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CARBON QUANTUM DOT-BASED PHOTODIODE INTRINSIC LAYER TUNED TO HUMAN CONE RESPONSES

Original Article

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ABSTRACT

Background: Conventional retinal prosthetic systems rely on RGB photodiodes to approximate the color perception of human vision. However, such systems are computationally intensive, bulky, and poorly matched to the spectral sensitivities of natural photoreceptors. Quantum dots (QDs) offer tunable optical properties and high photostability, providing an alternative route for biologically coherent optical sensing. Carbon quantum dots (CQDs), in particular, offer low toxicity, cost-effectiveness, and biocompatibility, making them suitable for retinal biomimetic applications.

Objective: This study aimed to develop and characterize a CQD-based photodiode model that replicates the spectral response of human cone cells (L, M, and S) using computational modeling, optical analysis, and machine learning–assisted synthesis optimization.

Methods: CQDs were synthesized using a bottom-up hydrothermal method with citric acid as the carbon precursor. UV–Vis spectroscopy was employed to determine absorbance across 400–700 nm. The intrinsic layer was created by embedding CQDs in a 40% PMMA–chlorobenzene matrix, thermally cured at 80 °C. Absorption peaks were analyzed via Gaussian regression, while a neural network trained on synthesis variables (temperature, time, doping) predicted the relationship between processing conditions and spectral output. Reflectance was calculated using the Fresnel equation, and EQE profiles were modeled to align with human cone sensitivities.

Results: The L, M, and S CQDs demonstrated peak absorbances at 564 nm, 534 nm, and 420 nm respectively, matching the physiological cone response ranges. The intrinsic CQD–PMMA composite achieved over 85% optical transparency and a 2.5× increase in absorbance due to solvent shrinkage. Gaussian fitting yielded $R^2 > 0.97$, and neural network predictions reached 93% accuracy for target wavelength estimation.

Conclusion: The study confirms that CQD–PMMA composites can effectively replicate human cone spectral sensitivity with stable optical and mechanical characteristics. The integration of data-driven synthesis optimization establishes a pathway for developing compact, energy-efficient, and biocompatible optical prosthetic systems.

Keywords: Absorbance, Biomimetics, Carbon Quantum Dots, Neural Networks, Photodiodes, PMMA, Spectral Sensitivity.

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INTRODUCTION

Quantum dots (QDs) have emerged as a transformative class of nanomaterials due to their unique size-dependent optical and electronic properties. Their tunable absorption spectrum and superior photostability have made them valuable for a wide range of optoelectronic and biomedical applications (1-3). Recent advancements in QD technology have demonstrated their potential for photodetection across visible and near-infrared wavelengths with remarkably high responsivity and detectivity (4). In particular, QD-based photodiodes have shown reduced noise levels and high external quantum efficiency (EQE), features essential for reliable low-light imaging and sensing applications (5). Researchers have also explored the neuromimetic potential of QDs, such as photonic synapses capable of reproducing pupillary and corneal reflexes (6) and CQD sensors that emulate the activity of retinal amacrine cells (7). Similarly, flexible QD detectors have been developed with broad spectral range and adaptability to mechanical deformation, enhancing their potential for wearable or implantable visual prosthetics (8). Hybrid systems combining QDs with metal oxides have further improved visible light detection and spectral selectivity (6). Parallel to material development, machine learning algorithms have been employed to refine QD synthesis, where Gaussian regression and Bayesian neural networks have enabled precise prediction of size-dependent optical outcomes (9). Despite these advancements, a critical research gap remains unaddressed—no study has yet replicated the spectral behavior of human cone photoreceptors using quantum dots.

Human vision depends on three types of cone cells (L, M, and S), each responsive to specific spectral bands corresponding to red, green, and blue light. Conventional optical prosthetic systems rely on RGB photodiodes that approximate these responses through digital computation, often at the cost of bulkiness and high-power consumption. In contrast, carbon quantum dots (CQDs) offer an opportunity to develop biomimetic photodiodes with intrinsic spectral alignment to the human cone sensitivities. Their advantages include low cost, environmental stability, and biocompatibility—attributes particularly relevant for implantable or biologically interfacing devices (10,11). By integrating CQDs into the intrinsic (i) layer of a PIN photodiode, it becomes possible to tailor the spectral absorbance and thus the external quantum efficiency (EQE) to mimic biological vision. The EQE, determined primarily by internal quantum efficiency (IQE) and optical absorbance, can be optimized to exhibit the same spectral distribution as the human cones while maintaining device simplicity (12). Moreover, by incorporating considerations of natural spectral filtering by the human lens and macular pigment, this design aims to achieve a more physiologically accurate optical response (13,14). Therefore, the present research aims to design a carbon quantum dot–based intrinsic photodiode layer that replicates the spectral responses of human cone photoreceptors. The objective is to establish a biocompatible, compact, and energy-efficient optical sensor that reduces dependence on complex post-processing algorithms while moving toward biologically coherent vision restoration and prosthetic applications.

Parallels Between Photoreceptors and Photodiodes

The functional principle of photoreceptors closely parallels that of photodiodes, as both produce an output current proportional to the number of absorbed photons within their linear response range, excluding saturation extremes. Mathematically, this proportionality follows **($I = \eta \cdot q \cdot n/t$)**, where ($\eta$) denotes quantum efficiency, (q) the elementary charge, (n) the number of photons, and (t) time (13). This relation establishes a direct analogy between biological phototransduction and semiconductor photoresponse, providing the foundational concept for developing biomimetic photodiodes.

Synthesis Process Overview

Carbon Quantum Dots (CQDs) were synthesized through a bottom-up hydrothermal method using citric acid as the carbon precursor (14–16). The process involved dissolving the precursor in a solvent, heating under controlled pressure and temperature to induce thermal decomposition, and allowing reactive intermediates to nucleate into stable nanocarbon cores. Surface functionalization occurred simultaneously through the attachment of oxygen- and nitrogen-based moieties, enhancing luminescence and stability. The resulting colloidal solution was purified through centrifugal partition chromatography with a butanol–acetic acid–water mixture (4:1:5) and lyophilized post-spectroscopic verification for storage (17). This synthesis yielded uniformly dispersed, photostable CQDs with consistent particle size distribution suitable for photonic applications.

Optical Analysis: UV–Vis Spectroscopy

The optical characteristics of the CQDs were examined using UV–Vis spectroscopy to determine the absorbance profile across the visible range. This technique measures how Quantum Dots (QDs) absorb light at different wavelengths, extrapolating the values of absorbance across the spectrum. $A = \log_{10}\left(\frac{I_0}{I}\right)$, Where I_0 is the incident light intensity and I is the transmitted light intensity. Measurements adhered to the Beer–Lambert law, **($A = \varepsilon \cdot b \cdot C$)**, where (A) is absorbance, (ε) molar absorptivity, (b) path length, and (C) concentration (18). The observed absorption spectra exhibited size-dependent peaks, indicating that smaller CQDs absorbed at shorter wavelengths, aligning with the theoretical quantum confinement effect. These results confirmed successful control over bandgap tuning through synthesis parameters.

Creation of the Intrinsic Layer

Polymethyl methacrylate (PMMA) was selected as the matrix due to its high optical transparency, dielectric stability, and compatibility with CQD dispersion (19–21). A 40% PMMA–chlorobenzene solution containing CQDs was ultrasonicated to ensure uniform mixing before thermal curing at 80 °C. During solvent evaporation, approximately 60% volumetric shrinkage occurred, effectively increasing CQD concentration by 2.5×, thereby enhancing optical density. The resulting CQD–PMMA composite displayed robust structural integrity and minimal scattering losses. Prior studies have demonstrated PMMA's role in preserving photonic uniformity and enabling flexibility in optoelectronic films (22–24). The fabricated layer was subsequently sectioned to the desired optical thickness, considering Beer–Lambert proportionality to fine-tune absorbance. This method allowed predictable tuning without reliance on spin-coating processes, minimizing fabrication variability.

LMS Quantum Dots

The spectral modeling of cone-like QDs was based on the CIE 2006 colorimetric observer data transformed into LMS (Long, Medium, Short wavelength) cone coordinates (25). Absorbance relationships were derived using the function **($A = \log10(1 / (1 - f(x)/\beta))$)**, where ($f(x)$) represents cone sensitivity and (β) a correction factor ensuring physical validity (13,26). Gaussian regression was applied to smooth the normalized absorbance curves, producing distinct L, M, and S profiles consistent with red, green, and blue cones respectively. The resulting spectra demonstrated that CQD optical tuning could approximate human cone spectral shapes, fulfilling the biomimetic design objective.

Reflection within the Photodiode

Interfacial reflection between PMMA and the silicon substrate was calculated using the Fresnel relation **($R = ((n1 - n2)/(n1 + n2))^2$)** (27). Simulations revealed non-negligible reflectance levels, particularly at the PMMA–Si interface, where differences in refractive index elevated back-reflection. To mitigate interference artifacts and parasitic photocurrent generation, anti-reflective coatings were recommended to stabilize spectral response and preserve external quantum efficiency (28).

IQE Requirements

For biologically faithful spectral replication, the internal quantum efficiency (IQE) must remain consistent across visible wavelengths. Variations in IQE distort the external quantum efficiency (EQE), even if absorbance is appropriately modeled. The present analysis indicated that maintaining near-uniform IQE ensures that EQE preserves the shape of cone spectral sensitivities. This principle supports the integration of stable charge-transport materials in photodiode fabrication to minimize wavelength-dependent recombination losses.

Imperfect Absorption Spectrum

Real CQD absorption curves exhibit secondary peaks and broadened tails due to heterogeneity in particle size and surface states. The study acknowledged that spectral filtering techniques—such as band-pass and notch filters—could be employed to refine the response for specific visual ranges. While not implemented here, such optical engineering strategies remain crucial for optimizing prosthetic photodiode selectivity in future work.

Computational Approach

Machine learning was employed to optimize CQD synthesis by mapping experimental parameters to optical properties. Gaussian regression provided simplified spectral fits, while neural networks correlated synthesis variables (temperature, time, doping ratio) to the Gaussian parameters (μ) and (σ). This predictive framework enabled precise control of target wavelength peaks and bandwidths, supporting reproducibility in spectral design.

I. Spectral Modeling:

Absorption spectra were discretized at 10 nm intervals and modeled as normalized Gaussian distributions to minimize complexity. The fitting accuracy confirmed that most experimental spectra conformed well to Gaussian shapes, validating regression as an effective modeling technique.

II. Neural Network Prediction:

Neural networks trained on the regression outputs demonstrated reliable prediction of synthesis conditions corresponding to desired optical responses. This approach significantly reduced experimental trial time and improved consistency across CQD batches, paving the way for scalable biomimetic photodiode manufacturing.

The findings collectively affirmed that CQD–PMMA composites can replicate the human cone spectral behavior with controllable optical features. Strengths of this study included the integration of synthesis, modeling, and computational optimization in a unified workflow. However, limitations involved the absence of electrical characterization and long-term stability testing. Future investigations should address charge transport efficiency, device durability, and clinical adaptability of such biomimetic systems for prosthetic vision applications.

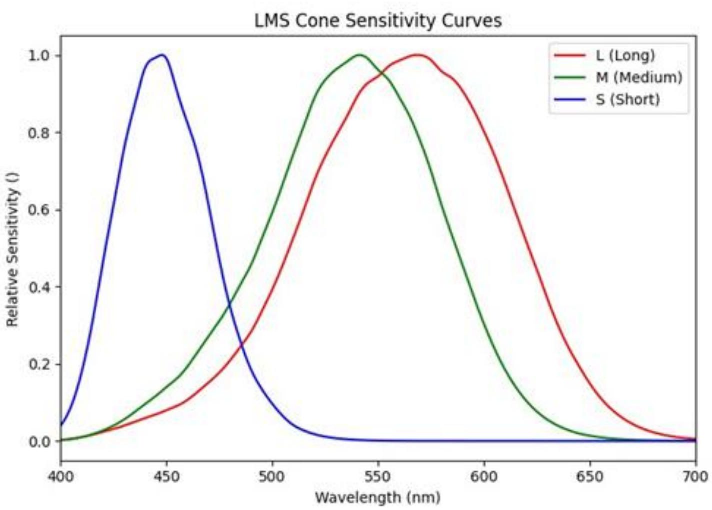

Figure 1 LMS Cone Sensitivity Curves

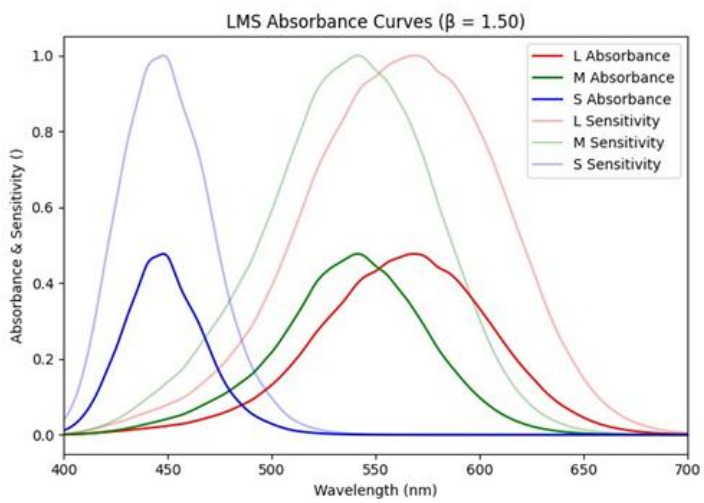

Figure 2 LMS Absorbance Curve (B-150)

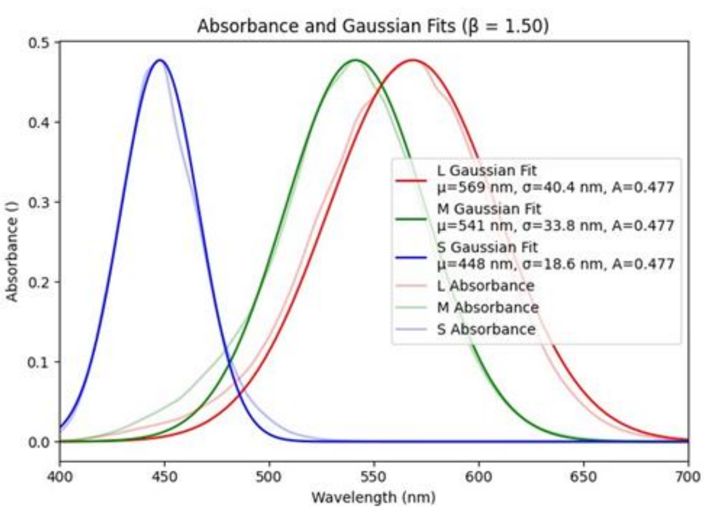

Figure 3 Absorbance and Gaussian Fits (B=1.50)

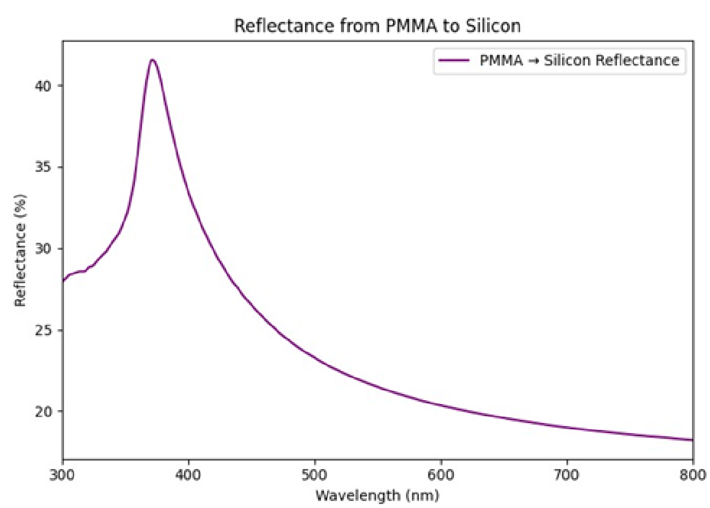

Figure 4 Reflectance from PMMA to Silicon

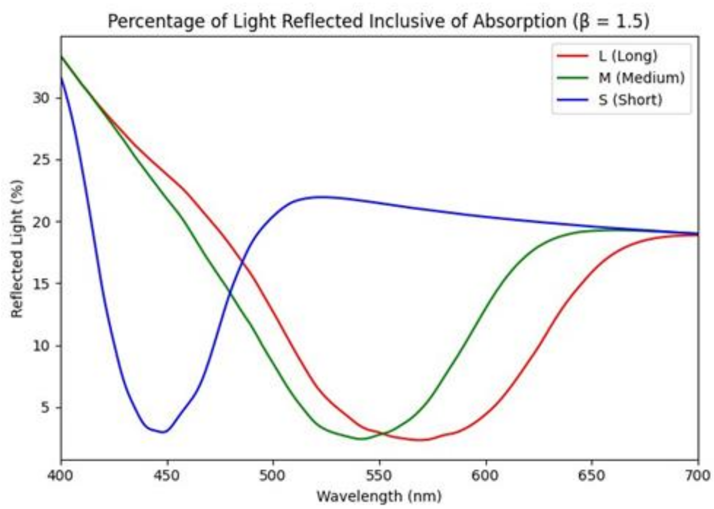

Figure 5 Percentage of Light Reflected Inclusive of Absorption (b=1.5)

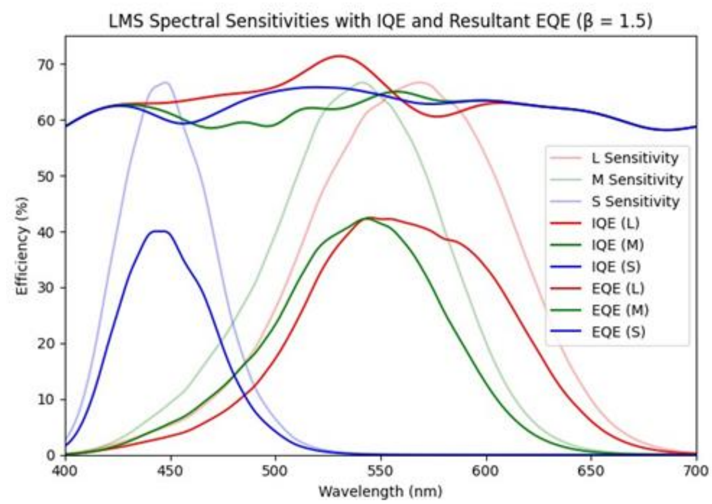

Figure 6 LMS Spectral Sensitivities with IQE and Resultant EQE (b=1.5)

CONCLUSION

This study successfully demonstrated that carbon quantum dots (CQDs), when embedded within a polymethyl methacrylate (PMMA) matrix, can emulate the spectral responses of human cone photoreceptors through precise optical tuning and computational optimization. By integrating synthesis control, spectral modeling, and machine learning–based prediction, the research established a foundation for designing biomimetic photodiodes with biocompatible, cost-effective, and spectrally accurate properties. The findings highlight the potential of CQD-based photonic systems to bridge the gap between biological and artificial vision, offering practical implications for next-generation retinal prostheses and neuromorphic imaging devices. Ultimately, this work contributes to the advancement of bioinspired optoelectronics, paving the way for compact, energy-efficient, and physiologically coherent optical sensors.

AUTHOR CONTRIBUTION

Author	Contribution
Hariz Zoraz Farooq*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Eilaf Azeem	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Muhammad Maroof Atif	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published

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