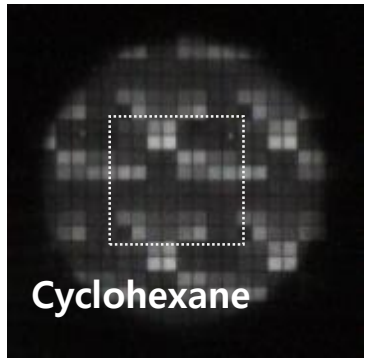


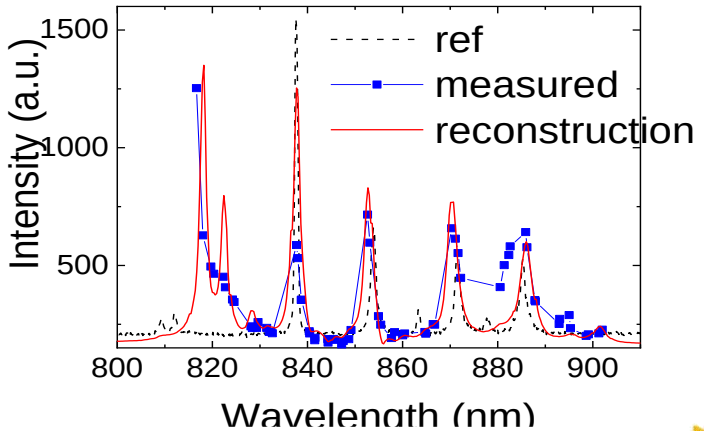
Broad LED spectrum





Narrow Raman Spectrum





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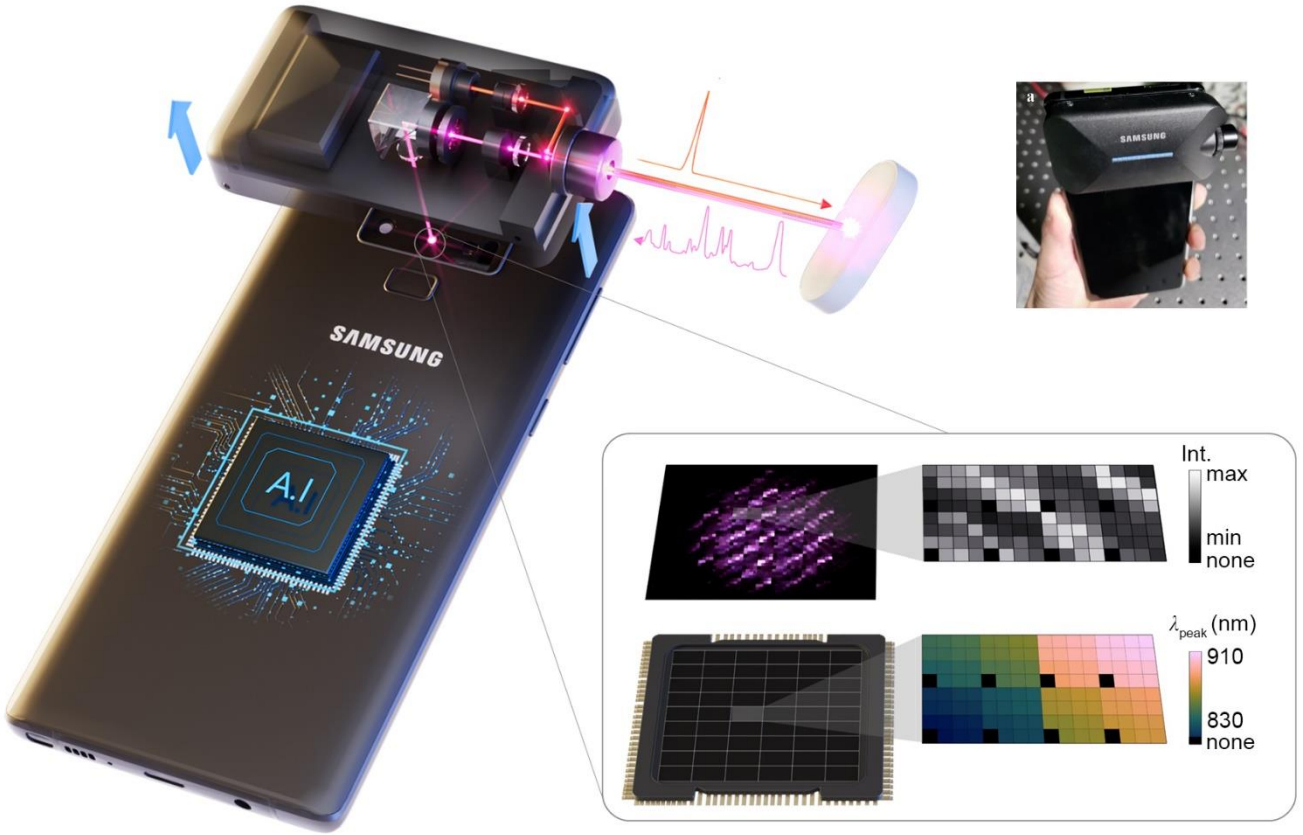
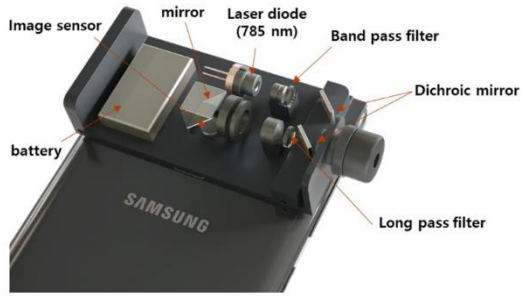
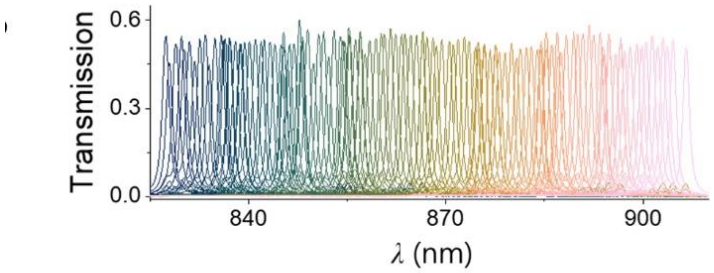
Spectral information for Drug Classification

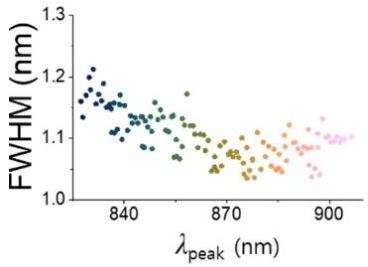
Spectral information with deep learning

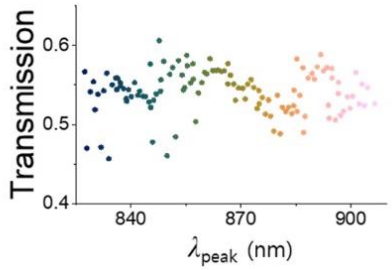
Raman and fluorescence signal detection with CMOS image sensor











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Conventional Methods for Drug Identification

DrugID, ID My Pill, Pill Identifier, Pill Finder, and Drug Info

https://www.drugs.com/imprints.php

Pill Identifier

Search by imprint, shape or color

Use the pill finder to identify medications by visual appearance or medicine name. All fields are optional.
Tip: Search for the **imprint first**, then refine by color and/or shape if you have too many results.

Pill Imprint

Imprint on pill

Color (optional)

Any color

Shape (optional)

Any shape

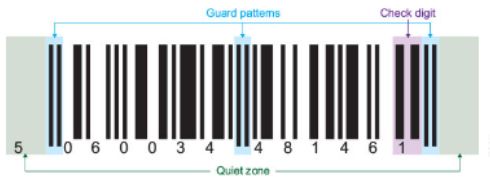
Search

Enter the letters or numbers from your pill

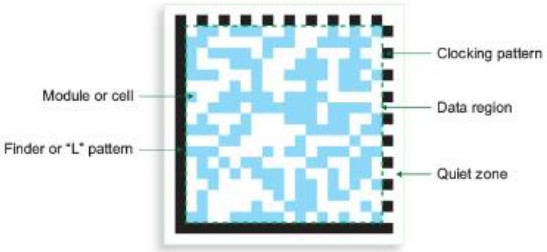
Example 9 | 3 (SIDE A) 5510 (SIDE B) FOR THIS TABLET YOU WOULD ENTER 9 3 5510

HINT: To get more results, enter an imprint only. To further expand your search, try entering only part of your imprint.

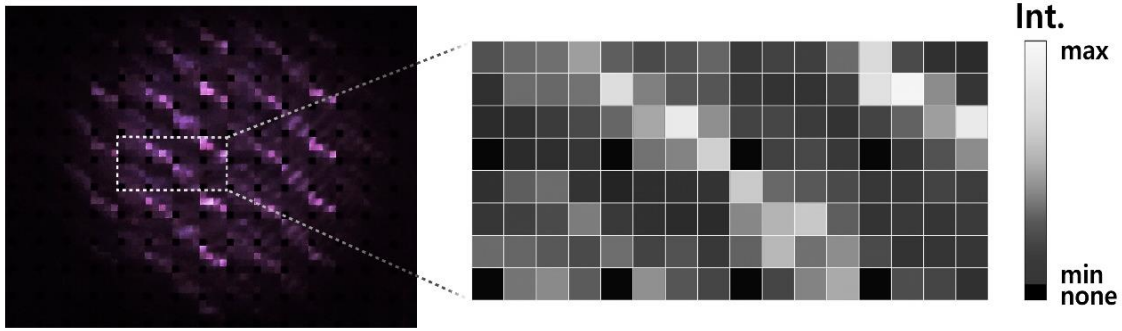
1D



2D



This work : Spectral Barcode



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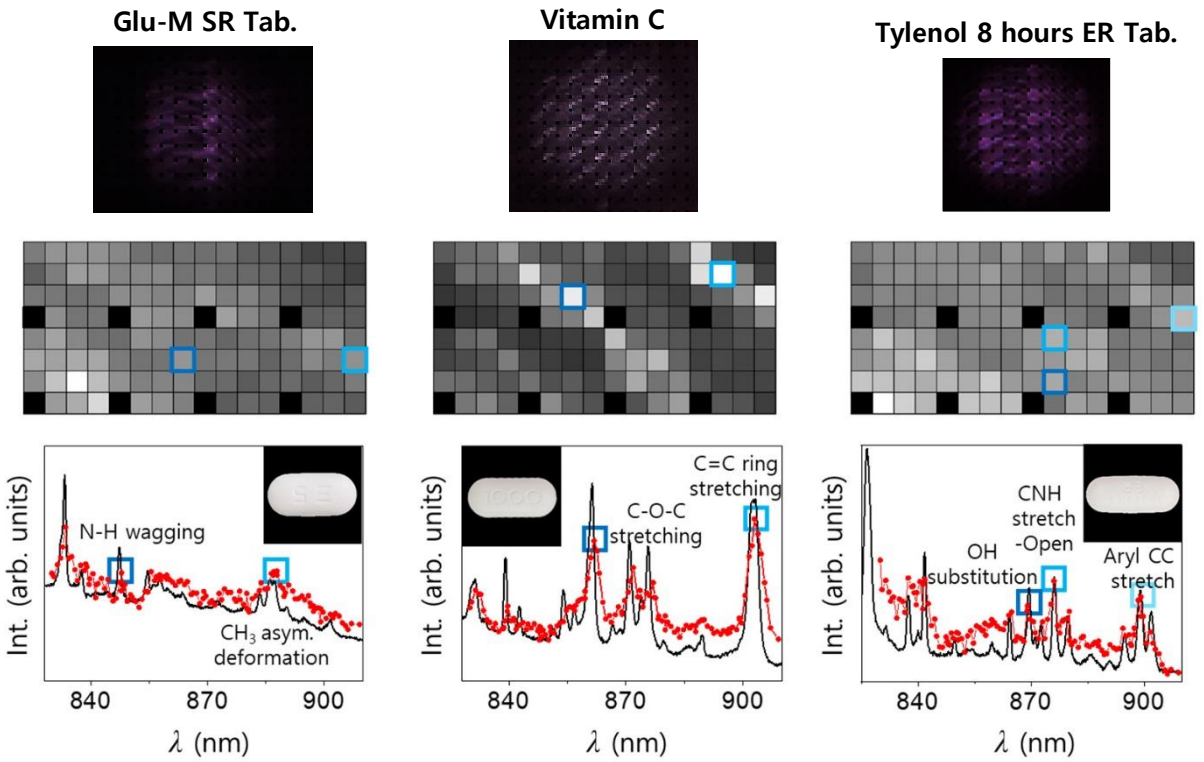
Raman Fingerprint

Glu-M SR Tab.

Vitamin C

Tylenol 8 hours ER Tab.

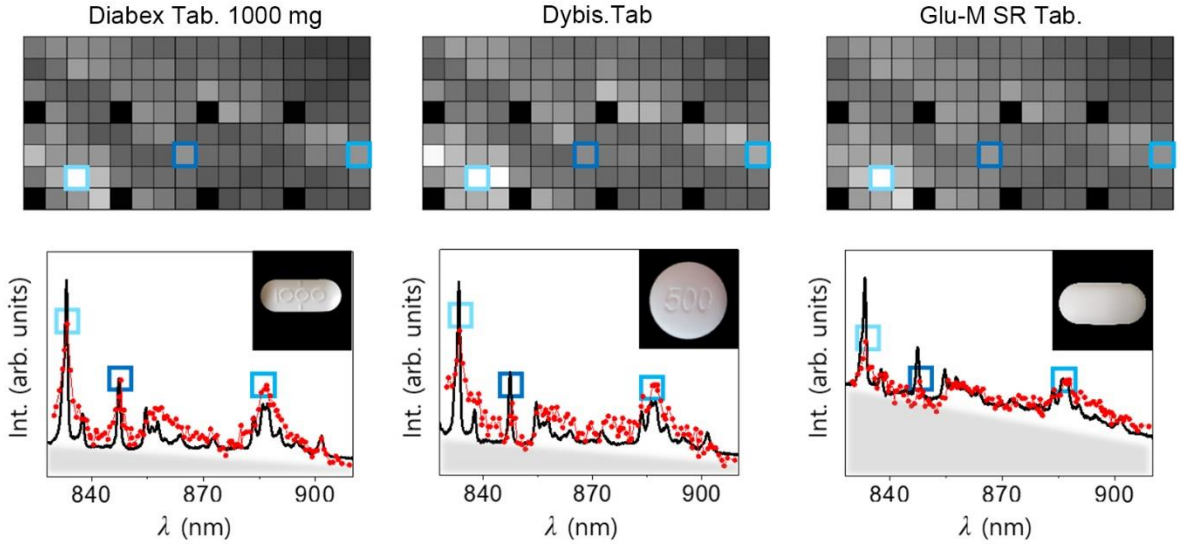


Diabetes -Metformin

Diabex Tab. 1000 mg

Dybis.Tab

Glu-M SR Tab.



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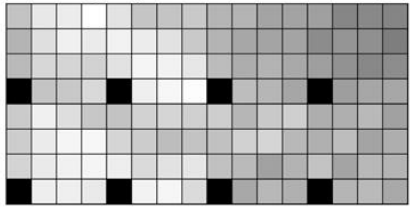
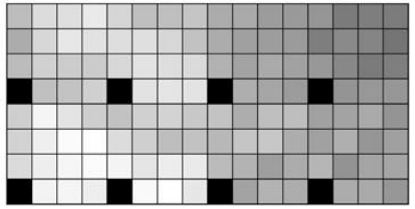
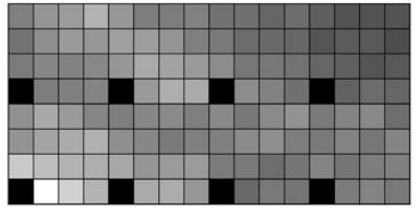
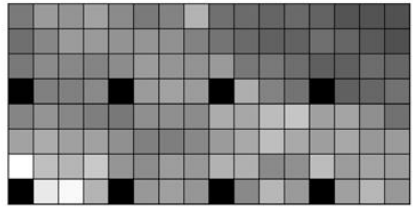
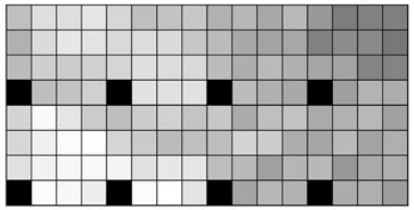
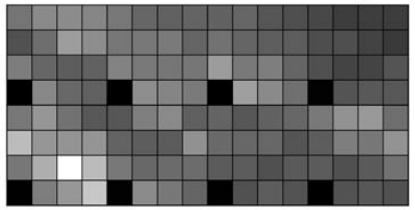
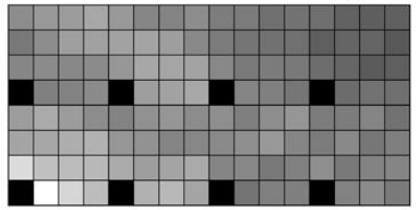
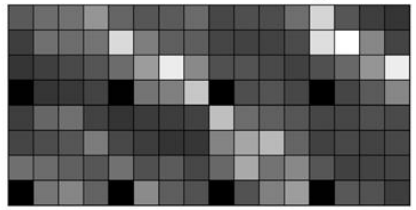
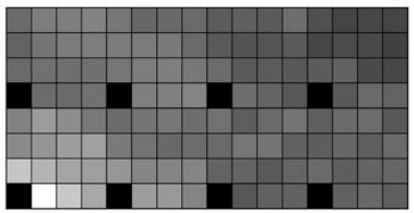
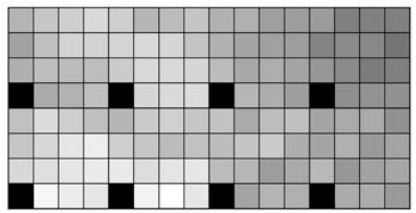
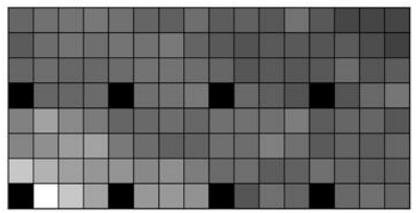
Spectral Barcode of Drugs

눈으로 구분이 가능할까요?

Hypertension	Diabetes	Hyperlipidemia	Over the counter
Amlodipine ($C_{20}H_{25}ClN_2O_5$)	Glimepiride ($C_{24}H_{34}N_4O_5S$)	Atorvastatin ($C_{33}H_{35}FN_2O_5$)	Vitamin B6 (Pyridoxine, $C_8H_{11}NO_3$)
Anydipine S Tab. 5 mg 	Diaride Tab. 2 mg 	Lipilou Tab. 20 mg 	Pilidoxine Tab. Sinil 
Losartan ($C_{22}H_{23}ClN_6O$)	Metformin ($C_4H_{11}N_5$)	Rosuvastatin ($C_{22}H_{28}FN_3O_6S$)	Vitamin C ($C_6H_8O_6$)
Bearlotan Tab. 50 mg 	Diabex Tab. 1000 mg 	Crestor Tab. 10 mg 	Vitamin C Tab. 1000 mg Yuhan 
Valsartan ($C_{24}H_{29}N_5O_3$)		Simvastatin ($C_{25}H_{38}O_5$)	Tylenol (Acetaminophen, $C_8H_9NO_2$)
Orosartan Tab. 10/160 mg 		Simvalord Tab. 20 mg 	Tylenol Tab. 500 mg 

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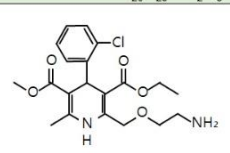
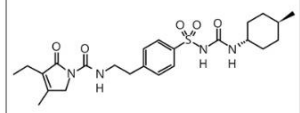
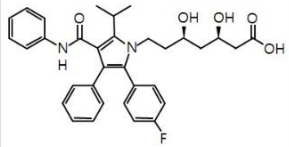
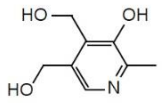
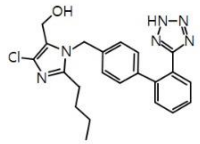
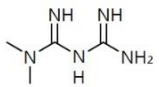
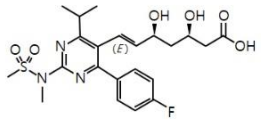
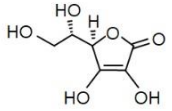
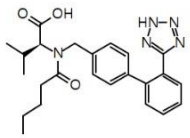
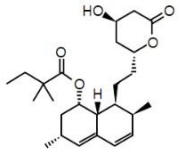
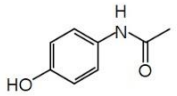
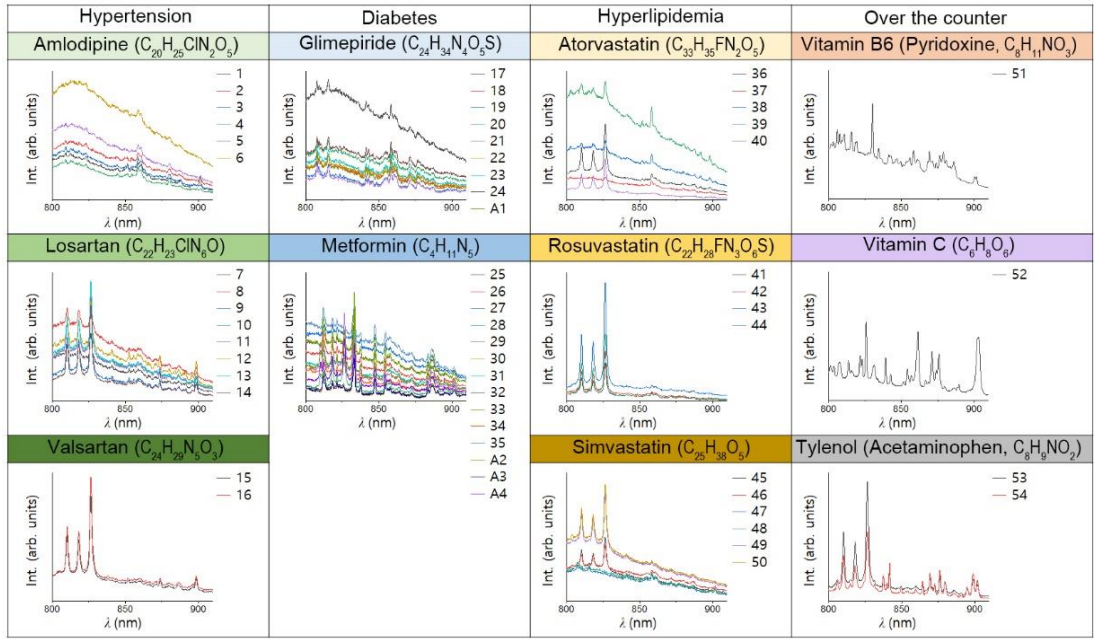
Major Component of Drugs

3대 성인병 : 고혈압, 당뇨, 고지혈증

Hypertension	Diabetes	Hyperlipidemia	Over the counter
Amlodipine ($C_{20}H_{25}ClN_2O_5$)	Glimepiride ($C_{24}H_{34}N_4O_5S$)	Atorvastatin ($C_{33}H_{35}FN_2O_5$)	Vitamin B6 (Pyridoxine, $C_8H_{11}NO_3$)
			
Losartan ($C_{22}H_{23}ClN_6O$)	Metformin ($C_4H_{11}N_5$)	Rosuvastatin ($C_{22}H_{28}FN_3O_6S$)	Vitamin C ($C_6H_8O_6$)
			
Valsartan ($C_{24}H_{29}N_5O_3$)		Simvastatin ($C_{25}H_{38}O_5$)	Tylenol (Acetaminophen, $C_8H_9NO_2$)
			

Raman Spectrum of Drugs



삼성 서울 병원 협업

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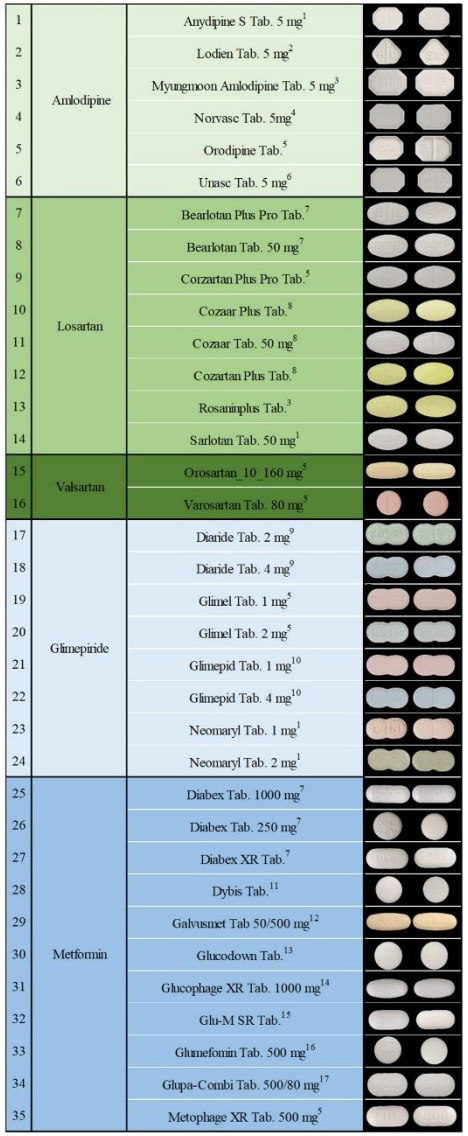
Data Base for Convolutional Neural Network



1	Amlodipine	Anydipine S Tab. 5 mg[1]
2		Lodien Tab. 5 mg[2]
3		Myungmoon Amlodipine Tab. 5 mg[3]
4		Norvasc Tab. 5mg[4]
5		Orodipine Tab.[5]
6		Unasc Tab. 5 mg[6]
7	Losartan	Bearlotan Plus Pro Tab.[7]
8		Bearlotan Tab. 50 mg[7]
9		Corzartan Plus Pro Tab.[5]
10		Cozaar Plus Tab.[8]
11		Cozaar Tab. 50 mg[8]
12		Cozartan Plus Tab.[8]
13		Rosaminplus Tab.[3]
14		Sarlotan Tab. 50 mg[1]
15	Valsartan	Orosartan_10_160 mg[5]
16		Varosartan Tab. 80 mg[5]
17	Glimepiride	Diaride Tab. 2 mg[9]
18		Diaride Tab. 4 mg[9]
19		Glimel Tab. 1 mg[5]
20		Glimel Tab. 2 mg[5]
21		Glimepid Tab. 1 mg[10]
22		Glimepid Tab. 4 mg[10]
23		Neomaryl Tab. 1 mg[1]
24		Neomaryl Tab. 2 mg[1]
25	Metformin	Diabex Tab. 1000 mg[7]
26		Diabex Tab. 250 mg[7]
27		Diabex XR Tab.[7]
28		Dybis Tab.[11]
29		Galvusmet Tab 50/500 mg[12]
30		Glucodown Tab.[13]
31		Glucophage XR Tab. 1000 mg[14]
32		Glu-M SR Tab.[15]
33		Glunefomin Tab. 500 mg[16]
34		Glupa-Combi Tab. 500/80 mg[17]
35		Metophage XR Tab. 500 mg[5]
36	Atorvastatin	Lipilou Tab. 20 mg[1]
37		Lipinon Tab. 20 mg[5]
38		Lipitor Tab. 10 mg[4]
39		Lipitor Tab. 40 mg[4]
40		Lipito-M SR Tab. 20/500 mg[18]
41	Rosuvastatin	Crestor Tab. 10 mg[19]
42		Crestor Tab. 20 mg[19]
43		Daewoong Rosuvastatin Tab. 20 mg[20]
44		Rosulord Tab. 20 mg[1]
45	Simvastatin	Simvalord Tab. 20 mg[1]
46		Simvast Tab. 20 mg[10]
47		Vytorin Tab. 10/10[8]
48		Vytorin Tab. 10/40[8]
49		Zocor Tab. 20 mg[8]
50		Zocor Tab. 40 mg[8]
51	Vitamin B6	Pldoxine Tab. Sinil (Vitamin B6)[21]
52	Vitamin C	Vitamin C Tab. 1000 mg Yuhan[22]
53	Acetaminophen	Tylenol Tab. 500 mg[23]
54		Tylenol 8 hours ER Tab.[24]
A1	Glimepiride	Glimel Tab. 3 mg[5]
A2	Metformin	Dymit XR Tab.[25]
A3		Glucophage Tab. 1000 mg[14]
A4		Metfol Tab. 500 mg[26]

[1] Chong Kun Dang Pharmaceutical Corp.
[2] Han Lim Pharm.
[3] Myung Moon
[4] Viatris Korea
[5] Donga ST
[6] Korea United Pharm.
[7] Daewoong Bio
[8] Organon Korea Ltd.
[9] Kwang-dong Pharm.
[10] Hanmi Pharm.
[11] Shin Poong Pharm.
[12] Novartis Korea
[13] Hanall Biophrma
[14] Merck Ltd.
[15] Samik Pharmaceutical
[16] Young Poong Pharmaceutical
[17] Dalim BioTech
[18] Jeil Pharm.
[19] AstraZeneca Korea Corporation
[20] Dae Woong
[21] Sinil Pharm.
[22] Yuhan
[23] Johnson & Johnson
[24] Janssen Korea
[25] Kyung Dong Pharma
[26] Il Dong

Untrained drugs !!
Not in the Database

A1	Glimepiride	Glimel Tab. 3 mg[5]
A2	Metformin	Dymit XR Tab.[25]
A3		Glucophage Tab. 1000 mg[14]
A4		Metfol Tab. 500 mg[26]

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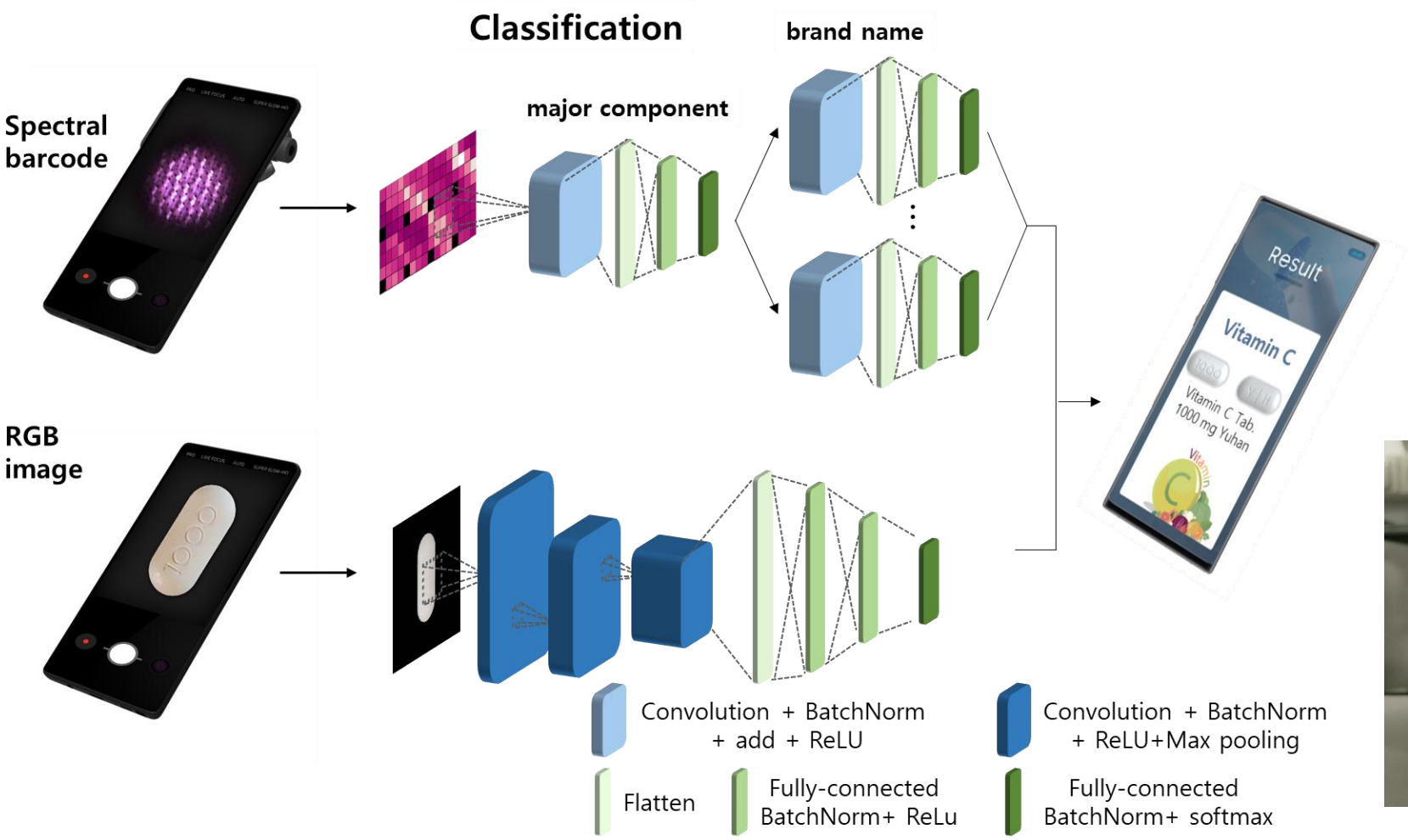
CNN training for Drug Classification

Classification with Convolutional Neural Network (CNN)



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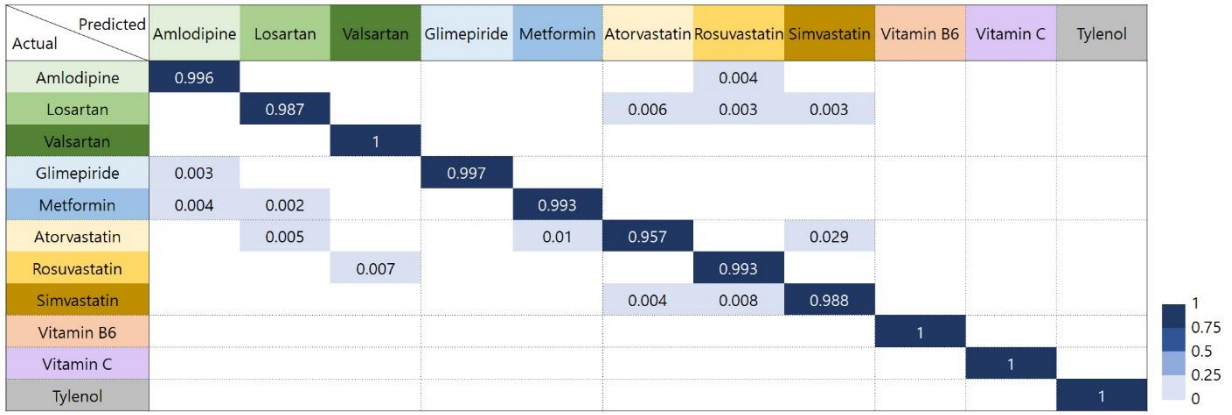
Confusion matrix

by Major Component



~ 99% accuracy for the same component

CNN for Spectral Barcode :

Major component : ~99%
Unknown four drugs : 99.8%
(only one failure out of several hundreds trials.)
Brand name : 79.5%

CNN for RGB image :
Shape and Color : 95.7%

Combination of two CNNs :
Brand name :83.2%

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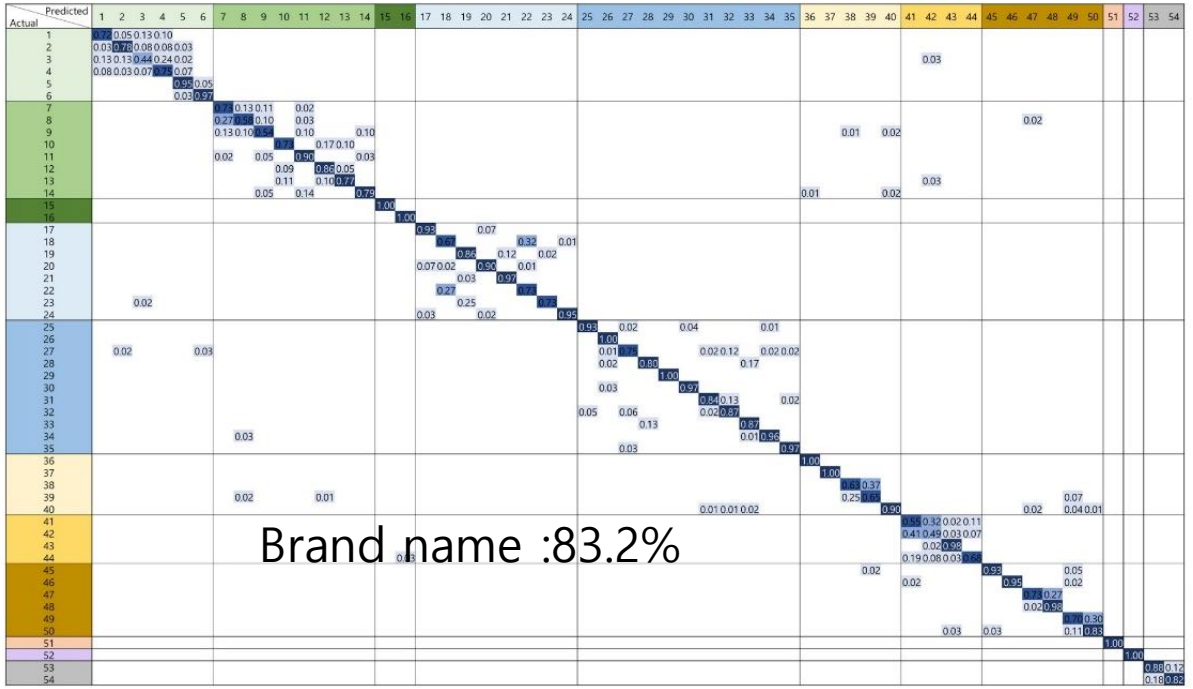
by Brand Name



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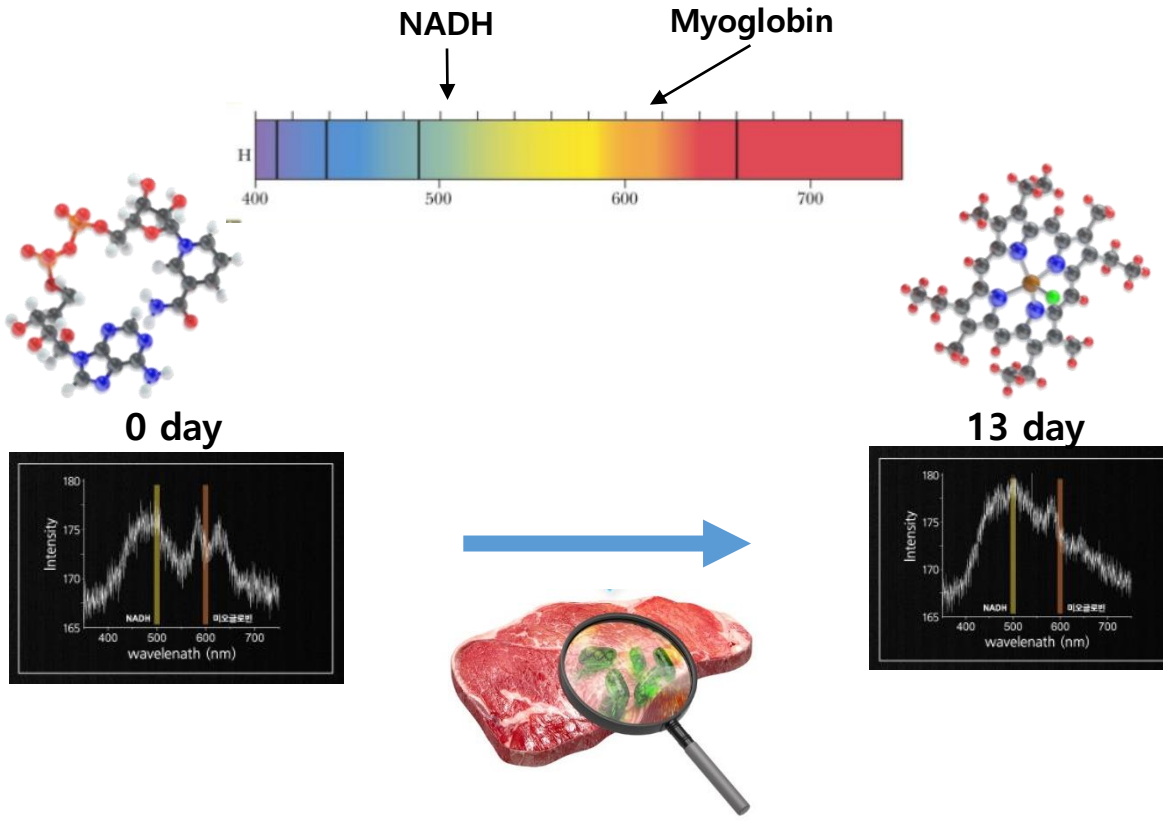
Hyperspectral Image Sensor for Machine Vision

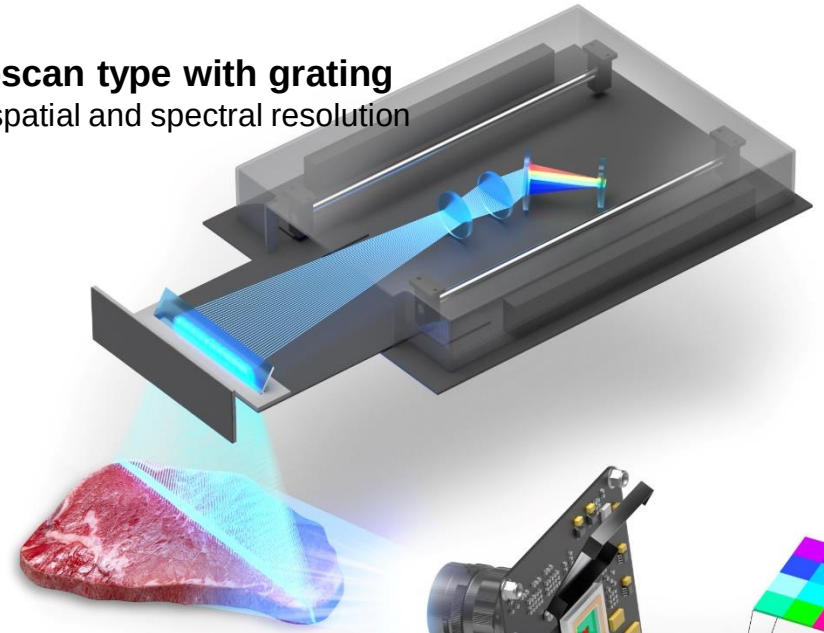
Finger prints for Meat freshness
in its fluorescence excited by 365nm LED



Hyperspectral image to food inspection

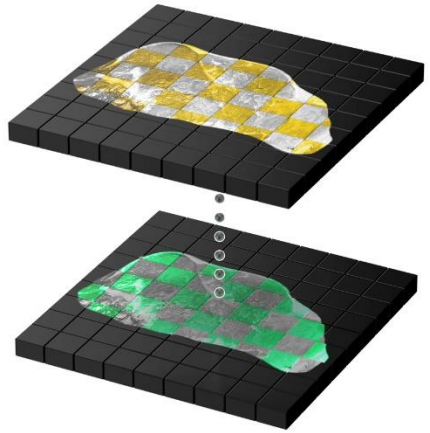
Hyperspectral Imaging System (HIS)

Line-scan type with grating
High spatial and spectral resolution



Snap-shot type
Low spatial and spectral resolution
Low data size

Hyperspectral data cube



Traditional analysis

Machine Learning

Food inspection

to be submitted

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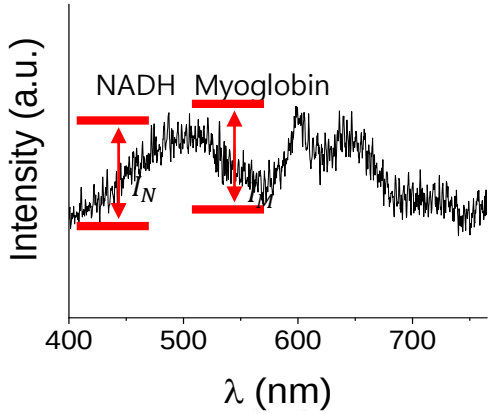
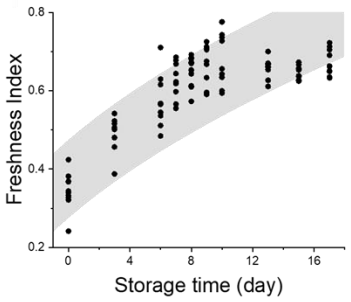
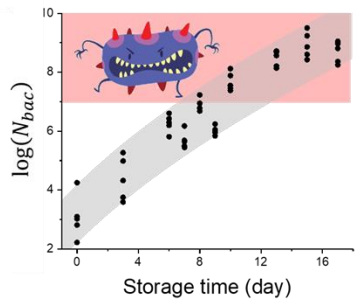
Hyperspectral image for food inspection

line scan type HIS + traditional analysis

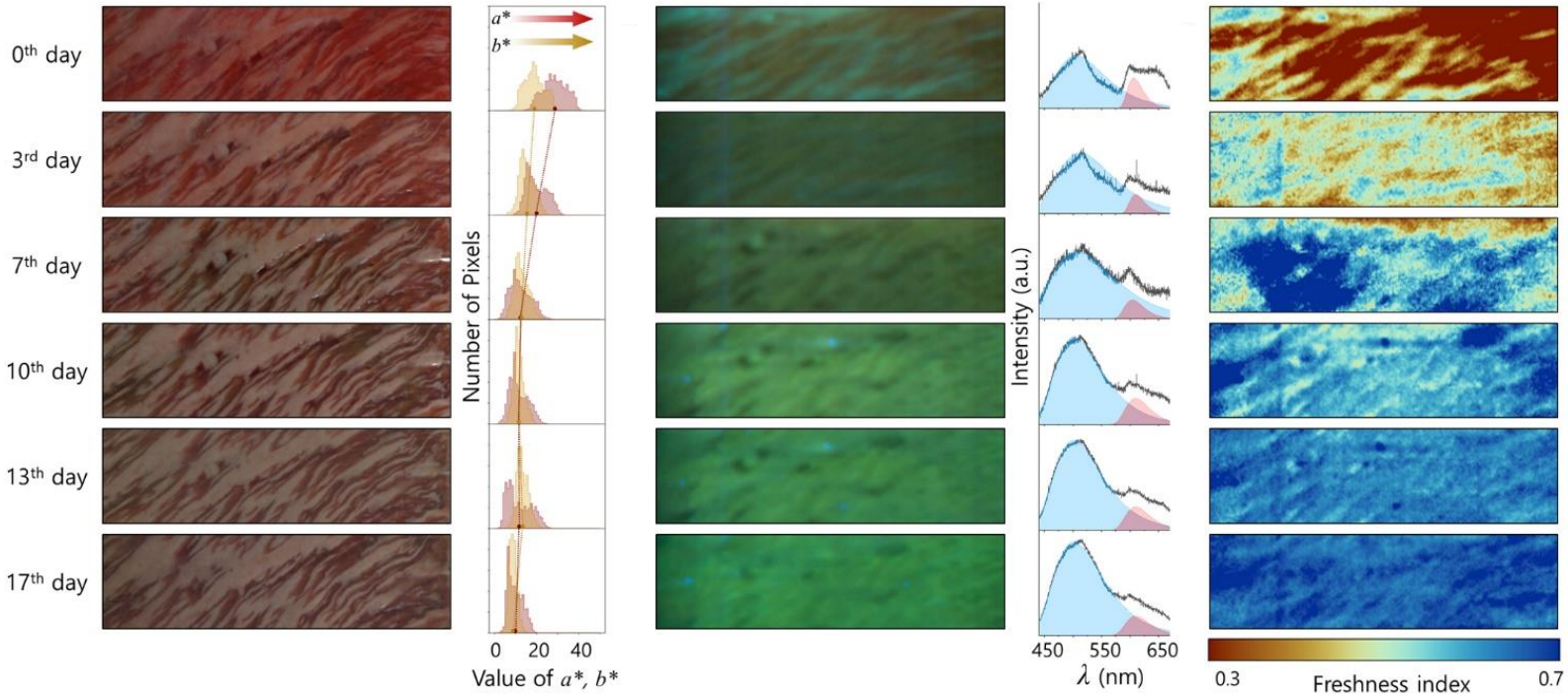
Freshness of beef : evaluated by data from spectral images
→ NADH and Myoglobin fluorescent peak determines freshness.







$$\text{Freshness Index} = (I_N - I_M) / (I_N + I_M)$$



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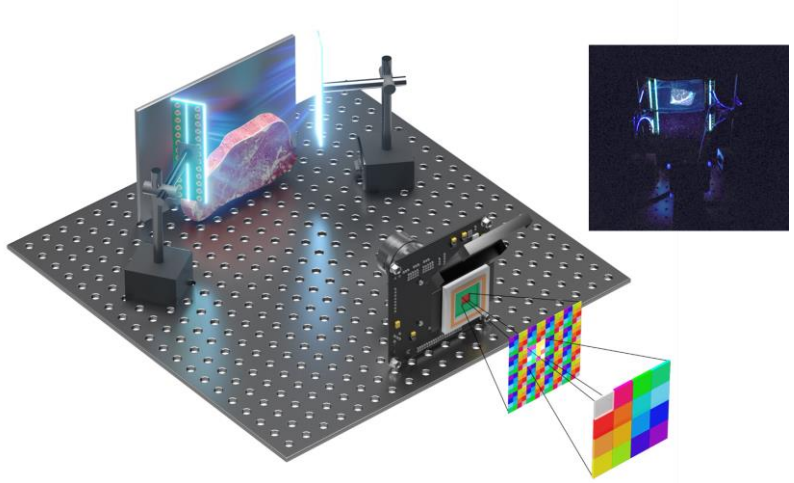
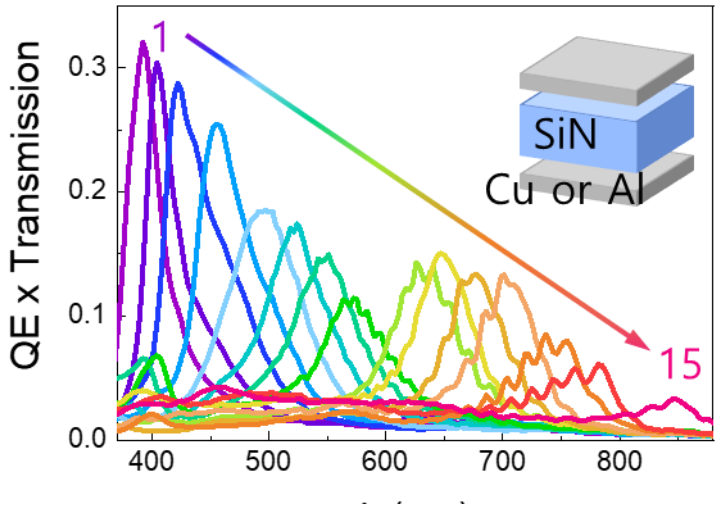
Hyperspectral image for food inspection

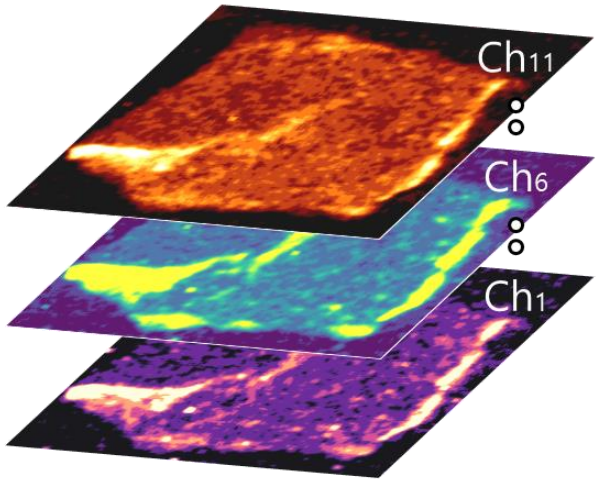
Snap shot type HIS with Machine learning

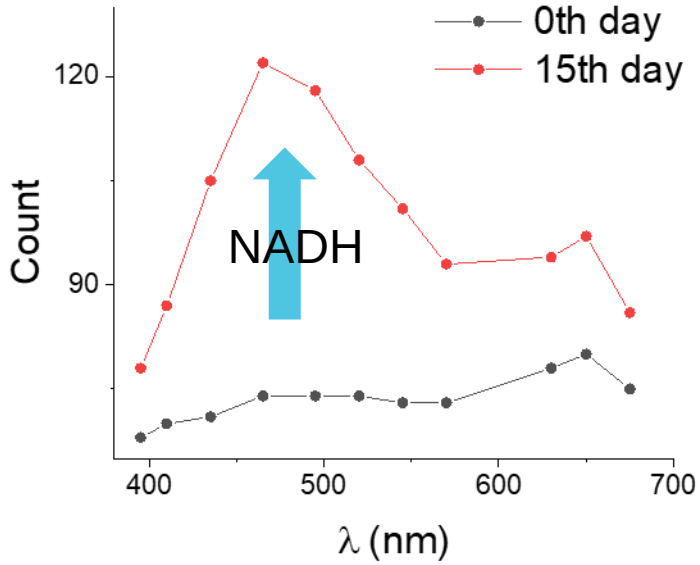


Filter arrays integrated on image sensor

Samsung's 4E8 image sensor







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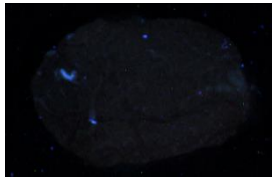
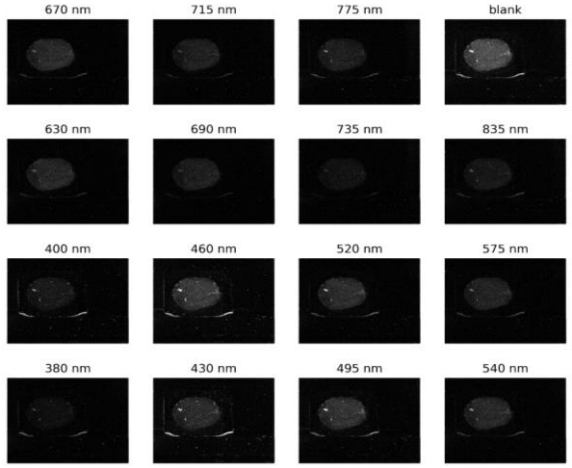
Hyperspectral image for food inspection

상

형광 이미지



Demosaic 이미지



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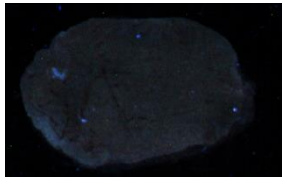

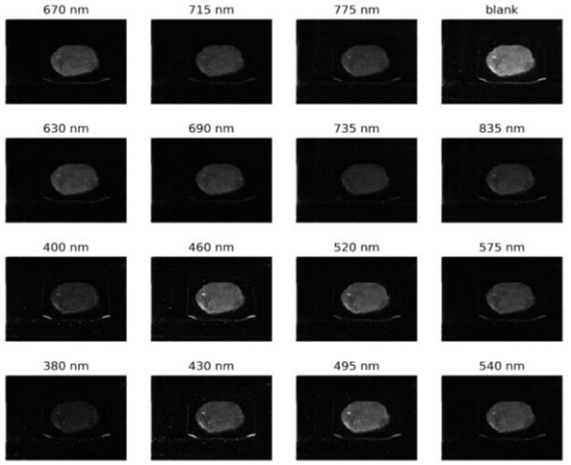

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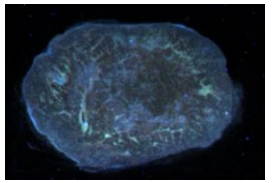

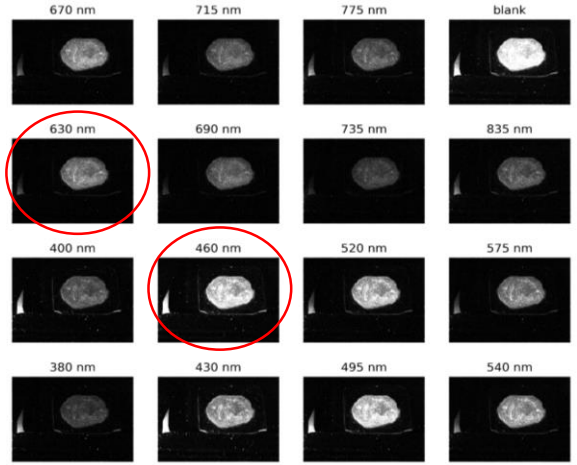

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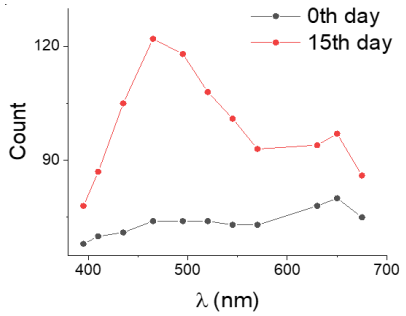
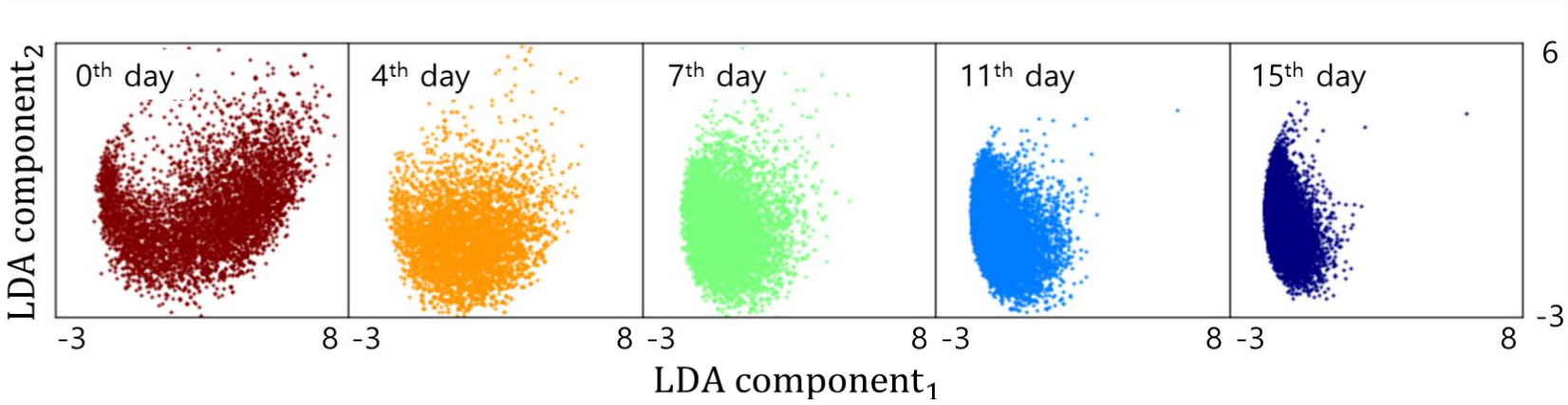
Hyperspectral image for food inspection

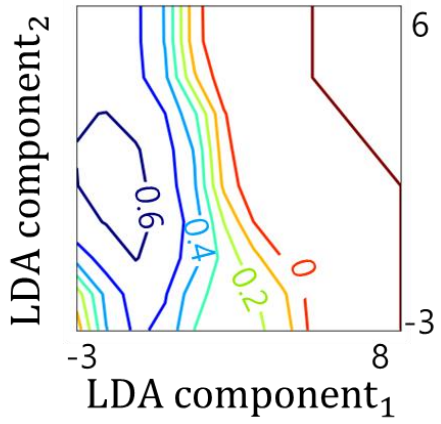
Dimensionality reduction

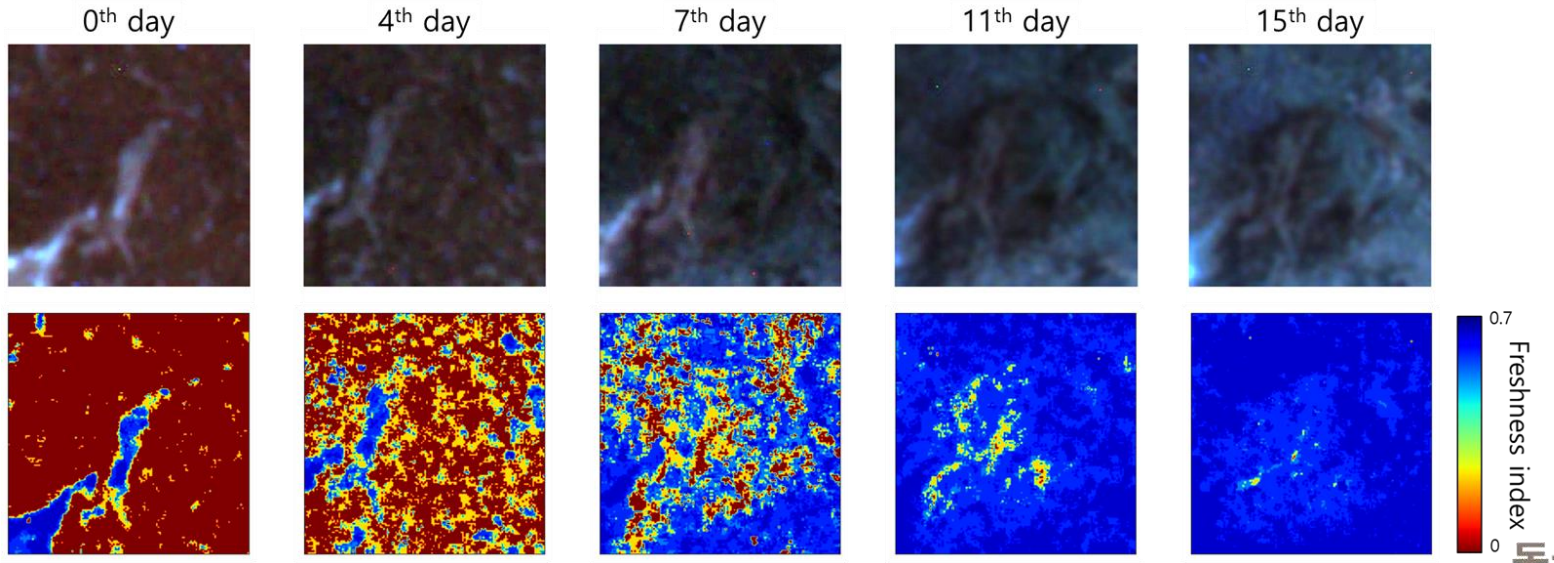




Generating decision boundary

supervised learning





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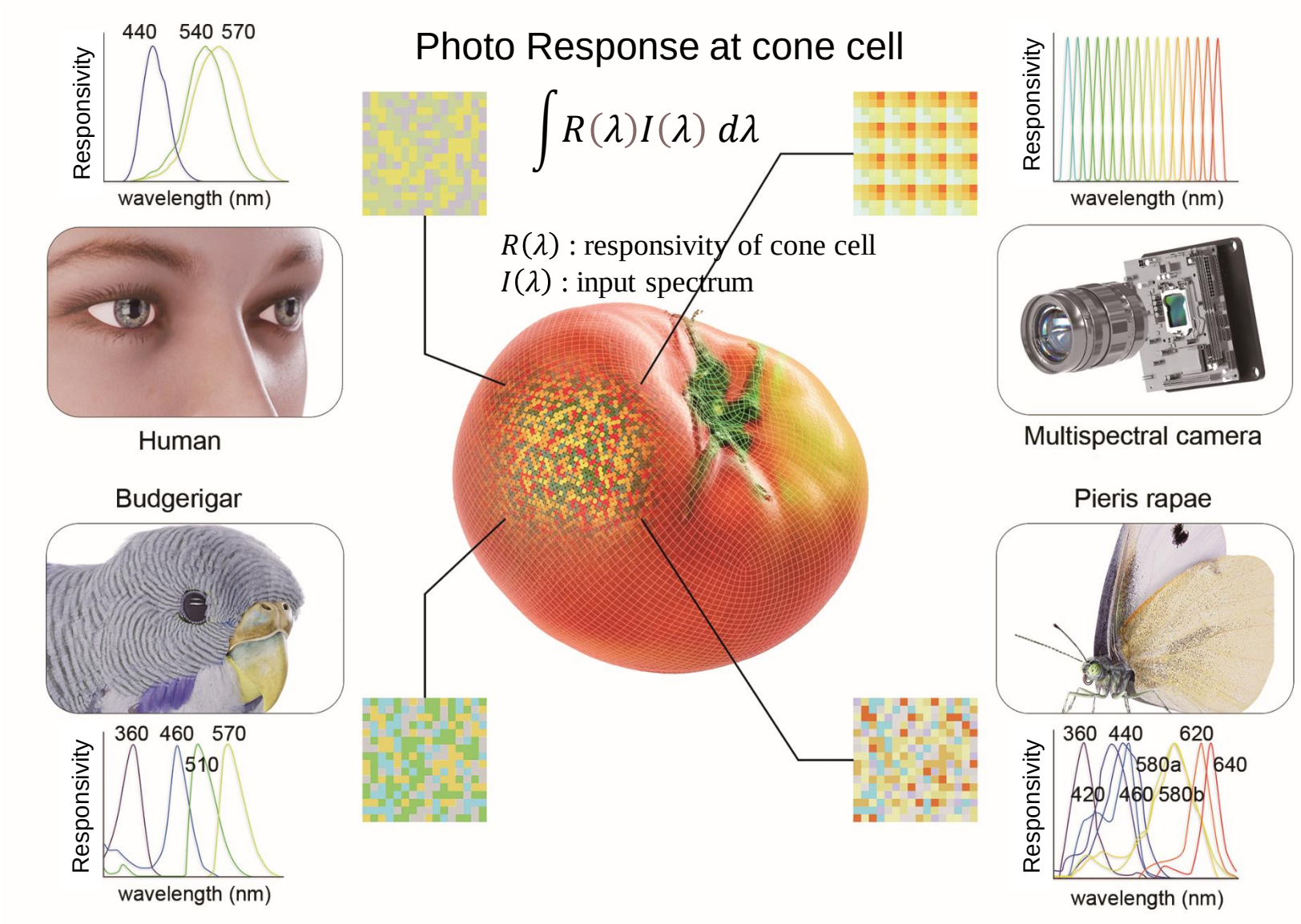
Polychromatic Vision for Smart Farming



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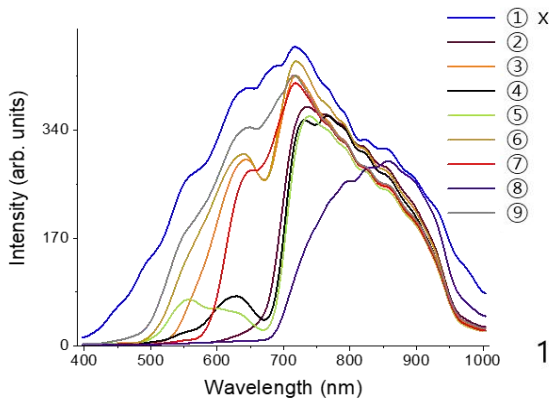
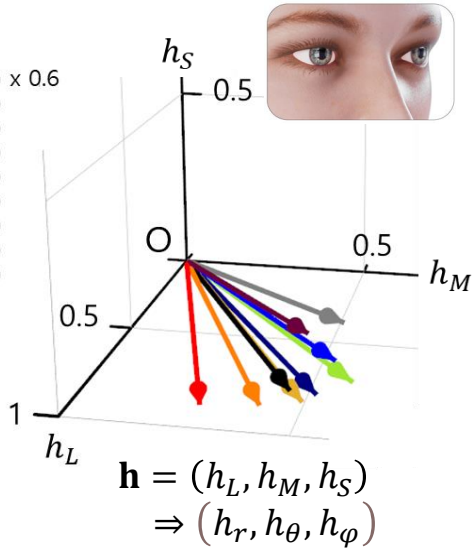
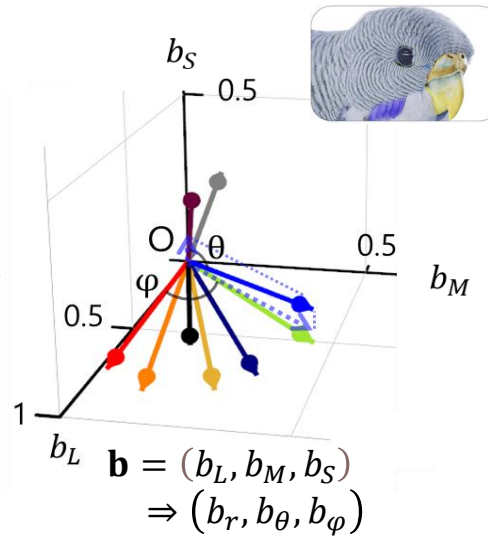
Color Discrimination Sharpness

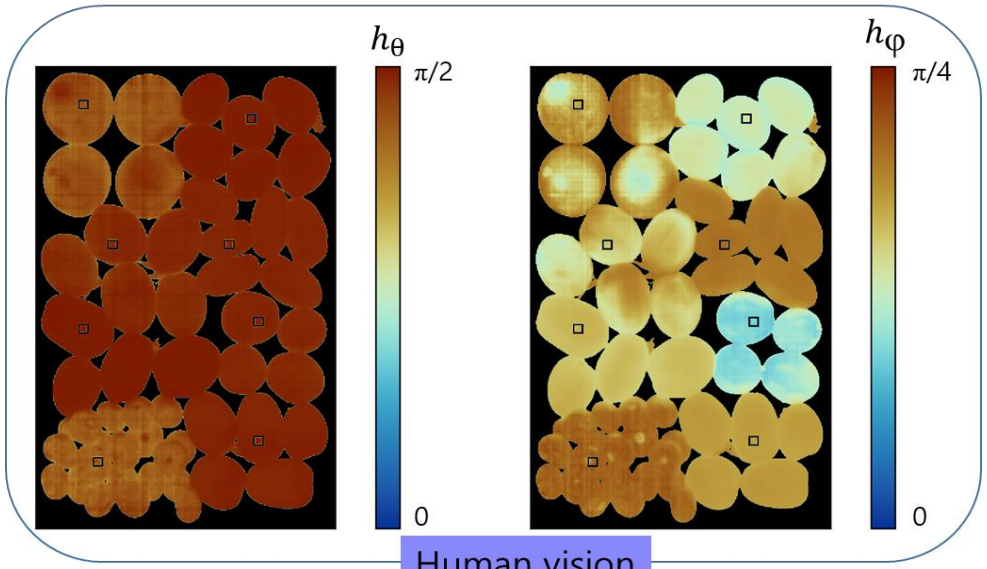


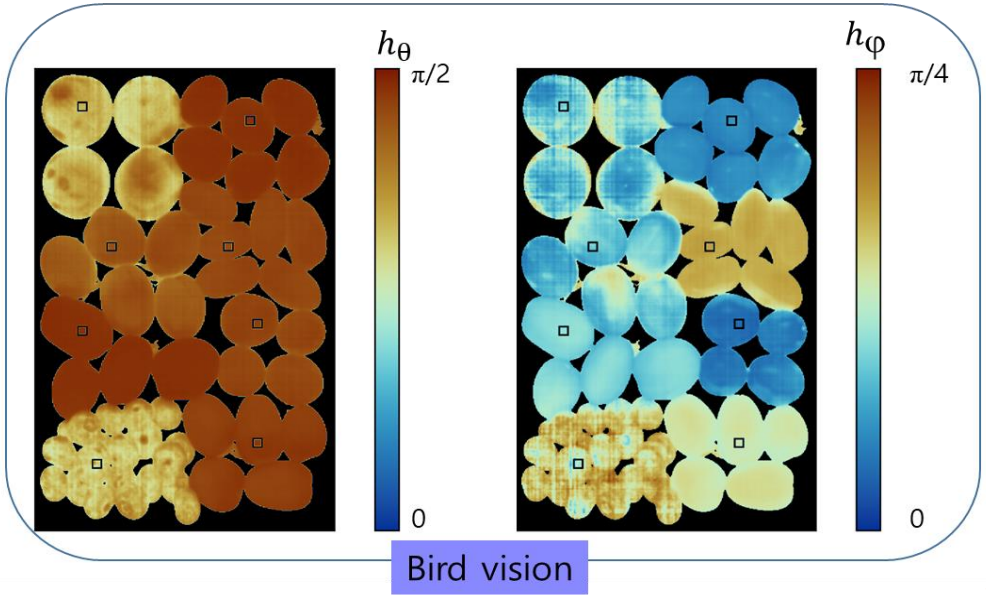


$\mathbf{h} = (h_L, h_M, h_S)$
$\Rightarrow (h_r, h_\theta, h_\varphi)$

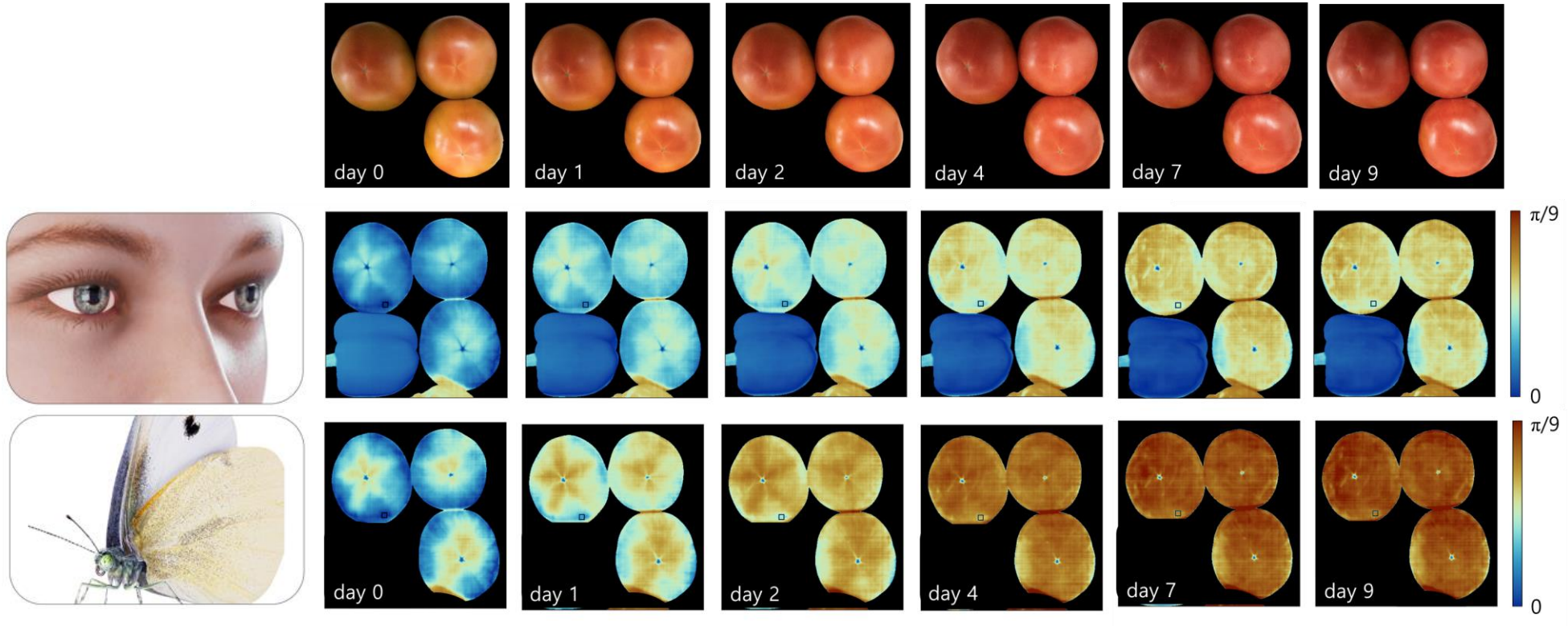


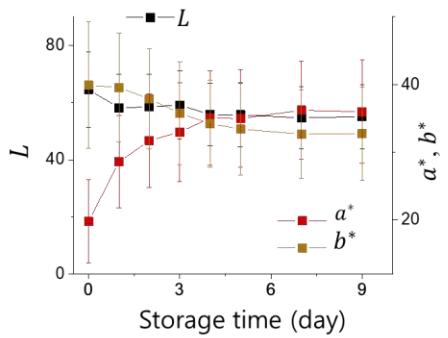
$\mathbf{b} = (b_L, b_M, b_S)$
$\Rightarrow (b_r, b_\theta, b_\varphi)$

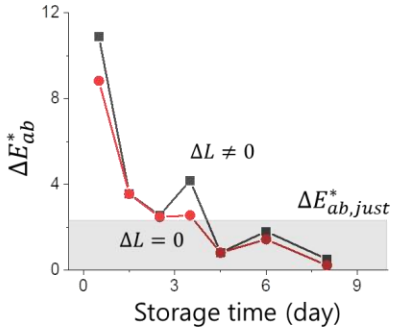


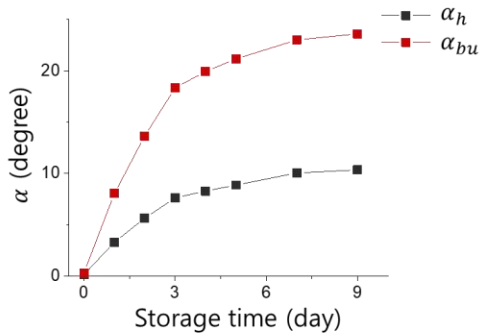


Post-Maturity Detection by Butterfly Vision









$$\Delta E^*_{ab} = \sqrt{\Delta L^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

$$\alpha = \arccos((\mathbf{h}(i) \cdot \mathbf{h_0}) / (|\mathbf{h}(i)||\mathbf{h_0}|))$$

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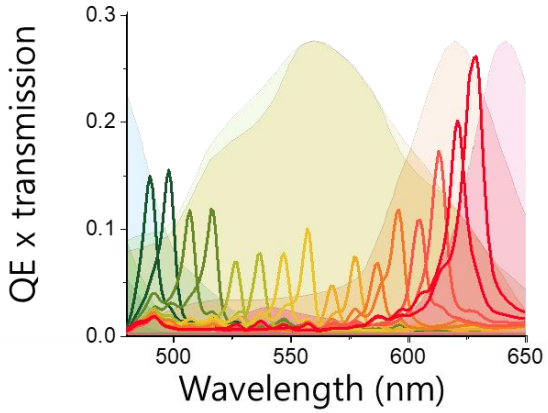
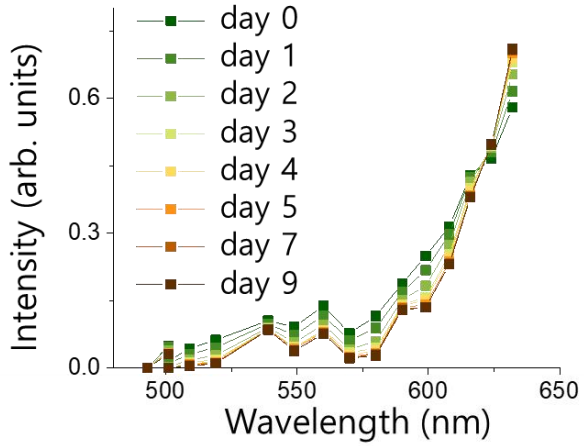
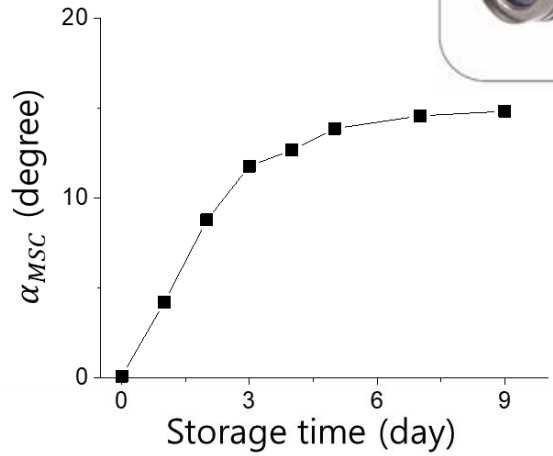
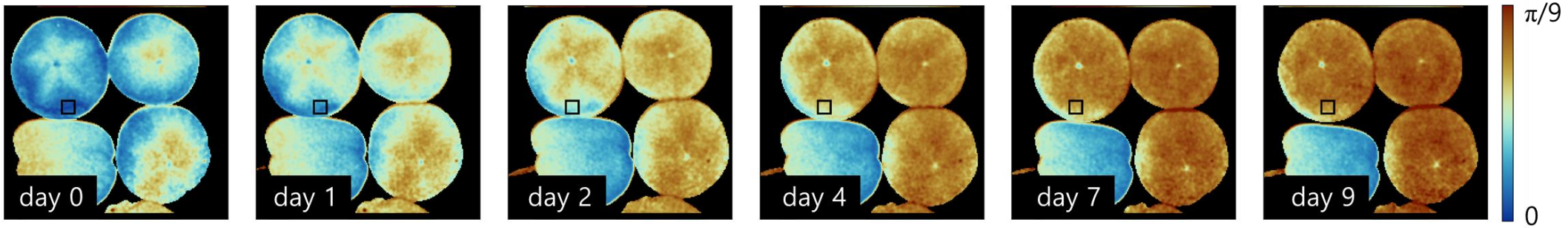
Poly Chromatic Vision for Post-Maturity









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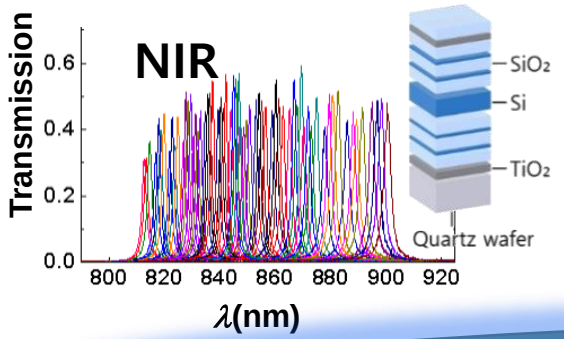
Summaries



Drug Classification

- NIR
- Low Spatial resolution
- High Spectral resolution

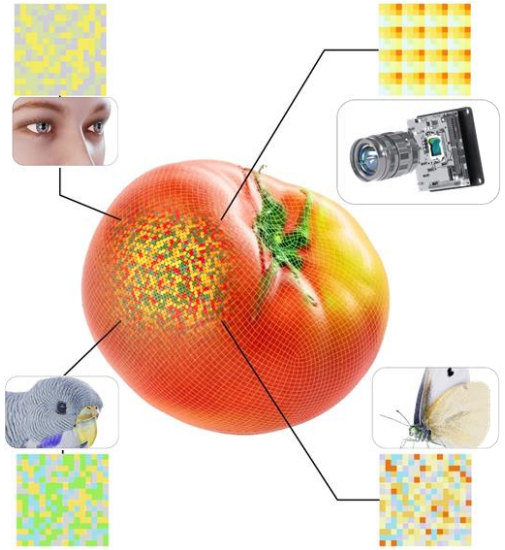
Raman spectrometer (785nm)

Raman Spectrometer

Fluorescence

Reflectance

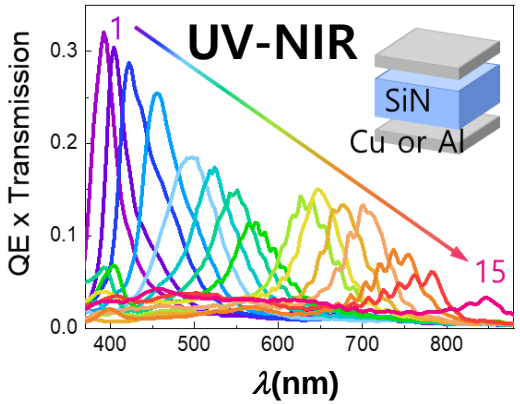
Smart Farming



- UV-NIR
- High Spatial resolution
- High Spectral resolution

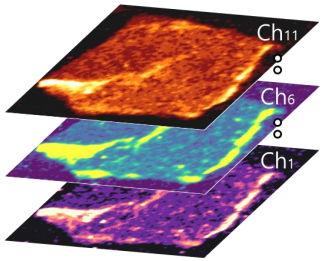
Hyperspectral image sensor
: Reflectance (ambient light)

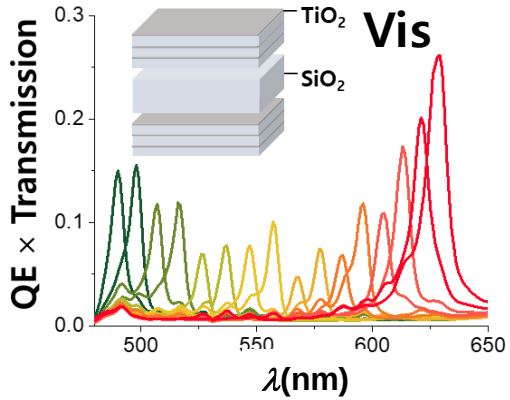
Machine Vision



- UV-NIR
- High Spatial resolution
- Low Spectral resolution

Hyperspectral image sensor
: Fluorescence (365nm)





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