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(REVIEW ARTICLE)

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# Exploring the potential of Wide Band Gap semiconductors in renewable energy system applications: A critical review

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## Abstract

The following paper is a critical review of wide band gap semiconductors and the potential they hold in the development of renewable energy systems. With the development of renewable energy systems, there have been an increasing need to adopt semi-conductor materials that improve the performance and reliability of power electronics. In this regard, there have been extensive research into the application of wide band gap materials which offer extensive performance features in power systems performance. The objective of this study is to review novel wide band gap materials, discuss their unique properties that make them ideal for electronic components in renewable energy systems. Using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, a total of 32 studies on six (6) wide band gap semiconductors; Bismuth Tri-iodide, Gallium Nitride, Silicon Carbide, Boron Nitride, and Zinc Oxide and Diamond were reviewed. These materials offer unique performance across multiple domains. They have excellent electron transport abilities, high breakdown voltage, and great thermal conductivity. Beyond optical uses, they can operate effectively in high-power and high-frequency settings with minimal energy loss. The materials are also tough, withstanding thermal, chemical, and mechanical challenges. Their ability to dissipate heat quickly is especially impressive, making them valuable for advanced technological applications.

**Keywords:** Power Electronics; Resilience; Weather; Renewable Energy

## 1. Introduction

When it comes to the conversion and control of energy, power electronics have a wide range of applications such as consumer products, wind and solar systems for power generation, electric vehicles and communication systems. By 2023 the market for power electronics is expected to exceed over $50billion [1]. Wide Band Gap Semiconductors have gained popularity over the years because of their superior material properties enabling power devices to perform at high temperatures, voltages and switching speeds as compared to Silicon based Semiconductor Technologies. This added advantage has the potential of transforming the outlook of renewable energy systems. 40% of the world's energy is consumed as electricity and power electronics play a key role in the conversion of energy to the more demanded electricity form [2]. Power electronics made from materials with wide band bandgap energies offer an added advantage of higher achievable junction temperatures and thinner drift regions. Other literature discussions suggests that GaN, SiC, and C(Diamond) are considered the best semiconductor materials for the future of power electronics [3]. With the growing worldwide energy consumption, it has become crucial that more efficient and reliable technology are developed in order to meet the increasing demand. As large amounts of energy are consumed in semiconductor devices during transformations, research is exploring the potential of WBG materials which have excellent properties that can guarantee a better energy efficiency in power conversion systems with respect to Silicon [4].

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This review delves into the application of semiconductor materials such as Bismuth tri-iodide ($BI_3$), Silicon Carbide (SiC), Gallium Nitride & Gallium Oxide and Diamond and the added advantages they offer in the development of energy systems.

### 1.1. Bismuth Tri-Iodide ($BI_3$)

Bismuth tri-iodide (BI3) has a property of high density (5.8 g/cm3) and high atomic number ($Z_{BI}$ =83, $Z_i$=53). It is also easier to grow and handle and often an option for radiation detection. Findings from a study conducted demonstrate that Bismuth tri-iodide does not suffer from some of the material issues, such as a solid-state phase transition and dissociation in air, that mercuric iodide (another high-Z, wide band-gap semiconductor) does. Thus, bismuth tri-iodide is both easier to grow and handle than mercuric iodide. The current resistivity values were found to be on the order of $10^8$ – $10^9$ Ω cm. However, significant limitations like polarization and poor hole transport due to significantly high amounts of impurities which can be addressed were identified. Decreasing the impurities in the crystals should increase the resistivity and reduce charge trapping. It was concluded that, BI3 performance can be significantly improved by enhancement of material purity making it more useful for practical applications in radiation detection [5].

BI3 has also been identified as a material suitable for photovoltaic applications as it is a lead-free photoelectric semiconductor material. In a study of the effects of halogen doping with bromine (Br) and Chlorine (Cl) on the morphology and photovoltaic performance on BI3 thin films were studied, the morphology of the thin films was altered whilst the bandgap increased from approximately 1.75 to 1.78 eV for $BiI_{2.91}Cl_{0.09}$ and 2.06 eV for $BiI_{2.91}Br_{0.09}$. The X-ray photoelectron spectroscopy showed that the band position of the two films which were doped increased. By fabrication of thin films of BiI3 by steam plating method, the films were doped with different doping ratios of Br and Cl. As shown in Figure 4d–f, it can be concluded that the bandgap of the films doped with Cl and Br has increased to varying degrees [6].

The doping process creates a sheet-like structure that enhances contact between the optical absorption layer and the hole transport layer (HTL). This reduces impedance, facilitating easier separation of current carriers and holes, thereby improving the device's photoelectric performance. Consequently, halogen doping may advance the application of BiI3 material in photovoltaic devices [5].

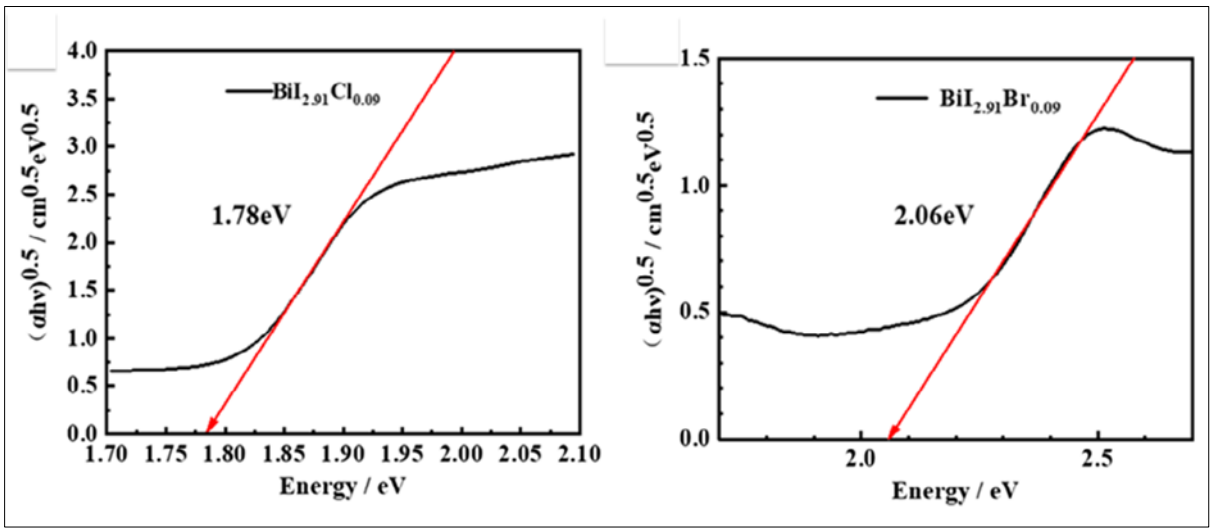


**Figure 1** Bandgap Tauc plots of $BiI_{2.91}Cl_{0.09}$ deposited as thin films on fluorine-doped tin oxide (FTO) and b) bandgap Tauc plots of $BiI_{2.91}Br_{0.09}$ deposited as thin films on FTO

In a similar laboratory experiment pure BiI3 was synthesized into thin films by physical vapor transport (PVT) and solution processing and single crystals by an electrodynamic gradient vertical Bridgman method. The bandgaps of these materials were approximately 1.8eV that demonstrate room-temperature photoluminescence which is a promising first step toward optoelectronic devices and the property of band-edge photo-luminescence are suitable for PV applications [7].

### 1.2. Gallium Nitride

Nitride semiconductor materials have an excellent electron transport property, high breakdown voltage, and high thermal conductivity aside its optical applications.

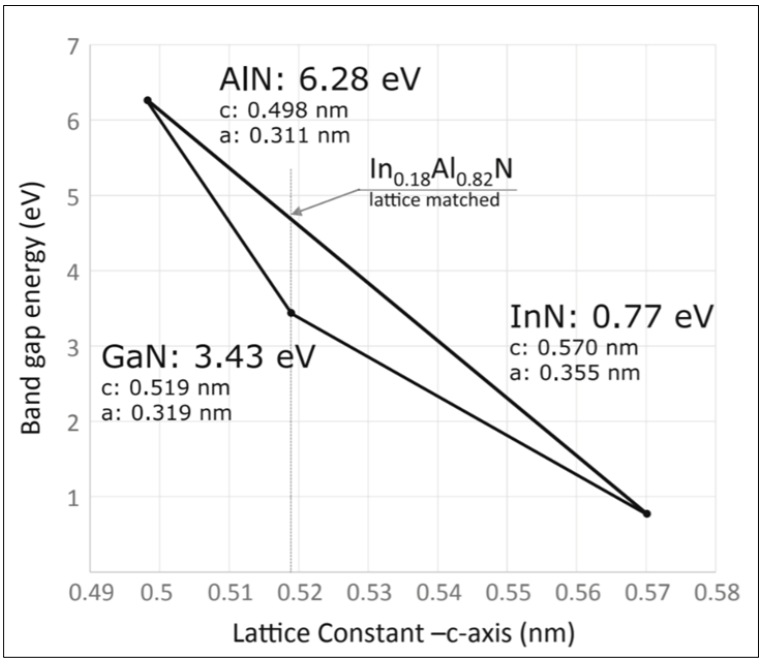


**Figure 2** Relationship of the bandgap energy and lattice constant for nitride-based semiconductors. Note that c-axis represented as lattice constant [8]

When it comes to energy and the environment, nitride semiconductors have proven to be an effective solution in the development of devices in this sector. GaN has a strong atomic bonding which makes it thermally, chemically and mechanically robust. Comparing them to conventional semiconductors, GaN shows greater ionicity and exhibit spontaneous polarization. At room temperature, GaN has a large bandgap of 3.4 eV and a breakdown electric field of 3.3 × 106 Vcm−1, which is 8–10 times larger than GaAs. Further, the saturation drift velocity of GaN is 2.5 × 107 cm s−1, approximately 1.2 times larger than that of GaAs. The thermal conductivity is a little less than that of SiC, but 4 times larger than that of GaAs. Nitrides offer a key advantage over SiC in creating heterostructures with large band discontinuities using AlGaN and AlInN materials. At the heterointerface, a two-dimensional electron gas (2DEG) forms due to spontaneous and piezoelectric polarization. This 2DEG enables high drift velocity and electron mobility, making these structures ideal for heterostructure field-effect transistors (HFETs). The material's large breakdown electric field allows these devices to operate at high current densities without damage. With the underlying capacity to dive current and large voltages through them allows for the fabrication of components with large output power. In terms of environmental impacts, nitride semiconductors contain elements that are less harmful to the environment [9].

The Johnson Baliga figures of merits demonstrate the ability of GaN to perform under high output power, high frequency with minimal losses. GaN is among the materials that exhibit both higher speed (decreasing switching losses) and lower on-resistance for the same surface area (decreasing conduction losses) when compared with Si technology. These properties enable its usage in the new generation of power converters.

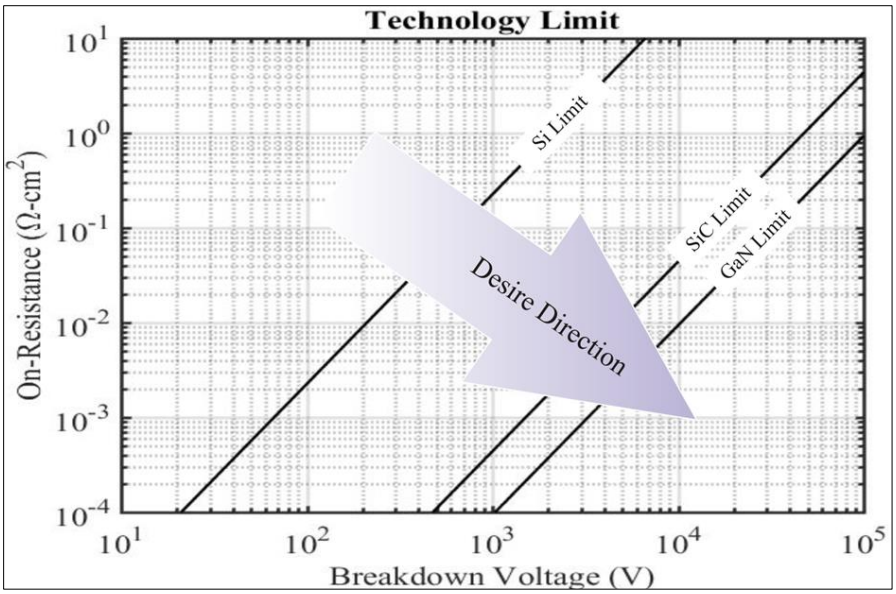


**Figure 3** Baliga's figure-of-merit to show the technological limit of each semiconductor material [10]

Following extensive discussions and the properties exhibited by Nitride semiconductors, other potent applications include current-fed converters and converters with short-circuit protection schemes integrated into them, the higher threshold voltage and resistance to gate Oscillation properties make them better for components that require multiple switches, multi-level converters, and high step-up and step-down power conversion scenarios.

### 1.3. Silicon Carbide (SiC)

Silicon has been widely used in semiconductor power devices, however with the current technology advancement and the need to develop more robust devices these Silicon-based devices are gradually approaching their material and functionality limits. This has sparked a lot of research into finding more robust alternatives to meet the growing technological need. Especially in the renewable industry where scientists are actively conducting research to develop highly efficient devices and application of silicon devices is woefully inadequate as the renewable sector will continue to grow in terms of technological advancements. SiC devices are no longer just experimental works but are fast becoming a viable alternative to Si in the development of high-power, high frequency and high-density applications in industry. The downside is that SiC materials are relatively more expensive than Si materials, however Sic Materials are still finding their way into system applications. With the added advantage of the benefits are significant enough to outweigh the cost of materials. The performance of SiC devices are highlighted below

**Table 1** Comparative properties, SiC and Si

| Electrical Property | Si | SiC (4H) | SiC (6H) | Diamond |
|---|---|---|---|---|
| Band Gap Energy (eV) | 1.12 | 3.28 | 2.96 | 5.5 |
| Critical Electrical Field ($cm^2$/VS) | 0.29 | 2.5 | 3.2 | 20 |
| Electron Mobility ($cm^2$/VS) | 1200 | 800 | 370 | 2200 |
| Hole Mobility ($cm^2$/VS) | 490 | 115 | 90 | 1800 |
| Thermal Conductivity (W/cmK) | 1.5 | 3.8 | 3.8 | 20 |
| Maximum Junction Temperature ($^oC$) | 150 | 600 | 600 | 1927 |

- Higher Critical Electric Field: SiC has 8 times higher critical electric field than Si. Thanks to higher values of critical electrical field, SiC is characterized by a possibility of utilization thin, efficient and robust semiconductor devices operating at higher voltage and power levels and with less energy losses as compared to Si – making it ideal for power electronics today.

- Higher Thermal Conductivity: SiC has about 3 times higher thermal conductivity than Si therefore exhibits a much advantages heat dissipation characteristic. Thermal management is another important characteristic that puts SiC ahead of the conventional material since it is capable of handling heat better than the other options giving it increased performance, durability and reliability in harsh operating conditions.
- High Operating Temperature: SiC devices operate well over 400$^{o}$C because of its high melting temperature. Cost is significantly reduced as there is a reduction in employing cooling systems.
- High Current Density: The current density of SiC is 2 to 3 times the maximum current density of silicon devices [11].

Silicon carbide is another wide band gap material that has showed promise for high temperature power and high frequency power generation. Two types of silicon crystals developed in laboratory experiments, i.e., undoped Semi-insulating crystals which is suitable for MESFETS (Metal Semiconductor Field Effect Transistors) and Nitrogen Doped Highly conductive crystals which is suitable for static Induction Transistors and power switches. With the advancement of research, it is now possible to use advanced growth methods such as multi-wafer epitaxial layer growth methods. SiC has proven superiority other semiconductors in that it has proven to outperform Gallium arsenide (GaAs) in regards to high power and high frequency switching across different frequency bands. Some other qualities that were highlighted in this study include:

UHF television module: Maintains signal fidelity at 2000 W PEP, S-band radar applications: Delivers 300 W peak power and X-band applications: Achieves 6 W power output. This study concluded by highlighting the potential of SiC to surpass other semiconductor materials and therefore holds the potential to transform the landscape in the development of high-temperature and high switching frequency semiconductors [12].

In order to find more cost-effective and sustainable means of producing these high-performance semiconductors, some laboratory experiments were able to synthesize SiC using concentrated solar energy provided by the IER-UNAM solar furnace. This research led to the development SiC from a low $CO_2$ emission process via carbothermic reduction of a silica/carbon (SiO2/C) nanocomposite that is more thermally stable [13].

By integrating solar energy in SiC production, this research aligns with the goals of developing cost effective and sustainable materials from sustainable and low carbon emissions means to improve renewable energy landscape.

### 1.4. Boron Nitride

Boron Nitride structures exhibit an exceptional surface area-to-volume ratio and share many remarkable characteristics with other nanomaterials like carbon nanotubes, nano scrolls, and boron nitride nanotubes. These properties include superior oxidation resistance, chemical inertness, enhanced lubricating qualities, and the ability to withstand high temperatures. They also function as electrical insulators and can effectively encapsulate molecules both internally and at their endpoints. Additionally, they maintain a wide bandgap regardless of their structural configuration.

Although these characteristics make them particularly promising for applications in biotechnology, energy storage systems, and electronic devices, researchers have only scratched the surface of boron nitride's potential as a transformative material. The full scope of its possible applications remains largely unexplored.

With miniature electrical circuits been developed in recent times, a lot of limitations such as heat dissipation are often encountered. The challenge lies as the devices keep getting smaller and smaller resulting in overheating and eventual failure as dissipating of heat becomes inefficient. Different techniques using heat spreaders and heat sinks made from silver and aluminium are often employed to curtail overheating. To efficiently manage heat, novel electrical insulators with high thermal conductivity are ideal for efficient and safe heat spreaders. Mateti et al., [14] proposed the use of hexagonal Boron nitride (h-BN) in this application due to its high thermal conductivity of 390 W $m^{-1}K^{-1}$ and a wide band gap of 5.8eV. The experimental work measured the thermal conductivity of Boron Nitride Nanosheets in two dimensions i.e Parallel to compression and perpendicular to compression. There was an initial challenge as the pellets were too thin making it difficult to measure perpendicular conductivity. An alternative method was developed where, they cut the square pellet into three equal bars, rotated these bars 90° clockwise and used high-temperature glue (JB Weld) to reassemble them into a new pellet. They tested pellets sintered at 2200°C. Measurements were taken across temperatures from 298K to 623K. Thermal diffusivity and conductivity were slightly higher in the parallel direction. The paper identified anisotropic conductivity as one of the challenges preventing its application in heat dissipation as this property prevents it from spreading heat vertically. In this experiment, large BN pellets with a quasi-isotropic thermal conductivity are produced from BN nanosheets using a spark plasma sintering (SPS) technique. The BN pellets have the same thermal conductivity from both perpendicular and parallel directions to the pellet surface. The pellet

sintered at 2300 °C has a very high cross-section thermal conductivity of 280 W m−1 K−1 (parallel to the SPS pressing direction) and exhibits superior heat dissipation performance due to more efficient heat transfer in the vertical direction. In conclusion, The BNNS pellets were found to be efficient in heat dissipation, making them a promising heat spreader and heat sink in a wide range of applications.

Even though Hexagonal Born Nitride have not been extensively considered in energy conversion and storage, however through physical and chemical modifications this material exhibits tuneable characteristics that make it ideal for energy conversion and storage [15].

Boron Nitride also has a hydrogen storage capacity making it a suitable alternative for clean energy generation. In the past years potential alternatives for hydrogen-based energy generation have been explored which include such as photo-catalysis, biomass conversion and water splitting by electrolysis.

The maximum hydrogen storage capacity of BN nanosheets were explored by introducing $H_2$ to different positions, (a) hexagonal hollow site, (b) between the bond of B and N (bridge site), (c) on top of B atom and (d) on top of N. The hexagonal hollow site produced favourable results as an efficient site with a binding energy of 0.212 eV.

**Table 2** Energy Bandgap $(E_g)$, Binding energies $(E_{BE})$, Average adsorption energies $(E_{ad})$, total bader charge transfer (Δq|e|), Desorption Temperature ($T_D$) for pristine and hydrogen adsorbed monolayer h-BN systems.

This study therefore highlights the BN nanosheet's potential for hydrogen storage.

| System | $E_{HM}$ (eV) | $E_{LM}$ (eV) | $E_g$ (Ev) | $E_{BE}$ (eV) | $E_{ads}$ (eV/$H_2$) | wt.% | $T_D$ (K) | Δq\| e \| |
|---|---|---|---|---|---|---|---|---|
| Pristine | -2.334 | 2.335 | 4.669 | - | - | - | - | |
| $1H_2$ | -2.334 | 2.334 | 4.667 | 0.212 | 0212 | 0.8 | 270 | 0.005 |
| $2H_2$ | -2.316 | 2.316 | 4.632 | 0.332 | 0.166 | 1.7 | 212 | 0.019 |
| $3H_2$ | -2.295 | 2.295 | 4.591 | 0.485 | 0.161 | 2.6 | 206 | 0.020 |
| $4H_2$ | -2.293 | 2.993 | 4.587 | 0.637 | 0.159 | 3.4 | 203 | 0.024 |
| $5H_2$ | -2.293 | 2.754 | 4.551 | 0.767 | 0.153 | 4.3 | 196 | 0.037 |
| $6H_2$ | -2.275 | 2.256 | 4.512 | 0.859 | 0.143 | 5.1 | 183 | 0.054 |
| $7H_2$ | -2.231 | 2.231 | 4.463 | 0.944 | 0.134 | 5.9 | 172 | 0.065 |
| $8H_2$ | -2.231 | 2.225 | 4.456 | 1.030 | 0.128 | 6.7 | 164 | 0.046 |

By increasing the hydrogen molecules from $1H_2$ al the way to $8H_2$ at the hexagonal hollow site, the corresponding binding energies, absorption energies, desorption temperature and gravimetric hydrogen density were recorded thus achieving a gravimetric hydrogen density of 6.7 wt.%. Subsequently, a plot of Average adsorption energy vs. the number of H2 molecule and Average adsorption energy vs. hydrogen gravimetric density were presented on the plot below. It has been observed that, with the increase in $H_2$ molecules, average adsorption energy decreases.

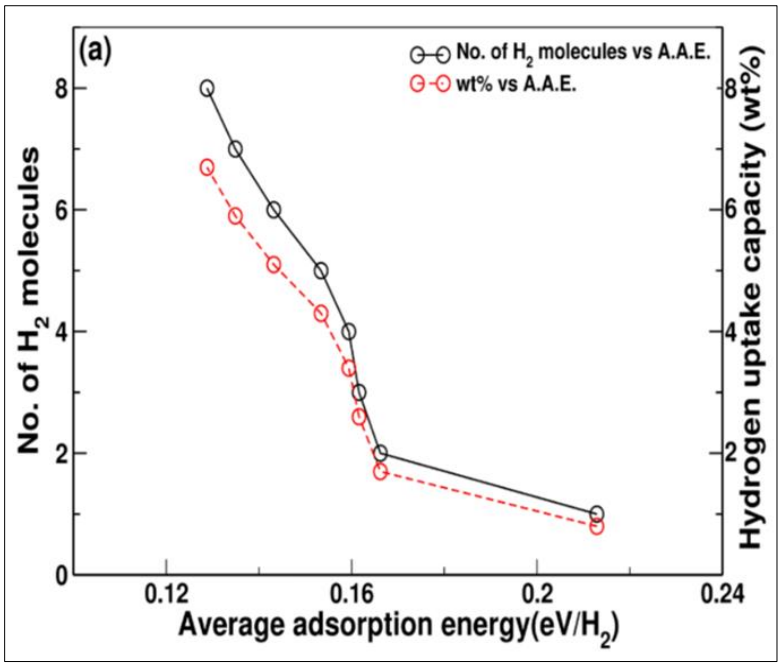


**Figure 4** Average adsorption energy and gravimetric density as a function of number of $H_2$ molecules

Bader charge analysis revealed a low charge transfer from the BN nanosheet to H2 molecules leading to weak binding of H2 on host material. To overcome the problem of low average adsorption energy, host materials

can be doped with metals (alkali, transition) to enhance the interaction between the host materials and the $H_2$ molecule [16].

## 2. Zinc Oxide

In a related experiment to identify the effect of doping on Zinc Oxide, different concentrations of indium were used for doping zinc oxide nanoparticles using an aqueous solution method which is cost effective and can be done under low temperatures. It was observed that doping has a profound effect on optical properties of ZnO. The resulting effect was that doping gave the ZnO particles the characteristic of capturing and transporting of photogenerated electrons of which were injected into the ZnO by excited dyes. The dye sensitized solar cells (DSSCs) based on 0.2 mm indium doped ZnO photoanode exhibited a high short-circuit photocurrent density of 12.58 mA/cm2 and a power conversion efficiency (PCE) of 2.7% whereas DSSCs made from pure ZnO NPs exhibited a current density of 8.02 mA/cm2 with 1.8 % efficiency. Doping with indium gives the ZnO the characteristic to collect more charges, enhances charge transport and increases the charge transport and in turn increases the conversion efficiency values [17].

In similar experiments, photovoltaic device was constructed using a [001]-oriented Wurtzite ZnO thin film which was synthesized when $ZN(NO_3)_2$ solution was heated. With an open circuit voltage and a short circuit current of the ZnO photovoltaic device of 0.6mV and 0.25μA respectively, and exposed to 365nm ultraviolet illumination, current rectification and photovoltaic effects across the top and bottom planes of the ZnO were produced. There was a presence of an internal electric field through spontaneous polarisation offering a fundamental basis for the foundational photovoltaic effect. The electrostatic force produced offers the force for the flow of photogenerated electrons. The results of this experimental work suggest thin film texturing as a strategy to develop photovoltaic devices beyond p-n junction. The experiment also provides an innovative approach to understandding photovoltaic effects in pyroelectric materials whilst giving us some context on how these materials can be fabricated for the application in advanced solar cells and other optoelectronic devices [18].

## 3. Diamond

Diamond exhibits outstanding thermal and electronic properties that make it an ideal candidate as a semiconductor material. With a wide-bandgap of 5.47 eV it holds tremendous potential in the application of devices such as high frequency field-effect transistors, high-power switches. Diamond is uniquely endowered with unique properties

however natural diamonds have a drawback as all these properties are rarely found in one stone. Among other applications of synthesized diamond are: use in high power electronics, development of diamond diodes, High power diamond switches and high frequency devices. With the development of technology to synthesise diamonds, various properties unique to specific applications can be produced [19].

In an experiment, high-performance hydrogenated diamond (C-H diamond) inverters were fabricated using normally-off metal-insulator-semiconductor field-effect transistors (MISFETs) with $Al/BaF_2/C$-H diamond structures and load resistors. Based on the high-performance diamond MISFET, the diamond inverters exhibit good voltage transfer characteristics and dynamic switching characteristics at the frequency of 50 kHz [20]

## 4. Conclusion

Bismuth Tri-iodide, Gallium Nitride, Silicon Carbide, Boron Nitride, Zinc Oxide were some of the wide band gap materials whose properties and applications were reviewed in this paper.

Bi3 exhibits radiation detection properties and its photovoltaic properties can be improved by halogen doping. Gallium Nitride exhibits high drift velocity and electron mobility making it ideal for field effect transistors. Due to its high switching properties, they can also be used in power converters. Silicon Carbide exhibits such properties as high critical electric field, high thermal conductivity, high operating temperature, high charge density. These properties set it apart for applications in areas of high power and high frequency power generation. SiC also demonstrated a cost-effective solution to solar systems production. Boron Nitride have extensively for energy storage and conversion have the property for hydrogen storage making this material ideal for renewable energy system applications. Zinc Oxide was observed to also exhibit photovoltaic effects and are applied in solar cells and other electric and optoelectronic devices.

Synthesized diamond demonstrates exceptional thermal and electronic properties that make it a promising semiconductor material for high-frequency and high-power electronic devices, with the ability to produce tailored characteristics through advanced synthesis techniques.

The comprehensive review highlights the diverse and remarkable properties of wide bandgap materials like Bismuth Tri-iodide, Gallium Nitride, Silicon Carbide, Boron Nitride, and Zinc Oxide and Diamond demonstrating their significant potential across various advanced technological applications including radiation detection, power electronics, solar systems, energy storage, and optoelectronic devices.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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