Semiconductor Materials in High Voltage and Temperature Applications

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Abstract. The rapid adoption of electric vehicles (EVs) is accelerating the shift from 400 V to 800 V battery systems, which reduce power losses and enable faster charging. This transition requires advanced semiconductors capable of operating under higher voltage and temperature conditions. This paper examines the limitations of silicon (Si), the dominant but increasingly inadequate semiconductor, and evaluates alternatives including silicon carbide (SiC), gallium nitride (GaN), gallium oxide (Ga_2O_3), and diamond. Key performance parameters such as breakdown field, bandgap, bond strength, electron mobility, carrier concentration, thermal conductivity, and cost are compared to determine their suitability for demanding applications. Silicon remains cost effective for low demand uses, while silicon carbide provides the most balanced performance by combining high efficiency with moderate cost. Gallium oxide and diamond show exceptional performance in extreme voltage and temperature environments, although their adoption is constrained by high cost. Industry practice highlights these benefits, as silicon carbide based on board chargers already achieve about five percent higher efficiency and ten times greater power density than silicon counterparts, resulting in savings in weight, space, and cost. However, challenges in manufacturing, including defect density and doping control, as well as issues in operational reliability such as threshold voltage drift and reduced breakdown voltage, continue to limit large scale commercialization.

Keywords: Electric Vehicle Battery Systems, Silicon Carbide, Gallium Nitride.

1. Introduction

In 2020, EVs broke through in the automobile market, going from 2.5% to 4.4% of the global market [1]. This trend hasn't shown signs of slowing down either, with 2024 having over 17 million EVs sold globally, over 5 times what was sold in 2020 [2]. The growing adoption of EVs is driving the development of more efficient and cost-effective vehicles, with a major advance being the transition from 400 V to 800 V battery systems that reduce power losses and charging times [3]. However, these high voltages put a strain on semiconductors and could lead to their failure if the voltages are high enough. Similarly, semiconductors in EV batteries also need to be able to withstand high temperatures that can result from heat dissipated when charging or the climate the car is in. A study showed how at temperatures of 40°C and higher, the efficiency of fast charging in EVs begins to drop [4]. As higher voltage and more efficient charging systems are required by EV companies, the need for semiconductors that can withstand them will only grow.

These extreme conditions are not only required in the automobile industry but are relevant in many modern-day technologies. To fulfill the requirements in these circuits, new semiconductor materials will need to be considered. In the past, Silicon has been used for its cheap cost, but as time goes on, it becomes apparent that its semiconductor properties of breakdown field, thermal conductivity, and carrier mobility. This paper will discuss 4 semiconductors that are currently being experimented or used to replace Si: SiC, GaN, Ga_2O_3, Diamond. This paper will focus on the characteristics that make these semiconductors good for high voltage and temperature applications but will also consider cost and feasibility of mass-producing products using these semiconductors.

2. Key Parameters for High Voltage Applications

Breakdown field is the maximum electric field that can be applied across a semiconductor before it experiences failure. As the voltage applied across a PN-junction increases, the electric field created inside increases. With a high enough electric field, the electrons will gain enough energy to where they will break bonds, releasing more electrons, and create a chain reaction, known as an Avalanche Breakdown. This causes irreparable damage to the semiconductor and makes it useless. Increasing the breakdown field is an important factor in determining which materials to use to create semiconductors.

2.1. Bandgap

Bandgap is an important characteristic that contributes to the breakdown field. The bandgap is the energy difference in energy between electrons in the valence band and the conduction band. The materials being experimented on in semiconductors are wide semiconductors that have bandgaps larger than 3.2eVs [5], such as SiC and GaN, and ultra-wide bandgap semiconductors, such as Ga_2O_3 and Diamond. For example, the bandgap of SiC is 3.3 eV as opposed to the 1.1 eV of the bandgap of Si [5,6]. With a larger bandgap, a higher voltage will be required to give electrons enough energy to enter the conduction band and become free moving, making it less likely that an electron will gain enough energy to start an avalanche breakdown.

2.2. Molecular Bonds

Molecular bonds also contribute to the breakdown field. With stronger bonds, the energy a carrier needs to knock electrons out of the bond and cause a breakdown becomes much higher. While bond energy is hard to find, it's more often the bond length or lattice parameter that is found and then relayed to show the bond energy. Molecules with a lower bond length have higher bond energy. For example, GaN has a lattice parameter of 3.19 Angstroms while Si’s lattice parameter is 5.43 Angstroms [6].

2.3. Electron Mobility

Electron mobility determines how far free electrons move in a lattice. The higher the mobility, the more these electrons are allowed to accelerate and potentially gain enough energy to cause a breakdown. However, the higher mobility also indicates a higher conductivity in the semiconductor making it more useful in circuits. In order to make sure that breakdown voltage and conductivity are both emphasized in the semiconductor, the concentration of doping will have to be balanced. By having a lower electron mobility, it limits the energy that electrons can gain and hence raises the breakdown field. For example, SiC has an electron mobility of 0.9×10^3 $cm^2/(Vs)$ while Si has an electron mobility of 1.45×10^3 $cm^2/(Vs)$ [7], assuming normal doping concentration.

3. Key Parameters for High-temperature Applications

High temperature resistance is also a key quality that semiconductor materials must have. High temperature resistance falls into 2 categories: one being able to still function under high temperature environments, one being able to dissipate the heat generated in the circuit quickly and efficiently. Functioning under high temperatures is key not only during charging but also to preserving its lifetime when not charging, since chargers will lose efficiency at higher ambient temperatures [4]. When charging, the internal resistance in the circuitry causes heat to be dissipated, which needs to be removed quickly or else it will lead to inefficiencies in the semiconductors.

3.1. Bandgap and Carrier Concentration

Dealing with semiconductors at high temperatures is similar to dealing with a high voltage. As the semiconductor increases in temperature, the atoms and carriers gain more kinetic energy. With a high enough temperature, the carriers will gain enough energy to cause an avalanche breakdown.

Using the same principle as stated previously, using materials with a higher bandgap will require higher energy in order to initiate the breakdown, making it less likely to occur in ambient temperature. Another aspect to decrease the likelihood of a breakdown is lower carrier concentration. With less carriers, the probability that one of them will have enough energy to cause a breakdown goes down. However, similar to electron mobility, lowering the carrier concentration usually means less doping, which also takes away from the important aspect of conductivity in the semiconductor. For this reason, usually the electron mobility of a semiconductor will be standard and should not be decreased to try to obtain a more temperature resistant material.

3.2. Thermal Conductivity and Heat Dissipation

Thermal conductivity is the measure of how fast the semiconductors dissipates heat. As the circuit the semiconductor runs, there will inevitably be heat generated. With a higher thermal conductivity, this heat can be dissipated faster, making it less likely that a significant temperature increase will occur that could cause a breakdown in the semiconductor. For example, Si only has a thermal conductivity of 1.5 W/cmK while diamond has a massive 20W/cmK [6].

4. Data and Analysis

Using all of the metrics listed previously, here is a list of the properties of the semiconductor. While looking at the atomic properties of semiconductors is important, it's also useful to consider the cost; no matter how good a material is, if its cost is too high, it will be useless to use in technologies. Exact cost values are hard to find and vary, so the relative prices will be considered. [5-9].

Table 1. The comparison of the typical semiconductor materials

Material	Bandgap	Lattice Parameter	Electron Mobility	Thermal Conductivity	Breakdown Field	Cost
Si	1.1 eV	5.43 Å	1450 $cm^2/(Vs)$	150 W/mK	0.4 MV/cm	Low
4H-SiC	3.3 eV	3.08 Å (hex)	900 $cm^2/(Vs)$	490 W/mK	3.1 MV/cm	Moderate
GaN	3.4 eV	3.19 Å	2000 $cm^2/(Vs)$	230 W/mK	4.9 MV/cm	Moderate
Ga_2O_3	4.9 eV	12.23 Å, 3.04 Å, 5.80 Å	150 $cm^2/(Vs)$	13 W/mK	10.3 MV/cm	High
Diamond	5.5 eV	3.57 Å	50 $cm^2/(Vs)$	2200 W/mK	4.4 MV/cm	Very High

For clarification, Ga_2O_3 has 3 values for its lattice parameter as it is measured as a rectangular prism, instead of a cube. Also, SiC's lattice parameter is the length of one side of the hexagon that the molecule forms.

From this data, we can clearly see that Silicon is nowhere near the best semiconductor in any category besides cost. However, its low cost can be a benefit in smaller scale and less extreme use cases of semiconductors, like in making a circuit at home. In terms of thermal conductivity, diamonds are by far the highest, being over 4 times the value of the next highest, being SiC. However, its high cost makes it impossible to use it in high quantities and could probably only be used in small quantities at the most critical points in the circuit where heat is a major issue. For bandgap, diamond and Ga2O3 both have bandgaps much higher than the rest, making them useful for environments where the ambient temperature may be high. For breakdown field, Ga2O3 has almost double the next 2 closest materials with 10.3 MV/cm. This allows it to be useful in key parts of the semiconductor that may have a large voltage applied across it, such as the power converting system inside an EV battery.

The best candidate for a new semiconductor is most likely either SiC or GaN. SiC has the advantage of being average in all categories (breakdown field, bandgap, thermal conductivity) while being affordable. GaN is similar but has the trade-off of a higher breakdown field with a lower thermal conductivity compared to SiC. SiC and GaN have around 3 to 5 times the effectiveness of Si, allowing manufacturers to save space, reduce weight, simplify circuitry, and perhaps save time and money when using it over Silicon. While other semiconductors like Diamond and Ga_2O_3 have higher values in thermal conductivity and breakdown field, respectively, their costs are so high to the point that it becomes impractical to use it in products that will be sold on the market. However, these materials can be useful in specific applications where only a small amount be used, such as particle accelerator experiments where they need high voltages to run.

5. Current Research in Semiconductors and Challenges

The semiconductor materials above have had their qualities recognized by researchers who are looking into ways to apply these semiconductors to solve problems. As stated previously, the automotive industry is a leader in making the jump to using wide bandgap semiconductors. With the wider bandgap, materials like SiC and GaN can store more energy, allowing them to be more energy dense to save space inside an EV. These wide bandgap semiconductors also increase the efficiency of the chargers. For example, SiC and GaN semiconductors are between 3-10% and 5-9% more efficient, respectively, than Si semiconductors when used in on-board chargers (OBC) [10]. OBCs are necessary in converting the AC power received from the power grid into DC that is used in the car battery. With a growing number of EV car companies using 800 V batteries, these OBCs are required to support voltages from 320 V to 820 V [11]. Toyota and APEI have developed an OBC system using SiC that has 95% efficiency and a power density that is 10 times that of Si-based OBC systems [12]. These advances in making batteries lightweight, low-cost, and efficient allow manufacturers to save costs on making EVs, which ultimately benefit consumers.

While these benefits of new semiconductors are already being seen in the market, there are still challenges with using materials such as SiC and GaN. A big issue with using these materials is the difficulty in manufacturing. Errors such as defects and dislocations make the material have a higher likelihood of not functioning inside the circuit [13]. Also, higher temperature doping is required for these new materials, meaning that doping will be more expensive and could lead to more failures since the conditions are so extreme [13]. This results in a high cost and slow production of SiC and GaN, slowing down the rate that companies and researchers are able to experiment with them. Since these materials are being specially made to be used in the most extreme scenarios, this puts a lot of strain on the materials, leading to threshold voltage drift and a reduction in the breakdown voltage [13]. Over a long period of time, threshold voltage drift could lead to a failure in that branch of the circuit or increased power consumption, which are both undesirable. The reduction in breakdown voltage is even worse, as it threatens failure in the OBC and requires it to be replaced.

6. Conclusion

In conclusion, SiC is a good candidate for semiconductors moving forward. Its quantities in terms of high breakdown field, thermal conductivity, and bandgap, are similar to the other new materials but come at a fraction of the cost. Its breakdown field and thermal conductivity are 10 and 3 times that of Silicon, respectively, allowing it to save space, weight, and possible money for manufacturers of not only EVs but all industries that require circuitry. SiC will be revolutionary as it can save space by reducing the need for bigger semiconductors that can spread out the applied voltage to keep the field below its breakdown field or the need for cooling components that dissipate the heat from the semiconductors. This can not only save money for producers and consumers due to increased efficiency but can also save time as the higher voltages a semiconductor can resist, the faster batteries can charge, which is especially important in EV charging stations. GaN is also excellent for similar reasons but differs from SiC by having a higher breakdown field but a lower thermal conductivity. Both SiC and GaN will be revolutionary in the future of semiconductor manufacturing. EV companies are noticing this, as they are using materials such as SiC and GaN in OBCs and seeing increases of around 5%, which allows companies and consumers to save money. They also have an increased power density, saving weight and giving space for other components in the car. However, these advancements are being held back by the difficulties in production, considering the high defect density and extreme doping conditions, and in lifetime, as threshold voltage drift and a reduction in breakdown voltage, which slow down the implementation of these materials to being sold on the market.

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