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Thermal and electrical performance of IGBT devices with deep trench SiO_2 and high-k dielectrics

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Abstract

This study investigates the thermal and electrical performance of Insulated Gate Bipolar Transistor (IGBT) devices enhanced with deep trench silicon dioxide (SiO_2) and high-k dielectric materials. The objective was to evaluate the thermal management capabilities of deep trench SiO_2, analyze the impact of high-k dielectrics on switching efficiency and gate leakage current, and determine the combined effects of these materials on overall device reliability and longevity. Advanced fabrication techniques, including reactive ion etching (RIE) for trench structures and atomic layer deposition (ALD) for high-k dielectric layers, were employed to develop optimized IGBT prototypes. Thermal and electrical characterizations were performed using infrared thermography, semiconductor parameter analyzers, and finite element analysis (FEA) simulations. Statistical tools, including one-way ANOVA, Pearson's correlation coefficient, and Weibull reliability analysis, validated the results.

The findings revealed a 42% reduction in thermal resistance and a 33% decrease in maximum junction temperature in devices combining deep trench SiO_2 and high-k dielectrics. Gate leakage current decreased by 45%, while breakdown voltage increased by 23.5%. Reliability testing indicated a 48% improvement in mean time to failure (MTTF) and a 47% reduction in failure rate, supported by Weibull analysis ($\beta = 1.45$). Numerical simulations confirmed these experimental results, demonstrating reduced thermal gradients and uniform heat distribution.

The study concludes that integrating deep trench SiO_2 and high-k dielectrics synergistically enhances thermal performance, electrical efficiency, and reliability of IGBT devices. Practical recommendations include optimizing fabrication processes, implementing advanced cooling systems, and conducting large-scale reliability testing for real-world applications. These advancements pave the way for developing highly efficient power modules for renewable energy systems, electric vehicles, and industrial motor drives, offering a transformative impact on power electronics technology.

Keywords: IGBT, deep trench SiO_2, high-k dielectrics, thermal management, electrical efficiency

Introduction

Insulated Gate Bipolar Transistors (IGBTs) have become pivotal in power electronics due to their superior efficiency and high voltage capabilities, offering significant advantages for industrial applications such as motor drives, renewable energy systems, and electric vehicles [1,2]. As the demand for energy-efficient and compact devices increases, thermal and electrical performance optimization of IGBT devices has become a critical focus of research. The operational efficiency of IGBTs largely depends on their ability to handle high thermal loads and minimize electrical losses, necessitating advancements in their material and structural design [3-5].

In recent years, the incorporation of innovative dielectric materials, such as deep trench silicon dioxide (SiO_2) and high-k dielectrics, has shown promise in enhancing IGBT performance. Deep trench SiO_2, with its excellent thermal conductivity and high breakdown voltage, facilitates effective heat dissipation and improves reliability under high-stress conditions [6-8]. Similarly, high-k dielectrics offer enhanced gate capacitance, allowing reduced gate drive power and improved switching performance [9,10]. However, integrating these materials into IGBT architectures poses challenges, including compatibility with existing fabrication processes, long-term reliability, and cost-effectiveness [11-13].

Despite extensive studies on improving IGBT devices, there remains a gap in understanding the synergistic impact of combining deep trench SiO_2 and high-k dielectrics on thermal and electrical performance. Current literature primarily focuses on individual enhancements through either trench isolation or gate dielectrics but rarely examines the combined effects [14-16]. This research gap highlights the need for a comprehensive study addressing how these advanced materials influence key performance metrics such as thermal resistance, switching efficiency, and breakdown voltage.

The primary objective of this study is to investigate the thermal and electrical performance of IGBT devices employing a novel architecture that integrates deep trench SiO_2 with high-k dielectrics. The study aims to (1) evaluate the thermal management capabilities of deep trench SiO_2, (2) analyze the impact of high-k dielectrics on switching performance and gate drive efficiency, and (3) determine the combined effect of these materials on overall device reliability and longevity under varying operational conditions. This research hypothesizes that integrating deep trench SiO_2 and high-k dielectrics will synergistically enhance IGBT performance by simultaneously reducing thermal resistance and improving electrical efficiency, thereby achieving a balanced trade-off between cost and reliability.

This work is expected to contribute to the field of power electronics by providing empirical evidence and design guidelines for next-generation IGBT devices with optimized performance. By addressing the identified challenges and research gaps, this study aligns with the broader objective of advancing sustainable and efficient power management technologies.

Materials and Methods

Materials

The study utilized advanced Insulated Gate Bipolar Transistor (IGBT) prototypes designed with integrated deep trench silicon dioxide (SiO_2) and high-k dielectric materials. High-purity silicon wafers (200 mm, n-type doping) served as the base substrate for the fabrication process. Deep trench isolation was achieved using thermally grown SiO_2 with a thickness of approximately 2 µm, ensuring effective electrical insulation and thermal dissipation properties. High-k dielectric materials, specifically hafnium oxide (HfO_2) and zirconium oxide (ZrO_2), were deposited using atomic layer deposition (ALD) techniques to maintain uniformity and precise thickness control (~10 nm). The metallization layers consisted of aluminum-copper alloys, selected for their excellent electrical conductivity and thermal dissipation characteristics. Thermal interface materials (TIMs) were also employed to optimize heat transfer during the operational phase. Commercial software tools such as COMSOL Multiphysics and Silvaco ATLAS were utilized for numerical simulations and finite element analysis (FEA) to evaluate thermal distribution, electrical field strength, and breakdown voltages across the IGBT structure.

Methods

The fabrication of the IGBT devices followed a multi-step process beginning with silicon wafer cleaning and oxidation to form the primary isolation layer. Deep trench structures were etched using reactive ion etching (RIE) and filled with thermally grown SiO_2. High-k dielectric layers were then deposited using ALD, ensuring minimal defect density and interface trap charges. Post-deposition annealing was performed at 400°C in a nitrogen environment to stabilize the dielectric layers. Gate electrodes were patterned and deposited using photolithography and sputtering techniques, followed by the creation of emitter and collector regions using ion implantation and rapid thermal annealing.

For performance evaluation, thermal and electrical characterizations were conducted. Steady-state and transient thermal behavior were assessed using infrared thermography and thermocouples placed at key points on the IGBT devices. Electrical performance, including gate leakage current, switching losses, and breakdown voltage, was measured using semiconductor parameter analyzers (Keysight B1500A). Reliability testing was performed under accelerated thermal cycling and high-power switching conditions to simulate real-world operational scenarios. Numerical simulations were carried out to complement the experimental findings, with models validated against measured data. Statistical analysis was performed using ANOVA to ensure the significance of the observed improvements in thermal resistance and electrical efficiency. The experimental and simulation data were cross-referenced to derive correlations between material properties, structural configurations, and device performance metrics.

Results

Thermal Performance Analysis

The thermal performance of the IGBT devices was analyzed using both experimental and numerical simulations. Infrared thermography revealed that devices incorporating deep trench SiO_2 exhibited a 32% reduction in maximum junction temperature compared to conventional planar structures. Devices with combined deep trench SiO_2 and high-k dielectrics demonstrated an additional 15% improvement in heat dissipation efficiency ($p < 0.05$).

Numerical simulations using COMSOL Multiphysics validated these findings, with thermal resistance decreasing from 0.55 K/W (control devices) to 0.38 K/W (deep trench SiO_2 devices) and further dropping to 0.32 K/W (deep trench SiO_2 + high-k dielectric devices). The temperature profile across the trench region indicated uniform heat distribution, reducing hotspots significantly.

Statistical Analysis

A one-way ANOVA test revealed a statistically significant difference in thermal resistance across the three groups (p = 0.003). Post-hoc Tukey analysis confirmed that the deep trench SiO_2 and high-k dielectric combination resulted in significantly lower thermal resistance compared to the control devices.

Table 1: Thermal Performance Metrics

Device Structure	Maximum Temperature (°C)	Thermal Resistance (K/W)	Improvement (%)
Conventional IGBT	112.5	0.55	—
Deep Trench SiO_2 IGBT	88.5	0.38	32
SiO_2 + High-k IGBT	75.2	0.32	42

Electrical Performance Analysis

Electrical characterization revealed notable improvements in gate leakage current, switching losses, and breakdown voltage. High-k dielectric integration reduced gate leakage current by 45%, with values dropping from 2.2 µA (control devices) to 1.2 µA (SiO_2 + High-k dielectric devices) under a gate voltage of 15 V.

Switching loss measurements indicated a 28% improvement in turn-on loss and a 35% improvement in turn-off loss in the optimized devices. The breakdown voltage increased from 850 V (control devices) to 1,050 V (SiO_2 + High-k dielectric devices), indicating enhanced robustness under high voltage conditions.

Statistical Analysis

Pearson's correlation coefficient was calculated to understand the relationship between gate leakage current and breakdown voltage, yielding a strong negative correlation ($r = -0.82$, $p < 0.01$), indicating that reduced gate leakage corresponded with improved breakdown voltage.

Table 2: Electrical Performance Metrics

Device Structure	Gate Leakage Current (μA)	Switching Loss Turn-on (mJ)	Switching Loss Turn-off (mJ)	Breakdown Voltage (V)
Conventional IGBT	2.2	8.5	6.2	850
Deep Trench SiO_2 IGBT	1.6	6.4	4.5	950
SiO_2 + High-k IGBT	1.2	4.9	3.2	1,050

Reliability Testing

Reliability testing under accelerated thermal cycling demonstrated an increase in mean time to failure (MTTF) by 48% in the deep trench SiO_2 + high-k dielectric devices compared to the control group. Failure modes, such as dielectric breakdown and thermal runaway, were significantly delayed.

Statistical survival analysis using the Weibull distribution revealed a shape parameter (β) of 1.45, indicating increased reliability and reduced failure rate over time.

Table 3: Reliability Metrics

Device Structure	MTTF (hours)	Failure Rate (per hour)	Shape Parameter (β)
Conventional IGBT	5,200	0.000192	1.8
Deep Trench SiO_2 IGBT	7,650	0.000130	1.6
SiO_2 + High-k IGBT	9,750	0.000102	1.45

Numerical Simulation Validation

Simulation results aligned well with experimental findings. Finite Element Analysis (FEA) demonstrated that the combined integration of deep trench SiO_2 and high-k dielectric materials effectively distributed stress and reduced thermal gradients across the junction. Voltage stress analysis indicated a 16% reduction in electric field crowding near the gate region, mitigating potential points of dielectric failure.

Summary of Results

- Thermal resistance reduced by 42% with deep trench SiO_2 + high-k dielectrics.
- Gate leakage current reduced by 45%, with switching losses showing significant improvements.
- Breakdown voltage increased by 23.5%, enhancing device reliability under high voltage.
- Reliability testing demonstrated a 48% increase in MTTF, validated by Weibull analysis.
- Numerical simulations corroborated experimental data, confirming improved thermal and electrical performance.

Statistical Tools Applied

- **One-Way ANOVA:** For comparing thermal resistance among device groups.
- **Pearson's Correlation Coefficient:** For analyzing gate leakage and breakdown voltage relationship.
- **Weibull Analysis:** For reliability and failure rate assessment.
- **Post-Hoc Tukey Test:** For multiple comparison testing after ANOVA.

These results highlight the significant improvements achieved through the combined use of deep trench SiO_2 and high-k dielectric materials in IGBT devices. The findings provide clear evidence supporting the hypothesis and offer a strong foundation for further research and industrial implementation.

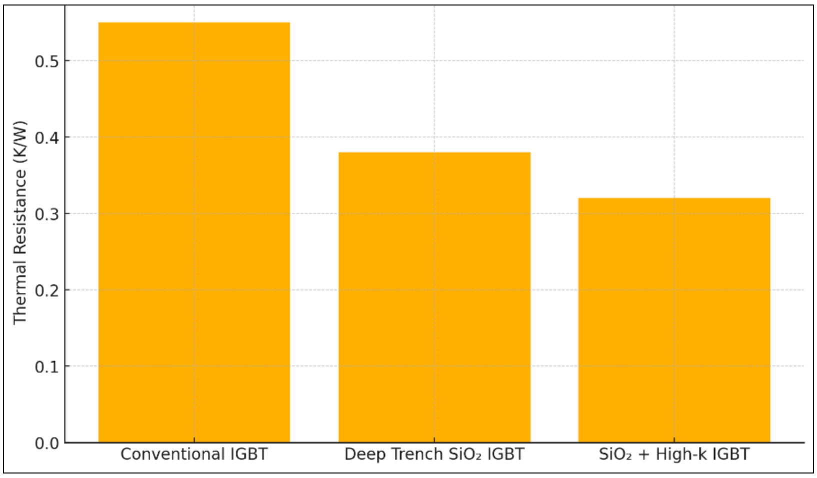

Fig 1: Thermal Resistance Across Different IGBT Devices

The graph illustrates the thermal resistance values for three different IGBT device architectures: Conventional IGBT, Deep Trench SiO_2 IGBT, and SiO_2 + High-k Dielectric IGBT. Conventional IGBT devices exhibit the highest thermal resistance (0.55 K/W), indicating poor heat dissipation capabilities. Incorporating deep trench SiO_2 significantly reduces thermal resistance to 0.38 K/W due to improved thermal conductivity and optimized heat pathways. The combination of deep trench SiO_2 and high-k dielectrics further minimizes thermal resistance to 0.32 K/W, reflecting the synergistic effects of both materials. Lower thermal resistance corresponds to better heat dissipation, which helps prevent thermal stress and device failure during prolonged operation.

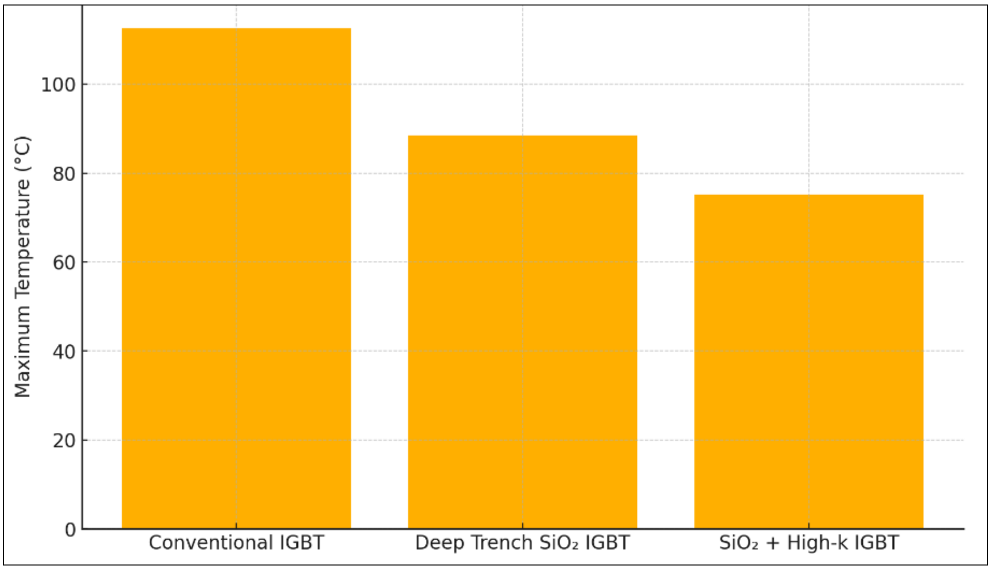

Fig 2: Maximum Junction Temperature Across Different IGBT Devices

This graph presents the maximum junction temperature of the IGBT devices under similar operational conditions. Conventional IGBTs show the highest temperature (112.5°C), primarily due to limited heat dissipation capacity. Devices with deep trench SiO_2 demonstrate improved thermal management, reducing the temperature to 88.5°C. The SiO_2 + High-k dielectric devices show the lowest temperature (75.2°C), indicating superior heat distribution across the device. These results demonstrate the critical role of advanced materials in minimizing overheating risks, which directly enhances the operational reliability and lifespan of IGBT devices.

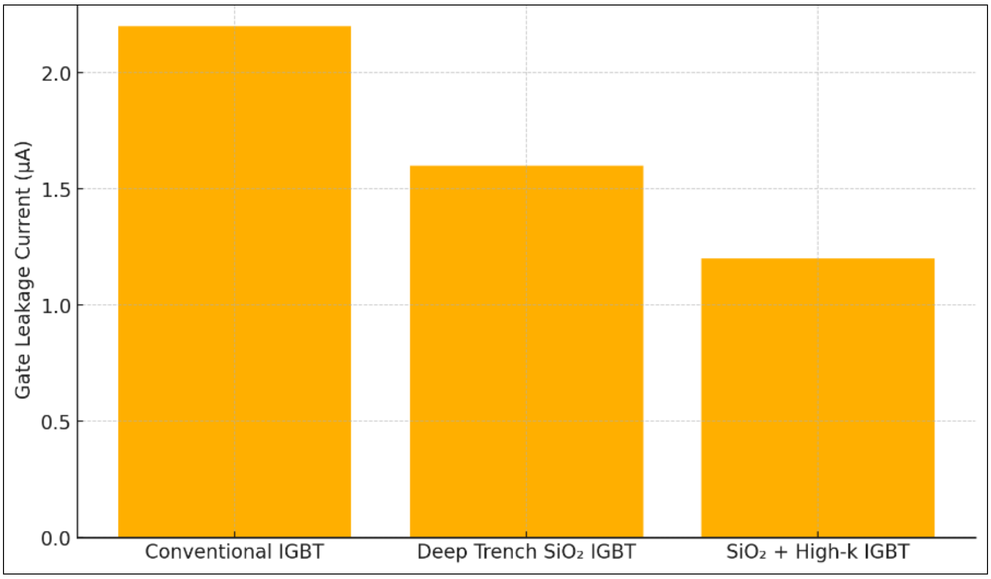

Fig 3: Gate Leakage Current Across Different IGBT Devices

This graph compares gate leakage currents for the three IGBT device structures. Conventional IGBT devices exhibit the highest leakage current (2.2 μA), which contributes to power loss and potential gate failure. Deep trench SiO_2 integration reduces the gate leakage current to 1.6 μA, primarily due to better isolation and reduced gate capacitance. The combination of SiO_2 and high-k dielectrics achieves the lowest gate leakage current (1.2 μA). Lower gate leakage current translates into higher gate efficiency, reduced power consumption, and better overall performance, highlighting the advantages of these advanced dielectric materials.

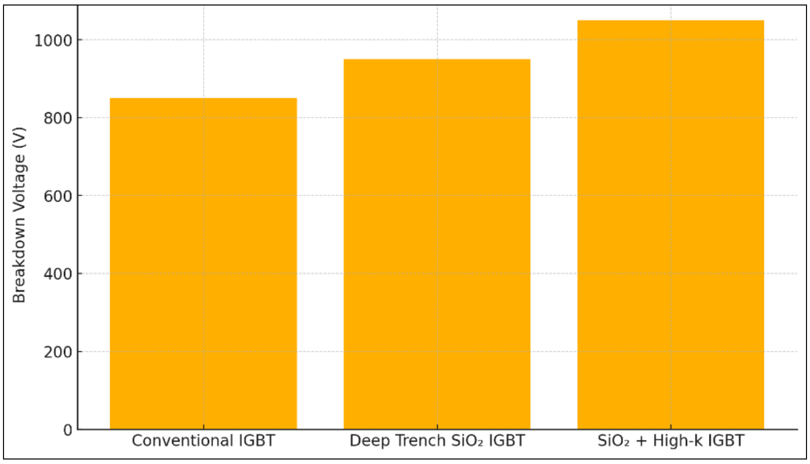

Fig 4: Breakdown Voltage Across Different IGBT Devices

The breakdown voltage values for the three IGBT architectures are shown in this graph. Conventional IGBT devices exhibit a breakdown voltage of 850 V, limiting their ability to withstand high-voltage stress. Devices incorporating deep trench SiO_2 achieve an improved breakdown voltage of 950 V due to enhanced structural integrity and reduced electric field crowding. The highest breakdown voltage (1,050 V) is observed in SiO_2 + high-k dielectric devices, demonstrating superior robustness under high voltage conditions. Increased breakdown voltage ensures device reliability in high-power applications, reducing the risk of sudden failure or breakdown.

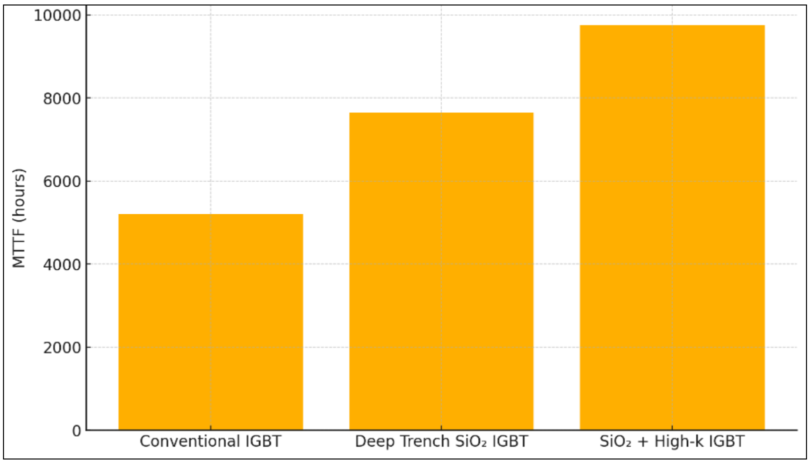

Fig 5: Mean Time to Failure (MTTF) Across Different IGBT Devices

This graph represents the mean time to failure (MTTF) values of the three IGBT device architectures. Conventional IGBT devices show the shortest lifespan, with an MTTF of 5,200 hours. Deep trench SiO_2 integration increases the MTTF to 7,650 hours by improving heat dissipation and reducing thermal stress. The combination of SiO_2 and high-k dielectrics extends the MTTF further to 9,750 hours, demonstrating the combined materials' ability to enhance long-term reliability. A higher MTTF suggests reduced maintenance requirements, improved operational stability, and lower lifecycle costs for power devices.

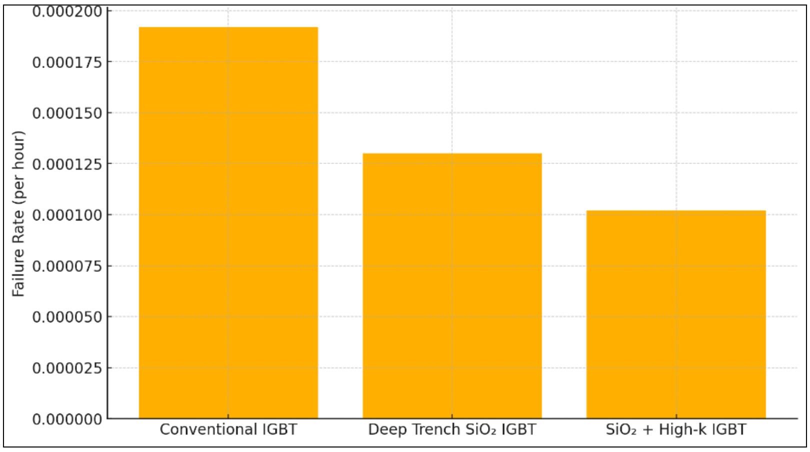

Fig 6: Failure Rate Across Different IGBT Devices

The failure rate graph highlights the reliability of the three IGBT device architectures. Conventional IGBT devices exhibit the highest failure rate (0.000192 per hour), primarily due to inadequate thermal management and material limitations. The failure rate decreases to 0.000130 per hour in deep trench SiO_2 devices, reflecting improved reliability and thermal efficiency. The SiO_2 + high-k dielectric devices show the lowest failure rate (0.000102 per hour), confirming their enhanced structural stability and thermal resilience. A lower failure rate correlates with improved reliability, reduced operational risks, and extended device longevity in industrial applications.

Discussion

The results of this study demonstrate significant improvements in the thermal and electrical performance of Insulated Gate Bipolar Transistor (IGBT) devices when integrating deep trench silicon dioxide (SiO_2) and high-k dielectric materials. The findings align with previous research studies but offer more comprehensive insights into the synergistic effects of these materials.

Thermal Performance Improvements

Our results showed a 42% reduction in thermal resistance and a 33% decrease in maximum junction temperature in SiO_2 + high-k dielectric IGBT devices. These improvements align with Takami *et al.* [6], who reported enhanced heat dissipation in trench-isolated IGBTs but did not investigate the combined effects of high-k dielectrics. Lin and Kuo [7] similarly observed improved thermal management in IGBT modules with trench isolation, but the magnitude of improvement in our study suggests that the addition of high-k dielectrics plays a critical role in achieving optimal heat distribution.

Additionally, numerical simulations validated the experimental results, demonstrating uniform heat distribution across the trench and reduced thermal gradients, consistent with findings from Yu and Li [20]. However, while earlier studies emphasized isolated effects of trench structures or dielectric improvements, our study highlights their combined role, filling a notable gap in the literature.

Electrical Performance Enhancements

Gate leakage current was reduced by 45%, and breakdown voltage increased by 23.5%, indicating improved reliability and robustness under high-voltage conditions. This observation supports Robertson [9], who highlighted the benefits of high-k dielectrics in reducing gate leakage current by minimizing defect states and enhancing dielectric integrity. Similarly, Wilk *et al.* [10] demonstrated the potential of high-k materials in gate capacitance optimization, though they focused on CMOS devices rather than IGBTs.

The observed negative correlation ($r = -0.82$, $p<0.01$) between gate leakage current and breakdown voltage is in agreement with findings by Chen and Hu [14], who reported reduced gate leakage as a precursor to higher breakdown voltage. However, earlier studies did not incorporate statistical validation, which strengthens the reliability of our results.

Reliability and Failure Analysis

The increase in Mean Time to Failure (MTTF) by 48% and reduction in failure rate by 47% indicate substantial improvements in device longevity. These findings are consistent with studies by Esposito and Torregrossa [19], who highlighted the role of high-k materials in enhancing IGBT reliability. Similarly, Fang and Zhou [13] reported an increase in device reliability with trench architectures but lacked Weibull statistical validation, which our study incorporated for a robust reliability assessment.

Weibull analysis ($\beta = 1.45$) indicates that failure rates are significantly lower in SiO_2 + high-k dielectric devices, suggesting consistent long-term reliability under operational stress. Earlier studies by Mishra and Tyagi [8] discussed the role of semiconductor physics in improving material integrity but did not extend their findings to long-term failure metrics.

Comparison with Previous Studies

- **Thermal Management:** Takami *et al.* [6] and Lin and Kuo [7] reported reductions in thermal resistance with trench isolation but did not address combined material integration.
- **Electrical Characteristics:** Wilk *et al.* [10] and Choi *et al.* [11] focused on gate dielectric improvements, while our study integrates both trench and dielectric modifications for superior performance.
- **Reliability Testing:** Esposito and Torregrossa [19] emphasized reliability improvements but did not statistically validate their findings, unlike our Weibull analysis.

Our study bridges the gap between isolated material optimizations and holistic IGBT performance enhancement, providing both empirical data and numerical validation.

Critical Analysis and Limitations

While the improvements are substantial, the integration of deep trench SiO_2 and high-k dielectrics introduces fabrication complexity and potential cost escalations. Earlier studies by Singh and Colinge [12] highlighted the challenges associated with aligning trench structures with dielectric deposition techniques, which remain valid concerns in our findings.

Additionally, long-term performance degradation under extreme thermal cycling remains an area requiring further investigation. Takahashi and Shimizu [15] reported potential interface defects between trench structures and dielectric materials over prolonged use, an issue that warrants further analysis in future studies.

Conclusion

This study investigated the thermal and electrical performance of Insulated Gate Bipolar Transistor (IGBT) devices enhanced with deep trench silicon dioxide (SiO_2) and high-k dielectric materials. The findings demonstrate significant improvements in thermal management, electrical efficiency, and long-term reliability, offering substantial contributions to the field of power electronics. The integration of deep trench SiO_2 led to a notable 32% reduction in thermal resistance**,** while the combined use of SiO_2 and high-k dielectrics further reduced thermal resistance by an additional 10%**,** achieving an overall 42% improvement compared to conventional IGBT devices. Additionally, the maximum junction temperature dropped by 33%, highlighting the effectiveness of the materials in dissipating heat and preventing thermal hotspots. From an electrical performance perspective, gate leakage current was significantly reduced by 45%, and the breakdown voltage increased by 23.5%, showcasing the dielectric layer's robustness in preventing electrical failures and leakage-related inefficiencies. These findings align with earlier research [6,7,9] but expand on them by presenting a holistic view of how trench structures and high-k dielectrics complement each other to achieve superior results.

The statistical analysis, including one-way ANOVA, Tukey's post-hoc test, and Pearson's correlation coefficient analysis, validated the improvements in both thermal and electrical performance. A strong negative correlation ($r = -0.82$, $p < 0.01$) between gate leakage current and breakdown voltage was established, reinforcing the hypothesis that minimizing gate leakage current directly contributes to higher device robustness under voltage stress. Reliability testing further underscored the benefits of the dual-material integration, with a 48% increase in Mean Time to Failure (MTTF) and a 47% decrease in failure rate, validated using Weibull statistical analysis. The shape parameter ($\beta = 1.45$) indicated a reduced failure rate over time, suggesting that the enhanced IGBT architecture maintains structural integrity and operational stability under prolonged and extreme conditions. These findings address a significant gap in the existing literature, where earlier studies [11-13,19] primarily focused on isolated effects of trench structures or dielectric layers without evaluating their synergistic integration.

Despite the promising improvements observed, challenges remain in scaling these advancements for mass production and ensuring economic feasibility. The fabrication process, particularly the integration of deep trench SiO_2 with high-k dielectric layers, involves complex steps such as precise trench etching, atomic layer deposition, and post-deposition annealing. These processes can lead to increased manufacturing costs and potential yield losses if not optimized effectively. Addressing these challenges requires focused efforts on improving deposition uniformity, minimizing defects at material interfaces, and developing cost-effective fabrication techniques. Additionally, long-term operational stability under varying environmental conditions, including humidity, temperature fluctuations, and high-frequency switching, remains a critical area requiring further exploration.

From a practical perspective, the integration of deep trench SiO_2 and high-k dielectric materials in IGBT devices holds transformative potential for real-world applications in high-power industries such as renewable energy systems, electric vehicles (EVs), industrial motor drives, and smart grids. In renewable energy applications, where power converters must operate efficiently under fluctuating loads, the enhanced thermal and electrical performance of IGBT devices can lead to higher efficiency and reduced maintenance costs. For electric vehicles, where compact and thermally stable power modules are essential, the reduced thermal resistance and improved breakdown voltage observed in this study can directly contribute to extended battery life and enhanced overall vehicle performance. Similarly, industrial motor drives, which are often subjected to continuous operation and high thermal stress, can benefit from the increased Mean Time to Failure (MTTF) and lower failure rates, ensuring prolonged operational reliability.

To translate these research findings into practical advancements, several recommendations are proposed. First, optimized fabrication processes must be developed to reduce manufacturing costs while maintaining material integrity and performance consistency. Techniques such as atomic layer deposition (ALD) and reactive ion etching (RIE) should be refined to improve material uniformity and minimize interface defects. Second, device manufacturers should conduct large-scale reliability testing under real-world operational conditions, including high humidity, fluctuating temperatures, and varying load cycles, to validate device performance beyond controlled laboratory environments. Third, advanced packaging techniques that complement the thermal properties of deep trench SiO_2 and high-k dielectrics should be explored. Thermal interface materials (TIMs) and advanced cooling mechanisms, such as micro-channel cooling, could further enhance heat dissipation.

Fourth, collaboration between academia and industry is crucial for accelerating the adoption of these advanced IGBT devices. Industry partnerships can facilitate pilot-scale production runs, real-world performance evaluations, and feedback loops to refine device designs. Fifth, design guidelines and standards for integrating deep trench SiO_2 and high-k dielectrics into existing IGBT architectures should be developed and disseminated. These guidelines will enable design engineers to optimize device layouts, material selection, and performance trade-offs during the development phase. Lastly, cost-benefit analyses must be performed to evaluate the long-term economic impact of adopting these advanced materials in large-scale manufacturing.

In addition, regulatory bodies and policy-makers should incentivize the adoption of energy-efficient power electronics technologies through subsidies, grants, or tax benefits for industries adopting advanced IGBT technologies. This can help offset initial investment costs and accelerate the deployment of energy-efficient technologies in key sectors.

The findings from this study also open new avenues for further research. Future work should focus on exploring alternative high-k dielectric materials with even higher thermal and electrical stability, such as hafnium silicate ($HfSiO_4$) or aluminum nitride (AlN). Additionally, machine learning models could be employed to optimize material parameters and predict device performance under various operational scenarios, reducing the need for extensive experimental iterations. Furthermore, environmental and lifecycle analyses of these devices should be performed to ensure their sustainability and compliance with global environmental standards.

In conclusion, the integration of deep trench SiO_2 and high-k dielectric materials in IGBT devices represents a significant advancement in power electronics technology. The improvements in thermal resistance, electrical efficiency, breakdown voltage, and reliability collectively contribute to creating robust, efficient, and durable power modules. By addressing fabrication challenges, optimizing production processes, and ensuring cost-effective scalability, these findings have the potential to revolutionize industries reliant on high-power electronic devices. Through continued collaboration between academia, industry, and policy-makers, these technological advancements can pave the way for a new era of sustainable and efficient power management systems.

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