

Noise Performance of a Photovoltaic Receptor for Dynamic Vision Sensors

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Abstract—The Photovoltaic Dynamic Vision Sensor (PVDVS), featuring a single photovoltaic receptor, enables reduced pixel pitch, wide dynamic range, and low power consumption. This paper investigates its noise performance under varying illuminance and temperature conditions, demonstrating that PVDVS reaches the fundamental limit set by diode shot noise without introducing a power-consumption trade-off. However, removing the feedback loop results in bandwidth limitations. To mitigate Background Activity (BA) noise, we propose a biasing-based noise filtering strategy, validated through theoretical modeling and electrical measurements. Our findings highlight PVDVS’s potential for low-noise, high-efficiency vision sensing applications.

I. INTRODUCTION

Dynamic Vision Sensors (DVS) [1] are bio-inspired cameras designed to detect temporal contrasts in the scene with high temporal resolution and low power consumption. Unlike conventional frame-based cameras, which capture visual scenes with fixed frame-rate, DVS asynchronously detects changes in brightness at individual pixels, making them suitable for fast and energy-efficient vision applications. However, DVS performance is often limited by noise, particularly Background Activity (BA) – spurious events that do not correspond to actual scene changes. BA reduces the Signal-to-Noise Ratio (SNR) and increases data bandwidth requirements [2], [3], negatively affecting sensor efficiency. It mainly arises from photon and electron shot noise in low-light conditions and leakage currents in brighter settings, with strong dependencies on illuminance, temperature, and circuit biasing [4], [5].

To address these limitations, the Photovoltaic Dynamic Vision Sensor (PVDVS) [6] has been proposed as an alternative to conventional DVS architectures. PVDVS replaces the traditional photoreceptor with a single photovoltaic diode – see Fig. 1, removing the need for an external bias current while reducing pixel pitch and power consumption. This design introduces fundamental changes to the noise characteristics of the sensor, as the noise power of the diode directly influences the generation of events and the overall performance.

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Understanding the noise performance of the photovoltaic diode is therefore crucial for optimizing PVDVS operation. In this work, we analyze the noise properties of the photovoltaic receptor under varying illuminance and temperature conditions, providing both theoretical modeling and experimental validation. Additionally, we propose a filtering strategy to mitigate BA noise, further enhancing the sensor’s performance.

II. A PHOTOVOLTAIC RECEPTOR

The output voltage of a photovoltaic diode (Fig. 1a) follows the logarithm of the input photocurrent, I_{ph} , since the open-circuit voltage of the photodiode, V_{oc} , is determined by a diffusion current that cancels the generated photocurrent [7],

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

where I_S and η represent the diode’s saturation current and emission coefficient, respectively, while U_T denotes the thermal voltage. Consequently, the steady-state response to illumination is functionally equivalent to the photoreceptor stage used in conventional DVS sensors [1], performing both photodetection and logarithmic compression within a single device – see Fig. 1b.

In the following sections, a detailed modeling of this device is presented and validated through experimental results. The key parameters for evaluating its noise performance and impact on DVS include bandwidth, noise power and noise events.

III. NOISE PERFORMANCE OF A PHOTOVOLTAIC DIODE

We analyze noise sources in the photovoltaic diode, where photon and thermal noise arise from the quantized nature of light and thermal energy, respectively. Since both contribute to the total current, they can be expressed as shot noise [8]:

$$\overline{i_{n,s}^2} = 2q\bar{I}\Delta f \quad (2)$$

At the open-circuit voltage, shot noise is generated by three current sources: the photocurrent, which drives photogenerated carriers; the diffusion current, caused by gradients in majority carrier concentration in neutral regions; and the dark current, resulting from the drift of minority carriers through the depletion region. The total noise current follows:

$$\overline{i_n^2} = \overline{i_{n,s}^2} = 2q\Delta f \left[I_{ph} + I_S \left(e^{\frac{qV_{oc}}{kT}} + 1 \right) \right] \quad (3)$$

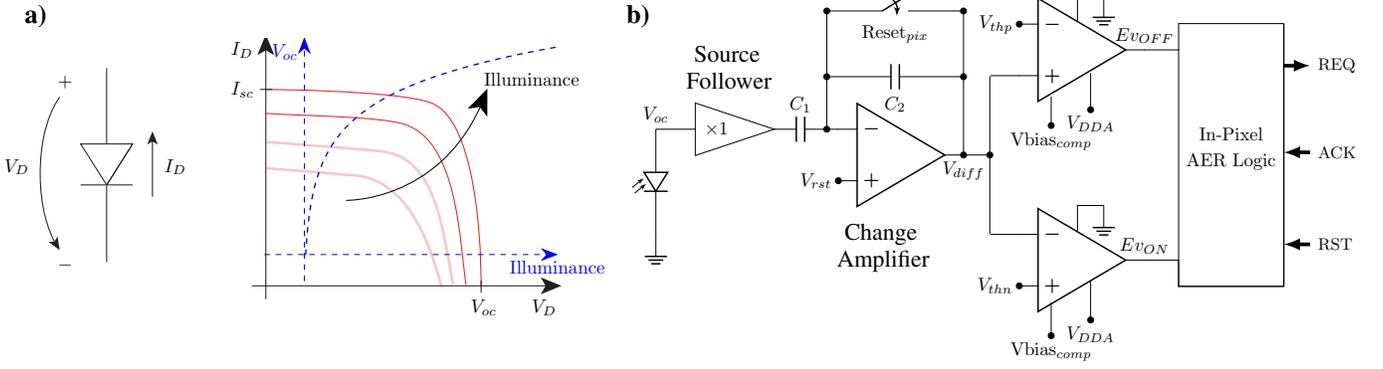


Fig. 1. (a) Diode IV characteristics in the photovoltaic regime and the open-circuit voltage as a function of illuminance. (b) The simplified PVDVS pixel schematic is composed of a photovoltaic diode as the photoreceptor stage, a PMOS source follower, a change amplifier, two comparators, and the in-pixel communication logic.

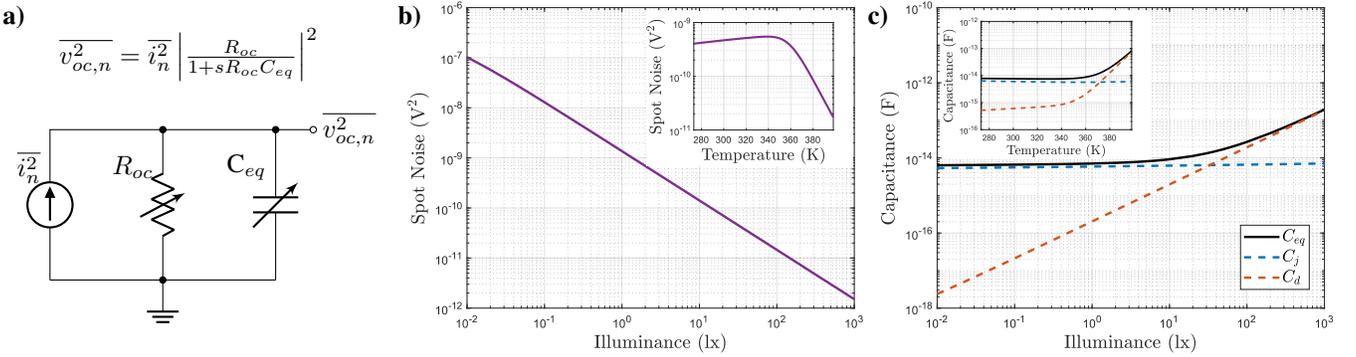


Fig. 2. (a) Photovoltaic diode equivalent circuit for noise analysis. (b) Spot noise and (c) Equivalent capacitance as a function of illuminance ($T = 298.15$ K) and temperature (Illuminance = 6 lx).

Under open-circuit conditions, the current noise power reaches $2 \times$ photon shot noise, $4qI_{ph}$, leading to the output voltage power noise shown in Fig. 2a.

$$\overline{v_{oc,n}^2} = \overline{i_n^2} \left| \frac{R_{oc}}{1 + sR_{oc}C_{eq}} \right|^2 \quad (4)$$

The behavior is modeled by a current source in parallel with the shunt resistance and the equivalent intrinsic capacitances of the diode. The former is expressed along the entire driving-point curve as $R_{oc} = \partial I_D / \partial V_D$. At the operating point ($V_D = V_{oc}$), it is given by:

$$R_{oc} = \frac{1}{\frac{I_S}{\eta U_T} e^{\frac{V_{oc}}{\eta U_T}} + \frac{qA}{2} \sqrt{\frac{2\epsilon(N_A + N_D)}{qN_A N_D (V_{bi} - V_{oc})}} \left(G_L + \frac{n_i}{\tau_g} \right)} \quad (5)$$

where A is the diode's area, ϵ is the silicon permittivity, $\{N_A, N_D\}$ are the doping profiles, V_{bi} is the built-in potential, G_L is the photogeneration rate, and $n_i/\tau_g = G_{th}$ is the thermal generation rate, with n_i representing the intrinsic carriers' density, and τ_g the generation lifetime. These parameters were extracted from a previous study [7]. Since the diode operates in the photovoltaic region, R_{oc} includes both forward and reverse components. The forward component dominates over a wide temperature range, being inversely proportional

to the diffusion current, causing R_{oc} to increase with U_T until the semiconductor becomes intrinsic, at which point R_{oc} drops sharply. Additionally, under open-circuit conditions, the diffusion current counteracts the photocurrent, increasing with illuminance and thereby reducing R_{oc} . The dependencies on illuminance and temperature can be extracted from Fig. 2b, which illustrates how it affects diode's spot noise $\overline{i_n^2} R_{oc}^2$, i.e., the noise power at low frequencies.

The equivalent capacitance C_{eq} consists of the junction capacitance (C_j), including both area and peripheral contributions, given by $C_j = \frac{C_{j0}}{\sqrt{1 - \frac{V}{V_{bi}}}}$; the diffusion capacitance (C_d), expressed as $C_d = \frac{\tau I_D |Q|}{U_T}$; and the load capacitance (C_L). Since C_L is designed to be negligible, the dominant capacitance depends on illuminance and temperature. At low illuminance, the junction capacitance is the primary contributor, as the diode is slightly forward-biased, behaving similarly to a reverse-biased junction. At high illuminance, the diffusion capacitance dominates due to the increased diffusion current needed to counteract the photocurrent – see Fig. 2c. Similarly, when temperature exceeds the critical threshold where the semiconductor becomes intrinsic, the diffusion capacitance becomes the main contributor.

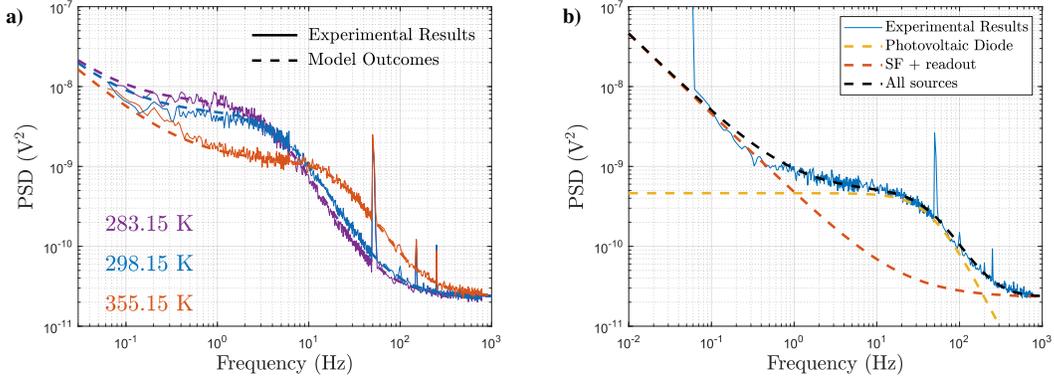


Fig. 3. Analytical model validation with experimental data for (a) different temperatures at 190 mlx, and (b) room temperature ($T = 298.15$ K) at 6 lx.

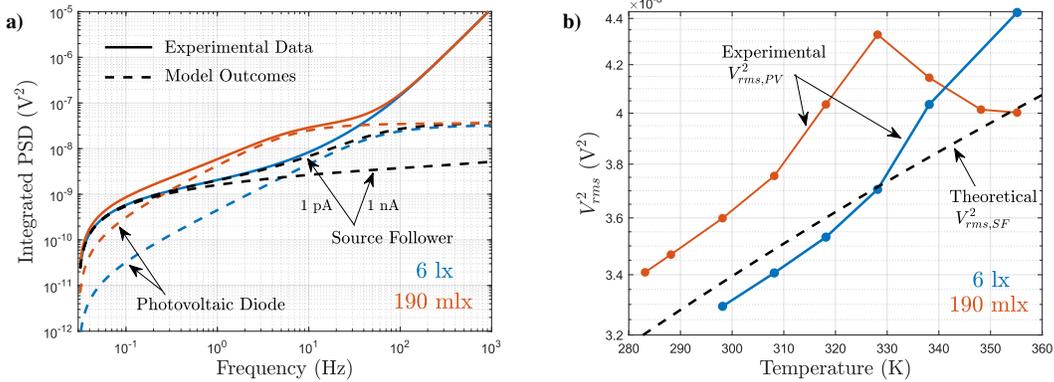


Fig. 4. (a) Integrated noise power as a function of the integration bandwidth at room temperature and two illuminances. (b) RMS Voltage at the output of the Source Follower for different temperatures and illuminances.

The diode behaves as a first-order system, where the time constant $R_{oc}C_{eq}$ determines the bandwidth, which depends on illuminance and temperature. By integrating (4) over the selected bandwidth, we obtain:

$$\overline{v_{oc,n}^2} = \overline{i_n^2} \frac{R_{oc}}{2\pi C_{eq}} \arctan(2\pi f_{max} R_{oc} C_{eq}) \quad (6)$$

where kT/C corresponds to the total noise power ($f_{max} \rightarrow \infty$) [8]. The root-mean-square (rms) noise voltage is given by $V_{rms} = \sqrt{\overline{v_{oc,n}^2}}$.

IV. A PHOTOVOLTAIC DYNAMIC VISION SENSOR

A 64×96 -pixel test chip prototype was fabricated in UMC 180nm technology [6]. This section presents and discusses the experimental results, validating our theoretical modeling.

A. Power Spectral Density

Fig. 3 shows the measured Power Spectral Density (PSD) at the output of the Source Follower under varying temperature and illuminance conditions. The noise sources are distinguishable: the Source Follower + readout flicker and shot noise dominate at low and high frequencies respectively, and diode's shot noise in between. The Source Follower spot noise depends on its transconductance and, therefore, its biasing. It was

biased at 1 nA (significantly higher than typical bias settings [9]), to observe the diode's contribution – see Fig. 4a, which illustrates the noise power as a function of the integration bandwidth (from 0.03 Hz, noise event rate due to leakage in the dark). As depicted in Fig. 4b, the dominant stage depends on both illuminance and temperature.

Fig. 5 presents the modeled and experimental results for the diode bandwidth and the RMS output voltage (V_{rms}) as functions of illuminance and temperature. The bandwidth is closely related to the Slew Rate (SR), the ratio of photocurrent to intrinsic capacitance. Although it increases with illuminance because of a higher photocurrent, its temperature dependence is more complex. At low illuminance, the bandwidth increases with temperature, eventually converging to an illuminance-independent value when the semiconductor becomes intrinsic. At high illuminance and cryogenic temperatures, the bandwidth reaches a maximum due to an increase in SR (Fig. 5a). Fig. 5b confirms strong agreement between the model and the experimental data. The V_{rms} improves with higher illuminance due to increased intrinsic capacitance but worsens with temperature as the dark current increases. At low illuminance and high temperatures, it reaches a peak of 0.8 mV – see Fig. 5c. Finally, Fig. 5d validates both tendencies, with

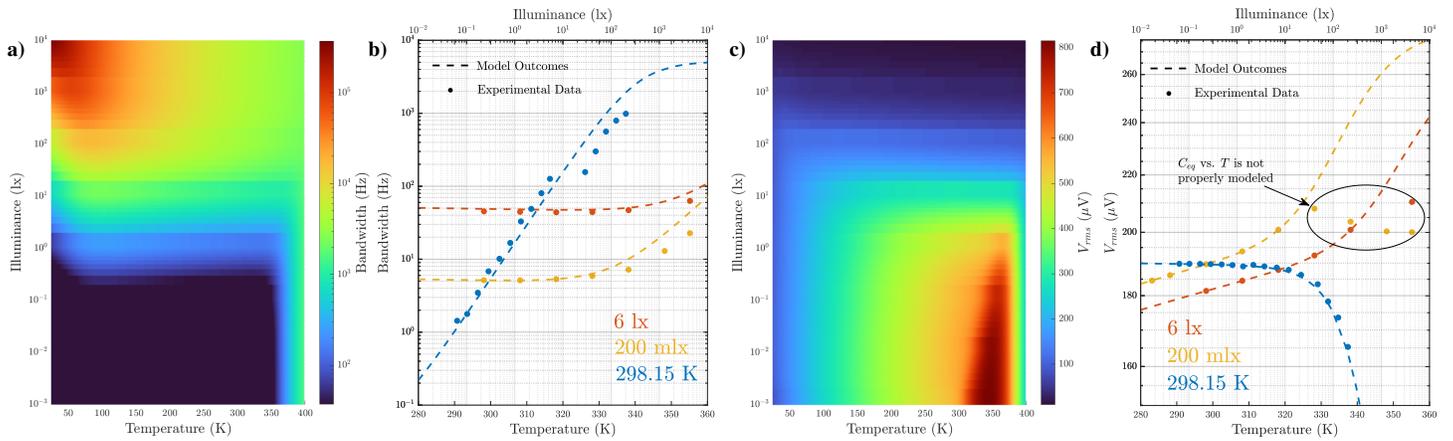


Fig. 5. Model outcomes and Experimental Validation of (a)-(b) the diode's bandwidth and (c)-(d) rms noise voltage as a function of illuminance and T .

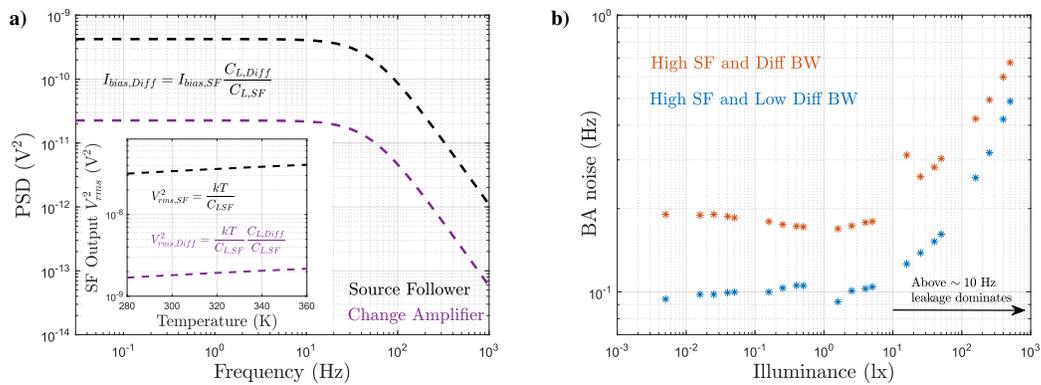


Fig. 6. (a) SF vs. Change Amplifier noise performance comparison (referred to the SF's output). (b) Background Activity Noise for different biasing.

minor discrepancies at high temperatures due to limitations in modeling intrinsic capacitance.

B. Background Activity Noise

To filter out high-frequency noise components, we propose a strategy of increasing the Source Follower bias to minimize its noise contribution in the band of interest and decreasing the biasing of the Change Amplifier to filter out noise from previous stages. Since the latter's input-referred noise power is lower than SF's – see Fig. 6a, the total noise power decreases with the mentioned strategy. Although this results in a longer reset time constant, it affects the signal time constant equally. Fig. 6b presents experimental data obtained for different biasing conditions. At low illuminances, the Background Activity (BA) remains constant, while at high illumination levels, the leakage current becomes significant.

V. CONCLUSION

In summary, unlike the conventional approach, the photovoltaic receptor reaches the fundamental shot noise and Signal-to-Noise Ratio without a power-noise trade-off, saving energy and area. It comes at the expense of limited bandwidth as we remove the feedback loop. In addition, we propose an

alternative strategy to mitigate BA noise. These findings offer key insights into the suitability of photovoltaic-based vision sensing for low-noise, high-efficiency applications.

REFERENCES

- [1] P. Lichtsteiner *et al.*, "A 128×128 120dB 15 μ s latency asynchronous temporal contrast vision sensor," *IEEE Journal of Solid-State Circuits*, vol. 43, no. 2, pp. 566–576, February 2008.
- [2] Y. Hu *et al.*, "V2e: From video frames to realistic DVS events," in *2021 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*. IEEE, 2021, Conference Paper, pp. 1312–1321.
- [3] S. Guo *et al.*, "Low cost and latency event camera background activity denoising," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 45, no. 1, pp. 785–795, 2023.
- [4] R. Graca *et al.*, "Unraveling the paradox of intensity-dependent DVS pixel noise," *CoRR*, vol. abs/2109.08640, 2021.
- [5] Y. Nozaki *et al.*, "Temperature and parasitic photocurrent effects in dynamic vision sensors," *IEEE Transactions on Electron Devices*, vol. 64, no. 8, pp. 3239–3245, 2017.
- [6] P. Fernández-Peramo *et al.*, "A Photovoltaic Dynamic Vision Sensor," *IEEE Journal of Solid-State Circuits*, pp. 1–0, 2025.
- [7] —, "Analytical Modeling of the Dependence of the Open-Circuit Voltage With Temperature in CMOS Photodiodes," *IEEE Transactions on Electron Devices*, vol. 71, no. 3, pp. 1987–1993, 2024.
- [8] D. S. Galbraith, "Signal and noise characteristics of photovoltaic P-N junction diodes," Ph.D. dissertation, University of British Columbia, 1957.
- [9] R. Graca *et al.*, "Optimal biasing and physical limits of DVS event noise," *CoRR*, vol. abs/2304.04019, 2023.