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Ultrafast and ambient-immune tandem architectures for 1,550-nm LiDAR application

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Abstract

A recently reported tandem colloidal quantum dot photodiode architecture simultaneously addresses two long-standing challenges related to response speed and spectral selectivity in 1,550-nm light detection and ranging (LiDAR) application. By halving the effective junction capacitance through series-connected subcells and suppressing visible-light interference, this work demonstrates a promising route toward solution-processed 3D LiDAR sensing. In the future, combining this architectural concept with low-dielectric-constant material platforms and robust surface defect engineering could further reduce speed limitations while enhancing tolerance to ambient-light interference, potentially enabling picosecond-scale response in next-generation LiDAR systems.

Keywords: LiDAR, Short-wave infrared, Photodiode, Colloidal quantum dots, Optoelectronics

Light detection and ranging (LiDAR) systems are critical to emerging three-dimensional imaging applications, from autonomous driving to mixed reality. The operational wavelength for LiDAR is transitioning from 905 nm to 1,550 nm, driven by the higher eye-safe laser power thresholds (1,550 nm), reduced atmospheric scattering, and extended detection ranges. While commercial 1,550-nm systems rely on InGaAs photodiodes, scaling these detectors to large-area arrays is costly because of the complex epitaxial fabrication and yield-limiting flip-chip bonding processes for array-level integration. Solution-processed colloidal quantum dots (QDs) are promising low-cost alternatives that can be monolithically integrated with silicon-based readout circuits.

However, the application of QD photodiodes to LiDAR has historically been hindered by two physical bottlenecks. First, QDs show an inherently stronger absorption coefficient in the visible spectrum than at the target

wavelength of 1,550 nm. Consequently, practical LiDAR systems rely on external optical bandpass filters to reject ambient solar interference. However, out-of-band leakage through the optical filter can degrade the signal-to-noise ratio under strong ambient illumination¹. Second, achieving nanosecond-scale response times in QD devices is constrained by the inherent trade-off between carrier transit time and RC delay: decreasing the absorber thickness shortens the carrier transit time but increases the junction capacitance, thereby increasing the RC delay^{2,3}.

Yang et al. recently developed a tandem PbSe QD photodiode architecture to simultaneously overcome the speed and spectral selectivity limitations in 1,550-nm LiDAR application¹. Vertical stacking of two identical subcells separated by a 1-nm evaporated Au recombination layer effectively decoupled these competing speed-limiting factors. When two identical subcells are connected in series, the effective capacitance can be nearly halved without increasing the carrier transit length, yielding a response time of 1.01 ns. Furthermore, this architecture allows for the intrinsic suppression of visible background light. Visible light is primarily absorbed by the front cell,

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creating a photocurrent mismatch with the rear cell. Because of the current continuity condition imposed by the series connection, the excess carriers generated by visible light in the front cell are not collected by the tandem device and instead undergo non-radiative recombination. This selective suppression of charge collection, which effectively narrows the spectral response, is referred to as charge-collection narrowing. Consequently, the external quantum efficiency (EQE) in the visible band is suppressed by a factor of 13, i.e., the EQE is reduced to 7%, while the photoresponse at 1,550 nm is preserved. To place these results in context, Table 1 compares the performance of the tandem device with that of representative nanosecond-scale short-wave infrared (SWIR) colloidal QD single devices. Recent single-junction devices have achieved response times in the range of 2–10 ns while maintaining high EQEs at the target wavelengths, but their broadband photoresponse necessitates external spectral filtering for LiDAR operation. In contrast, the tandem device shows a response time of 1.01 ns while retaining an EQE of 25.06% at 1,550 nm and suppressing the visible-band EQE to approximately 7%, highlighting the distinctive combination of speed and intrinsic spectral selectivity.

Beyond the reported metrics, transitioning from a single-junction architecture to a stacked tandem architecture introduces fundamental shifts in the device physics and manufacturing paradigm. Table 2 outlines the theoretical

distinctions and physical trade-offs between these two structural approaches.

Although conceptually elegant, the tandem architecture inherently caps the theoretical maximum EQE at 50%, necessitating a compromise in absolute sensitivity. Furthermore, transitioning this multilayered design to large-area industrial manufacturing presents a tangible challenge, particularly regarding the 1-nm Au intermediate layer. Depositing such an ultrathin film over rough topographies risks the formation of discontinuous nanoislands, which can introduce parasitic leakage pathways, elevate the noise floor, and complicate scalable fabrication. From a material perspective, a forward-looking approach to overcome the RC limitation involves transitioning to absorbing materials with intrinsically low dielectric constants (ϵ_r). For instance, shifting from traditional PbS QDs ($\epsilon_r \approx 35$) to III-V QDs such as InAs QDs ($\epsilon_r \approx 6$) can fundamentally reduce the junction capacitance⁷. However, surface defects in III-V QDs can introduce mid-gap trap states that promote trap-assisted recombination, thereby degrading the photodiode performance⁸. Thus, combining low-permittivity materials with robust defect engineering to fabricate high-mobility QD films, together with the tandem architecture, would further reduce both material- and device-level speed limitations. These advances could push QD LiDAR detectors beyond the nanosecond regime while preserving

Table 1 Performance comparison of nanosecond-scale SWIR colloidal QD photodiodes.

Architecture (Material)	Response Time (ns)	Wavelength (nm)	EQE (%)	Detectivity (Jones)	Ref.
Tandem (PbSe)	1.01	1,550	7 (Vis)/25 (IR)	2.29×10^{11}	1
Single (PbSe)	1.69	1,550	25.5	—	1
Single (PbS)	4	1,330	42	3.9×10^{11}	2
Single (PbS)	2	1,330	49	2.6×10^{12}	3
Single (PbS)	7	1,550	70	1.6×10^{12}	4
Single (PbS)	10	1,550	80	8×10^{11}	5
Single (InAs)	10	1,140	75	5×10^{11}	6

Table 2 Fundamental physical and theoretical comparisons between single-junction and tandem photodiode architectures.

Parameter	Single-Junction Architecture	Tandem (PIN) ₂ Architecture
Theoretical EQE Limit	$\leq 100\%$ (Fundamental limit without avalanche gain)	$\leq 50\%$ (Restricted by the series current-matching requirement)
Response Time Limit (T)	T (Bound by RC delay vs. carrier transit time trade-off)	$T/2$ (Capacitance halved without extending the sub-cell transit path)
Noise & Detectivity (D^*)	Lower noise (Minimised active volume restricts bulk thermal generation)	Elevated noise (Doubled volume and intermediate layer induce parasitic leakage)
Ambient Light Immunity	Low (Relies on external optical bandpass filters)	High (Inherent charge-collection narrowing eliminates mismatched carriers)
Manufacturing Complexity	Low (Standard layer-by-layer solution deposition)	High (Requires precise optical matching and ultrathin metal evaporation)

strong ambient-light rejection, thereby opening a new route toward picosecond-scale detection.

Conflict of interest

The author declares no competing interests.

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