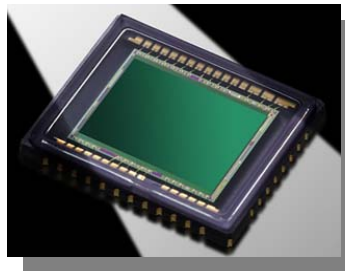


Pixel Design and Technologies for Time-of-Flight Sensors



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Outline

- 1. Introduction**
- 2. Principle of Pulsed Time-of-Flight (ToF)**
- 3. Comparison of Global Shutter Pixels**
- 4. Pixel Design and Technologies for ToF Sensors**
- 5. Technology for Future ToF Sensors**
- 6. Summary**

Market Trends of Image Sensors

Entry of 3D imagers to Gaming market creates new applications for Consumer, Industrial and Automotive markets.

	Before	After
Market demands	Picture Viewing, Recording, sharing	Object Recognition Classification
Requirements for IS	High-quality 2D Visible Imaging	Accurate 3D Imaging (Depth, Shape, Color)
Applications	Visible light	Visible light and Infrared (IR) light
	DSC, DVC, Smartphone  <i>Picture Shooting and Recording</i>	Consumer  @Microsoft XBOX <i>Natural U/I</i> Industry  @KIVA Systems <i>Robotic vision</i> Automobile  <i>Autonomous Driving</i>

3D imaging technologies will become as pervasive as 2D-DSCs

Panasonic Image Sensors

Digital AV



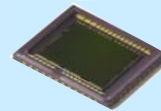
**Small Pixel
High Sensitivity**

Security / Automotive



**High IR Sensitivity
Wide Dynamic Range**

IT-CCD*



* Interline Transfer CCD

Broadcast

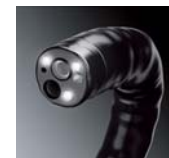


**Global Shutter
Low Smear**

**CMOS (CIS)
Image Sensor**



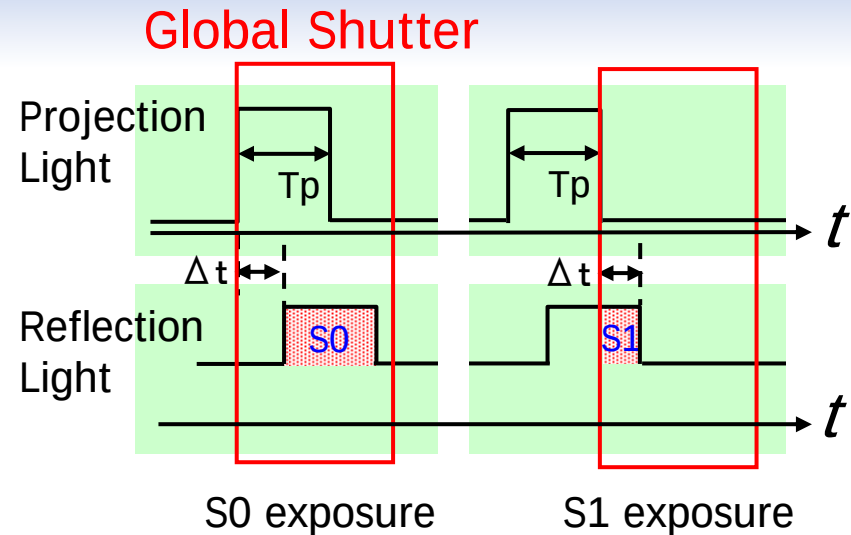
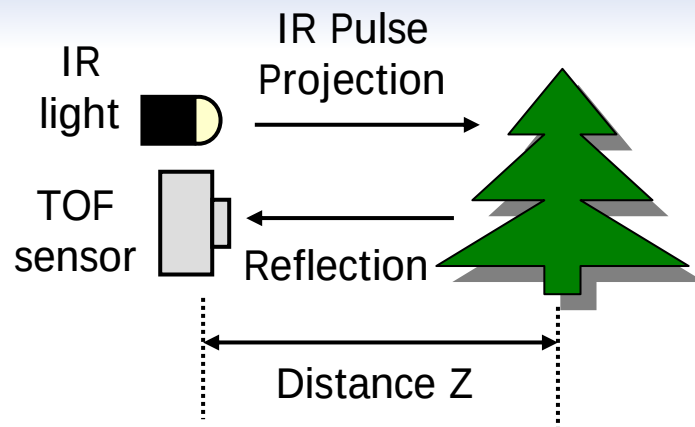
Medical



**Color Reproducibility
Small Die Size**

Enhancing 2D imaging technologies will make further progress on ToF sensors

Basic Principle of Pulsed ToF



Depth Calculation

$$Z = C \times \frac{\Delta t}{2} = \frac{C \cdot T_p}{2} \times \left(\frac{S1}{S0} \right)$$

Δt : Time of Flight
 C : Light Speed
 T_p : IR Pulse width

Requirements for Pulsed ToF Pixels

- High IR Sensitivity -> Long Distance Ranging
- Fast Global Shutter (GS) -> Accurate Depth Measurement



Revolutionized IT-CCD pixel will satisfy these requirements

Global Shutter Pixels – GS-CIS vs. IT-CCD

IT-CCD provides better performance in Sensitivity, Smear, Dark Current and Crosstalk.

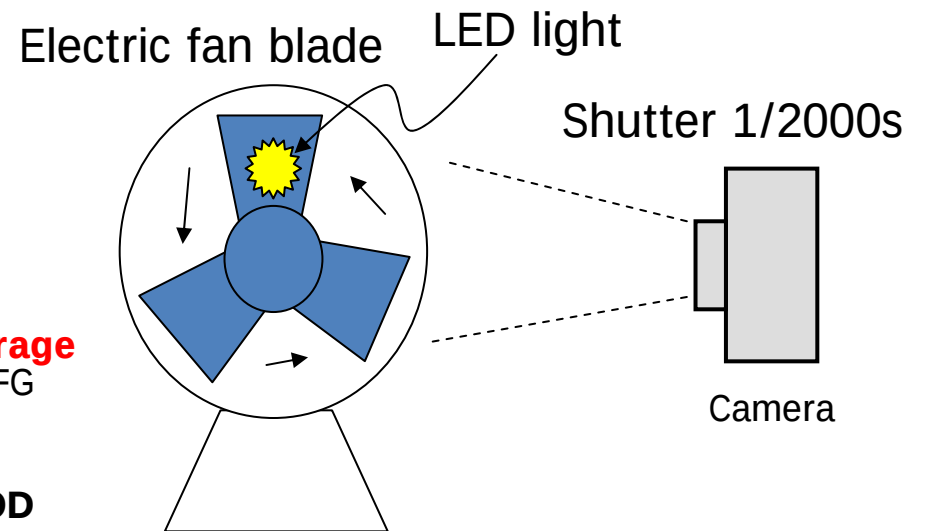
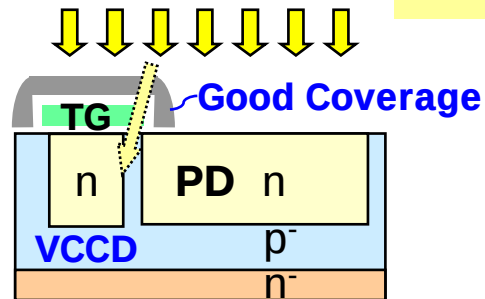
	GS-CIS (5-Tr. type*) 1/3" WVGA (752x480) 6.0um $\square$	Panasonic IT-CCD (MN39784) 1/3" qHD (960x540) 5.4um $\square$
Pixel Architecture	*RST-Tr, SEL-Tr are not shown	
Pixel performances	Many Defects	Defect-free
Signal Storage Region	C _{FD} (Floating Diffusion Capacitance)	VCCD (Vertical CCD)
Overflow Control /Electronic Shutter	LOD (Lateral Overflow Drain)	VOD (Vertical Overflow Drain)
Sensitivity (@550nm)	4.8V/lux·s ⁽¹⁾	6.3V/lux·s
Parasitic Sensitivity /Smear	0.5 % / -46dB ⁽²⁾	0.0003 % / -130dB
Dark Current (@25°C)	14mV/s ⁽¹⁾	0.5mV/s
Crosstalk (IR Light)	Several pixels (p ⁻ -sub.)	Within one pixel (n ⁻ -sub.)

Smear (Parasitic Sensitivity) – GS-CIS vs. IT-CCD

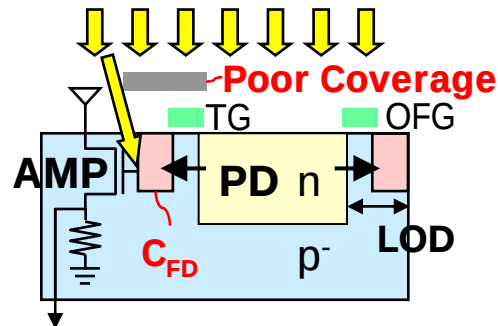
Panasonic IT-CCD (MN39784)
1/3" qHD (960x540) 5.4 μm □

Good photo-shield of IT-CCD reduces parasitic sensitivity in VCCD; no image artifact caused by LED light can be seen.

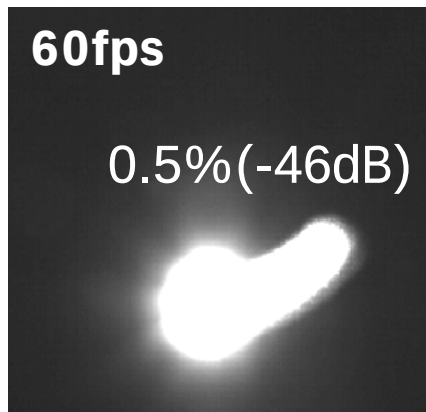
60fps
0.00003%
(-130dB)



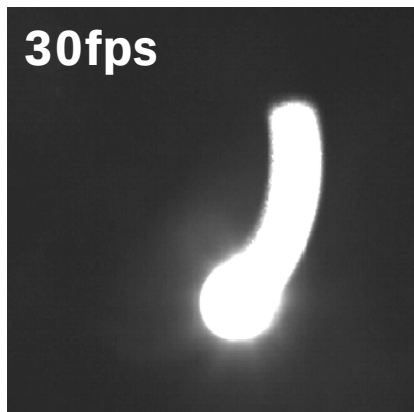
GS-CIS 1/3" WVGA
(752x480) 6.0 μm □



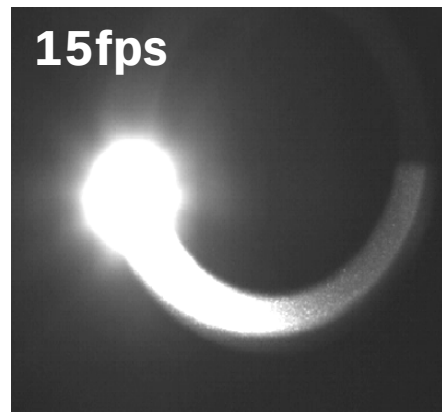
60fps
0.5% (-46dB)



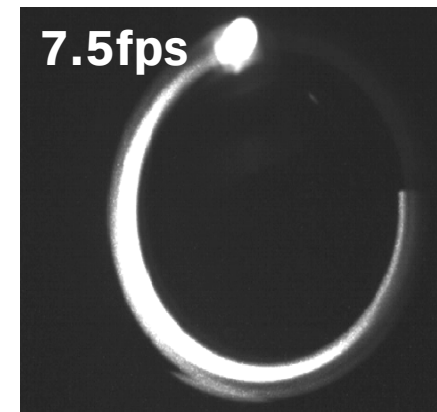
30fps



15fps

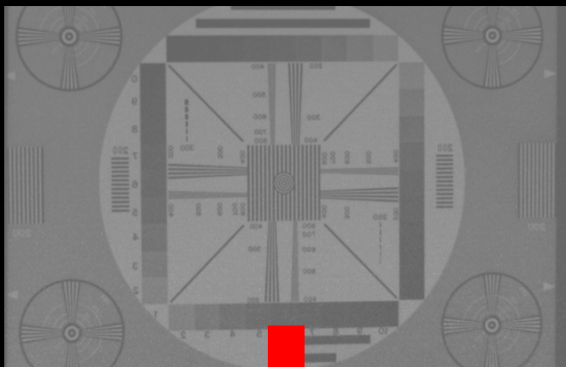
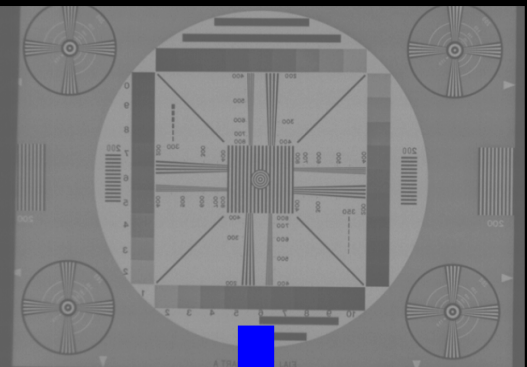
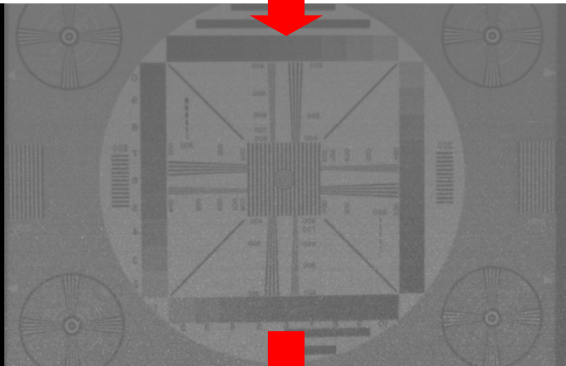
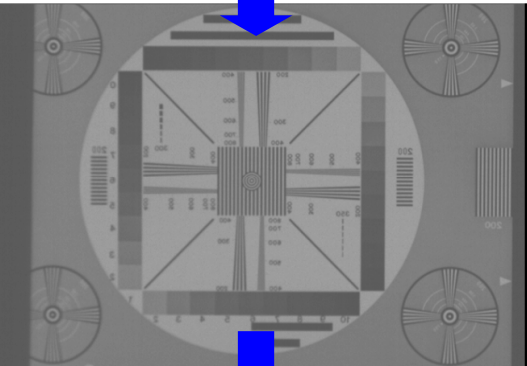
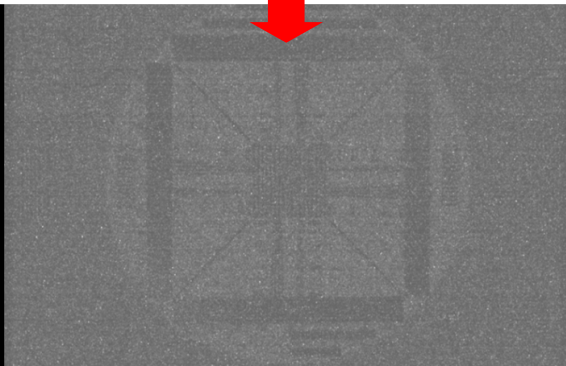
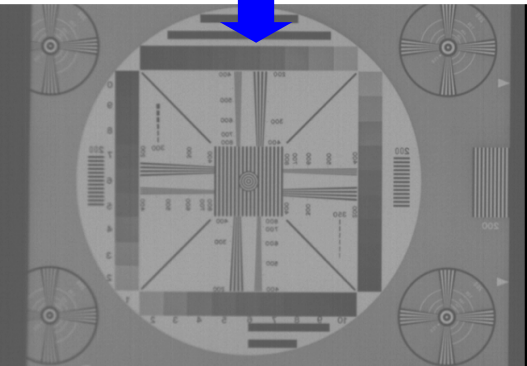


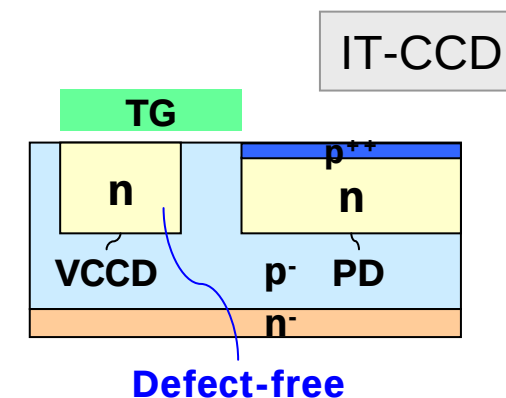
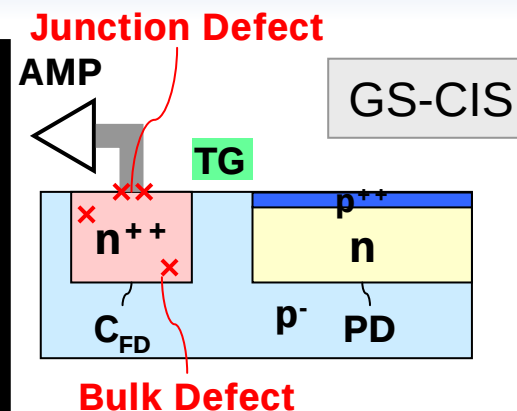
7.5fps



Dark Current – GS-CIS vs. IT-CCD

Sensor temperature 80 degrees; exposure time 1/10000s

Readout time	GS-CIS	IT-CCD (MN39784)
16.7ms (60fps)		
33ms (30fps)		
66.7ms (15fps)		

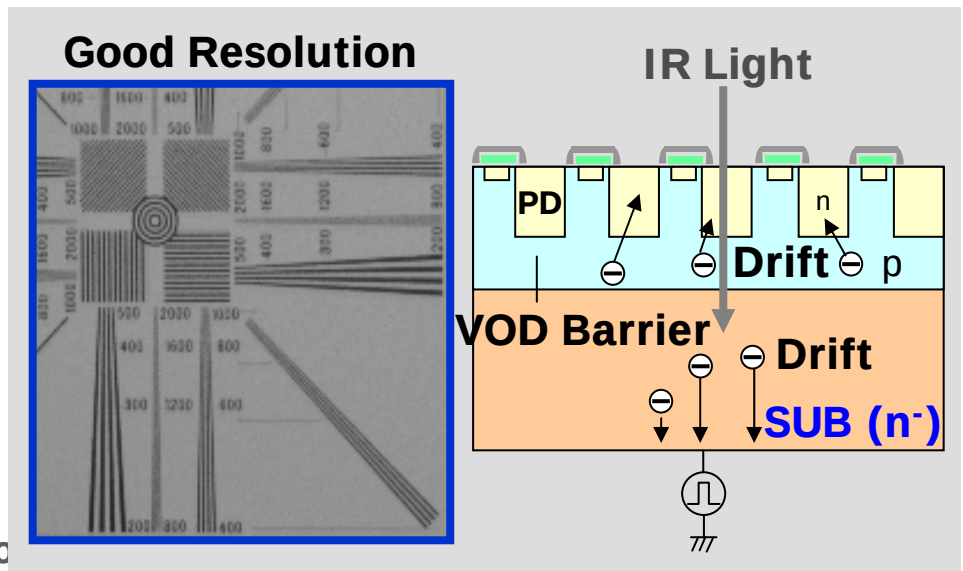
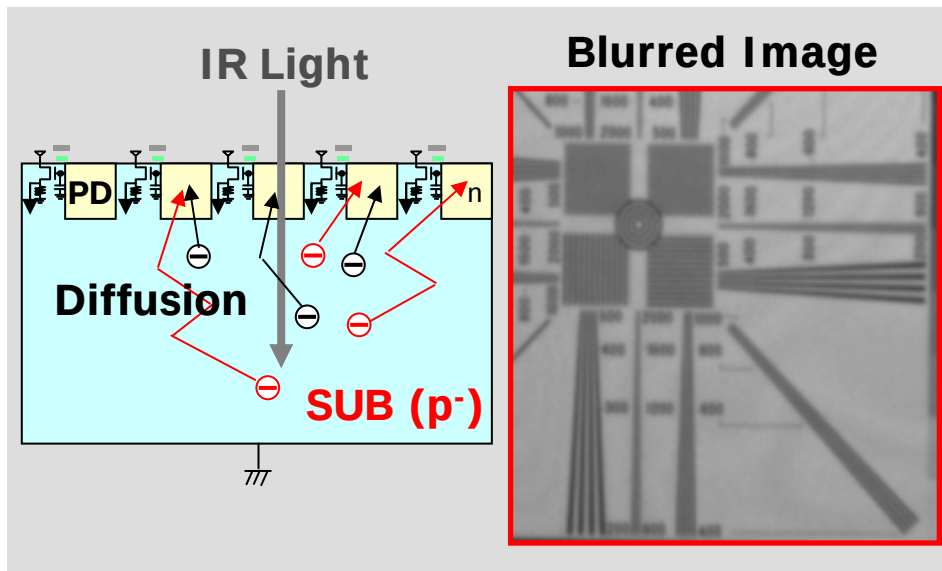
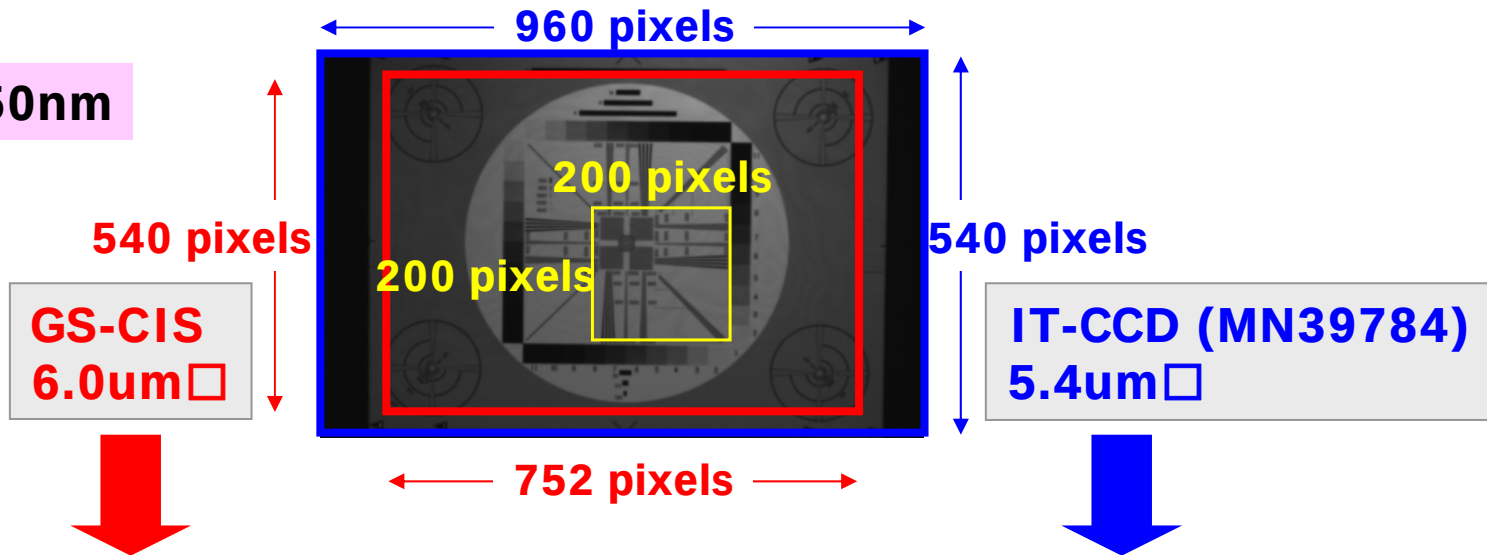


VCCD of IT-CCD has low doped channel and no metal junction; this can reduce surface and bulk defects, resulting in low dark current.

IR Image Resolution – GS-CIS vs. IT-CCD

Resolution chart of IT-CCD taken by IR light has Good Resolution.
VOD structure can suppress Bulk Crosstalk by Drift transfer of Photo-electrons.

IR light = 850nm



Pixel Design and Technologies for ToF Sensors

Advantages of IT-CCD pixels

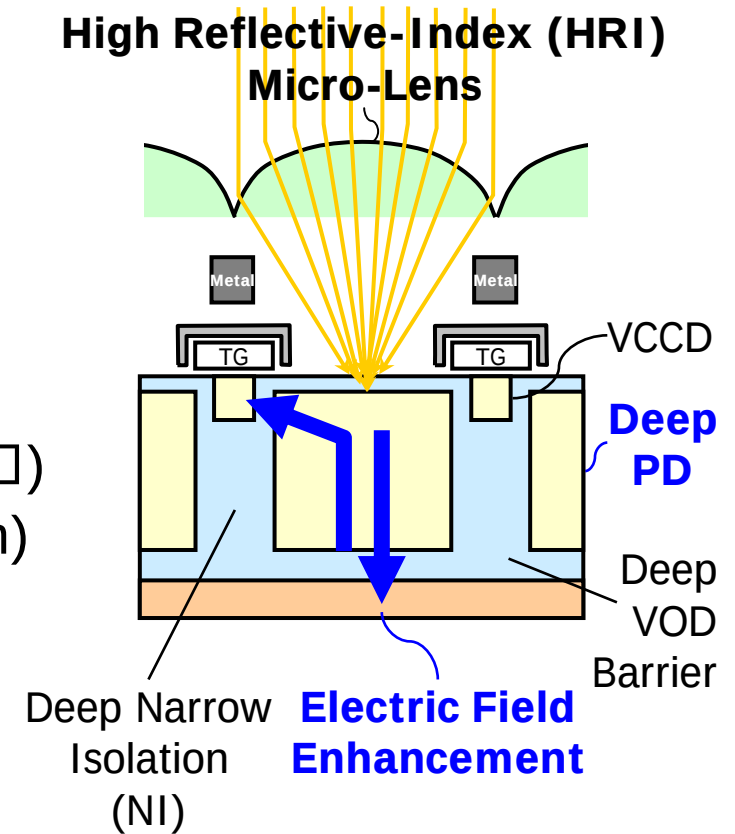
- High Sensitivity (@Visible Light)
- Low Parasitic Sensitivity (Low Smear)
- Low Dark Current
- Low Crosstalk (@IR Light)

Challenges for ToF Sensor

1. Long Distance Ranging
 - High Fill-Factor (Effective FF=70%@5.4 μm^2)
 - Enhanced IR Sensitivity (Q.E.=18%@850nm)
2. Accurate Depth Measurement
 - Electronic Fast Shutter ($t_r, t_f < 2\text{nsec}$)

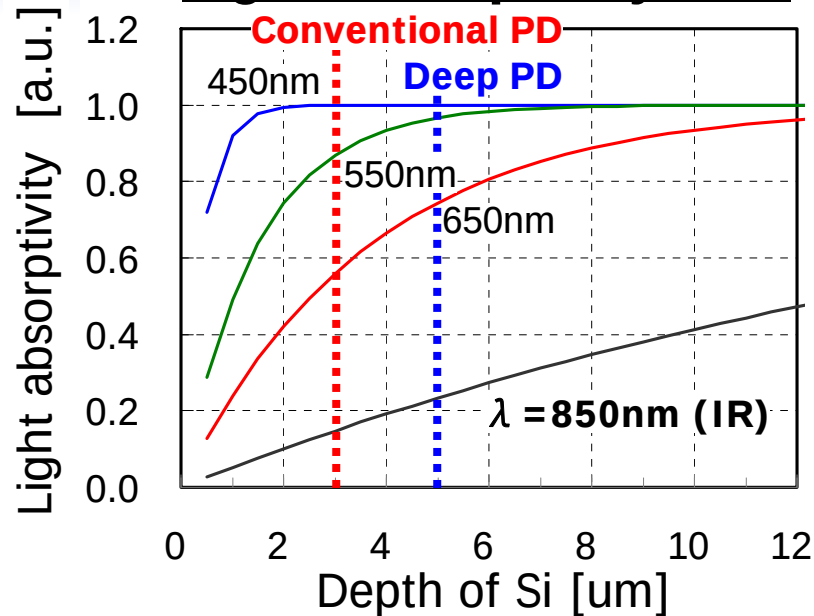
Approach

- High Reflective-Index Micro-Lens
- **Deep PD w/ VOD**
- **Electric Field Enhancement in the Deep PD**



Enhanced IR Sensitivity – Deep PD w/ VOD

Light Absorptivity in Si



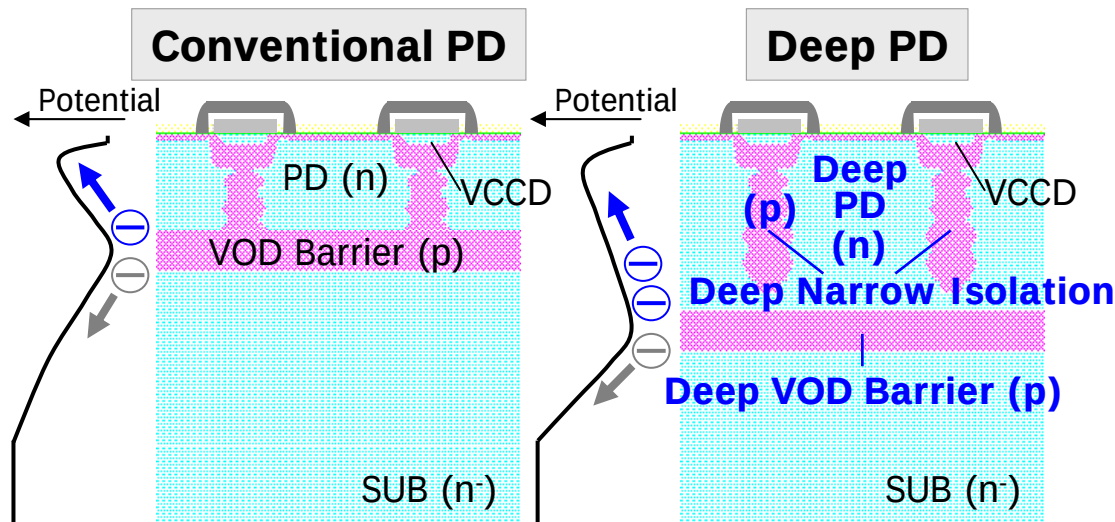
IR Light penetrates deeply into Si substrate.



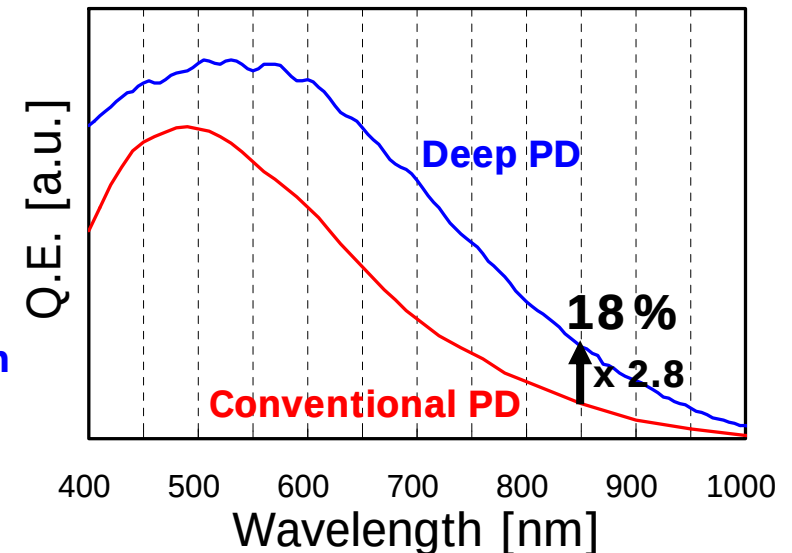
Deep PD is necessary to obtain higher IR sensitivity.

Deep PD is created by forming Deep VOD Barrier and Deep Narrow Isolation through High-Energy Ion-Implantation process.

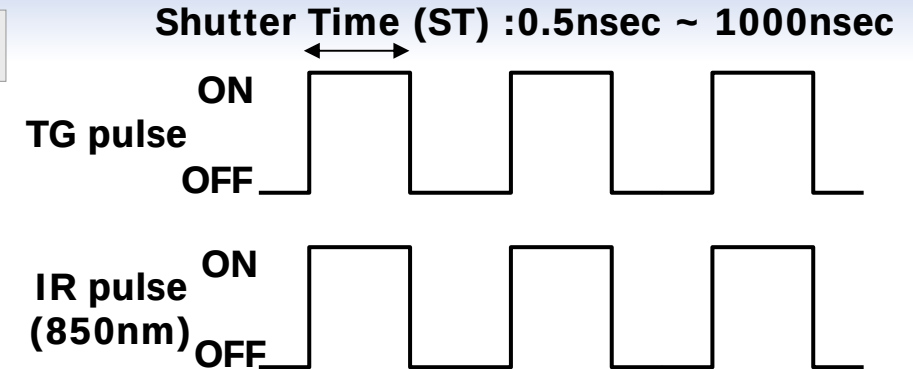
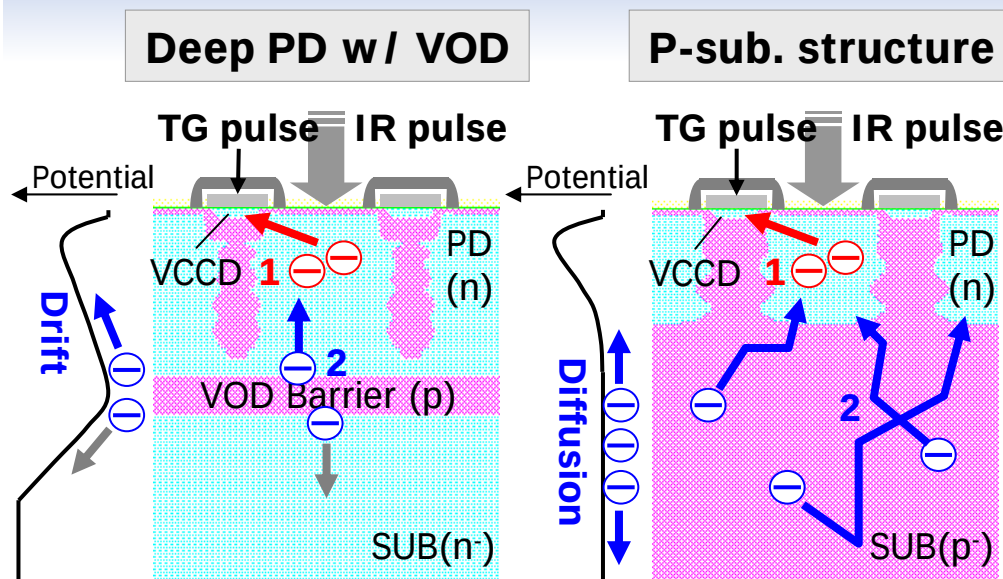
Pixel Impurity Profiles



Quantum Efficiency (Q.E.)

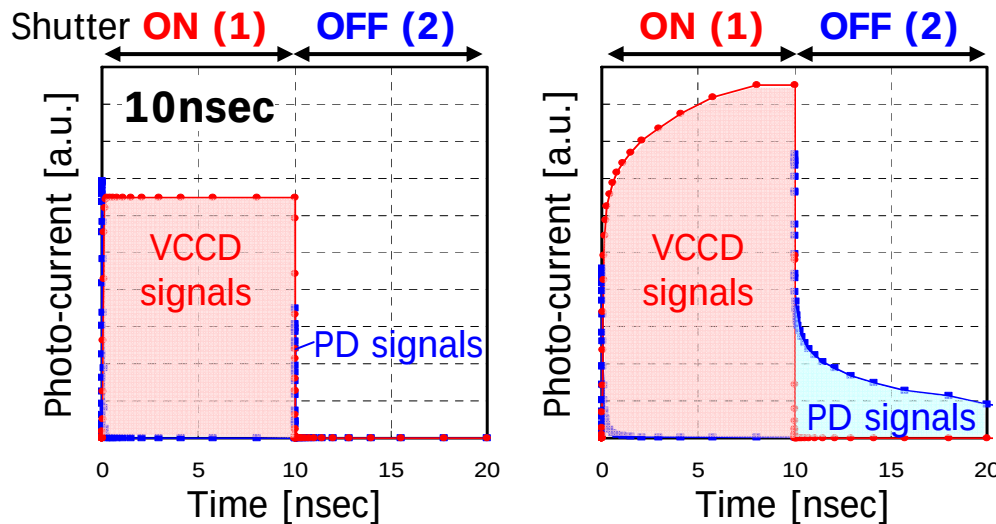


Fast Shutter Characteristics– Deep PD w/ VOD

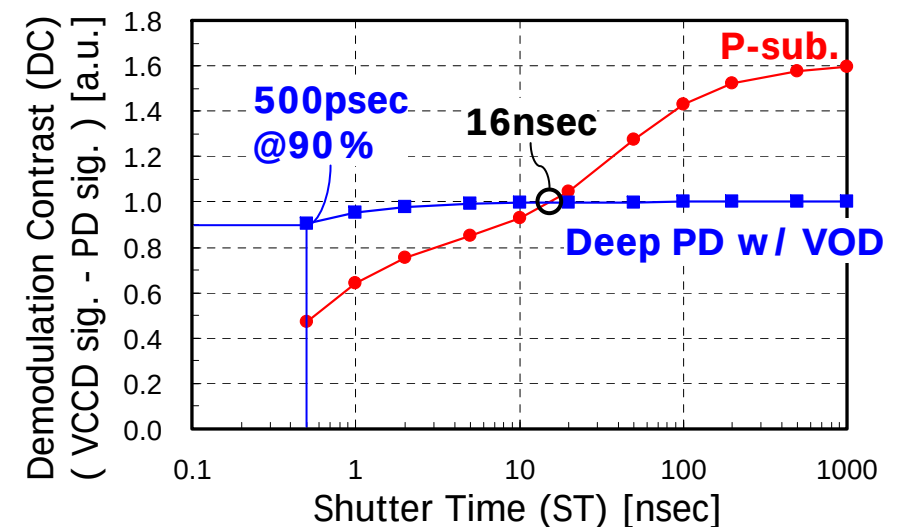


1. Photo-electrons are generated in PDs and transferred to VCCDs.
2. After TG pulse turns off, electrons in deep regions of substrate belatedly move to PD.

Photo-Current Simulations



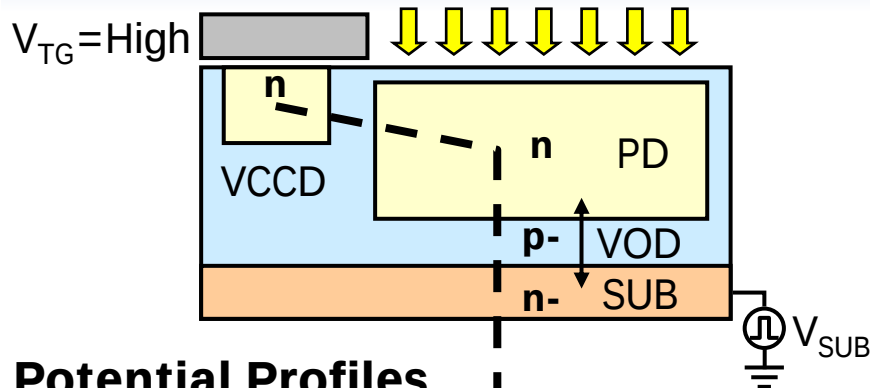
Fast Shutter Simulations



Even though p-sub. obtains higher DC at ST longer than 16nsec, the DC plummets as ST becomes shorter, while Deep PD w/ VOD retains DC and 90% of it is obtained at ST of 500psec.

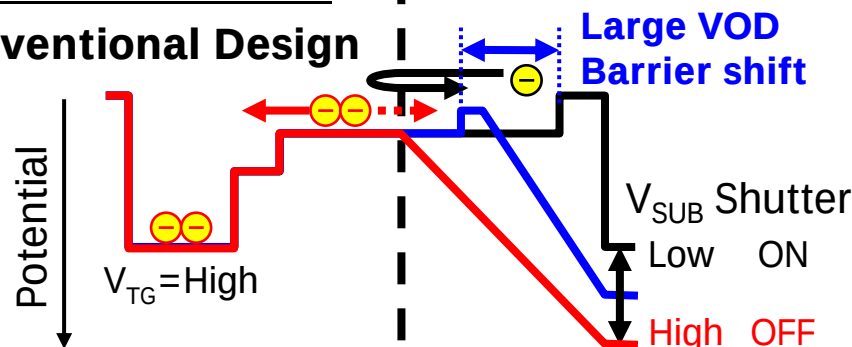
Pixel Design for Fast Shutter in Deep PD w/ VOD

Pixel Cross Section

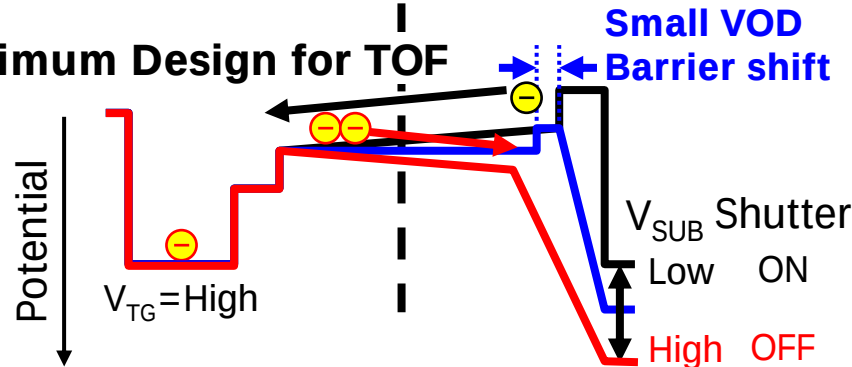


Potential Profiles

Conventional Design



Optimum Design for TOF



Fast Shutter Evaluation

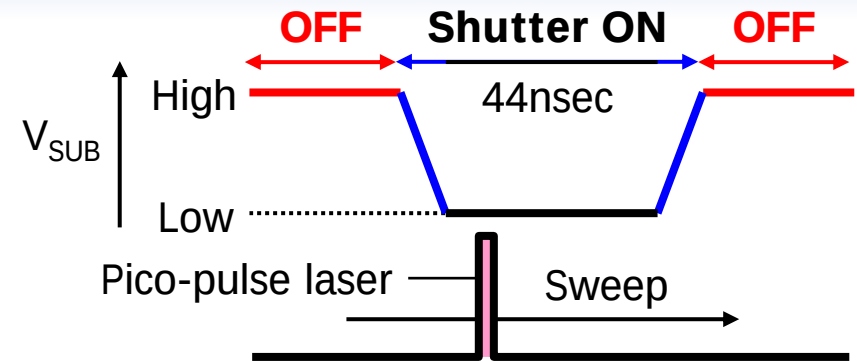
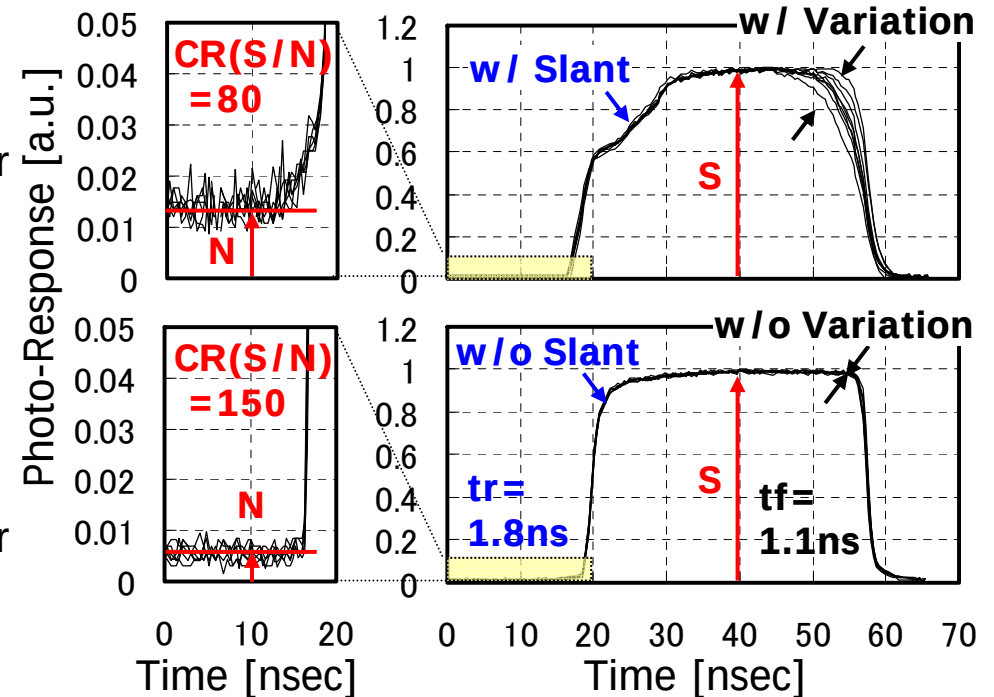
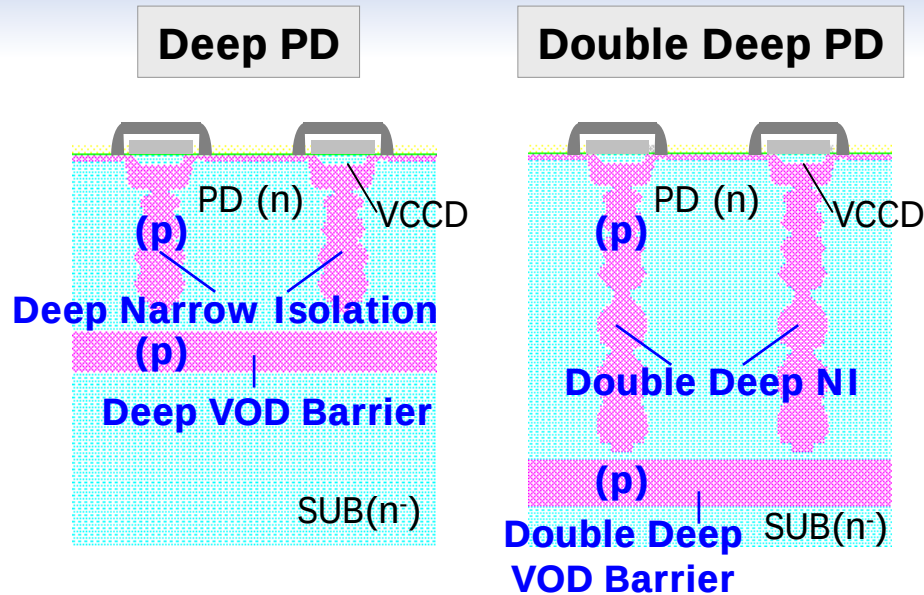


Photo-Response of SUB Shutter



Enhancing Electric Field Modulation and Suppressing VOD Barrier Shift through a V_{SUB} change can remove the Variation and the Slant of Photo-Response and improve the CR at the same time.

Technology for Future TOF – Double Deep PD



Quantum Efficiency (Q.E.)

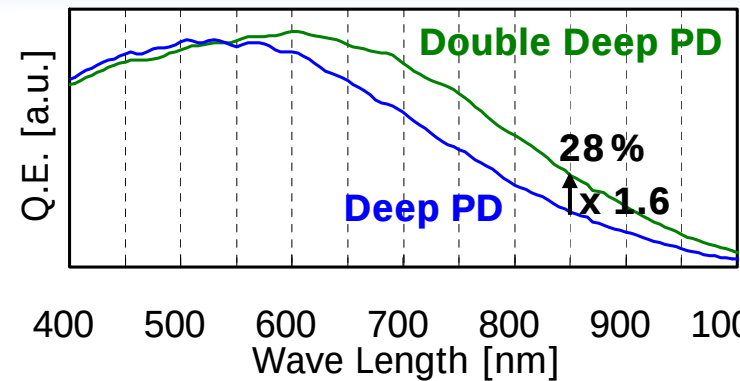
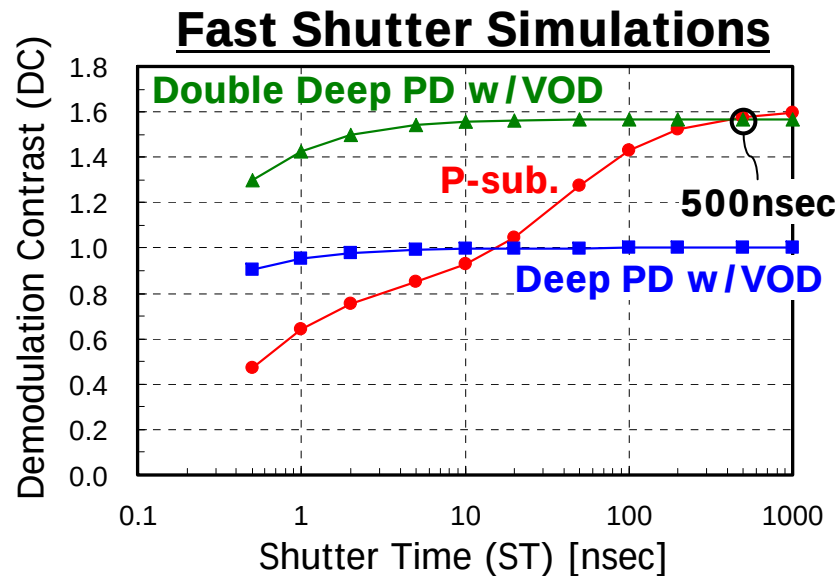
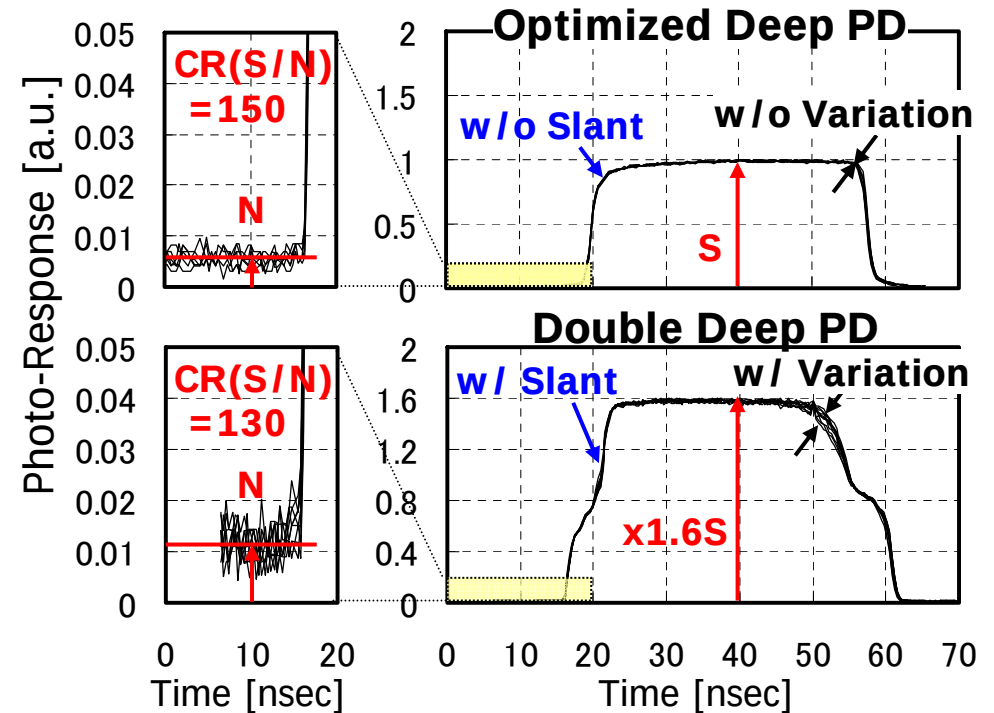


Photo-Response of SUB Shutter



Double Deep PD realizes 1.6 times higher IR sensitivity than Deep PD. DC of this PD will surpass P-sub. at ST < 500 nsec. Slants and Variations could be removed through optimum pixel design.

Summary

Advantages of IT-CCD Pixel

- Better performance in areas of Sensitivity, Smear, Dark Current and Crosstalk.

Requirements for Pulsed ToF

- 1. High IR Sensitivity -> Long Distance Ranging
- 2. Fast Global Shutter -> Accurate Depth Measurement

IT-CCD pixel can satisfy these requirements.

This work

- 1-1. High Reflective-Index Micro-Lens -> High F.F. (70%@5.4um $\square$)
- 1-2. Deep PD w/ VOD -> High IR Q.E. (18%@850nm)
- 2. Electric Field Enhancement in the Deep PD -> Fast Shutter ($t_r, t_f < 2\text{nsec}$)

Next Approach to Future ToF

- Double Deep PD w/ VOD -> Higher IR Q.E. (28%@850nm)

Revolutionized IT-CCD pixel will aid further progress on ToF sensors



Thank you