The Detector Seminar at CERN

# Recent Progresses of Visible Light Image Sensors

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# Contents

# What is Image Sensors?

- Semiconductor device, which converts light image to electric signal.
- Used in cameras.

## Examples of applications

Smart-phone

Movie

Automobile

Endoscope

Iris verification

Security

## Image Sensor

DSC

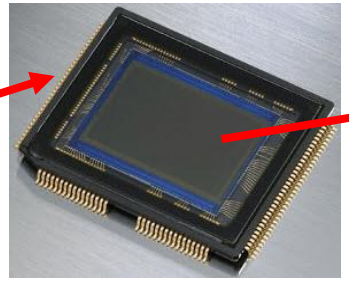
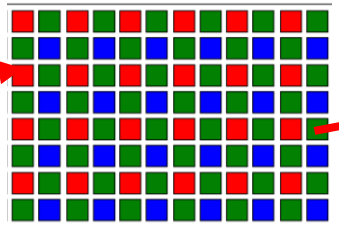
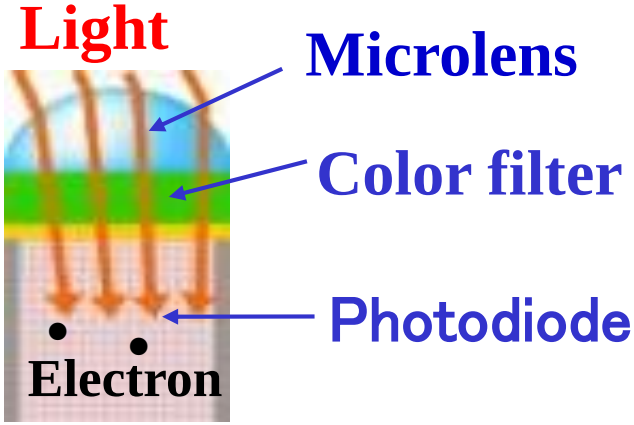


Image sensor



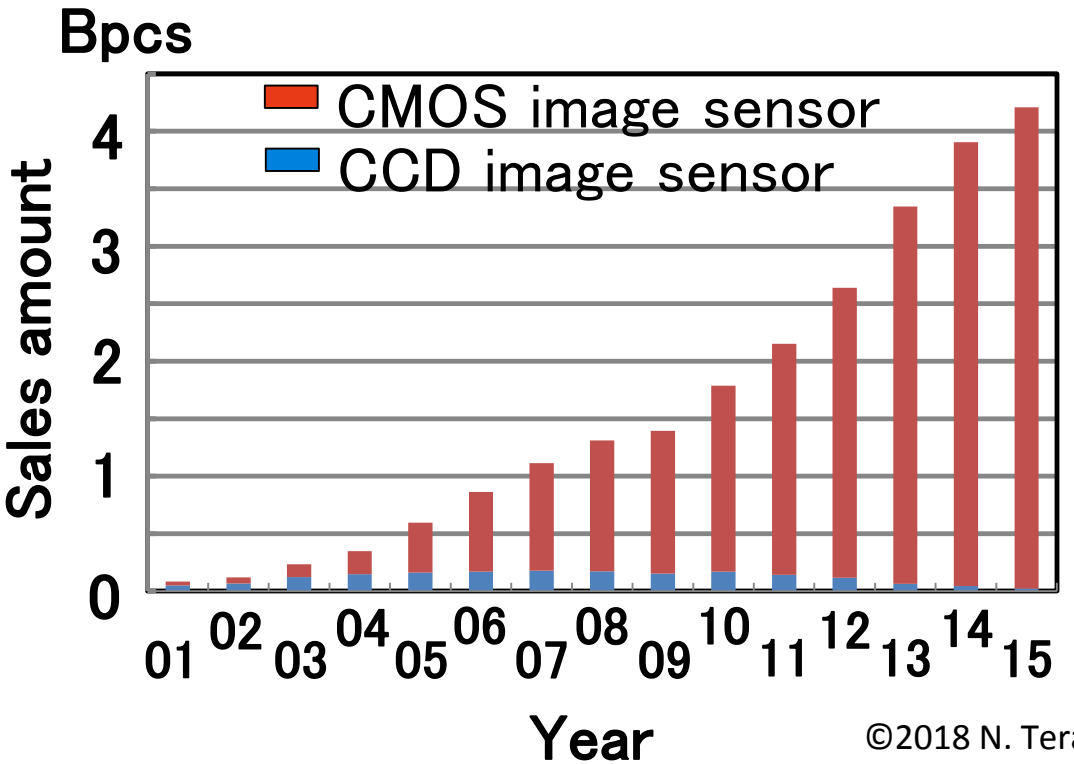
Pixel array

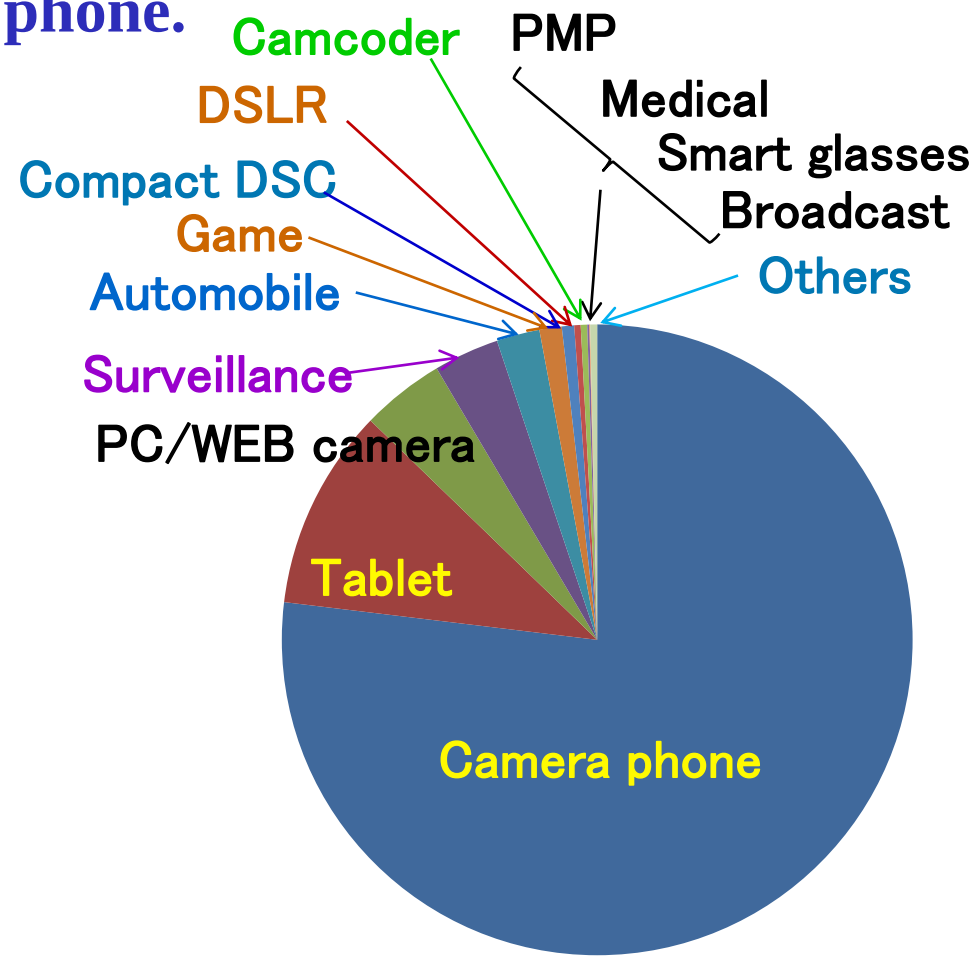



Pixel cross-section

# Image Sensor (IS) Market

- IS sales amount has grown by camera phone.
- IS spreads into various applications,
- "Others" includes scientific, industrial, …

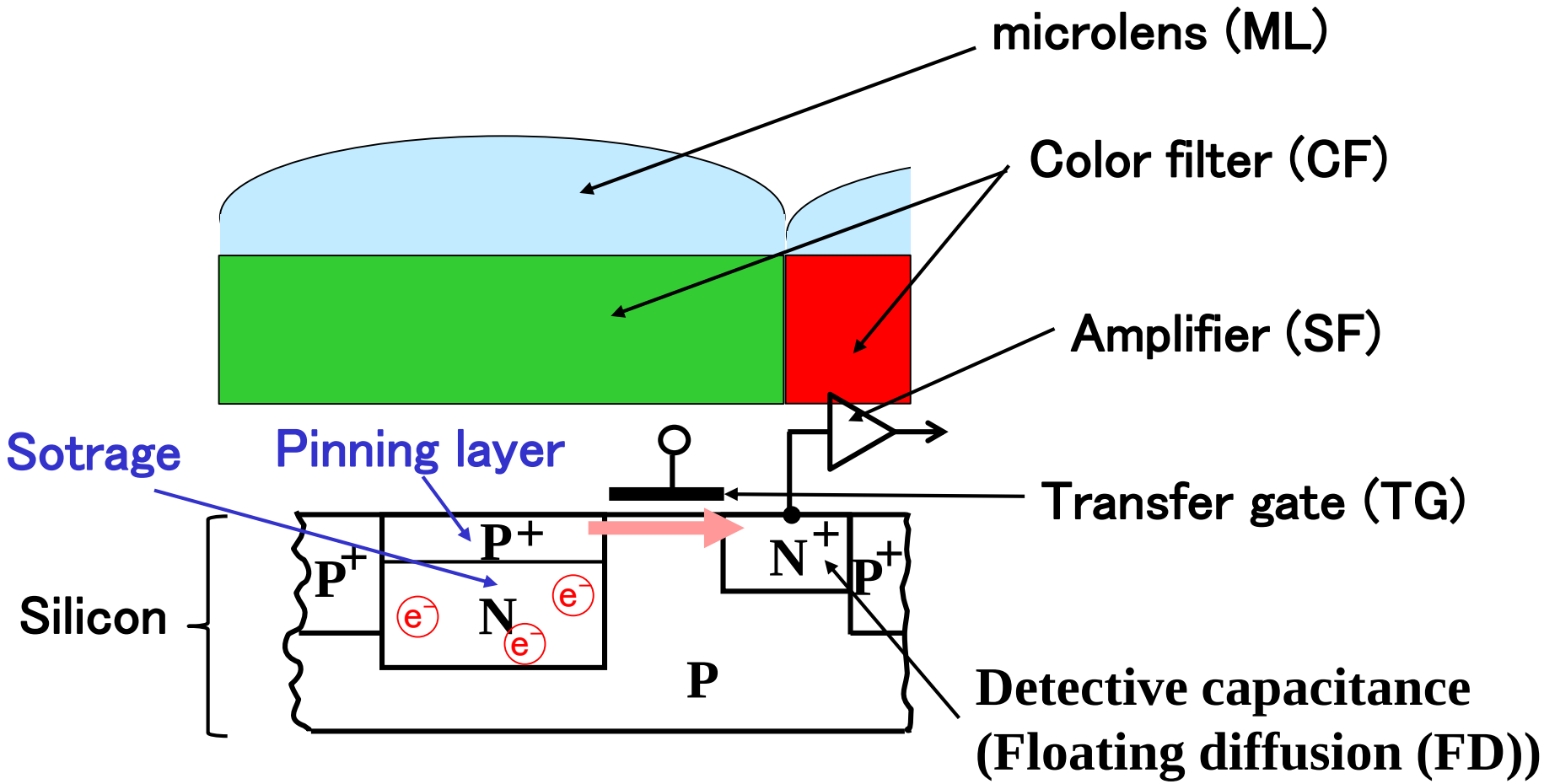



Application in amount (2015)

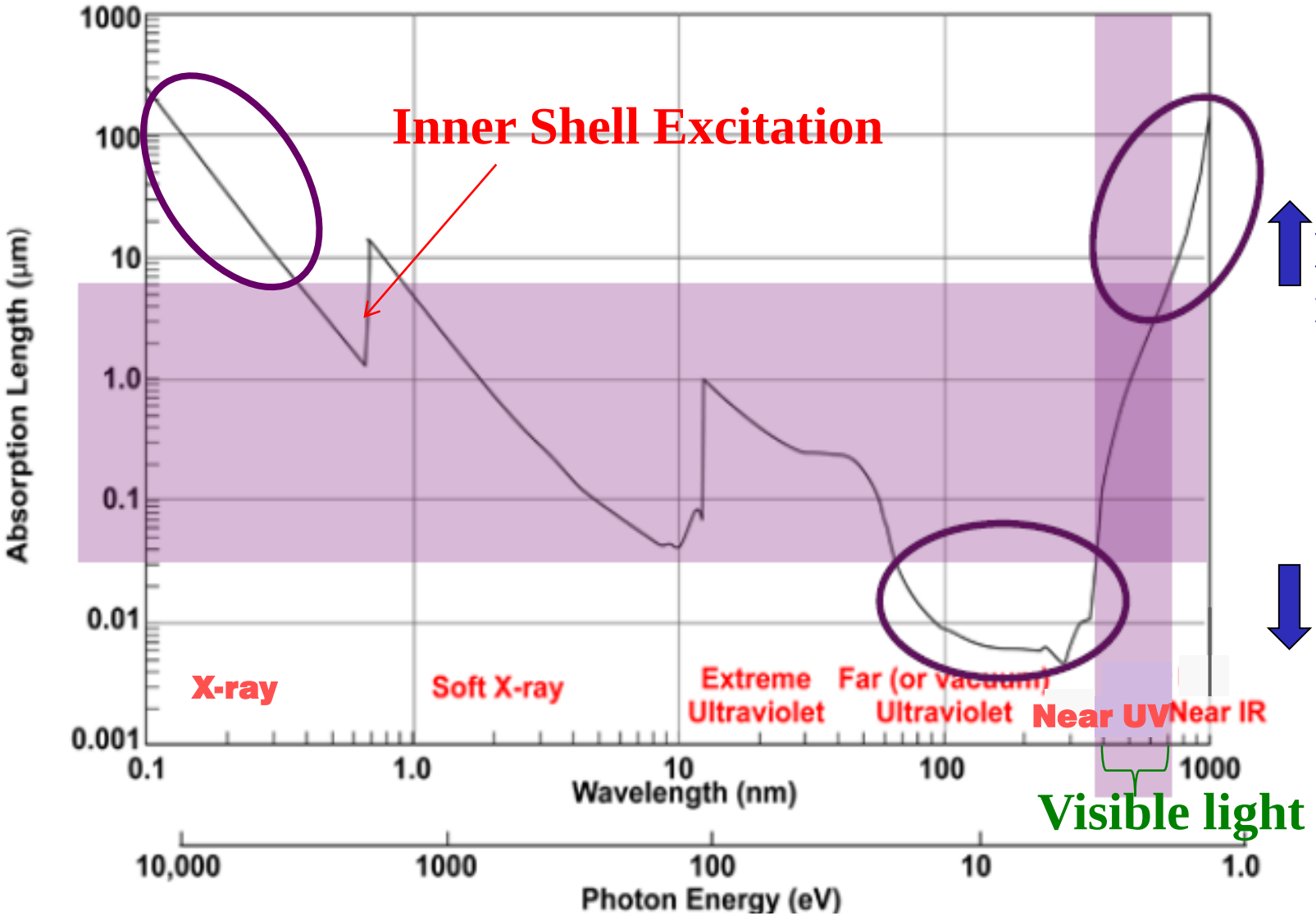
(Source: TSR)

# Pixel Structure




Cross-section of frontside illumination type CMOS image sensor pixel

# Sensitivity Expansion to Invisible




Large depletion is needed.

Small surface dead layer is needed.

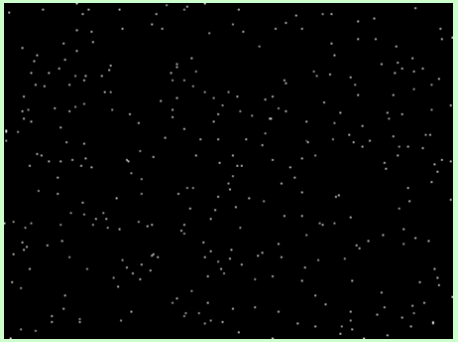
Based on (Piet De Moor (IMEC))

# Contents

# Classification of Dark Current and Blemish

Average: Dark current
- Dark current shot noise
- Black level shift by temperature

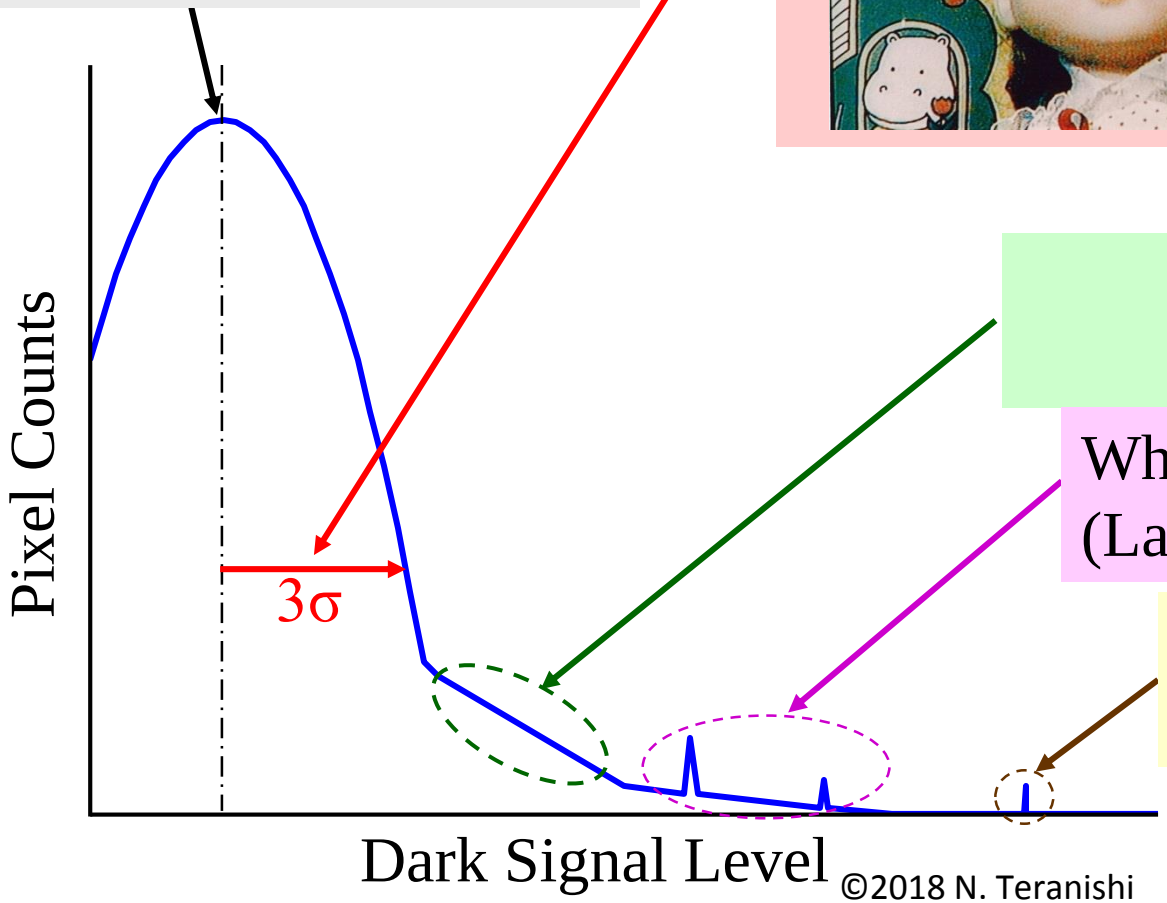
Dark current FPN
(Dark current pixel-by-pixel fluctuation)



Micro white blemish
(Mid-range)

White blemishes
(Large-range)

Very large level blemish
by radiation damage



# Metal Contamination (1)

- Metals, especially transition metals, form mid-gap levels, which become GR centers.
- Generate dark current based on Shockley-Read-Hall (SRH) process

$$U = \sigma v_{th} N_t \frac{pn - n_i^2}{n + p + 2n_i \cosh\left(\frac{E_t - E_i}{kT}\right)}$$

$U$: Recombination Rate

(Sze: "Semiconductor Devices" Chap. 1 Eq.(59))

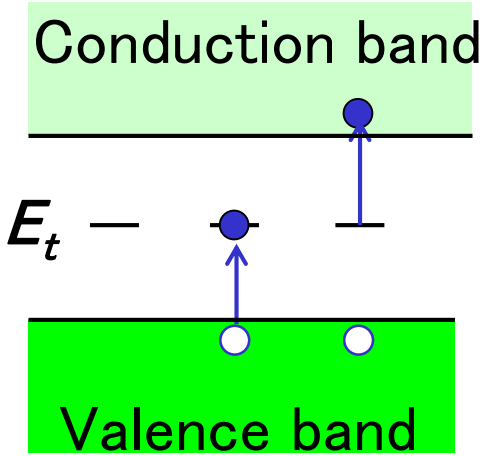
Assuming the cross sections, $\sigma_n = \sigma_p = \sigma$

$N_t$: GR center (trap) density

- **Assuming depletion condition, then, $n$, $p$ = 0, and $E_t$=$E_i$ because $U$ becomes the largest;**

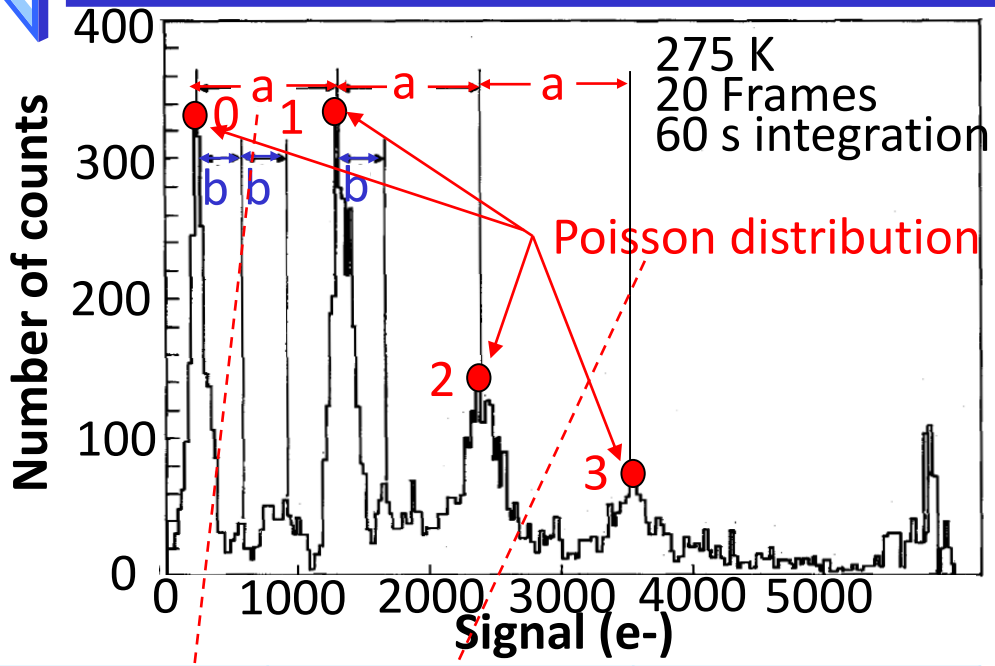
$$U = -\frac{\sigma v_{th} n_i N_t}{2} \quad \text{(Unit : 1/cm}^3\text{s)}$$

- **One GR center generates** $U = -\frac{\sigma v_{th} n_i}{2}$, **(Unit : 1/s)**




Dark current by mid-gap level

# Metal Contamination (2)




| | σ(cm²) | Density(1/pixel) | Density(cm⁻³) |
|---|---|---|---|
| a | 1.8E-15 | 1.25 | 1.3E9 |
| b | 5.4E-16 | 0.15 | 1.5E8 |

**Two series of specific and periodic peaks, labeled as "a" and "b".**

**Assuming metals are distributed as Poisson distribution, metal density per pixel can be derived.**

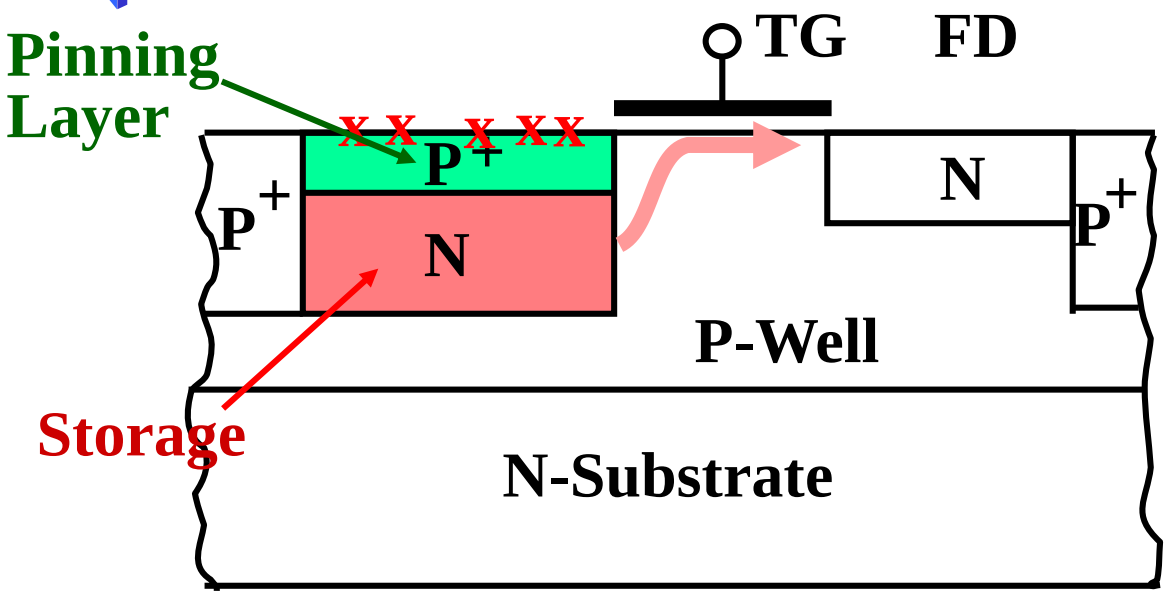
**σ s are derived from the pitches using the previous slide formula.**

- **"Dark Current Spectroscopy" identifies metals and estimates concentrations.**
- **It can measure very small amounts of metal contamination.**

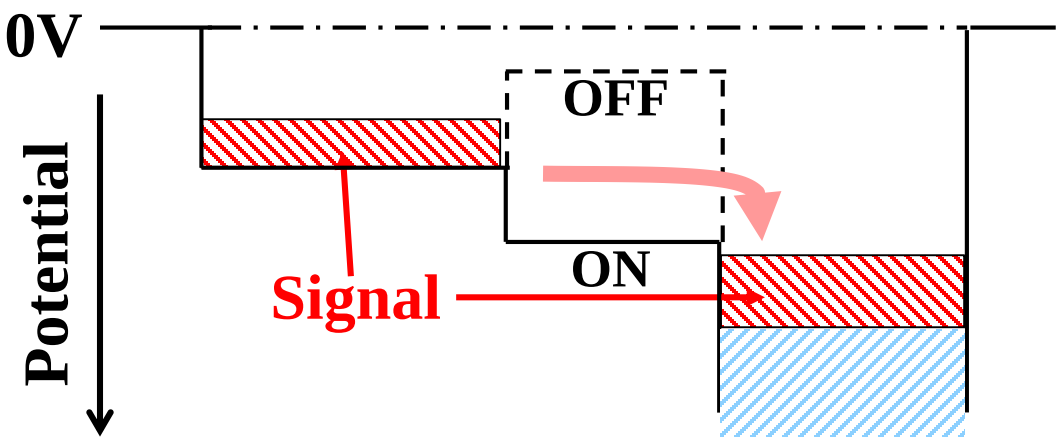
(D. McGrath et al. (TI); "Counting of Deep-Level Traps Using a Charge-Coupled Devices")

# Contents

# PPD (Pinned PD) Structure and Advantages




x: GR (generation-recombination) center




1. Grounded $P^+$ pinning layer prevents interface to be depleted, and stabilizes PD electrically.
   - Low dark current
   - Large saturation
   - High blue sensitivity

2. Complete electron transfer
   - No image lag,
   - No transfer noise

Shallow $P^+$ pinning layer (Low energy implantation) ⇒ Good electron transfer

# Dark Current Reduction by PPD

– Theoretical dark current reduction ratio using Shockley–Read–Hall Process:

$$\frac{|U(\text{Not depleted})|}{|U(\text{Depleted})|} \leq \frac{\sigma v_{th} N_t n_i / 2}{\sigma v_{th} N_t n_i^2 / p} = \frac{p}{2n_i} \sim \boxed{10^{-7}}$$

Assuming hole density ($p$) at the $P^+$ pinning layer is $10^{17}$ $h^+$ $cm^{-3}$

– Actual dark current reduction ratio:

| | Non-PPD (1982) | PPD (2012) | Unit |
|---|---|---|---|
| Scheme | CCD | FSI CMOS | |
| Pixel size | 23 x13.5 | 1.12 x 1.12 | µm |
| Dark current | 1,300 | 5.6<br>0.4 % | $e^-/s/\mu m^2$ at 60℃ |

Still big reduction!

# Example of Dark Current Reduction by PPD


Conventional PD


PPD

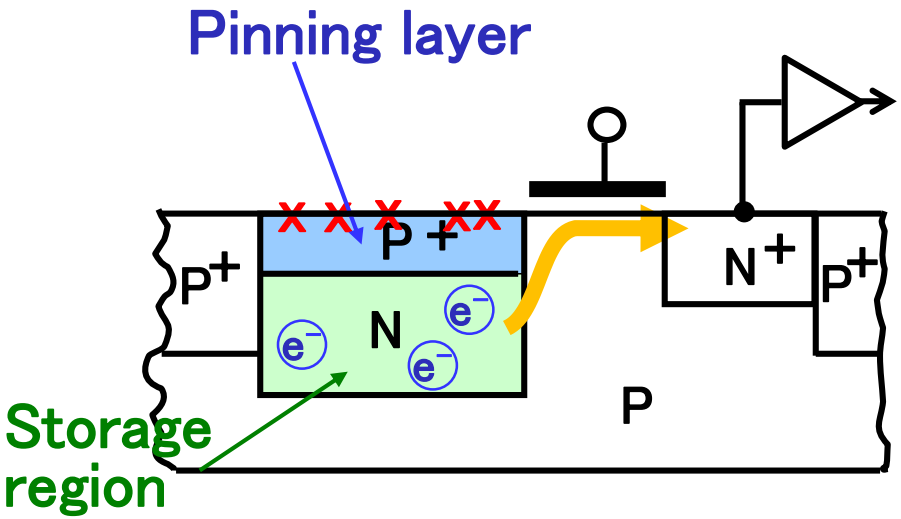
**If Dark current is reduced,**
**dark current FPN, and dark current shot noise are also reduced.**

**Dark current FPN is suppressed, then, picture quality is much improved.**

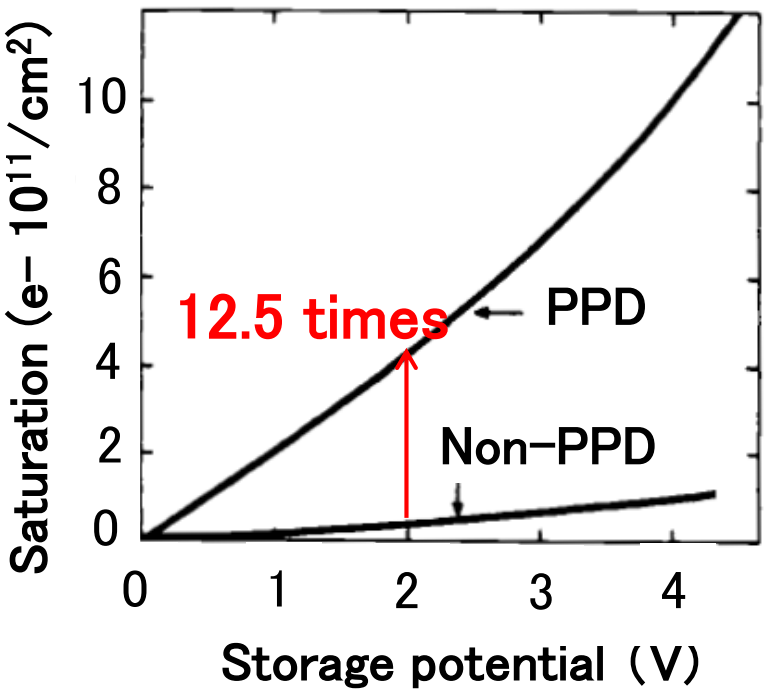
# Saturation is Increased by PPD

Saturation becoms12 times larger by PPD.

- PN junction area is increased.
- Acceptor density at pinning layer >> Donor density at storage




PPD pixel cross-section

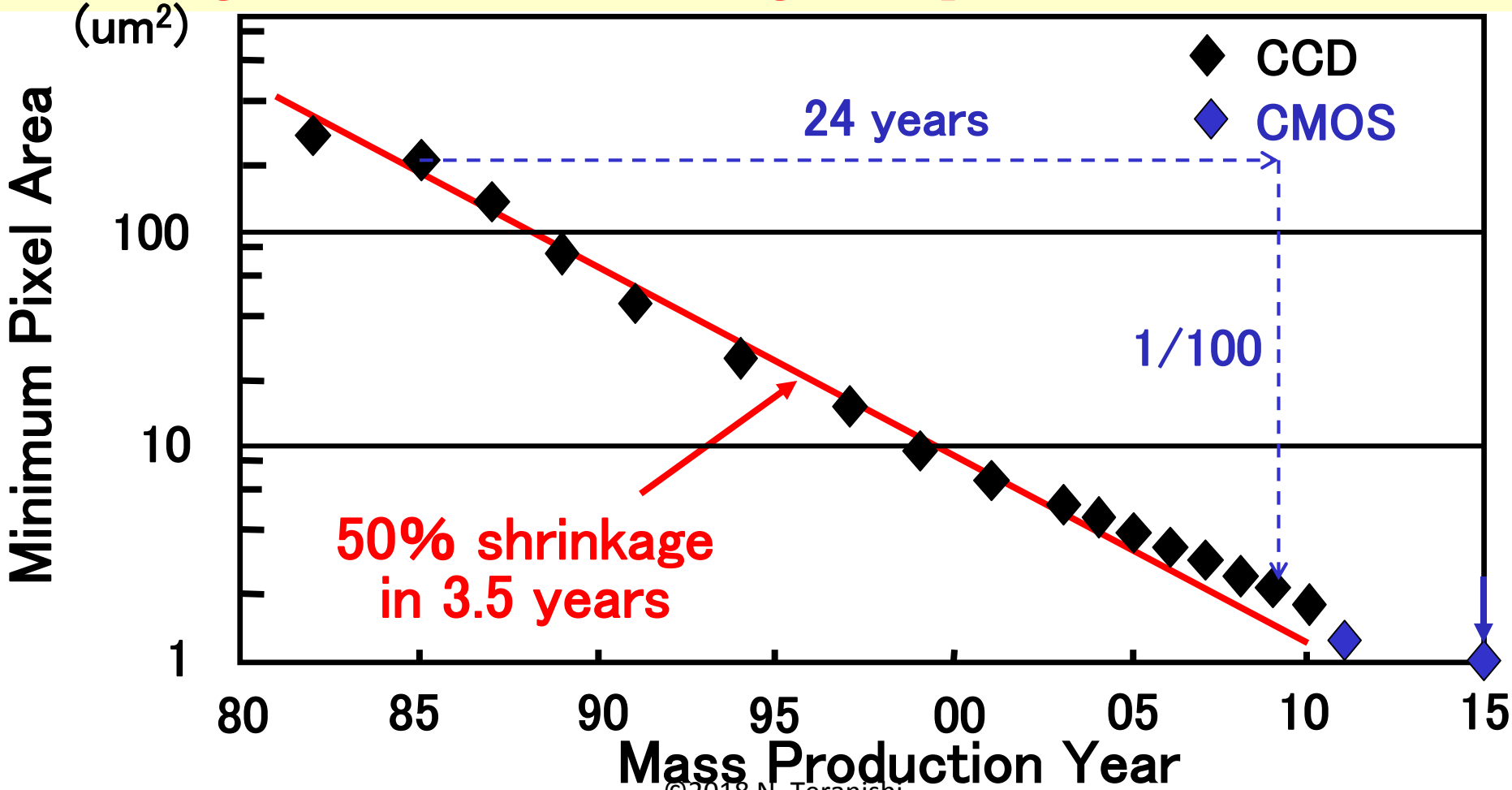



Saturation by simulation

1984 B. C. Burkey et al.(Kodak)

# Pixel Shrinkage Trend

- Shrinkage has been carried out steadily.
- Lens volume and weight become 1/1000 when pixel size becomes 1/100, assuming that F-number, view angle and pixel number are constant,



# Contents

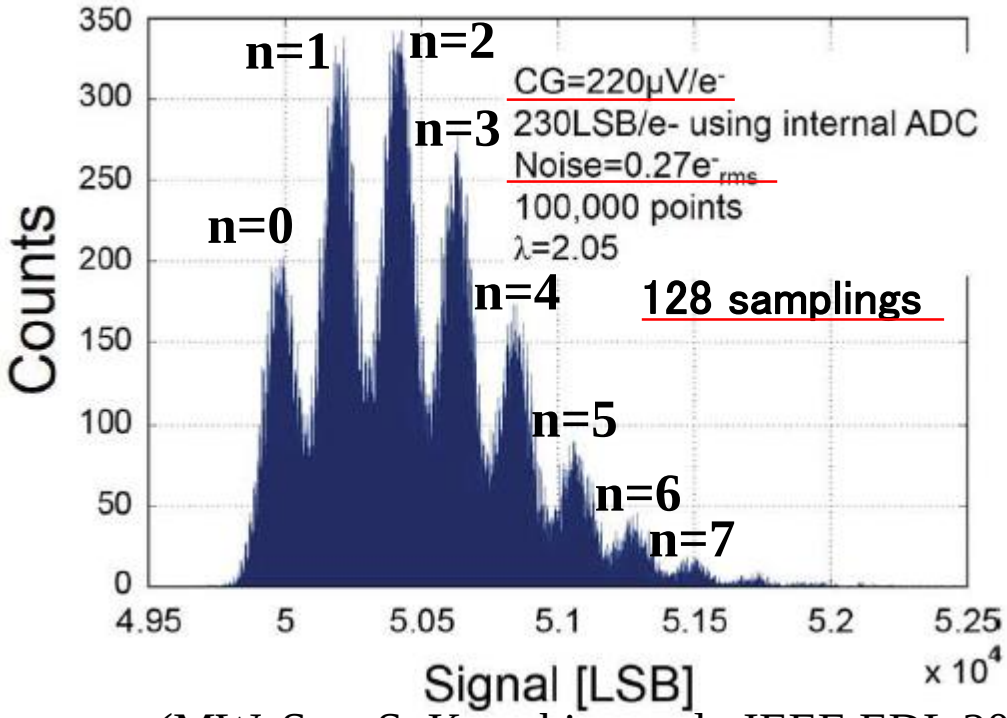
# Photon Counting Image Sensor

**SPAD**
**(Single photon avalanche diode)**

(N. Dutton et al., VLSI Symposium 2014

- QVGA SPAD, 20 fps, room temperature
- High avalanche gain makes following circuit noise negligible.
- Large dark count. Small fill factor

**4-Tr CMOS + High conversion gain + CMS (Correlated multiple sampling)**




(MW. Seo, S. Kawahito et al., IEEE EDL 2015)

- In 2015, several organization reported low noise < 0.3 e- rms.
- DEPFET (Max Plank)

# Photon Counting (2)

(a) Original object
(USAF test chart)


(b) Image by the
RG-less CIS
($0.27e^-_{rms}$)

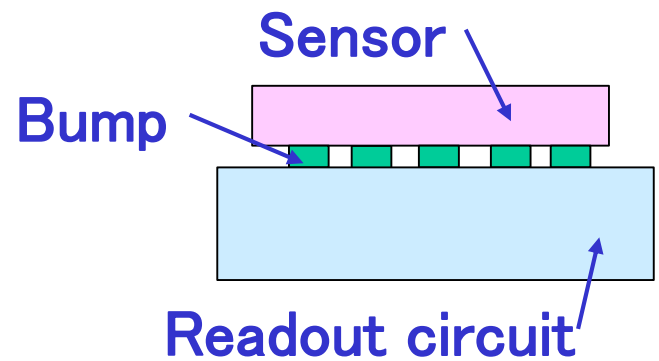

(c) Image by a
conventional
low-noise CIS
($0.44e^-_{rms}$)


(Seo, Kawahito et al, IEEE EDL, Dec. 2015)

# Contents

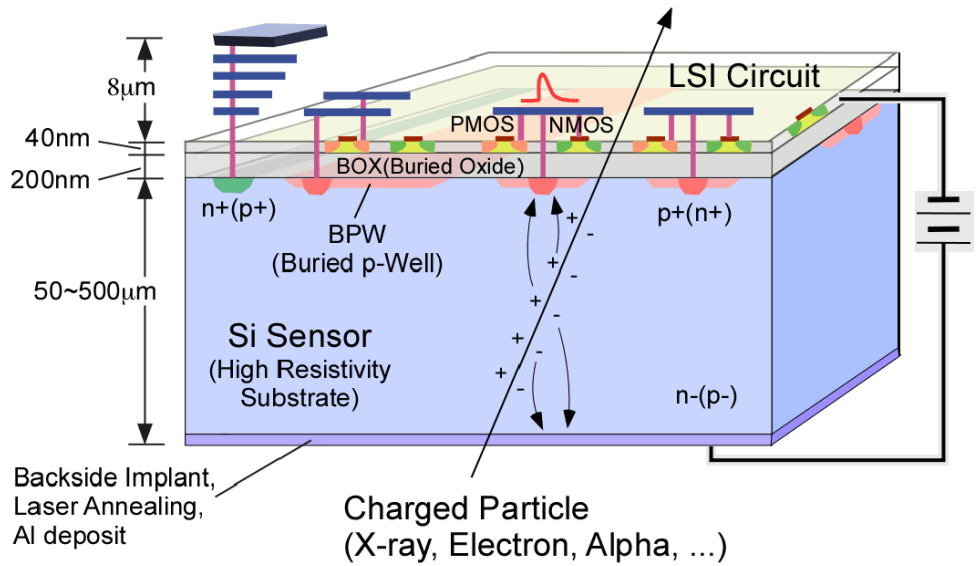
# Stack (1)

Motivation of stack image sensors
- Non-silicon material for sensor part
- Finer process technology for logic part
- Smaller footprint
- More flexibility of wiring
- Isolation between analog and digital circuits




Bump bonding

Approach
- Bump bonding (In, solder Au, …)
- SOI
- Wafer-to-wafer oxide bonding + TSV
- Wafer-to-wafer hybrid bonding



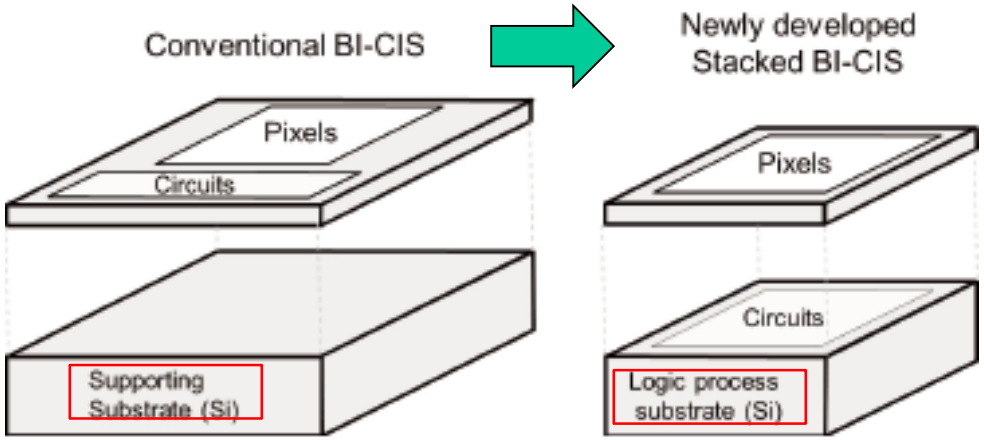

SOI pixel detector (KEK Arai et al.)

# Stack (2). Wafer-to-Wafer Oxide Bonding

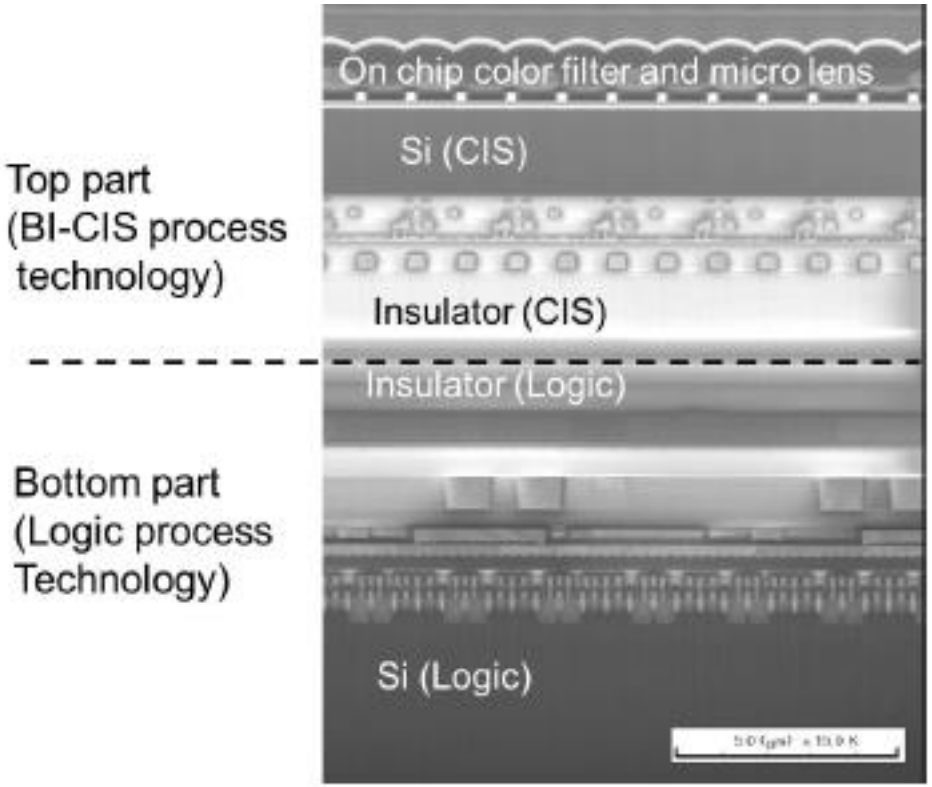
Wafer-to-wafer oxide bonding + TSV(Through silicon via) at peripheral

- Smaller chip size → Smaller camera, lower cost
- Optimal processes for both sensor and logic
- More functions can be integrated.

Suitable for large volume applications




Conceptual Diagram




SEM Cross-section (S. Sukegawa et al., ISSCC 2013)

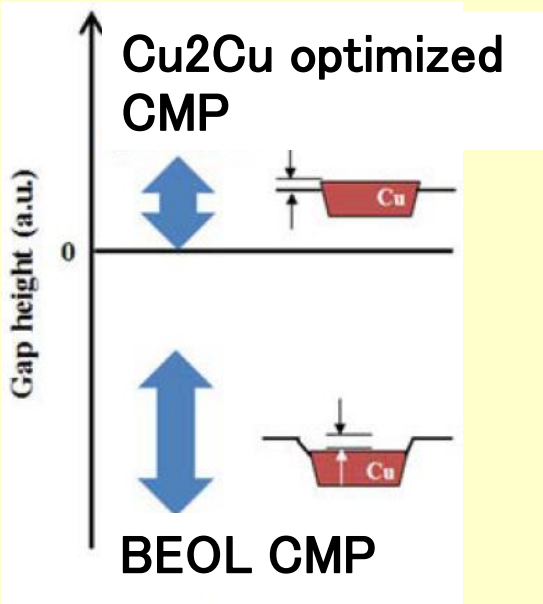
# Stack (4). Wafer-to-Wafer Hybrid Direct Bonding

- **Oxide bonding**
  **+ TSV(Through silicon via)**

**Interconnections are limited at only peripheral.**

- **Hybrid bonding**

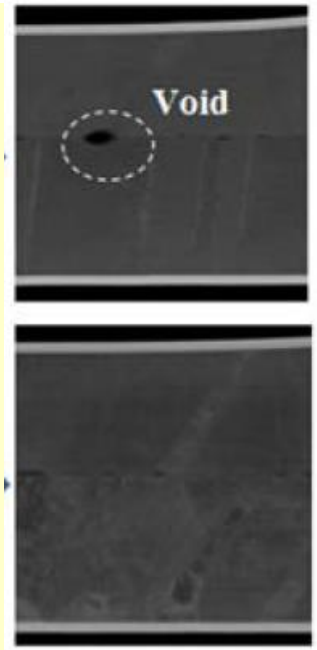
**Interconnection can be located at pixel array also.**




**CMP optimization**

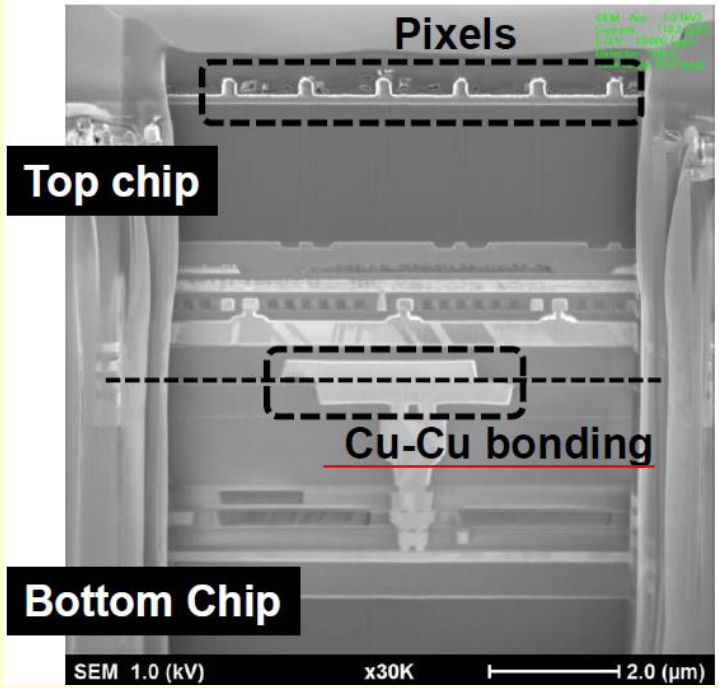
< 150 ℃

400 ℃




**Post-bond annealing**

Y. Kagawa et al. (Sony), IEDM 2016




K. Shiraishi et al. (Toshiba), ISSCC 2016

- **2 um pitch interconnection**

E. Beyne (IMEC), 2018

# Contents

# NIR --- Motivation

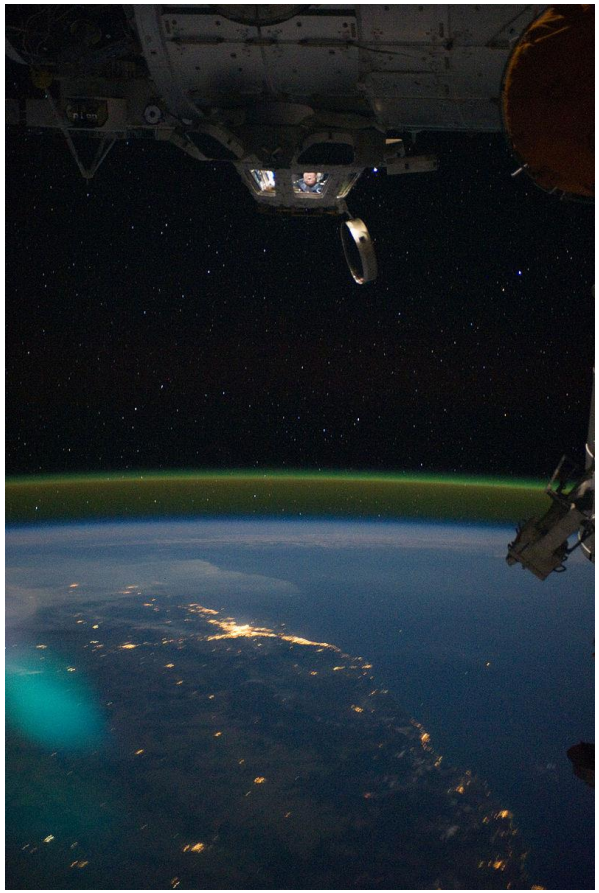
1. To cover shortage of visible light and to increase sensitivity
   eg. Most illuminations have NIR.
   Night glow
   - Security use
2. Invisible for mankind and animal.
   - Gesture interface, ToF,
   - Animal observation at night
3. Eye safe laser (1.4-2.6um)
   - Longer than Si cutoff wavelength
4. Specific wavelength for each application
   - Window to living organisms
   - Fluorescent protein
   - Hemoglobin (Hb)
   - Bill validator (NIR and UV inks are used.)
5. Smaller sunlight background

# Nightglow (Airglow)

- Emission in the upper atmosphere
  - Photoionization by the sun
  - Luminescence by cosmic ray
  - Chemiluminescence
- Light intensity at near IR is larger than that of visible light

| Wavelength ($\lambda$) | Photons (/cm$^2$/s) |
|---|---|
| 0.4-0.7 μm (visible) | $7\times10^{8}$ |
| 0.4-1.0 μm (Si) | $3\times10^{9}$ |
| 0.4-1.4 μm | $2.5\times10^{10}$ |
| 0.4-2.0 μm | $1\times10^{11}$ |

Intensity of night glow

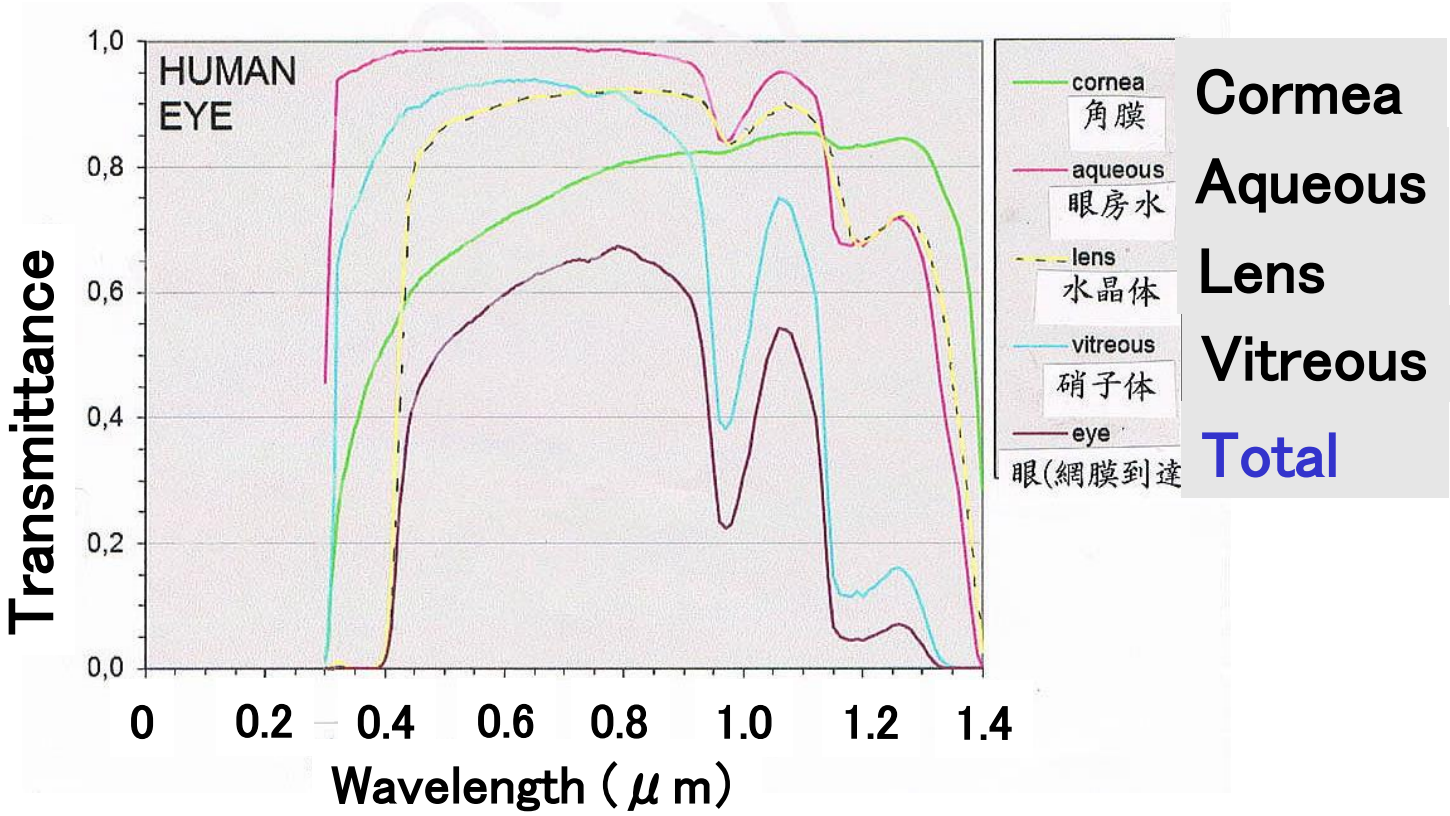


Night glow from ISS

http://en.wikipedia.org/wiki/Nightglow

# Eye-Safe Laser

- 1.4 – 2.6 μm wavelength light hardly reaches retina.
- Application: Night vision, range finder, obstacle detection
- Note: Silicon cannot detect 1.4 – 2.6 μm wavelength light.




Transmittance of young human eye

http://syounanakaribit.sakura.ne.jp/newpage605.html

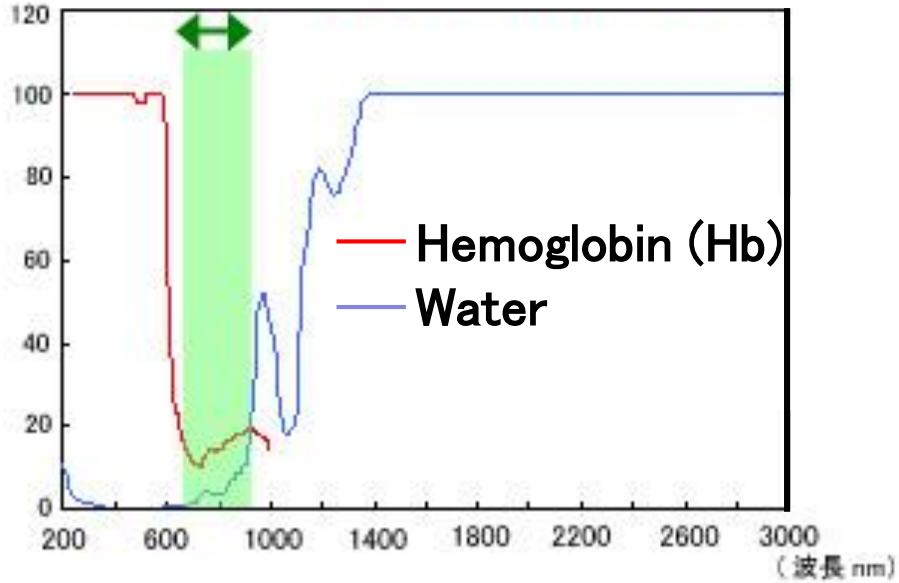
# Window to Living Organisms

- NIR, 700～900 (1400) nm, has a good transmittance of human body.
- It can pass through even 30 cm thick human body.

Specific wavelengths
- Hemoglobin (Hb):
  Oxygen density in vein
- Myoglobin:
  Oxygen density in cardiac muscle and skeleton muscle
- Cytochrome *c* oxidase (COX)
- Melanin

Application
- Vein authentication
- Optical topography
- Fluorescent protein

Window to living organisms




Wavelength (nm)

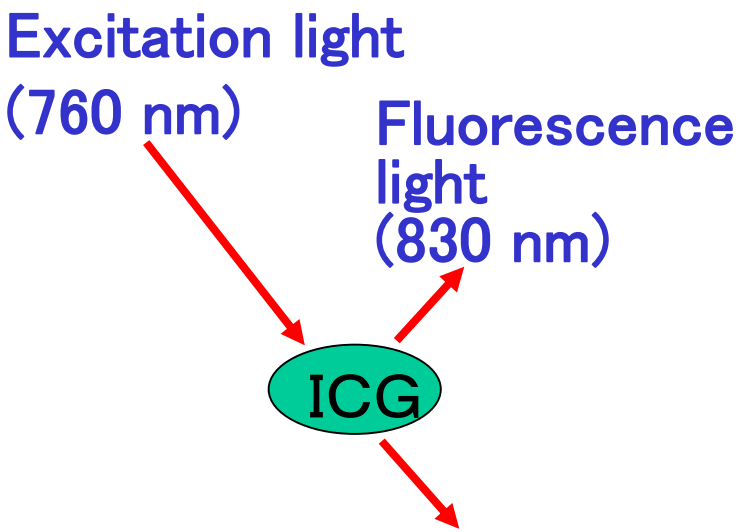
Absorptance of hemoglobin and water

https://www.an.shimadzu.co.jp/bio/nirs/nirs2.htm

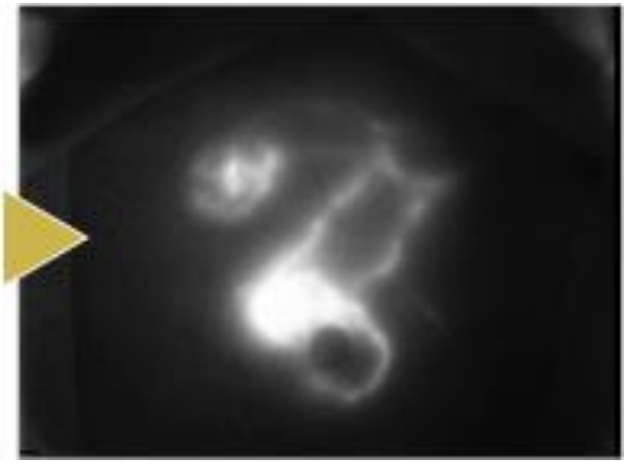
# NIR Fluorescence Imager (ICG Fluorescence)

- Portable intraoperative diagnosis
- Both excitation light and fluorescence light are inside the widow of living organisms.

**NIR fluorescence camera**




**Visible light image**



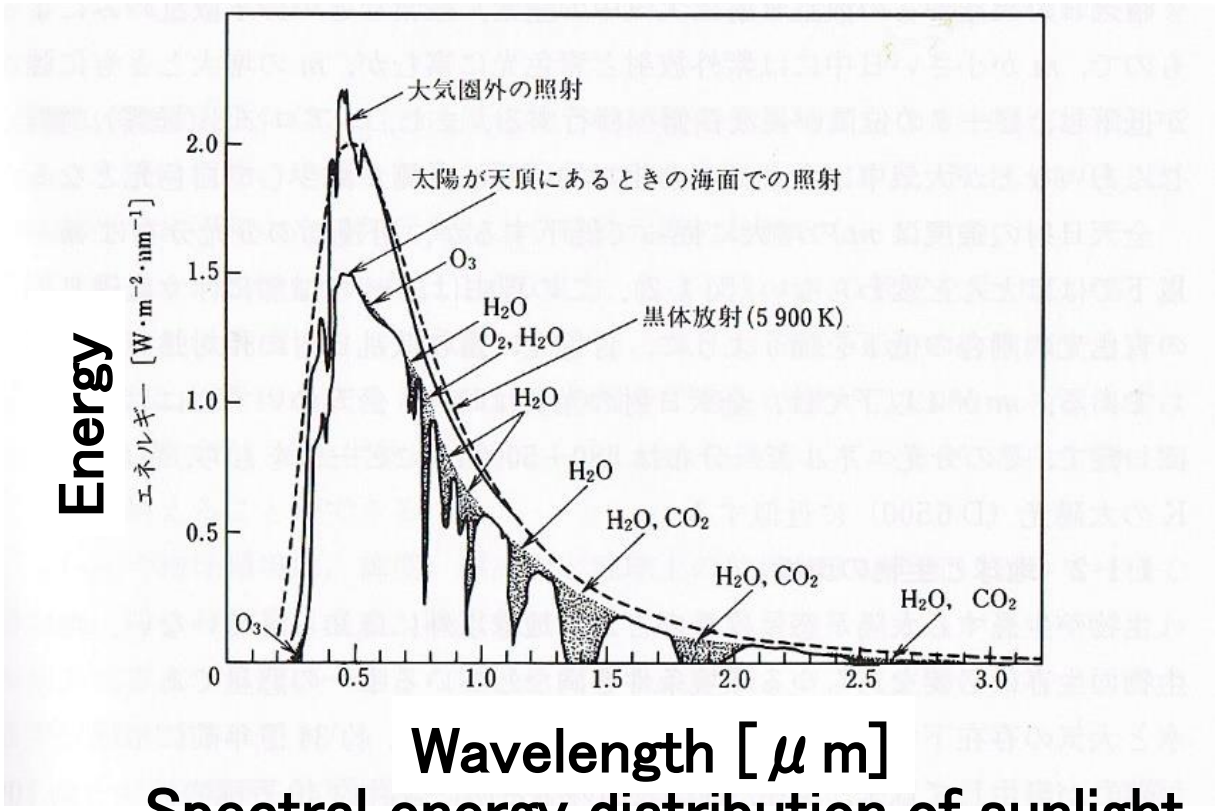
**NIR fluorescence image**

ICG: Indocyanine-green

https://www.hamamatsu.com/resources/pdf/sys/SMES0020J_pde-neo.pdf

# Sunlight Background

- ToF, for example, uses active illumination or modulated illumination.
- Longer wavelength at NIR, the sunlight background becomes smaller, and SN ratio will be improved.

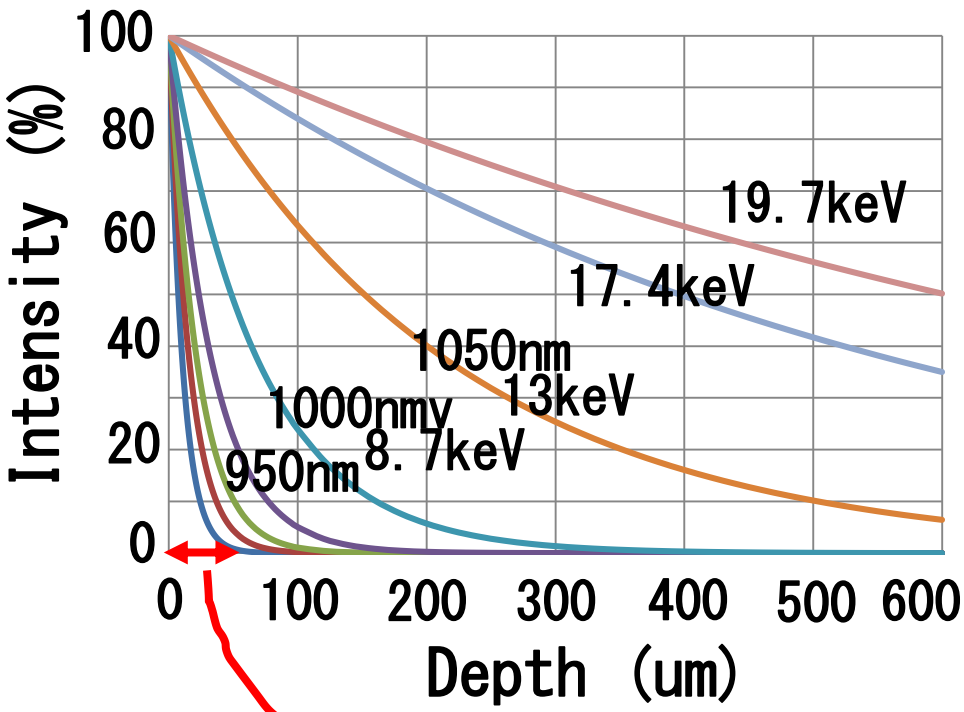


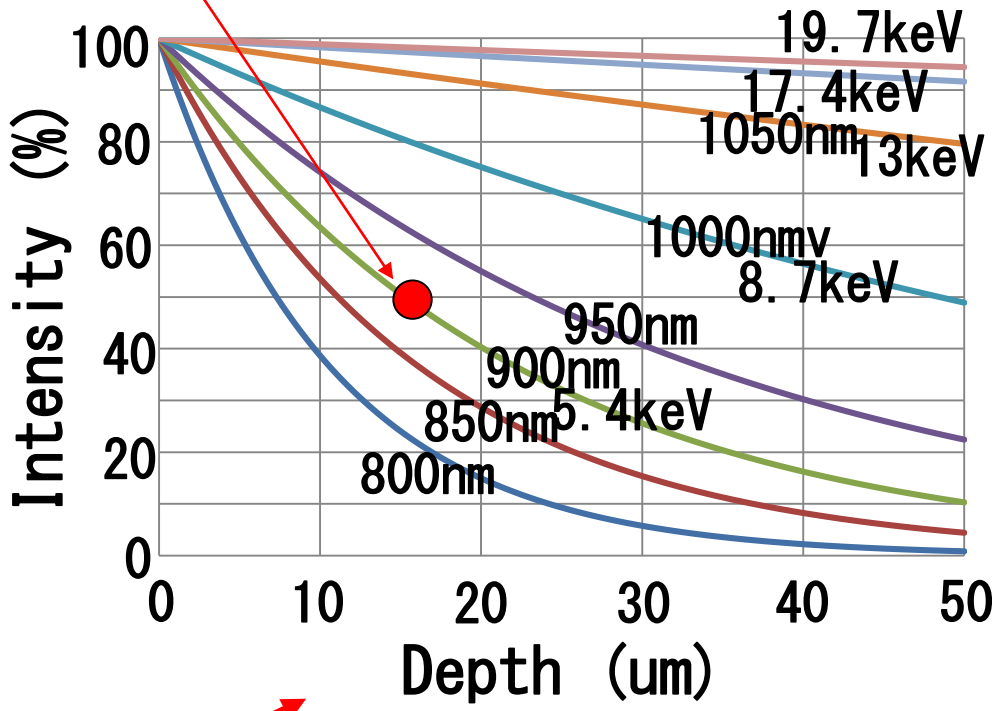

Spectral energy distribution of sunlight

1965 Valley http://syounanakaribit.sakura.ne.jp/newpage605.html

# Absorption of NIR and X-ray in Silicon

- Large depletion layer is needed to detect NIR or X-ray.
  For example, 900 nm wavelength NIR (equivalent with 5.4 keV X-ray) is absorbed half by 15 um silicon.
  ref: 3 um silicon for 700 nm



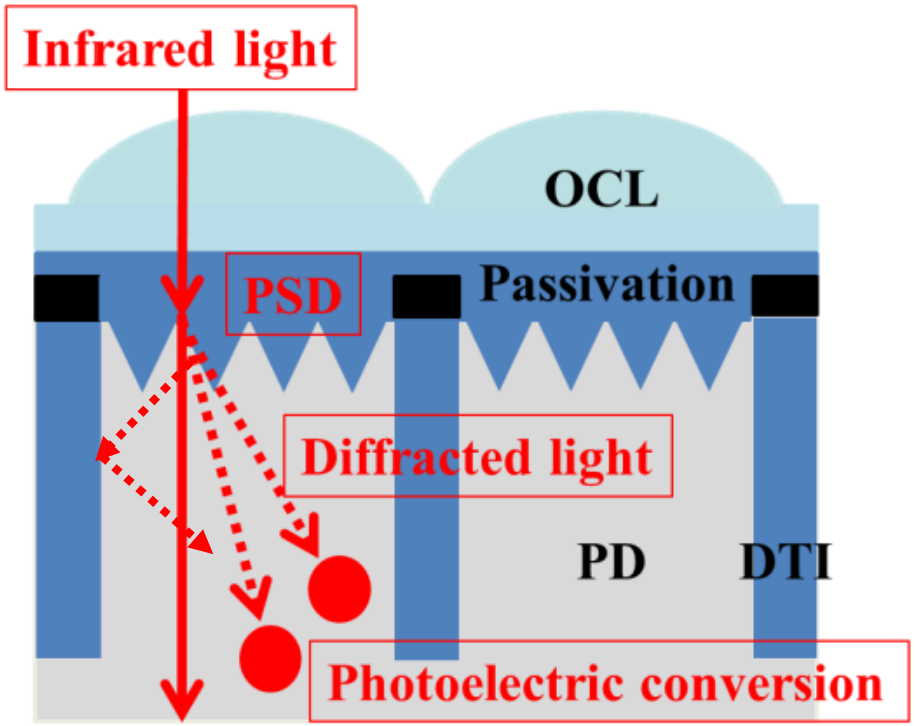

Enlarge

# NIR QE Increase (1), Pyramid Surface for Diffraction

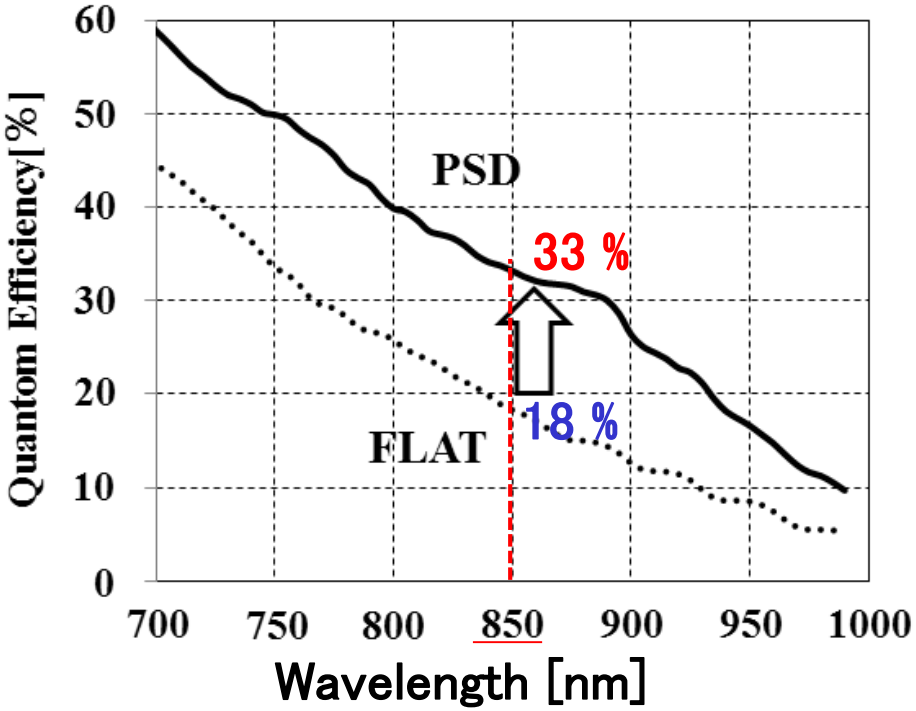
- Pyramid Surface, which enhances diffraction.
- DTI(deep trench isolation) between pixels to suppress crosstalk

⇩

Increase effective sensor thickness and increase NIR QE.



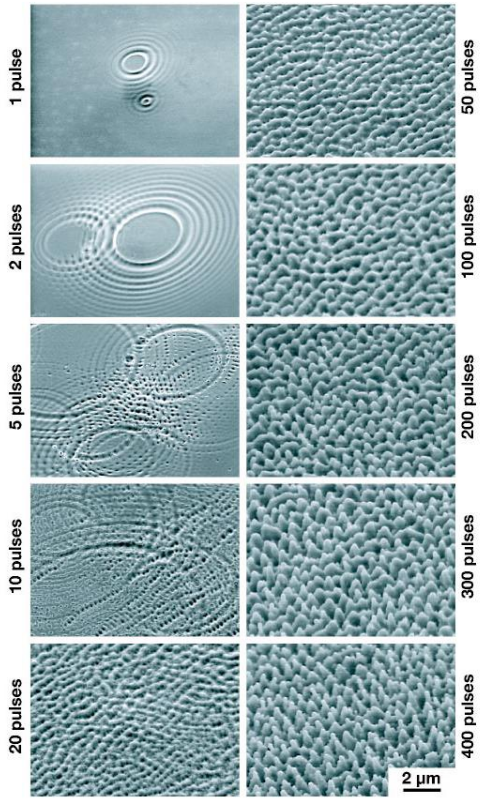

Pyramid surface ofr diffraction



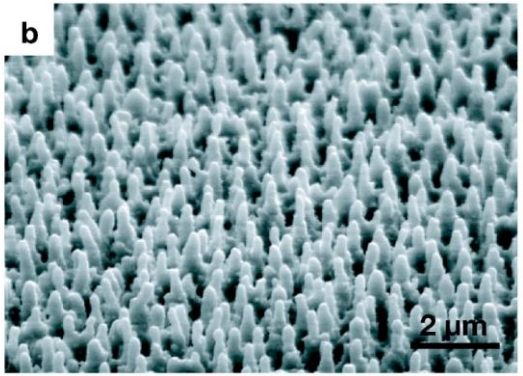

(2017IEDM Oshiyama (Sony))

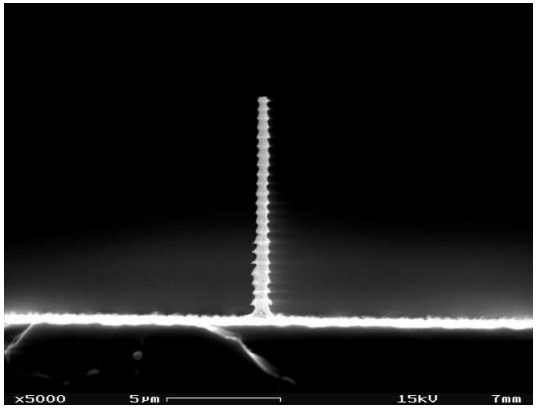
# Black Silicon

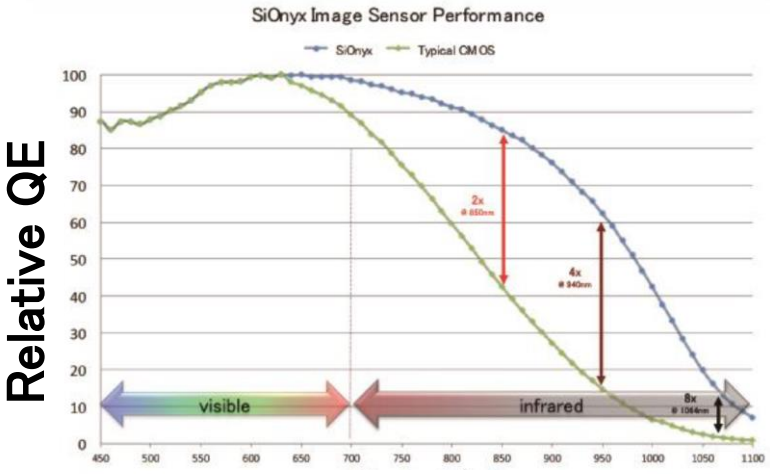
- Black silicon is formed on illuminated surface by femtosecond laser
- As well as NIR QE is much improved, the cutoff wavelength is enlarged beyond 1.2 μm.

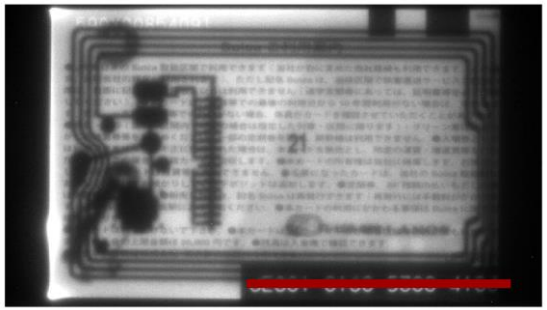



Pulse Number dependence
( 50 μm squqre)
(2004 Shen, Harvard University)



NIR image of IC card (2017 Bitran)

# Ge Image Sensor for NIR

(B. Ackland et al. 2009)

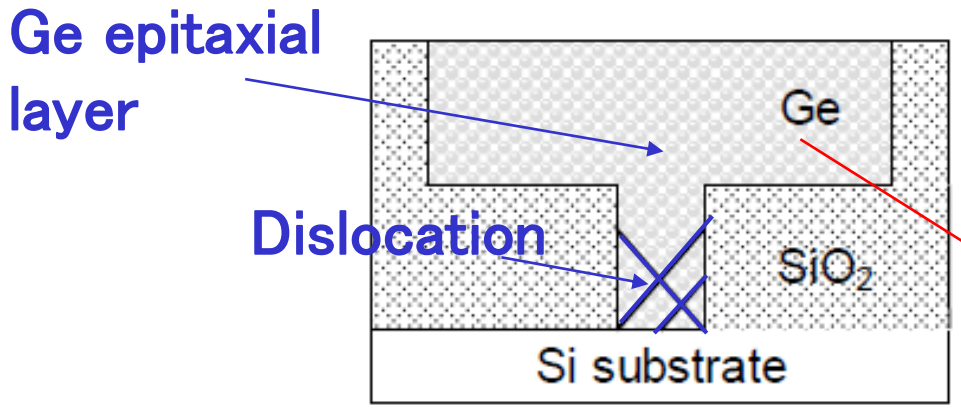



Figure 2 – Germanium selective growth

Figure 3 – Germanium diode embedded in CMOS

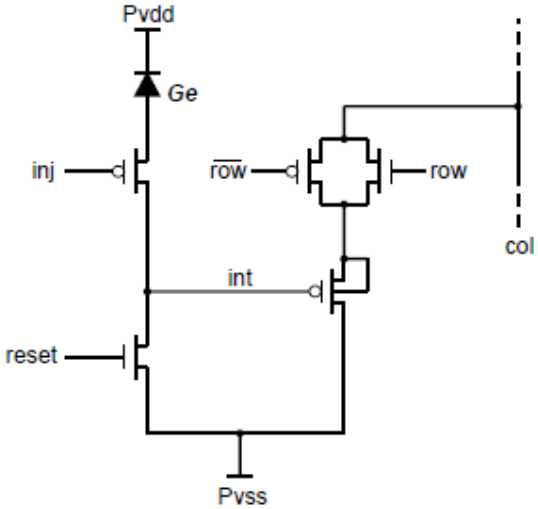



Figure 4 – Pixel circuit

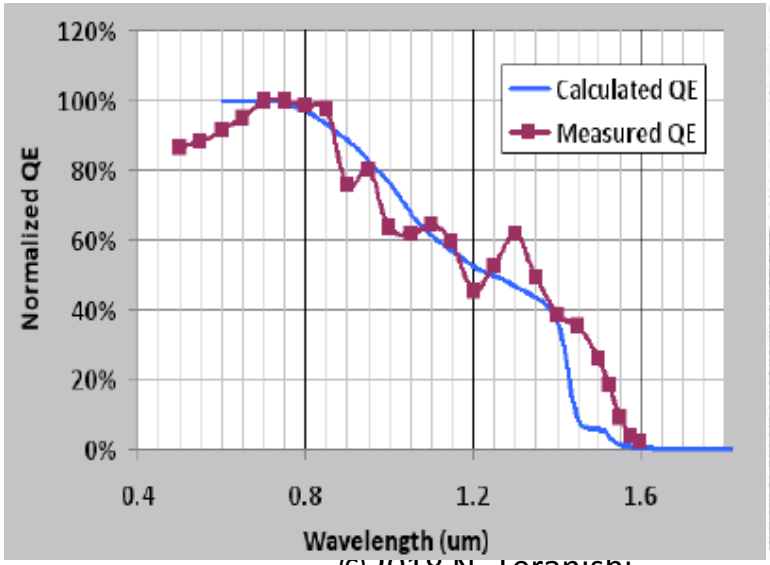
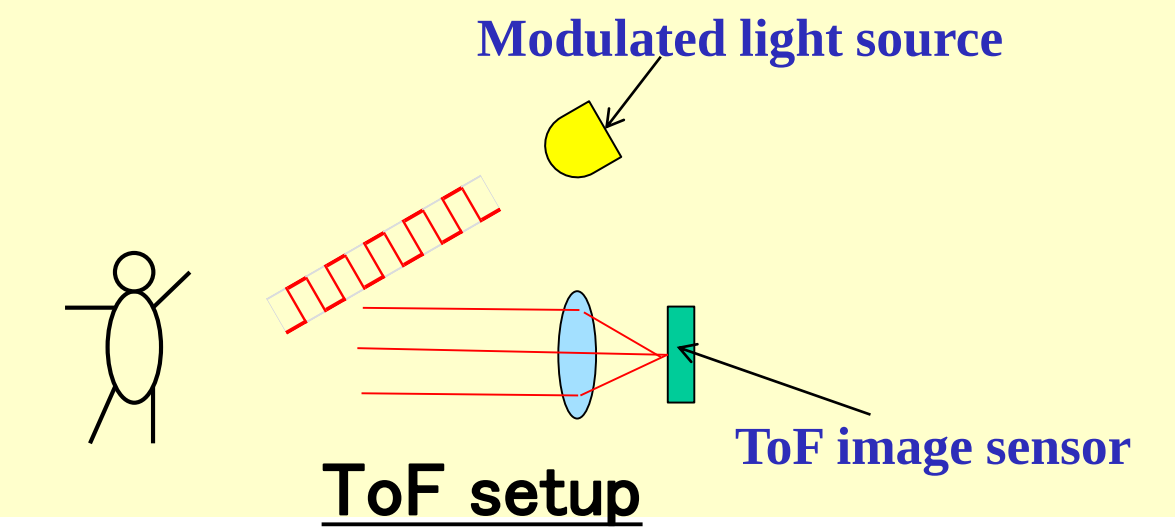



Figure 13 - Moonless night image

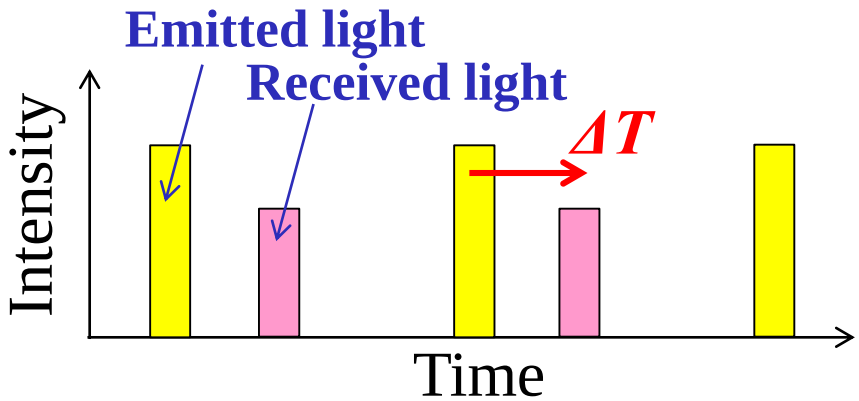
# Contents

# ToF (Time of Flight) Mechanism

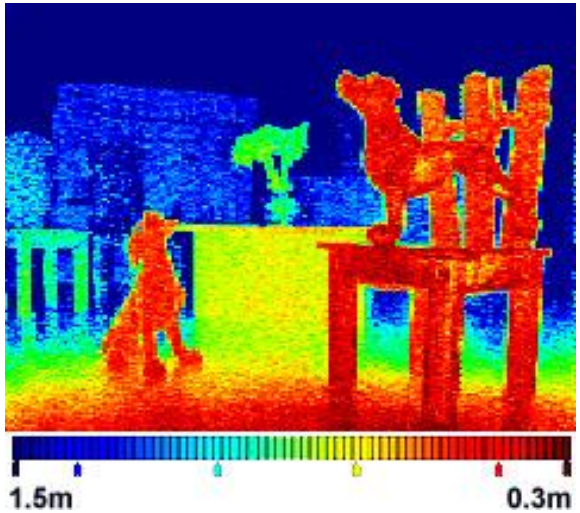



ToF setup

Intensity image




$$\text{Distance} = \frac{1}{2} c\Delta T \quad (c\text{: light velosity})$$




Distance image by ToF

(Kawahito Lab., Shizuoka University)

http://www.idl.rie.shizuoka.ac.jp/study/project/tof/index_e.html

# ToF Applications

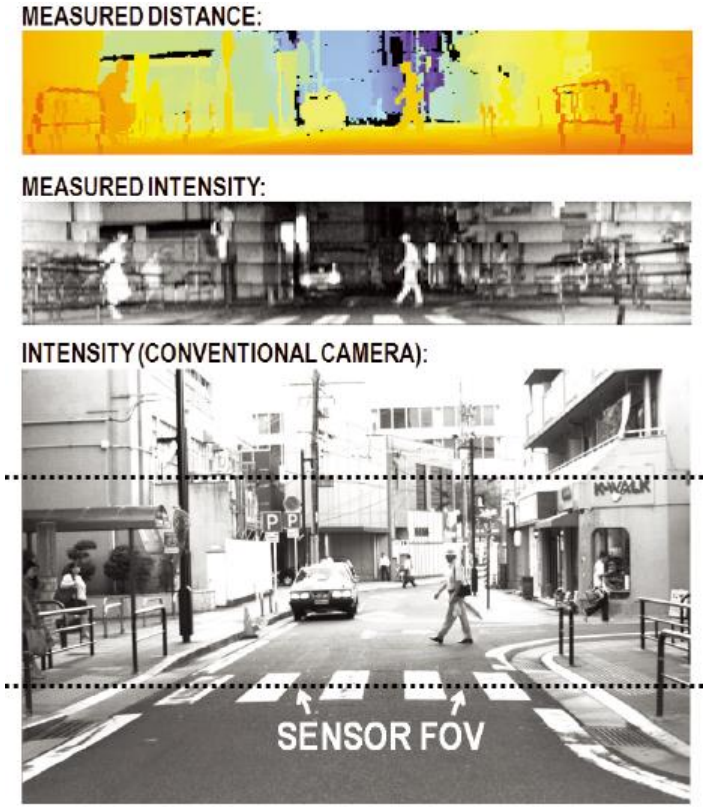
- **Gesture input**: game, medical, digital signage, automobile
- **Range finder, 3D measurement**: automobile, dental, robot

**Game**
(EETimes Japan, 2011)

**Digital signage**

**Smart Chart**

**Dental**

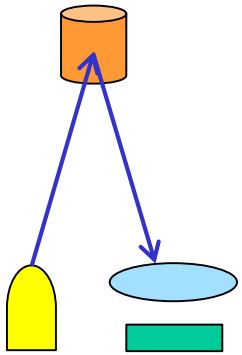



**Forward looking (Obstacle detection)**
(C. Niclass, ISSCC 2013)

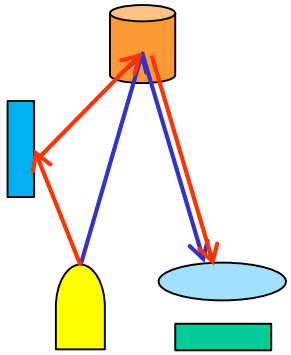
# ToF Challenges (Multi-Pass Errors)

・To resolve the multi-pass errors is challenge at ToF.

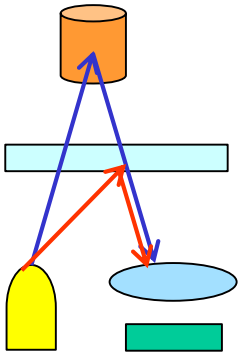
(a) Normal



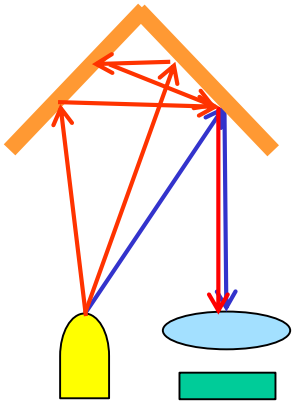
(b) Reflector



(c) Semi-Transparent



(d) Corner

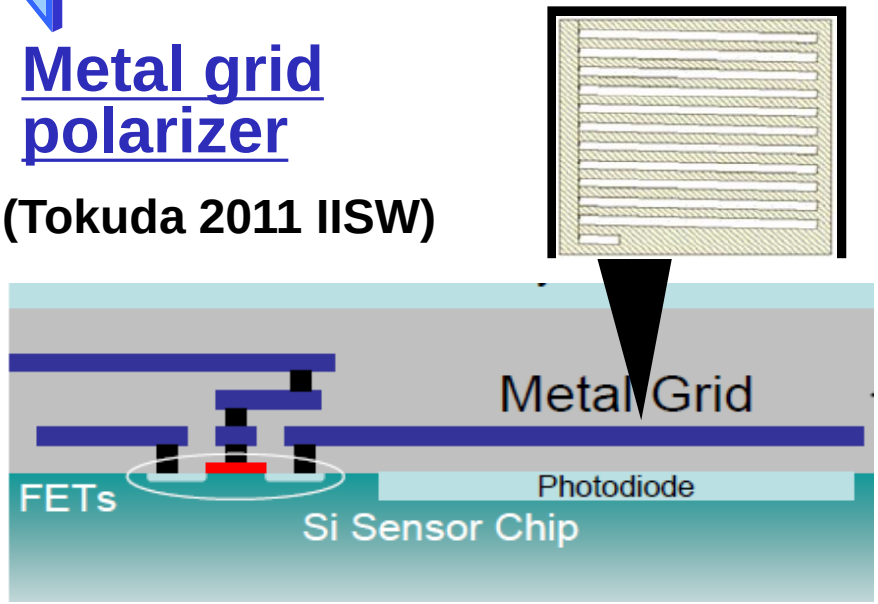


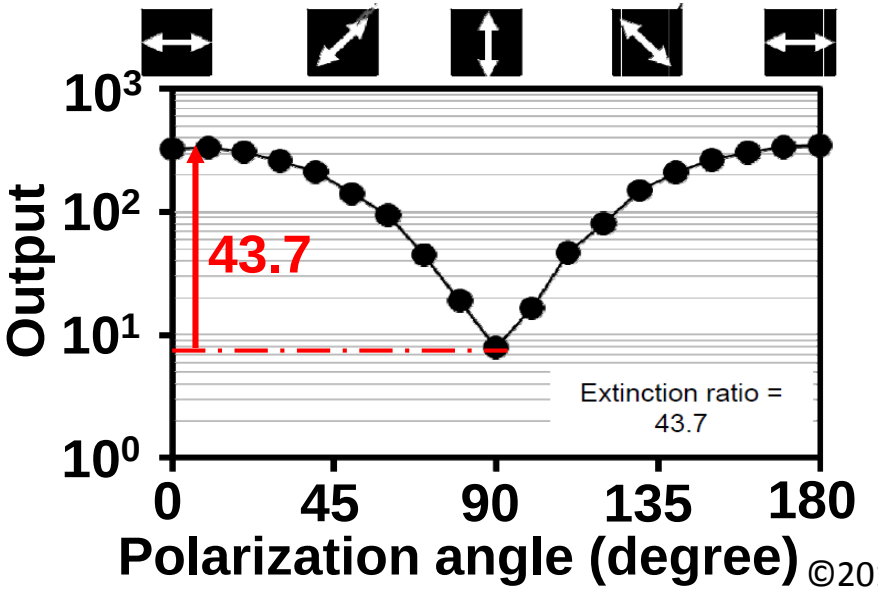
# Contents

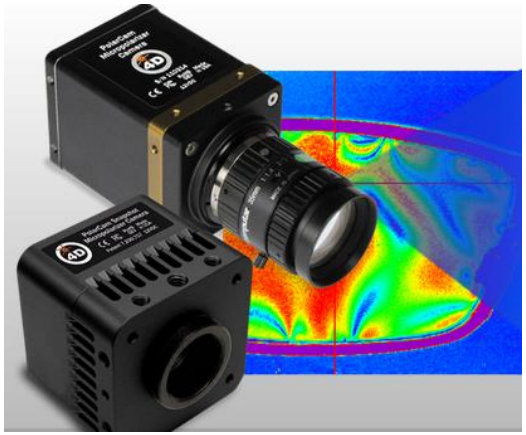
# Polarization Image Sensor

## Metal grid polarizer

(Tokuda 2011 IISW)



## Stress image (Plastic lens)

https://www.4dtechnology.com/


## Antireflection

R. Muller
ISEurope2017

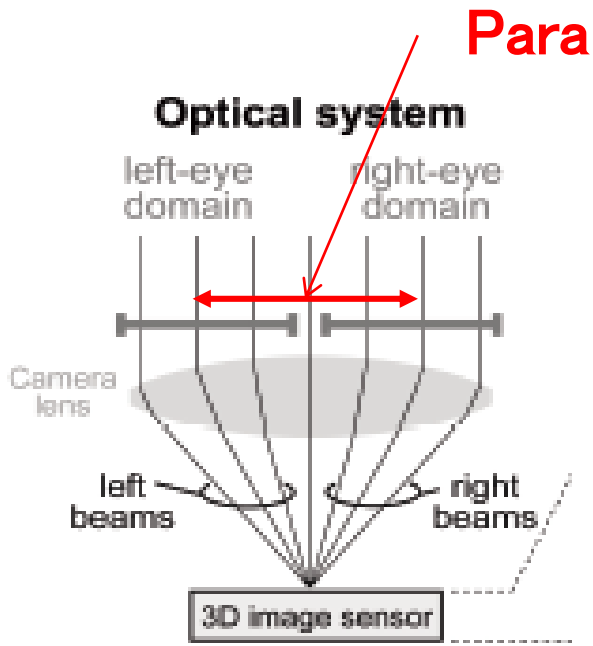

## Optical Rotation

# Contents

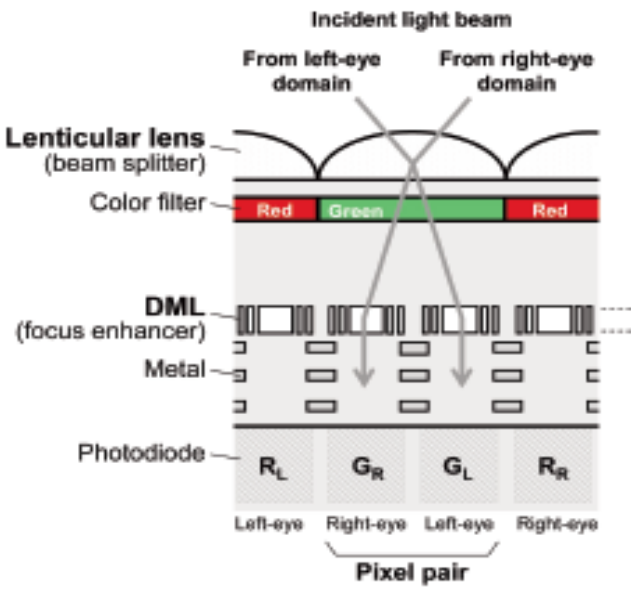
# Monocular 3D Image Senosr

Monocular 3D is required instead of binocular 3D

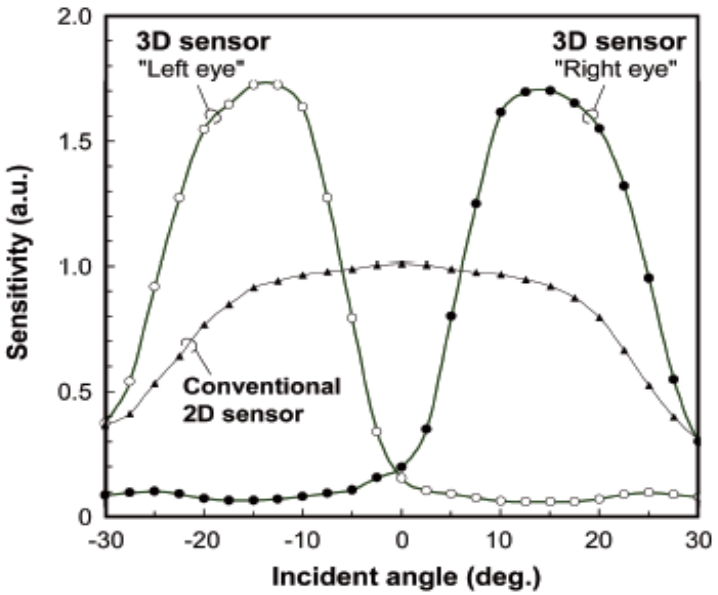
・Compact, ・No precise assembling is needed.




Camera diagram




Pixel cross section

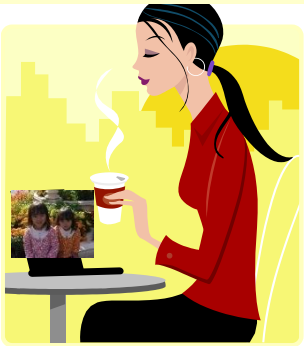



Angular response

(S. Koyama et al.@Panasonic, ISSCC 2013)

# New world of image sensors

## Human sees photos and videos.

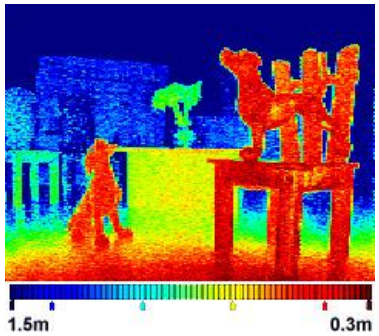



(Panasonic)

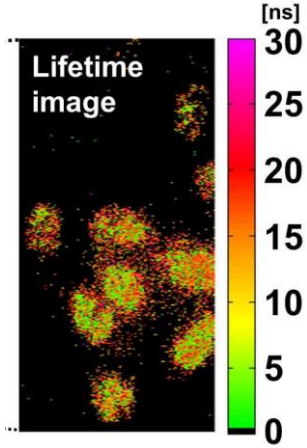
+

+

## New Functions




Range image




Fluorescence lifetime image

(Kawahito, Shizuoka University)

## Computer vision (Computers see photos)

Driving assistance

(Subaru)


Face recognition

(NEC)

Barcode

Gesture input

Robot

(SoftBank)

# Contents

# Queen Elizabeth Prize for Engineering

Purpose： The world's most prestigious engineering prize,
to celebrates world-changing innovations in engineering

Citation： The creation of digital imaging sensors

Winners： - Eric Fossum: CMOS image sensor

- George Smith: CCD (Charge-Coupled Device)
- Nobukazu Teranishi: Pined photodiode (PPD)
- Michael Tompsett: CCD image sensor

# Presentation at Buckingham (1)

EIIR

*The Master of the Household*
*has received Her Majesty's command to invite*

*Professor Nobukazu Teranishi*

*to a Reception to be given at Buckingham Palace for*
*The Queen Elizabeth Prize for Engineering 2017*
*in the presence of*
*H.R.H. The Prince of Wales*
*on Wednesday, 6th December, 2017 at 12.40 p.m.*

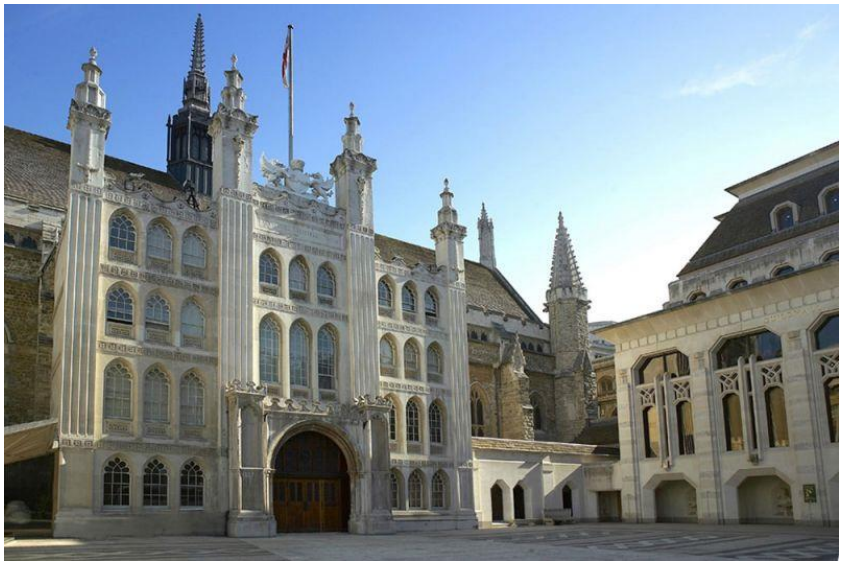
*A reply is requested to:*
*The Master of the Household*
*Buckingham Palace, London SW1A 1AA*
*Email: master.household@royal.gsx.gov.uk*

*Dress: Lounge Suit / Day Dress*

*Guests are asked to arrive between 12.15 and 12.30 p.m.*

**Invitation letter**

Reception at Guildhall hosted by the Lord Mayer of London



N. Teranishi



http://www.guildhall.cityoflondon.gov.uk/gallery

# Presentation at Buckingham (2)

From left, Prince Charles, Eric Fossum, Michael Tompsett, Nobukazu Teranishi (Absent: George Smith)

# Impression

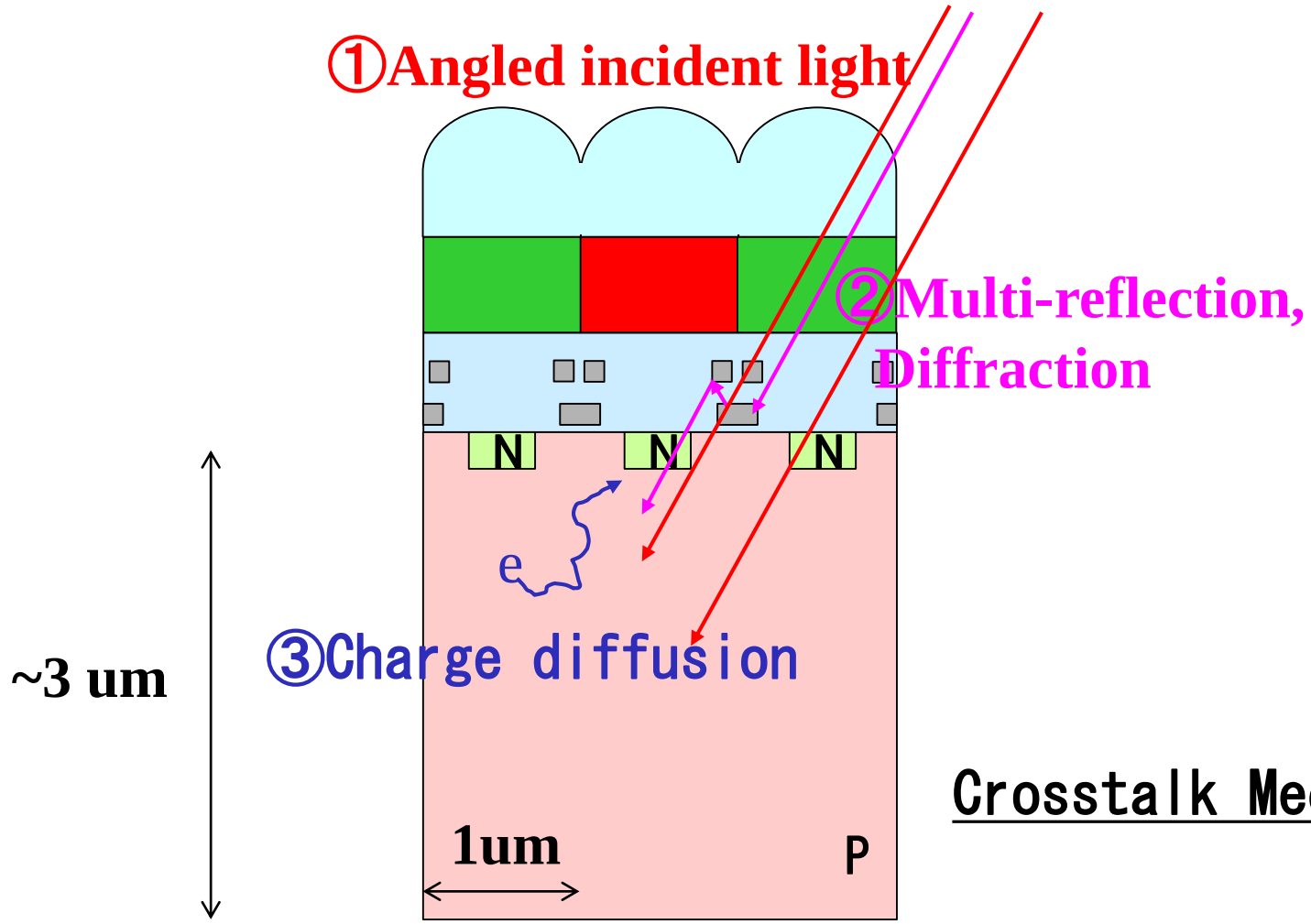
- Proud and happy
  The best award for engineers
- Lucky
  There are so many important and beneficial technologies.
- Acknowledgement
  To family, teachers, seniors, colleagues, and everybody
- Step-up
  I would like to grow up as a person of the Prize.
- Education for engineers
  Good engineers are needed to evolve industries.
  So, I would like to introduce respectable engineers to young generation, and help them to learn technologies.

Anyone can take a photo
anywhere, anytime!

# Thank you !

# Pixel Shrinkage —Crosstalk—

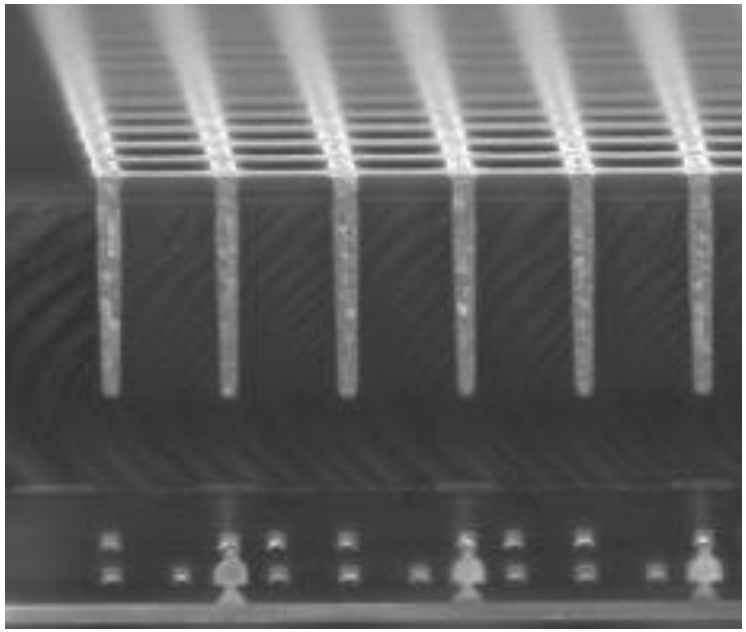
**Crosstalk effect:** ・**Color mixture, degradation of chromatic S/N.**
・**Degradation of resolution**




Crosstalk Mechanism

# Pixel Shrinkage —DTI (Deep Trench Isolation)—

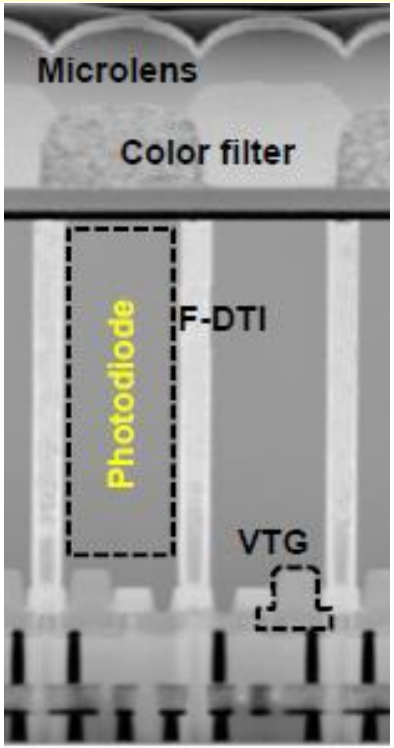
- **BSI is used for small pixel to reduce crosstalk and increase sensitivity.**
- **DTI suppress both optical cross talk and charge diffusion cross talk.**



## B-DTI (Back-side DTI)

- DTI is formed from backside.
- Metal is buried in DTI.
- Sufficient cross talk reduction

(Y. Kitamura et al. (Toshiba), IEDM, 2012)

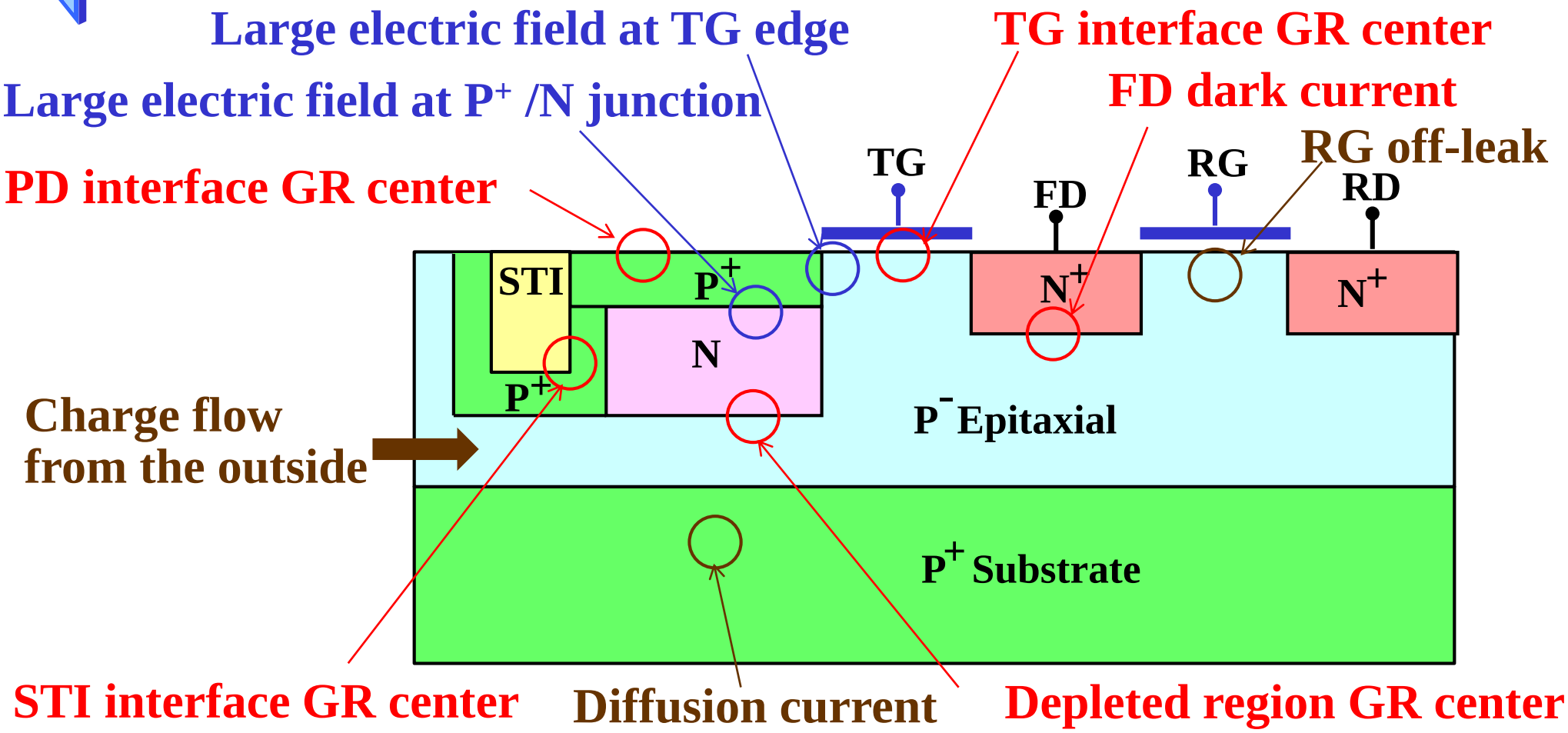



## F-DTI (Front-side DTI)

- DTI is formed from front side.
- Poly-silicon is buried in DTI.
- Better DTI interface

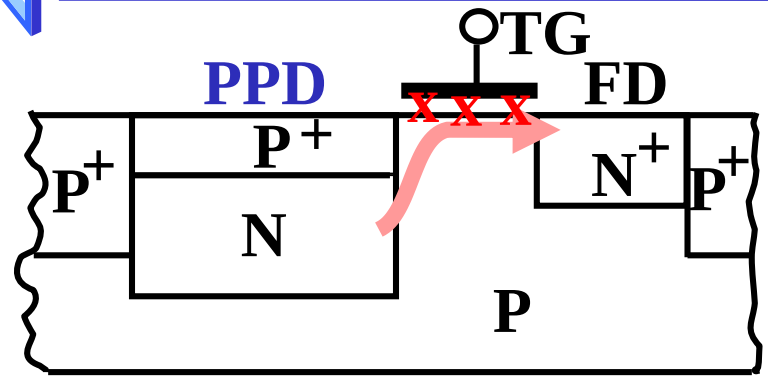
(JC Ahn et al. (Samsung), ISSCC, 2014)

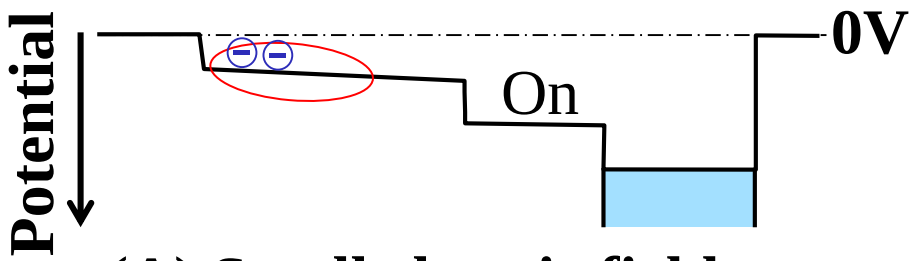
# Dark Current Possible Causes



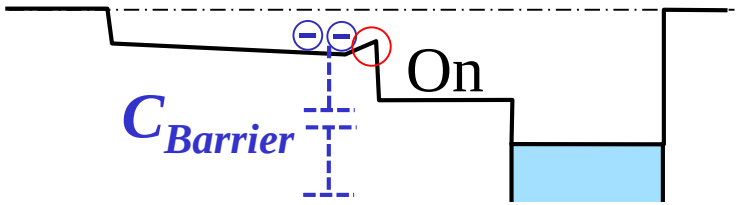

- Pixels should be carefully designed by using precise ion implantations.
- Implantations occasionally bring metals and damages into silicon.

# Causes of Image Lag in PPDs (1)

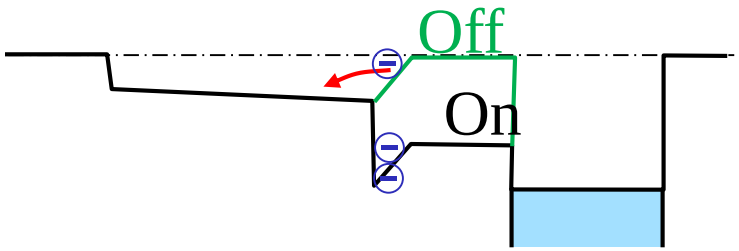


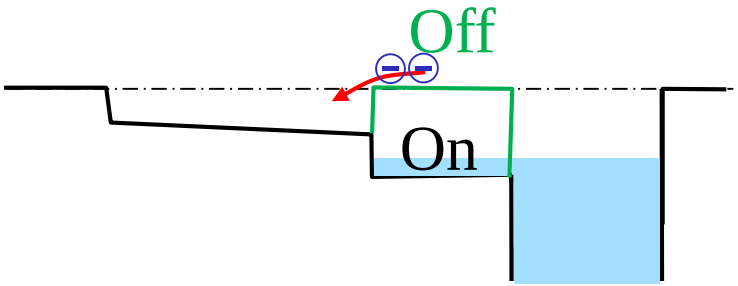

(A) Small electric field




(B) Barrier at the PD edge




(C) Pocket at the TG edge




(D) Pump back when the signal is large

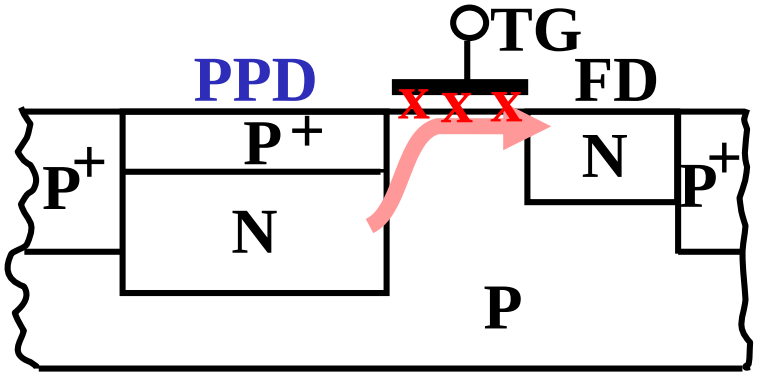
(E) Traps at the TG interface
On the next slide.

# Causes of Image Lag in PPDs (2)

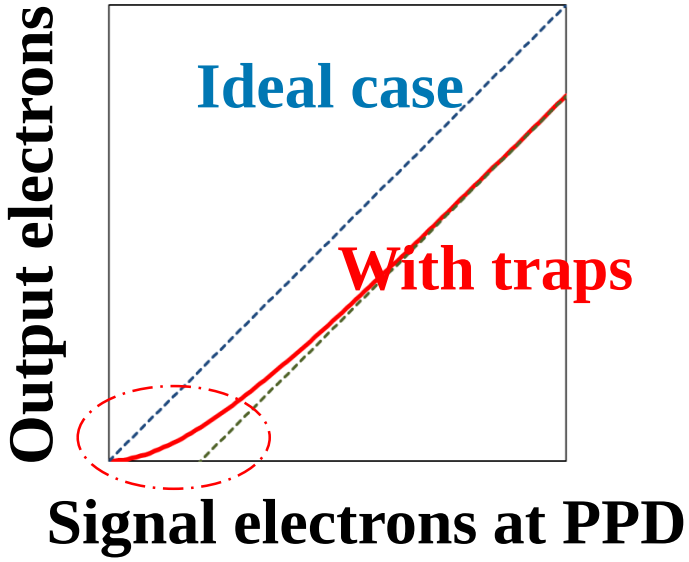
**(E) Traps at the TG interface**

**If the electron transfer path touches the interface, some electrons are captured by traps.**

- **Some of them are detrapped in the following frames, causing lag.**
- **Some of them are annihilated, causing non-linearity.**



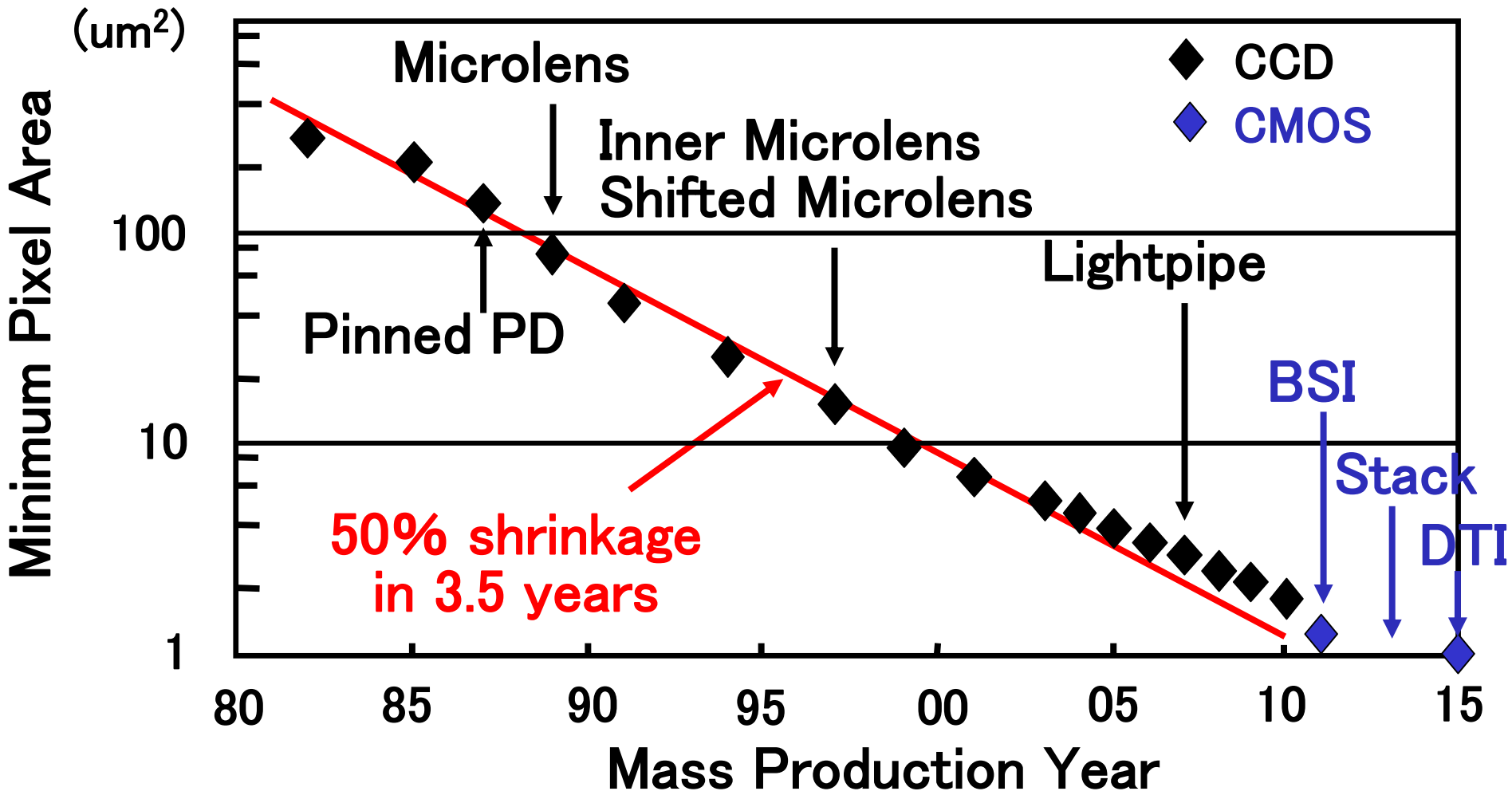

**x : Traps at the TG interface**



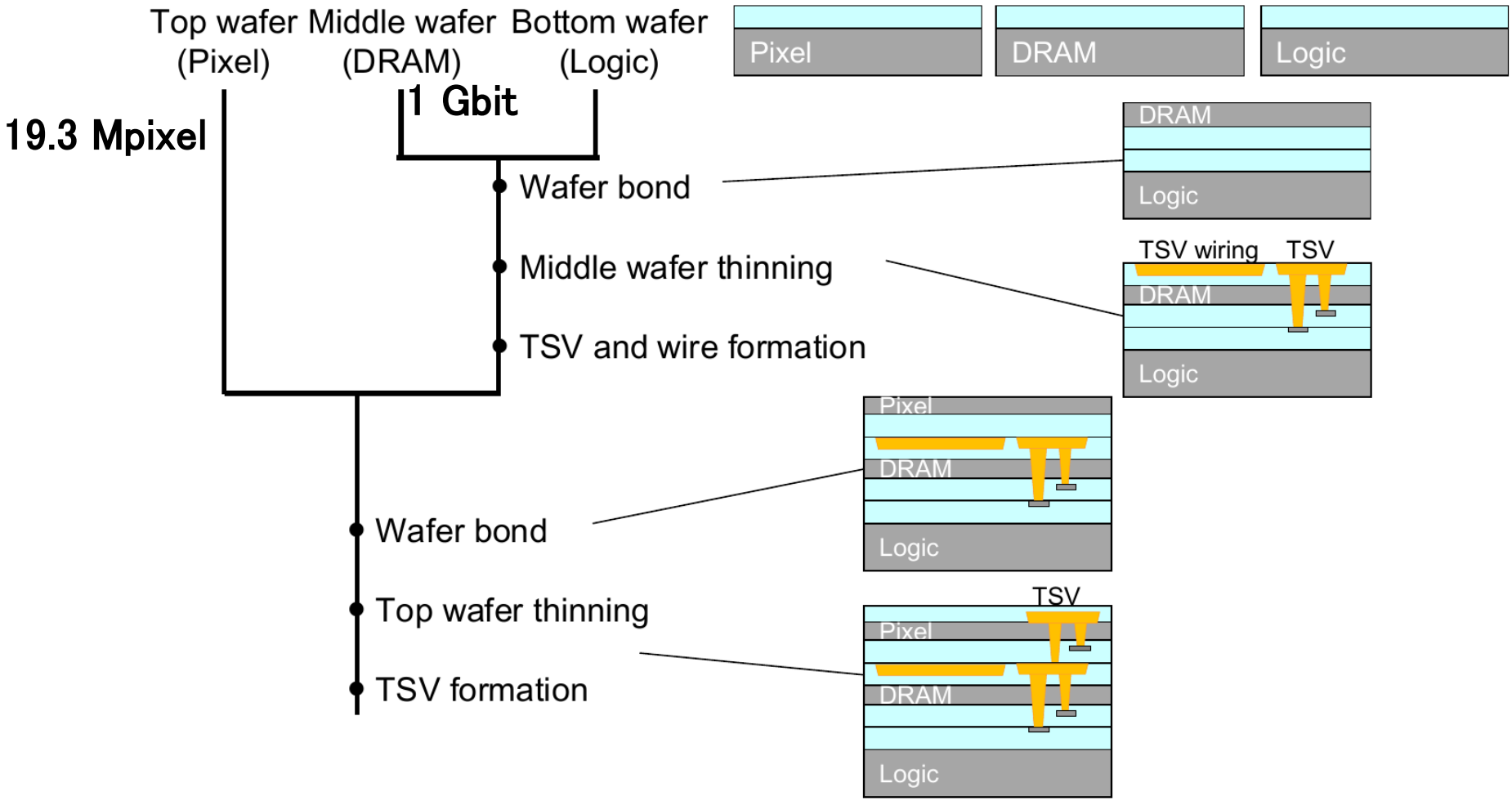

**- The signal electron annihilation exhibits this kind of non-linearity.**
**- A buried transfer path is needed to suppress these phenomena.**

# Pixel Shrinkage Trend

- Shrinkage speed becomes slower recently.
- In 2017, 0.9 um pixel began to be mass produced.



# Stack (3). Pixel-DRAM-Logic Oxide Bonding




(WikiChip Fuse, 2018/02/3)

# On-chip Optics Functions

**(1) Light collecting**

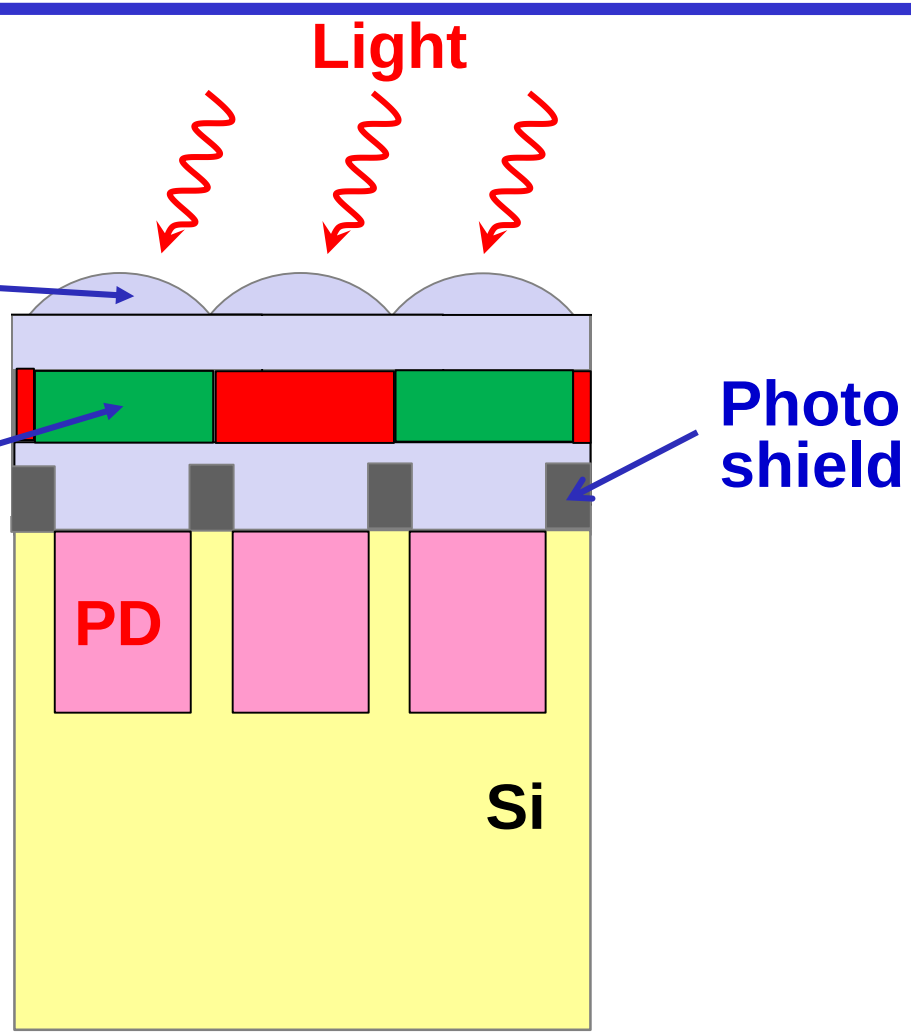
- Microlens
- Lightpipe
- BSI (Back Side Illumination)

**(2) Color filtering**

- Color filter
- Vertical color separation

**(3) New specific functions**

- Polarization image sensor
- Phase detection autofocus
- Computational photography



# RGB-IR Image Sensor

- RGB-IR image sensor is proposed to obtain IR image and RGB image simultaneously.
- Double bandpass filter in stead of conventional IR-cut filter is used to detect NIR.
- Color reproductivity is not sufficient.