International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Review Article)

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Study on enhanced real time applications of compound semiconductor (SiC and GaN) power devices with AI and IoT Technologies

B. Prakash Ayyappan [1,*], T. Parthiban [1], M. Barkavi [1], V. Nithyapoorani [2], M. Sathya [2] and G. Gopperumdevi [2]

[1] Department of EEE, Sri Bharathi Engineering College for Women, Kaikkurichi, Pudukkottai-622 303, Tamil Nadu, India.
[2] Department. of ECE, Sri Bharathi Engineering College for Women, Kaikkurichi, Pudukkottai-622 303. Tamil Nadu, India.

International Journal of Science and Research Archive, 2024, 12(02), 947–964

Publication history: Received on 09 June 2024; revised on 16 July 2024; accepted on 19 July 2024

Article DOI: https://doi.org/10.30574/ijsra.2024.12.2.1309

Abstract

Compound semiconductors, composed of two or more elements, differ from single-element semiconductors like silicon. These materials are crucial because they have a direct band gap, unlike elemental semiconductors such as silicon and germanium, making them ideal for optoelectronic applications like LEDs, semiconductor lasers, and photo detectors. Robots rely on sophisticated sensors to collect vital data for their operation, including internal data on temperature, moisture, movement, and position, as well as external data from images, infrared light, and sound, processed through semiconductor units. Compound semiconductors are integral to numerous technologies around us, including electric cars, solar panels, satellites, spacecraft, and smart phones. Future innovations like driverless cars and artificial intelligence will also heavily depend on these materials.

Keywords: Silicon Carbide; Gallium Nitride; Artificial Intelligence; Internet of Things; Emerging Technologies

1. Introduction

In the quest for more efficient, reliable, and compact power electronics, two semiconductor materials have emerged as frontrunners: Silicon Carbide (SiC) and Gallium Nitride (GaN). With their unique properties and capabilities, SiC and GaN power devices are revolutionizing industries ranging from automotive and renewable energy to consumer electronics and telecommunications. This article delves into the intricacies of SiC and GaN power devices, exploring their origins, fundamental principles, current applications, and future prospects. In recent decades, scientists have made great strides in progressing semiconductor innovation.

Researchers have consistently kept pace with Moore's Law, which states that the number of circuits on a microchip doubles every two years. They have accomplished this by experimenting with variations of semiconductor materials. For example, scientists have seen potential in revisiting germanium for use in transistor technology. Electrons move four times faster in germanium than in silicon, providing a great opportunity to improve speed. Additionally, manufacturers have experimented with the following semiconductor materials:

- High-power gallium nitride (GaN)
- Silicon carbide (SiC)
- Tin oxide
- Antimonide-based and bismuthide-based materials
- Graphene
- Pyrite

* Corresponding author: B. Prakash Ayyappan

Today's IC technology at AI/IoT era drives all aspects of high-tech industry as nation's strength. Power ICs and devices are progressed from Si to SiC and GaN based technologies and are also utilizing AI techniques extensively in product design as well as manufacturing toward superior performance, yield and reliability.

AI crunches the data collected by IoT sensors to uncover insights and optimize processes. Meanwhile, IoT connects sensors, machines, and products into a massive information network. Together, they enhance automation, predictive maintenance, and quality control. Sensors are the superheroes of the factory floor, silently checking every inch of the operation.

The IoT sensors collect and transmit vital data on temperature, vibration, pressure, and flow rate, leaving no detail unnoticed. They provide real-time monitoring, giving early warnings of potential issues before they escalate into problems. AI analyzes sensor data swiftly, detecting anomalies and recommending solutions without human intervention. They are cost-effective, compact, and energy-efficient, communicating wirelessly via Wi-Fi or Bluetooth. While occasional interference or false readings may occur, AI cross-checks data from multiple sensors to minimize errors. The integration of historical data helps validate sensor readings against past patterns.

Sensors and AI technologies will continue to advance, becoming more sophisticated and ubiquitous on the factory floor. Real-time data insights will increasingly drive manufacturing success and competitiveness in the Industries.

2. Compound Semiconductor Power Devices

2.1. Silicon carbide (SiC)

Silicon carbide (SiC) has gained popularity as an alternative to silicon for semiconductor power devices, along with gallium nitride. Low ON resistance and high breakdown voltage, among other performance specifications, make SiC power devices a go-to material for high voltage uses, like power trains for railways and wind turbines.

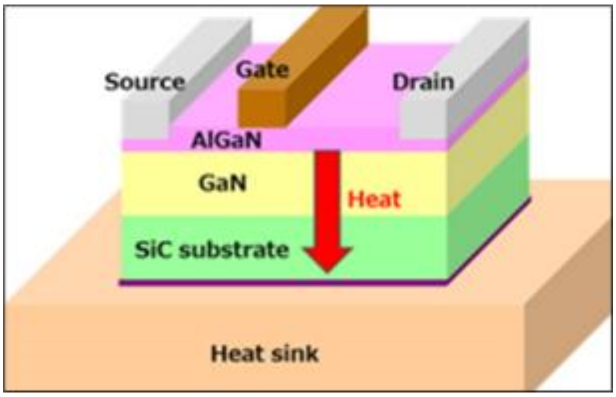

Figure 1 Structure of Silicon Carbide (SiC) and Gallium Nitride (GaN)

These materials can also withstand higher operating temperatures, which, when combined with the lower leakage and thermal resistance, means they can handle a lot more power for a given device size.

Figure 2 Silicon Carbide (SiC) Characteristics

A SiC semiconductor is a compound semiconductor composed of silicon (Si) and carbon (C). Compared to the conventional silicon semiconductors, it has the following features,

- Low on-resistance, so it can carry a large current
- High breakdown voltage
- High-speed operation, so it can operate at high frequencies
- High-temperature tolerance, even at 400 degree celsius
- SiC semiconductors are the next generation of power devices for handling high power loads. It can handle high voltages and high currents from 10 kV to hundreds of kV and from 10 A to 1000 A.

2.2. Gallium nitride (GaN)

Gallium nitride (GaN) is the chosen material for next-generation power devices due to its high breakdown strength, high electron mobility and lower power consumption. At Beneq, we use Atomic Layer Deposition workflows to reduce interface traps and extract the best performance from GaN power devices.

Gallium nitride (GaN) is a very hard, mechanically stable, binary III/V direct bandgap semiconductor. With higher breakdown strength, faster switching speed, higher thermal conductivity and lower on-resistance, power devices based on GaN significantly outperform silicon-based devices. Gallium nitride crystals can be grown on a variety of substrates, including sapphire, silicon carbide (SiC) and silicon (Si). By growing a GaN epi layer on top of silicon, the existing silicon manufacturing infrastructure can be used eliminating the need for costly specialized production sites and leveraging readily available large diameter silicon wafers at low cost.

The characterization of a material as being wide bandgap pertains to the energy required for an electron to jump from the top of the valence band to the bottom of the conduction band within the semiconductor. Materials which require energies typically larger than one or two electronvolts (eV) are referred to as wide bandgap materials. SiC and GaN semiconductors are also commonly referred to as compound semiconductors because they are composed of multiple elements from the periodic table The table below compares material properties for Silicon (Si), Silicon Carbide (SiC) and Gallium Nitride (GaN). These material properties have a major influence on the fundamental performance characteristics of the devices.

2.3. Characteristics of SiC and GaN

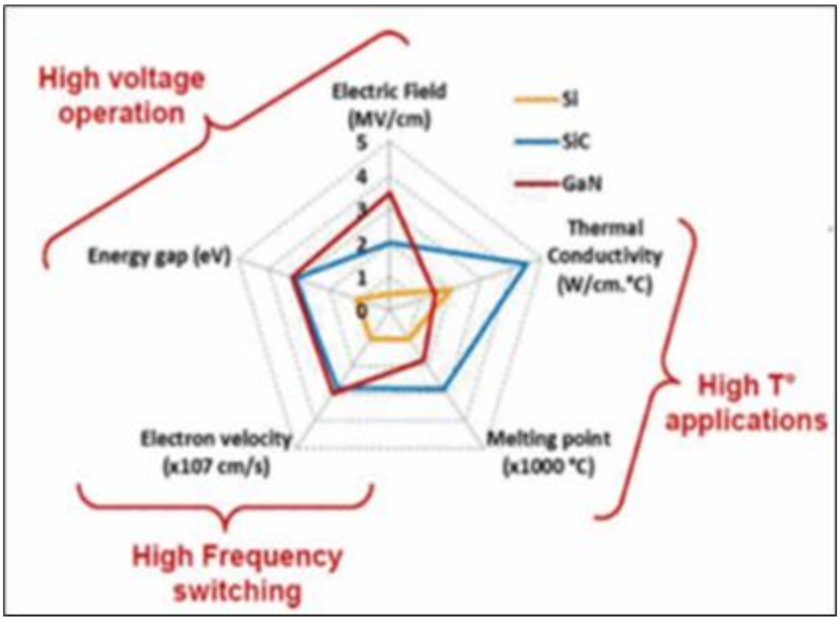

Figure 3 Silicon Carbide (SiC) and Gallium Nitride (GaN) Properties

Both SiC and GaN have material properties superior to Si for RF and Switching Power devices. The high critical field of both GaN and SiC compared to Si is a property which allows these devices to operate at higher voltages and lower leakage currents. Higher electron mobility and electron saturation velocity allow for higher frequency of operation.

While SiC has higher electron mobility than Si, GaN's electron mobility is higher than SiC meaning that GaN should ultimately be the best device for very high frequencies.

Higher thermal conductivity means that the material is superior in conducting heat more efficiently. SiC has higher thermal conductivity than GaN or Si meaning that SiC devices can theoretically operate at higher power densities than either GaN or Si. Higher thermal conductivity combined with wide bandgap and high critical field give SiC semiconductors an advantage when high power is a key desirable device feature.

Table 1 Material Property

Materials Property	**Si**	**SiC**	**GaN**
Band Gap (eV)	1.1	3.2	3.4
Critical Field (10^6 V/cm)	0.3	3	3.5
Electron Mobility (cm^2/V-sec)	1450	900	2000
Electron Saturation Velocity (10^6 cm/sec)	10	22	25
Thermal Conductivity (Watts/cm^2 K)	1.5	5	1.3

3. General Applications of Compound Semiconductor

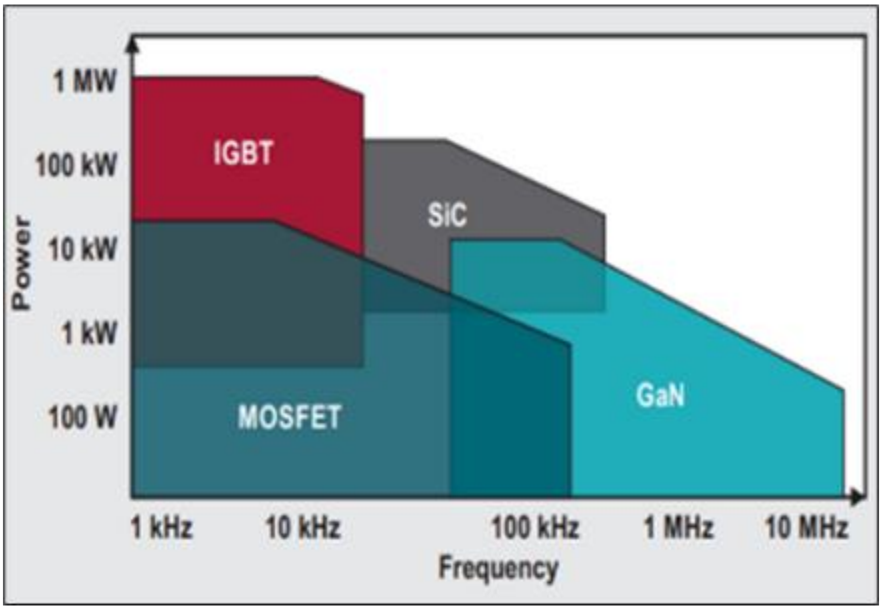

Figure 4 Power vs Frequency Characteristics

3.1. Sensing and data acquisition

Semiconductor-based sensors are essential components in IOT applications for data collection. They can promptly detect various environmental parameters like temperature, light, motion, and pressure. They detect and then convert these data or physical quantities into electrical signals that can be processed by other components of the devices. For example, pressure sensors in wearable health monitors, temperature sensors in smart thermostats, light sensors in smart lighting systems, etc.

3.2. Processing and control

The brain of IOT devices are microcontrollers and microprocessors which are powered by semiconductor technology. The semiconductor chips interpret the data received from the sensors, execute programmed instructions, and then make real-time decisions. Actuators are devices that convert electrical signals back into physical quantities or actions that proceed with tasks like adjusting room temperature based on sensor data, or trigger alarms when anomalies are detected. The functionality of the processor unit in IOT devices depends on the specific requirements of the respective device. Devices with simple sensing activities might utilize low-power microcontrollers, while complex IOT devices leverage the advanced processing capabilities of microprocessors.

3.3. Connectivity and communication

Semiconductors with their advanced functionality facilitate communication between IOT devices and other systems of the network. Wireless communication modules such as Wi-Fi, Bluetooth, and cellular radio chips are all built using semiconductors. These modules enable data transmission between devices and gateways or cloud platforms that validate remote monitoring, control, and data analysis.

3.4. Security and privacy

Security is the most concerning aspect in the interconnected world of IoT. Thus semiconductor companies are moving forward to incorporate security measures in semiconductors. They are developing chips with built-in security features such as encryption engines and secure boot capabilities. These features are developed to safeguard sensitive data collected by IOT devices as well as prevent the situations of potential security risks.

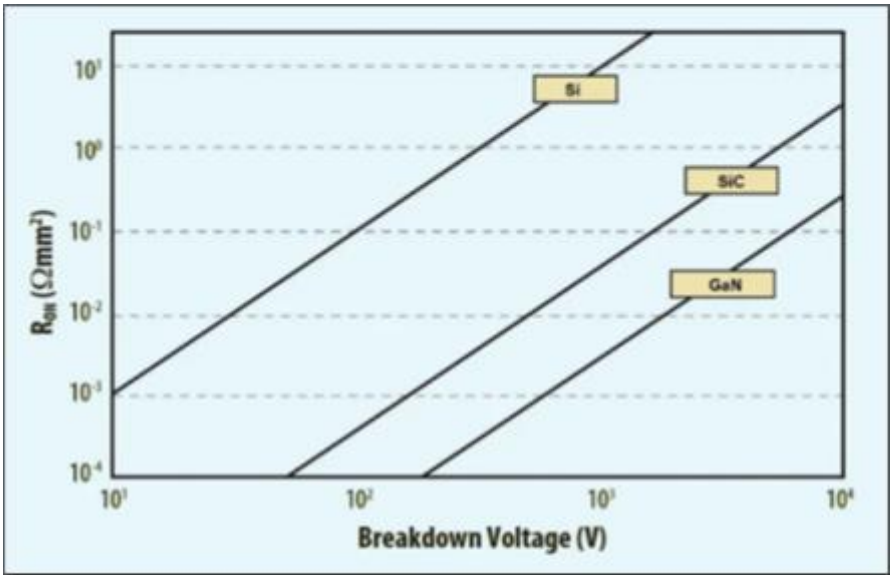

Figure 5 Relationship between resistance vs breakdown voltage

SiC and GaN power devices find applications across a wide range of industries and technologies:

3.5. Electric Vehicles (EVs)

SiC and GaN power devices are instrumental in improving the efficiency, range, and charging speed of electric vehicles. SiC-based inverters and GaN-based DC-DC converters enable higher power densities, faster switching speeds, and reduced thermal management requirements in EV powertrains.The application of wide-band gap (WBG) power semiconductor devices (Silicon carbide and gallium nitride) in EV power electronics systems has a huge potential to increase EV efficiency, reliability and mileage. However, they extend cutting-edge research where both opportunities and challenge exist.

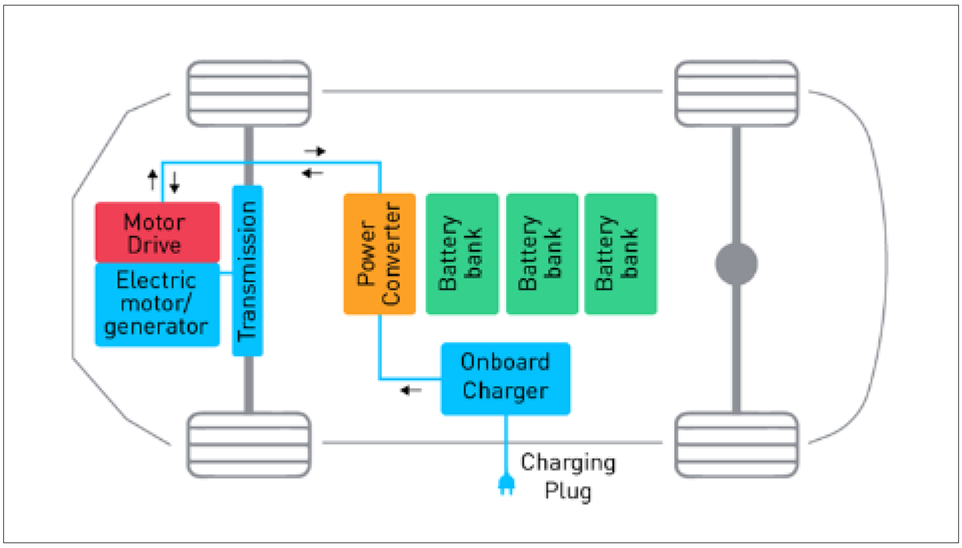

Figure 6 Onboard charging of electric vehicle

3.6. Renewable Energy Systems

SiC and GaN power devices play a crucial role in renewable energy systems, including solar inverters, wind turbines, and energy storage systems. Their high efficiency and reliability make them ideal for converting and managing power from renewable sources, contributing to the transition towards a more sustainable energy future.

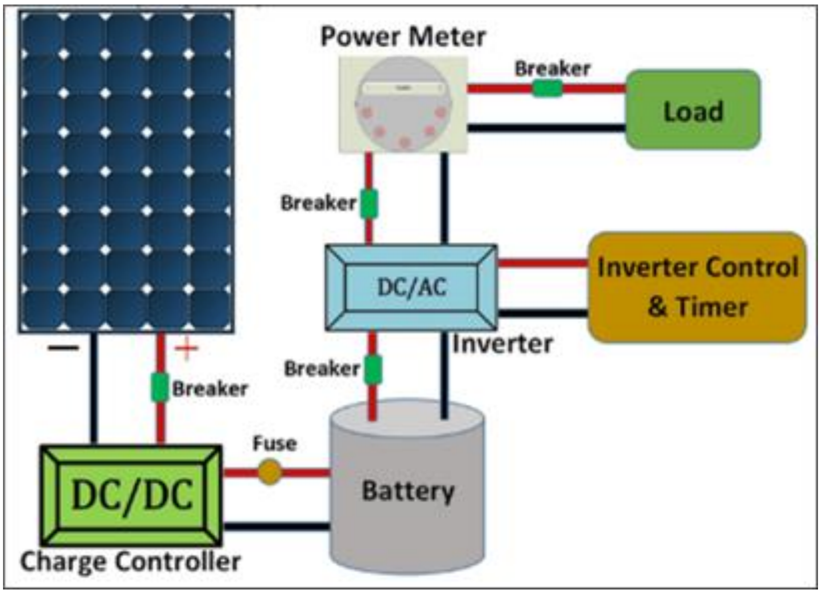

Figure 7 Power semiconductor based Solar Controller

3.7. Power Supplies and Converters:

SiC and GaN power devices are widely used in power supplies, converters, and DC-DC converters for consumer electronics, data centers, and telecommunications infrastructure. Their high efficiency and compact form factor enable smaller, lighter, and more energy-efficient power conversion solutions.

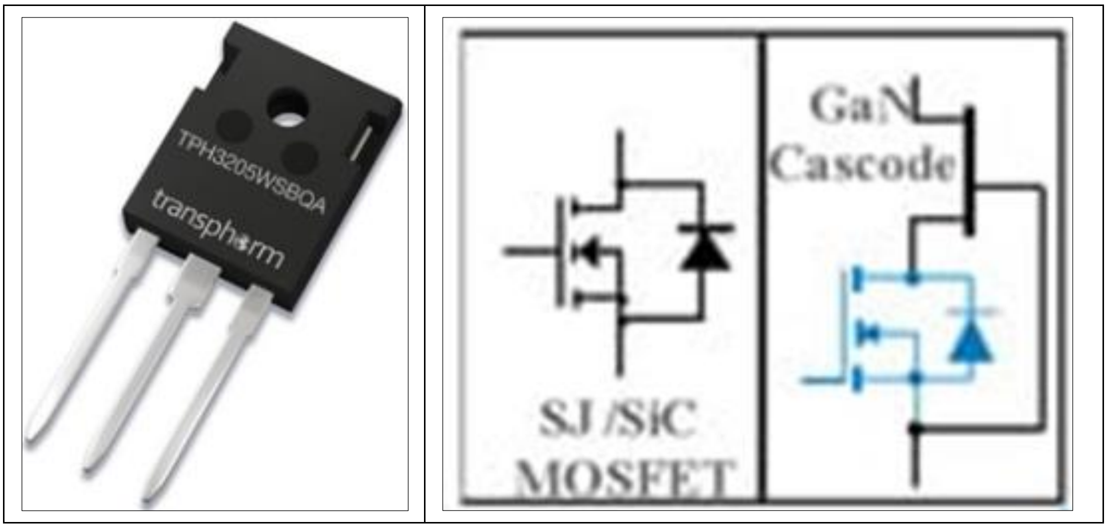

Figure 8 Structural overview of SiC and GaN

3.8. Industrial Motor Drives

SiC and GaN power devices enhance the performance and efficiency of industrial motor drives, robotics, and automation systems. Their high power density, fast switching speeds, and ruggedness make them suitable for high-power, high-voltage applications in industrial environments. In addition, SiC and GaN power devices holds promise for further advancements and widespread adoption:

3.9. Integration and Miniaturization

Continued research and development efforts aim to enhance the integration and miniaturization of SiC and GaN power devices, enabling compact, energy-efficient solutions for a wide range of applications.

3.10. Automotive Electrification

With the growing trend towards automotive electrification, SiC and GaN power devices are expected to play a pivotal role in improving the efficiency, performance, and reliability of electric vehicles, hybrid vehicles, and autonomous driving systems.

3.11. 6G Infrastructure

The rollout of 6G networks requires high-efficiency, high-frequency power electronics solutions, making SiC and GaN power devices essential components in 6G infrastructure, including base stations, RF amplifiers, and power amplifiers.

4. Emerging Technologies of SiC and GaN in the field of robotics

SiC and GaN power devices hold promise for emerging technologies such as wireless power transfer, quantum computing, and Internet of Things (IoT) devices, where their high efficiency, reliability, and performance are critical.Compared to traditional silicon technology, the main advantages offered by GaN can be summarized as follows:

- Great efficiency, small footprint and low weight;
- High power density;
- High operating and switching frequencies;
- Low on-resistance;
- Near zero reverse recovery time.

Robots need sophisticated sensors that acquire important information. Using semiconductor processing units, sensors can gather external information like images, infrared light and sound, along with internal data on temperature, moisture, movement and position. Robots use this data 'aware of' their operational state and the surrounding working conditions.

Figure 9 Data processing robot

Compound semiconductor power devices play essential roles in the control of motors and actuators. High-end power devices using high-bandgap semiconductor materials like gallium nitride will likely be used in industrial operations to enable accurate and low-power robot operation.

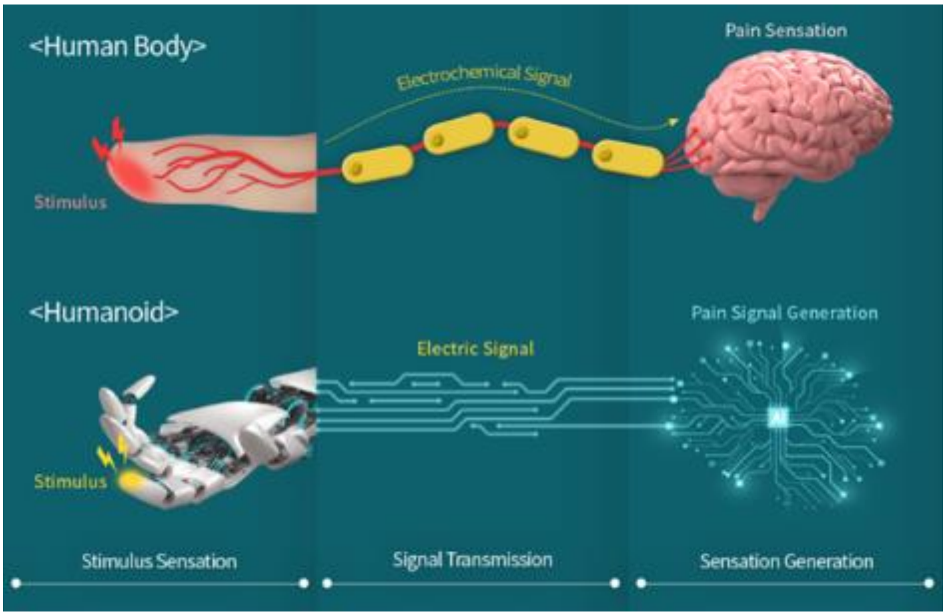

Figure 10 Sensation mechanism of human body and humanoids

Robotic technologies are widely used in astronomy, atomic energy, metallurgy, textiles, automotive, and manufacturing industries. It has proven to be a rapidly expanding field, opening up new opportunities in recent years. Many experts believe that robotics is best suited for automation industries such as manufacturing, packaging, and curating. According to research, robotics and automation have the same potential as computer systems to affect significant change in India's industrial aspects.

In the automation sector, robotics has proven to increase productivity, ensure safety, and improve end product quality while allowing human employees to take on more value-added responsibilities. Furthermore, India's health sector has begun to extensively use robotic technology in operating rooms and even rehabilitation centres to improve quality of life.

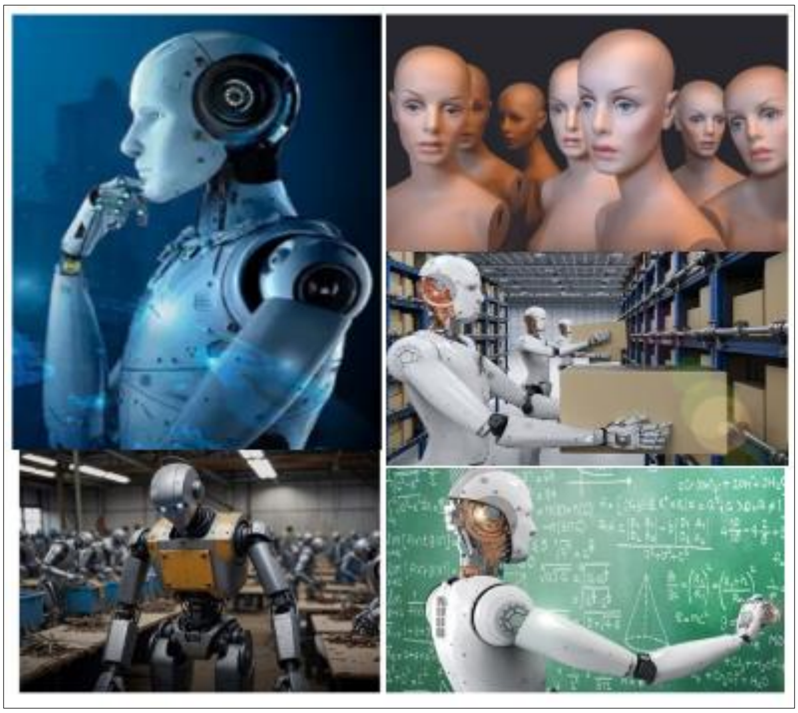

Figure 11 Various applications of robots with IoT based SiC and GaN

4.1. Rolling robots

The most common method or movement is on four wheels. But there are also robots with one or two wheels to increase mobility and save components. All-terrain robots have six or more wheels.

Figure 12 IoT Rolling robots

4.2. Rail-mounted robots

Feeding robots in the agricultural industry are one example of this type of movement. The feed container, mixing device and weighing device are suspended on a rail or are guided laterally. Power is supplied by batteries, a trailing cable, or a supply rail. The robots are controlled by a process computer installed on the container. The feeding robot gets new feed from stationary storage or mixing containers.

Figure 13 Rail-mounted robots

4.3. Walking robots

Robots that walk upright on two legs are still a great challenge for developers, especially as regards stability. The ZMP (Zero Moment Point) algorithm is a solution from Honda that is used by the ASIMO robot to move on two legs. However, this model needs a flat surface to move. Consequently, this robot is not suitable for trips in rough terrain. A more advanced method is the use of a dynamic compensation algorithm. It is more robust than ZMP technology, as the robot's movement is constantly monitored and the feet are placed to ensure stability.

Robots that use this technology can even jump. Another approach is passive dynamics in which the momentum of the swinging limb is used for more efficiency. With this technology, robots can even walk uphill and are said to move ten times more efficiently than robots with ZMP technology. Currently the most impressive example as regards movement and balance comes from Boston Dynamics: The latest version of the walking robot Atlas is able to perform incredible jumps and backflips.

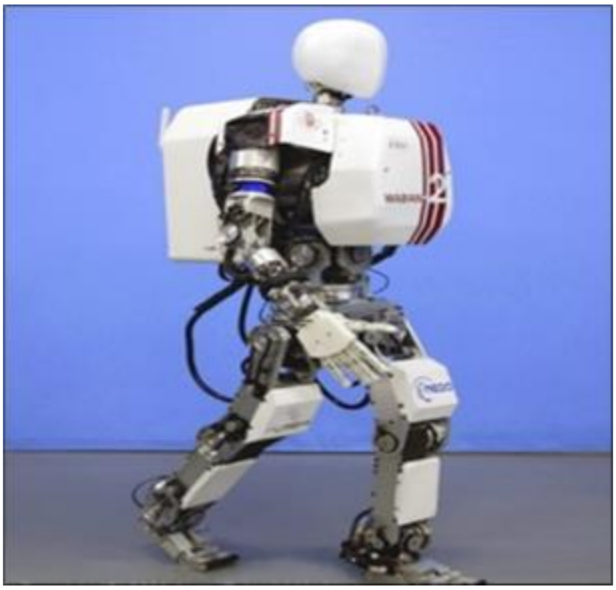

Figure 14 Walking robots

4.4. Flying robots

If we think about flying robots, the first thing that comes to mind is the drone, which is now used extensively in civil and military areas. But there are other interesting concepts, such as the EU project ARCAS (Aerial Robotics Cooperative Assembly System). Scientists at the German Aerospace Center have integrated a robotic gripper arm in an autonomous helicopter. This robot is used to inspect and repair pipelines. Other conceivable areas of use are maintenance of satellites or industrial plants or building infrastructures on other planets. In 2013, researchers at Harvard University developed robot bees that can fly and dive into water.

Figure 15 Flying robots

4.5. Navigation of autonomous robots

Mobile robots are equipped with a combination of navigation hardware and software to perceive their surroundings, navigate optimally and respond to dynamic events, such as people or moving objects. In most cases, a mixture of GPS navigation device, radar sensors, but also Lidar technology or cameras ensures that the robots can navigate and act safely in the environment.

Figure 16 Navigation of autonomous robots

Robotics has been used for decades in the automotive industry, but many industries since have seen the benefits of robotic automation. The rule of thumb for what industrial tasks are best for robots is the "Three D's" rule: Any task that is Dirty, Dull or Dangerous. Typical robotic applications are simple and repetitive tasks that require dedicated resources to perform. With recent advancements in machine vision, artificial intelligence, collaborative robotics and other technologies, robots are more capable than ever to perform complex tasks that typically require human-like recognition, judgement and dexterity.

4.6. Industrial robots

Any industry that makes something or moves something at scale has a potential use for industrial robots. In manufacturing industries, robotics are generally used for the fabrication, finishing, transfer and assembly of parts. In material handling industries where finished products are prepared for distribution, robotics are used for picking, sorting, packaging and palletizing of products.

Figure 17 Industrial robots

The majority of military robots are tele-operated and not equipped with weapons; they are used for reconnaissance, surveillance, sniper detection, neutralizing explosive devices. Autonomous robotics would save and preserve soldiers' lives by removing serving soldiers.

A four-wheeled robot outfitted with several cameras, radar, and possibly a firearm, that automatically performs random or pre-programmed patrols around a military base or other government installation. It alerts a human overseer when it detects movement in unauthorized areas, or other programmed conditions. The operator can then instruct the robot to ignore the event, or take over remote control to deal with an intruder, or to get better camera views of an emergency. The robot would also regularly scan radio frequency identification tags (RFID) placed on stored inventory as it passed and report any missing items.

Figure 18 Army robots

IoT in robotic systems can streamline operations and foster innovation in data analysis and decision-making. IoT devices collect massive volumes of data; therefore, robotic systems with sensors and AI capabilities are necessary for effective data collection in various contexts.

5. AI and IoT based Applications

5.1. Healthcare

IoT and robotics are essential for assisting patient care and enhancing operational effectiveness in healthcare environments. These robots help with several activities, such as drug distribution, patient monitoring, and rehabilitation exercises. By utilizing IoT technology in healthcare, medical organizations can improve patient outcomes and safety by ensuring precise and timely medication administration, therapy sessions, and data collection.

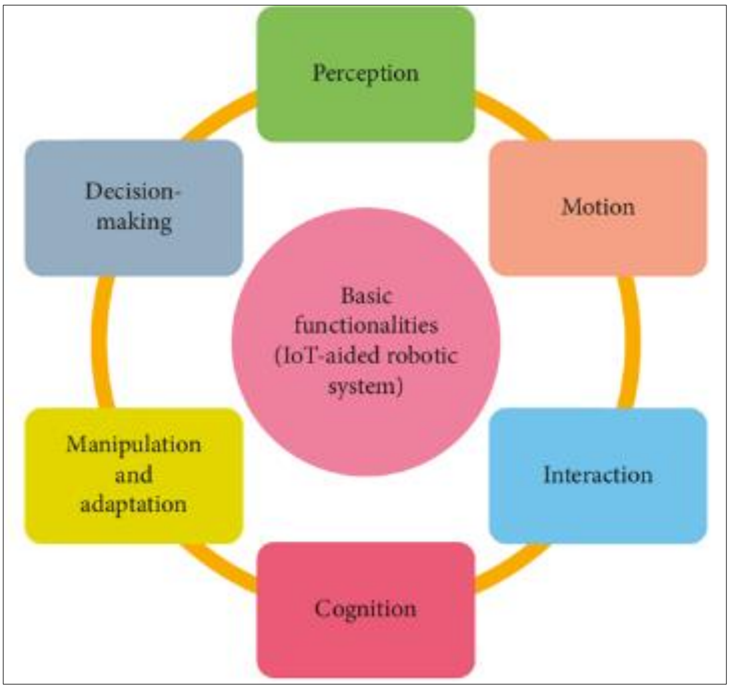

Figure 19 Healthcare Applications

Our IoT-powered robotics software automates logistics processes such as picking, sorting, and replenishment, transforming inventory management. These systems efficiently navigate warehouse environments using IoT sensors and data analytics, cutting order fulfillment times and labour costs.

IoT technology's real-time tracking and monitoring features help warehouses maintain ideal inventory levels, improving customer satisfaction and operational efficiency.

5.2. Manufacturing

IoT-enabled robotic systems are key in streamlining assembling, welding, and packing procedures in contemporary manufacturing processes. The underlying software in these robotic systems use IoT technology to gather and analyze data in real-time, optimizing workflow efficiency and enabling pre-emptive maintenance to avoid expensive downtime.

Figure 20 Manufacturing Process

Integrating robotics with IoT in manufacturing improves operational performance by increasing productivity and guaranteeing constant quality control across the production line.

5.3. Agriculture

IoT-powered robotics software in agriculture enhances precision farming methods, which maximize resource efficiency and crop management. These systems monitor environmental variables, crop health, and soil conditions, giving farmers important information they may use to make informed decisions.

Figure 21 Agricultural Applications

IoT-enabled robots increase production and efficiency with minimal negative environmental impact by autonomously planting, applying pesticides, and harvesting

5.4. Finance

The merger of robotics and IoT for the finance industry can accomplish tasks such as risk assessment, fraud detection, and automated client support. Real-time financial transaction monitoring by IoT devices allows for detecting irregularities and possible fraud attempts.

Figure 22 Finance Software Application

The underlying robotics software can automate back-office tasks like data entry, customer service, and even algorithmic trading to increase productivity and decrease human error.

5.5. Smart Home Appliances

IoT-enabled robots that clean houses and mow lawns are examples of smart home appliances revolutionizing domestic duties. These self-navigating robots provide homeowners with efficiency and convenience in indoor and outdoor areas.

Figure 23 Smart Home Applications

In smart home applications, IoRT technology enables devices to adapt to changing environments, navigate obstacles, and optimize cleaning or maintenance schedules. This integration enhances the comfort and convenience of modern living spaces and frees up occupants time for other pursuits.

5.6. Construction

IoT-enabled robots assist with various jobs in the construction industry, from building inspection and maintenance to site surveying. In difficult conditions, these robots evaluate structural integrity, spot flaws, and repair using sensors and cameras.

Figure 24 Building Construction

Incorporating IoRT technology in construction projects increases productivity, accuracy, and safety. Robots can perform jobs precisely and navigate dangerous environments independently. This integration guarantees adherence to quality and safety standards, expedites project deadlines, and lowers costs.

5.7. Education

IoT-connected robots are revolutionizing education by giving students immersive and engaging learning experiences. These robots use practical exercises and real-world applications to engage students in learning programming, robotics, or STEM subjects.

Figure 25 Learning and Education

Educational institutions can deepen students' grasp of complicated subjects by enhancing their involvement and comprehension through IoT technology. These robots also help students develop their creativity, problem-solving abilities, and teamwork, which will help them in their future employment.

5.8. Energy

IoT and robotics are essential in the energy sector to optimize resource management, increase operational efficiency, and guarantee safety. IoRT sensors enable predictive maintenance and optimize energy output by monitoring environmental factors, equipment performance, and energy consumption in power plants and distribution networks.

Figure 26 Energy Application

Robotics reduces downtime and improves worker safety in hazardous situations by performing jobs like infrastructure inspection, maintenance, and repair. Exxon Mobil Corporation, for instance, integrates IoT-enabled robots into its oil and gas operations. Their use of robotic inspection and maintenance systems, such as drones and remote-operated vehicles (ROVs), enhances safety and efficiency in oilfield operations, reducing downtime and mitigating risks.

6. Conclusion

In conclusion, Silicon Carbide (SiC) and Gallium Nitride (GaN) power devices represent a transformative shift in power electronics, offering superior performance, efficiency, and reliability compared to traditional silicon-based devices. With their wide bandgap, high electron mobility, and reduced switching losses, SiC and GaN power devices are driving innovation across industries ranging from automotive and renewable energy to telecommunications and consumer electronics. As research and development efforts continue to advance, SiC and GaN power devices are poised to power the future of technology, enabling a more sustainable, connected, and efficient world.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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