DOI: 10.5281/zenodo.15955969

Research Article

Improving Characterization Methods for Semiconductor Quantum Dot Using Fuzzy Logic Based-Controller

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Cite as:
Ogharandukun, M., Nwagu, C. C., Ogbuokebe, S. K. & Ngang, N. B. (2025). Improving Characterization Methods for Semiconductor Quantum Dot Using Fuzzy Logic Based-Controller. *International Journal of Computational Mechanics and Materials, 6(1), 1-14.* https://doi.org/10.5281/zenodo.15955969

Abstract

Businesses that rely solely on semiconductors face severe challenges due to various factors degrading semiconductor quality. Primary issues include inconsistent synthesis conditions, material impurities, surface defects, passivation problems, inaccurate characterization methods, batch-to-batch production inconsistencies, and degradation over time. To overcome these issues, improved characterization methods for semiconductor quantum dots are introduced by integrating a fuzzy logic–based controller. The approach begins by identifying and characterizing the root causes of poor semiconductor Quantum dot performance. A SIMULINK model is designed for the characterization process, alongside another model for implementing the fuzzy logic controller. An algorithm is developed to execute these processes and enforce the controller's rule set, which aims to minimize defects and inconsistencies in the quantum dots. The system is then validated by comparing the performance of the conventional process with that achieved using the fuzzy logic controller. Results indicate that inconsistent synthesis conditions, originally contributing 30% to poor characterization, were reduced to 27.05% with the fuzzy controller, representing an enhancement of 2.95%. Similarly, the issue of inadequate control of quantum dot size, responsible for a 15% performance deterioration, improved to 13.53% upon fuzzy controller integration. Additionally, inconsistent batch-to-batch production, which accounted for 5% of the issues, was lowered to 4.508%. Overall, the fuzzy logic–based controller yielded an improvement of 0.492% in the characterization methods. This study demonstrates that incorporating fuzzy logic can effectively mitigate several critical causes of semiconductor quantum dot degradation, thereby enhancing performance and reliability in semiconductor-dependent operations.

Keywords: Characterization Methods; Semiconductor Quantum Dot; Fuzzy Logic Based-Controller; SIMULINK Model

Introduction

Semiconductor quantum dots (QDs) are nanoscale materials characterized by their distinctive optical and electronic behaviors, which arise from the quantum confinement of charge carriers (Alivisatos, 1996). These properties have positioned QDs as promising candidates for various applications, including optoelectronics, biological imaging, and quantum computing (Chen, Wang, & Liu, 2018; Klimov, 2003). Effective utilization of QDs in these domains necessitates accurate characterization techniques to understand and control their behavior.

Traditional QD characterization methods, such as photoluminescence (PL) and absorption spectroscopy, allow for evaluating size distribution, quantum yield, and energy bandgaps. Imaging tools like scanning electron microscopy (SEM) and transmission electron microscopy (TEM) provide atomic-level structural detail (Murray, Kagan, & Bawendi, 1993). However, these conventional methods can be limited by high costs, slow processing times, and sensitivity to environmental variables, making them less effective for real-time or adaptive monitoring (Shi, Liu, & Li, 2020).

In response to these challenges, fuzzy logic-based controllers (FLCs) have emerged as powerful alternatives. Rooted in fuzzy set theory (Zadeh, 1973, 1996), FLCs are particularly suited to systems characterized by uncertainty and imprecision. These systems operate using linguistic rules rather than binary logic, allowing them to manage vague or incomplete data while maintaining robust performance (Ross, 2010; Sivanandam, Sumathi, & Deepa, 2007). When applied to QD characterization, FLCs can enhance processes such as temperature and pressure regulation during synthesis, thereby ensuring better control of QD size, shape, and optical properties (Shi et al., 2020).

Furthermore, the integration of artificial intelligence (AI) and machine learning (ML) models—such as artificial neural networks (ANNs) and support vector machines (SVMs)—has further improved characterization accuracy, offering predictive capabilities and adaptability in dynamic environments (Ogharandukun & Ngang, 2025; Nwagu, Ngang, & Ogharandukun, 2025). These intelligent systems reduce dependence on human intervention, minimize error, and enhance the scalability of QD production.

Overall, the synergy between fuzzy logic-based control systems and advanced characterization techniques represents a significant advancement in QD technology. As applications of QDs continue to grow, integrating intelligent, adaptive systems will be crucial in addressing existing limitations and enabling real-time, precise, and scalable characterization (Ogharandukun, Nwagu, & Ngang, 2025; Ngang, Ogharandukun, & Nwagu, 2025).

Methodology

Characterizing and establishing the causes of poor Semiconductor Quantum Dot

Table 1: Characterized and established Causes of Poor Semiconductor Quantum Dots and Estimated Percentages

Cause	*Description*	*Estimated Percentage Contribution to Poor QDs*
Inconsistent Synthesis Conditions	Variations in temperature, pressure, and reaction time lead to non-uniformity in QD size and shape.	30%
Impurities in Materials	Contaminants in raw materials negatively impact the optical and electronic properties of QDs.	15%
Inadequate Control of QD Size	Poor control of size during synthesis affects the bandgap and emission wavelength of QDs, reducing their effectiveness.	20%
Environmental Factors	Exposure to air, moisture, and temperature variations degrades QDs, causing oxidation and diminishing optical performance.	10%
Surface Defects and Passivation Issues	Defects or improper passivation cause non-radiative recombination centers, lowering quantum yield and overall efficiency.	10%
Inaccurate Characterization Methods	Traditional methods not suited for real-time monitoring can result in mischaracterization, leading to poor quality control.	5%
Inconsistent Batch-to-Batch Production	Variations in process conditions or equipment performance between batches result in inconsistent QD quality.	5%
Degradation Over Time	Long-term exposure to light or stress factors causes aging and degradation of QD properties, affecting their performance.	5%

Total Contribution to Poor Semiconductor Quantum Dots: 100%

1. Inconsistent Synthesis Conditions: Variations in temperature, pressure, and reaction time during the synthesis of quantum dots (QDs) can lead to non-uniformity in size and shape. These inconsistencies directly affect the optical and electronic properties of the QDs, leading to poor performance.
2. Impurities in Materials: The presence of impurities or contaminants in the raw materials used for QD synthesis can degrade the quality of the final product. Even trace amounts of impurities can affect the optical properties and stability of the QDs.
3. Inadequate Control of Quantum Dot Size: The size of quantum dots plays a critical role in determining their bandgap and emission wavelength. Poor control over the size distribution during synthesis can result in quantum dots with unpredictable and inconsistent properties.
4. Environmental Factors: Exposure to air, moisture, or temperature fluctuations can degrade the surface of QDs, causing oxidation or other chemical changes. This leads to diminished optical performance and a shorter lifespan of the quantum dots.
5. Surface Defects and Passivation Issues: Surface defects or improper passivation (the process of coating QDs to protect them from environmental degradation) can result in non-radiative recombination centers. This reduces the quantum yield, making the QDs less efficient.
6. Inaccurate Characterization Methods: Using traditional characterization techniques that are not adaptable to real-time monitoring or sensitive to environmental noise can result in mischaracterized quantum dots. This can lead to poor-quality control and suboptimal QDs for their intended applications.
7. Inconsistent Batch-to-Batch Production: In large-scale production, maintaining consistency between batches is crucial. Variations in process conditions, precursor quality, or equipment performance can lead to significant differences in QD quality from one batch to another.
8. Degradation Over Time: Semiconductor quantum dots are prone to degradation over time, particularly under prolonged exposure to light or other stress factors. This aging process can cause a decline in their optical and electronic performance, leading to poor-quality QDs.

Designing a Conventional SIMULINK Model for Characterization Methods for Semiconductor Quantum Dot

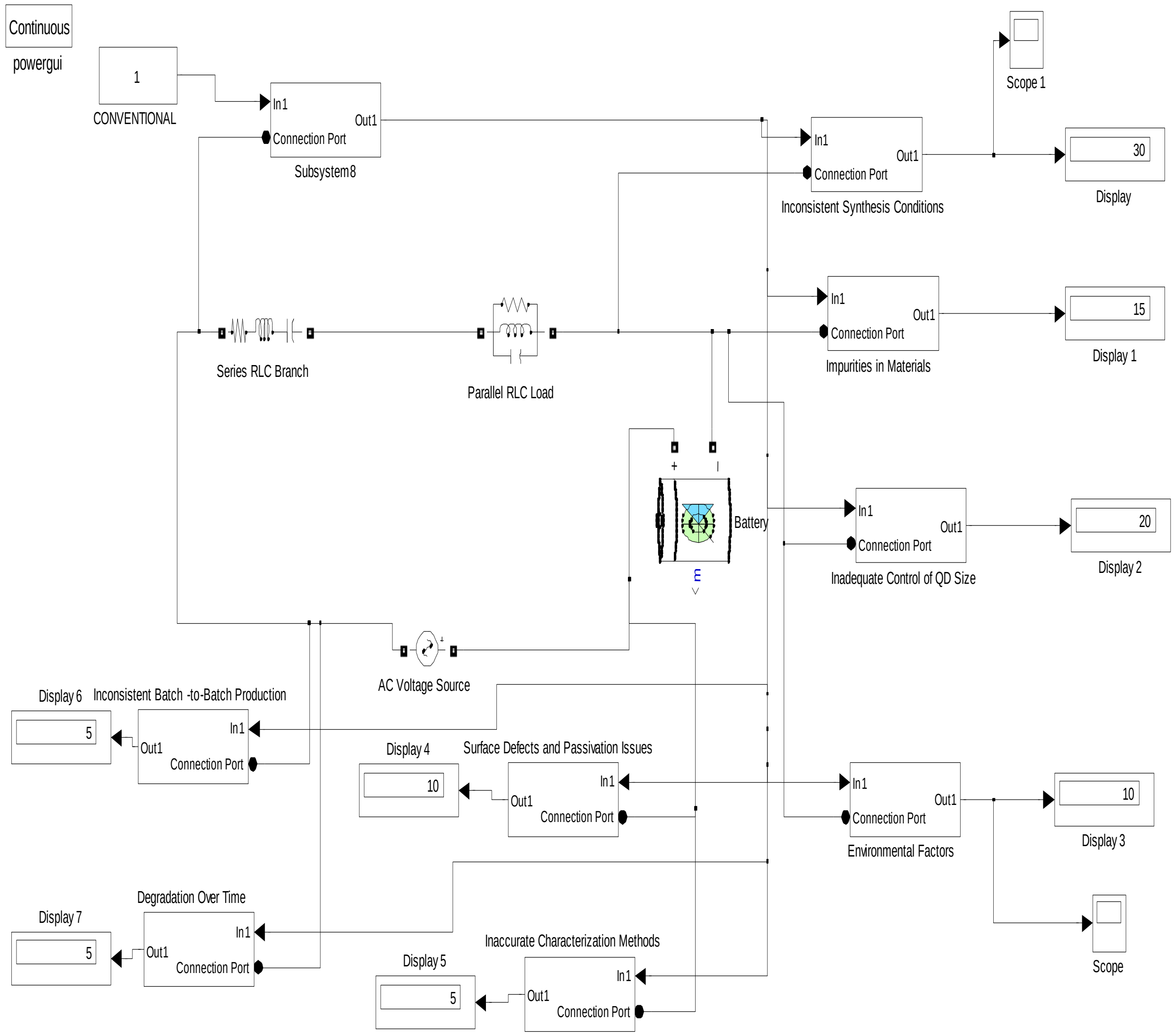

Figure 1: Designed Conventional SIMULINK model for characterization methods for semiconductor quantum Dot

Developing a Fuzzy Based Controller Rule that will minimize the causes of Poor Semiconductor Quantum Dot thereby enhancing its Performance

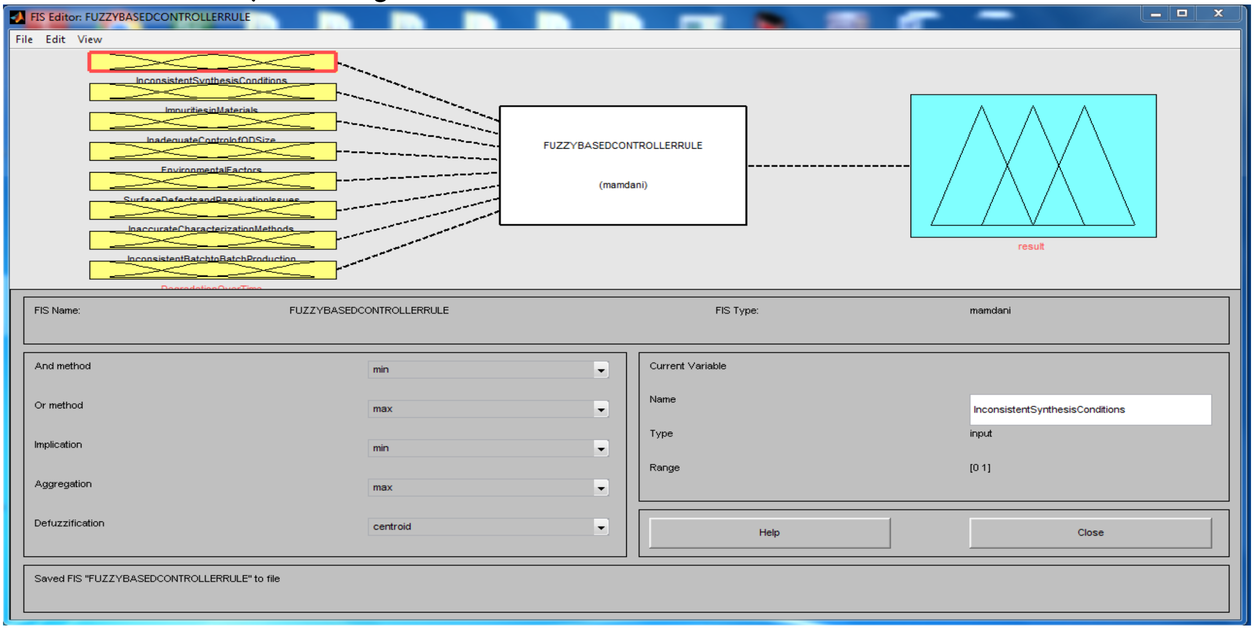

Figure 2. Developed Fuzzy Inference System (FIS) that will minimize the causes of poor Semiconductor Quantum Dot thereby enhancing its performance

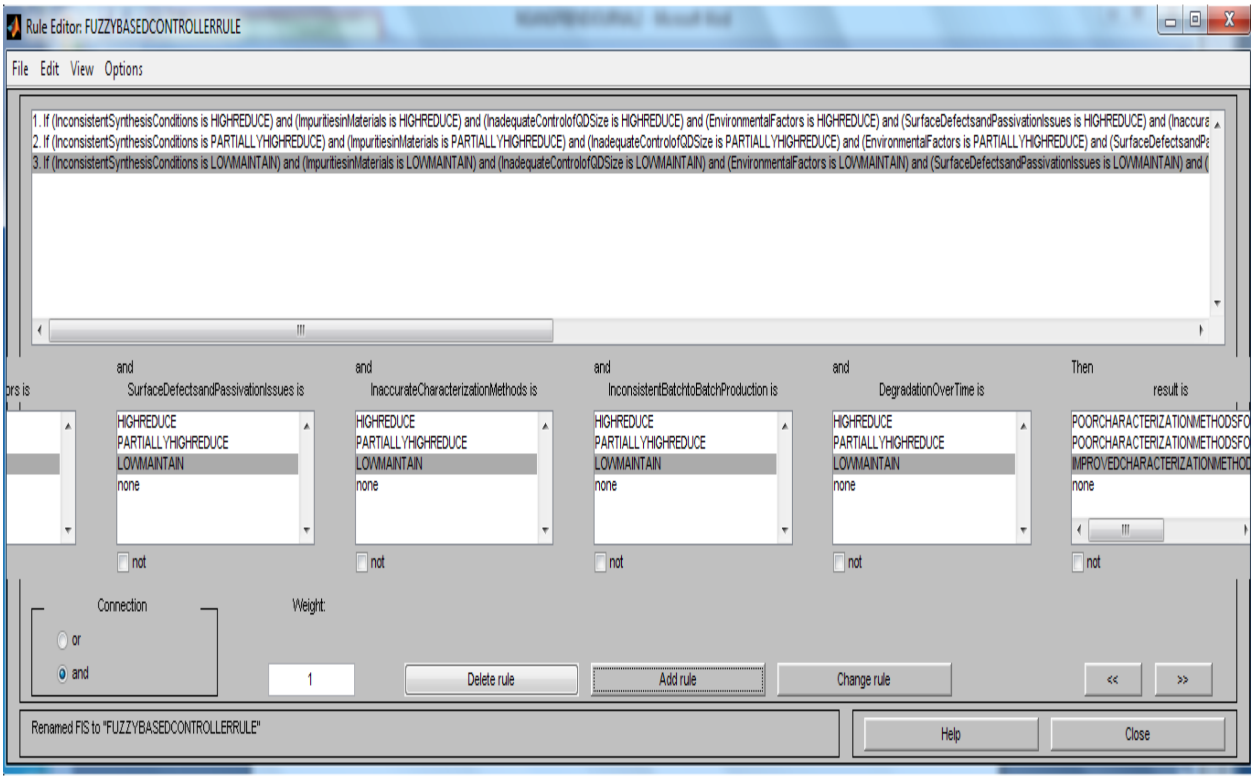

Figure 3: Developed fuzzy based controller rule that will minimize the causes of poor Semiconductor Quantum Dot thereby enhancing its performance

The three fuzzy based controller rules that will minimize the causes of poor Semiconductor Quantum Dot thereby enhancing its performance are as enumerated were comprehensively enumerated in Table 2.

Table 2: Comprehensive developed fuzzy based controller rule that will minimize the causes of poor SEMICONDUCTOR QUANTUM DOT thereby enhancing its performance

1	If inconsistent synthesis conditions is high reduce	and impurities in materials is high reduce	And environmental factors is high reduce	and surface defects and passivation issues is high reduce	and inaccurate characterization methods is high reduce	and inconsistent batch-to-batch production is high reduce	And degradation over time is high reduce	then result is poor characterization methods for semiconductor quantum dot
2	If inconsistent synthesis conditions is partiallyhigh reduce	and impurities in materials is partially high reduce	and environmental factors is partially high reduce	and surface defects and passivation issues is partially high reduce	and inaccurate characterization methods is partially high reduce	and inconsistent batch-to-batch production is partially high reduce	And degradation over time is partially high reduce	then result is poor characterization methods for semiconductor quantum dot
3	If inconsistent synthesis conditions is low maintain	and impurities in materials is low maintain	and environmental factors is low maintain	and surface defects and passivation issues is high reduce	and inaccurate characterization methods is low maintain	and inconsistent batch-to-batch production is low maintain	And degradation over time is low maintain	then result is improved characterization methods for semiconductor quantum dot

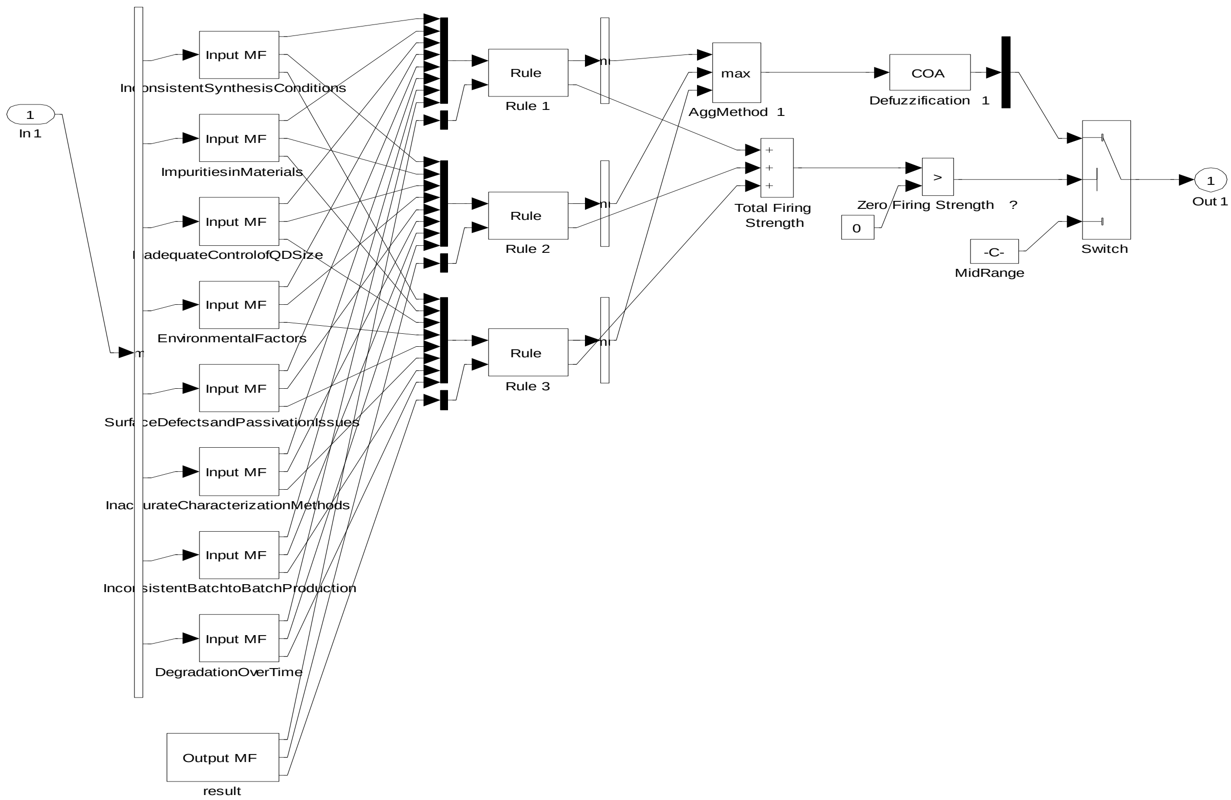

Figure 4: Result when the three rules are in operation

Designing a SIMULINK Model for Fuzzy Based Controller

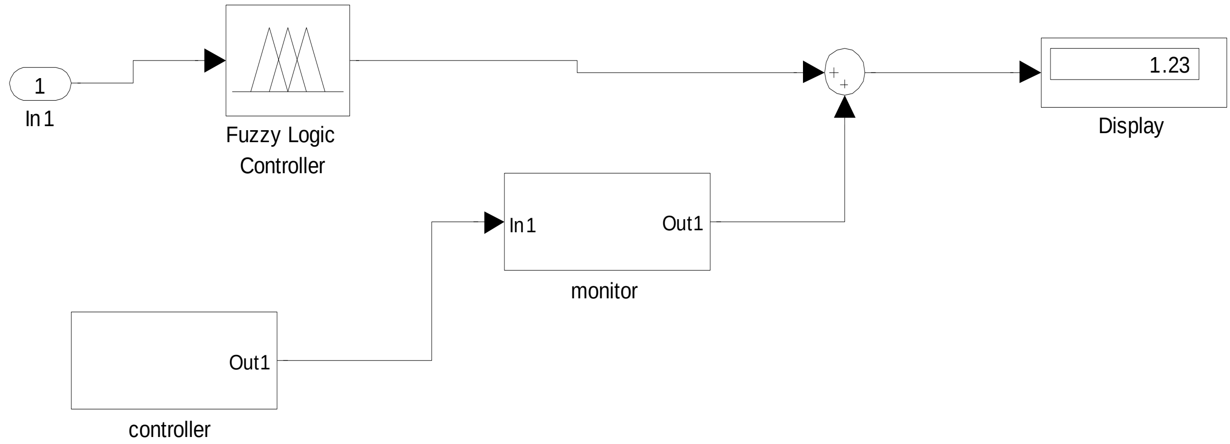

Figure 5. Designed SIMULINK model for fuzzy based controller

This will be integrated in the designed Conventional SIMULINK model for characterization methods for semiconductor quantum dot

Developing an algorithm that will implement the process

1. Characterize and establish the causes of poor semiconductor quantum dot
2. Identify inconsistent synthesis conditions
3. Identify impurities in materials
4. identify surface defects and passivation issues
5. identify inaccurate characterization methods
6. identify inconsistent batch-to-batch production
7. identify degradation over time
8. Design a SIMULINK model for characterization methods for semiconductor quantum dot and integrate 2 through 7.
9. Develop a fuzzy based controller rule that will minimize the causes of poor SEMICONDUCTOR QUANTUM DOT thereby enhancing its performance.
10. Design a SIMULINK model for fuzzy based controller
11. Integrate 9 and 10
12. Integrate 11 and 8
13. Do the causes of poor semiconductor quantum dot reduced?
14. If NO go to 12
15. If YES go to 16
16. Improved characterization methods for semiconductor quantum dot
17. Stop
18. End

Designing a SIMULINK model for characterization methods for semiconductor quantum dot using fuzzy logic-based controller

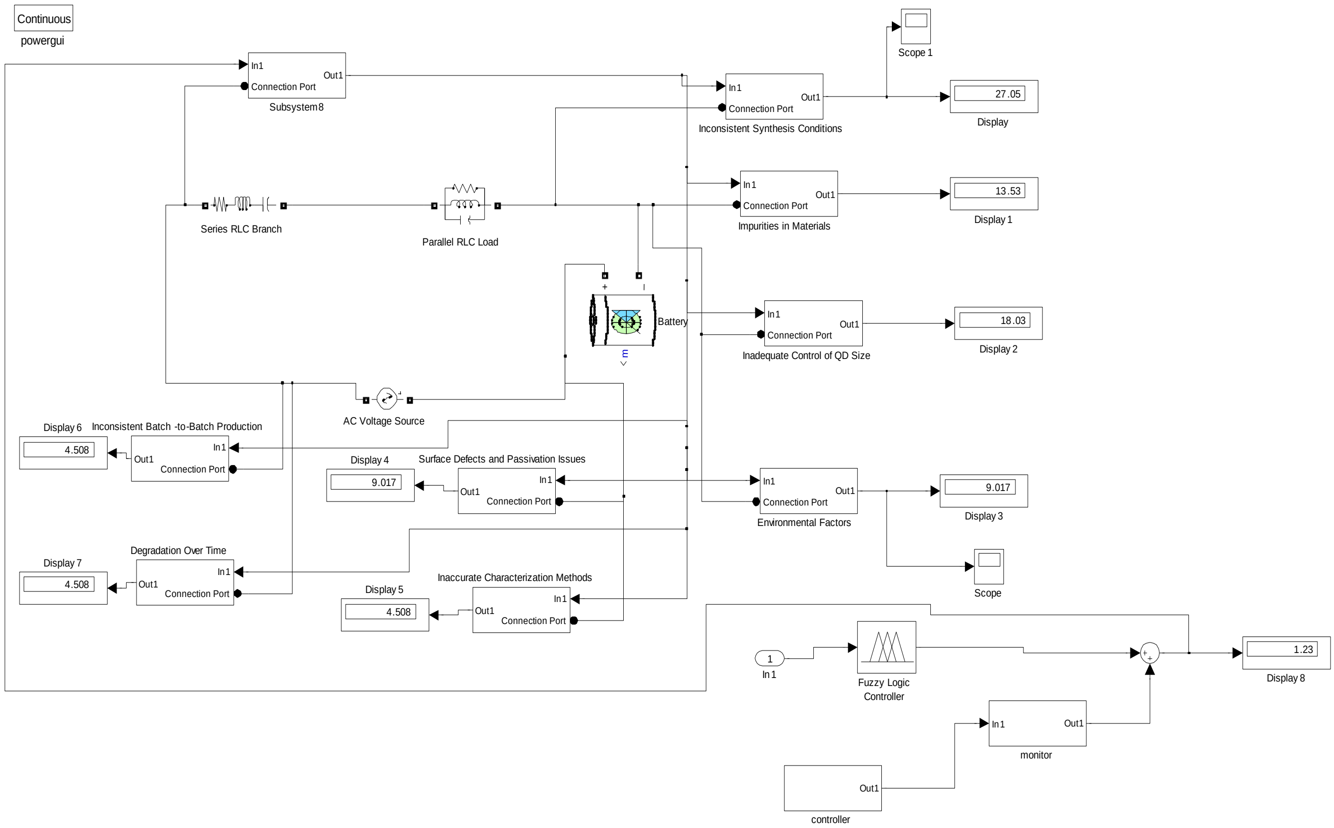

Figure 6: Designed SIMULINK model for characterization methods for semiconductor quantum dot using fuzzy logic-based controller

Validating to Justify the percentage Improvement in Reduction of Causes of Poor Characterization Methods for Semiconductor Quantum Dot with and without Fuzzy Logic Based Controller

To find percentage improvement in the reduction of inconsistent synthesis conditions that cause poor characterization methods for semiconductor quantum dot

Conventional inconsistent synthesis conditions =30%

Fuzzy logic based controller inconsistent synthesis conditions=27.05%

%improvement in the reduction of inconsistent synthesis conditions that cause poor characterization methods for semiconductor quantum dot=

Conventional inconsistent synthesis conditions - Fuzzy logic based controller inconsistent synthesis conditions

%improvement in the reduction of inconsistent synthesis conditions that cause poor characterization methods for semiconductor quantum dot=30% - 27.05%

%improvement in the reduction of inconsistent synthesis conditions that cause poor characterization methods for semiconductor quantum dot=2.95%

To find percentage improvement in the reduction of Inadequate Control of QD Size that cause poor characterization methods for semiconductor quantum dot

Conventional Inadequate Control of QD Size =15%

Fuzzy logic based controller Inadequate Control of QD Size =13.53%

%improvement in the reduction of Inadequate Control of QD Size that cause poor characterization methods for semiconductor quantum dot=

Conventional Inadequate Control of QD Size - Fuzzy logic based controller Inadequate Control of QD Size

%improvement in the reduction of Inadequate Control of QD Size that cause poor characterization methods for semiconductor quantum dot=15% - 13.53%

%improvement in the reduction of Inadequate Control of QD Size that cause poor characterization methods for semiconductor quantum dot=1.47%

To Find Percentage Improvement in the Reduction of Inaccurate Characterization Methods that Cause Poor Characterization Methods for Semiconductor Quantum Dot

Conventional inaccurate characterization methods =5%

Fuzzy logic-based controller inaccurate characterization methods =4.508%

%improvement in the reduction of inaccurate characterization methods that cause poor characterization methods for semiconductor quantum dot=

Conventional inaccurate characterization methods - Fuzzy logic-based controller inaccurate characterization methods

%improvement in the reduction of inaccurate characterization methods that cause poor characterization methods for semiconductor quantum dot=5% - 4.508%

%improvement in the reduction of inaccurate characterization methods that cause poor characterization methods for semiconductor quantum dot=0.492%

To find percentage improvement in the reduction of inconsistent batch-to-batch production that cause poor characterization methods for semiconductor quantum dot

Conventional inconsistent batch-to-batch production =5%

Fuzzy logic based controller inconsistent batch-to-batch production =4.508%

%improvement in the reduction of inconsistent batch-to-batch production that cause poor characterization methods for semiconductor quantum dot=

Conventional inconsistent batch-to-batch production - Fuzzy logic based controller inconsistent batch-to-batch production

%improvement in the reduction of inconsistent batch-to-batch production that cause poor characterization methods for semiconductor quantum dot=5% - 4.508%

%improvement in the reduction of inconsistent batch-to-batch production that cause poor characterization methods for semiconductor quantum dot=0.492%

Results and Discussion

The designed conventional SIMULINK model for semiconductor quantum dot characterization methods is presented in Figure 1. This model serves as the foundation for analyzing and improving the performance of quantum dot characterization techniques.

To address the causes of poor semiconductor quantum dot performance, a fuzzy inference system (FIS) was developed, as shown in Figure 2. The FIS aims to minimize these issues, thereby enhancing overall performance. It utilizes eight key input parameters:

i. Inconsistent Synthesis Conditions
ii. Impurities in Materials
iii. Inadequate Control of QD Size
iv. Environmental Factors
v. Surface Defects and Passivation Issues
vi. Inaccurate Characterization Methods
vii. Inconsistent Batch-to-Batch Production
viii. Degradation Over Time

The output of this system reflects the improvement in semiconductor quantum dot characterization.

Further optimization was achieved through the development of a fuzzy-based controller rule, illustrated in Figure 3. This controller effectively reduces the adverse effects associated with poor quantum dot performance, enhancing its reliability. The three core fuzzy-based controller rules that drive this improvement are systematically detailed in Table 2.

The impact of the fuzzy-based controller rules when activated is demonstrated in Figure 4. Additionally, a SIMULINK model integrating the fuzzy-based controller into the conventional system was designed, as depicted in Figure 5. The performance of the enhanced system was then analyzed, with results presented in Figures 7 to 10.

A refined SIMULINK model incorporating fuzzy logic-based control for semiconductor quantum dot characterization was designed, as illustrated in Figure 6. The effectiveness of this system is evaluated through a comparative analysis of conventional and fuzzy logic-based controllers.

Comparative Analysis of Conventional and Fuzzy Logic-Based Controllers

1. Inconsistent Synthesis Conditions (Figure 7 & Table 3)

i. In the conventional system, inconsistent synthesis conditions contributed to 30% of characterization inefficiencies.
ii. With the integration of the fuzzy logic-based controller, this value was significantly reduced to 27.05%, reflecting an improvement of 2.95%.

2. Inadequate Control of QD Size (Figure 8)

i. In the conventional system, inadequate control of QD size caused a performance decline of 15%.
ii. When the fuzzy logic-based controller was applied, this percentage decreased to 13.53%, showcasing a substantial improvement.

3. Inaccurate Characterization Methods (Figure 9)

i. The conventional system exhibited inaccuracies in characterization methods at a rate of 5%.
ii. The fuzzy logic-based controller reduced these inaccuracies to 4.508%, thereby enhancing measurement precision.

4. Inconsistent Batch-to-Batch Production (Figure 10 & Table 6)

i. Conventional batch-to-batch inconsistencies led to a 5% reduction in performance.
ii. With fuzzy logic-based control, this figure was lowered to 4.508%, demonstrating an improvement in consistency.

Table 3: Comparison of conventional and Fuzzy logic based controller inconsistent synthesis conditions in **characterization methods for semiconductor quantum dot**

Time(s)	*Conventional **inconsistent synthesis conditions in** characterization methods for semiconductor quantum dot(%)*	*Fuzzy logic based controller **inconsistent synthesis conditions in** characterization methods for semiconductor quantum dot(%)*
1	30	**27.05**
2	30	**27.05**
3	30	**27.05**
4	30	**27.05**
10	30	**27.05**

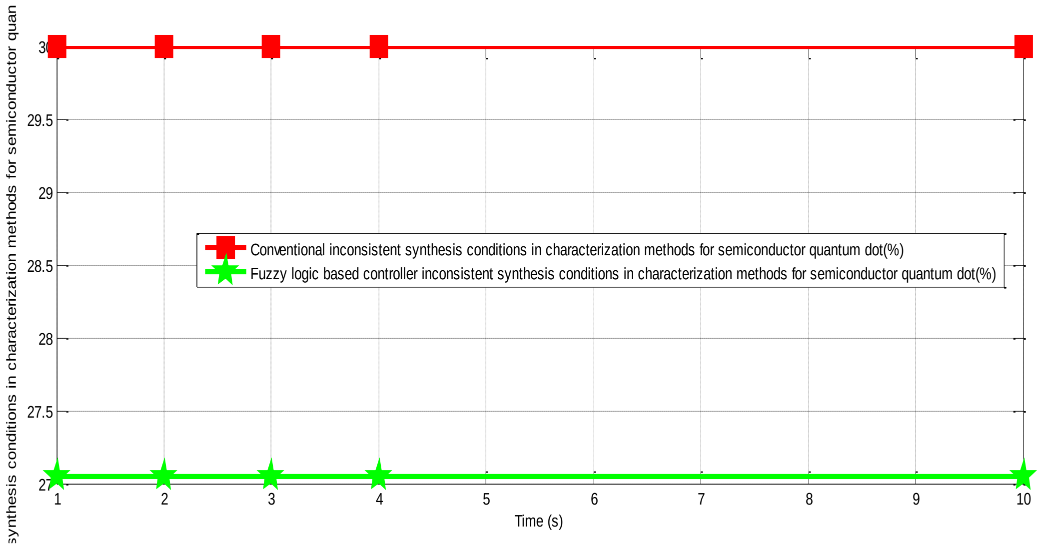

Figure 7. Comparison of conventional and Fuzzy logic based controller **inconsistent synthesis conditions in** characterization methods for semiconductor quantum dot

Table 4: Comparison of conventional and Fuzzy logic based controller Inadequate Control of QD Size in **characterization methods for semiconductor quantum dot**

Time(s)	*Conventional **Inadequate Control of QD Size in** characterization methods for semiconductor quantum dot (%)*	*Fuzzy logic-based controller **Inadequate Control of QD Size in** characterization methods for semiconductor quantum dot (%)*
1	15	**13.53**
2	15	**13.53**
3	15	**13.53**
4	15	**13.53**
10	15	**13.53**

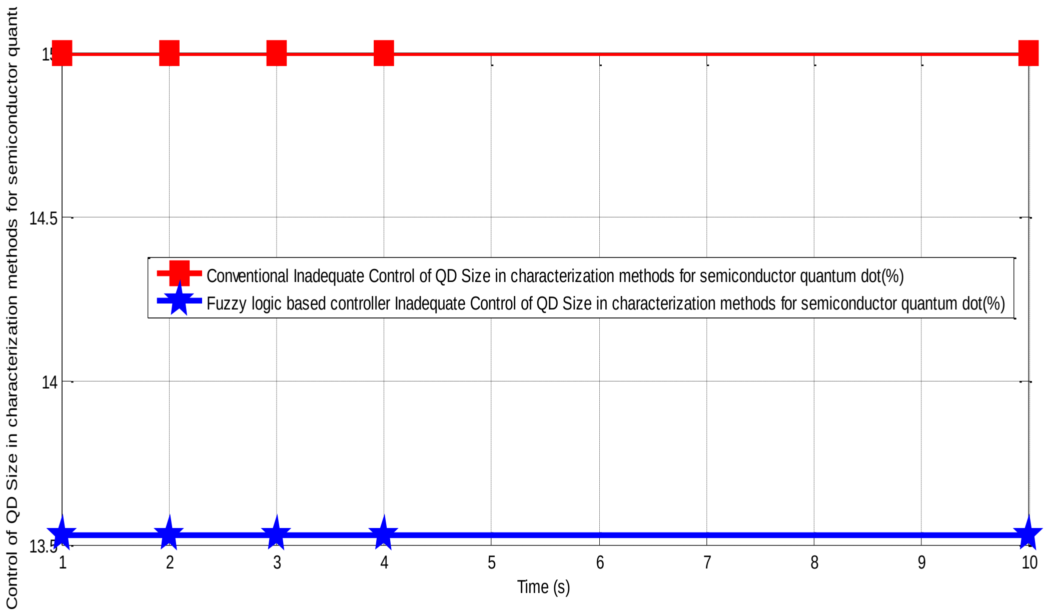

Figure 8: Comparison of conventional and Fuzzy logic-based controller **Inadequate Control of QD Size in** characterization methods for semiconductor quantum dot

Table 5: Comparison of Conventional and Fuzzy Logic Based Controller Inaccurate Characterization Methods in **Semiconductor Quantum Dot**

Time(s)	*Conventional **inaccurate characterization methods in** semiconductor quantum dot (%)*	*Fuzzy logic based controller **inaccurate characterization methods in** semiconductor quantum dot (%)*
1	5	4.508
2	5	4.508
3	5	4.508
4	5	4.508
10	5	4.508

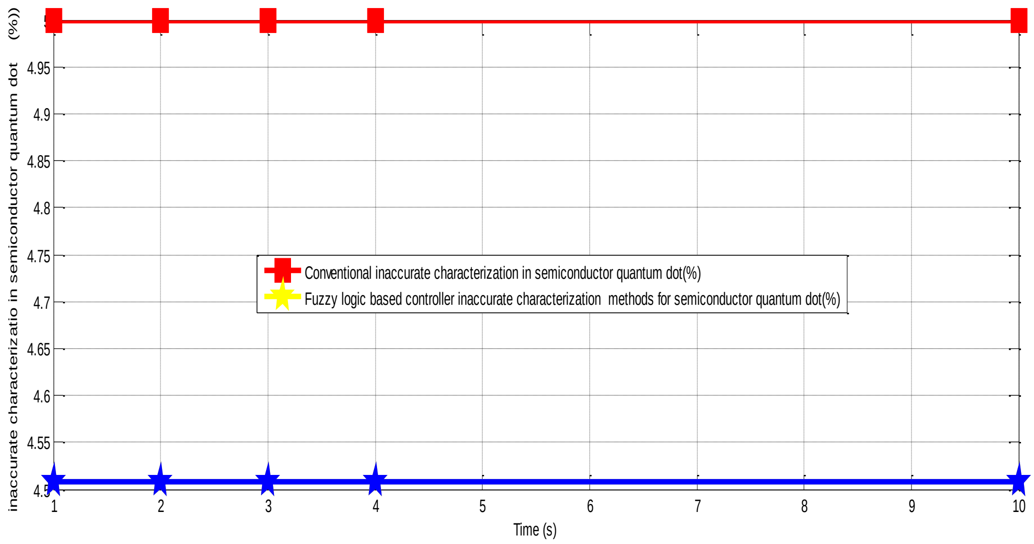

Figure 9. Comparison of conventional and Fuzzy logic-based controller **inaccurate characterization methods in** semiconductor quantum dot

Table 6: Comparison of Conventional and Fuzzy Logic-Based Controller Inconsistent Batch-to-Batch Production in Characterization Methods for Semiconductor Quantum Dot

Time(s)	*Conventional **inconsistent batch-to-batch production in** characterization methods for semiconductor quantum dot(%)*	*Fuzzy logic based controller **inconsistent batch-to-batch production in** characterization methods for semiconductor quantum dot(%)*
1	5	4.508
2	5	4.508
3	5	4.508
4	5	4.508
10	5	4.508

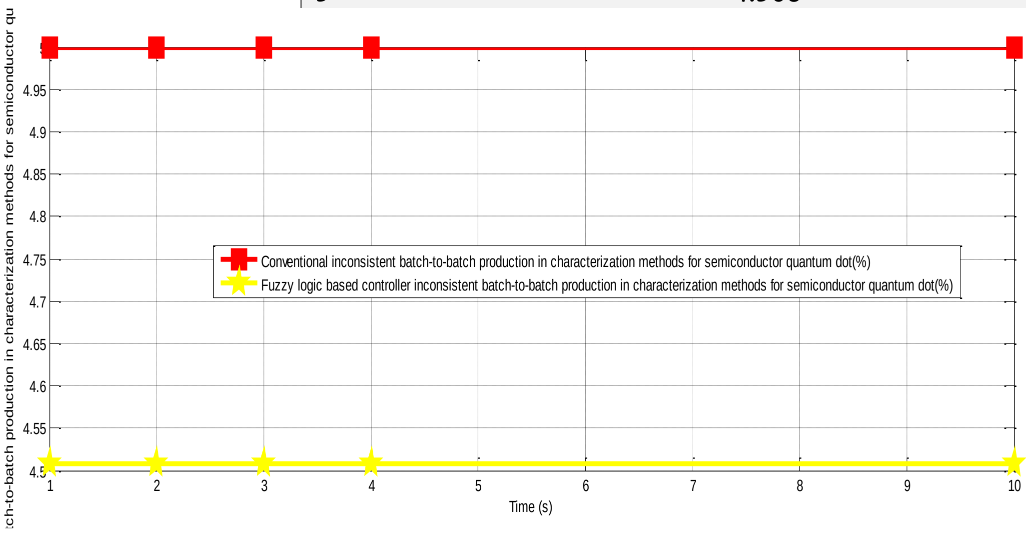

Figure 10: Comparison of conventional and Fuzzy logic-based controller inconsistent batch-to-batch production in characterization methods for semiconductor quantum dot

Conclusion

The decline in semiconductor quantum dot (QD) performance, driven by inconsistent synthesis, material impurities, surface defects, and inaccurate characterization, has disrupted dependent industries. To address this, a fuzzy logic-based controller was developed to enhance characterization methods. The approach included identifying performance issues, designing SIMULINK models, formulating fuzzy logic rules, and validating improvements. The integration of fuzzy logic significantly improved QD characterization, achieving a 0.492% increase in efficiency. These results highlight the effectiveness of fuzzy logic in reducing inconsistencies and refining QD synthesis and characterization processes.

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