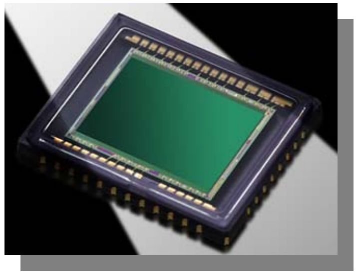
# Pixel Design and Technologies for Time-of-Flight Sensors



Tohru Yamada, Takuya Asano

Image Sensor Division
Semiconductor Business Division
Automotive & Industrial Systems Company
Panasonic Corporation

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# 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<br>DSC, DVC, Smartphone<br> <br>*Picture Shooting and Recording* | Visible light and Infrared (IR) light<br>Consumer<br><br>@Microsoft XBOX<br>*Natural U/I*<br>Industry<br><br>@KIVA Systems<br>*Robotic vision*<br>Automobile<br><br>*Autonomous Driving* |

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

# Panasonic Image Sensors

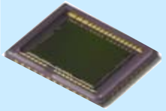
## Digital AV

**Small Pixel**
**High Sensitivity**

## Security / Automotive

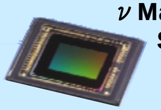
**High IR Sensitivity**
**Wide Dynamic Range**

**IT-CCD***



*Interline Transfer CCD

**CMOS (CIS)**
**Image Sensor**

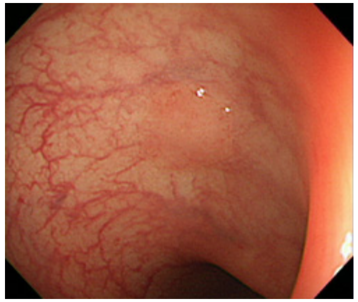


$\nu$ Maicovicon®
SmartFSI®

## Broadcast

**Global Shutter**
**Low Smear**

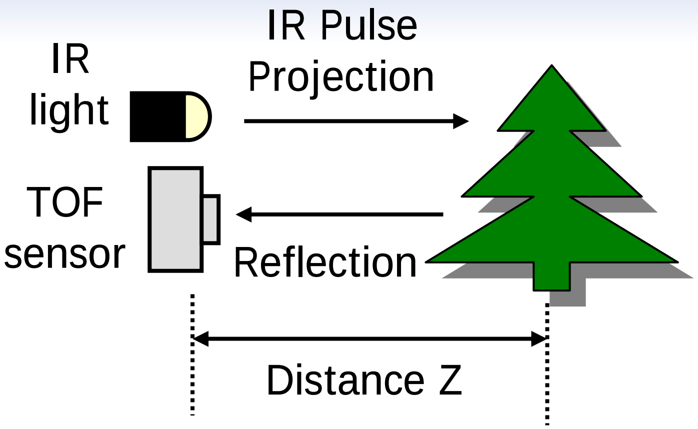
## Medical

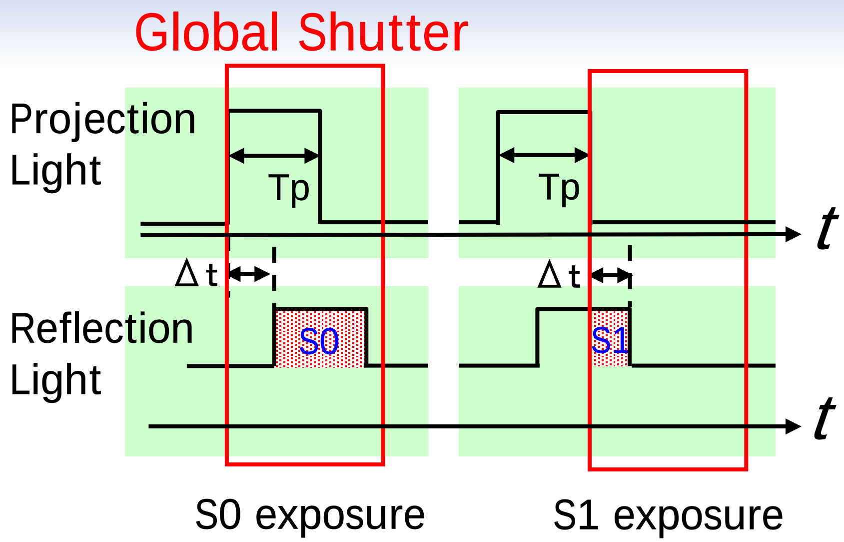


**Color Reproducibility**
**Small Die Size**

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

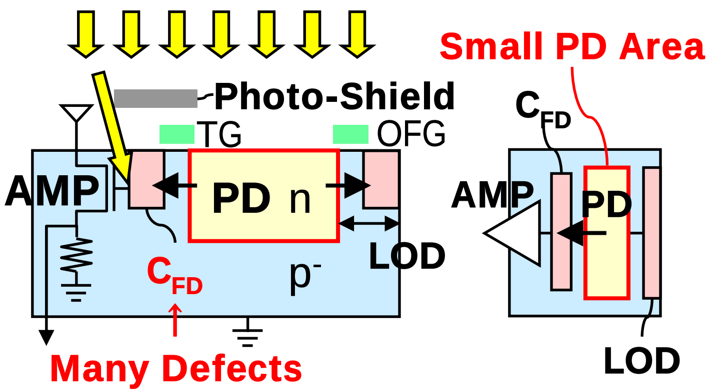
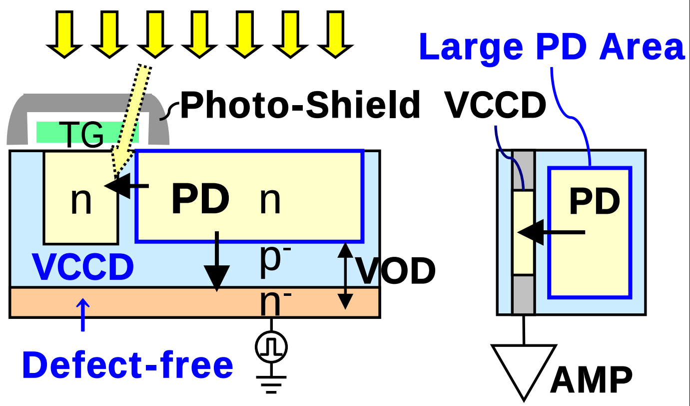
## Requirements for Pulsed ToF Pixels

- 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.

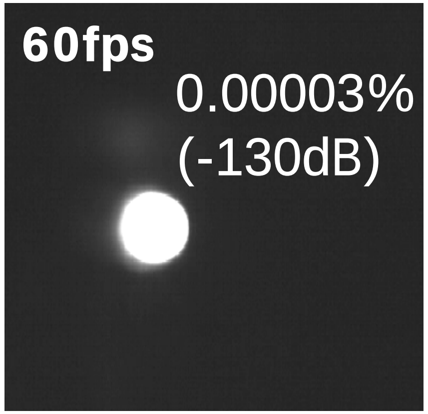
| | GS-CIS (5-Tr. type*)<br>1/3" WVGA (752x480) 6.0um□ | Panasonic IT-CCD (MN39784)<br>1/3" qHD (960x540) 5.4um□ |
|---|---|---|
| Pixel Architecture<br><br>**Pixel performances** | *RST-Tr, SEL-Tr are not shown<br> |  |
| Signal Storage Region | $C_{FD}$ (Floating Diffusion Capacitance) | VCCD (Vertical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

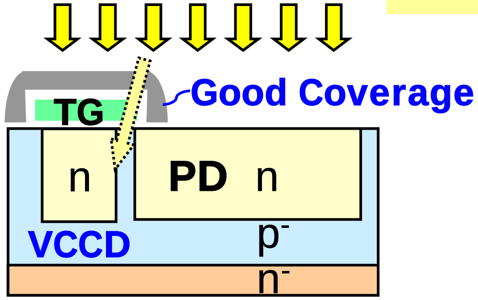
Reference :(1)Data sheet (2)IIWS2005

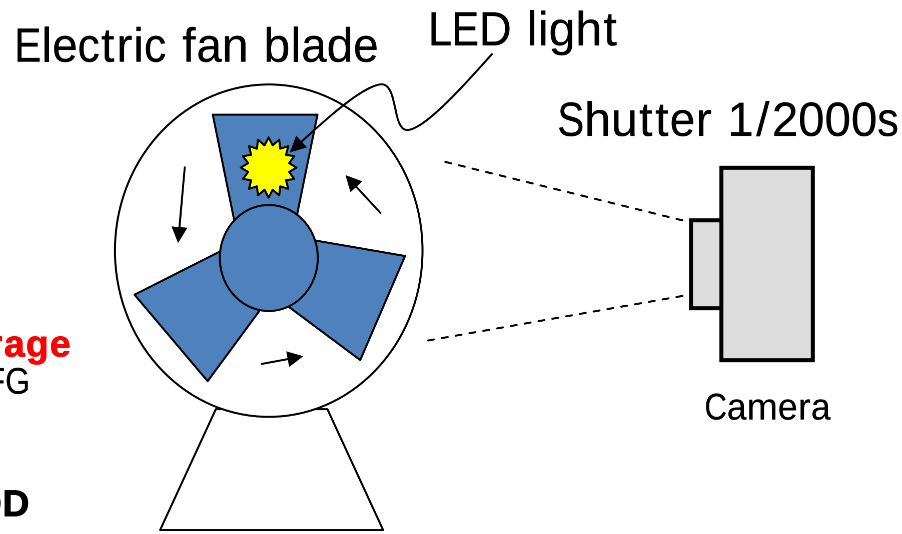
# Smear (Parasitic Sensitivity) – GS-CIS vs. IT-CCD

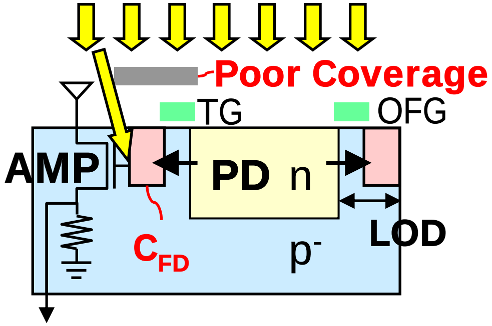
Panasonic IT-CCD (MN39784)
1/3" qHD (960x540) 5.4um☐

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

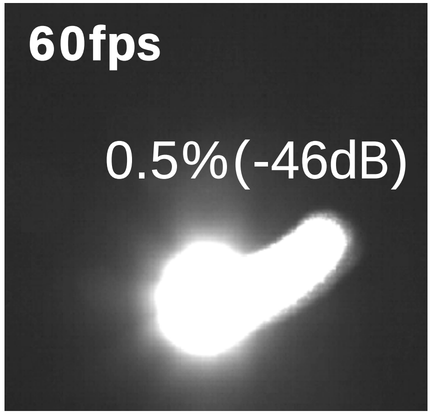


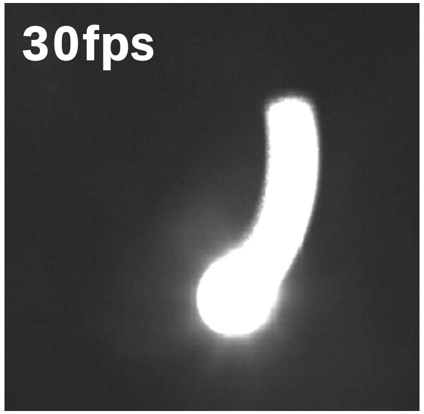



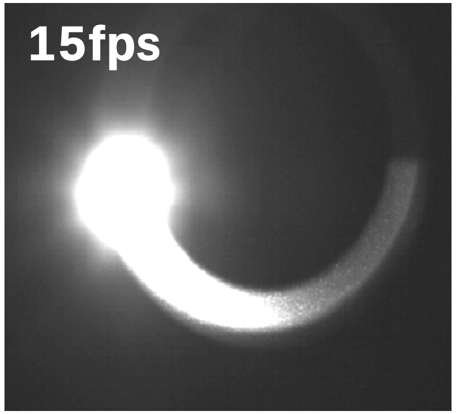



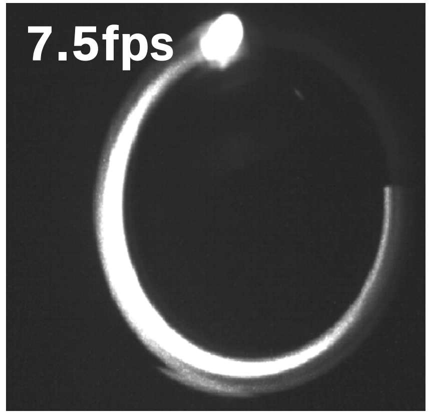




GS-CIS 1/3" WVGA
(752x480) 6.0um☐



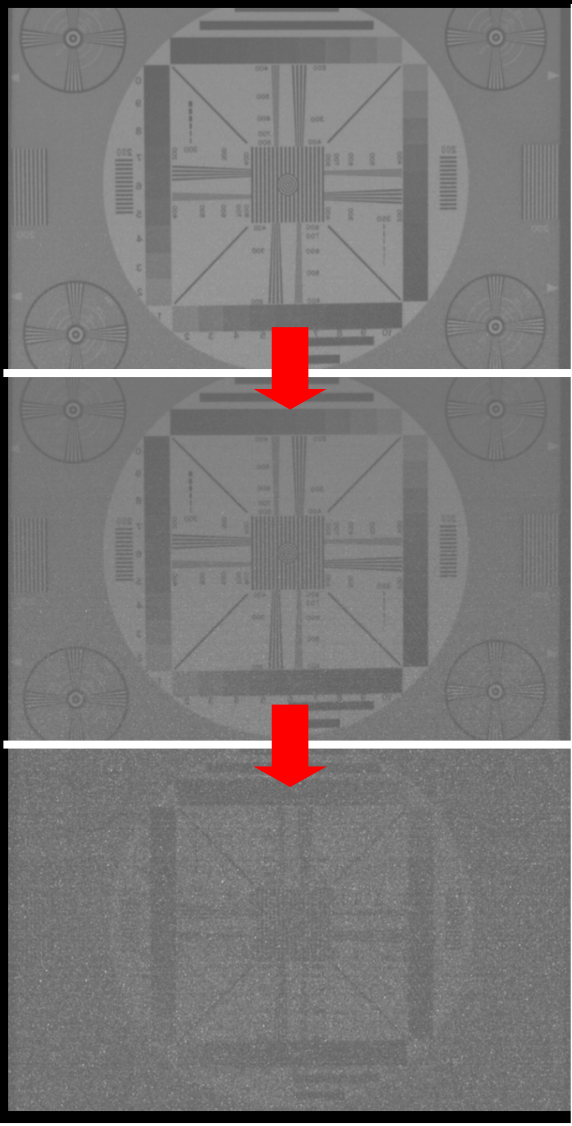



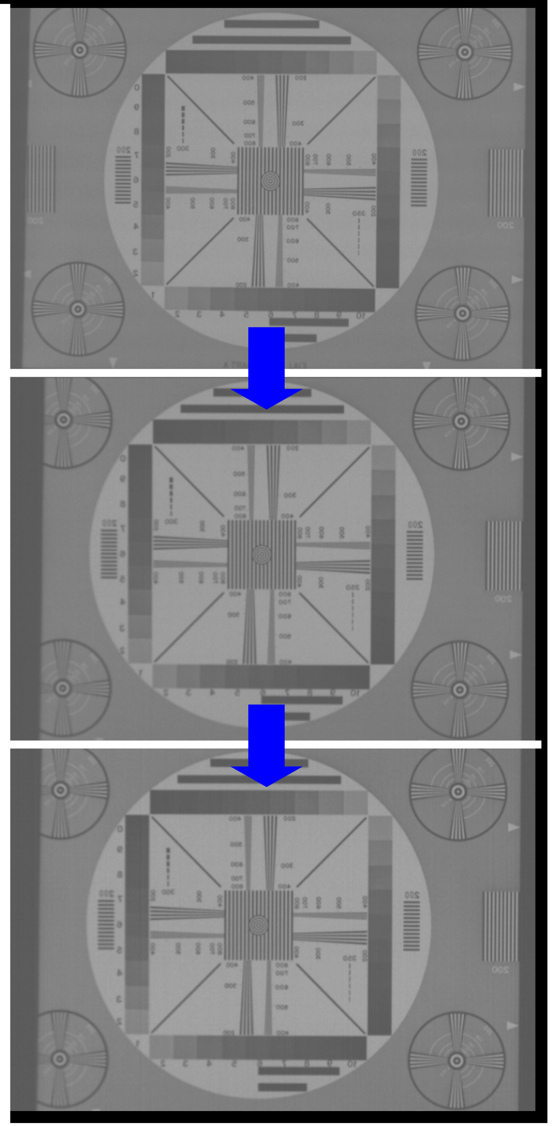



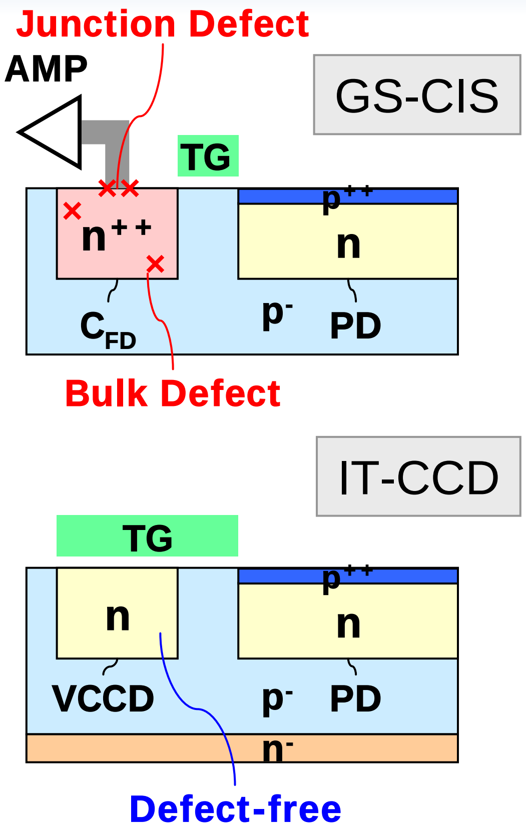
# Dark Current – GS-CIS vs. IT-CCD

Sensor temperature 80 degrees; exposure time 1/10000s

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



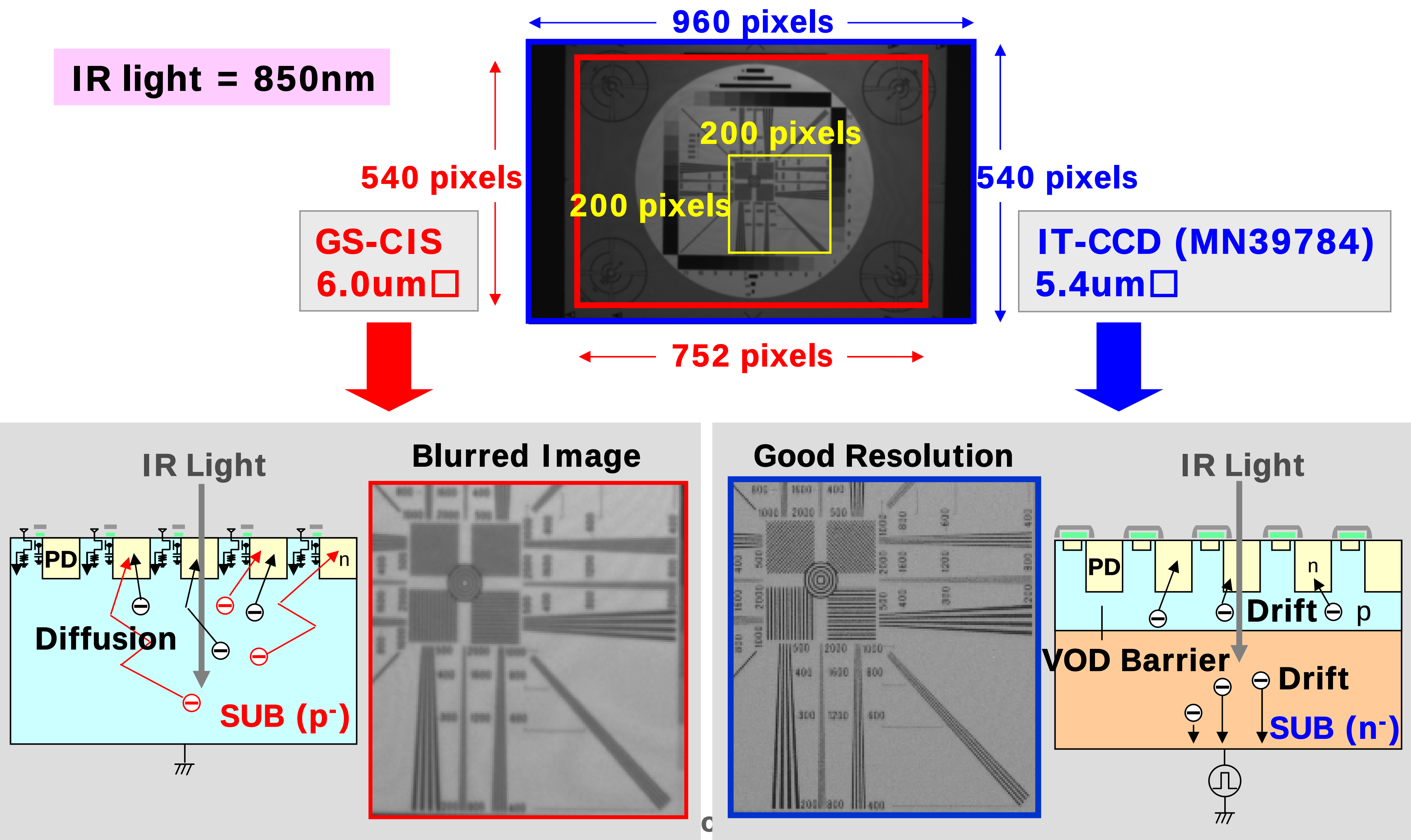





VCCD of IT-CCD has low doped channel and no metal junction; this can reduce surface and bulk defects, resulting in low dark current.

# 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.



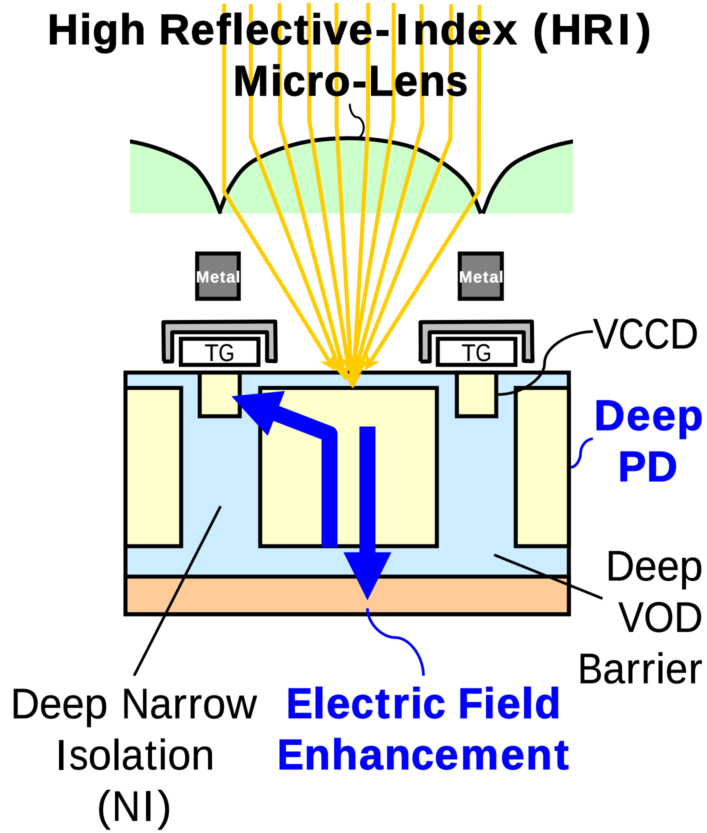
# Pixel Design and Technologies for ToF Sensors

## 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
   - Enhanced IR Sensitivity
2. Accurate Depth Measurement
   - Electronic Fast Shutter

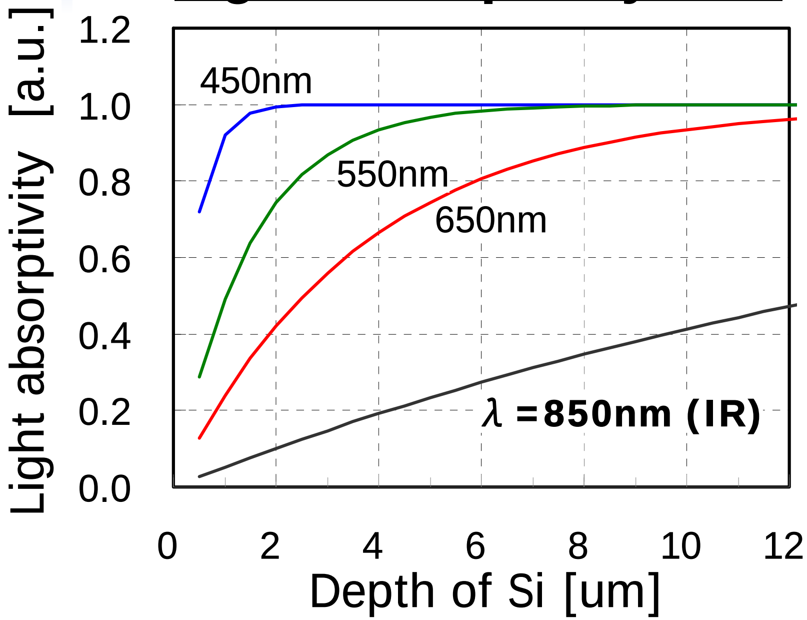



## Approach

- 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

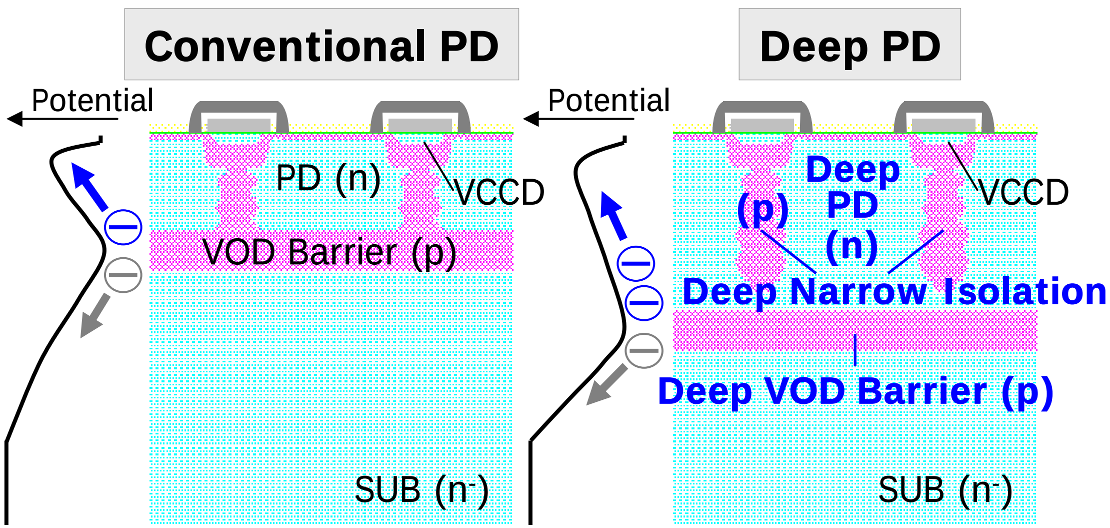



IR Light penetrates deeply into Si substrate.

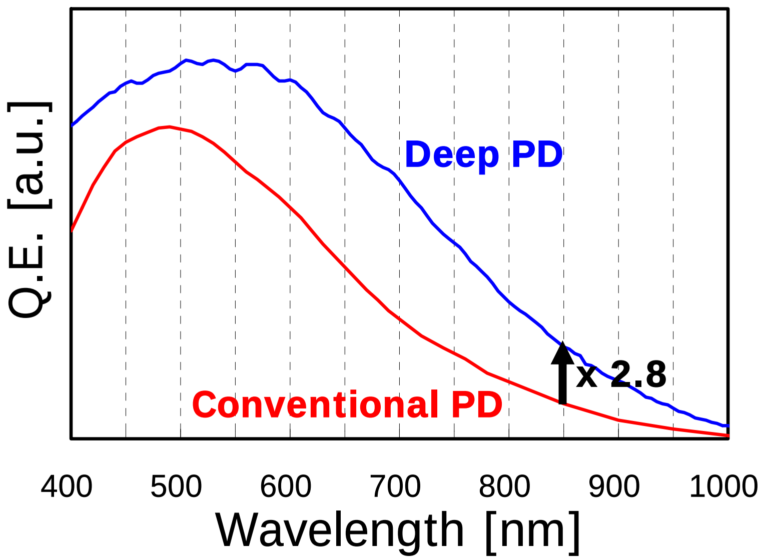
Deep PD is necessary to obtain higher IR sensitivity.

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

## Pixel Impurity Profiles

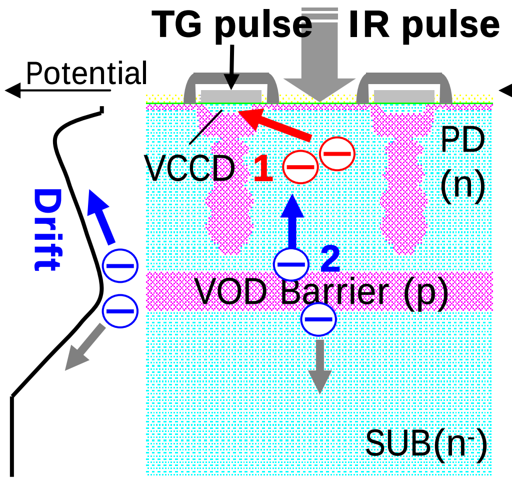



## Quantum Efficiency (Q.E.)

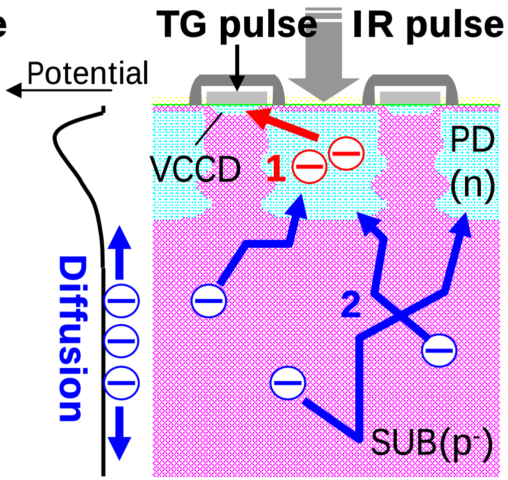


# Fast Shutter Characteristics– Deep PD w/ VOD

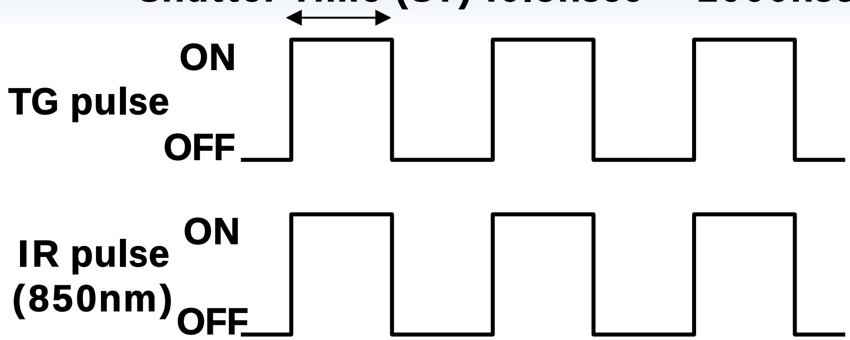
### Deep PD w/ VOD




### P-sub. structure

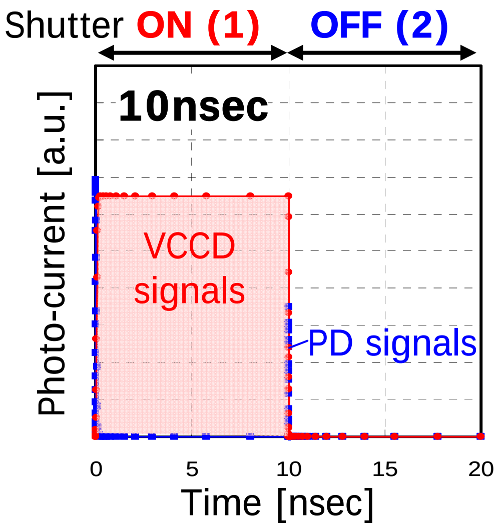


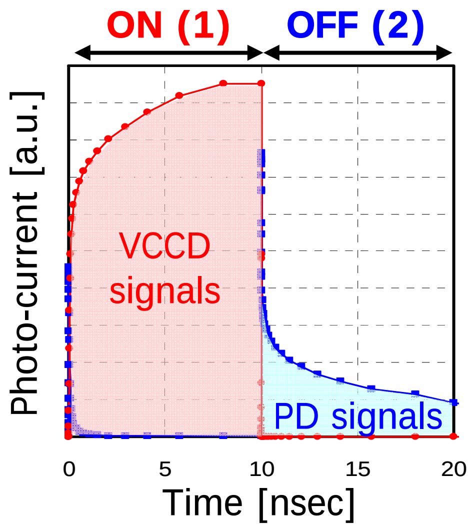

Shutter Time (ST) :0.5nsec ~ 1000nsec



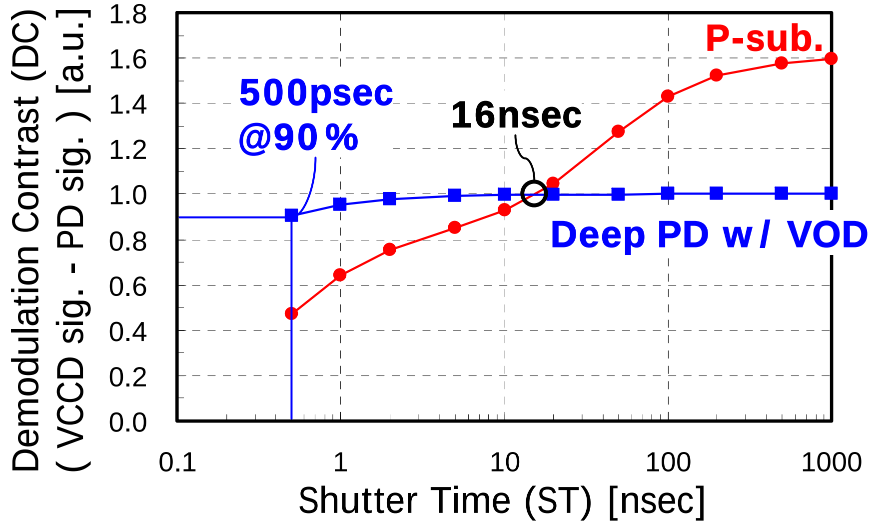

1. Photo-electrons are generated in PDs and transferred to VCCDs.
2. After TG pulse turns off, electrons in deep regions of substrate belatedly move to PD.

## Photo-Current Simulations



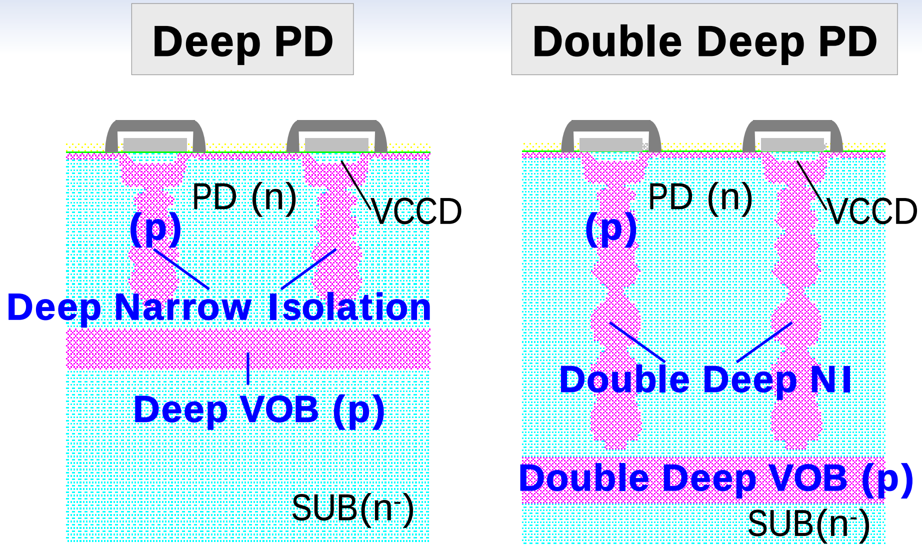



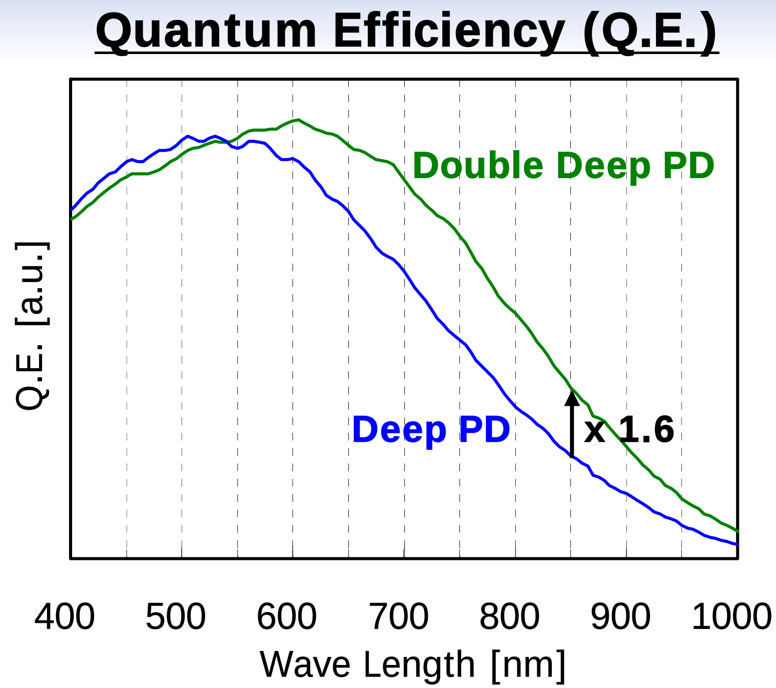

## Fast Shutter Simulations

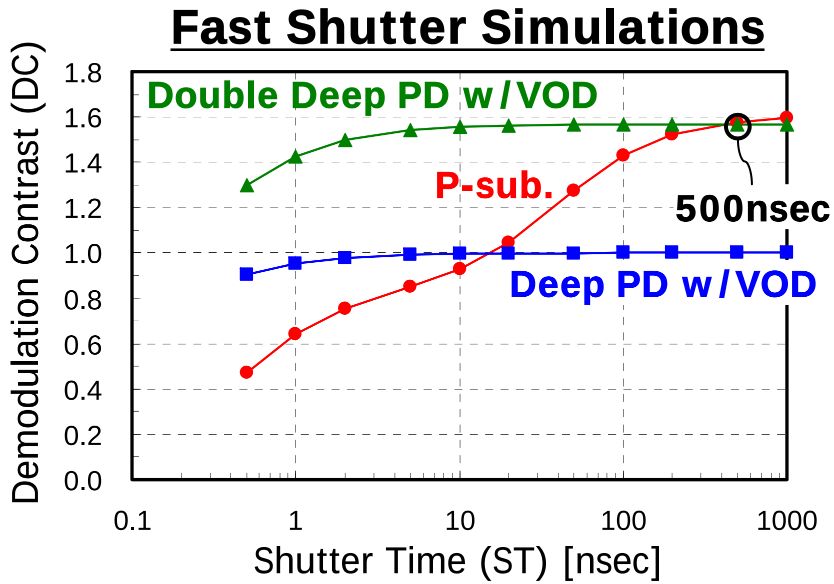



Even though p-sub. obtains higher DC at ST longer than 16nsec, the DC plummets as ST becomes shorter, while Deep PD w/ VOD retains DC and 90% of it is obtained at ST of 500psec.

# Technology for Future TOF – Double Deep PD




Double Deep PD realizes 1.6 times higher IR sensitivity than Deep PD. DC of this PD will surpass P-sub. at ST <500nsec.

# 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.

1-2. Deep PD w/ VOD -> High IR Q.E.

2. Electric Field Enhancement in the Deep PD -> Fast Shutter

## Next Approach to Future ToF

➢ Double Deep PD w/ VOD -> Higher IR Q.E.

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