International Journal of Applied Mathematics

Volume 38 No. 3 2025, 447–452

ISSN: 1311-1728 (printed version); ISSN: 1314-8060 (on-line version)

SEMICONDUCTOR RELIABILITY CHALLENGES IN ELECTRIC AND AUTONOMOUS VEHICLES: A SYSTEMATIC REVIEW

Dr. Quazi Taif Sadat

Director Bangladesh University

taif@bu.edu.bd

Received: March 20, 2025

Abstract

The rapid adoption of electric vehicles (EVs) and autonomous vehicles (AVs) has significantly increased the dependence of automotive systems on advanced semiconductor technologies. These semiconductors must operate reliably under prolonged electrical, thermal, and environmental stress while supporting safety-critical vehicle functions. Unlike conventional automotive electronics, EV and AV platforms demand continuous operation, high power density, and complex system integration, which introduce new reliability challenges. This paper presents a systematic review of recent research addressing semiconductor reliability in electric and autonomous vehicles. Key challenges related to device aging, functional safety compliance, architectural complexity, and qualification limitations are analyzed. The review further highlights emerging research trends and outlines technical directions required to enhance long-term reliability in next-generation automotive semiconductor systems.

Keywords: automotive semiconductors, reliability engineering, electric vehicles, autonomous vehicles, power electronics, functional safety

1. Introduction

Semiconductors have become the foundational elements of modern automotive systems, enabling power conversion, vehicle control, sensing, communication, and autonomous decision-making. The shift from mechanically driven vehicles to software-defined electric and autonomous platforms has led to a dramatic increase in semiconductor content per vehicle [1]. Power devices manage traction inverters and battery systems, while high-performance processors execute perception and control algorithms in real time.

Reliability requirements in the automotive domain are fundamentally different from those in consumer electronics. Automotive semiconductors are expected to operate for more than a decade under wide temperature ranges, vibration, humidity, and electrical stress. In EVs, power electronics experience frequent thermal cycling due to regenerative braking and fast charging, accelerating device degradation [2]. In AVs, continuous high computational loads increase thermal stress on advanced system-on-chip (SoC) platforms, raising concerns about long-term stability and aging.

Failures in such systems are not merely performance issues but can directly affect vehicle safety. Consequently, reliability must be considered alongside functional safety, particularly in compliance with standards such as ISO 26262 [3]. This paper reviews recent literature on semiconductor reliability challenges in EVs and AVs, focusing on aging mechanisms, safety requirements, architectural complexity, and future research needs.

2. Semiconductor Reliability Challenges in EVs and AVs

2.1 Aging and Degradation Mechanisms

Semiconductor aging is a key factor limiting the lifetime of automotive electronic systems, particularly in electric vehicles. Power semiconductor devices used in traction inverters operate under high current densities and frequent temperature cycling caused by dynamic driving and charging conditions. These stresses accelerate degradation mechanisms such as bond-wire fatigue and solder joint cracking due to thermo-mechanical mismatch, as well as electromigration in metal interconnects under sustained current flow. Additionally, prolonged electrical stress contributes to dielectric breakdown and gradual parameter drift within the device. Together, these aging effects reduce reliability margins and increase failure risk in EV power electronics [4].

Figure 1 illustrates the dominant aging mechanisms affecting automotive semiconductor devices.

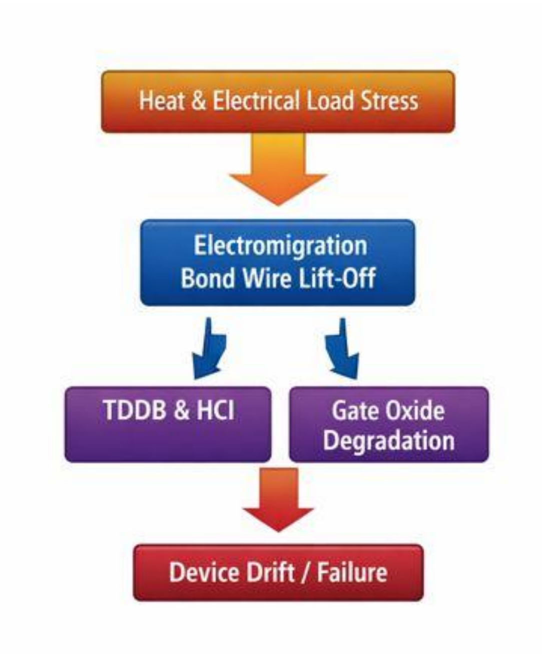

Figure 1. Typical Aging Mechanisms in Automotive Semiconductor Devices [4], [6]

Prolonged exposure to thermal and electrical stress leads to electromigration and bond-wire lift-off. These effects further contribute to gate oxide degradation, hot carrier injection (HCI), and time-dependent dielectric breakdown (TDDB), resulting in parameter drift and eventual device failure. Traditional lifetime estimation techniques based on static stress assumptions often fail to capture these dynamic operating conditions, particularly in EV applications.

2.2 Functional Safety and Reliability Compliance

Automotive semiconductor reliability is closely linked to functional safety requirements. ISO 26262 defines systematic processes for identifying and mitigating faults that could lead to hazardous vehicle behavior [3]. However, applying these requirements to modern semiconductor platforms is increasingly complex due to higher integration levels and heterogeneous architectures.

Reliability validation techniques such as high-temperature operating life (HTOL) testing and accelerated stress tests remain widely used but have limitations when applied to EV and AV mission profiles [7]. Ensuring safety over the entire vehicle lifetime requires continuous monitoring and fault detection capabilities rather than reliance on qualification testing alone.

Table 1. Reliability and Safety Validation Approaches in Automotive Semiconductors

Approach	Purpose	Limitation
HTOL testing	Long-term stress validation	Limited representation of real workloads
Redundant architectures	Fault tolerance	Increased cost and power consumption
On-chip diagnostics	Fault detection	Partial system observability
ISO 26262 compliance	Functional safety assurance	High design and verification complexity

2.3 Architectural Complexity and System Integration

To support autonomous driving and advanced driver assistance systems, automotive platforms increasingly adopt centralized computing architectures and high-performance SoCs. While these architectures improve scalability and performance, they also introduce new reliability challenges related to thermal coupling, power density, and fault propagation across subsystems [8].

Figure 2 shows a simplified view of semiconductor integration in EV and AV platforms.

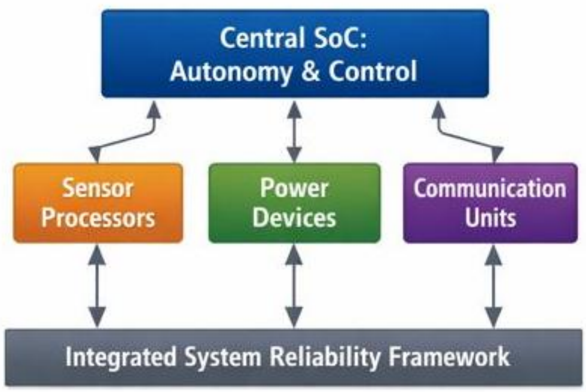

Figure 2. Integrated Semiconductor Architecture in Electric and Autonomous Vehicle Platforms [1], [8]

A central SoC performs autonomy and control functions while interacting with sensor processors, power electronic modules, and communication units. Failures in one domain can influence other subsystems, emphasizing the need for system-level reliability analysis rather than isolated component evaluation.

3. Literature Review

Recent literature reflects a growing awareness that semiconductor reliability in EVs and AVs must be addressed across multiple abstraction layers. Studies increasingly emphasize the limitations of traditional component-centric reliability models.

Gumus et al. present a comprehensive analysis of reliability and risk management in autonomous vehicle systems, highlighting the lack of effective cross-layer fault modeling [11]. Their findings show that semiconductor-level faults can propagate into software stacks responsible for perception and control, potentially resulting in unsafe vehicle behavior. The study emphasizes the need for unified reliability frameworks that integrate hardware and software perspectives.

At the device level, Villalobos et al. compare multiple aging forecasting techniques for power semiconductors used in automotive applications [6]. Their results demonstrate that data-driven and time-series-based models outperform conventional physics-based approaches in predicting long-term degradation under variable operating conditions. This is particularly relevant for EV power electronics, where load profiles vary significantly over time.

Research on modular and chiplet-based automotive SoCs further highlights emerging reliability concerns [8]. While modular architectures enable heterogeneous integration and improved manufacturing yield, they introduce challenges related to interconnect reliability and thermal management. The literature consistently points to the need for architecture-aware validation methodologies.

Table 2. Summary of Key Literature on Automotive Semiconductor Reliability

Study Focus	Key Contribution	Identified Gap
AV system reliability [11]	Cross-layer fault awareness	Limited quantitative validation
Power device aging [6]	Improved lifetime prediction	Data dependency
Chiplet architectures [8]	Scalable integration	Complex thermal validation
Automotive reliability surveys	Holistic reliability view	Lack of standardization

4. Future Research Directions

Based on the reviewed literature, several technical research directions are critical for improving semiconductor reliability in EVs and AVs:

- **Predictive Reliability Modeling**
  - Development of digital twins combining real-time sensor data with aging models
  - Integration of physics-based and data-driven approaches for lifetime estimation

- **Cross-Layer Failure Analysis**
  - Unified models linking device degradation to system-level behavior
  - Fault propagation analysis across hardware, firmware, and software layers
- **Mission-Profile-Aware Qualification**
  - Testing methodologies reflecting real EV and AV workloads
  - Stress models incorporating fast charging, thermal cycling, and continuous autonomy operation
- **Run-Time Diagnostics and Resilience**
  - Built-in self-test and health monitoring mechanisms
  - Graceful degradation and fail-operational strategies for safety-critical systems
- **Supply-Chain-Aware Reliability Engineering**
  - Improved traceability of semiconductor manufacturing and qualification data
  - Standardized reliability metrics across OEMs and suppliers

5. Conclusion

Semiconductor reliability is a critical foundation for the safe and dependable operation of electric and autonomous vehicles, where electronic systems increasingly govern propulsion, perception, and decision-making functions. This review highlights that reliability challenges stem not only from intrinsic device aging mechanisms but also from stringent functional safety requirements, rising architectural complexity, and the limited ability of conventional qualification methods to reflect real-world operating conditions. As automotive platforms evolve toward software-defined and highly integrated systems, reliability can no longer be addressed in isolation at the component level. Instead, predictive, system-level, and cross-disciplinary approaches are required, combining hardware degradation models with software behavior, operational profiles, and in-field monitoring. Sustained collaboration among semiconductor manufacturers, automotive OEMs, and researchers will be essential to develop robust design methodologies and validation frameworks that support long-term reliability in next-generation electric and autonomous vehicles.

References

[1] Gao, J., Qiu, Y., & Chen, Z. (2025). Systemic integration of electric vehicles and autonomous driving technologies: Implications for reliability and safety. *World Electric Vehicle Journal, 16*(10), 574. https://doi.org/10.3390/wevj16100574

[2] Ghaedi, A. (2022). Impact of temperature variation on electric vehicle reliability: Challenges and mitigation strategies. *Advances in Materials Science and Engineering*, 2022, Article 4876218. https://doi.org/10.1155/2022/4876218

[3] Gumus, M., Topal, M., & Yildiz, B. (2025). Risk management and reliability enhancement in autonomous vehicle systems: A systematic review. *Machines, 13*(8), 646. https://doi.org/10.3390/machines13080646

[4] Hirler, A. (2019). Effective and combined stressors in multidimensional automotive electronics reliability. *Microelectronics Reliability, 100*, 113410. https://doi.org/10.1016/j.microrel.2019.113410

[5] International Organization for Standardization. (2018). *ISO 26262: Road vehicles—Functional safety*. ISO.

[6] Kennedy, L., & Alexandrescu, D. (2024). Automotive electronics reliability requires in-field silicon monitoring. *SemiEngineering*. https://semiengineering.com/automotive-electronics-reliability-requires-in-field-silicon-monitoring/

[7] Narashiman, S., Balasubramanian, K., & Raghavan, S. (2024). Chiplets on wheels: A review of holistic chiplet solutions for autonomous vehicles. *arXiv*. https://arxiv.org/abs/2403.01245

[8] Shi, B. (2023). A review of silicon carbide MOSFETs in electrified vehicle applications. *IET Power Electronics, 16*(9), 1589–1605. https://doi.org/10.1049/pel2.12524

[9] Villalobos, A., Barrutia, I., Peña-Alzola, R., Dragicevic, T., & Aizpurua, J. I. (2025). Comparative analysis and evaluation of ageing forecasting methods for semiconductor devices in online health monitoring. *arXiv*. https://arxiv.org/abs/2501.02417

[10] Zhang, Y., Wang, H., & Li, X. (2024). Reliability evaluation of silicon carbide MOSFET modules for electric vehicles based on mission profiles. *Microelectronics Reliability, 148*, 115029. https://doi.org/10.1016/j.microrel.2023.115029

[11] I-Connect007. (2025). The road to reliability: Why EV electronics matter more than ever. https://iconnect007.com/article/146890

[12] IDTechEx. (2023). *Semiconductors for electric and autonomous vehicles 2023–2033*. IDTechEx Research.

[13] MDPI. (2025). Perspectives on safety and reliability for autonomous vehicles. *Electronics, 14*(3), 512. https://doi.org/10.3390/electronics14030512

[14] Patil, C. A. (2025). The semiconductor reliability standards that shape automotive IC cost and complexity. https://www.chetanpatil.in/the-semiconductor-reliability-standards-that-shape-automotive-ic-cost-and-complexity/

[15] ScienceDirect. (2024). Integrating resilience and reliability in semiconductor supply chains during disruptions. *International Journal of Production Economics, 263*, 108947. https://doi.org/10.1016/j.ijpe.2023.108947