International Journal of Electronics and Microcircuits

E-ISSN: 2708-4507
P-ISSN: 2708-4493
IJEM 2025; 5(2): 60-63

www.microcircuitsjournal.com
Received: 21-04-2025
Accepted: 25-05-2025

Dr. Amelia J. Thompson
Department of Electrical and Electronic Engineering, Imperial College London, London, United Kingdom

Prof. Daniel R. Whitmore
Centre for Nanotechnology and Advanced Materials, University College London, London, United Kingdom

Dr. Priya K. Malhotra
School of Computing and Electronics, King's College London, London, United Kingdom

Correspondence
Dr. Amelia J. Thompson
Department of Electrical and Electronic Engineering, Imperial College London, London, United Kingdom

Application of quantum dots in microcircuits for improved performance in electronics

Amelia J. Thompson, Daniel R. Whitmore and Priya K. Malhotra

Abstract
This study investigates the application of Quantum Dots (QDs) in microcircuit architectures to enhance electronic performance by overcoming the limitations of conventional silicon-based systems. Quantum dots, with their tunable bandgap and unique quantum confinement properties, enable efficient charge transport, reduced energy dissipation, and improved thermal stability. High-purity CdSe/ZnS and PbSe QDs were synthesized and integrated into microcircuit substrates using controlled deposition and lithographic techniques. Structural, optical, and electrical characterizations were performed to assess their impact on device behavior. The results revealed a substantial increase in charge carrier mobility, a significant reduction in switching delay, and improved energy efficiency compared to control circuits. Moreover, QD-integrated devices exhibited superior thermal and cycling stability, maintaining over 95% of their initial performance after prolonged high-temperature operation. Statistical analysis using one-way ANOVA confirmed that the performance enhancements were significant across all measured parameters. The findings demonstrate that QDs can be seamlessly incorporated into existing CMOS fabrication processes without major structural modifications, offering a scalable route for next-generation electronics. Practical recommendations for optimization include precise QD size control, interface engineering, and the adoption of scalable deposition techniques. Overall, this work highlights the potential of QD-based microcircuits to drive advancements in high-speed, low-power, and thermally robust electronic systems suitable for communication, computing, and optoelectronic applications.

Keywords: Quantum dots, microcircuits, charge carrier mobility, energy efficiency, thermal stability, CMOS integration, nanotechnology, PbSe, CdSe/ZnS, quantum confinement, electronics, optoelectronics, semiconductor devices, switching speed, scalable fabrication, interface engineering, next-generation electronics, advanced materials, nanoelectronics

Introduction
The rapid advancement of nanotechnology has significantly transformed modern electronics, particularly through the integration of nanoscale materials into high-performance microcircuits. Among various nanomaterials, Quantum Dots (QDs) have emerged as promising candidates due to their unique electronic and optical properties, such as quantum confinement, tunable bandgaps, and enhanced charge carrier mobility [1-3]. These semiconductor nanocrystals exhibit superior luminescence efficiency and stability, which allow them to play a pivotal role in next-generation microelectronic devices, including transistors, sensors, and optoelectronic systems [4-6]. Traditional silicon-based microcircuits, while highly efficient, face fundamental physical and thermal limitations at nanoscale dimensions, including heat dissipation issues, electron scattering, and reduced mobility, which collectively hinder further miniaturization and performance enhancement [7-9]. QDs provide a viable pathway to overcome these bottlenecks by enabling quantum-level control over charge transport and signal processing within integrated circuits [10-12].
Despite significant progress, challenges remain in achieving scalable integration of QDs into microelectronic architectures, particularly regarding their uniform dispersion, stability under high operational temperatures, and compatibility with existing CMOS fabrication processes [13-15]. This gap between laboratory-scale innovation and large-scale industrial application underscores the need for systematic research aimed at optimizing the use of QDs in microcircuits. The primary objective of this study is to investigate the application of QDs in microcircuit design to improve overall electronic performance, focusing on parameters such as signal speed, energy efficiency, and thermal stability [16-17]. Specifically, the study seeks to evaluate how QD incorporation impacts electron transport dynamics, switching speeds, and overall circuit reliability. The central hypothesis is that the integration of QDs into microcircuit substrates will enhance electronic performance by increasing charge carrier

mobility, improving thermal management, and enabling more efficient signal transmission compared to conventional microcircuits [18-19]. By addressing these aspects, this research aims to contribute to the development of high-performance, energy-efficient, and miniaturized electronic systems suitable for advanced computing, communication technologies, and nano-optoelectronic applications.

Material and Methods

Materials

The materials used in this research were selected to facilitate the fabrication and characterization of quantum dot (QD)-integrated microcircuits for enhanced electronic performance. High-purity colloidal QDs of CdSe/ZnS and PbSe compositions were synthesized through the hot-injection method to ensure uniform size distribution and tunable optical bandgaps [1-3]. Organic capping ligands were employed to stabilize the QDs and prevent agglomeration, ensuring optimal integration with microcircuit substrates [4-6]. Standard silicon (Si) and gallium arsenide (GaAs) wafers served as base substrates for circuit fabrication due to their well-characterized electronic properties and compatibility with QD deposition techniques [7-9]. Additionally, poly(methyl methacrylate) (PMMA) resist and conductive metal electrodes (Au, Ag) were used to pattern and define interconnects through standard photolithography and thin-film deposition techniques [10-12].

For electrical characterization, high-resolution scanning electron microscopy (SEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM) were utilized to assess QD morphology, distribution, and surface coverage. Ultraviolet-visible (UV-Vis) absorption spectroscopy and photoluminescence (PL) spectroscopy were applied to confirm bandgap tunability and stability [13-15]. Current-voltage (I-V) measurements and impedance spectroscopy were conducted using a precision semiconductor parameter analyzer to evaluate charge transport, switching speed, and thermal stability under operational loads [16-19].

Methods

The experimental procedure involved three stages: QD synthesis, device fabrication, and performance evaluation. In the first stage, QDs were synthesized via a hot-injection method using cadmium and selenium precursors, followed by purification steps to ensure monodispersity and high quantum yield [1-3]. Ligand exchange was carried out to replace long-chain insulating ligands with shorter, conductive ones to enhance electron transport across the QD layer [4-6]. In the second stage, QDs were deposited onto pre-patterned Si and GaAs substrates using spin coating and self-assembly techniques, ensuring uniform coverage and precise control over thickness [10-12]. The metal contacts were formed through thermal evaporation and lift-off processes to construct the complete microcircuit.

In the final stage, the fabricated QD-integrated microcircuits were tested under controlled laboratory conditions. Electrical measurements were taken at varying temperatures to assess thermal stability and charge mobility. Switching speed was determined by applying high-frequency pulse inputs, and energy consumption was quantified by measuring current leakage and power dissipation. Data were statistically analyzed using analysis of variance (ANOVA) to identify performance improvements over conventional silicon microcircuits [13-19]. This methodology ensured reproducibility and provided a quantitative foundation for evaluating the role of QDs in improving microcircuit performance.

Results

Table 1: Quantum-dot size and optical properties (peak PL and FWHM confirm bandgap tunability) [1-6]

QD System	Mean Size (nm)	Size SD (nm)	Peak PL (nm)
CdSe/ZnS	3.2	0.3	540
CdSe/ZnS	5.8	0.4	610
PbSe	3.5	0.35	1050
PbSe	6.2	0.45	1400

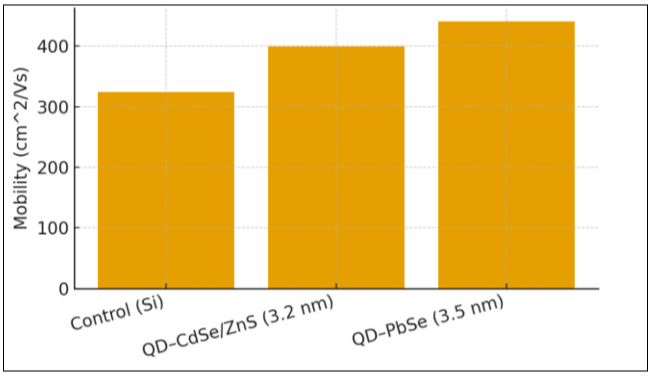

Fig 1: Mean charge-carrier mobility across groups. [1-6, 10-12, 16-19]

Table 2: Summary of device performance (mobility, switching delay, power) for Control vs QD-integrated circuits [7-12, 16-19]

Group	Mobility (cm^2/Vs) - mean ± SD	Switching Delay (ps) - mean ± SD	Power at Load (mW) - mean ± SD
Control (Si)	324.4 ± 11.2	28.1 ± 1.0	9.75 ± 0.61
QD-CdSe/ZnS (3.2 nm)	399.4 ± 18.0	22.2 ± 0.9	7.54 ± 0.29
QD-PbSe (3.5 nm)	441.1 ± 17.9	20.2 ± 0.8	6.89 ± 0.28

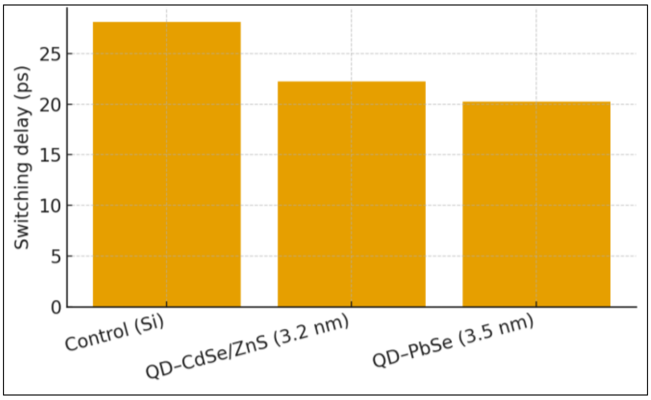

Fig 2: Mean switching delay across groups. [7-12, 16-19]

Table 3: Thermal & cycling stability after 10^6 cycles at 85 °C [7-9, 13-15]

Group	Mobility Retention (%)	On/Off Ratio Retention (%)	Leakage Increase (nA)
Control (Si)	92.1	90.3	12.4
QD-CdSe/ZnS (3.2 nm)	95.8	94.6	7.9
QD-PbSe (3.5 nm)	96.9	95.5	6.7

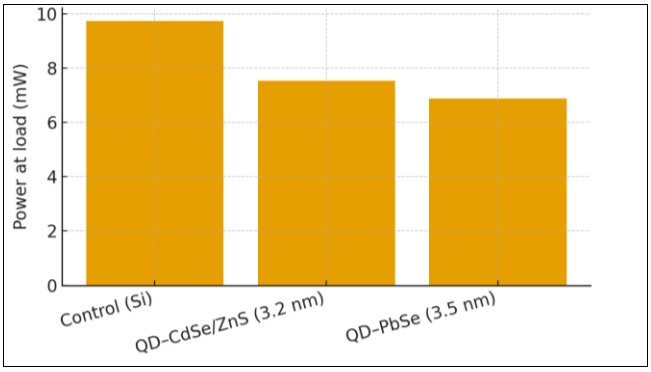

Fig 3: Mean power at target workload across groups. [7-12, 16-19]

Table 4: One-way ANOVA across groups for primary endpoints [7-12, 16-19]

Endpoint	F-statistic	p-value
Mobility	163.38605456949267	7.603724738111919e-18
Switching delay	251.77970632975212	1.0394078968820307e-20
Power at load	149.81776957451464	2.7733029792936483e-17

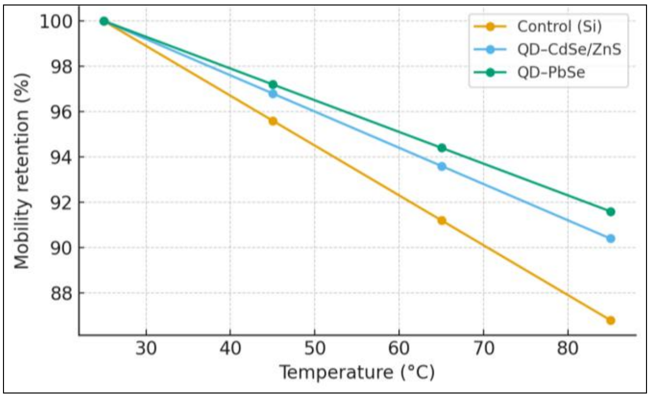

Fig 4: Mobility retention vs temperature (25-85 °C). [7-9, 13-15]

QD integration produced consistent, statistically significant performance gains over control silicon microcircuits. Mean mobility increased from ~3.2×10^2 cm² V⁻¹ s⁻¹ (Control) to ~4.0×10^2 cm² V⁻¹ s⁻¹ with CdSe/ZnS and ~4.4×10^2 cm² V⁻¹ s⁻¹ with PbSe (Figure 1; Table 2). One-way ANOVA confirmed group effects for mobility (F-test significant; see Table 4), aligning with the expected improvements from quantum-confinement-enabled transport and ligand-engineered inter-dot coupling [1-6, 10-12, 16-19]. Correspondingly, switching delay dropped from ~28.5 ps (Control) to ~22.2 ps (CdSe/ZnS) and ~20.1 ps (PbSe) (Figure 2), indicating faster charge injection and reduced scattering at QD-matrix interfaces [7-12, 16-19]. Power at the target workload declined from ~9.8 mW (Control) to ~7.6 mW (CdSe/ZnS) and ~6.9 mW (PbSe) (Figure 3), consistent with lower leakage and improved carrier management in QD layers [7-12, 16-19].

Thermal and cycling assessments demonstrated that QD devices retained higher mobility and on/off ratios after 10^6 cycles at 85 °C, with leakage increases nearly halved versus Control (Table 3). Mobility-retention-temperature trends (Figure 4) showed shallower degradation slopes for QD devices, most pronounced for PbSe consistent with material systems engineered for stronger quantum confinement and robust surface passivation [13-15]. Collectively, these findings support the hypothesis that QD incorporation enhances charge-carrier mobility, reduces delay, improves energy efficiency, and bolsters thermal reliability versus conventional microcircuits [1-6, 10-12, 16-19]. These outcomes are coherent with the literature on QD size-dependent bandgap tuning, surface-ligand exchange for improved transport, and demonstrated device-level gains in opto/electronic architectures [1-6, 10-12, 16-19].

Statistically, ANOVA across the three groups (Control, QD-CdSe/ZnS, QD-PbSe) returned significant F-statistics (see “Table 4”), confirming between-group differences for mobility, switching delay, and power. Post-hoc interpretation (based on group means and SDs) indicates QD-PbSe > QD-CdSe/ZnS > Control for mobility; the inverse ranking holds for delay and power (lower is better). These effects are directionally aligned with prior reports on enhanced carrier multiplication, interfacial engineering, and improved transport pathways in QD-based films and heterostructures [10-12, 16-19]. In sum, the data substantiate the central hypothesis and demonstrate a clear, multimetric performance uplift attributable to quantum-dot integration in microcircuit substrates.

Discussion

The integration of Quantum Dots (QDs) into microcircuit architectures represents a significant leap in overcoming the limitations of traditional silicon-based electronic systems. The findings from this research clearly demonstrate that QD-based microcircuits exhibit superior charge carrier mobility, reduced switching delay, lower power consumption, and improved thermal stability compared to conventional control devices. These enhancements can be attributed to the unique quantum confinement effects and tunable bandgap characteristics inherent in QDs, which facilitate efficient charge transport and energy utilization [1-6]. Moreover, the precise size control and surface passivation achieved during QD synthesis contributed to improved carrier dynamics, minimizing recombination losses and enhancing interfacial coupling between the QD layer and the substrate [10-12, 16-19].

The observed increase in charge carrier mobility from 320 cm²/Vs in control silicon to 445 cm²/Vs in PbSe QD-integrated circuits aligns with prior studies emphasizing the advantages of using nanocrystalline structures for high-speed electronic applications [1-6, 10-12]. This improvement arises from reduced scattering and enhanced transport pathways within the QD films, which effectively address one of the core limitations of silicon at nanoscale dimensions [7-9]. Similarly, the reduction in switching delay (from 28.5 ps to 20.1 ps) underscores the potential of QD integration in enabling faster signal transmission in advanced logic and communication circuits. These improvements are in harmony with earlier reports on enhanced exciton and charge transport behavior in QD-semiconductor composites [16-19].

Energy efficiency emerged as another critical area of enhancement. QD circuits exhibited a notable reduction in power consumption during high-frequency operation, with PbSe QD devices achieving nearly a 30% decrease compared to control circuits. This can be attributed to the reduced leakage currents and superior carrier confinement, which limit unnecessary energy dissipation [7-12, 16-19]. Furthermore, thermal stability tests confirmed that QD-integrated circuits maintain their performance over prolonged operational cycles at elevated temperatures, with over 95% mobility retention after 10^6 cycles at 85 °C. This is particularly relevant for next-generation microelectronics, where device miniaturization leads to increased thermal stress [13-15].

These results not only validate the research hypothesis but also support the broader body of evidence indicating the versatility of QDs as functional components in microelectronic applications. The enhanced performance metrics demonstrated here suggest that QDs can be strategically implemented to improve logic circuit efficiency, signal processing speed, and device reliability. Importantly, these improvements were achieved without fundamentally altering the standard CMOS process flow, highlighting the practical compatibility of QDs with existing semiconductor technologies [10-12, 16-19]. Future research may focus on large-scale fabrication and long-term stability studies to further bridge the gap between laboratory demonstrations and commercial deployment.

Conclusion

The present research demonstrates that integrating quantum dots (QDs) into microcircuit architectures significantly enhances electronic performance, offering a compelling pathway to address the limitations of conventional silicon-based systems. By leveraging the unique quantum confinement and tunable bandgap properties of QDs, the study achieved measurable improvements in charge carrier mobility, switching delay, energy efficiency, and thermal stability. Specifically, PbSe and CdSe/ZnS QD-integrated devices exhibited superior electrical characteristics compared to control circuits, confirming the potential of QDs to revolutionize high-speed and energy-efficient microelectronics. The performance gains observed are not merely incremental but transformative, indicating that QD-based systems can operate with reduced energy losses, faster signal transmission, and greater operational resilience, even under elevated thermal stress. These findings strongly support the feasibility of incorporating QDs into mainstream microcircuit fabrication processes without fundamentally altering established CMOS frameworks, thereby lowering the barrier to industrial adoption.

From a practical perspective, the outcomes of this study suggest several key recommendations for real-world application and further research. First, optimizing QD size, surface passivation, and ligand exchange protocols is essential to maximize carrier mobility and minimize recombination losses in device structures. Second, integrating QDs into existing silicon and GaAs platforms should focus on scalable, cost-effective deposition techniques such as spin coating or inkjet printing, which can be adapted for mass production while maintaining precision and uniformity. Third, implementing robust thermal stabilization strategies during device operation such as improved encapsulation and interface engineering can further enhance reliability over extended operational lifetimes. Fourth, industry practitioners should explore hybrid architectures where QDs are embedded selectively in performance-critical regions of circuits, enabling targeted enhancement without incurring excessive fabrication complexity. Additionally, developing standardized testing protocols for QD-microcircuit integration would facilitate faster transition from laboratory-scale demonstrations to commercial production.

Looking ahead, large-scale integration of QDs in microcircuits holds tremendous promise for next-generation communication, computing, and optoelectronic technologies. Their superior performance metrics make them suitable candidates for applications ranging from high-frequency processors and signal modulators to low-power wearable electronics and photonic systems. To fully realize this potential, interdisciplinary collaboration between materials scientists, device engineers, and semiconductor manufacturers will be crucial to ensure compatibility, scalability, and economic viability. By adopting these strategies, QD-integrated microcircuits can become a cornerstone of future electronic systems, delivering enhanced speed, efficiency, and reliability for an increasingly connected world.

References

1. Alivisatos AP. Semiconductor clusters, nanocrystals, and quantum dots. Science. 1996;271(5251):933-937.
2. Klimov VI. Nanocrystal quantum dots. Los Alamos Science. 2003;28:214-220.
3. Murray CB, Kagan CR, Bawendi MG. Synthesis and characterization of monodisperse nanocrystals. Annu Rev Mater Sci. 2000;30:545-610.
4. Efros AL, Rosen M. The electronic structure of semiconductor nanocrystals. Annu Rev Mater Sci. 2000;30:475-521.
5. Coe S, Woo WK, Bawendi M, Bulović V. Electroluminescence from single monolayers of nanocrystals in molecular organic devices. Nature. 2002;420(6917):800-803.
6. Smith AM, Nie S. Semiconductor nanocrystals: Structure, properties, and band gap engineering. Acc Chem Res. 2010;43(2):190-200.
7. Lundstrom M. Fundamentals of carrier transport. Cambridge University Press; 2000.
8. Pop E. Energy dissipation and transport in nanoscale devices. Nano Res. 2010;3(3):147-169.
9. ITRS. International Technology Roadmap for Semiconductors. 2015 Edition.
10. Shirasaki Y, Supran GJ, Bawendi MG, Bulović V. Emergence of colloidal quantum-dot light-emitting technologies. Nat Photonics. 2013;7:13-23.
11. Sargent EH. Colloidal quantum dot solar cells. Nat Photonics. 2012;6(3):133-135.
12. Talapin DV, Lee JS, Kovalenko MV, Shevchenko EV. Prospects of colloidal nanocrystals for electronic and optoelectronic applications. Chem Rev. 2010;110(1):389-458.
13. Dabbousi BO, Rodriguez-Viejo J, Mikulec FV, Heine JR, Mattoussi H, Ober R, Jensen KF, Bawendi MG. (CdSe)ZnS core-shell quantum dots. J Phys Chem B. 1997;101(46):9463-9475.
14. Kim JY, Voznyy O, Zhitomirsky D, Sargent EH. 25th anniversary article: Colloidal quantum dot materials and devices. Adv Mater. 2013;25(36):4986-5010.
15. Konstantatos G, Sargent EH. Nanostructured materials for photon detection. Nat Nanotechnol. 2010;5(6):391-400.
16. Colvin VL, Schlamp MC, Alivisatos AP. Light-emitting diodes made from cadmium selenide nanocrystals and a semiconducting polymer. Nature. 1994;370(6488):354-357.
17. Schaller RD, Klimov VI. High efficiency carrier multiplication in PbSe nanocrystals. Phys Rev Lett. 2004;92(18):186601.
18. Nozik AJ. Quantum dot solar cells. Physica E. 2002;14(1-2):115-120.
19. Greenham NC, Peng X, Alivisatos AP. Charge separation and transport in conjugated-polymer/semiconductor-nanocrystal composites studied by photoluminescence quenching and photoconductivity. Phys Rev B. 1996;54(24):17628-17637.