A DVS sensor with a Photovoltaic Receptor

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Outline

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- Introduction
  - Dynamic Vision Sensor
  - DVS in Industry
  - A Photovoltaic Receptor
- PV diode suitability for EBS
  - Temporal Response
  - Frequency Response
- Understanding PVDVS
  - PVDVS Architecture
  - Experimental Results
- Conclusions
  - Assessment of Pros and Counters

Introduction. Dynamic Vision Sensor

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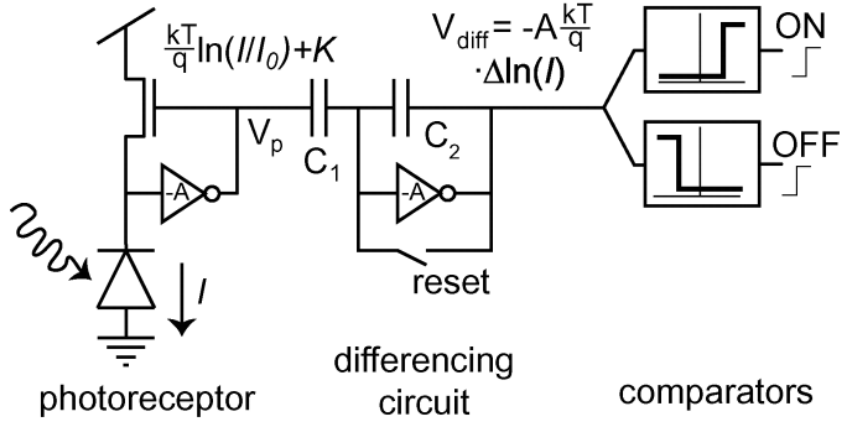
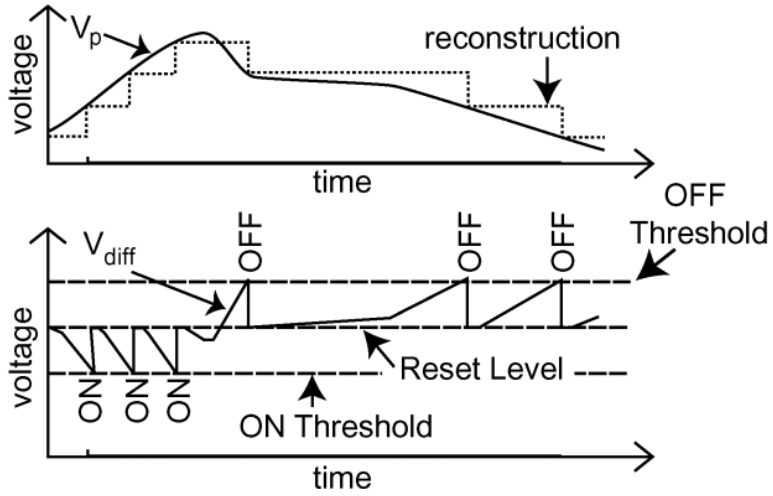
a) Abstracted pixel core schematic



b) Principle of operation



Benefits

- It removes redundant data.
  - Low power consumption ($\leq 100\,\mathrm{mW}$).
  - High temporal resolution ($\sim \mu s$).
- Autonomous pixels.
  - Low latency ($< \mathrm{ms}$).
  - High intra-dynamic range ($\sim 120\,\mathrm{dB}$).

[1] P. Lichtsteiner, C. Posch, and T. Delbruck. "A 128×128 120 dB $15\,\mu s$ Latency Asynchronous Temporal Contrast Vision Sensor", *IEEE Journal of Solid-State Circuits*, vol. 43, no. 2, pp. $566 - 576$, 2008.

Introduction. DVS in Industry

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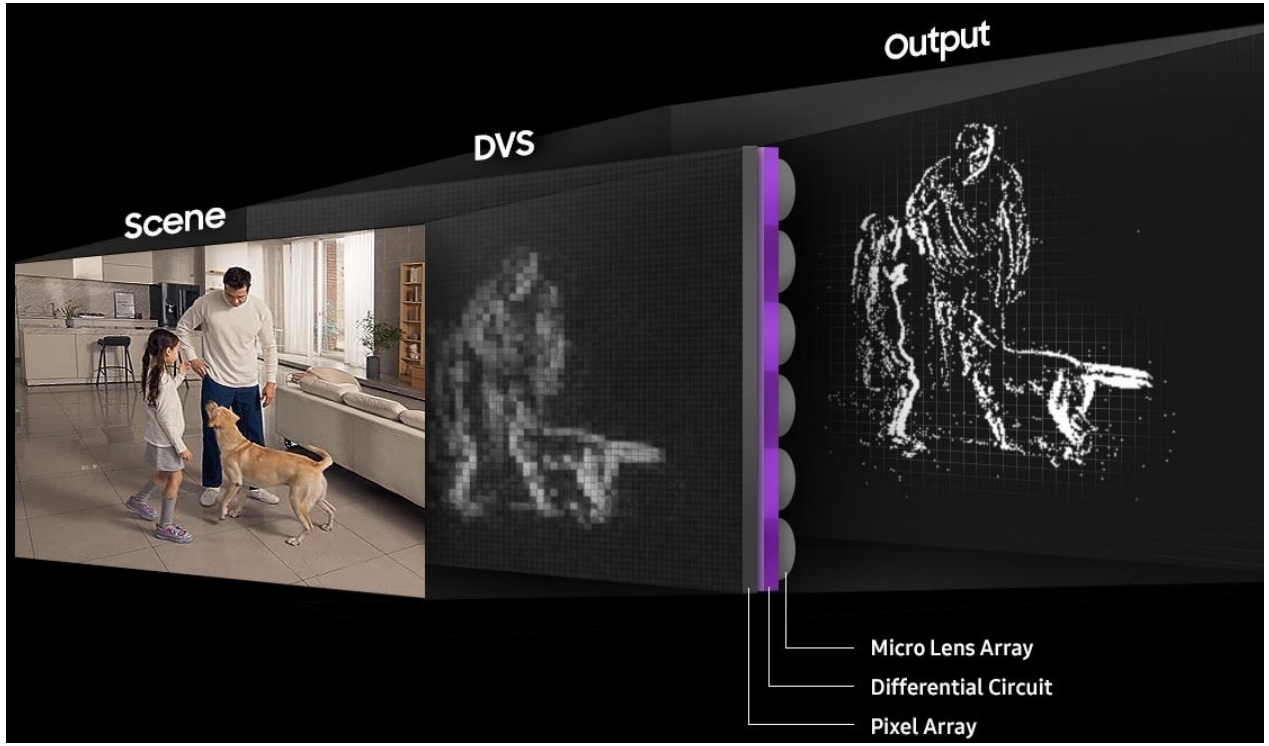

Challenges

- Unconventional space-time output.
  - Asynchronous events.
  - Sparse data.
- Limited to low matrix resolutions.
  - Power consumption.
  - Small Fill Factor.
- Limited by noise and mismatch.
  - Generation of fake events.

Introduction. DVS in Industry

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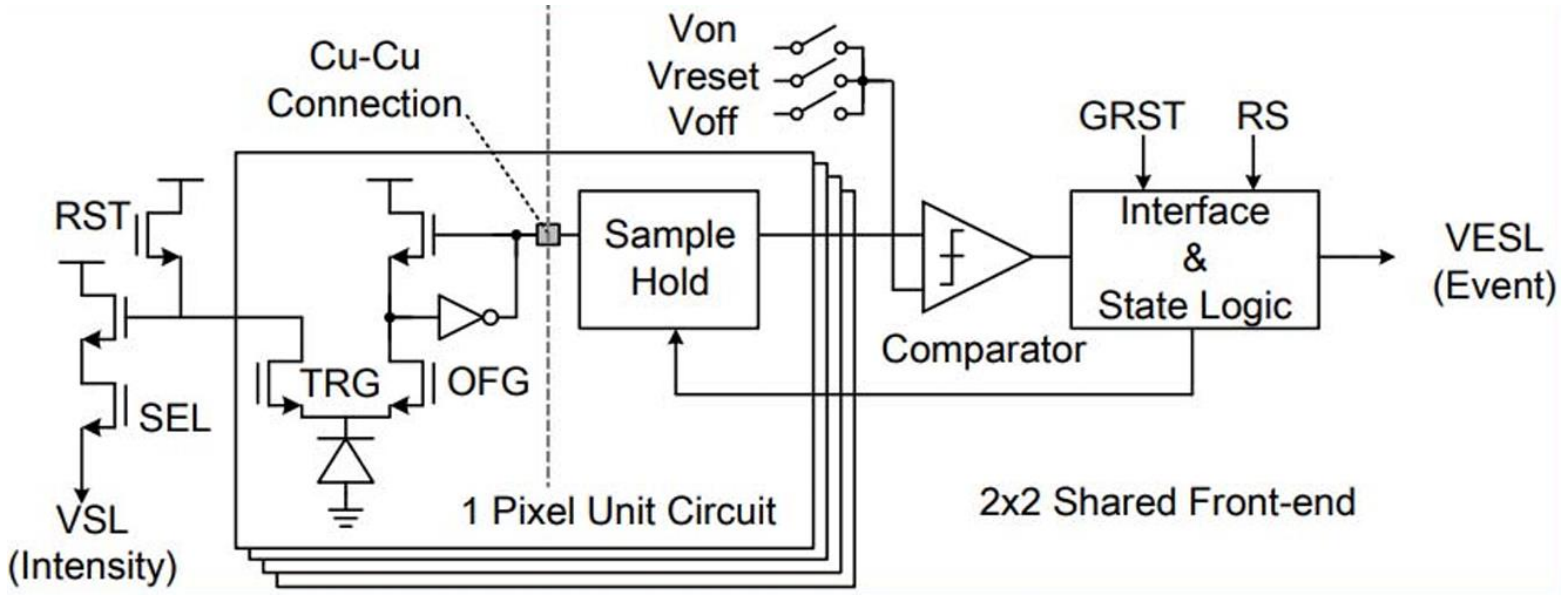

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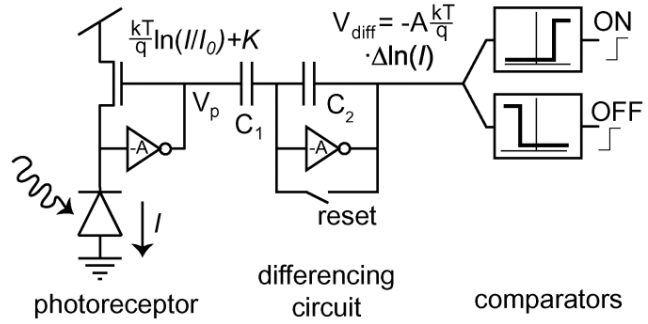

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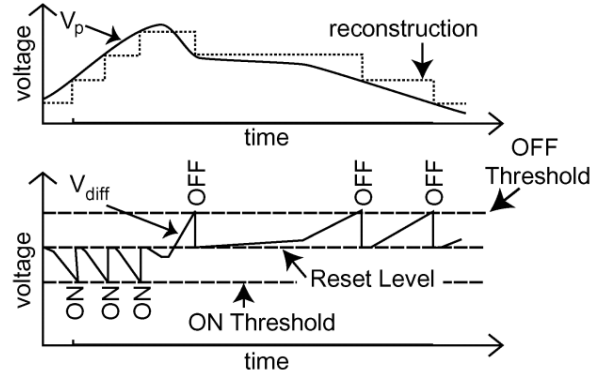

Alternative DVS architecture proposed by SONY ISSCC2023. [2]

[1] P. Lichtsteiner, C. Posch, and T. Delbruck. "A 128×128 120 dB 15 μs Latency Asynchronous Temporal Contrast Vision Sensor", *IEEE Journal of Solid-State Circuits*, vol. 43, no. 2, pp. $566 - 576$, 2008.

[2] A. Niwa et al., "A 2.97µm-Pitch Event-Based Vision Sensor with Shared Pixel Front-End Circuitry and Low-Noise Intensity Readout Mode," 2023 IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, USA, 2023, pp. 4-6, doi: 10.1109/ISSCC42615.2023.10067566.

Introduction. DVS in Industry

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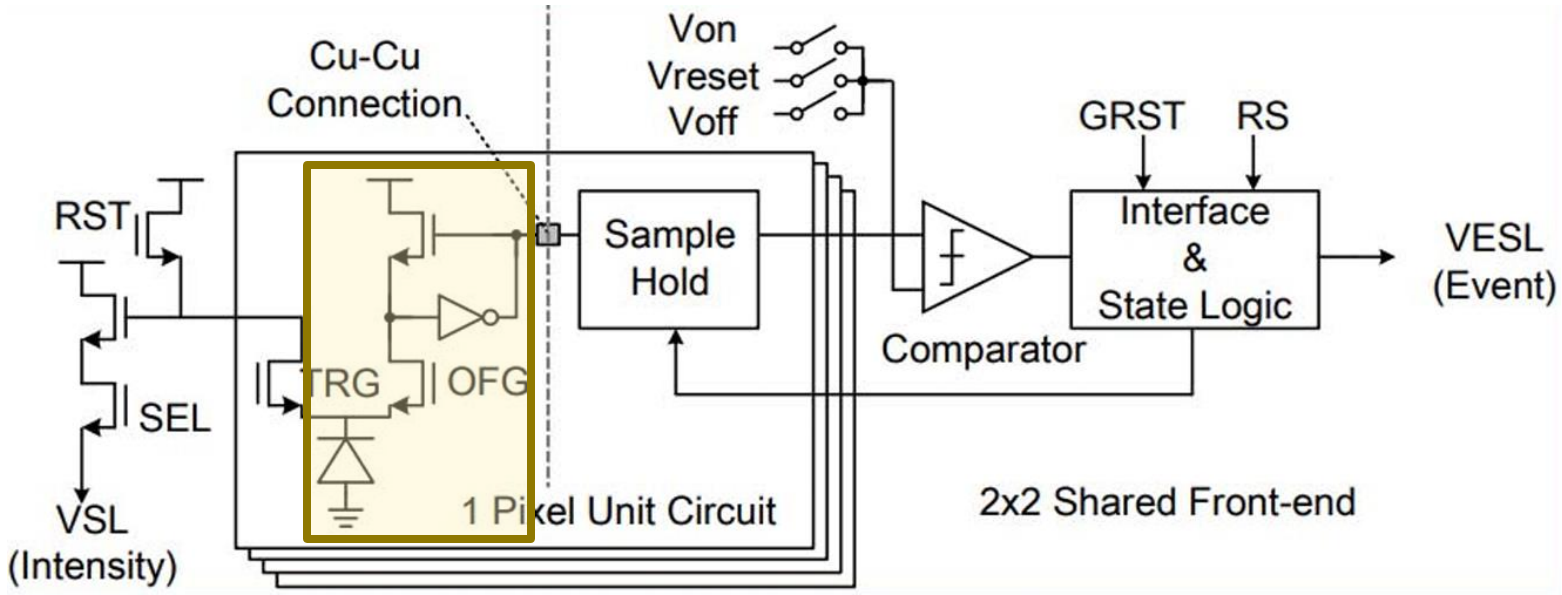

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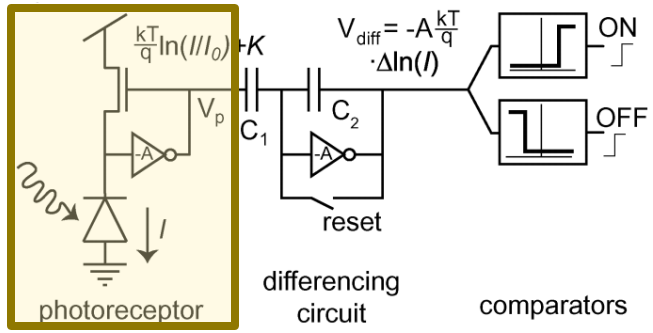

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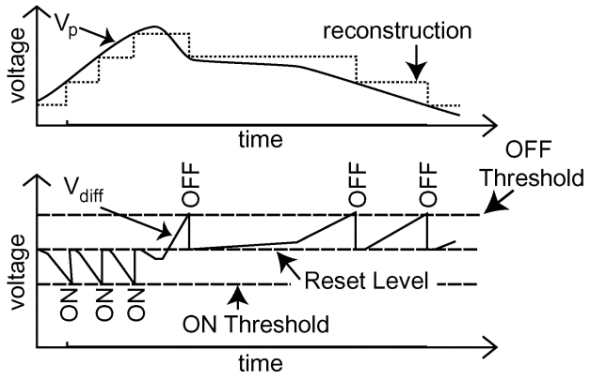

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Introduction. A Photovoltaic Receptor

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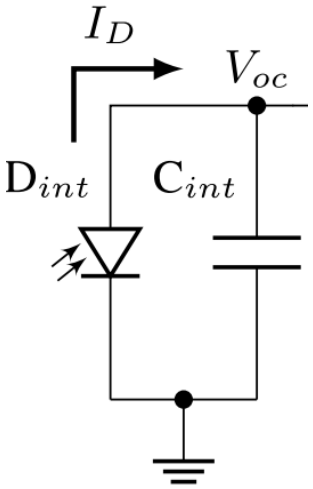
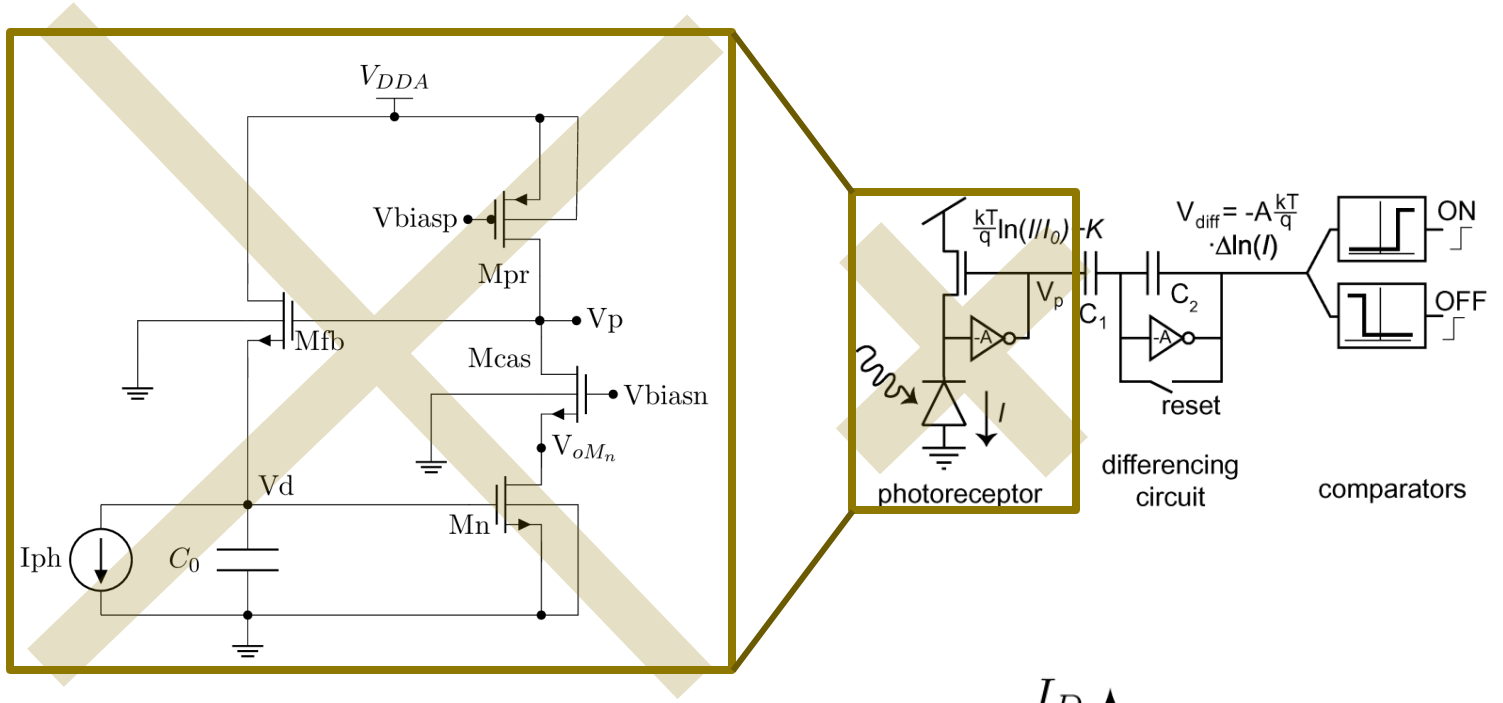
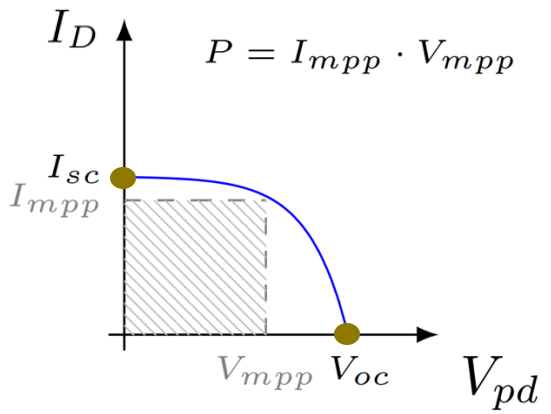




- V_{oc}/I_{sc} ➡ highest voltage/current available from the photocell.
  - $I_{sc} \propto I_{ph}$
  - $V_{oc} \propto \ln I_{ph}$



Introduction. A Photovoltaic Receptor

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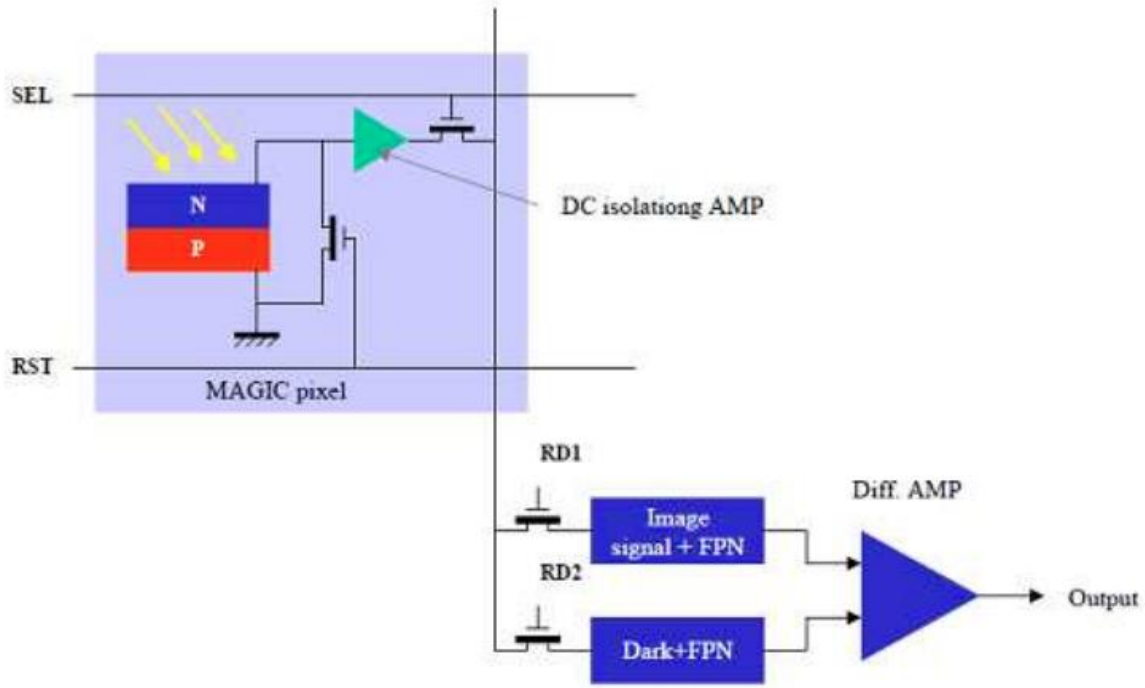
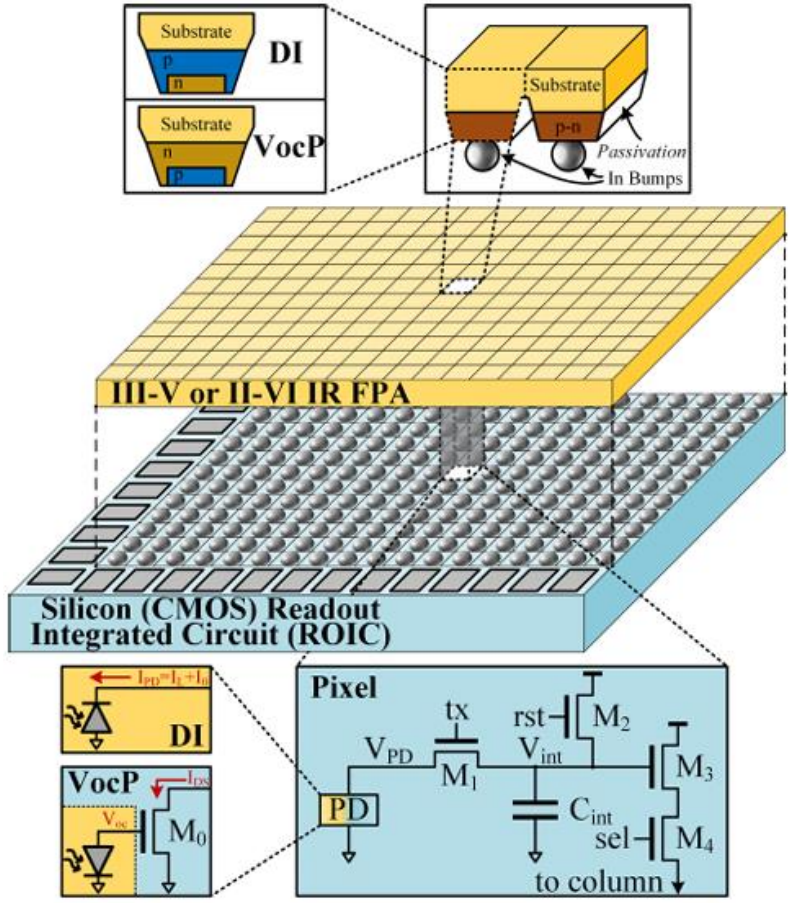


A Photovoltaic Receptor for HDR imaging. [3]



A Photovoltaic Receptor for IR applications. [4]

[3] Ni, Yang & Zhu, Yiming & Arion, Bogdan. (2011). A 768x576 Logarithmic Image Sensor with Photodiode in Solar Cell mode. 10.13140/2.1.3309.9526.
[4] R. Fragasse et al., "Signal and Noise Analysis of an Open-Circuit Voltage Pixel for Uncooled Infrared Image Sensors," in IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 68, no. 5, pp. 1827-1840, May 2021, doi: 10.1109/TCSI.2021.3068595.

PV diode suitability for EBS. Temporal Response

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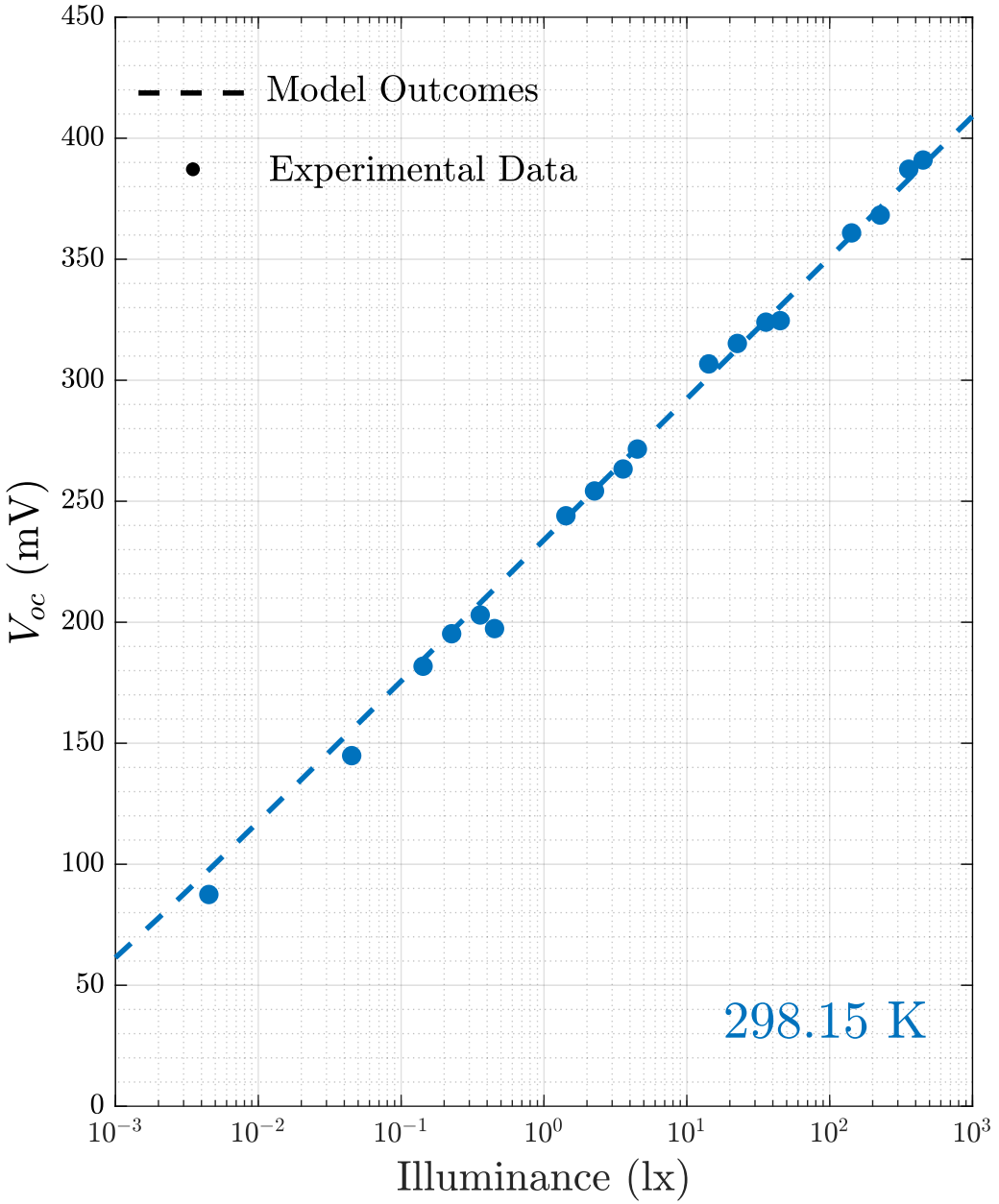
Steady-State

$$V_{oc} = \eta U_T \ln\left(1 + \frac{I_{GR}}{I_S}\right) \approx$$

$$\approx \eta U_T \ln\left(1 + \frac{I_{ph}}{I_S}\right)$$

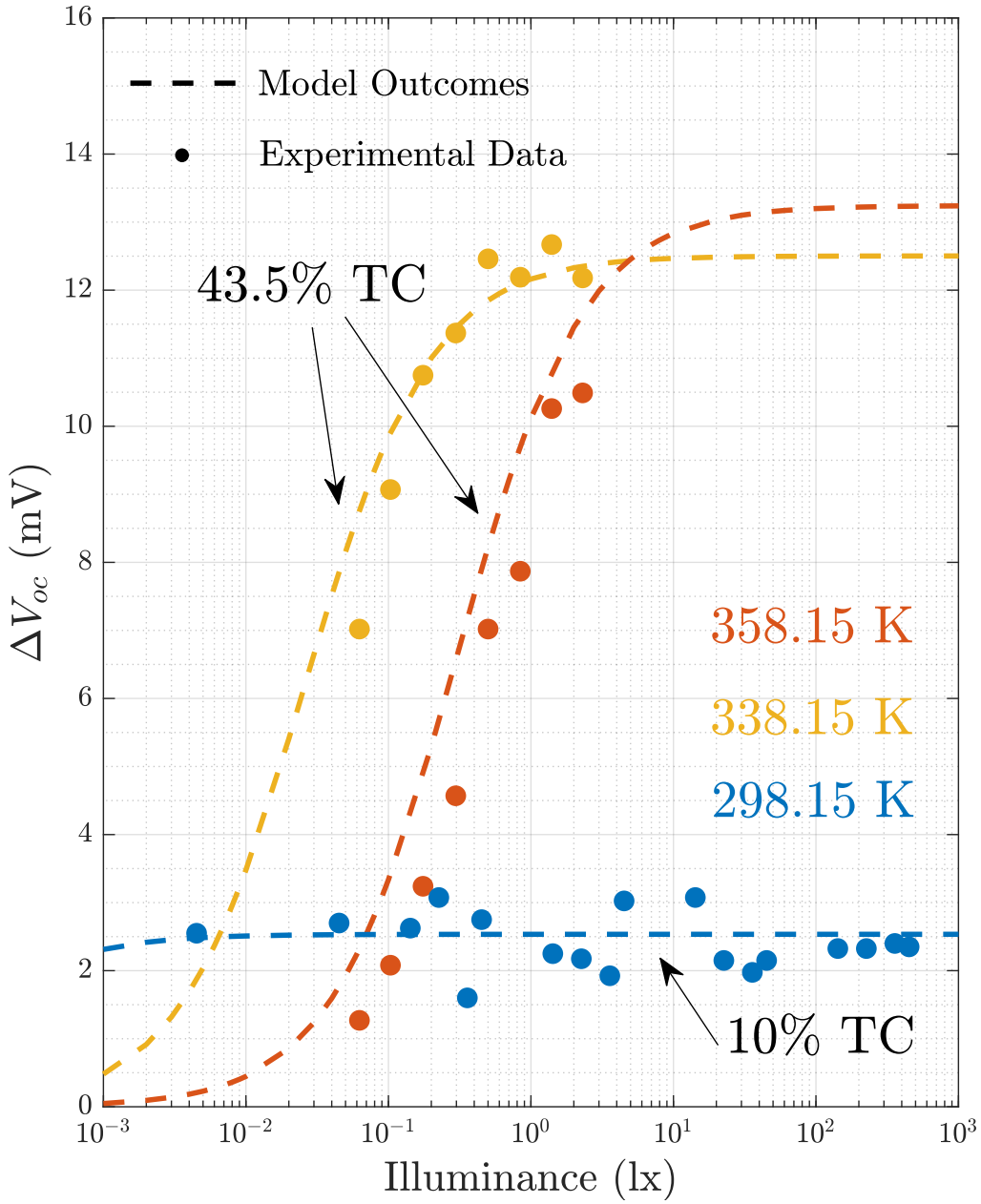


PV diode suitability for EBS. Temporal Response

Contrast Sensitivity

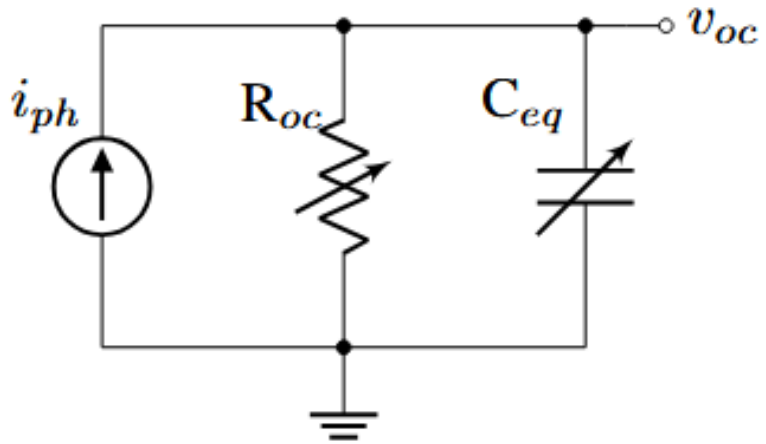
$$TC = \frac{\partial I_{ph}}{\partial t}\frac{1}{I_{ph}} = \frac{\partial \ln\left(I_{ph}\right)}{\partial t} \approx$$

$$\approx \frac{\partial V_{oc}}{\partial t}\frac{1}{\eta U_T} \approx \frac{\Delta V_{oc}}{\eta U_T}$$

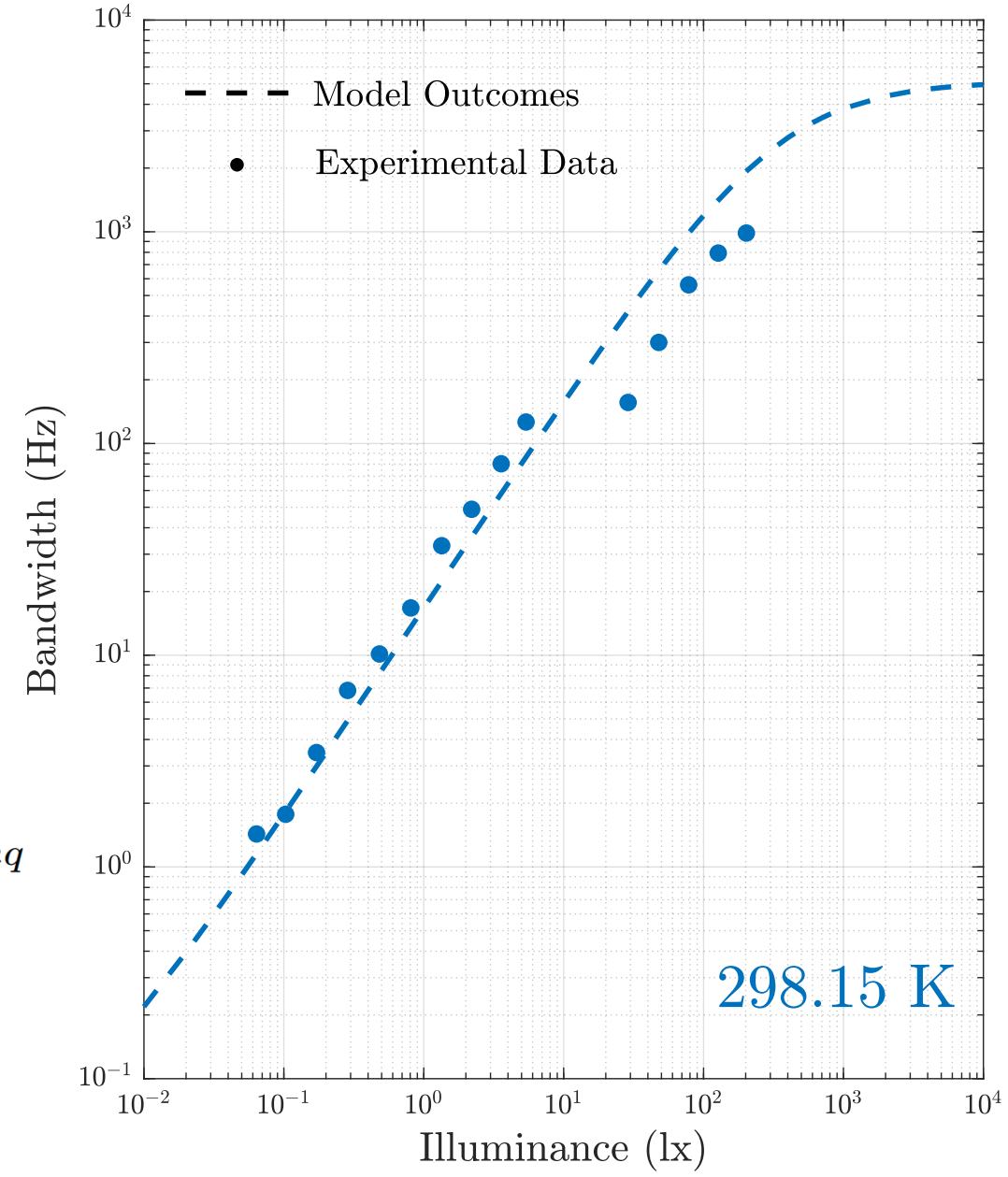


PV diode suitability for EBS. Frequency Response

Bandwidth



$$H_{PV}(s) = \frac{v_{oc}}{i_{ph}} = \frac{R_{oc}}{1 + s\tau_{oc}} \qquad \tau_{oc} = R_{oc}C_{eq}$$



PV diode suitability for EBS. Frequency Response

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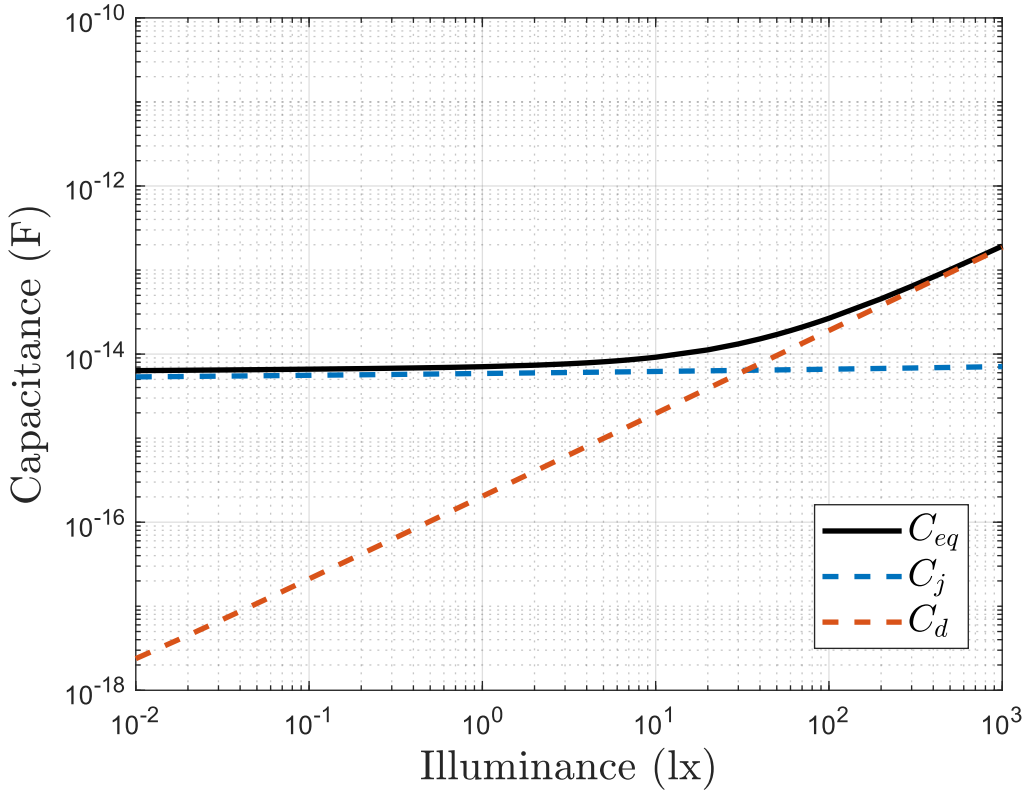

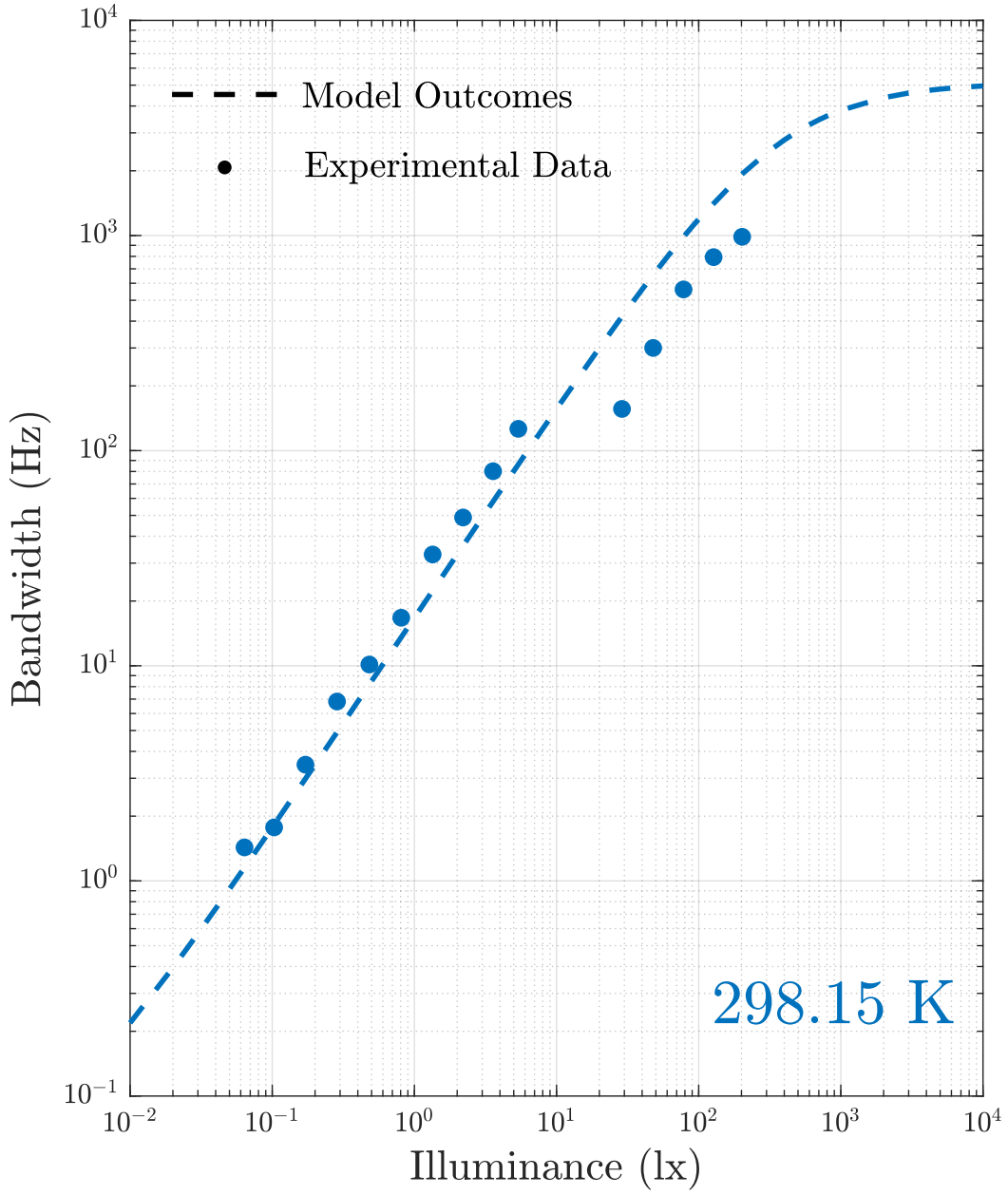

PV diode suitability for EBS. Frequency Response

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Noise Performance

$$\overline{\nu_n^2} = \overline{i_n^2}\frac{R_{oc}}{2\pi C_{eq}}\arctan\left(2\pi f_{max} R_{oc} C_{eq}\right)$$

$\overline{i_n^2} = 4qI_{ph}$

$f_{max} \to 0$

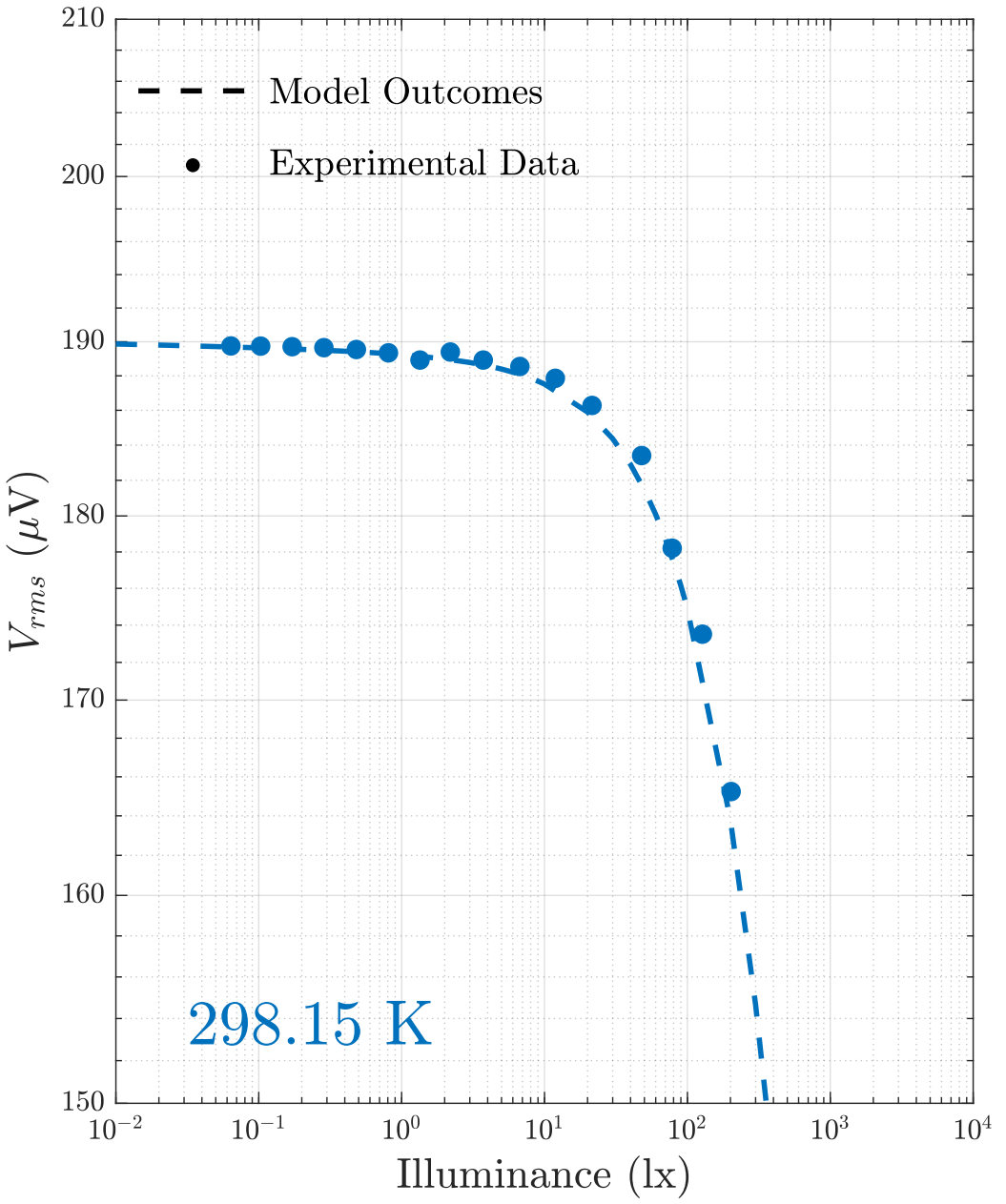
$$\overline{\nu_n^2} = 4q\left(\frac{\eta U_T}{I_{diff}}\right)^2$$

Spot Noise

$f_{max} \to \infty$

$$\overline{\nu_n^2} = \eta\frac{kT}{C_{eq}}$$

KT/C Noise



Understanding PVDVS. PVDVS Architecture

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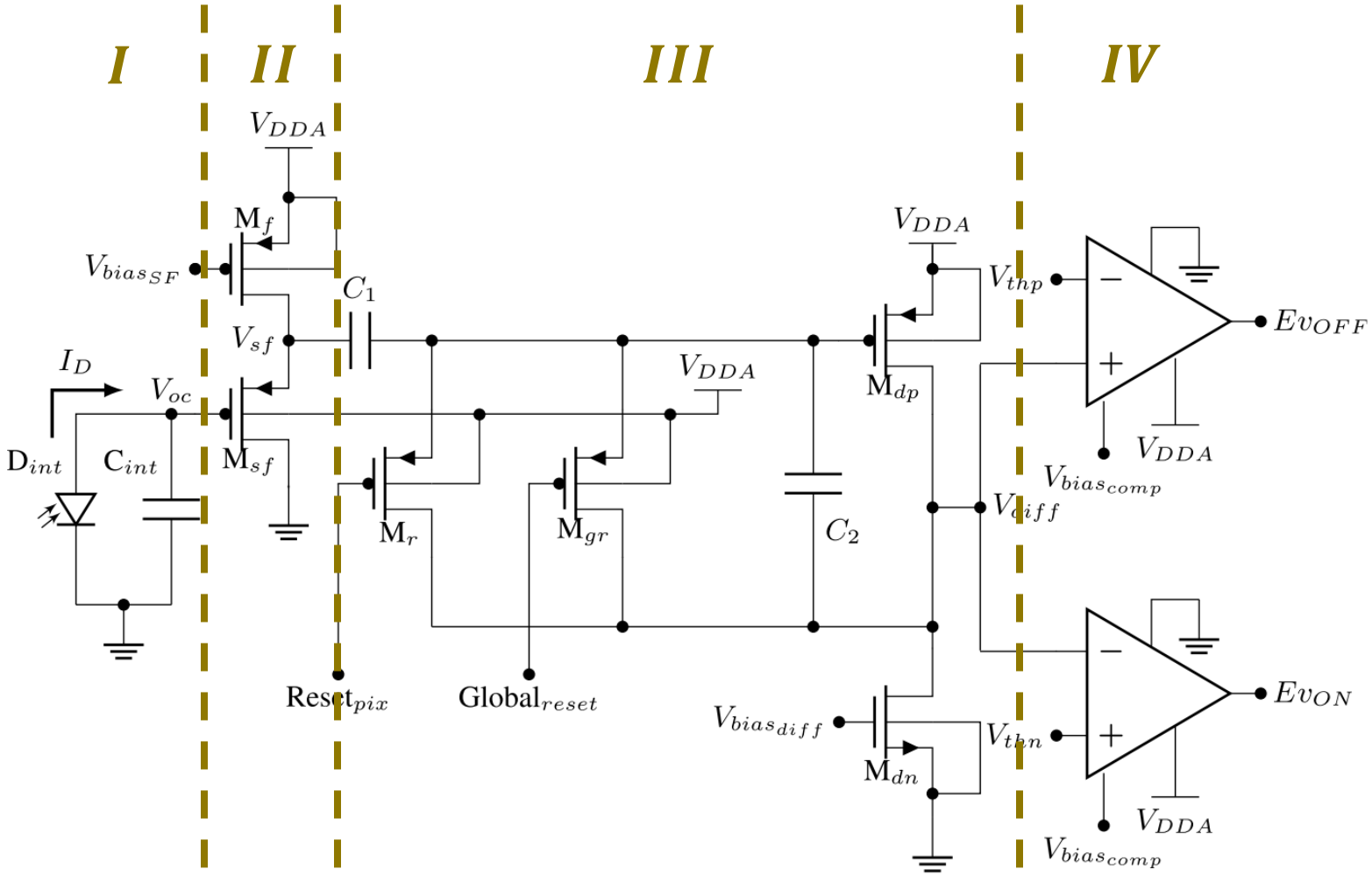
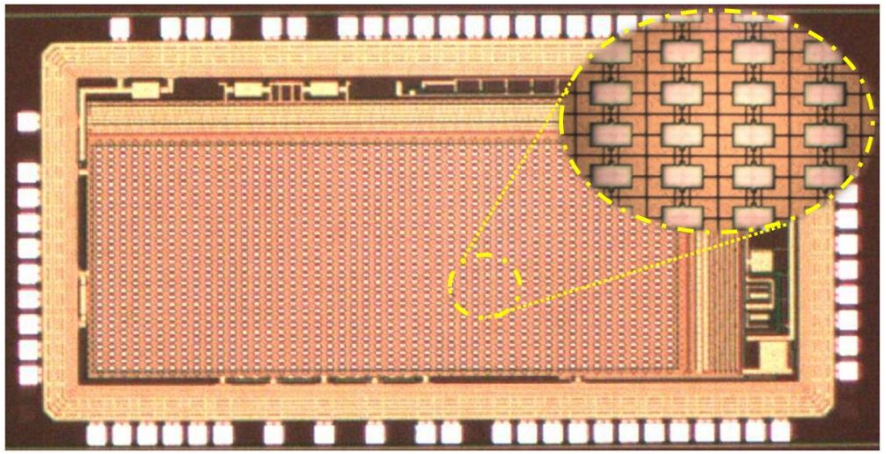


I. Photovoltaic Diode.

II. PMOS Source Follower.

III. Change Amplifier.

IV. 2-Staged OTA comparators.



Understanding PVDVS. Experimental Results

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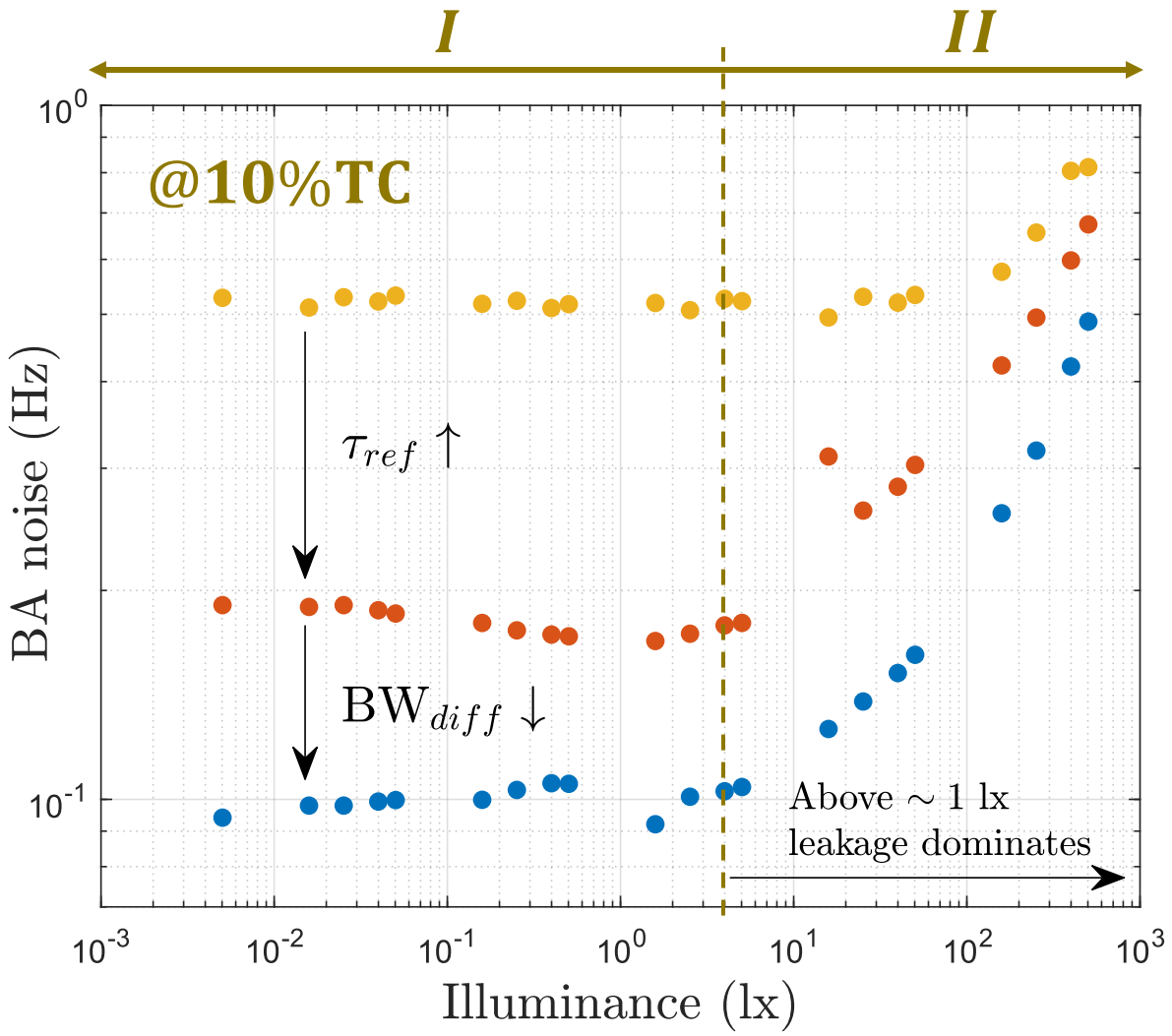
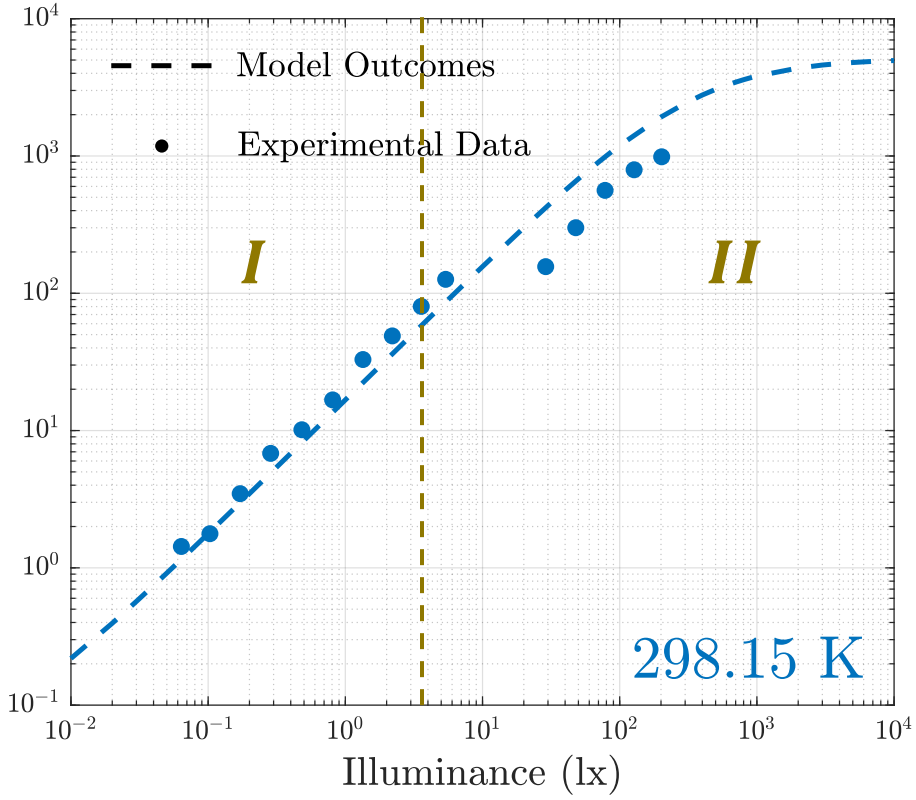


I. $BW_{PV} < BW_{SF}, BW_{diff}$

II. I_{leak} ↑↑



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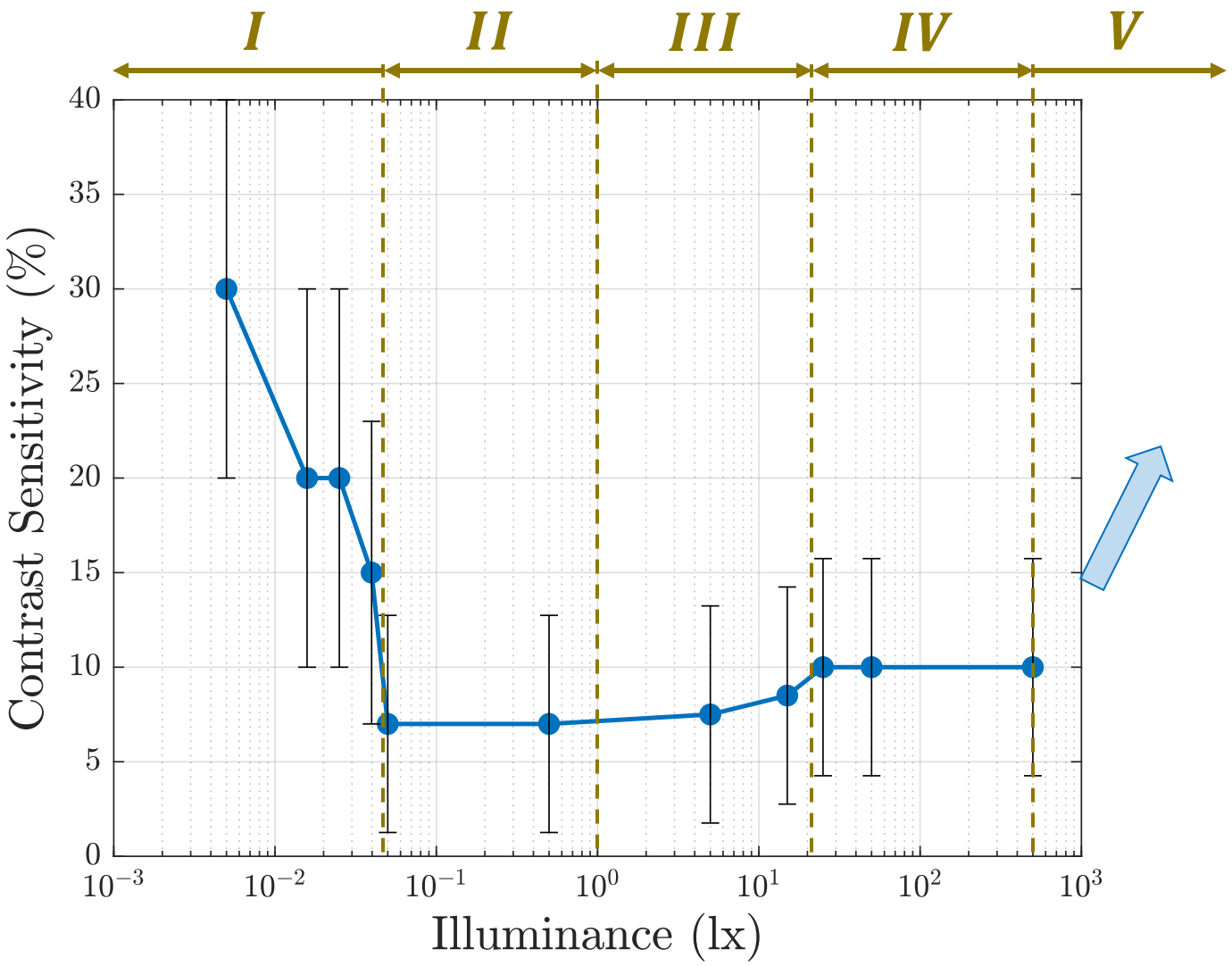


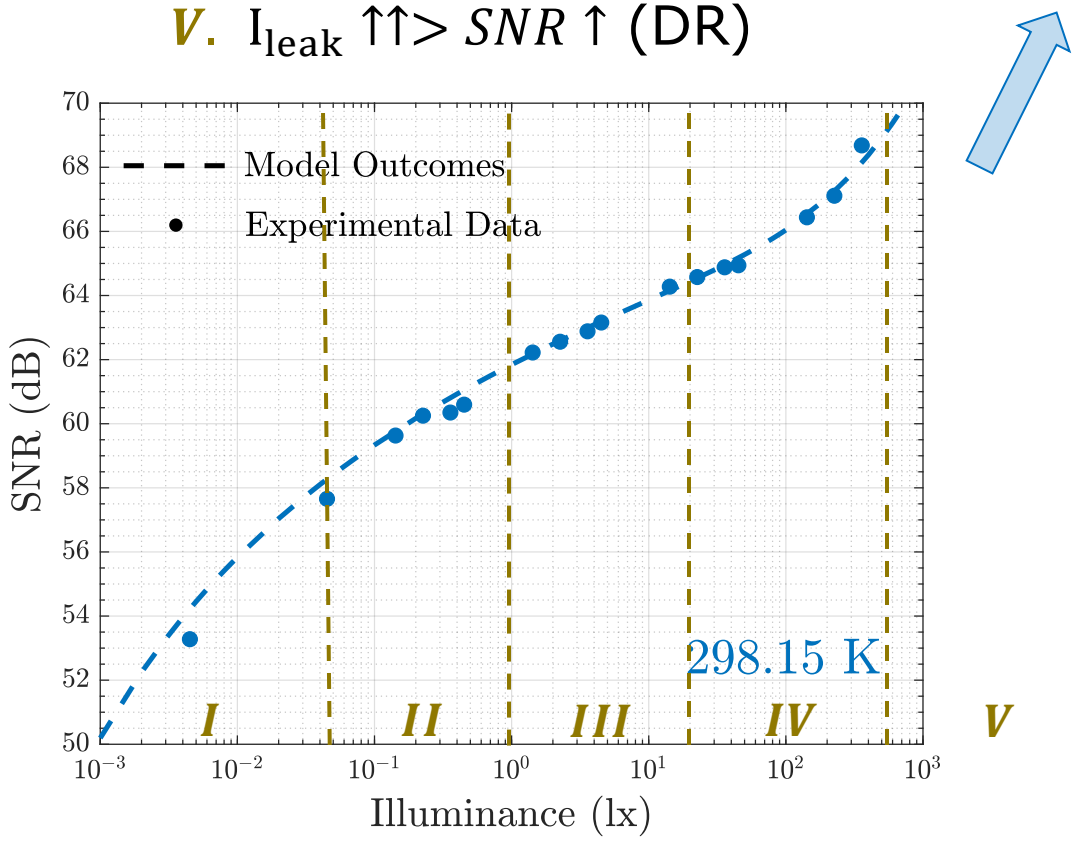
I. $SNR \downarrow\downarrow$

II. $SNR \uparrow > I_{leak} \uparrow$

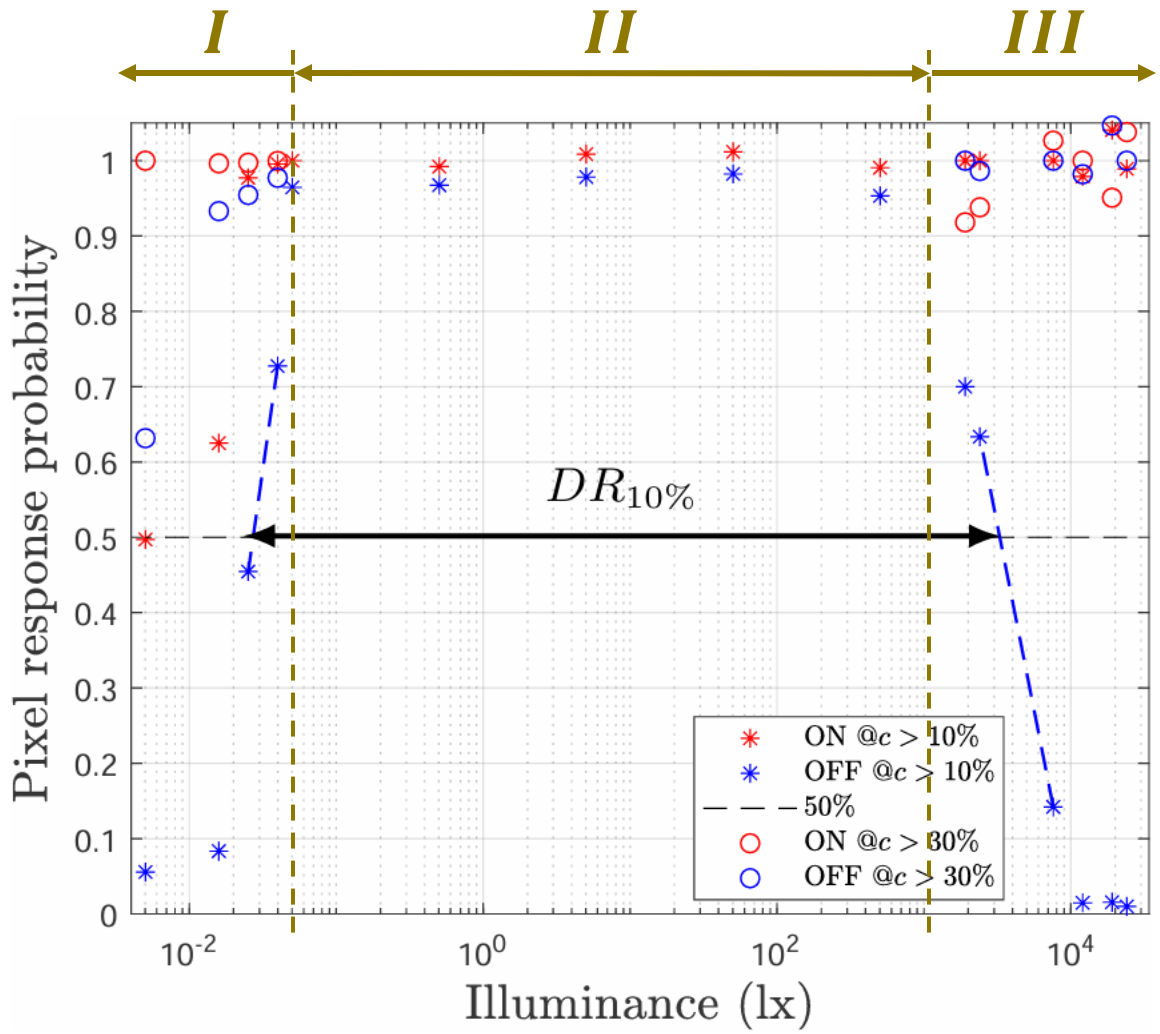
III. $I_{leak} \uparrow > SNR \uparrow$

IV. $I_{leak} \uparrow \sim SNR \uparrow$

V. $I_{leak} \uparrow\uparrow > SNR \uparrow$ (DR)



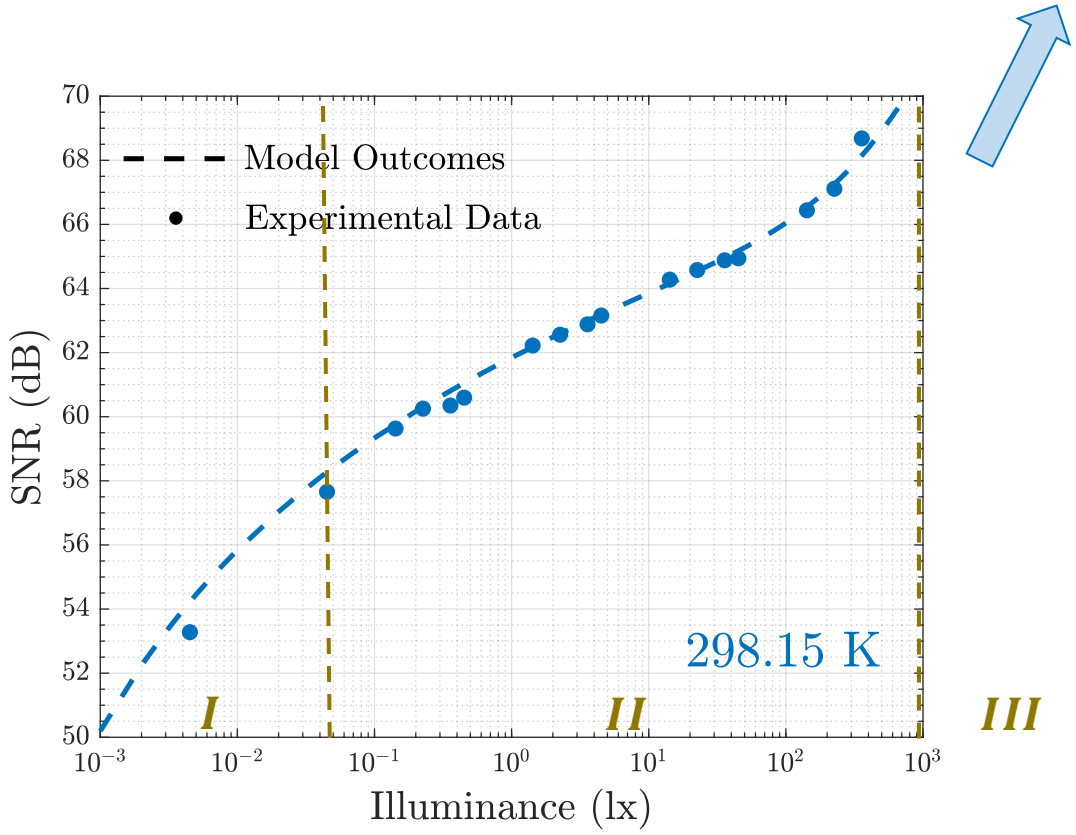
Understanding PVDVS. Experimental Results



I. $SNR \downarrow\downarrow$

II. SNR good enough

III. $I_{leak} \uparrow\uparrow$



Understanding PVDVS. Experimental Results

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	This work	iniVation DAVIS346 [13]	OmniVision 2023 [2]	PROPHESEE 2020 [6]
Technology	0.18 µm 1P6M UMC	0.18 µm 1P6M MIM CIS	40 nm BSI-CIS +65 nm CMOS +3DMIM +40 nm CMOS	90 nm BI-CIS +40 nm CMOS
Supply Voltage (V)	1.8	1.8	–	2.5, 1.1
Resolution	64 × 96	346 × 260	1032 × 928	1280 × 720
Pixel size (μm^2)	12.45 × 21.5*	18.5 × 18.5	8.8 × 8.8	4.86 × 4.86
Fill Factor	18%	22%	1/16	> 77%
Power/Pixel (nW)	410*	–	31	35
Max event rate (Meps)	10.64	12	4600	1066
Contrast Sensitivity	**7% (0.05 – 0.5 lx)** **10% (0.5 – 500 lx)**	14.3% (ON) 22.5% (OFF)	15% (10 – 1000 lx)	11%
CTNU	< 6% (> 50 mlx)	3.5%	3% (> 10 lx)	3%
Dynamic Range (dB)	**100 (10% TC)** **> 140 (30% TC)**	120	–	> 124 (40% TC)
Latency +/− (µs)	**3.7/7.6@500 lx** **200/267@5 lx** **2180/2380@50 mlx**	< 1000	200@100 lx 100@1 klx	–
Peak Noise Activity (Hz)	**< 1**	1 (I_{pr} = 2 pA) 100 (I_{pr} = 50 pA)	< 1	8.3
V_{rms} (mV)	**0.19 (< 1 lx, T_{room})** **0.21 (High T)** **@$\Delta f \sim$ 100 kHz**	1.7 (I_{pr} = 2 pA) 2.4 (I_{pr} = 50 pA) (< 1 lx) @$\Delta f \sim$ 4 kHz	–	–

* Pixel pitch and power consumption could be reduced by optimizing the building block topologies.

Understanding PVDVS. Experimental Results

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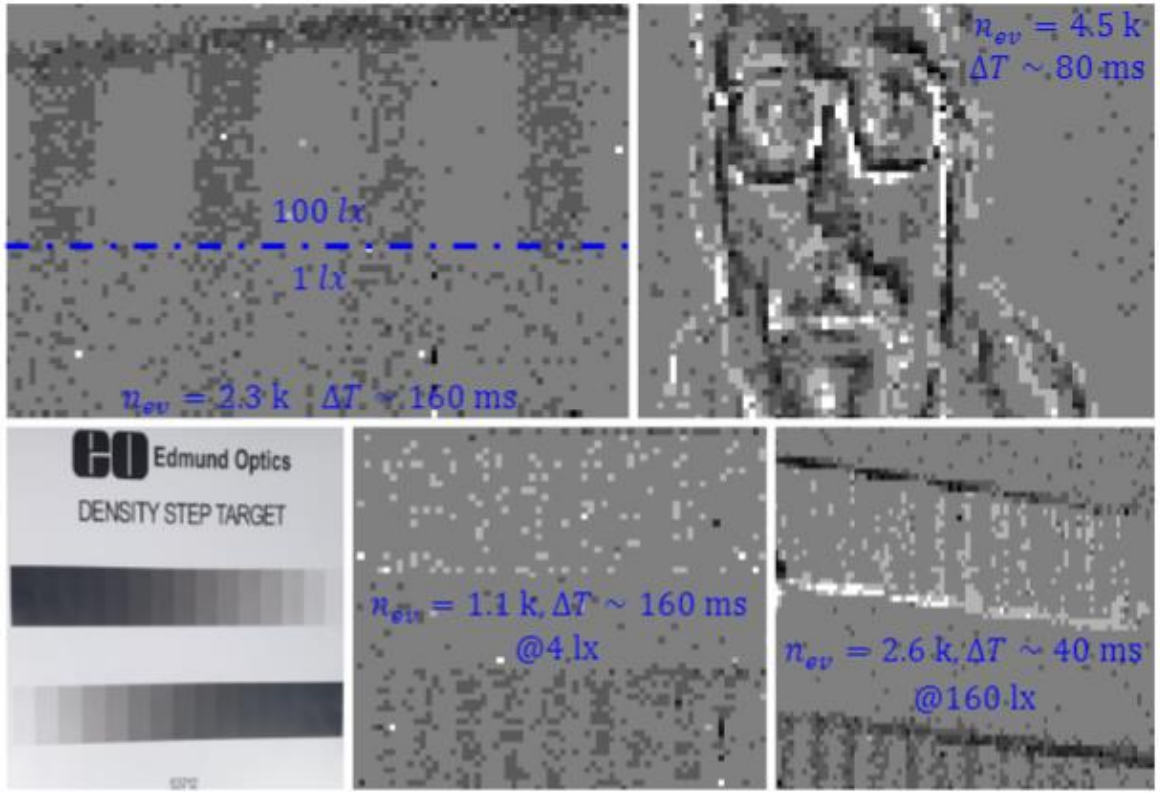

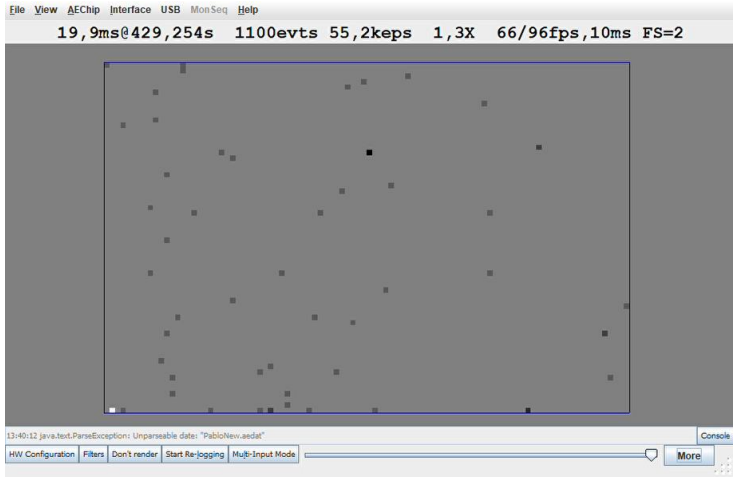

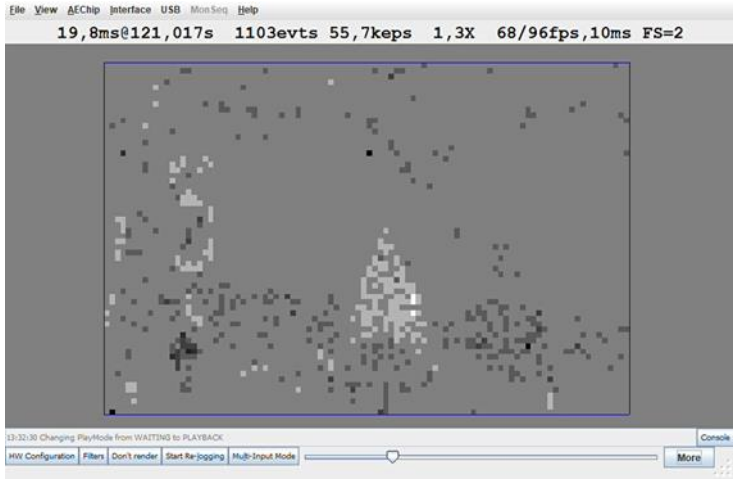

Understanding PVDVS. Experimental Results

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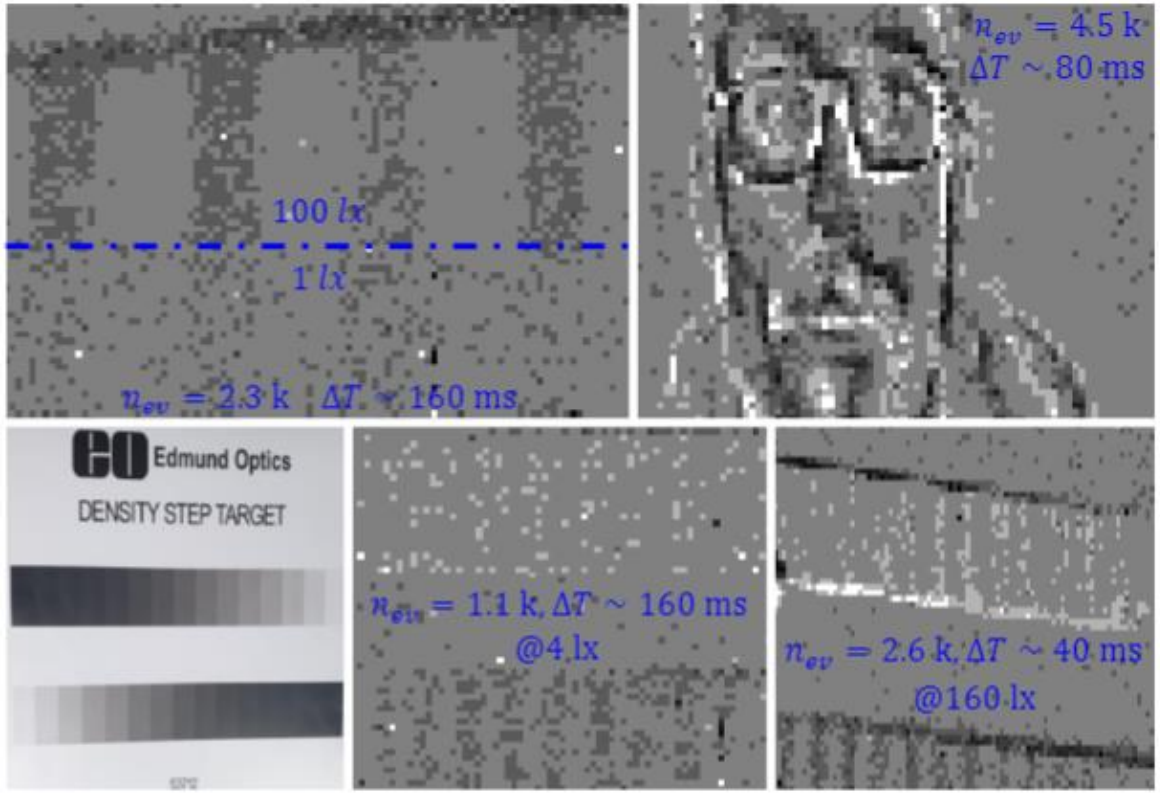

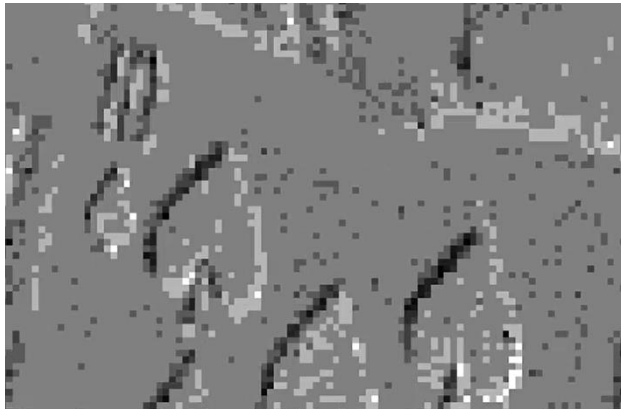

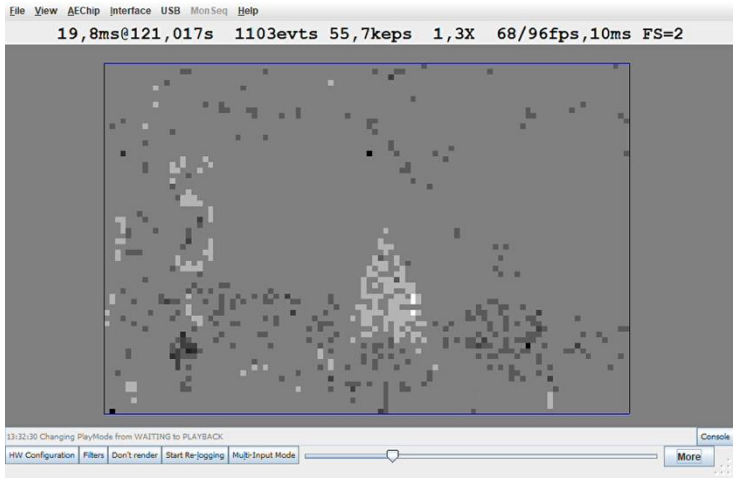

Conclusions. Assessment of Pros and Counters

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- ☺ Photodetection + Log. Compression in a single, self-biased device.
  - Reduced pixel pitch and power consumption.
  - Static power consumption independent on illuminance.
  - Simultaneous operation in shared-diode configurations (DAVIS, ATIS).
- ☺ Noise power is reduced to $2\times$ the fundamental photon shot noise limit,
  - Improving SNR.
  - Expanding DR.

  without additional power consumption.

High resolution, HDR, Energy-efficient, low noise applications

- ☺ Higher integrated capacitance as there is no longer a feedback loop.
  - Reduced integrated noise.
  - Reduced bandwidth.
- ☹ Implementation limits pixel Fill Factor in 2D process.
  - Mandatory Deep N-well layer.

3D stacking, moderate speed applications

Conclusions. Acknowledgements

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THANK YOU SO MUCH!

どうもありがとうございます！

ANY QUESTION?

何か質問はありますか？

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AGENCIA ESTATAL DE INVESTIGACIÓN

BACK-UP SLIDES

Back-Up. PV Diode. Alternative Structures

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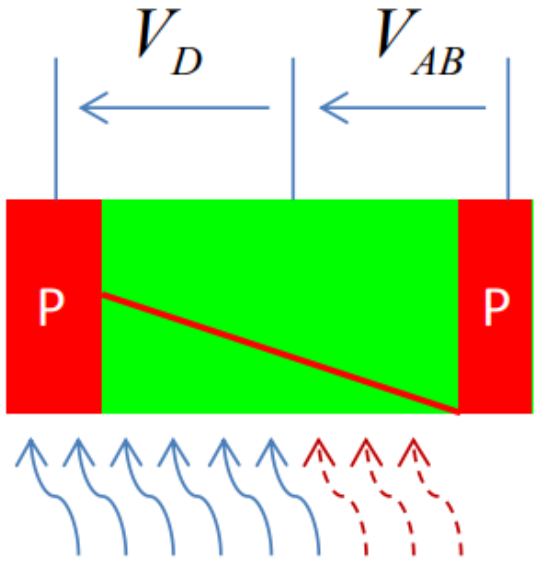
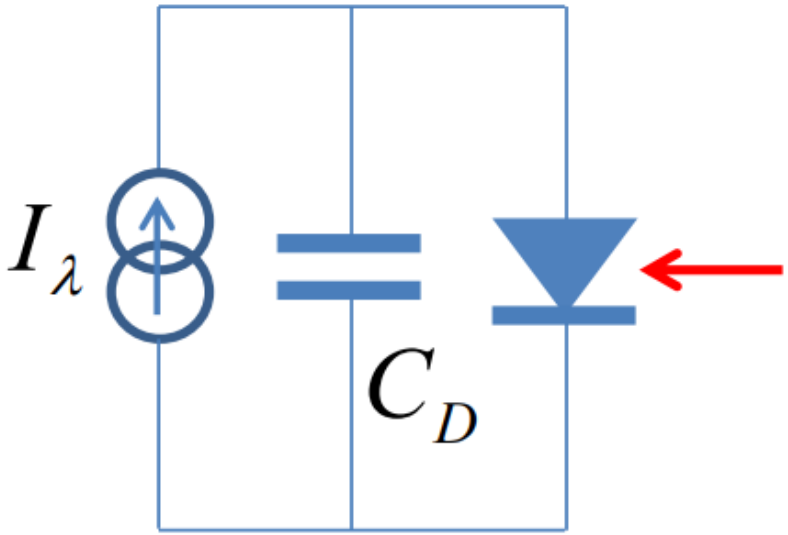


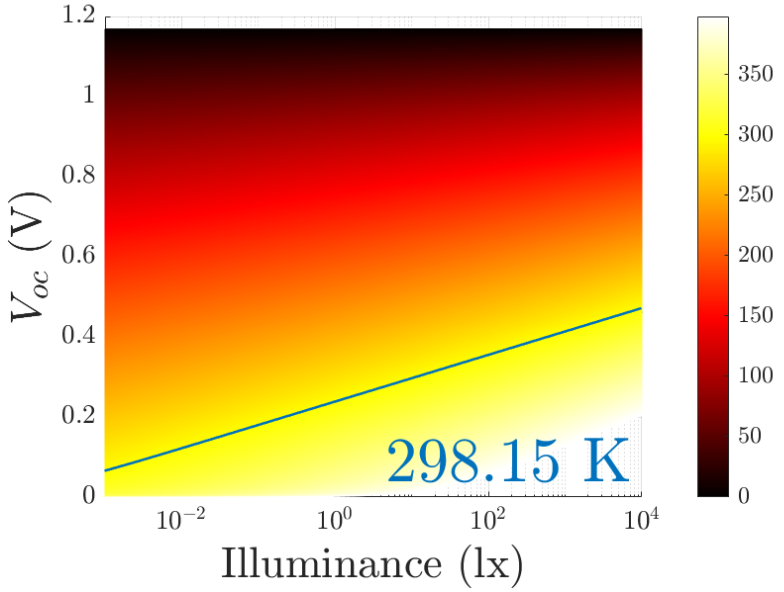


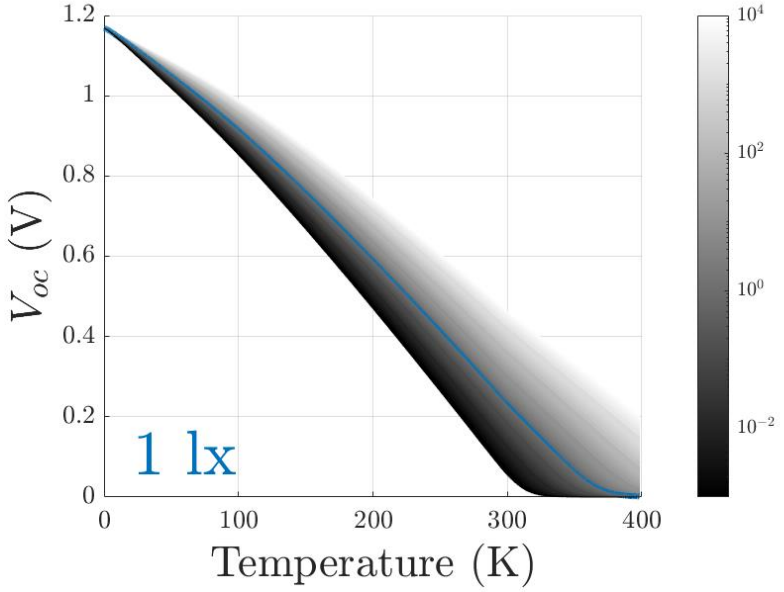
$$I_D = I_S e^{\frac{V_D}{V_t}} - I_S e^{-\frac{V_{AB}}{Vt}}$$

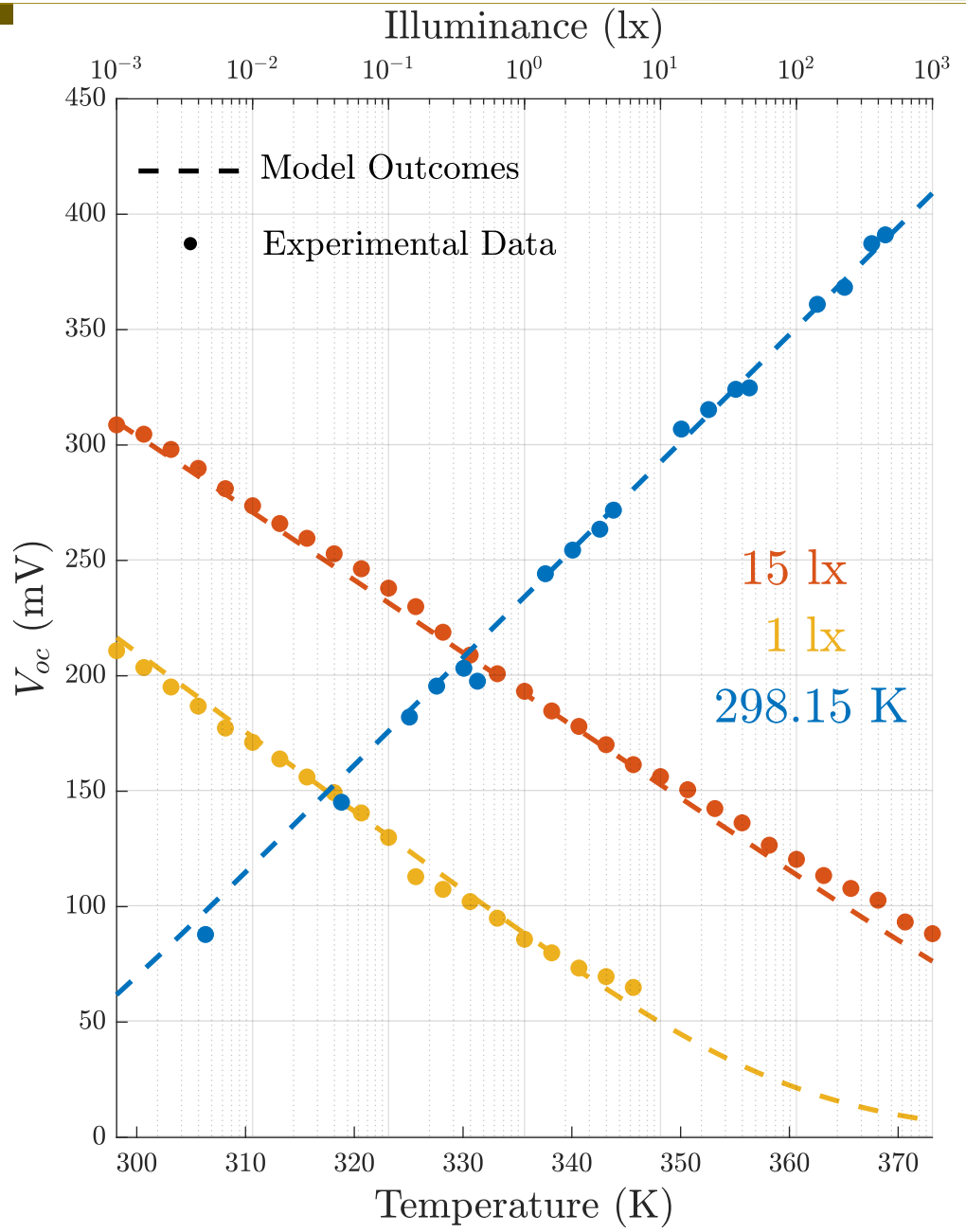
- Active dark current reduction structure that enable solar cell mode at room temperature without sensitivity loss.

[1] Ni, Yang & Arion, Bogdan & Bouvier, Christian. (2015). Logarithmic InGaAs detectors with global shutter and active dark current reduction. 10.1117/12.2176392.

Back-Up. PV Diode. Steady-State Response

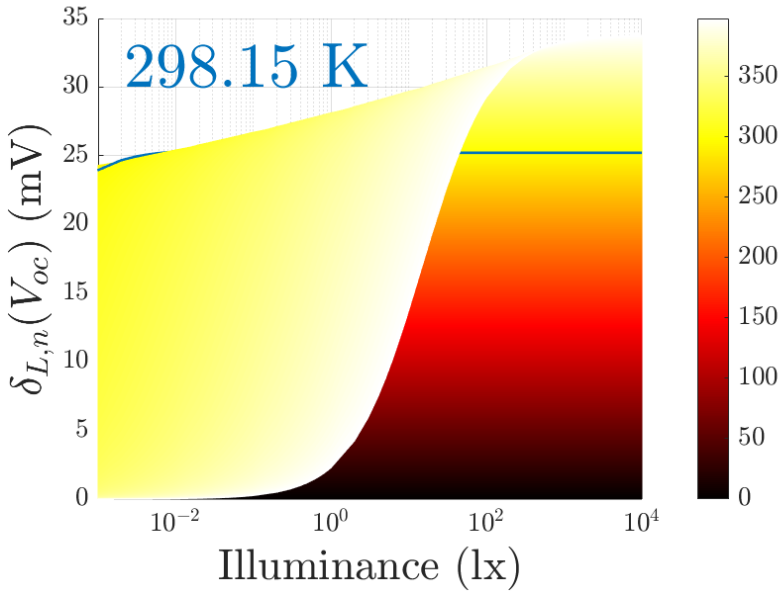


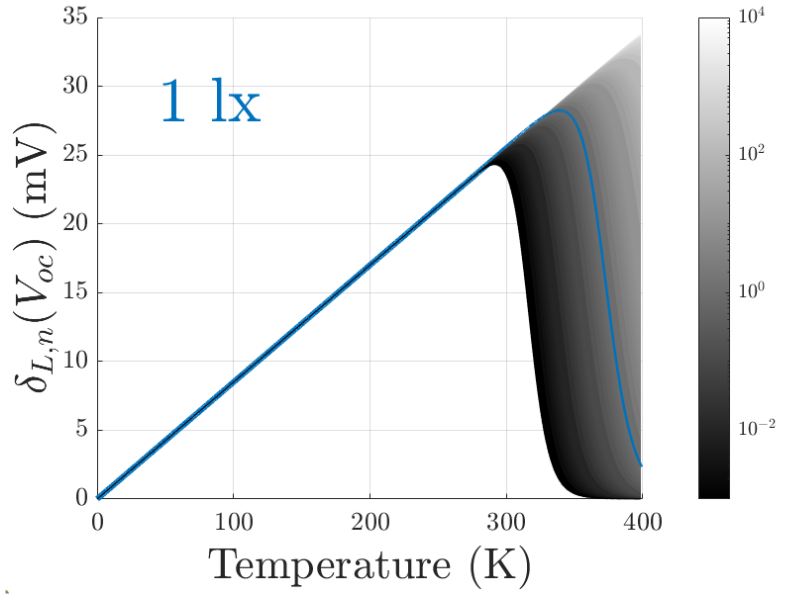


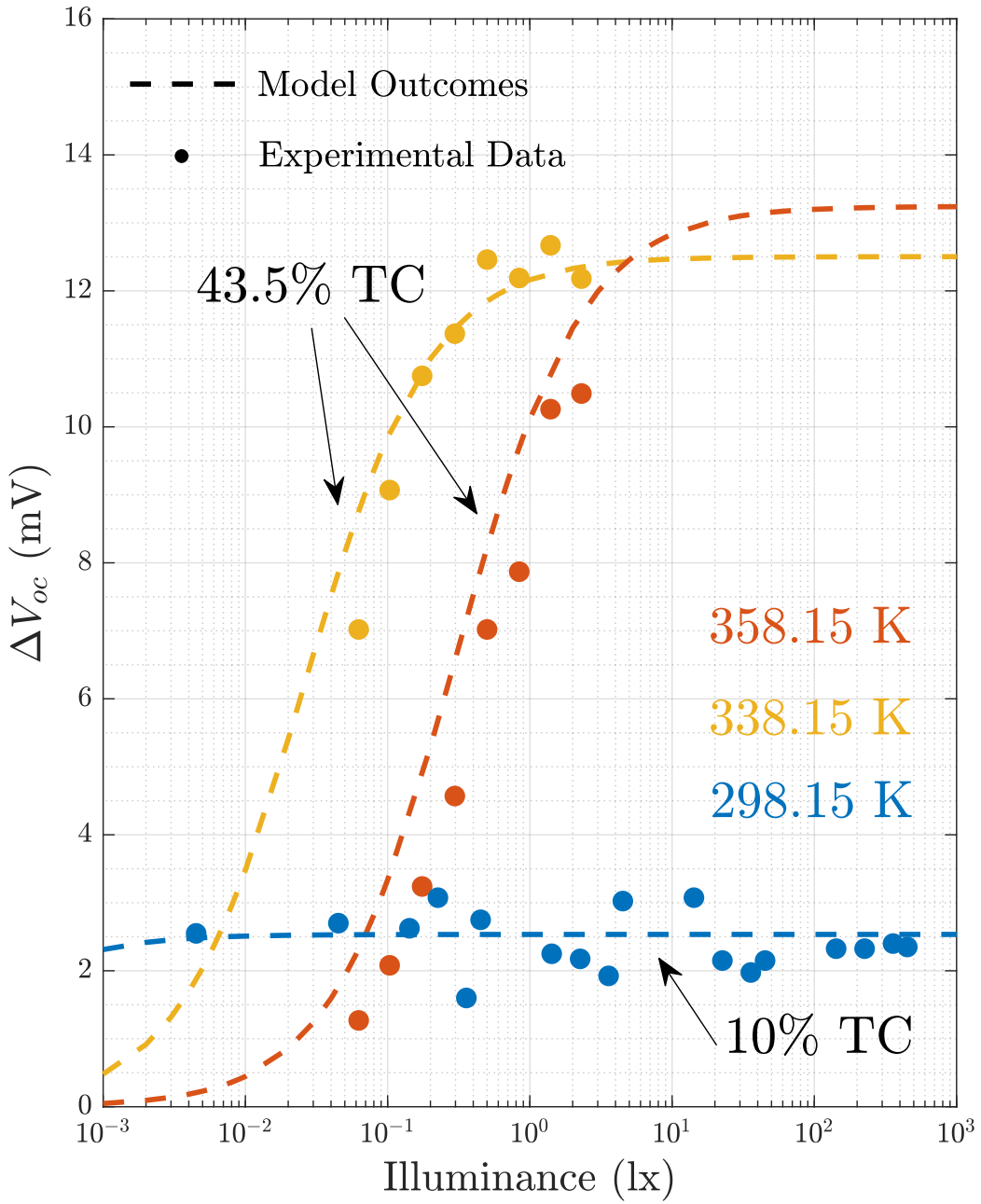


Back-Up. PV Diode. Contrast Sensitivity

International Image Sensor Society

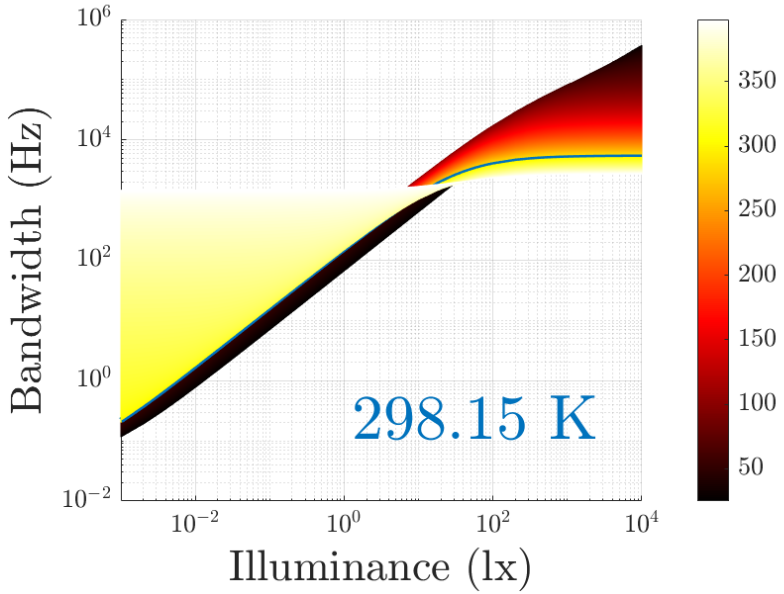


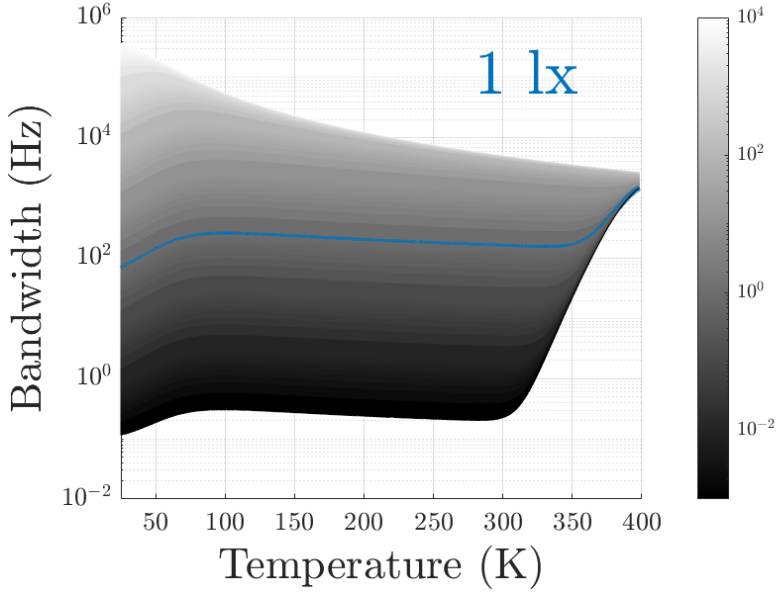


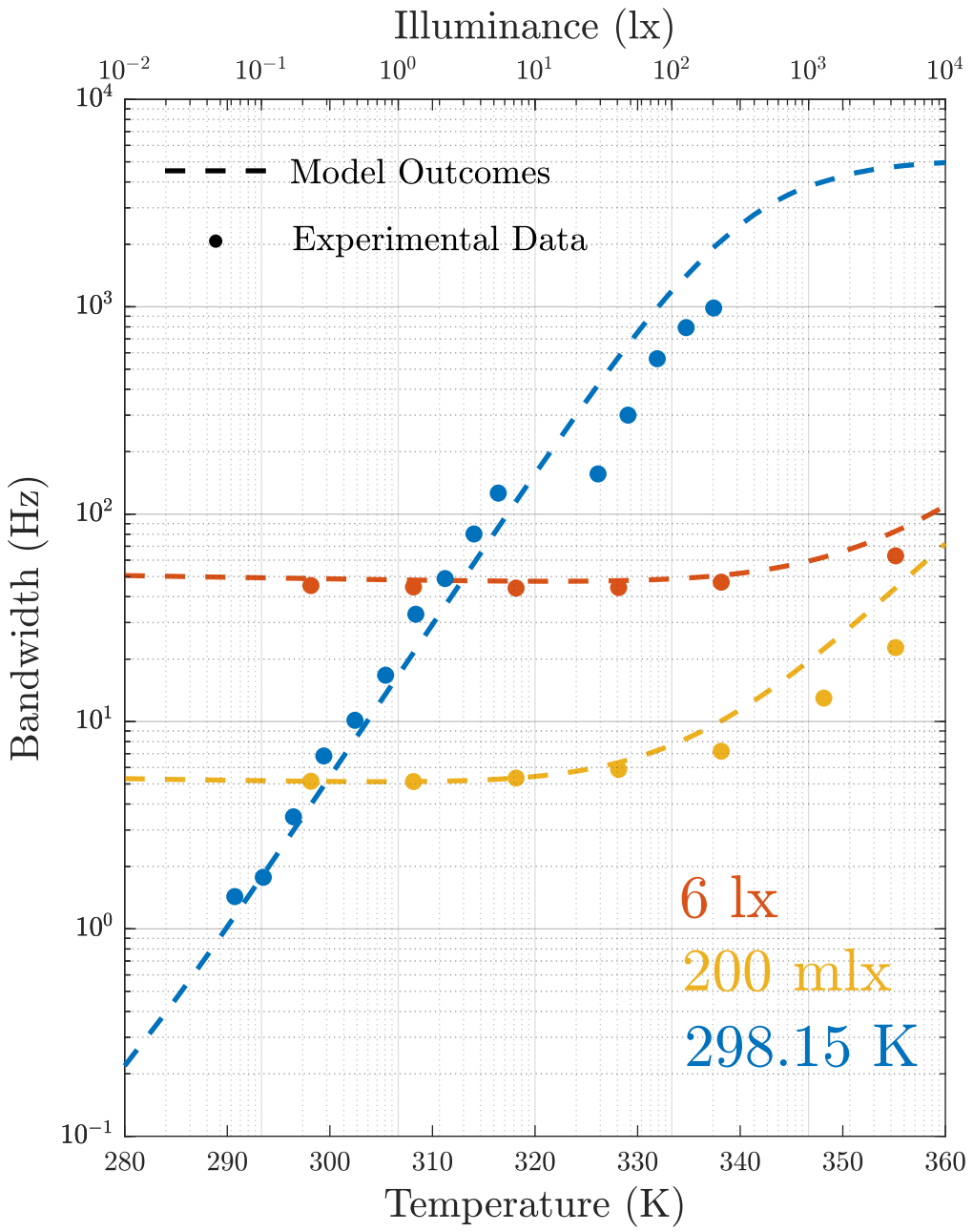


Back-Up. PV Diode. Bandwidth

International Image Sensor Society

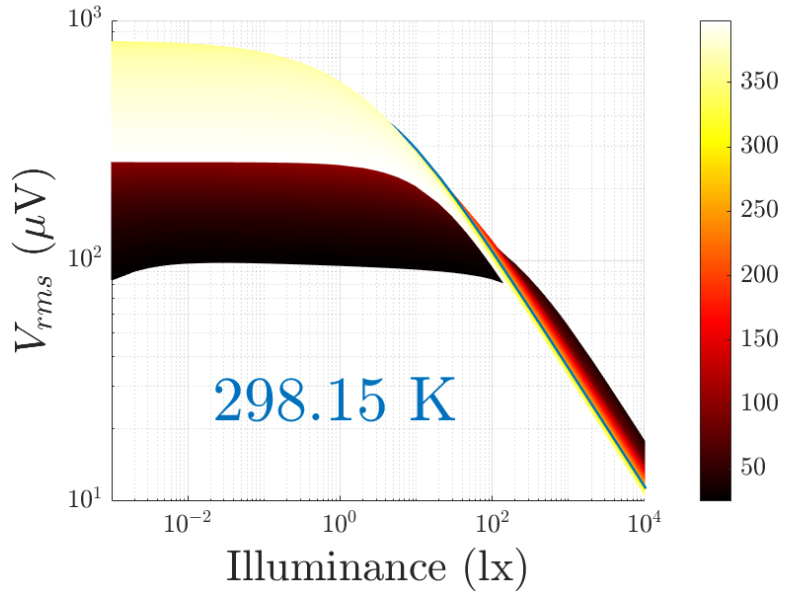


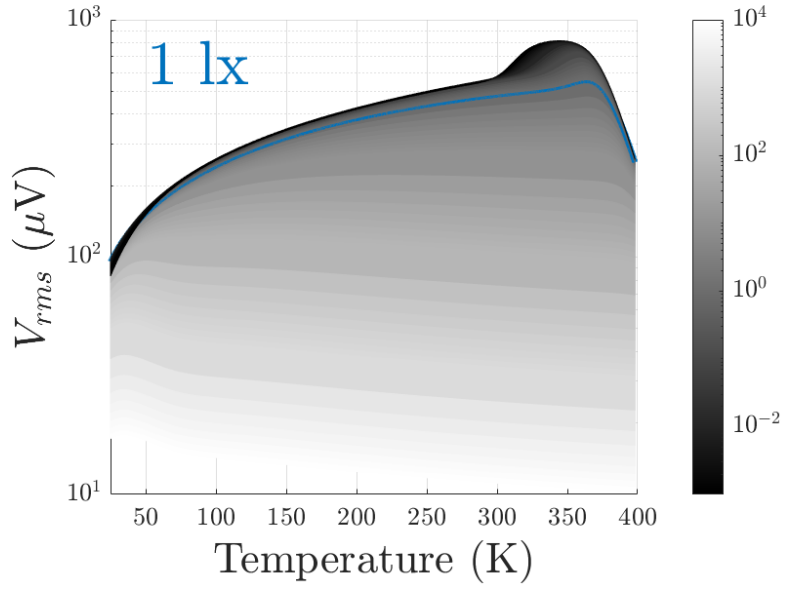


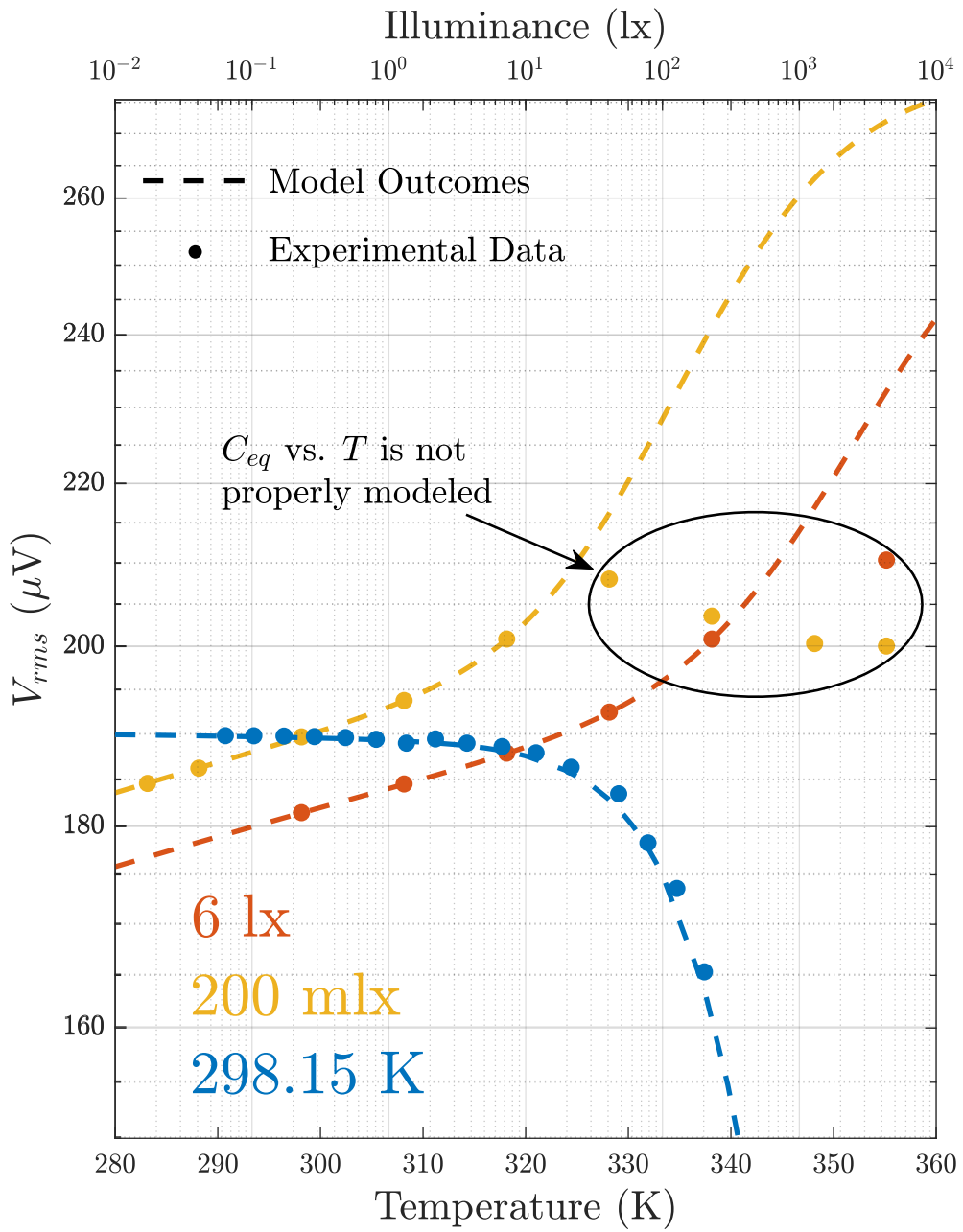


Back-Up. PV Diode. Noise Performance

International Image Sensor Society

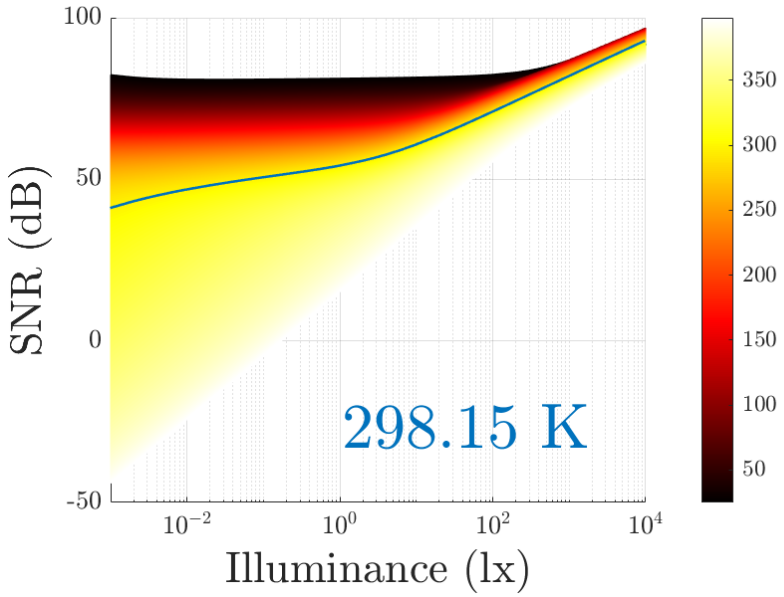


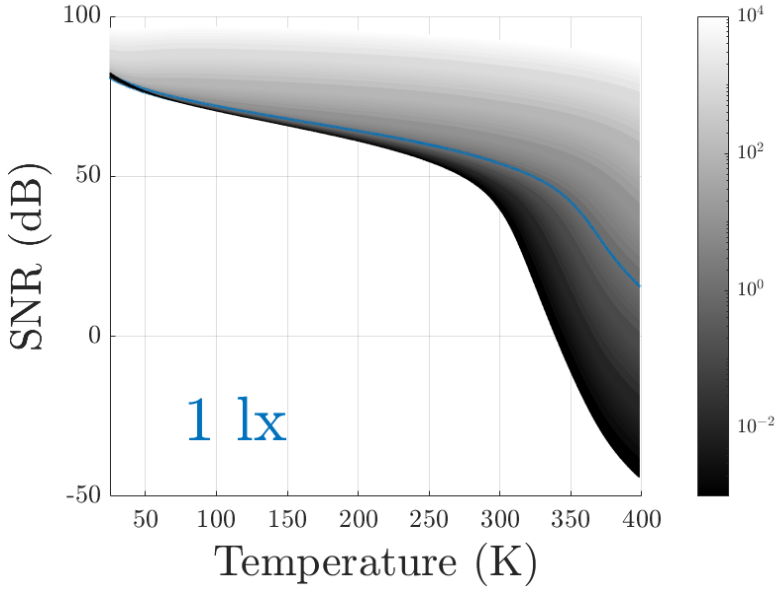


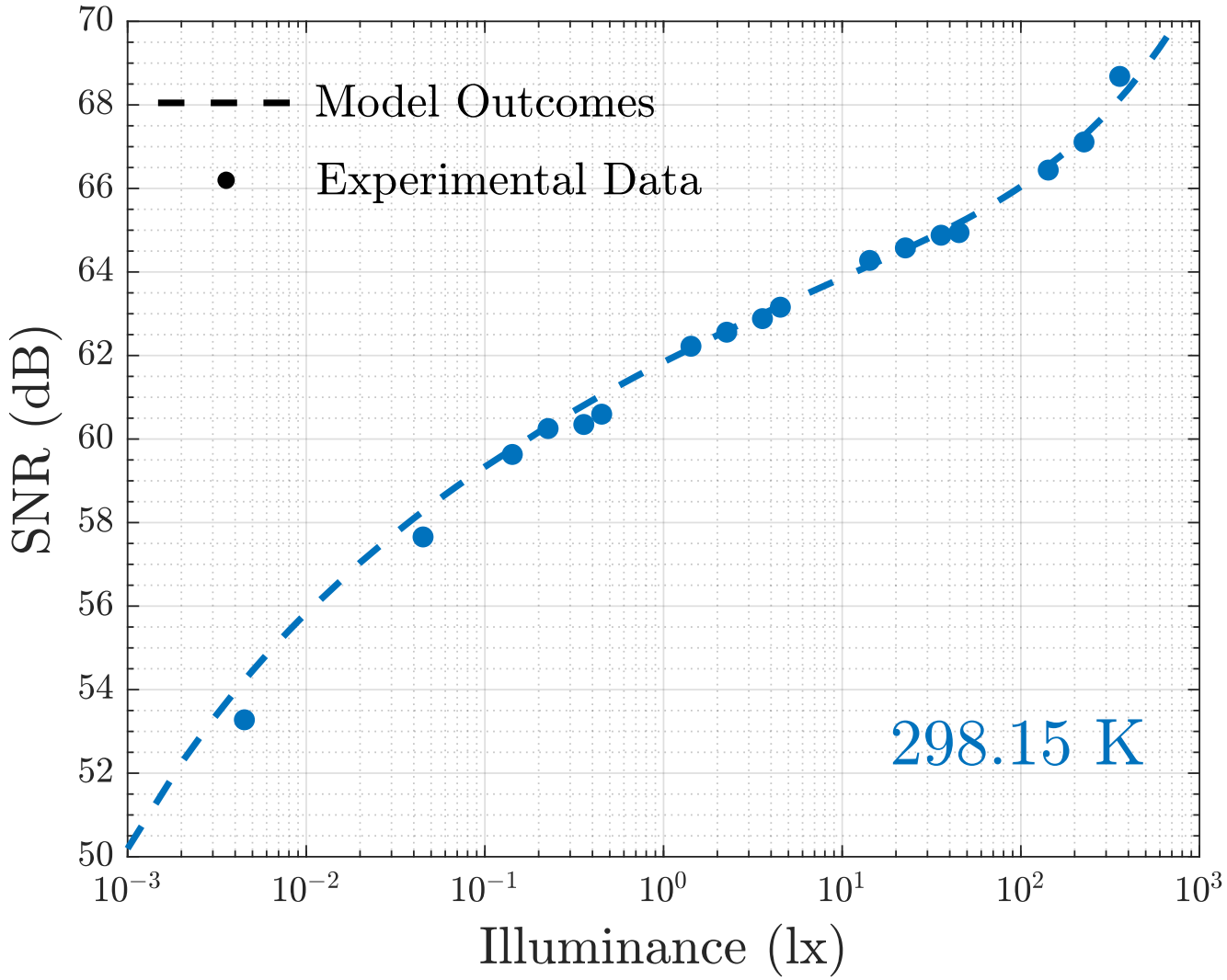


Back-Up. PV Diode. Signal-to-Noise Ratio

International Image Sensor Society







Back-Up. PV Diode. Implementation

International Image Sensor Society

DRC rules:

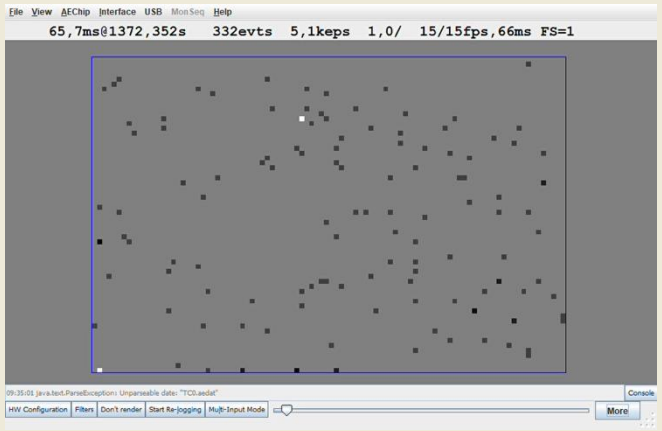
- Deep Nwell minimum distance to unrelated Nwell ($\sim 2.5\,\mu m$).

- Nwell minimum distance to NW at different potential ($\sim 1\,\mu m$).

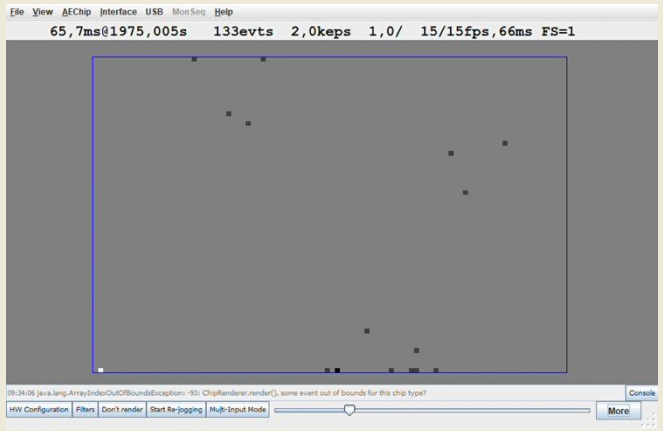
Back-Up. PVDVS. TC Sensitivity

International Image Sensor Society

0%



1%



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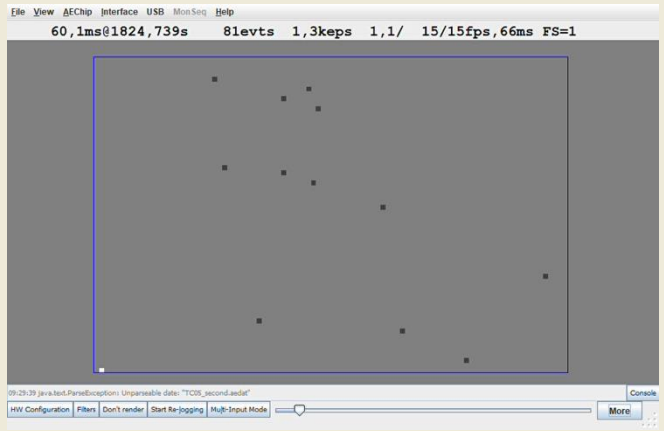

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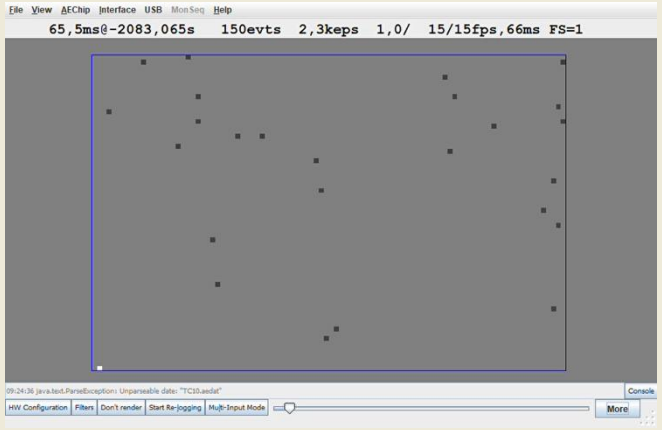
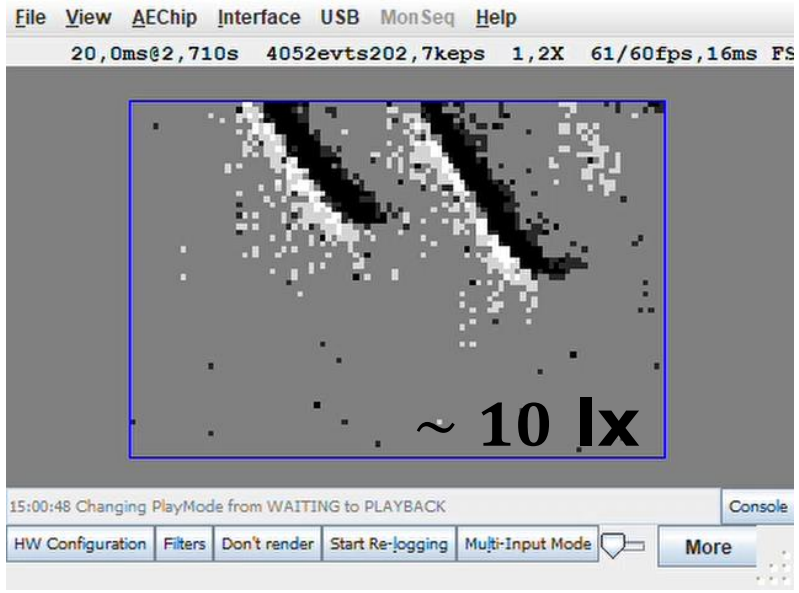
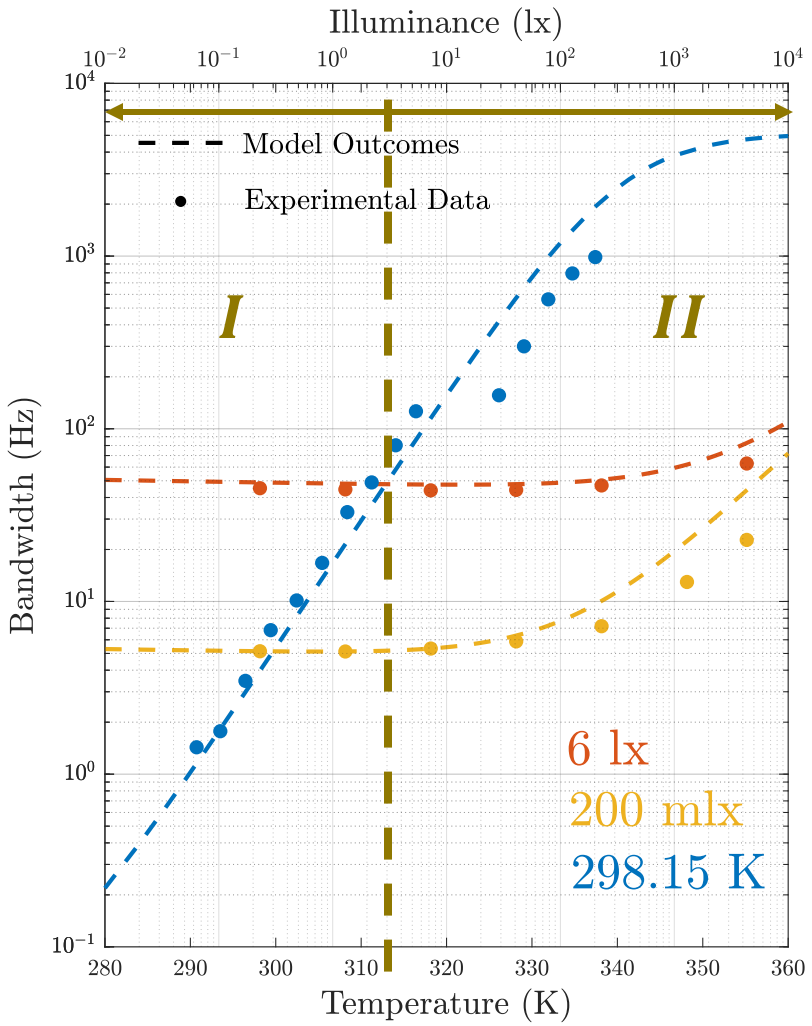


50 mlx



Back-Up. PVDVS. Background Activity Noise

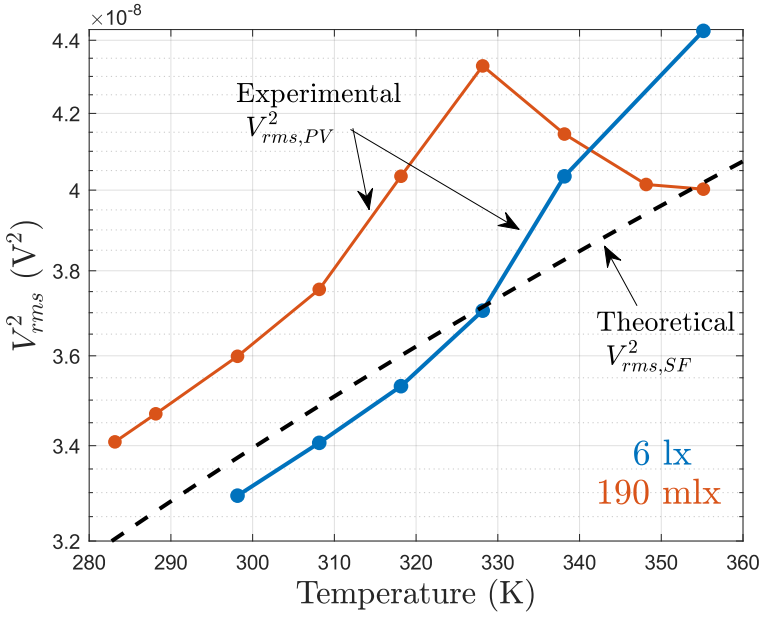
International Image Sensor Society

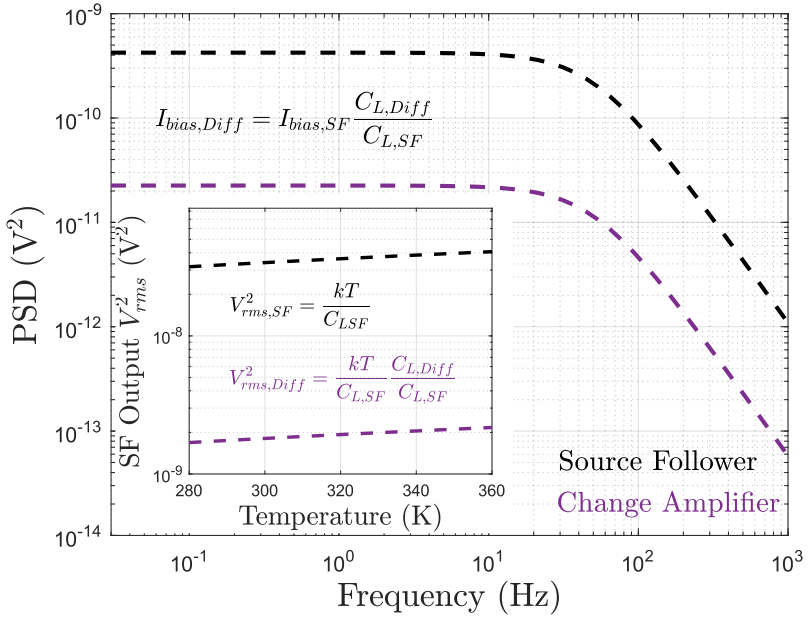


$BW_{sf} \gg BW_{diff,min} \sim [0.5, 60]$ Hz

I. $BW_{PV} < 50$ Hz

II. $I_{leak} \uparrow\uparrow$





Back-Up. Integrated PSD

Noise Performance

$$\overline{\nu_n^2} = \overline{i_n^2} \frac{R_{oc}^2}{1 + (2\pi f R_{oc} C_{eq})^2} \xrightarrow{\Delta f = [0, f_{max}]} R_{oc}^2 \int_0^{f_{max}} \frac{df}{1 + (2\pi f R_{oc} C_{eq})^2}$$

$$\overline{\nu_n^2} = \overline{i_n^2} \frac{R_{oc}}{2\pi C_{eq}} \arctan\left(2\pi f_{max} R_{oc} C_{eq}\right)$$

Back-Up. Spot Noise

International Image Sensor Society

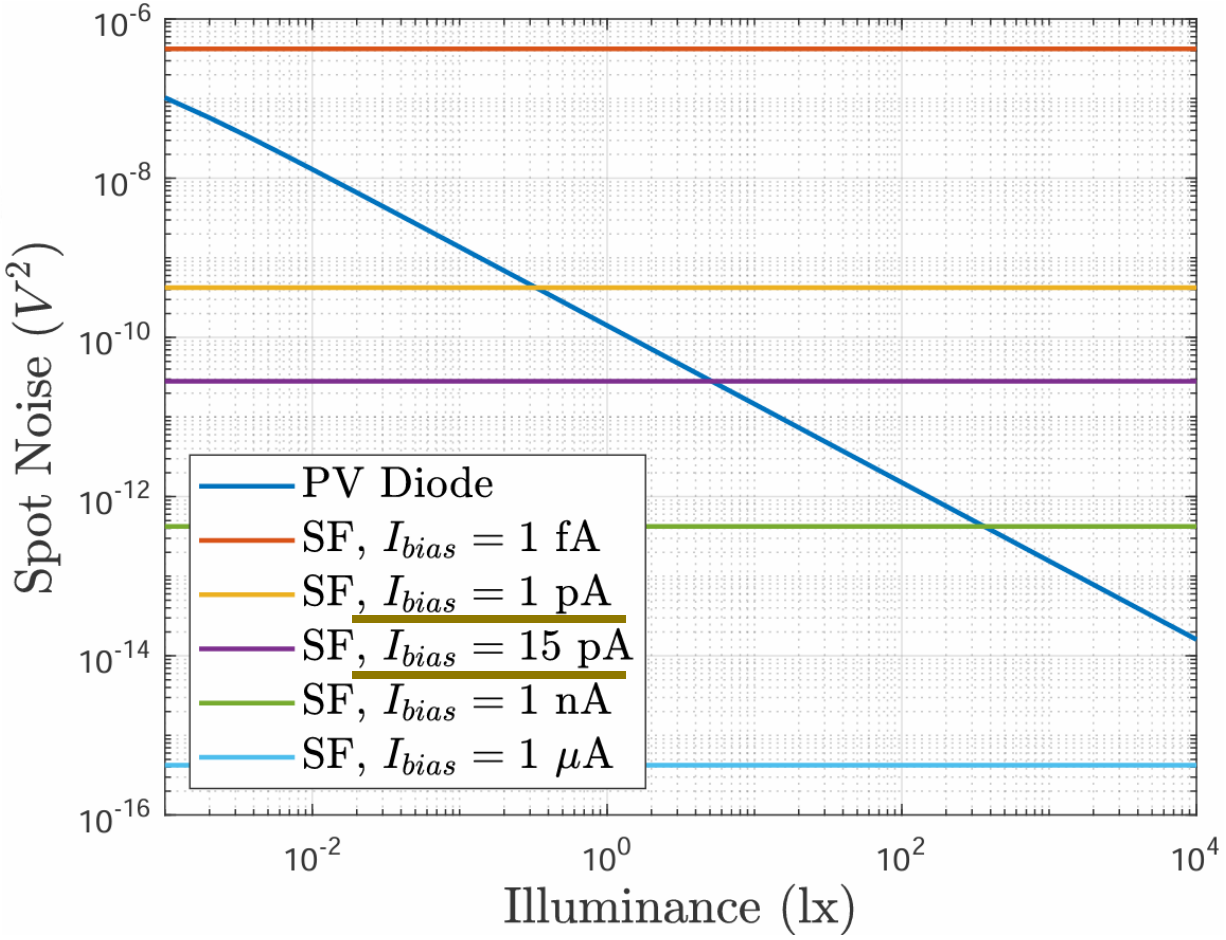
Noise Performance

$$\overline{\nu_n^2} = \overline{i_n^2}\frac{R_{oc}}{2\pi C_{eq}}\arctan\left(2\pi f_{max} R_{oc} C_{eq}\right)$$

$$f_{max} \to 0 \qquad \left(\overline{i_n^2} = 4qI_{ph}\right)$$

$$\overline{\nu_n^2} = 4q\left(\frac{\eta U_T}{I_{diff}}\right)^2$$

Spot Noise



Back-Up. Photoreceptor Stage. Mismatch

International Image Sensor Society

PV Diode

$$V_{oc} = \eta U_T \log\left(\frac{\boldsymbol{I_{ph}}}{\boldsymbol{I_s}} + 1\right)$$

☺ Independent of device's area.

- Low mismatch → High uniformity.

Photodiode + Logarithmic Photoreceptor

$$V_{pr} = V_{g,fb} - \left|\boldsymbol{V_{th,fb}}\right| - \eta U_T \log\left(\frac{\boldsymbol{I_{ph}} + \boldsymbol{I_s}}{\boldsymbol{I_{s,fb}}}\right)$$

☹ Dependent on V_{th} and devices' area.

- High mismatch → Poor uniformity.