Response estimation and evaluation of direct-conversion dual-layer perovskite X-ray detectors: a numerical study with a cascaded signal model

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Abstract

This study aims to investigate the responses of a perovskite-based direct-conversion dual-layer flat-panel detector (DL-FPD) numerically. To this end, the X-ray sensitivity, spatial resolution quantified by the modulation transfer function (MTF), and detective quantum efficiency (DQE) of the DL-FPD are evaluated numerically using a linear cascade model. In addition, both the single-crystal (SC) and polycrystalline (PC) structures of MAPbI3 are investigated, along with various other key parameters such as the material thickness, electric field strength, X-ray beam spectrum, and electronic readout noise. The results demonstrate that SC perovskite consistently exhibits better performance than PC perovskite owing to fewer material defects. Increasing the layer thickness may decrease the MTF, but can also enhance the sensitivity and DQE. Moreover, appropriately increasing the external electric field within the material can improve the sensitivity, MTF, and DQE. Finally, reducing the electronic readout noise can significantly enhance the DQE for low-dose imaging. This study demonstrates the potential of high-quality dual-energy X-ray imaging using direct-conversion perovskite DL-FPDs.

Full Text

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Abstract

This study aims to investigate the responses of a perovskite-based direct-conversion dual-layer flat-panel detector (DL-FPD) numerically. To this end, the X-ray sensitivity, spatial resolution quantified by the modulation transfer function (MTF), and detective quantum efficiency (DQE) of the DL-FPD are evaluated numerically using a linear cascade model. In addition, both the single-crystal (SC) and polycrystalline (PC) structures of $MAPbI_3$ are investigated, along with various other key parameters such as the material thickness, electric field strength, X-ray beam spectrum, and electronic readout noise. The results demonstrate that SC perovskite consistently exhibits better performance than PC perovskite owing to fewer material defects.

Increasing the layer thickness may decrease the MTF, but can also enhance the sensitivity and DQE. Moreover, appropriately increasing the external electric field within the material can improve the sensitivity, MTF, and DQE. Finally, reducing the electronic readout noise can significantly enhance the DQE for low-dose imaging.

This study demonstrates the potential of high-quality dual-energy X-ray imaging using direct-conversion perovskite DL-FPDs.

Keywords: X-ray imaging, Dual-layer flat-panel detector, Perovskite X-ray detector

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Introduction

In recent years, metal halide perovskites (MHPs), denoted as ABX_3 (e.g., A: Cs^+, MA^+; B: Pb^{2+}, Bi^{2+}; and X: Br^-, I^-) [1], as illustrated in Fig. 1(a), have emerged as promising alternatives to traditional semiconductors such as Si, α-Se, CdTe, CdZnTe, diamond, HgI_2, and Ga_2O_3 [2–7]. MHPs exhibit high X-ray absorption capabilities, high charge carrier mobilities ( ), and long carrier lifetimes (τ). They can be grown in both single-crystal (SC) and polycrystalline (PC) forms and integrated with various readout circuits. Owing to their orientation-dependent transport behavior and low defect concentrations, SC MHPs demonstrate excellent potential for X-ray detection. For instance, flat-panel detectors (FPDs) fabricated from hybrid organic-inorganic SC $MAPbBr_3$ [8,9] and $MAPbI_3$ [10,11] achieved significantly higher X-ray detection sensitivity than commercial α-Se detectors.

Despite their superior X-ray detection performance, fabricating SC MHPs with scalable dimensions for large-area X-ray detectors remains challenging and expensive. Fortunately, experiments have demonstrated that conversion layers made of PC MHPs can be more easily scaled up to cover large areas at much lower cost [12,13]. The first PC $MAPbI_3$-based FPD prototype was demonstrated in 2015, enabling direct detection of soft X-ray photons [14]. In 2017, Kim et al. reported the first direct hard-X-ray imaging using a thick $CH_3NH_3PbI_3$ film on a thin-film transistor (TFT) array [12]. In 2021, Deumel et al. developed a new manufacturing procedure for direct X-ray detectors by soft-sintering $CH_3NH_3PbI_3$ on a hydrogenated amorphous silicon TFT array, employing a grid structure to mechanically adhere the thick perovskite film

[15].

In 2022, Xia et al. prepared a TFT array via soft pressing and in situ polymerization of a multifunctional binder (TMTA) for a $CH_3NH_3PbI_3$ film [16]. In 2024, Liu et al. developed a novel complementary metal oxide semiconductor (CMOS) array-based dynamic perovskite X-ray detector using a $CsPbBr_3$ film [17]. Although many studies have demonstrated the excellent potential of FPDs composed of MHP materials for X-ray imaging (Fig. 1(c)), few have extended this research to spectral imaging—a technique that captures X-ray attenuation information at multiple energy levels. X-ray spectral imaging allows distinction between different materials, enhancing image contrast and specificity for medical, industrial, and security applications [18,19]. In 2022, Pang et al. proposed a vertical-structure perovskite X-ray detector offering opportunities for improved multi-energy X-ray imaging [20]. However, this innovative vertical design presents challenges for fabricating large-area detectors, necessitating further investigation of alternative solutions for utilizing MHP materials in spectral imaging.

In biomedical X-ray imaging applications, the dual-layer FPD (DL-FPD) has emerged as a promising tool for quantitative dual-energy X-ray imaging [21–23]. The DL-FPD comprises two stacked FPD layers with varying thicknesses, where lower-energy X-ray photons are detected by the top layer and higher-energy photons by the bottom layer. Studies have also explored DL-FPDs for dual-energy computed tomography imaging [24–27]. However, current DL-FPDs primarily employ scintillator materials, posing a significant challenge: the imaging performance of the bottom detector—including spatial resolution, sensitivity, and DQE—is inferior to that of the top detector, limiting dual-energy X-ray imaging results.

Alternatively, DL-FPDs can be constructed using MHP materials (Fig. 1(d)). Unlike scintillator-based indirect X-ray detectors, MHP-based detectors directly convert X-ray photons into electric charges, which are driven by the applied electric field and collected by electrodes. MHP-based DL-FPDs offer improved imaging performance compared to scintillator-based detectors. For instance, because the applied electric field can be well confined, signal spreading in direct-conversion X-ray FPDs is less severe than in indirect-conversion FPDs, where X-ray-converted visible light photons may spread across neighboring detector elements. Consequently, the spatial resolution of the bottom layer in MHP-based DL-FPDs can be enhanced. Despite this potential, comprehensive investigations evaluating the imaging performance of direct X-ray DL-FPDs have not yet been conducted.

This study focuses on estimating and evaluating responses of a novel direct-conversion X-ray DL-FPD made of MHP material. Specifically, we explore the imaging performance—including X-ray sensitivity, MTF, and DQE—of MHP-based direct X-ray DL-FPDs through numerical calculations based on a linear cascaded model (Fig. 1(e)). We investigate how overall imaging performance depends on various factors such as MHP material layer thickness, X-ray beam spectra, and external electric fields. Additionally, we analyze electronic readout noise effects by considering three readout arrays: hydrogenated amorphous silicon TFT (α-Si: TFT), indium gallium zinc oxide-based metal oxide TFTs (IGZO-TFT), and CMOS (Fig. 1(b)). To date, α-Si: TFT arrays have been the leading choice for perovskite X-ray FPDs due to their simple structure, low cost, and suitability for large-area applications.

The TFT [28] consists of a substrate, gate electrode separated by a dielectric layer, amorphous silicon layer, and source and drain electrodes arranged to control charge carrier flow in the semiconductor channel. CMOS technology [29] combines p-type and n-type metal-oxide-semiconductor field-effect transistors to achieve low power consumption and high noise immunity, offering advantages such as lower readout noise and higher readout speeds. IGZO-TFTs [30] have a structure similar to α-Si: TFT, differing primarily by using an IGZO layer instead of amorphous silicon, resulting in less readout noise and increased readout speed—positioning IGZO-TFT as a competitive intermediate option between α-Si: TFT and CMOS for fabricating X-ray detectors.

The remainder of this paper is organized as follows: Section II reviews the linear cascade model and derives calculations for sensitivity, MTF, and DQE. Section III introduces the main parameters and presents numerical calculation details. Section IV presents DL-FPD response results for different parameters. Section V provides discussion and conclusion.

II. Detector Response Model

A. Linear Cascade Model

The linear cascade model [31–34] describes signal and noise propagation from X-ray photons to electric signals in a direct FPD through seven dominant stages: stage 0 (X-ray input), stage 1 (X-ray photon absorption), stage 2 (electron-hole cloud effect), stage 3 (electron-hole conversion), stage 4 (electron-hole collection), stage 5 (electron-hole blurring by charge traps), stage 6 (electron-hole blurring by pixel aperture), and stage 7 (signal output). These stages comprise three steps: the gain step (stages 1, 2, and 4), the stochastic blurring step (stages 3 and 5), and the deterministic blurring step (stage 6). Further details appear in Appendix V.

For a gain stage n, signal quantum Φ and noise power spectrum NPS propagate as follows [31,33]:

$$\bar{\Phi}_n(E;f) = \bar{g}_n(E)\bar{\Phi}_{n-1}(E;f)$$

$$\mathrm{NPS}_n(E;f) = \bar{g}_n^2(E)\mathrm{NPS}_{n-1}(E;f) + \bar{\sigma}_n^2(E)\bar{\Phi}_{n-1}(E;f)$$

For a stochastic blurring stage n, Φ and NPS propagate as:

$$\bar{\Phi}_n(E;f) = \bar{\Phi}_{n-1}(E;f)$$

$$\mathrm{NPS}_n(E;f) = \mathrm{NPS}_{n-1}(E;f) \cdot \mathrm{MTF}_n^2(E;f)$$

B. Response Evaluation

To evaluate perovskite DL-FPD responses, we calculate sensitivity, MTF, and DQE separately for top and bottom layers. Sensitivity S represents the ability to convert X-ray photons into electric charges for layer i (where $i = t$ or b denotes top or bottom layer). Mathematically:

$$S_i = \frac{\int \bar{\Phi}_0^i(E) S_{\max}(E) \int_0^{L_i} \bar{g}_1(E,x) \bar{g}_4(E,x)\, dx\, dE}{\int \bar{\Phi}_0(E)\, dE}$$

where S (E) represents maximum sensitivity [35]:

$$S_{\max}(E) = 1.14 \times 10^8 \cdot \frac{5.45 \times 10^{13} e(\alpha(E)/\rho)_{\mathrm{air}}}{W \alpha_{\mathrm{en}}(E)}$$

Here, e (C) is elementary charge, W (eV) is average electron-hole pair creation energy, $(\alpha/\ )$ (cm^2/g) is air's mass-energy absorption coefficient, and α and α (cm^{-1}) are the material's energy absorption and absorption coefficients. The factor 1.14×10^2 converts exposure units from R^{-1} to Gy^{-1} [36], yielding sensitivity in μC · Gy^{-1} · cm^{-2}.

X-ray quanta received on the top layer $\Phi\ ^0(E)$ differ from bottom layer quanta $\Phi\ ^0(E)$ due to top-layer filtration:

$$\Phi_t^0(E) = \bar{\Phi}_0(E)$$

$$\Phi_b^0(E) = \bar{\Phi}_0(E) \left[1 - \int_0^{L_t} \bar{g}_1(E,x)\, dx \right]$$

MTF quantifies object contrast at various spatial frequencies f (line pairs per millimeter, lp/mm) to characterize detector spatial resolution. MTF for each layer is:

$$\mathrm{MTF}_i(f) = \frac{\int \bar{\Phi}_0^i(E) \mathrm{MTF}_i^m(E;f) \mathrm{MTF}_i^{\mathrm{tr}}(E;f)\, dE}{\int \bar{\Phi}_0^i(E)\, dE} \cdot \mathrm{MTF}_i^a(f)$$

DQE describes spatial frequency-dependent SNR propagation efficiency, defined as the squared ratio of output SNR to top-layer input SNR :

$$\mathrm{DQE}_i(f)=\frac{(\mathrm{SNR}_i^{\mathrm{out}})^2}{(\mathrm{SNR}_t^{\mathrm{in}})^2}=\frac{(\bar{\Phi}_7^i(f))^2}{\bar{\Phi}_0\cdot\mathrm{NPS}_7^i(f)}$$

Both layers utilize the same input SNR as the input X-ray quantum.

III. Methods

A. Detector Configuration

This study assumes a metal-semiconductor-metal (MSM) structure with ohmic contacts for the perovskite detector, ignoring internal photoconductive gain. Numerical calculations consider key parameters affecting DL-FPD imaging performance: input beam spectra, layer thickness, electric field, dark current, readout noise, and material structure.

1. Material Structure Calculations are performed for both SC and PC $\mathrm{MAPbI_3}$. The mobility-lifetime product for electrons (τ) and holes (τ) is assumed equal, set to 1×10^{-3} $\mathrm{cm^2\cdot V^{-1}}$ for SC $\mathrm{MAPbI_3}$ and 1×10^{-4} $\mathrm{cm^2\cdot V^{-1}}$ for PC $\mathrm{MAPbI_3}$ [10–12,15].

2. Beam Spectra Three X-ray beam spectra with different radiation qualities (RQA) are simulated per IEC 61267:1994 guidelines: (a) RQA5, (b) RQA7, and (c) RQA9 (see Table 1 and Fig. 2(a)).

Table 1. Key parameters for different X-ray beam settings.

Radiation qualities	Voltage	Half-value layer (mm Al)	Added filtration (mm Al)	X-ray quanta ($\mathrm{mm^{-2}\cdot \mu Gy^{-1}}$)
RQA5	70 kV	2.58	2.0	3480
RQA7	90 kV	6.80	4.0	2890
RQA9	120 kV	11.5	5.0	2260

3. Layer Thickness The total thickness L of top and bottom MHP layers is fixed at 1.0 mm to ensure sufficient ($ 80_{3}$ layer attenuation efficiencies are 82%, 88%, and 96% for RQA5, RQA7, and RQA9 beams, respectively. The top layer thickness L increases from 100 μm to 500 μm in 100 μm intervals, corresponding to top-layer thickness occupation $L\ /L$ of 10%, 20%, 30%, 40%, and 50%. Sensitivities, MTF(f), and DQE(f) are calculated for both layers across these $L\ /L$ values.

4. Electric Field The electric field inside each MHP layer is calculated as $F = U\ /L$ (where $i = t$ or b). For sensitivity estimations, the electric field ranges from 0.01 to 0.6 V/µm in 0.01 V/µm increments. MTF and DQE responses are investigated at 0.01, 0.05, 0.1, 0.5, and 1.0 V/µm.

5. Dark Current As discussed in Section V, dark current impacts DQE through additive noise. Assuming ohmic contacts, dark current density is J_d = *σ_dF, where *σ_d* is material dark conductivity. Literature indicates PC $MAPbI_3$ can achieve dark conductivity comparable to SC $MAPbI_3$, both approximately 1×10^{-10} $(\Omega \cdot \mathrm{cm})^{-1}$ [11,12,14,15,37]. Therefore, *σ_d* = 1×10^{-10} $(\Omega \cdot \mathrm{cm})^{-1}$ is assigned to both materials. Dark current density depends on the electric field, and its DQE impact is included in electric field analysis.

6. Readout Noise Electronic readout noise *σ_{readout}* affects DQE by introducing additive noise (Section V). Three pixelated readout circuits are compared: CMOS (200 e^-), IGZO-TFT (700 e^-), and traditional α-Si: TFT (2000 e^-) [30].

B. Numerical Study

RQA5, RQA7, and RQA9 beam spectra are generated using SpekCal [38]. Pixel size is 100 µm. $MAPbI_3$ mass density _{*mass*} is 4.16 g/cm^3. X-ray absorption coefficients are obtained from NIST. Electron-hole pair creation energy $W\pm$ is 4.7 eV [12,15]. Signal integration period Δt is 10.0 ms. Incident X-ray exposure is examined at 1.0 and 0.1 µGy for electric field and readout noise effects, and fixed at 1 µGy for other parameters. Detailed settings appear in Table 2. All calculations use Python 3.10 on a Dell XPS desktop (Intel i7-13700, 16 GB DDR5 RAM).

Table 2. Key parameters for numerical simulations.

Parameter	Specifications
X-ray spectra	RQA5, RQA7, RQA9
Dose (µGy)	0.1, 1
Pixel size (µm)	100
Δt (ms)	10
σ_{readout} (e^-) [30]	200 (CMOS), 700 (IGZO-TFT), 2000 (α-Si: TFT)
L (µm)	L + L_b = 1000, L /L = 10%, 20%, 30%, 40%, 50%
F (V/µm)	0.01, 0.05, 0.1, 0.5, 1

Parameter	Specifications
Material [10–12,15]	MAPbI$_3$
_{mass} (g/cm^3)	4.16
W± (eV)	4.7
τ_e,h (cm^2/V)	1×10^{-3} (SC), 1×10^{-4} (PC)

IV. Results

A. Dependence on Material Thickness

Figure 3 presents calculated sensitivity responses for five L /L ratios (10%, 20%, 30%, 40%, 50%) with RQA7 input spectrum. Solid and dashed lines represent top and bottom layer sensitivities, respectively. Sensitivity increases with electric field, reaching maximum when external field exceeds a threshold. SC MAPbI$_3$ achieves maximum sensitivity at lower electric fields than PC MAPbI$_3$, indicating sufficient charge collection efficiency at lower fields. Top and bottom layer sensitivities exhibit a competitive relationship as L /L varies: top layer sensitivity increases with L /L while bottom layer sensitivity decreases, because more X-ray photons are absorbed by the thicker top layer. The L /L ratio is crucial for determining relative sensitivities—top layer sensitivity exceeds bottom layer when L /L $\geq$ 30%, but is lower when L /L $\leq$ 20%. Therefore, L /L between 20% and 30% is preferred for balanced sensitivities.

Figure 3. Numerical results of sensitivities versus electric field for L /L varying from 10% to 50% (RQA7 spectrum). Solid and dashed lines show top and bottom layer results, respectively.

Estimated MTF(f) curves for the five L /L ratios appear in Fig. 4 (RQA7 spectrum, 0.1 V/µm electric field). Cyan lines indicate ideal MTF determined by pixel aperture collection blurring. For SC MAPbI$_3$, MTF(f) curves are nearly identical across L /L values and closely match ideal MTF (Fig. 4(a)), indicating minimal material impact on spatial resolution. However, PC MAPbI$_3$ detector MTF(f) varies dramatically with L /L, with most values below ideal MTF except for the thinnest top layer at L /L = 10% (Fig. 4(b)). Top and bottom layer MTF(f) show competitive behavior: for thin top layers (L /L = 10%), top MTF(f) notably exceeds bottom MTF(f). As L /L increases, top layer MTF(f) decreases while bottom layer MTF(f) increases due to more severe charge trapping with increasing thickness. At equal thickness (L /L = 50%), top and bottom layer MTF(f) converge as expected.

Figure 4. Numerical results of MTF(f) for L /L varying from 10% to 50% (RQA7 spectrum, 0.1 V/µm field). Solid and dashed lines show top and bottom layer results, respectively.

Estimated DQE(f) curves for different L /L values appear in Fig. 5 (RQA7 spectrum, 0.1 V/µm field, 1 µGy dose, CMOS readout noise). For both SC and PC $MAPbI_3$, top layer DQE(f) increases with L /L while bottom layer DQE(f) decreases, because thicker top layers absorb more photons. PC $MAPbI_3$ DQE(f) values decrease more rapidly at high spatial frequencies than SC $MAPbI_3$, especially for the bottom layer (Fig. 5(b)), due to more severe signal blurring from charge trapping. Similar to sensitivity, top layer DQE(f) is lower than bottom layer when L /L ≤ 20% but exceeds it when L /L ≥ 30%. Thus, L /L between 20% and 30% yields similar DQE(f) for both layers.

Figure 5. Numerical results of DQE(f) for L /L varying from 10% to 50% (RQA7 spectrum, 0.1 V/µm field, 1 µGy dose, CMOS readout noise). Solid and dashed lines show top and bottom layer results, respectively.

Overall, top layer sensitivity, MTF(f), and DQE(f) exhibit competitive relationships with bottom layer values across L /L variations. Subsequent studies focus on L /L = 30%.

B. Dependence on Beam Spectrum

Figure 6 shows estimated sensitivities for RQA5, RQA7, and RQA9 input spectra at L /L = 30%. For the top layer, RQA5 and RQA7 sensitivity responses are identical and higher than RQA9 (solid lines in Fig. 6), jointly determined by X-ray absorption efficiency and charge-conversion multiplication. For the bottom layer, sensitivity is highest for RQA9 and lowest for RQA5 (dashed lines), because the thick bottom layer generates similar absorption efficiencies for different photon energies, yielding higher sensitivity for higher-energy spectra. Interestingly, top and bottom layer sensitivities are similar for RQA9, indicating that a lower L /L should be selected for low-energy spectra to generate comparable sensitivity responses.

Figure 6. Numerical results of sensitivities versus electric field for RQA5, RQA7, and RQA9 input spectra (L /L = 30%). Solid and dashed lines show top and bottom layer results, respectively.

MTF(f) curves for different input spectra appear in Fig. 7 (0.1 V/µm field, L /L = 30%). For SC $MAPbI_3$, MTF(f) curves are nearly identical and closely resemble ideal MTF (Fig. 7(a)). For PC $MAPbI_3$, MTF(f) curves are consistently lower than ideal MTF (Fig. 7(b)) due to charge-trapping-induced signal blurring. High-energy spectra generate slightly better MTF(f) than low-energy spectra for the bottom layer.

Figure 7. Numerical results of MTF(f) for RQA5, RQA7, and RQA9 input spectra (0.1 V/µm field, L /L = 30%). Solid and dashed lines show top and bottom layer results, respectively.

DQE(f) responses appear in Fig. 8 (1 µGy dose, CMOS readout noise). For the top layer, DQE(f) is highest for RQA5 and lowest for RQA9 (solid lines). Conversely, bottom layer DQE(f) is highest for RQA9 and lowest for RQA5 (dashed lines). High-energy RQA9 spectrum exhibits a narrower DQE(f) gap between layers than RQA5 and RQA7. Consequently, lower L /L ratios are preferable for achieving similar DQE(f) responses between layers.

Figure 8. Numerical results of DQE(f) for RQA5, RQA7, and RQA9 input spectra (0.1 V/µm field, L /L = 30%, 1 µGy dose, CMOS readout noise). Solid and dashed lines show top and bottom layer results, respectively.

C. Dependence on Electric Field

MTF(f) responses for five electric field strengths (0.01, 0.05, 0.1, 0.5, and 1.0 V/µm) appear in Fig. 9 (RQA7 spectrum, L /L = 30%). For SC $MAPbI_3$, MTF(f) shows little dependence on electric field except for the ultra-low 0.01 V/µm field in the bottom layer (Fig. 9(a)). For PC $MAPbI_3$ detectors, bottom layer MTF(f) depends heavily on electric field—higher fields significantly enhance MTF(f) response (Fig. 9(b)). At high fields, bottom layer MTF(f) can match or exceed top layer performance. For example, bottom layer at 0.5 V/µm exhibits similar MTF(f) to top layer at 0.05 V/µm. However, higher fields increase dark current density, potentially compromising detection limits and DQE(f) response. Therefore, electric field must be optimized to generate comparable MTF(f) in both layers.

Figure 9. Numerical results of MTF(f) for different electric fields (RQA7 spectrum, L /L = 30%). Solid and dashed lines show top and bottom layer results, respectively.

DQE(f) responses for different electric fields appear in Fig. 10 for 1 µGy and 0.1 µGy doses (RQA7 spectrum, CMOS readout noise). For SC $MAPbI_3$, electric field has negligible impact on DQE(f) except for the ultra-low 0.01 V/µm field (Figs. 10(a) and 10(c)). For PC $MAPbI_3$ detectors, reducing electric field dramatically degrades DQE(f) (Figs. 10(b) and 10(d)) due to insufficient charge collection efficiency. PC $MAPbI_3$ DL-FPDs can achieve SC-like DQE(f) at higher electric fields. However, increasing field beyond saturation does not improve DQE(f)—the 0.5 V/µm and 1 V/µm curves are similar. Continuous field increases raise dark current without improving DQE(f).

Figure 10. Numerical results of DQE(f) for different electric fields (RQA7 spectrum, L /L = 30%, CMOS readout noise). Solid and dashed lines show top and bottom layer results, respectively.

D. Dependence on Readout Noise

DQE(f) responses for three electronic readout noise levels appear in Fig. 11 (CMOS, IGZO-TFT, and α-Si: TFT circuits). Electric field is 0.5 V/µm to ensure sufficient charge collection. Only PC $MAPbI_3$ material is investigated. At 1 µGy dose, IGZO-TFT DQE(f) is comparable to CMOS and higher than α-Si: TFT (Fig. 11(a)). At 0.1 µGy dose, CMOS DQE(f) is slightly higher than IGZO-TFT but significantly higher than α-Si: TFT (Fig. 11(b)). Therefore, back-plane readout noise more strongly impacts low-dose imaging—lower readout pixel noise is recommended for low-dose scenarios.

Figure 11. Numerical results of DQE(f) for different readout noise types (L /L = 30%, 0.5 V/µm field, RQA7 beam). Solid and dashed lines show top and bottom layer results, respectively.

V. Discussion and Conclusion

This study numerically investigated direct-conversion perovskite DL-FPD responses using a linear cascade signal model under various configurations. Sensitivity, MTF(f), and DQE(f) were evaluated across beam spectrum, material structure, thickness, electric field, and readout noise settings. Although parameters like attenuation coefficient and mobility-lifetime product (τ) were tailored to MAPbI$_3$, methods and results can be generalized to other MHP materials like CsPbBr$_3$.

Material thickness strongly impacts top and bottom layer sensitivity, MTF(f), and DQE(f). Top layer sensitivity and DQE(f) improve with increasing L /L, while bottom layer values decrease. Conversely, top layer MTF(f) degrades with increasing L /L while bottom layer MTF(f) improves. Thickness should be optimized for good low-energy imaging performance, especially for the top layer. X-ray beam spectra significantly affect sensitivity and DQE(f) but minimally impact MTF(f). In high-energy imaging, top layer sensitivity and DQE(f) may decrease while bottom layer values increase.

Increasing electric field improves sensitivity, MTF(f), and DQE(f), potentially bridging performance gaps between PC and SC materials. However, sensitivity may saturate beyond certain thresholds, and higher fields increase dark current, potentially degrading DQE. Therefore, optimal electric field selection is required for satisfactory imaging performance. Additionally, pixel arrays with lower readout noise are necessary for high DQE performance in low-dose applications.

This study has several limitations. First, it considered fairly ideal detector settings without non-uniform material responses, which can impact imaging performance. Second, we assumed photoresistor operation without photoconductive gain, though perovskite detectors may be p-i-n photodiodes with higher sensitivity from internal gain [47,48]. Additionally, traps causing signal blurring may enhance sensitivity and SNR [49], requiring careful balancing. Third, we assumed equal τ values for electrons and holes in MAPbI$_3$ [50], though τ may slightly exceed τ , potentially affecting performance when electrodes are interchanged. Fourth, we assumed uniform electric fields opposite electrodes with zero field at pixel boundaries, though weak boundary fields may cause signal loss or charge sharing, degrading MTF and DQE. These issues can be mitigated through advanced designs like guard rings and nodal separation on CMOS chips [51]. Fifth, only the popular MAPbI$_3$ material was investigated—other MHP materials require detailed exploration. Finally, imaging performance was only studied for 1.0 mm total thickness; thicker detectors require reanalysis. No experimental verification was performed due to lack of DL-FPD prototypes, warranting future validation studies.

In conclusion, direct-conversion DL-FPDs made of MHP material can achieve superior sensitivity, consistent spatial resolution, and high detection efficiency compared to traditional indirect-conversion scintillator-based DL-FPDs. High-quality dual-energy imaging using novel direct-conversion perovskite DL-FPDs will be highly valuable.

Appendix: Detailed Model Derivations

1. X-Ray Input

Mean input quantum $\bar{\Phi}_0$ of X-ray photons per unit exposure and area is [33,39]:

$$\bar{\Phi}_0 = \int \frac{5.45 \times 10^{13} p(E)}{E \cdot (\alpha(E)/\rho)_{\text{air}}} \, dE$$

where $p(E)$ is X-ray probability density at energy E. $\bar{\Phi}_0$ has units $\text{cm}^{-2} \cdot \text{R}^{-1}$ from Eq. 8 and converts to $\text{cm}^{-2} \cdot \text{Gy}^{-1}$ by multiplying by $(8.76 \times 10^{-3})^{-1}$ R/Gy [36]. Input X-ray quanta follow Poisson distribution with variance:

$$\bar{\sigma}_0 = \sqrt{\bar{\Phi}_0}$$

2. X-Ray Absorption

X-ray photon absorption probability $\bar{g}_1$ at normalized position x in material with attenuation coefficient $\alpha(E)$ is:

$$\bar{g}_1(E, x) = e^{-x/\Delta(E)}$$

where $x = x\ /L$ $(0 < x \leq 1)$ and Δ is normalized attenuation coefficient: $\Delta(E)$ $= 1/[\alpha(E)L]$. As a binary selection process, $g_1(x)$ has variance [33]:

$$\bar{\sigma}_1(x) = \bar{g}_1(x)(1 - \bar{g}_1(x))$$

3. EHP Cloud Blurring

The primary photoelectron deposits energy and creates electron-hole pairs (EHPs) within a distance depending on photoelectron energy and material. An X-ray photon creates an EHP cloud causing stochastic blurring that degrades intrinsic spatial resolution. The MTF contribution is [40]:

$$\mathrm{MTF}_m(E;f) \approx \exp(-\pi^2\sigma(E)^2 f^2)$$

where σ is proportional to primary photoelectron maximum range *R_{max}*. An empirical expression for *R_{max}* is [41]:

$$R_{\max}(E) = \frac{2.761 \times 10^{-6} \times \mathrm{Mat} \cdot E^{5/3}}{\rho Z^{8/9}(1+0.978\times 10^{-6}E)^{5/3}(1+1.957\times 10^{-6}E)^{4/3}}$$

where Mat is atomic mass and Z is atomic number. According to [40], σ *R_{max}*/2.5.

4. EHP Conversion

An X-ray photon with energy E absorbed by the material emits a primary photoelectron creating thousands of charge carriers (EHPs). The mean number of carriers per X-ray photon is [33]:

$$\bar{g}_3(E) = \frac{E\alpha_{\mathrm{en}}(E)}{\alpha W^{\pm}}$$

where *α_{en}* is material energy absorption coefficient and $W\pm$ is EHP creation energy. This Poisson process has variance $\bar{\sigma}_3 = \bar{g}_3(E)$.

5. Charge Collection

Charge carriers are collected by electrodes with efficiency g_4. Assuming electron collection by bottom electrodes, mean efficiency at normalized position x is described by Ramo's theorem [42] and expressed as [43]:

$$\bar{g}_4(x) = \chi_h(1-e^{-x/\chi_h}) + \chi_e(1-e^{-(1-x)/\chi_e})$$

where *_e(h)* is electron (hole) normalized schubweg: *_e(h)* = * _e(h)τ_e(h)F/L, *and* F* is detector bulk electric field. Corresponding variance is [43]:

$$\bar{\sigma}_4(x) = \chi_e^2+\chi_h^2-\chi_h^2e^{-2x/\chi_h}-\chi_e^2e^{-2(1-x)/\chi_e}-2\chi_h x e^{-x/\chi_h}-2\chi_e(1-x)e^{-(1-x)/\chi_e}$$

6. Trap Blurring

Trapped charge carriers in detector bulk cause stochastic signal blurring. The MTF from charge-trapping (*MTF_{tr}*) is modeled by Fourier transform of the line spread function from trapped charges [44]:

$$\mathrm{MTF}_{\mathrm{tr}} = G(f)/G(0)$$

where $G(f)$ and $G(0)$ are given by complex expressions involving _e, _h, $\mathit{\Delta}$, , and $\omega = 2\pi f$.

7. Aperture Collection Blurring

Electric signals collected and averaged by pixels create deterministic blurring:

$$\mathrm{MTF}_a = |\mathrm{sinc}(af)|$$

where a is pixel dimension.

8. Additive Noise

Additive noise comprises dark current noise *σ_d* and electronic readout noise *σ_{readout}. *Dark current* I_d* exists in perovskite materials, with fluctuations creating noise [34,45]. Accumulated dark charge Q_d contributes shot noise:

$$\sigma_{\mathrm{shot}} = \sqrt{Q_d} = \sqrt{I_d \Delta t}$$

Dark current follows Poisson distribution. In addition to shot noise, $1/f$ noise is a dominant fluctuation source [46] but can only be determined experimentally and is often unavailable. Therefore, $1/f$ effects are not discussed.

Dark current contribution to NPS is:

$$\mathrm{NPS}_d = \sqrt{\frac{I_d \Delta t}{e}}$$

Electronic noise includes readout noise contribution:

$$\mathrm{NPS}_{\mathrm{readout}} = \sigma^2_{\mathrm{readout}}$$

Total additive electronic noise NPS is:

$$\mathrm{NPS}_{\mathrm{add}} = \mathrm{NPS}_d + \mathrm{NPS}_{\mathrm{readout}}$$

Author Contributions

All authors contributed to study conception and design. Material preparation, data collection, and analysis were performed by Han Cui. The first draft was written by Han Cui; all authors commented on previous versions and approved the final manuscript.

Data Availability

Data supporting this study are openly available at https://cstr.cn/31253.11.sciencedb.j00186.00816 and https://www.doi.org/10.57760/sciencedb.j00186.00816.

Conflict of Interest

The authors declare no competing interests.

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Note: Figure translations are in progress. See original paper for figures.