R09.1

3D-Stacked 1Megapixel Dual-Time-Gated Color SPAD Image Sensor with Simultaneous Dual Image Output Architecture for Efficient Sensor Fusion

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Outline

- Background & Motivation

- Sensor Architecture & Operations

- RGB-D Imaging Demonstration

- 2D HDR Imaging Demonstration

- Conclusion

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- **Background & Motivation**

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Background

- **SPAD image sensor**
  - Natively digital operation principle & picosecond temporal resolution

- **Time-gated SPAD image sensor**
  - Capable of multiple sensing modalities (2D imaging, 3D ToF sensing, event based sensing, ...) with monocular configuration suited for machine vision applications
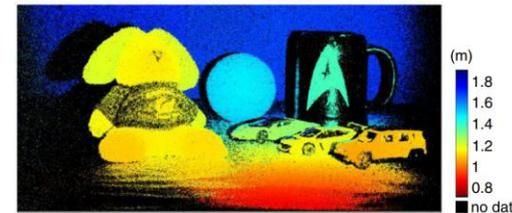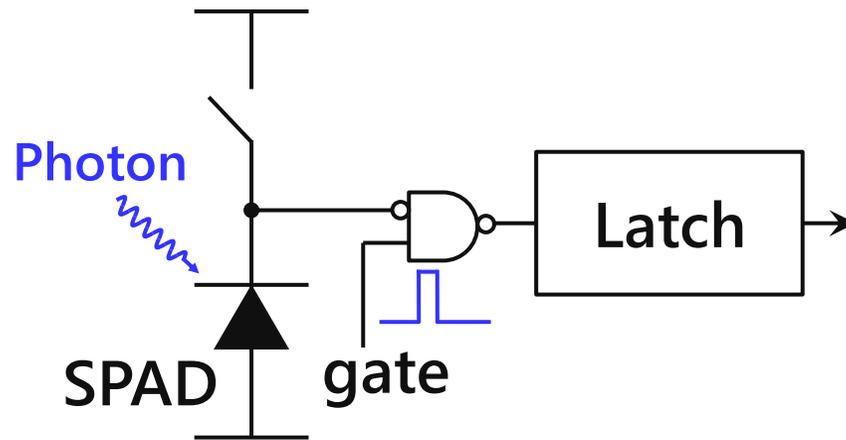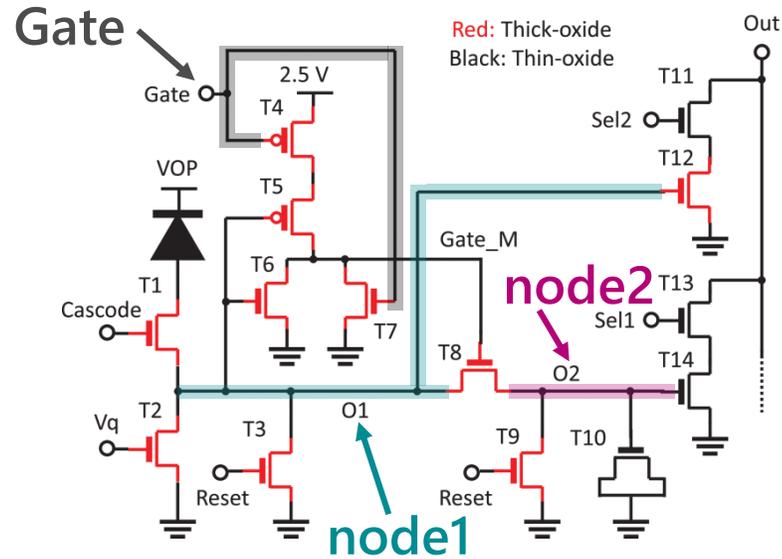

(K. Morimoto et al., Optica, 2020)

  - Frame timing of images are different (e.g., 2D & 3D images, short/long exp. images for HDR)
    → Integrating images requires temporal alignment when capturing moving object

Objective

Related Work: Dual-Gated SPAD Image Sensor for FLIM (M. Wayne et al., IEEE TED, 2022)

Dual in-pixel storage nodes
→ Can capture **dual images simultaneously**

Limitations due to bio-application focus

- Large pixel size (16.38 μm)
- Medium resolution (500×500 pixels)
- Unable to independently control each exposure time of dual images

Goal of This Work

- **To realize dual-time-gated** SPAD sensor enabling **simultaneous dual-image output** with **small pixel size** & **high resolution**
- **To demonstrate RGB-D imaging** & **2D HDR imaging** utilizing novel HDR technique

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- **Sensor Architecture & Operations**

- RGB-D Imaging Demonstration

- 2D HDR Imaging Demonstration

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Chip Architecture
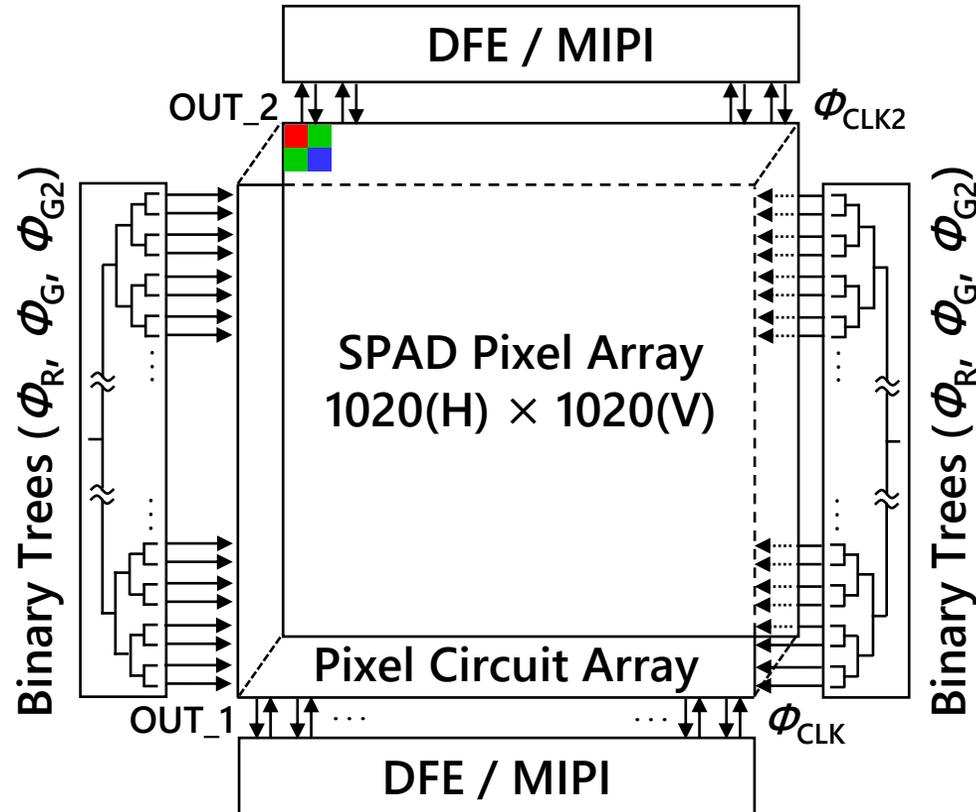
Sensor Specifications

- 3D-BSI SPAD sensor
- 1,020×1,020 effective pixels
- 5μm pixel pitch
- On-chip color filter
- Simultaneous dual-image output
- 1,310fps readout (4-bit depth)

- Global clock trees (Φ_R, Φ_G, Φ_{G2}) optimized for reduced gate skew
- 1-bit pixel output summed to 4-bit with on-chip frame memory

Pixel Architecture & Operation

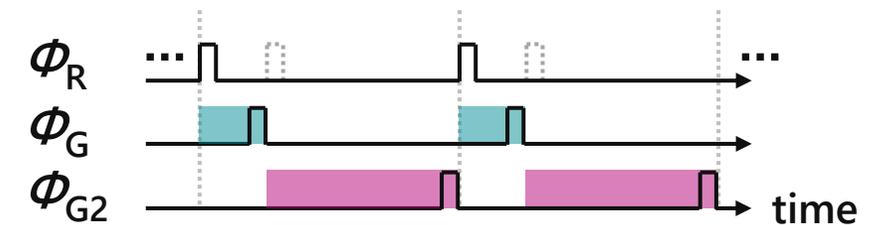- Each pixel has two parallel 1-bit memories
- Gate windows are defined by Φ_R, Φ_G, Φ_{G2}
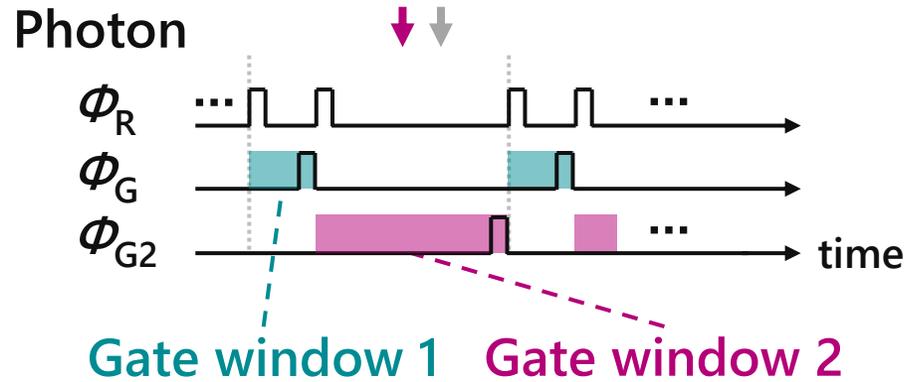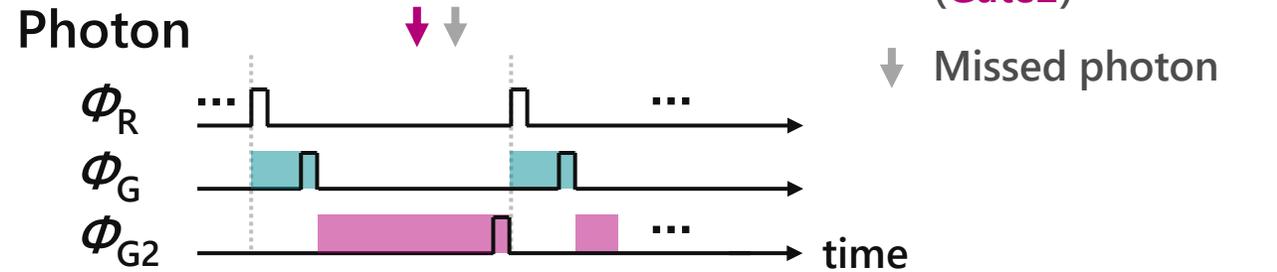- Two operation modes can be utilized

Dual Recharge Mode
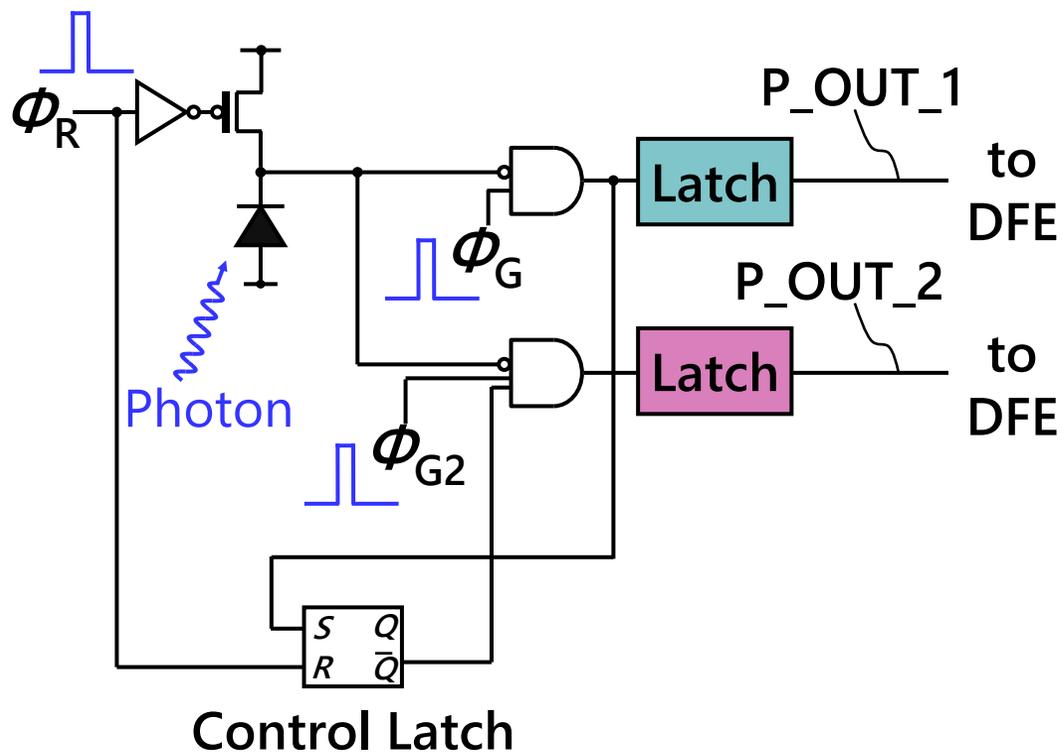
Gate window 1   Gate window 2
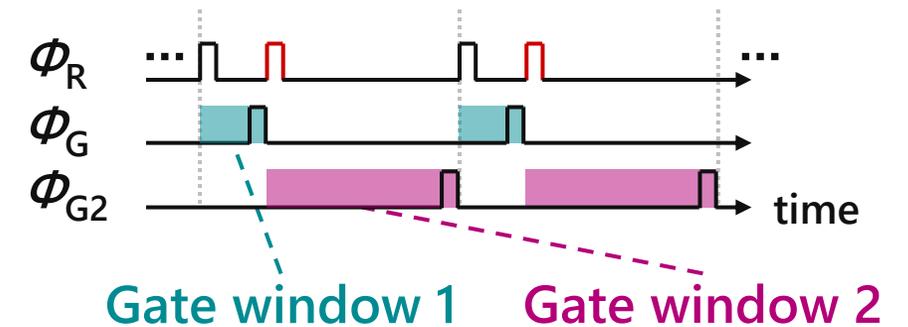
Single Recharge Mode

Pixel Operation

Dual Recharge Mode

Photon

Φ_R ... ⬤ ⬤ ...

Φ_G

Φ_{G2} ... → time

Gate window 1   Gate window 2

Single Recharge Mode

⬇ Detected photon (Gate2)

⬇ Missed photon

Photon

Φ_R ... ⬤ ⬤ ...

Φ_G

Φ_{G2} ... → time

photon detection in one of gate windows → same behavior at both modes

Arrive Photon?		Pixel Output			
		Dual Recharge		**Single Recharge**	
Gate1	**Gate2**	P_OUT_1	P_OUT_2	P_OUT_1	P_OUT_2
No	No	0	0	0	0
No	**Yes**	0	**1**	0	**1**
Yes	No	**1**	0	**1**	0
Yes	**Yes**	**1**	**1**	**1**	**0**

Φ_R

Photon

Φ_G

Φ_{G2}

P_OUT_1
Latch → to DFE

P_OUT_2
Latch → to DFE

S Q
R Q̄
Control Latch

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Pixel Operation

Dual Recharge Mode

Single Recharge Mode

↓ ↓ Detected photon (Gate1 / Gate2)

↓ Missed photon

Photon

Φ_R ... ...

Φ_G

Φ_{G2} ... time

Gate window 1   Gate window 2

Photon

Φ_R ... pileup effect ...

Φ_G

Φ_{G2} ... time

photon detection in gate window 1 → disables gate window 2 via control latch

Arrive Photon?		Pixel Output			
		Dual Recharge		**Single Recharge**	
Gate1	**Gate2**	P_OUT_1	P_OUT_2	P_OUT_1	P_OUT_2
No	No	0	0	0	0
No	**Yes**	0	**1**	0	**1**
Yes	No	**1**	0	**1**	0
Yes	**Yes**	**1**	**1**	**1**	**0**

Φ_R

P_OUT_1

Latch to DFE

Photon Φ_G

P_OUT_2

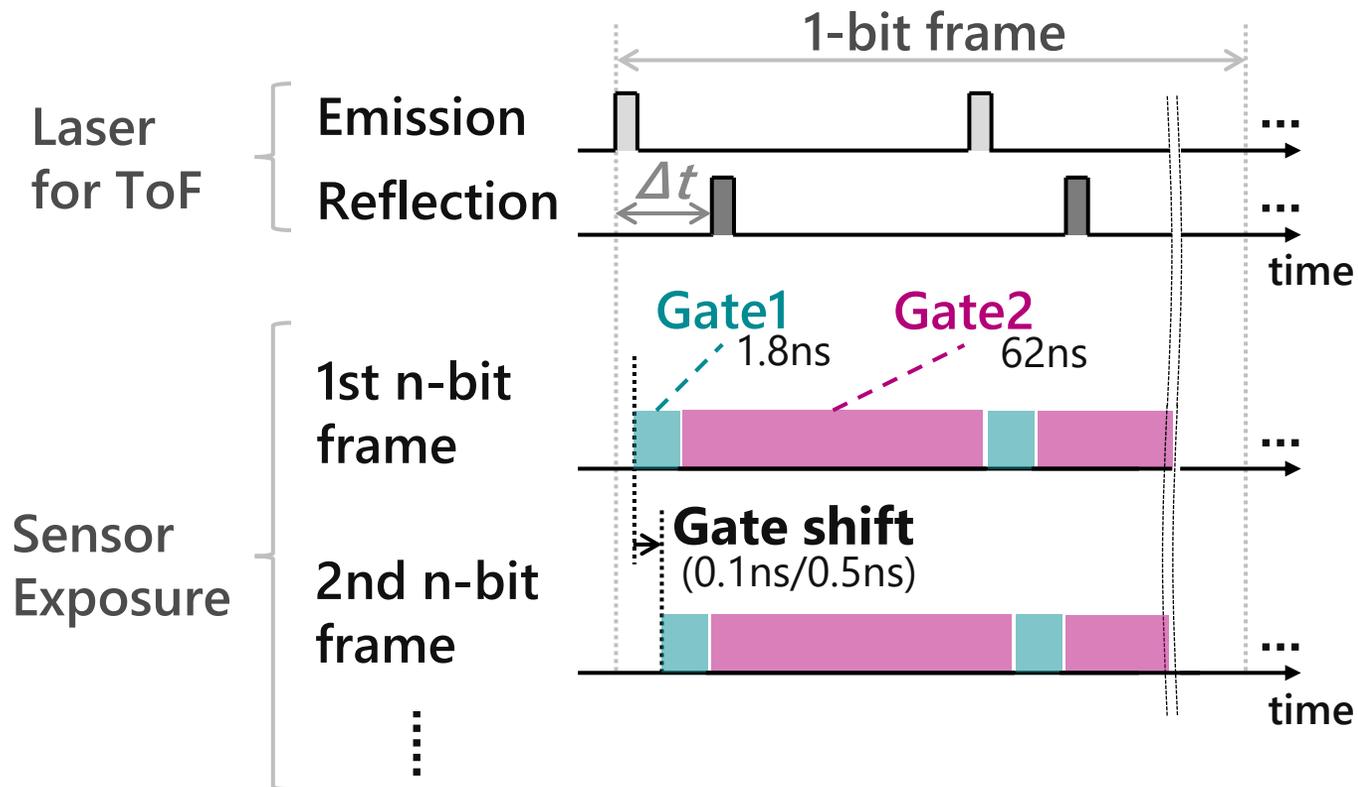Latch to DFE

Φ_{G2}
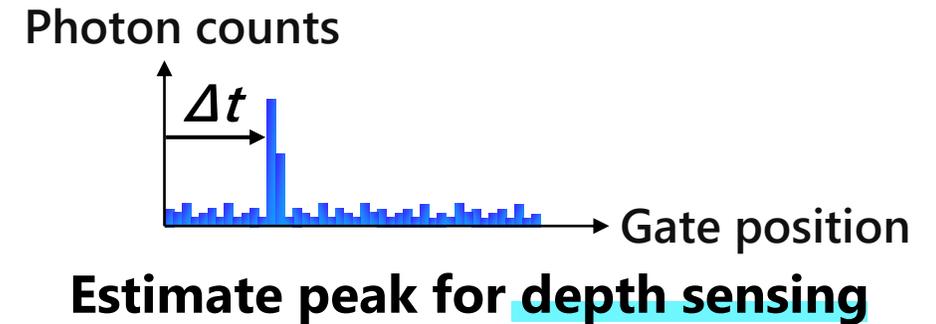
S Q
R Q̄

Control Latch

Outline

- Background & Motivation

- Sensor Architecture & Operations

- **RGB-D Imaging Demonstration**

- 2D HDR Imaging Demonstration

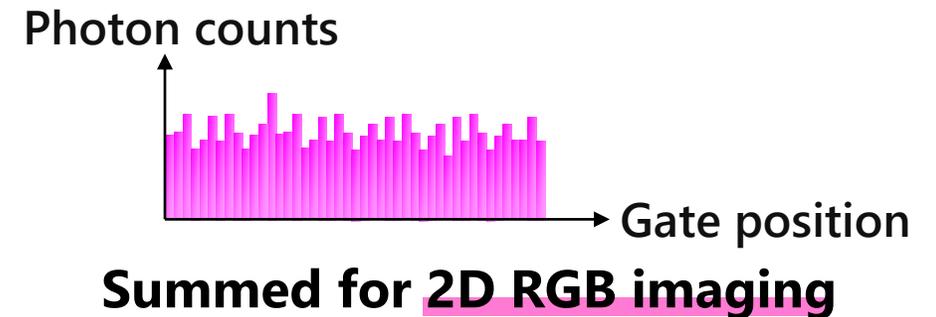- Conclusion

Pixel Operation for RGB-D Imaging

- 3D ToF image is captured at gate window 1

- 2D RGB image is captured at gate window 2

- Operation mode is Dual Recharge Mode

Laser for ToF

Emission

Reflection Δt

1-bit frame

time

Sensor Exposure

Gate1 1.8ns Gate2 62ns

1st n-bit frame

Gate shift (0.1ns/0.5ns)

2nd n-bit frame

time

Pixel data at gate window 1

Photon counts

Δt

Gate position

Estimate peak for depth sensing

Pixel data at gate window 2

Photon counts

Gate position

Summed for 2D RGB imaging
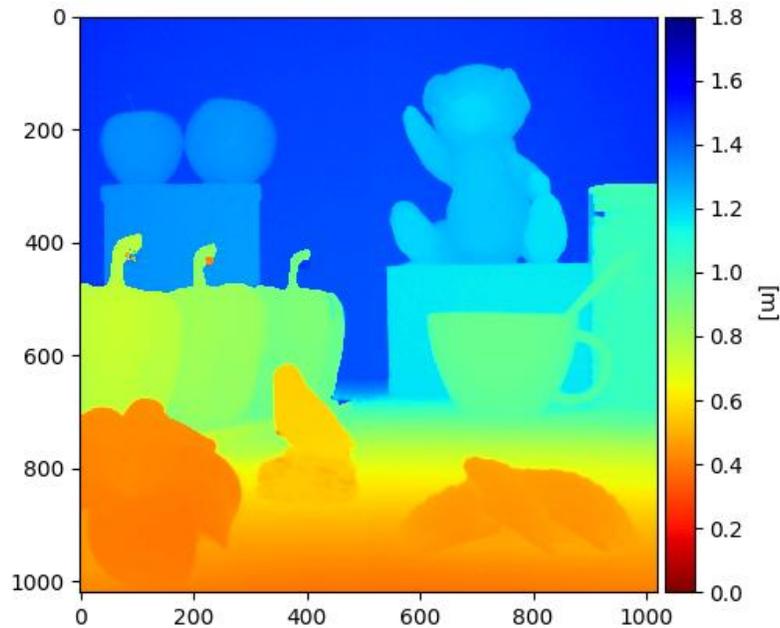
RGB-D Imaging Results

- ToF & RGB images have full resolution at same field-of-view and frame timing
  → simplifying the reconstruction process of point cloud

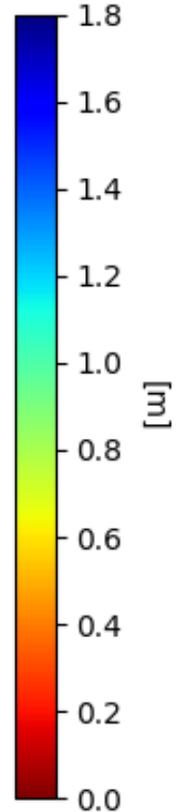**3D ToF Image
(Gate Window 1)**
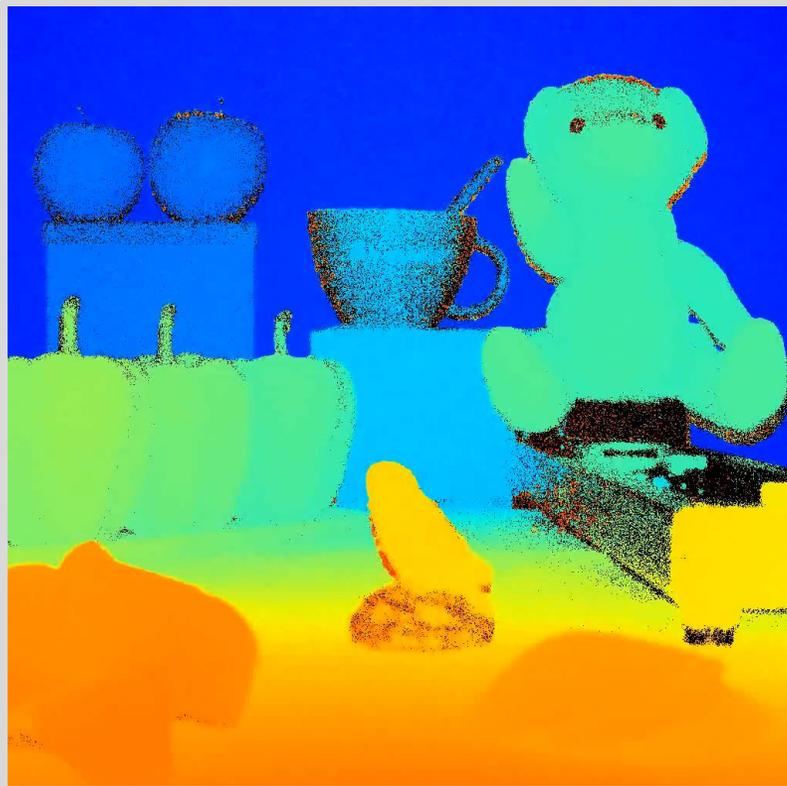
**2D RGB Image
(Gate Window 2)**

Point Cloud

frame rate: 0.45fps (appropriate for 3D scanning of stationary objects)

Demo Video (RGB-D Imaging)

3D ToF Image

2D RGB Image

- **This video shows that ToF & RGB images are captured at the same frame timing**

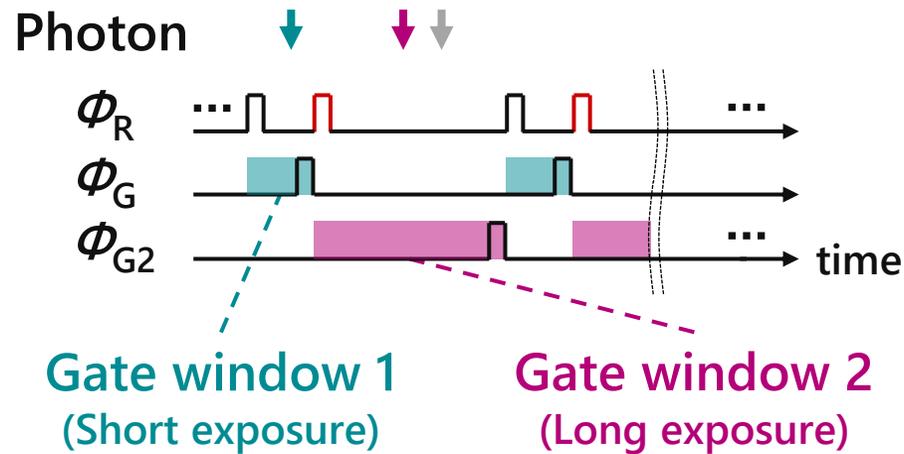 frame rate: 9.12fps (appropriate for moving objects)

Outline

- Background & Motivation

- Sensor Architecture & Operations

- RGB-D Imaging Demonstration
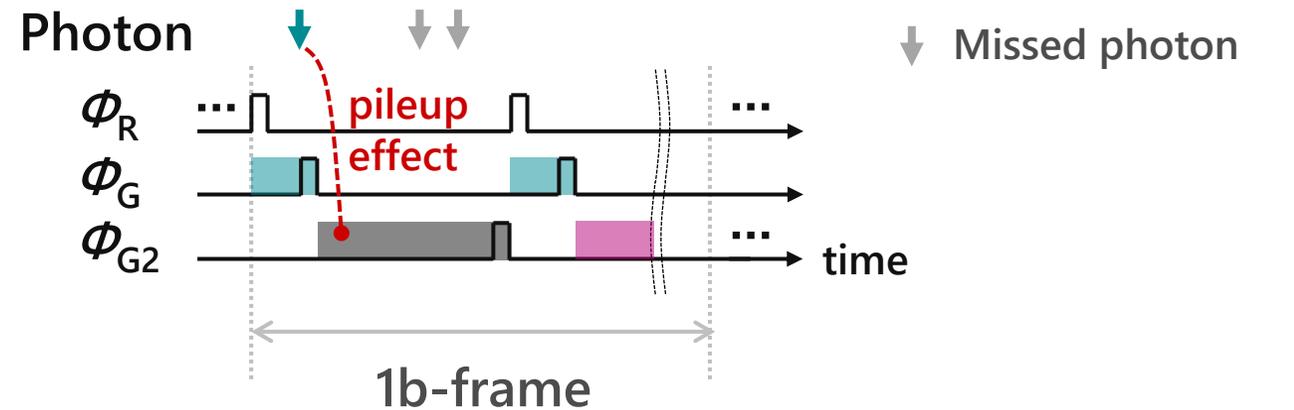
- **2D HDR Imaging Demonstration**

- Conclusion

Pixel Operation for 2D HDR Imaging

- Short exposed image is captured at gate window 1

- Long exposed image is captured at gate window 2

Dual Recharge Mode

Single Recharge Mode

⬇ ⬇ Detected photon
(Gate1 / Gate2)

⬇ Missed photon

Photon

Φ_R
Φ_G
Φ_{G2}

time

Gate window 1
(Short exposure)

Gate window 2
(Long exposure)

Ratio 1 : 10

Photon
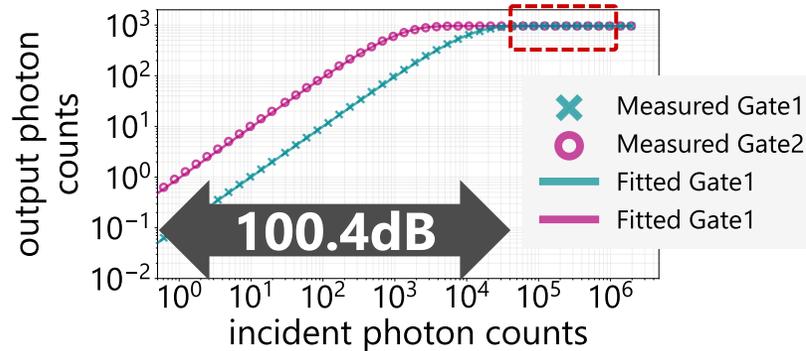
Φ_R
Φ_G
Φ_{G2}

pileup
effect

time

1b-frame

We demonstrate novel HDR technique utilizing pileup effect

HDR Imaging Results

Dual Recharge Mode

Single Recharge Mode

Photon Response Curve

Dual Recharge Mode plot — output photon counts vs incident photon counts, with Measured Gate1, Measured Gate2, Fitted Gate1, Fitted Gate1 legend, marked **100.4dB**

Single Recharge Mode plot — **119.5dB**, with annotation **Dropped due to pileup effect**

10-bit Raw Image

Gate1 (short exp.)   Gate2 (long exp.)

Gate1 (short exp.)   Gate2 (long exp.)
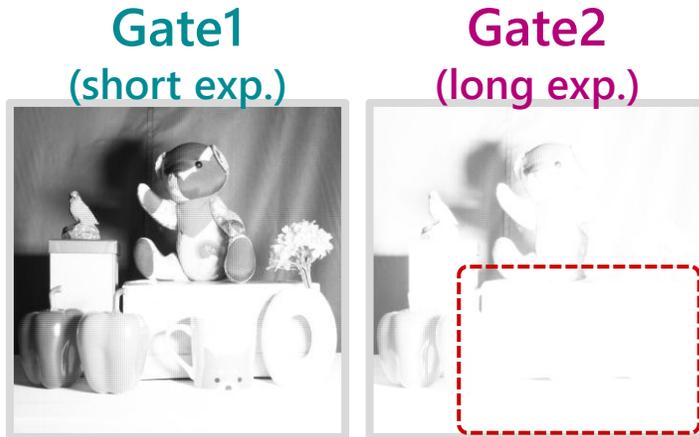
Saturated at gate 1 and gate 2, we can NOT reconstruct incident count
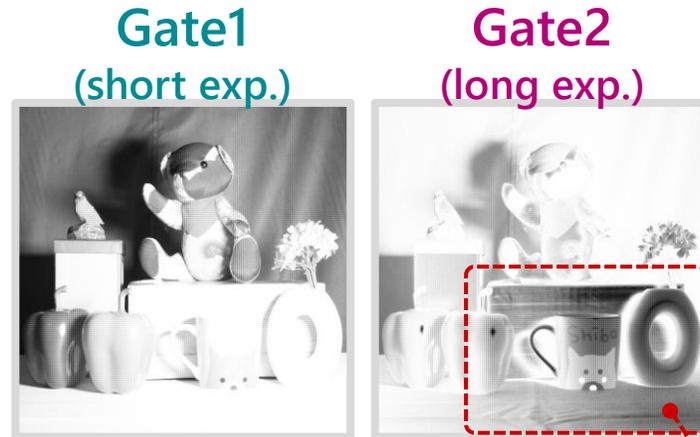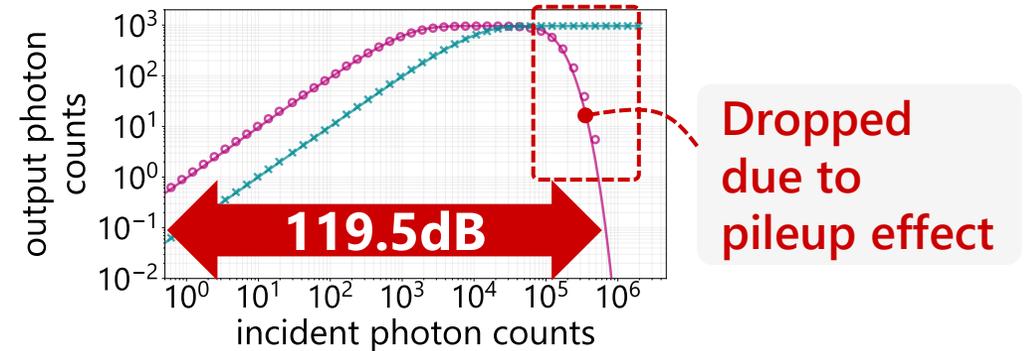
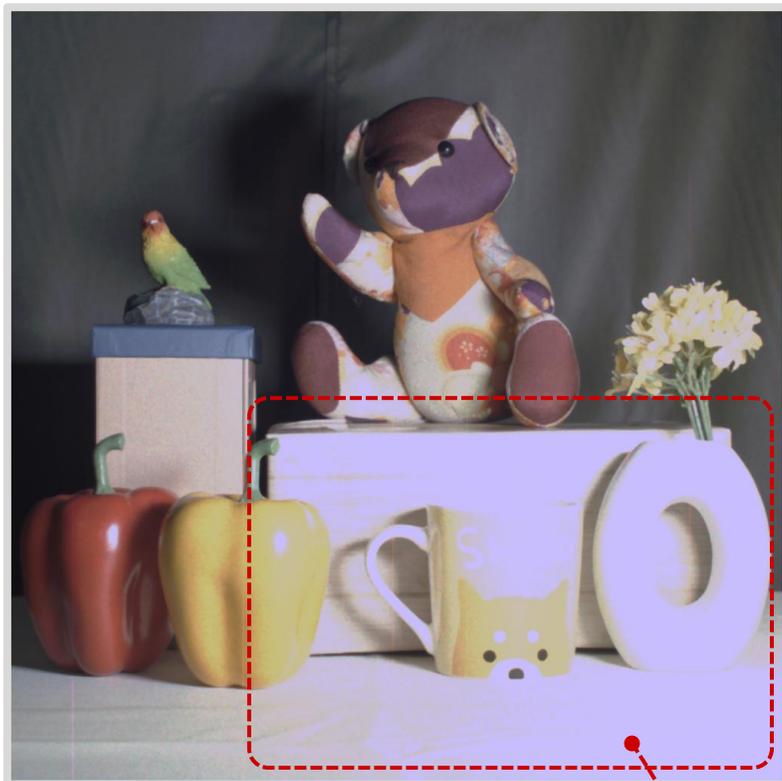**Thanks to different counts at gate1 and gate2, we can reconstruct incident count**

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Reconstructed HDR Image
(After demosaicing / Tone curve correction)

Dual Recharge Mode

Overexposed

Single Recharge Mode

✓ **Clearly visible**
✓ **Color is recognized**

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State-of-the-Art Comparison

	Perenzoni (2016)	Gyongy (2018)	Morimoto (2020)	Wayne (2022)	Morimoto (2024)	This work (Gate1 / Gate2)
Process technology	350nm HV CMOS	130nm CIS	180nm CMOS	180nm CMOS	90nm/55nm 3D-BSI CMOS	**90nm/55nm 3D-BSI CMOS**
Sensor resolution	160×120	256×256	1,024×1,000	500×500	1,020×1,020	**1,020×1,020**
Pixel pitch (μm)	15	16	9.4	16.38	5	**5**
Exposure modes	GS	RS / GS	RS / GS	RS	Seamless GS	**Seamless GS**
Frame rate (fps)	486 (5.4b)	100,000 (1b)	24,000 (1b)	49,800 (1b×2)	1,310 (4b)	**1,310 (4b×2)**
Min. gate length (ns)	0.75	4.0	3.8	1.0	1.85	**1.60 / 1.70**
Gate length variation (ps)	80.2 (std. dev.) 189 (FWHM)[1]	N/A	120 (FWHM)	70 (std. dev.) 165 (FWHM)[1]	125 (FWHM)	**135 / 118 (FWHM)**
Gate skew (ps)	N/A	N/A	410 (FWHM)	109.4 (FWHM)	80 (FWHM)	**94 / 119 (FWHM)**
Power consumption at saturation (mW)	N/A	N/A	18,236 (per 1Mpixel)	N/A	505	**1053**
Pixel output bit depth	5.4b (analog)	1b	1b	1b×2channels	4b	**4b×2channels**
Mono/Color	Monochrome	Monochrome	Monochrome	Monochrome	Monochrome	**Color**

[1] Standard deviation (σ) converted to FWHM by: $FWHM = 2\sigma\sqrt{2\log 2}$

Conclusion

- **Novel high-definition dual-time-gated SPAD image sensor is demonstrated**

- **Developed SPAD image sensor achieved:**
  - Simultaneous output of dual images with full resolution
  - 1Mpixel
  - 5μm-pitch pixels
  - Individually controllable dual-gate windows with best-in-class gating performance

- **RGB-D imaging & HDR imaging utilizing developed sensor**
  - Developed sensor achieved RGB-Depth imaging without complex alignment
  - Newly proposed HDR technique achieved dynamic range extension (119.5dB)

- **Applications**
  - Systems require miniaturization: AR/VR, mobile phones, machine vision applications etc.

Thank You for Your Attention!