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Dielectric oligonucleotide fragments enable ultralow threshold photomultiplication in infrared quantum dot photodetectors

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ABSTRACT

Colloidal quantum dot-based shortwave infrared photodetectors offer a low-cost, scalable platform for applications such as autonomous driving and night vision. However, high-gain operation typically demands large operating voltages (V_{OP}) due to inefficient carrier multiplication processes. Here, we report a photomultiplication (PM) photodiode mediated by a deoxyribonucleic acid (DNA) nucleotide-based charge tunneling layer (CTL). Systematic modulation of the DNA-based CTL suppresses dark current and enables precise control of the tunneling onset. The shallow energy levels and high permittivity of the DNA-based CTL enable efficient charge accumulation and hole injection via Fowler–Nordheim tunneling, yielding PM at -0.14 ± 0.05 V. The resulting device achieved a gain of 57.6 and a specific detectivity (D^*) of 1.2×10^{13} Jones at -0.5 V and 1550 nm.

1. Introduction

Shortwave infrared (SWIR) photodetectors have significant potential for applications in night vision and autonomous driving owing to their low atmospheric scattering and inherent eye safety. [1] Because SWIR technologies are used in sensor-dense, power-constrained environments, low-power consumption is increasingly critical, particularly for prolonged operation and minimal thermal load. [2]

Current SWIR photodetectors are primarily based on epitaxially grown semiconductors, such as InGaAs, Ge, and III–V compounds. [3,4] High-gain device structures, such as avalanche photodiodes (PDs), have been employed to achieve high performance in ranging applications. [5,6] Nevertheless, the achievable gain is typically limited to ≈ 20 under the operating voltages (V_{OP}) of tens of volts, limiting their suitability for energy-efficient platforms. [7,8]

SWIR colloidal quantum dot (CQD)-based photodetectors are promising low-cost alternatives that offer broadband absorption tunability of CQDs via quantum confinement. [9,10] The potential for high-gain operation using CQD-based photoconductors and phototransistors has been demonstrated in several studies; [11–15] however, both devices rely on multiple carrier recirculation cycles, which necessitate high V_{OP}. [16] Photomultiplication (PM) PDs have also been proposed; however, non-ideal electronic structures, such as defects and deep energy levels, increase dark current or decrease tunneling efficiency, causing poor performance. [17–19]

In this study, we reconstructed the conventional photodiode by employing oligonucleotides as a charge tunneling layer (CTL) for efficient PM. The unique physical features of nucleotides—including a wide bandgap with shallow energy levels and a high dielectric constant (ε_r)—make them attractive candidates for interfacial engineering in optoelectronic devices. [20–22] Leveraging the configurability of nucleotide sequences, we systematically screened their base compositions and lengths via molecular dynamics (MD) simulations and spectroscopic analysis and identified optimal nucleotide structures. We found that purine bases stabilize the unfolded conformation of nucleotides and ensure uniform charge transport for an effective CTL.

We elucidated the underlying mechanisms via which the optimized DNA-based CTL effectively modulates the tunneling onset, yielding PM at a threshold voltage (V_{th}) of -0.1 V with a $>100\%$ external quantum efficiency (EQE). The resulting photodetector, operating at 1550 nm,

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