

Selection of Semiconductor Material for Power Electronics Switching Devices in Electric Vehicles using TOPSIS Method

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Abstract

Semiconductor switches are an integral part of electric vehicles (EVs). The semiconductor materials used for fabrication of these switching devices has evolved a lot in the past few decades. Starting with Germanium which was later succeeded by Silicon, a wide number of semiconductor materials has been utilized in making power electronics switching devices. Recently Wide Band-gap (WBG) semiconductor materials are drawing a lot of attention in device manufacturing due to its superior performance over conventional semiconductor materials. In this paper various semiconductor materials which can be used for fabrication of power electronics switching devices in electric vehicles are compared with each other based on their material properties using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method which is a multi-criteria decision analysis method. The materials are then ranked according to its performance upon various attributes. An optimum semiconductor material for switching devices in electric vehicles can be then decided depending on this rank.

Keywords EV (electric vehicle), optimization, semi-conductor, materials.

1 Introduction

Power Electronics has played a vital role in making Electric Vehicles (EVs) what it is today. A brief description about the various power electronics devices and their uses in EVs are carried out by *Chan et al* [1]. Performance of semiconductor switches used in these power electronics devices are primarily influenced by the material characteristics of the semiconductor. Processing techniques, technological constraints etc also plays a significant role in determining the device performance [2]. The efficiency and power density of switch mode power supplies (SMPS) has been greatly improved with the introduction of wide bandgap (WBG) semiconductors [3]. Also the switching losses are reduced considerably. EVs essentially require power devices with high thermal conductivity, high breakdown voltage and high frequency which cannot be fully accomplished by existing silicon technologies due to its limitations [4].

The latest development of power semiconductor devices in EVs done by *Shen et al* [5] undoubtedly highlights the impact of semiconductor switches in the success of EVs and also throw light on predominantly used switches like IGBTs and power MOSFETs. Various parameters affects the performance of semiconductor devices in EVs. Wide bandgap semiconductors attain considerable attention these days due to their superior properties over conventional semiconductors like Silicon and Germanium. Materials possessing high thermal conductivity and high saturation velocities allows more efficient heat transfer and improves high frequency switching capabilities and also posses a much smaller specific on-resistance [6]. The low on-resistance results in reduced switching losses which contributes to switching at higher frequencies. High frequency switching can ultimately result in reduction of filter sizes [5]. Lower size of filters can further help in compact packing of the components and also due to

lower losses less sized heat sinks can be used. Some parameters which determine the performance of semiconductor switches in electric vehicles are (1) Breakdown voltage, (2) Low On-resistance, (3) Rise and fall times, (4) Safe-operating area, (5) Thermal resistance, (6) High frequency operating capability, (7) EMI compatibility, and (8) Size and packaging. Almost all of the power electronics converter systems in automotive applications use silicon based power semiconductor switches. Silicon has already reached its fundamental theoretical limits. This leads to exploring new semiconductor materials which can be used in the fabrication of semiconductor switches. Some semiconductor materials which can replace the use of silicon in power devices in near future are GaAs, 3C-SiC, 4H-SiC, 6H-SiC, GaN and Diamond etc. The performance of these particular semiconductors hugely rely on their material properties. Some semiconductors may excel in certain properties but may lag behind when it comes to some other properties. Hence selection of a proper semiconductor material to make power electronics switching device out of it requires considerable attention. An optimization technique, known as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is used to select appropriate semiconductor material for manufacturing power semiconductor switching devices.

In this paper different semiconductor materials used to manufacture switching devices are discussed in detail in section 2. Section 3 discusses the effects of various semiconductor material properties on the performance of power electronics switching devices. In section 4 conventional semiconductor materials like Si and GaAs along with WBG materials like 3C-SiC, 4H-SiC, 6H-SiC, GaN and Diamond are compared with each other using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. The materials has been ranked according to the impact of its properties on semiconductor device performance which further help in selection of semiconductor material for device fabrication. It is then followed by summary and conclusion in section 5.

2 Semiconductor Materials

There are many different types of semiconductor materials that can be used within electronic devices. Each has its own advantages, disadvantages and areas where it can be used to offer the optimum performance. Different semiconductor materials differ in their properties. Some commonly used semiconductor devices are semiconductor devices are Germanium, Silicon, Gallium arsenide. Silicon carbide, Gallium Nitride, Gallium phosphide, Cadmium sulphide, Lead sulphide etc. In this paper focus is mainly on Silicon, Gallium Arsenide, 3 different grades of Silicon Carbide, Gallium Nitride and Diamond. A study about the effect of the material properties of all these semiconductors on the performance of a power electronics switching device if they are used to manufacture the same is done in detail. A brief description about these semiconductor materials are given below.

2.1 Silicon

Silicon-based power devices have long dominated the power electronics and power systems applications. There is a host of bipolar, unipolar, controlled, uncontrolled, and Metal-Oxide-Semiconductor (MOS)-gated Si devices that are widely used by power electronics and power systems designers. Examples of such devices are diodes (p-i-n and Schottky rectifiers), thyristors, gate turn-off thyristors (GTOs), gate-controlled thyristors (GCT), bipolar junction transistors (BJTs), insulated-gate bipolar transistors (IGBTs), and power metaloxidesemiconductor field-effect transistors (MOSFETs) [3].

The need for faster devices with high voltage and high switching frequency capability is growing, especially for advanced power conversion. Applications where devices are required to operate at higher than 150°C junction temperature, high voltages, high switching frequencies, and high power densities are growing especially for electric vehicle applications. Silicon-based devices are not able to meet these stringent requirements without costly cooling systems, large number of devices in series and parallel, and costly active or passive snubbers. The latter adds to the overall size and weight, a mostly undesirable feature of silicon-based power converters. Wide-bandgap-based semiconductor devices such as silicon carbide and gallium nitride offer multiple advantages for power electronic designers [7][8]. The superior physical properties of these semiconductors offer a lower intrinsic carrier concentration (10-35 orders of magnitude), a higher electric breakdown field (4-20 times), a higher thermal conductivity (3-13 times), a larger saturated electron drift velocity (2-2.5 times), when compared to silicon.

2.2 Silicon Carbide

SiC is a wide band gap semiconductor material which is mostly used for the production of power switching devices. These devices are lighter, smaller, more compact and more efficient which make them ideal for high voltage power electronic applications. SiC is suitable for elevated temperature applications due to its high thermal conductivity and wider band gap [9]. SiC-based power devices have higher breakdown voltages (5 to 30 times higher than those of Si) because of their higher electric breakdown field. SiC devices are thinner, and they have lower on resistances [10]. SiC-based devices have excellent reverse recovery characteristics [11]. With less reverse recovery current, the switching losses and electromagnetic interference (EMI) are reduced and there is less or no need for snubbers.

2.3 Gallium Nitride

Unique materials properties of GaN-based semiconductors have stimulated a great deal of interest in research and development in materials growth and opto-electronic, and electronic devices using this semiconductor system. The major advantages of nitride-based devices that make them extremely promising for high power high temperature applications are high electron mobility and saturation velocity, high sheet carrier concentration at hetero-junction interfaces, high breakdown field, and low thermal impedance when grown over SiC substrates. The chemical inertness of nitrides is a key property to provide high reliability [12]. GaN and SiC diodes have similar switching properties, but as the temperature increases, the switching performance of the GaN diode is better than that of the SiC diode.

GaN has some disadvantages compared to SiC. The first one is that GaN does not have a native oxide, which is required for MOS devices. SiC uses the same oxide as Si, SiO₂. For GaN, more studies are under way to find a suitable oxide; without it, GaN MOS devices are not possible. The second important problem is that with present technology, GaN boules are difficult to grow. Therefore, pure GaN wafers are not available. Instead, GaN wafers are grown on sapphire or SiC [13][14]. Even then, thick GaN substrates are not commercially available. As a consequence, GaN wafers are more expensive than SiC wafers. An additional disadvantage of GaN compared with SiC is that its thermal conductivity is almost one-fourth that of SiC. This property is especially important in high-power, high-temperature operation because the heat generated inside the device needs to be dissipated as quickly as possible. The higher the thermal conductivity, the more quickly the heat is dissipated. Growing GaN on SiC wafers increases the overall thermal conductivity, but the material still does not equal the performance of SiC.

2.4 Diamond

Diamond shows the best theoretical performance, exceeding every other WBG semiconductor by a factor of several times in every category. However, its processing problems have not yet been solved. After several years of research, there are still processing issues with SiC because of the high temperatures required; diamond is a harder material and needs even higher temperatures for processing, and not as much research has been done on its processing yet. The literature has reported the use of diamond in sensors [15] and field emission devices [16]. These field emission devices are vacuum tubes and should not be confused with the solid-state power devices discussed in the earlier sections. The reason for using field emission technique is to utilize diamond's high temperature operation capability without worrying about the junction failure with high temperature. A diamond field emission device has rows of diamond tips that have to turn on for current conduction; however, making sure all the tips are turned on is a major problem. More research is required to build high-power diamond device.

3 Properties of Semiconductor Materials

The properties of various semiconductor materials namely Si, GaAs, 3C-SiC, 4H-SiC, 6H-SiC, GaN and Diamond at 300K are discussed below and is shown in Table 1.

Table 1: Properties of semiconductor materials at 300 K [12],[17],[18]

Semi-conductor Material	Band-gap (eV)	Electron Mobility (μ_e) ($cm^2/V.s$)	Hole Mobility (μ_h) ($cm^2/V.s$)	Breakdown or Critical Field (E_c) (V/cm ($\times 10^5$))	Saturation velocity (cm/s) ($\times 10^7$)	Thermal Conductivity (σ_T) (W/cm.k)	Maximal operation temperature ($^{\circ}C$)	Coefficient of thermal expansion (ppm/k)	Dielectric constant	Cost Approx. (\$/gm)
Si	1.12	1450	450	3	1	1.3	150	2.6	11.7	12.5
GaAs	1.4	8500	400	4	2	0.54	350	5.73	12.9	46.5
3C-SiC	2.3	1000	45	20	2.5	5	600	2.77	9.6	1040
6H-SiC	2.9	415	90	25	2	5	700	5.12	9.7	186.5
4H-SiC	3.2	950	115	30	2	5	750	5.12	10	186.5
GaN	3.39	1000	35	50	2	1.3	700	5.59	8.9	2213
Diamond	5.6	2200	1800	560	3	20	1100	0.8	5.7	3834

3.1 Bandgap (BG)

The minimum energy difference between the top of the valence band and the bottom of the conduction band is called as Bandgap. It is a major factor determining the conductivity of a material. A semiconductor has a relatively small non-zero band gap. Some semiconductors are classified as wide-bandgap semiconductors because of their wider bandgap [19]. Higher energy gap devices are able to operate at higher frequencies and temperatures [20]. Also wide-bandgap semiconductors can withstand more radiation without losing their electrical characteristics. Thirdly, the larger bandgap results in a lower intrinsic carrier concentration and higher operating junction temperature [5].

3.2 Electron Mobility (EM)

Electron Mobility is a parameter which throws light on how quickly an electron can move through a semiconductor. The conductivity of a semiconductor is proportional to the product of mobility and carrier concentration. So higher the mobility is better will be the conductivity of the semiconductor. Mobility is a very important parameter which effects the performance in semiconductors. Higher electron mobility and electron saturation velocity allow for higher frequency of operation. The best material for high-frequency power switching applications should have a large mobility.

3.3 Hole Mobility (HM)

Hole mobility is the analogous quantity of electron mobility for holes. The highest electron and hole mobilities at room temperature of any wide-bandgap semiconductor is clearly an immensely attractive property. Very few semiconductors have an electron to hole mobility ratio below three and also have an electron mobility above $1000 \text{ cm}^2/\text{V.s}$ [12].

3.4 Breakdown or Critical Field (BF)

A material's electric field strength is the greatest determinant of its voltage blocking capability. For many devices, a semiconductor material with a high electric breakdown field is desirable. High breakdown electric field enables the fabrication of very high-voltage, high-power devices. High doping levels can be achieved with a high electric breakdown field, which ultimately helps to form thinner device layers at the same breakdown voltage levels. The breakdown field in SiC is about 8 times higher than in silicon. This is important for high-voltage power switching transistors. For example, a device of a given size in SiC will have a blocking voltage 8 times higher than the same device in silicon. WBG-semiconductor-based power devices are thinner than their Si-based counterparts and have smaller drift region resistances [19]. High critical Field allows devices to operate at higher voltages and lower leakage currents. If devices are able to withstand higher electric fields then it can be designed with smaller dimensions, which results in faster switching. Integration of devices with high breakdown electric field and high thermal conductivity is possible with higher packaging densities and, thereby the current handling capability of these devices can be improved [21].

3.5 Saturation Velocity (SV)

In a semiconductor the maximum velocity a charge carrier (generally an electron) can attain is called as saturation velocity. A high saturation velocity is advantageous for the performance of FETs operating at high frequencies. The high frequency switching capability of a semiconductor material is directly proportional to its saturation velocity. Higher saturation velocity allows charge in the depletion region of a device to be removed faster; therefore, the reverse recovery current of WBG semiconductor based diodes is smaller, and the reverse recovery time is shorter [19].

3.6 Thermal Conductivity (TC)

Thermal conductivity is the property of a material's ability to conduct heat. Higher thermal conductivity means that the material is superior in conducting heat more efficiently. Higher thermal conductivity combined with wide bandgap and high critical field give WBG semiconductors an advantage when high power is a key desirable device feature. Generally, maximizing the thermal conductivity of the semiconductor material and the associated package material is desirable [12]. Very high thermal conductivity reduces the thermal resistance of the device die and also allows more efficient heat transfer from heat sink and yields a lower junction temperature. Higher thermal conductivity means that heat generated in a device can be more easily be transmitted to the case, heat sink, and then to the ambient. Like diamond, getting heat away when generated itself without any additional solutions helps in handling high powers relatively simply [22].

3.7 Maximal Operation Temperature (MOT)

There is a great need for electronic circuits and devices to work at high temperatures. The need for electronics to work at high operating temperatures is the result of two primary situations, either the need for greater power delivery or a higher temperature environment. For high-temperature operation of power semiconductor devices their thermal stability in terms of high-temperature performance and possibility of thermal runaway are very important considerations [21]. The importance of higher operating temperatures was discussed by *Shenai et al* [23] and found out that Si-based power devices has a limited operating capability up to 200°C whereas WBG devices are capable of operating at temperatures as high as 600°C. Thus the converter has a higher reliability. The switching frequency of the devices is also limited because of the heat generated by the devices, primarily the switching losses. The increased operating temperature will also reduce the weight, volume, cost, and complexity of thermal management systems. The operation temperatures for various semiconductor materials were discussed by *Willander et al* [24].

3.8 Coefficient of Thermal Expansion (CTE)

Every material has a CTE measured in parts per million per degree Celsius/kelvin (ppm/°C or ppm/k). It is the rate at which a material expands in response to heat. This is an important property because two joined materials that do not expand identically when heated will inflict stress on each other until a break occurs. Semiconductor materials that have a closer CTE match to available electrically insulating ceramics can more easily be adapted for high power and wider temperature excursion applications. It is this phenomenon that is the basis of nearly every single mechanical failure type in power modules. Semiconductor materials that have a closer CTE match to available electrically insulating (thermally conducting) ceramics can more easily be adapted for higher power and wider temperature excursion applications than for Si [12]. GaN has two coefficients of thermal expansion (CTEs), one for the c-axis and another for the a-axis which are respectively $3.17 \times 10^{-6} K^{-1}$ and $5.59 \times 10^{-6} K^{-1}$ [25]. Both CTEs are temperature dependent, with higher temperature dependency at higher temperatures.

The CTE of Si (2.6 ppm/k) and SiC (2.77 ppm/k) are of considerable importance because most of the semiconductor devices are typically fabricated in one of these two materials and cannot be replaced from the module package. Therefore this CTE is considered as the benchmark for every other material CTE to be used in any power module. Since large CTE mismatch is bad, then ultimately every material should have as similar CTE to Si or SiC as possible [26]. The larger the CTE mismatch between joined materials the larger the stress per degree Celsius. Unfortunately, some of the materials do not have low CTEs as desired, this often can be because of price of material or complication of changing the manufacture of the modules, but also it may be because the other material has a lower thermal resistance which is also important. Stress relaxation caused by a CTE mismatch is a critically important issue for next-generation power semiconductor modules [27].

3.9 Dielectric Constant (DC)

It is desirable that the dielectric constant of the semiconductor to be low. The dielectric constant is the measure of the capacitive loading of the device and a low DC produces reduced device impedances [28]. But there is a contradiction that larger the DC, smaller will be the device [29]. So the selection of materials depending on the DC parameter is a trade-off depending on the application.

3.10 Cost (CO)

Cost of semiconductor is often expressed in terms of cost per wafer. Cost per wafer is perhaps the most widely used cost metric in the semiconductor industry. It is used to compare different equipment, processes, materials, Fab operating costs etc to obtain one indicator of operating cost. Cost per wafer can also be used as a benchmarking metric. Cost per wafer at the fab level can be simply obtained using the total manufacturing cost upon the total number of wafers produced. Cost per wafer at the equipment level is typically computed using the cost of equipment depreciation, cost of labor, maintenance and materials cost, cost of energy and other facilities as well as building depreciation costs.

4 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) Method

Developed by *Hwang and Yoon et al* [30], this method is based on the concept that the chosen alternative should have the shortest Euclidean distance from the ideal solution. TOPSIS gives a solution that is not only closest to the hypothetically best, but that is also farthest from the hypothetically worst. The procedure for the selection of the best alternative from the available alternatives using TOPSIS method is discussed below:

1. Determine the objective and identify the pertinent evaluation attributes.
2. Based on the information available on attributes prepare a matrix. In this particular case this matrix is nothing but the matrix shown as table properties (i.e., Table 1). Each row of this matrix is allocated to one alternative, and each column to one attribute.

Table 2: Value of attribute

Subjective measure of Attribute	Assigned Value
Exceptionally low	0.0
Extremely low	0.1
Very low	0.2
Low	0.3
Below average	0.4
Average	0.5
Above average	0.6
High	0.7
Very High	0.8
Extremely High	0.9
Exceptionally High	1.0

3. In the case of subjective attributes we can use the machinability index table [31] as shown in Table 2 to get an objective value for it.
4. Next step is to obtain the normalized decision matrix, T_{ij} . This can be obtained using the following relation:

$$T_{ij} = m_{ij} / [\sum_{i=1}^N m_{ij}^2]^{\frac{1}{2}}$$

where m_{ij} is an element of the actual table which is non-normalized and m_{ij} corresponds to the value of the j -th attribute for the i -th alternative and N is the number of alternatives.

Here again normalization of CTE is to be done with special care as mentioned previously. Initially the CTE attribute values has to be normalized using the method of subjective measure of attribute (Refer Table 2) because the CTE performance is determined by measuring the closeness to the substrate over which it is mounted (here Silicon). This makes it a subjective quantity which should be assigned a value depending on its closeness to the substrate. Similarly all the attributes of all the alternatives can be normalized using TOPSIS method which is shown in Table 3. It is also considered as a 7×10 matrix T_1 for future purposes.

Table 3: Normalized properties of semiconductor materials using TOPSIS method T_1

Semi-conductor Material	Band-gap (eV)	Electron Mobility (μ_e) ($cm^2/V.s$)	Hole Mobility (μ_h) ($cm^2/V.s$)	Breakdown or Critical Field (E_c) V/cm ($\times 10^5$)	Saturation velocity (cm/s) ($\times 10^7$)	Thermal Conductivity (σ_T) (W/cm.k)	Maximal operation temperature ($^{\circ}C$)	Coefficient of thermal expansion (ppm/k)	Dielectric constant	Cost Approx. (\$/gm)
Si	0.134	0.16	0.236	5.32×10^{-3}	0.176	0.059	0.083	0.631	0.442	2.74×10^{-3}
GaAs	0.167	0.937	0.21	7.09×10^{-3}	0.352	0.025	0.194	0.126	0.487	0.01
3C-SiC	0.275	0.11	0.024	0.035	0.44	0.229	0.332	0.568	0.363	0.228
6H-SiC	0.347	0.046	0.047	0.044	0.352	0.229	0.388	0.252	0.366	0.041
4H-SiC	0.382	0.105	0.06	0.053	0.352	0.229	0.416	0.252	0.378	0.041
GaN	0.405	0.11	0.018	0.089	0.352	0.059	0.388	0.189	0.336	0.486
Diamond	0.669	0.243	0.945	0.993	0.528	0.914	0.609	0.316	0.215	0.842

5. Next is to decide the weights of the different attributes weights can be obtained arbitrarily or using Analytic Hierarchy Process (AHP) method. For this particular case i.e, the selection of semiconductor materials using TOPSIS method, we can use the AHP method to determine the weights.

6. Determining the weights using AHP Method

- The properties of semiconductors which was shown in Table 1 is normalized using the below relations

For a beneficial attribute

$$w_{(ij)norm} = \frac{w_{(ij)}}{w_{(jmax)}}$$

For a non-beneficial attribute

$$w_{(ij)norm} = \frac{w_{(jmin)}}{w_{(ij)}}$$

where, $w_{(jmax)}$ is the maximum value of attribute in the alternatives for a beneficial parameter and $w_{(jmin)}$ is the minimum value of attribute in the alternatives for a non-beneficial parameter. A beneficial attribute is the one where the maximum value is considered as the better performance (eg: BG, EM etc.) and a non-beneficial attribute is the one where the minimum value is considered as the better performance (eg: DC, CO etc.)

Normalization of CTE invites special attention as it is not normalized depending upon least or higher values of attributes. Since every material should have a similar CTE to Si or SiC as possible (Si is considered as the substrate for all materials here) [26], the difference between the CTE's of different alternatives with Si is found out and this measure of closeness to the CTE of Si is later used to assign values or weights for all alternatives ranging from 0 to 1 with the help of a machinability index table [31] as shown in Table 2. The final normalized semiconductor materials Properties are shown in Table 4. This table is also considered to be a 7×10 matrix, A_1 for future computations.

Table 4: Normalized semiconductor materials Properties matrix A_1

SCM	BG	EM	HM	BF	SV	TC	MOT	CTE	DC	CO
Si	0.2	0.171	0.25	5.35×10^{-3}	0.333	0.065	0.136	1	0.487	1
GaAs	0.25	1	0.222	7.14×10^{-3}	0.667	0.027	0.318	0.2	0.442	0.269
3C-SiC	0.411	0.118	0.025	0.036	0.833	0.25	0.545	0.9	0.594	0.012
6H-SiC	0.518	0.049	0.05	0.045	0.667	0.25	0.636	0.4	0.588	0.067
4H-SiC	0.571	0.112	0.064	0.054	0.667	0.25	0.682	0.4	0.57	0.067
GaN	0.605	0.118	0.019	0.089	0.667	0.065	0.636	0.3	0.64	5.64×10^{-3}
Diamond	1	0.259	1	1	1	1	1	0.5	1	3.26×10^{-3}

- Determining the relative importance of each attributes with respect to the objective:

Here a pair-wise comparison matrix using a scale of relative importance is constructed. When an attribute is compared with itself it is assigned a value of 1. Which means the diagonal elements of the pair-wise comparison matrix will be always 1. Numbers 3, 5, 7 etc correspond to verbal judgments 'moderate importance', 'strong importance', 'very strong importance' etc [32]. Now considering N attributes we will have a square matrix A_2 of order $N \times N$. Here a_{ij} value denotes the comparative importance of attribute i with respect to attribute j. Also $a_{ij}=1$ if $i=j$ and $a_{ji}=1/a_{ij}$. The pair-wise comparison matrix (also known as the relative importance matrix) A_2 for the semiconductor materials parameters are shown in Table 5.

- Once the normalized matrix is formed then the relative normalized weight w_j of each attribute has to be found out by first calculating the geometric mean of the i-th row and then normalizing the geometric means of rows in the comparison matrix. This can be done using the following relations:

$$P_j = \left[\prod_{j=1}^N a_{ij} \right]^{\frac{1}{N}}$$

Table 5: Relative importance matrix A_2

	BG	EM	HM	BF	SV	TC	MOT	CTE	DC	CO
BG	1	3	5	3	3	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	5	$\frac{1}{5}$
EM	$\frac{1}{3}$	1	5	3	3	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	3	$\frac{1}{5}$
HM	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{7}$
BF	$\frac{1}{3}$	$\frac{1}{3}$	1	1	1	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{7}$
SV	$\frac{1}{3}$	$\frac{1}{3}$	1	1	1	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{7}$
TC	3	5	5	5	5	1	1	1	3	$\frac{1}{3}$
MOT	3	5	5	5	5	1	1	1	3	$\frac{1}{3}$
CTE	3	5	5	5	5	1	1	1	3	$\frac{1}{3}$
DC	$\frac{1}{5}$	$\frac{1}{3}$	3	3	3	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1	$\frac{1}{5}$
CO	5	5	7	7	7	3	3	3	5	1

$$w_j = P_j / \sum_{j=1}^N P_j$$

The final tabulated values P_j and relative normalized weights (w_j) of all the attributes is shown in Table 6. This is also considered to be a 10×1 matrix, A_3 for future computations.

Table 6: Final weight matrix A_3

Attribute	P_j	$w_j = \frac{P_j}{\sum P} = A_3$	$A_4 = A_2 \times A_3$	$A_5 = \frac{A_4}{A_3}$
BG	1.175	0.084	0.958	11.405
EM	0.769	0.055	0.64	11.636
HM	0.33	0.023	0.25	10.87
BF	0.365	0.026	0.268	10.308
SV	0.365	0.026	0.268	10.308
TC	2.125	0.151	1.589	10.523
MOT	2.125	0.151	1.589	10.523
CTE	2.125	0.151	1.589	10.523
DC	0.649	0.046	0.515	11.196
CO	4.04	0.287	3.096	10.787

- Calculate matrices A_4 and A_5 such that $A_4 = A_2 \times A_3$ and $A_5 = A_4 / A_3$.
- Determine the maximum eigen value λ_{max} which is the average of matrix A_5 .

$$\lambda_{max} = [\sum_{j=1}^N A_{5j}] / N$$

- Calculate the consistency index CI using below relation. The smaller the value of CI, the smaller will be the deviation from consistency.

$$CI = \frac{\lambda_{max} - N}{N - 1}$$

- From the Random Index (RI) values shown in Table 7 [31], obtain the RI for the number of attributes used in decision making. Here N=10 and hence RI= 1.49.

Table 7: Random Index (RI) Values

Attributes	3	4	5	6	7	8	9	10
RI	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

- Calculate the consistency ratio CR using below equation. A CR of 0.1 or less is considered to be acceptable and indicates the selection of relative importance matrix is properly done.

$$CR = \frac{CI}{RI} = \frac{0.09}{1.49} = 0.06 < 0.1$$

- Once the CR value is verified we can make sure that the obtained values for weights are correct and can be chosen for further computations.

7. We can use now the matrix A_3 which is the normalized weight matrix of AHP method (Refer Table 8). It can be noted that the sum of all the weights of attributes is equal to 1.

Table 8: Weight matrix (A_3) for TOPSIS method

Attributes	BG	EM	HM	BF	SV	TC	MOT	CTE	DC	CO
Weight	0.084	0.055	0.023	0.026	0.026	0.151	0.151	0.151	0.046	0.287

8. Find out the weighted normalized matrix V_{ij} . It can be obtained by the multiplication of each elements of the column of the matrix T_{ij} with its associated weight w_j . The elements of the weighted normalized matrix V_{ij} can be expressed as,

$$V_{ij} = w_j \times T_{ij}$$

The complete weighted normalized matrix V_1 is shown in Table 9.

Table 9: Weighted Normalized matrix using TOPSIS method V_1

Semi-conductor Material	Band-gap (eV)	Electron Mobility (μ_e) ($cm^2/V.s$)	Hole Mobility (μ_h) ($cm^2/V.s$)	Breakdown or Critical Field (E_c) V/cm ($\times 10^5$)	Saturation velocity (cm/s) ($\times 10^7$)	Thermal Conductivity (σ_T) (W/cm.k)	Maximal operation temperature ($^{\circ}C$)	Coefficient of thermal expansion (ppm/k)	Dielectric constant	Cost Approx. (\$/gm)
Si	0.011	8.80×10^{-3}	5.43×10^{-3}	1.38×10^{-4}	4.58×10^{-3}	8.90×10^{-3}	0.013	0.095	0.020	7.86×10^{-4}
GaAs	0.014	0.052	4.83×10^{-3}	1.84×10^{-4}	9.15×10^{-3}	3.78×10^{-3}	0.029	0.019	0.022	2.87×10^{-3}
3C-SiC	0.023	6.05×10^{-3}	5.52×10^{-4}	9.10×10^{-4}	0.011	0.035	0.050	0.086	0.0167	0.065
6H-SiC	0.029	2.53×10^{-3}	1.08×10^{-3}	1.14×10^{-3}	9.15×10^{-3}	0.035	0.059	0.038	0.0168	0.012
4H-SiC	0.032	5.78×10^{-3}	1.38×10^{-3}	1.38×10^{-3}	9.15×10^{-3}	0.035	0.063	0.038	0.017	0.012
GaN	0.034	6.05×10^{-3}	4.14×10^{-4}	2.31×10^{-3}	9.15×10^{-3}	8.90×10^{-3}	0.059	0.029	0.015	0.139
Diamond	0.056	0.013	0.022	0.026	0.014	0.138	0.092	0.048	9.89×10^{-3}	0.242

9. Obtain the positive ideal and the negative ideal solutions, i.e., the best and worst solutions. It can be determined as,

$$V^+ = \max \text{ of } V_j, \text{ if } j \text{ is a beneficial attribute}$$

$$V^- = \min \text{ of } V_j, \text{ if } j \text{ is a non-beneficial attribute}$$

$$V^+ = [V_1^+, V_2^+, V_3^+, \dots, V_N^+]$$

and

$$V^- = \min \text{ of } V_j, \text{ if } j \text{ is a beneficial attribute}$$

$$V^- = \max \text{ of } V_j, \text{ if } j \text{ is a non-beneficial attribute}$$

$$V^- = [V_1^-, V_2^-, V_3^-, \dots, V_N^-]$$

V_j^+ means the positive ideal or best value of the particular attribute among the values of the attributes of different alternatives. Where higher values are desirable i.e., beneficial attributes (here BG, EM etc up-to CTE), V_j^+ indicates the higher value of the attribute. V_j^- indicates the lower value of the attribute if the attributes are non-beneficial i.e., where least values are desirable (here DC and CO).

V_j^- means the negative ideal or worst value of the particular attribute among the values of the attributes of different alternatives. Where higher values are desirable i.e., beneficial attributes (here BG, EM etc up-to CTE), V_j^- indicates the lower value of the attribute. V_j^- indicates the higher value of the attribute if the attributes are non-beneficial i.e., where least values are desirable (here DC and CO).

The positive ideal value V_j^+ and the negative ideal value V_j^- of all the attributes are shown in Table 10 and Table 11.

Table 10: Positive and Negative Ideal values of attributes-I

Attribute	BG	EM	HM	BF	SV
V_j^+	0.056	0.052	0.022	0.026	0.014
V_j^-	0.011	2.53×10^{-3}	4.14×10^{-3}	1.38×10^{-4}	4.58×10^{-3}

Table 11: Positive and Negative Ideal values of attributes-II

Attribute	TC	MOT	CTE	DC	CO
V_j^+	0.138	0.092	0.095	9.89×10^{-3}	7.86×10^{-4}
V_j^-	3.78×10^{-3}	0.013	0.019	0.022	0.242

- Determine separation measures. The separation of each alternatives from the ideal value can be obtained using the following equations.

$$S_i^+ = \left(\sum_{j=1}^N [V_{ij} - V_j^+]^2 \right)^{\frac{1}{2}}$$

$$S_i^- = \left(\sum_{j=1}^N [V_{ij} - V_j^-]^2 \right)^{\frac{1}{2}}$$

where i varies from 1 to N i.e., 1 to 7 here.

The complete S_i^+ and S_i^- values of all the alternatives are shown in Table 12.

Table 12: Separation measures of each alternatives S_i^+ and S_i^-

Alternative	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
S_i^+	0.167	0.175	0.145	0.139	0.137	0.212	0.249
S_i^-	0.261	0.244	0.195	0.239	0.239	0.114	0.168

11. Obtain the relative closeness of a particular alternative to the ideal solution. It is denoted as P_i which can be determined as,

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

The complete composite performance score P_i of all the alternatives and their ranks accordingly are shown in Table 13.

Table 13: Relative closeness of each alternatives P_i and their Ranks

Alternative	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
P_i	0.610	0.582	0.574	0.632	0.636	0.350	0.403
Rank	3	4	5	2	1	7	6

The rank of all the alternatives are obtained by arranging them in the descending order of the P_i values. The alternative having the highest P_i value is ranked one and so on. Hence we can decide the most preferred and least preferred alternatives for a particular problem (here selection of semiconductor materials) accordingly. We can see 4H-SiC is the most preferable choice for selection of semiconductor material whereas GaN is the least preferred.

5 Conclusion

The different material properties of semiconductors like Si, GaAs, 3C-SiC, 6H-SiC, 4H-SiC, GaN and Diamond are studied. Also their effect on the performance of switching devices are discussed. The ranks of different semiconductor materials which can be used for the fabrication of high power semiconductor switches are estimated using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. The ranks using both the methods are shown in Table 13. WBG semiconductors has already been projected as the future of semiconductor switches due to their superior characteristics. The higher breakdown voltages and high thermal conductivity makes it an excellent choice for harsh environments like those of EVs. Also higher operation temperature of WBG materials is an added advantage when it comes of EV perspective. Low switching losses and high switching frequency helps in reduction of component size and helps in compact packaging which helps in reducing space of power-train components in EVs where effective space utilization plays a vital role in its design, performance and efficiency. Using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method, 4H-SiC achieves the highest ranking. 6H-SiC ranks second followed by Si which shows that the significance of silicon as a material for switching device hasn't faded completely. It is due to its cheaper cost. GaN turned out to be the material which is least preferred.

Diamond even though having better electrical properties, its research and development is still at an infant stage. In EV applications where cost of the vehicle plays a huge role in its success and acceptability, the high cost of diamond makes its use in EV application nearly close to impossible currently. In WBG semiconductors, SiC technology is getting more matured than GaN technology due to its better research and commercialization. Also the reduced thermal conductivity of GaN pulls it out of competition with SiC when it comes to deciding switching devices for EVs. Gallium is not naturally found in a deposit which makes it further complicated in extracting the material. GaAs is fairly brittle which limits the wafer diameter whereas silicon wafers can typically found in higher diameters. This significant decrease in usable area adds again to the expense of a GaAs wafer. Also the toxicity of arsenic itself invites special handling to prevent adverse effects. In an application like electrical vehicles where cost and availability of materials play a significant role, the selection of materials has to be a trade-off between its performance along with its cost and availability. Diamond having a superior performance over other materials are still lagging behind when it comes to its selection for switching devices due to its higher cost and complexity in fabrication technology. Si, even though reached its technological limits and having a poor device performance compared to WBG semiconductor materials hasn't lost its significance due to its rich available technology and reduced cost and high availability. In the WBG materials SiC is ranked over GaN due its better thermal conductivity and cost. In future when the WBG semiconductors technology advances in par with Si technology, then SiC materials are going to be the best contenders for power electronics semiconductor switches out of which 4H-SiC will have an upper-hand when compared with its fellow material grades due to its superior performance and reduced cost.

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