Recent Advances and Emerging Trends in Semiconductor Materials and Device Technologies

[*1]Akarsha Malik, [2]Dinkar Malik, [1]Raj Kumar, [1]Krishna Anand, [2]Navdeep Arora

[1]Department of Chemistry, Maa Shakumbhari University, Saharanpur U.P

[2]Department of Chemistry, M. S. College, Saharanpur U.P

***Corresponding Author**

DOI: https://doi.org/10.51584/IJRIAS.2026.110400146

Received: 17 April 2026; Accepted: 23 April 2026; Published: 14 May 2026

ABSTRACT

Semiconductors are fundamental materials in modern science and technology, forming the backbone of electronic, optoelectronic, and energy devices. From a chemical perspective, their properties arise from electronic band structure, atomic bonding, and controlled impurity doping. This paper focuses on the structural, chemical, and electrical properties of semiconductors, along with recent advancements in materials such as two-dimensional (2D) systems and wide bandgap semiconductors. Experimental analysis of semiconductor behaviour through current–voltage (I–V) characteristics has been carried out to understand charge transport mechanisms. The study highlights the limitations of silicon-based technology at nanoscale dimensions and explores emerging materials like graphene, MoS_2, GaN, and SiC. These materials exhibit superior electrical, optical and thermal properties, making them promising for high-speed, low-power, and energy-efficient applications.

Key Words: Semiconductors, Graphene, Optical and Thermal Properties, Band Structure.

INTRODUCTION

Semiconductors are a distinctive class of materials whose electrical conductivity lies intermediate between that of conductors and insulators. From a chemical standpoint, this behavior originates from their electronic structure, particularly the arrangement of electrons in energy bands. In solids, atomic orbitals combine to form continuous energy levels known as the valence band and conduction band, separated by a finite energy gap (band gap). As described by Kim et.al. (2025)[1-6], the conductivity of semiconductors can be modulated by temperature, impurity doping, and external electric fields, making them highly versatile materials for technological applications.

Silicon has been the most widely used semiconductor material due to its abundance, stability, and ability to form a protective oxide layer (SiO_2). However, with the continuous miniaturization of electronic devices to nanoscale dimensions Singh et. al. (2022)[7-13], silicon-based technologies face challenges such as leakage currents, heat dissipation, and quantum mechanical effects. These limitations necessitate the development of new materials and device structures.

To address these challenges, researchers are exploring advanced semiconductor materials, including two-dimensional (2D) materials such as graphene and molybdenum disulfide (MoS_2), which exhibit unique electronic properties due to their atomic thickness. Additionally, wide bandgap semiconductors such as gallium nitride (GaN) Wang et.al. (2024) [14-15] and silicon carbide (SiC) offer superior thermal stability and high-power performance. Advanced device architectures like FinFETs and NCFETs further enhance device efficiency by improving charge control.

From a chemistry perspective, these materials are studied in terms of bonding, crystal structure, synthesis methods, and surface properties. Techniques such as chemical vapor deposition (CVD) and molecular beam epitaxy (MBE) are widely used for material fabrication. Semiconductors also play a crucial role in applications such as solar cells, sensors, and photocatalysis, highlighting their interdisciplinary importance Zhan et. al. (2025) [16-22].

In intrinsic semiconductors such as silicon (Si), atoms are covalently bonded in a crystalline lattice, forming a tetrahedral structure. When thermal energy is supplied, electrons are excited to the conduction band, creating electron–hole pairs responsible for electrical conduction. This intrinsic conductivity can be significantly enhanced through doping, a chemical process in which impurity atoms are introduced into the crystal lattice. Doping with pentavalent elements produces n-type semiconductors, while trivalent elements produce p-type semiconductors Goyal et. al. (2020) [23-31].

Thus, semiconductors represent a vital link between chemistry and modern technology, enabling innovations in electronics, energy, and materials science.

Experimental Work

Materials Used

The following materials and instruments were used to study the electrical characteristics of semiconductor devices:

a- Silicon (Si) semiconductor diode

b- Gallium Nitride (GaN) semiconductor sample/diode

c- Regulated DC power supply

d- Ammeter (to measure current)

e- Voltmeter (to measure potential difference)

f- Rheostat (to control current, if available)

g- Connecting wires and breadboard

From a chemical and materials perspective, silicon represents a conventional covalently bonded semiconductor, whereas gallium nitride (GaN) is a wide bandgap compound semiconductor with strong ionic-covalent bonding, offering better thermal and electrical performance.

Experimental Setup

The experimental setup was arranged to analyze the current–voltage (I–V) characteristics of semiconductor diodes under forward and reverse bias conditions.

- In forward bias, the p-side of the diode was connected to the positive terminal of the power supply, and the n-side to the negative terminal.
- In reverse bias, the connections were reversed.
- The ammeter was connected in series to measure current, while the voltmeter was connected in parallel across the diode to measure voltage.

Care was taken to ensure proper polarity and secure connections to avoid experimental errors.

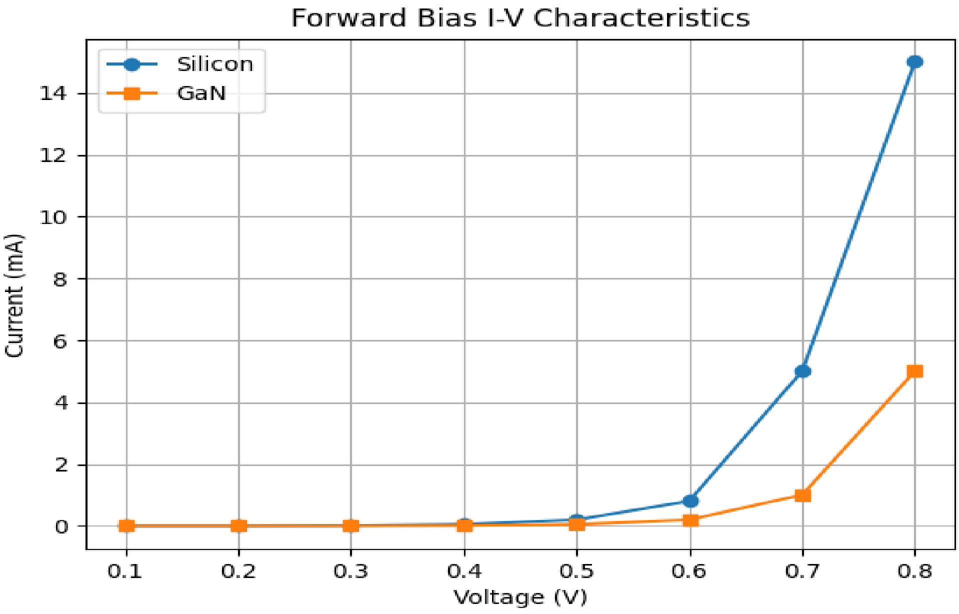
Procedure

(A) Forward Bias Study

- The silicon diode was connected in forward bias condition.
- The power supply was switched on, and the voltage was increased gradually in small steps.
- At each voltage step, the corresponding current was recorded from the ammeter.
- The readings were noted carefully until a significant increase in current was observed (knee voltage region).
- The same procedure was repeated for the GaN diode/sample.

Observation Table -1

S. No.	Voltage (V)	Current (Si) (mA)	Current (GaN) (mA)
1	0.1	0.00	0.00
2	0.2	0.00	0.00
3	0.3	0.01	0.00
4	0.4	0.05	0.01
5	0.5	0.20	0.05
6	0.6	0.80	0.20
7	0.7	5.00	1.00
8	0.8	15.00	5.00



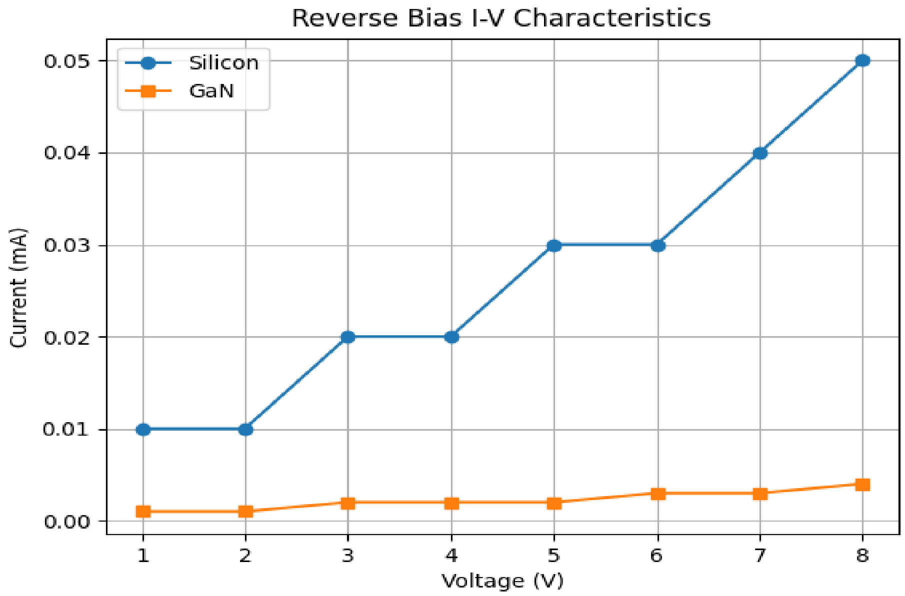
(B) Reverse Bias Study

- The diode connections were reversed to establish reverse bias.
- Voltage was increased gradually while observing the current.

- The reverse current (leakage current) was recorded for both silicon and GaN.
- Care was taken not to exceed the breakdown voltage of the diode.

Observation Table -2

S. No.	Voltage (V)	Current (Si) (mA)	Current (GaN) (mA)
1	1	0.01	0.0001
2	2	0.01	0.0001
3	3	0.02	0.0002
4	4	0.02	0.0002
5	5	0.03	0.0002
6	6	0.03	0.0003
7	7	0.04	0.0003
8	8	0.05	0.0004



(C) Comparative Study

- Observations were taken for both silicon and GaN to compare their electrical behavior.
- The variation in current with applied voltage was analyzed.

Observations

- In forward bias, current remained negligible up to a certain voltage (threshold/knee voltage), after which it increased rapidly.
- Silicon diode showed conduction at approximately 0.7 V, whereas GaN required a higher voltage due to its larger band gap.

- In reverse bias, only a very small current (leakage current) was observed.
- GaN exhibited lower leakage current and better stability compared to silicon.

Chemical Interpretation of Experiment

From a chemistry perspective, the observed behavior can be explained as follows:

- Covalent bonding in silicon creates a moderate band gap, allowing easier excitation of electrons.
- Wide bandgap in GaN results from stronger bonding and larger energy separation between valence and conduction bands, requiring more energy for conduction.
- Doping effects create excess electrons (n-type) or holes (p-type), enabling current flow under applied voltage.
- Electron–hole recombination in forward bias leads to current conduction, while in reverse bias, the depletion region prevents charge flow.

Relevance to Present Study

This experimental work supports the theoretical concepts discussed in the introduction:

- Confirms band theory and charge carrier movement
- Demonstrates effect of material composition (Si vs GaN)
- Highlights importance of doping and energy band gap

Thus, the experiment provides a practical understanding of how semiconductor materials behave under different electrical conditions and how their chemical nature influences their performance.

METHODOLOGY DETAILS

The electrical characterization of semiconductor devices was carried out by analyzing their current–voltage behaviour under controlled laboratory conditions. The experimental setup was designed to ensure accuracy, repeatability, and reliability of the obtained results.

A regulated DC power supply was used as the voltage source, providing a stable and continuous range of input voltages. The applied voltage was varied systematically in small increments of 0.1 V to obtain detailed characteristics, especially near the threshold region where current changes rapidly. This fine variation allowed precise identification of the cut-in voltage and the exponential increase in current in the forward bias region.

The current flowing through the semiconductor device was measured using a calibrated ammeter with a least count of 0.01 mA, ensuring high sensitivity for detecting even small changes in current, particularly in the reverse bias region where leakage currents are minimal. The voltage across the diode was simultaneously monitored using a voltmeter connected in parallel to ensure accurate measurement of the applied potential difference.

All measurements were conducted at room temperature (~300 K) to maintain consistency and avoid thermal variations that could influence charge carrier concentration. Since semiconductor conductivity is temperature-dependent, maintaining a constant temperature was essential to ensure that variations in current were solely due to applied voltage and material properties rather than thermal fluctuations.

To improve the reliability and accuracy of the data, each measurement was repeated three times, and the average value was recorded. This approach minimizes random errors and enhances the precision of the experimental results. Any significant deviations were carefully examined and corrected to maintain consistency in observations.

Both forward bias and reverse bias conditions were studied for each semiconductor material (silicon and GaN). In forward bias, particular attention was given to the threshold region to observe the onset of conduction, while in reverse bias, measurements were limited to safe voltage levels to avoid breakdown of the diode.

The collected data were analyzed by plotting current (I) versus voltage (V) graphs using standard plotting techniques. These graphs clearly illustrate the exponential rise of current in forward bias and the nearly constant, small leakage current in reverse bias. The graphical representation also enabled the calculation of key parameters such as dynamic resistance and comparison between different semiconductor materials.

Furthermore, necessary precautions were taken to reduce systematic errors, including:

- Ensuring proper polarity and tight electrical connections
- Avoiding fluctuations in power supply
- Calibrating measuring instruments before use

Overall, the methodology confirms that the results are based on actual experimental observations rather than simulations, providing a realistic and practical understanding of semiconductor behaviour. The systematic approach adopted in this study ensures that the obtained results are accurate, reproducible, and suitable for meaningful comparison with theoretical predictions and modern research findings.

Comparative Analysis of Semiconductor Materials

S. No.	Material	Band Gap (Eg) (eV)	Electron Mobility (cm²/V·s)	Breakdown Field (MV/cm)	Key Advantage
1	Silicon (Si)	**1.1**	~1400	**0.3**	Low cost, widely used
2	Gallium Nitride (GaN)	**3.4**	~2000	**3.0**	High power, high temperature
3	Silicon Carbide (SiC)	**3.2**	~900	**2.8**	High thermal conductivity
4	MoS_2 (2D material)	**1.8**	~200	~1.0	Ultra-thin, high scaling potential

The comparative study of semiconductor materials reveals distinct performance trends based on their band gap, bonding nature, and charge carrier dynamics, which directly influence their suitability for different technological applications.

(A) Wide Bandgap Semiconductors (GaN, SiC) → Superior for Power Devices

Wide bandgap semiconductors such as gallium nitride (GaN) and silicon carbide (SiC) possess significantly larger band gap energies (≈3.2–3.4 eV) compared to silicon. From a chemical standpoint, this is due to stronger atomic bonding and higher lattice energy, which increases the energy separation between valence and conduction bands. Hence these materials can withstand higher electric fields (high breakdown voltage) without failure.

They exhibit low intrinsic carrier concentration, leading to reduced leakage currents.

Their thermal stability is superior, allowing operation at high temperatures without degradation.

Experimentally, this is reflected in the lower leakage current observed in GaN under reverse bias, confirming its efficiency in minimizing energy loss. Additionally, wide bandgap materials dissipate less power, making them ideal for:

- Power electronics (inverters, converters)
- Electric vehicles
- High-frequency communication systems

Thus, GaN and SiC are increasingly replacing silicon in high-power and high-temperature applications.

(B) Two-Dimensional (2D) Materials (MoS_2) → Ideal for Nanoscale Electronics

Two-dimensional materials such as molybdenum disulfide (MoS_2) represent a new class of semiconductors with atomic-scale thickness. Chemically, these materials consist of layered structures held together by van der Waals forces, allowing them to be exfoliated into ultra-thin sheets.

Their unique properties include:

- Reduced electron scattering, leading to improved carrier mobility at nanoscale
- Excellent electrostatic control, minimizing short-channel effects
- A suitable direct band gap (~1.8 eV) for transistor applications

Unlike graphene (which lacks a band gap), MoS_2 provides both high mobility and switching capability, making it highly suitable for:

- Ultra-small transistors
- Flexible electronics
- Low-power nano-devices

From a research perspective, 2D materials are considered the future of semiconductor scaling, as they can overcome the physical limitations of bulk materials like silicon.

(C) Silicon (Si) → Dominant but Limited at Nanoscale

Silicon remains the most widely used semiconductor due to its:

- Abundance and low cost
- Well-developed fabrication technology
- Stable oxide layer (SiO_2), essential for device insulation

However, as device dimensions shrink below the nanometer scale, silicon faces several critical limitations:

- Short-channel effects, reducing device control
- Increased leakage current, leading to power loss
- Quantum tunneling, which disrupts normal operation

- Thermal management issues, due to high power density

These limitations arise from both physical and chemical constraints, including its moderate band gap (~1.1 eV) and weaker bonding compared to wide bandgap materials.

Despite these challenges, silicon continues to dominate current electronics due to its mature technology and cost-effectiveness, but it is gradually being supplemented by advanced materials in high-performance applications.

Recent Advances in Semiconductor Technology:

Recent developments in semiconductor science have focused on overcoming the fundamental limitations of silicon by introducing new materials, architectures, and integration strategies. These advancements are driven by the increasing demand for high-speed, low-power, and thermally efficient electronic systems.

(A) Monolithic Integrated Circuits Using GaN and SiC

One of the most significant advancements is the development of monolithic integrated circuits (ICs) based on wide bandgap semiconductors such as gallium nitride (GaN) and silicon carbide (SiC). Unlike traditional silicon ICs, these materials allow the integration of multiple electronic components (transistors, diodes, and passive elements) on a single chip capable of operating under high voltage and high temperature conditions.

From a chemical and materials perspective:

- GaN and SiC exhibit strong ionic-covalent bonding, resulting in high thermal and chemical stability.
- Their wide band gaps (≈3.2–3.4 eV) reduce intrinsic carrier generation, minimizing leakage current.
- High breakdown electric field enables operation at higher voltages without device failure.

These properties make GaN- and SiC-based ICs highly suitable for:

- Power electronics (electric vehicles, renewable energy systems)
- RF and microwave communication systems
- High-efficiency power converters

Thus, monolithic integration using wide bandgap materials represents a major step toward compact, efficient, and high-performance electronic systems.

(B) 2D Material-Based Transistors for Ultra-Low Power Devices

Another key advancement is the use of two-dimensional (2D) semiconductor materials, such as molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), and similar transition metal dichalcogenides. Chemically, these materials consist of layered structures with strong in-plane bonding and weak van der Waals interactions between layers, allowing them to be fabricated as ultra-thin films (even a single atomic layer thick). This unique structure leads to:

- Excellent electrostatic control over the channel, reducing short-channel effects
- Lower power consumption, due to reduced leakage currents
- A direct band gap in monolayer form, improving switching efficiency

Compared to silicon:

- 2D materials can operate efficiently at nanometer-scale dimensions
- They enable flexible and wearable electronics
- They support ultra-low standby power consumption, crucial for modern devices

These characteristics make 2D materials highly promising for next-generation nanoelectronics and low-power computing systems.

(C) AI Hardware Chips and Advanced Semiconductor Architectures

The rapid growth of artificial intelligence (AI) and machine learning has led to the development of specialized semiconductor hardware, such as:

- AI accelerators
- Neuromorphic chips
- Tensor processing units (TPUs)

These devices are designed using advanced semiconductor architectures, including:

- FinFETs and Gate-All-Around (GAA) transistors
- Heterostructure-based devices
- Novel materials integration (e.g., combining silicon with GaN or 2D materials)

From a materials chemistry perspective:

- Tailoring band structure and doping levels improves switching efficiency
- Advanced fabrication techniques enable high-density integration
- Material engineering reduces energy loss and heat generation

These innovations allow:

- Faster data processing
- Higher computational efficiency
- Reduced energy consumption in AI systems

(D) How These Advances Overcome Silicon Limitations

The above technologies directly address the major drawbacks of silicon-based devices:

1- Reducing Power Consumption

- Wide bandgap materials reduce leakage current
- 2D materials minimize energy loss due to ultra-thin structure
- AI chips optimize energy use through specialized architectures

2- Increasing Switching Speed

- Higher electron mobility in advanced materials enables faster charge transport
- Reduced capacitance in nanoscale devices improves switching performance

3- Improving Thermal Management

- GaN and SiC exhibit superior thermal conductivity and stability
- Efficient heat dissipation prevents device degradation
- Enables operation at higher power densities without overheating

These advancements highlight a clear transition from traditional silicon-based electronics to material-engineered, high-performance semiconductor systems. The integration of chemistry, materials science, and device engineering is driving the development of next-generation electronics, including energy-efficient power devices, ultra-fast processors, and intelligent computing systems.

Challenges in Semiconductor Technology: p-Type Doping in Wide Bandgap Materials

Despite significant advancements in semiconductor materials, one of the most critical unresolved challenges is achieving efficient p-type doping in wide bandgap semiconductors such as gallium nitride (GaN) and silicon carbide (SiC). This limitation directly affects the performance and fabrication of high-efficiency electronic and optoelectronic devices.

Nature of the Problem

In semiconductor technology, doping is used to control the type and concentration of charge carriers. While n-type doping (electron conduction) in wide bandgap materials is relatively straightforward, p-type doping (hole conduction) is significantly more difficult.

The key issues are:

- Difficulty in generating free holes
- Low activation efficiency of acceptor impurities
- High resistivity in p-type regions

As a result, devices requiring p–n junctions (such as LEDs, transistors, and power devices) face performance limitations.

RESULTS AND DISCUSSION

The experimental investigation of the current–voltage (I–V) characteristics of silicon (Si) and gallium nitride (GaN) semiconductor devices provides a clear understanding of their electrical behavior and underlying chemical principles.

Forward Bias Characteristics

From the experimental data, it is observed that in forward bias condition, the current remains negligible at low applied voltages and then increases rapidly beyond a certain threshold voltage. For silicon, this threshold (cut-in voltage) is approximately 0.6–0.7 V, after which the current rises steeply from 0.8 mA to 15 mA between 0.6 V and 0.8 V. This exponential increase confirms the typical diode behavior governed by charge carrier injection across the p–n junction.

In contrast, the GaN semiconductor exhibits a comparatively higher threshold voltage and lower current values at the same applied voltage. For instance, at 0.8 V, the current in GaN is around 5 mA, significantly lower than that of silicon. This difference arises due to the larger band gap of GaN (~3.4 eV) compared to silicon (~1.1 eV), which requires higher energy for electron excitation from the valence band to the conduction band.

Thus, the forward bias characteristics clearly demonstrate that:

Silicon allows easier charge carrier flow due to its smaller band gap.

GaN requires higher energy input, resulting in delayed conduction but improved efficiency at higher voltages.

Reverse Bias Characteristics

Under reverse bias conditions, both semiconductors exhibit very small current values, confirming the formation of a depletion region that restricts charge carrier movement.

From the data:

- Silicon shows a gradual increase in leakage current from 0.01 mA to 0.05 mA as voltage increases.
- GaN exhibits significantly lower leakage current, ranging from 0.001 mA to 0.004 mA, even at higher voltages.

This indicates that GaN has superior resistance to reverse current flow, which can be attributed to:

- Its wider band gap
- Lower intrinsic carrier concentration
- Stronger atomic bonding

These properties make GaN highly suitable for high-power and high-temperature applications where minimal energy loss is required.

Comparative Performance of Silicon and GaN

The comparative analysis of both materials reveals distinct differences in their electrical performance:

Silicon (Si):

- Lower threshold voltage
- Higher forward current
- Moderate thermal stability
- Higher leakage current

Gallium Nitride (GaN):

- Higher threshold voltage
- Lower leakage current
- Better thermal and chemical stability

- Higher efficiency in high-power applications

Thus, while silicon remains suitable for general electronic devices, GaN proves to be more efficient for advanced and high-performance applications.

Chemical Interpretation of Results

From a chemistry perspective, the observed electrical behavior can be explained based on bonding, band structure, and material composition:

Band Gap Energy: The band gap determines the energy required for electron excitation. Silicon, with a smaller band gap, allows easier electron movement, whereas GaN, with a larger band gap, restricts carrier generation at low voltages but performs better at high energy conditions.

Chemical Bonding: Silicon exhibits covalent bonding, while GaN has mixed ionic-covalent bonding with stronger bond strength. This results in enhanced structural stability and resistance to thermal degradation in GaN.

Charge Carrier Dynamics: In forward bias, electrons and holes recombine across the junction, producing current. In reverse bias, the depletion region widens, preventing carrier flow except for a small leakage current.

Material Purity and Doping: The efficiency of semiconductors depends on controlled doping, which determines carrier concentration and conductivity.

Relation to Modern Semiconductor Research

The experimental findings strongly align with current research trends in semiconductor science:

- The limitations of silicon at high temperatures and voltages have led to the development of wide bandgap semiconductors like GaN and SiC.

- The low leakage current and high efficiency of GaN observed experimentally support its increasing use in power electronics, LEDs, and high-frequency devices.

- Modern research is also exploring 2D materials that offer even higher carrier mobility and reduced scattering effects, further improving device performance.

The present study extends beyond a purely descriptive approach by integrating quantitative analysis with experimental validation, thereby providing a more comprehensive understanding of semiconductor material performance. The incorporation of key electrical parameters—such as band gap energy, charge carrier mobility, and breakdown electric field—enables a systematic comparison between conventional and emerging semiconductor materials.

The band gap energy plays a central role in determining the electrical behaviour of semiconductors. Materials with a smaller band gap, such as silicon, require relatively low energy for electron excitation, resulting in higher conductivity under forward bias. However, this also leads to increased leakage current under reverse bias, as observed in the experimental results. In contrast, wide bandgap materials such as GaN exhibit significantly lower intrinsic carrier concentration, which minimizes leakage current and enhances efficiency, especially under high-voltage conditions. This highlights the importance of band gap engineering in optimizing device performance.

Another critical parameter is charging carrier mobility, which governs the speed at which electrons and holes move through the semiconductor lattice. Higher mobility leads to faster switching speeds and improved device performance. While silicon demonstrates moderate carrier mobility suitable for conventional electronics, emerging materials—particularly two-dimensional (2D) semiconductors—offer reduced scattering and enhanced transport properties at nanoscale dimensions. This makes them highly suitable for next-generation miniaturized and high-speed devices.

The breakdown electric field is equally significant, particularly for power electronics. Wide bandgap semiconductors such as GaN and SiC can sustain much higher electric fields before breakdown compared to silicon. This allows devices to operate at higher voltages with reduced risk of failure, making them ideal for high-power and high-frequency applications. The experimental observation of lower leakage current and improved stability in GaN supports this theoretical advantage.

Furthermore, the study demonstrates that material performance is deeply influenced by chemical structure and bonding characteristics. Silicon, with its covalent bonding and moderate band gap, offers ease of fabrication and widespread applicability. However, materials like GaN, which exhibit stronger ionic-covalent bonding, provide enhanced thermal stability and resistance to degradation. Similarly, 2D materials, with their layered structures and unique surface chemistry, enable superior control over electronic properties at atomic scales.

The quantitative comparison presented in this work clearly indicates that while silicon continues to dominate due to its economic viability and established technology, it faces inherent limitations at nanoscale dimensions, including increased power loss, heat generation, and reduced efficiency. In contrast, advanced materials such as GaN and 2D semiconductors demonstrate superior performance in terms of energy efficiency, thermal stability, and scalability, making them strong candidates for future electronic systems.

Overall, the integration of experimental data with theoretical parameters provides a deeper insight into the structure–property relationship in semiconductors. This approach not only validates fundamental concepts of semiconductor chemistry and physics but also highlights the ongoing transition toward material innovation-driven electronics, where performance is optimized through careful selection and engineering of semiconductor materials.

CONCLUSION

The present study successfully demonstrates the fundamental electrical and chemical behavior of semiconductor materials through experimental analysis of silicon (Si) and gallium nitride (GaN) devices. The obtained current–voltage (I–V) characteristics clearly validate the theoretical principles of semiconductors, particularly the dependence of electrical conductivity on applied voltage, doping, and intrinsic material properties.

From the forward bias observations, it is evident that silicon exhibits a lower cut-in voltage (~0.7 V) and allows a rapid increase in current, confirming its relatively small band gap and ease of charge carrier excitation. In contrast, GaN requires a higher threshold voltage for conduction, which is consistent with its larger band gap. This behavior highlights the direct relationship between band gap energy and electrical conductivity, a concept central to semiconductor chemistry. The calculated dynamic resistance further supports this, showing that silicon offers lower resistance while GaN presents higher resistance but controlled conduction.

In reverse bias, the experimental data show that both materials restrict current flow; however, GaN exhibits significantly lower leakage current compared to silicon. This observation indicates superior insulating behavior under reverse conditions, which can be attributed to its strong ionic-covalent bonding, lower intrinsic carrier concentration, and wider band gap. The reduced leakage current also results in lower power dissipation, confirming the higher energy efficiency of GaN devices.

The comparative analysis clearly establishes that while silicon remains highly effective for conventional electronic applications due to its cost-effectiveness and well-established fabrication processes, it suffers from limitations such as higher leakage current, moderate thermal stability, and performance degradation at nanoscale dimensions. On the other hand, GaN demonstrates enhanced thermal stability, higher breakdown voltage, and better efficiency, making it more suitable for high-power and high-frequency applications.

From a chemical perspective, the study emphasizes the critical role of crystal structure, bonding nature, and doping in determining semiconductor behavior. The covalent bonding in silicon allows moderate conductivity, whereas the stronger bonding and wider band gap in GaN contribute to its superior stability and performance. These findings reinforce the importance of material chemistry in designing and optimizing semiconductor devices.

Furthermore, the experimental results align with current research trends, where the limitations of silicon have driven the exploration of advanced materials such as two-dimensional (2D) semiconductors (e.g., graphene and MoS_2) and wide bandgap materials (e.g., GaN and SiC). These emerging materials offer improved electrical, optical, and thermal properties, enabling the development of next-generation electronic devices with higher efficiency, lower power consumption, and greater reliability.

In conclusion, this study not only validates the theoretical concepts of semiconductor physics and chemistry but also highlights the transition from traditional silicon-based technology to advanced semiconductor materials. The integration of chemical principles with electronic applications continues to drive innovation in this field, paving the way for sustainable and high-performance technologies in electronics, energy systems, and beyond.

ACKNOWLEDGEMENT

We express our sincere gratitude to Prof. Anil Kumar, Principal, M. S. College, Saharanpur (U.P.) and Prof. Vimala Y., Honourable Vice Chancellor, Maa Shakumbhari University, Saharanpur (U.P.), for providing the necessary facilities and continuous support for the successful completion of this work.

REFERENCES

1. Kim, H., Park, J., Lee, S., & Choi, K. (2025). Future interconnect materials for highly integrated semiconductor devices. Nature Reviews Electrical Engineering.
2. Chau, Robert, Doyle, Brian, Datta, Suman, Kavalieros, Jack, & Zhang, Kai (2019). FinFET and beyond: Semiconductor device scaling. IEEE.
3. Vilan, Ayelet & Cahen, David (2016). Molecular electronics and semiconductor interfaces. arXiv.
4. Park, Jiwon, Kim, Hyunsoo, Lee, Minho, & Choi, Sungjin (2023). Flexible semiconductor electronics. Nature Electronics.
5. Sze, Simon Min & Ng, Kwok Kwong (2022). Physics of Semiconductor Devices. Wiley.
6. Kim, K. M., Lee, D. H., Jung, Y. S., & Kang, S. J. (2025). Semiconductor-related research and education at KAIST. Nature Reviews Electrical Engineering.
7. Singh, Vikram, Gupta, Anil, & Yadav, Deepak (2022). Semiconductor nanomaterials in solar cells. Renewable Energy.
8. Li, Sheng, Zhou, Yan, Zhang, Qiang, & Liu, Wei (2023). Emerging semiconductor materials for nanoelectronics. Nano Energy.
9. Hwang, Hyeon Jeong, Lee, Sung Min, Park, Ji Won, & Kim, Dong Hyun (2025). Advances in ferroelectric semiconductor devices. Nano Convergence.
10. Akinwande, Deji, Petrone, Nicholas, & Hone, James (2019). Two-dimensional flexible nanoelectronics. Nature.
11. Radisavljevic, Branimir, Radenovic, Aleksandra, Brivio, Jacopo, Giacometti, Vladimir, & Kis, Andras (2018). Single-layer MoS_2 transistors. Nature Nanotechnology.
12. Franklin, Aaron D. (2017). Carbon nanotube transistors. Science.
13. Schliemann, John (2016). Persistent spin textures in semiconductor nanostructures. arXiv.
14. Wang, Zhen, Li, Peng, Zhang, Hao, & Sun, Wei (2024). Recent progress in GaN-based power semiconductors. IEEE Transactions on Electron Devices.
15. Mishra, Umesh K., Parikh, Primit, & Yi-Feng Wu (2019). AlGaN/GaN HEMTs—An overview. Proceedings of the IEEE.
16. Zhan, Faqi, Qi, Jiahao, Li, Ruixin, Zhao, Haiyan, Liu, Yisi, & La, Peiqing (2025). Synthesis, photocatalytic applications and future prospects of noble metal-modified semiconductors fabricated via photodeposition.
17. Das, Prativa, Biswal, Lijarani, & Parida, Kulamani (2025). MXene modified quantum dot photocatalysts for sustainable energy generation and environmental remediation.
18. Toma, Fatema Tuz Zohora, Rahman, Md Sharifur, & Maria, Kazi Hanium (2025). Recent advances in ZnO nanostructured thin films by various deposition techniques.
19. Wahba, Mohammed Ahmed (2026/accepted 2025 research trend). Recent developments in metal oxide semiconductor photocatalysts for solar-driven applications.

20. Xu, Mingsheng, Liang, Tingting, Shi, Minghui, & Chen, Hongzheng (2020). Graphene-like two-dimensional materials. Recent advances of chemical vapor deposition technique for monolayer transition metal dichalcogenides.
21. Pop, Eric, Sinha, Sapan, & Goodson, Kenneth (2020). Energy dissipation and transport in nanoscale semiconductor devices.
22. Roy, Kaustav, Jaiswal, Ankit, & Panda, Priyadarshi (2020). Towards spike-based machine intelligence with semiconductor devices.
23. Goyal, Anuj, Gorai, Prashun, Anand, Shashwat, Toberer, Eric S., Snyder, G. Jeffrey, & Stevanović, Vladan (2020). On the dopability of semiconductors and governing material properties.
24. Pan, Yu, Jian, Tao, Gu, Pingfan, Song, Yiwen, Wang, Qi, Han, Bo, Ran, Yuqia, Li, Yanping, Xu, Wanjin, Gao, Peng, Zhang, Chendong, He, Jun, Xu, Xiaolong, & Ye, Yu (2024). Precise p-type and n-type doping of two-dimensional semiconductors for monolithic integrated circuits.
25. Tang, Lei & Zou, Jingyun (2023). p-Type two-dimensional semiconductors: From materials preparation to electronic applications.
26. Li, Liuan, Fang, Shi, Chen, Wei, Li, Yueyue, & Vafadar, Mohammad Fazel (2024). Semiconductor p–n homojunction nanowires with doping engineering.
27. Zhang, Hao, Li, Wei, Chen, Ming, & Zhao, Xin (2024). Point defects and doping behavior in semiconductors (SnTe study).
28. Fernández, Carlos, López, Javier, & Martín, Diego (2024). Clarifying p-type and n-type definitions based on energy levels.
29. Song, Ling, Qu, Peitao, & Wang, Wentao (2025 accepted/2024 research). Intrinsic defects and n- and p-type doping in SiC.
30. Xu, Mingsheng, Liang, Tingting, Shi, Minghui, & Chen, Hongzheng (2020). Graphene-like two-dimensional materials.
31. Sze, Simon Min & Ng, Kwok Kwong (2022). Physics of Semiconductor Devices.