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Research article

An advanced semiconductor material selection for switching devices in electric vehicles using three multiple attribute decision making methods

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Abstract: Electric Vehicle (EV) has emerged as a solution for the growing concerns on pollution and depleting oil resources all over the world. The performance and efficiency of an EV mainly depends on the power electronic switching devices used in it which, in turn depends on the properties of materials used in its fabrication. Traditional semiconductor material like Silicon has been widely used for the fabrication of these switches. However, improvised material technology and incessant demand for better performance has triggered the use of wide band-gap (WBG) semiconductors in switching devices. This paper aims to compare a few WBG semiconductors with traditional semiconductors based on their material properties. Three decision making methods has been used for comparison and the possibly best material for fabrication of switching devices has been chosen based on their rankings achieved. Adoption of the suggested material can improve the performance and efficiency of EV's theoretically.

Keywords: power semiconductor devices; electric vehicles; wide band gap semiconductors; semiconductor materials; optimization methods

1. Introduction

Electric vehicles (EV) have become a very prominent choice for pollution-less transportation. All the environmental threats arisen by the green house gases emitted by conventional vehicles and the economic concerns of different countries over the unavailability of petroleum resources has propelled the search for an alternative fuel which can replace the fossil fuels used in vehicles. This has kick-started the use of electric energy for the propulsion of a vehicle. Electrical vehicle generates less pollution due to the absence of any form of emissions but the generation of electricity for EV's can indirectly contribute to pollution from power plants. This can be taken care by using renewable energy for generation which can make EV a zero emission vehicle.

Power Electronics has been vital in boosting the research on Electric Vehicles (EV's). A brief description about the various power electronics devices and their uses in EV's are carried out by [1]. The latest development of power semiconductor devices in EV's done by [2] highlights the impact of semiconductor switches in the success of EV's and also discusses predominantly used switches likes IGBT's and power MOSFET's. Unlike other applications, inside an EV power semiconductor device are subjected to face high load fluctuations due to the unpredictability in drive conditions. Hence, the design of power switching devices invites special care. There are many semiconductor materials available at material level for device manufacturing. Selection of a proper material can considerably improve the performance. The paper intends to do the selection based on many material properties along with cost constraint, which is a novel approach. Various parameters affecting the performance of semiconductor devices in EV's are discussed.

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, the selection of a proper semiconductor material to make power electronics switching devices out of it requires considerable attention. In this paper, three Multiple Attribute Decision Making (MADM) methods namely Analytical Hierarchy Process (AHP) method, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method and PROMETHEE method are used to identify the best possible material, which can be used for the fabrication of semiconductor switches to be used in an EV. Si, GaAs, 3C-SiC, 4H-SiC, 6H-SiC, GaN and Diamond are the materials chosen as primary candidates for switch fabrication. These materials are compared with each other based on their material properties and the most suitable material is chosen using above MADM methods. In this paper, a brief description about different semiconductor materials are presented in Section 2. The material properties which determines the performance of semiconductor switches are discussed in Section 3. The three MADM methods used to determine the ranking of semiconductor materials are explored in Section 4 which is followed by the 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. Some commonly used semiconductor devices are semiconductor devices are Germanium, Silicon, Gallium arsenide. Silicon carbide, Gallium Nitride, Gallium phosphide, Cadmium sulphide, Lead sulphide etc. This paper focuses 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 device 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. 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.

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 [3]. 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 [4].

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 [5]. 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.

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 [6] and field emission devices [7].

3. Properties of semiconductor materials

The properties of semiconductor materials which affect the performance of devices are discussed below. The properties of various semiconductor materials namely Si, GaAS, 3C-SiC, 4H-SiC, 6H-SiC, GaN and Diamond at 300K is shown in Table 1 [8, 9].

Table 1. Properties of semiconductor materials at 300 K.

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 (^{o}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 [10]. Higher energy gap devices are able to operate at higher frequencies and temperatures [11]. 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 [2].

3.2. Electron mobility (EM)

Electron Mobility is a parameter which decides how quickly an electron can move through a semiconductor. The conductivity of a semiconductor is proportional to the product of mobility and carrier concentration. Higher mobility will result in better 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 cm^2 /V.s which is considered as a desirable parameter [5]..

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.

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 FET's 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 [10].

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 [5]. 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.

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 [12]. The importance of higher operating temperatures was discussed by [13] 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 [14].

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 [5].

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 [15]. But there is a contradiction that larger the DC, smaller will be the device [16]. 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.

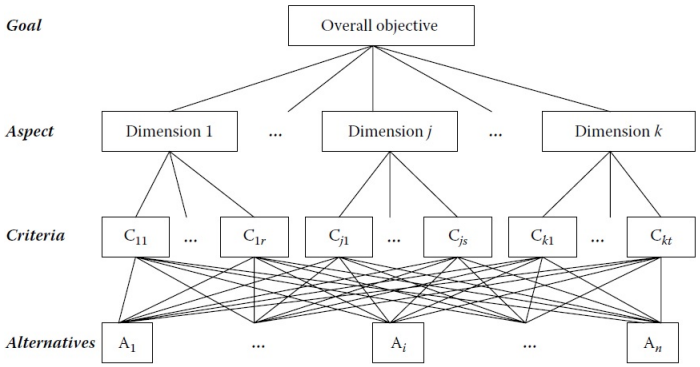
4. Multiple attribute decision making (MADM) methods

Decision making is one type of optimization method which can be defined as the study of identifying and choosing alternatives based on the values and preferences of the decision maker. Making a decision implies that there are alternative choices to be considered, and in such a case we want not only to identify as many of these alternatives as possible but to choose the one that best fits with our goals, objectives, desires, values, and so on [17]. According to [18], decision making should start with the identification of the decision maker(s) and stakeholder(s) in the decision, reducing the possible disagreement about problem definition, requirements, goals and criteria. The procedures of MADM can be summarized in five main steps as follows [19]:

- Step 1: Define the nature of the problem;
- Step 2: Construct a hierarchy system for its evaluation (Figure 1);
- Step 3: Select the appropriate evaluation model;
- Step 4: Obtain the relative weights and performance score of each attribute with respect to each alternative;
- Step 5: Determine the best alternative according to the synthetic utility values;

- Step 6: Outrank the alternatives referring to their utility values.

Figure 1. Hierarchical system for MADM.



For finding out the best semiconductor material for making a switching device with superior performance for an EV, some important methods, known as Multiple Attribute Decision Making (MADM) methods have been used. MADM methods is used to solve problems which involves selection from a finite number of alternatives [20, 21]. Using MADM methods we can arrive at a solution, i.e., best alternative or rank of entire alternatives, if we have the information about the attributes of various alternatives. An MADM method is carried out with the help of a decision table which has the information about alternatives (here Si, GaAS, 3C-SiC, 4H-SiC, 6H-SiC, GaN and Diamond), attributes (here SCM, BG, EM, HM, BF, SV, TC, MOT, CTE, DC and CO), weight or relative importance of attributes and measures of performance of alternatives. The alternatives and attributes are available from Table 1 and the weights has to be found out. Once the weights are obtained then Analytical Hierarchy Process (AHP) method, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method and PROMETHEE method are used to obtain the ranks of all materials. Based on these ranks, the best material has been chosen for fabrication of semiconductor switches used in EV's.

4.1. Determination of weights

The procedure for determination of weights of all alternatives are as follows:

1. Obtaining the normalized semiconductor materials properties:
   All the elements in the decision table must be normalized to the same units in order to carry out the MADM techniques. 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.).
Similarly all the attributes for different alternatives are normalized using the above relations. Now 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) [22], 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 [20] as shown in Table 2.

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

The final normalized semiconductor materials properties are shown in Table 3. This table is also considered to be a 7×10 matrix, A_1 for future computations.

Table 3. 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}

2. 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 [23]. Now considering N attributes, we will have a square matrix A_2 of order N×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 4.

Table 4. 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

3. Determining the relative normalized weight:
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:

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

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

The final tabulated values P_j and (w_j) of all the attributes is shown in Table 5. This is also considered to be a 10×1 matrix, A_3 for future computations.

4. Calculate matrices A_4 and A_5 such that $A_4 = A_2 \times A_3$ and $A_5 = A_4/A_3$.
A_5 can be obtained as $A_5 = A_4/A_3$. For eg., A_{51} can be calculated as,

$$A_{51} = \frac{0.958}{0.084} = 11.405$$

Table 5. Final weight matrix A_3.

Attribute	P_j	$w_j=\frac{P_j}{\Sigma P}=A_3$	$A_4= A_2\times A_3$	$A_5=\frac{A_4}{A_3}$
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

5. Determine the maximum eigen value λ_{max} which is the average of matrix A_5.

$$\lambda_{max} = [\sum_{j=1}^{N} A_{5_j}]/N = 10.808$$

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

$$CI = \frac{\lambda_{max} - N}{N - 1} = 0.09$$

7. From the Random Index (RI) values shown in Table 6 [20], obtain the RI for the number of attributes used in decision making. Here N=10 and hence RI= 1.49.

Table 6. 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

8. 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.

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

9. 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.

4.2. Analytic Hierarchy Process (AHP) method

Developed by [23], the Analytic Hierarchy Process (AHP) Method is one of the most popular technique for decision making problems. The determination of rank of materials using AHP method is as follows:

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

Table 7. Determined weight matrix (A_3) for MADM methods.

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

2. Once the CR value is verified, the overall or composite performance scores for the alternatives has to be obtained by multiplying the normalized value of each alternative with its corresponding normalized weight value w_j and summing over the attributes for each alternatives.i.e., the 7×10 matrix A_1 is multiplied with the 10×1 matrix A_3 to get a 7×1 column matrix A_6 (as shown in Table 8) whose values are the composite performance scores of the corresponding alternatives.

Table 8. Analytic hierarchy process method score A_6.

$$\begin{vmatrix} 0.2 & 0.171 & 0.25 & 5.35\times10^{-3} & 0.333 & 0.065 & 0.136 & 1 & 0.487 & 1 \\ 0.25 & 1 & 0.222 & 7.14\times10^{-3} & 0.667 & 0.027 & 0.318 & 0.2 & 0.442 & 0.269 \\ 0.411 & 0.118 & 0.025 & 0.036 & 0.833 & 0.25 & 0.545 & 0.9 & 0.594 & 0.012 \\ 0.518 & 0.049 & 0.05 & 0.045 & 0.667 & 0.25 & 0.636 & 0.4 & 0.588 & 0.067 \\ 0.571 & 0.112 & 0.064 & 0.054 & 0.667 & 0.25 & 0.682 & 0.4 & 0.57 & 0.067 \\ 0.605 & 0.118 & 0.019 & 0.089 & 0.667 & 0.065 & 0.636 & 0.3 & 0.64 & 5.64\times10^{-3} \\ 1 & 0.259 & 1 & 1 & 1 & 1 & 1 & 0.5 & 1 & 3.26\times10^{-3} \end{vmatrix} \begin{vmatrix} 0.084 \\ 0.055 \\ 0.023 \\ 0.026 \\ 0.026 \\ 0.151 \\ 0.151 \\ 0.151 \\ 0.046 \\ 0.287 \end{vmatrix} = \begin{vmatrix} 0.532 \\ 0.278 \\ 0.351 \\ 0.306 \\ 0.321 \\ 0.26 \\ 0.598 \end{vmatrix}$$

3. Arranging the score in descending order gives the rank of the semiconductor materials according to which it can be chosen for power electronics devices. Diamond ranks the highest whereas GaN ranks the lowest. The score and rank of all the alternatives and their ranks are shown in Table 9.

Table 9. Score and rank of each alternatives using AHP method.

Alternative	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
AHP Score	0.532	0.278	0.351	0.306	0.321	0.260	0.598
Rank	2	6	3	5	4	7	1

4.3. Technique for order preference by similarity to ideal solution (TOPSIS) method

Developed by [24], 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.
3. In the case of subjective attributes we can use the machinability index table [20] which was explained earlier (See 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. This value can be directly taken from Table 3 mentioned previously. These values are latter normalized using the TOPSIS method. Similarly, all the attributes of all the alternatives can be normalized using TOPSIS method which is shown in Table 10. It is also considered as a 7×10 matrix T_1 for future purposes.

Table 10. 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 (^oC)	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. Decide the weights of the different attributes. Weights determined earlier can be used for this purpose. We can recall the matrix A_3 which is the normalized weight matrix of AHP method (Refer Table 7).
6. 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,

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

All the equivalent weighted normalized elements of the 7×10 matrix V_1 can be determined using the above equation. The complete weighted normalized matrix V_1 is shown in Table 11.

Table 11. 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 (^{o}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

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

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

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

$$V^+ = [V_1{}^+, V_2{}^+, V_3{}^+, ..., V_N{}^+]$$

and

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

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

$$V^- = [V_1{}^-, V_2{}^-, V_3{}^-, ..., V_N{}^-]$$

$V_j{}^+$ 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 12 and Table 13.

Table 12. 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 13. 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

8. 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 14.

Table 14. 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

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

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

10. The complete composite performance score P_i of all the alternatives and arranging the score in descending order gives the rank of the semiconductor materials according to which it can be chosen for power electronics devices. The score and rank of all the alternatives and their ranks are shown in Table 15.

Table 15. 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 alternative having the highest P_i value is ranked one and so on. Hence we can decide on the most preferred and least preferred alternatives for a particular problem (in this case, 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.

4.4. PROMETHEE method

The PROMETHEE method was first proposed by [25] and [26] and later improvised [27]. The values of attributes need not necessarily be normalized or transformed into a common dimensionless scale in this method. Instead it is assumed higher score value means a better performance. The weights of the criteria has to be determined separately in this method, which has been already carried out. The procedure to use PROMETHEE method to determine the rank of semiconductor materials to be used in switching devices in EV's is as follows:

1. Determine the individual alternative comparison matrix for all the attributes.
   A 7×7 matrix A_N is formed comprising of zeros and ones. For a beneficial attribute, an alternative having an higher value is assigned 1 when compared with an alternative having lower value and assigned 0 when compared with an alternative having higher value. For a non-beneficial attribute, an alternative having an higher value is assigned 0 when compared with an alternative having lower value and assigned 1 when compared with an alternative having higher value. An alternative compared with itself is assigned 1 which makes all the diagonal elements of the 7×7 matrix A_N as 1. If both alternatives has the same value it is assigned as 0 when comparing. The A_1 matrix for the attribute band-gap (BG) is shown in Table 16. Similarly the alternative comparison matrix for the nine other attributes have been found out.
2. Multiply the individual alternative comparison matrix of all the attributes with its corresponding weights.
   For eg., All the elements of Table 16 is multiplied with the weight obtained for the attribute band-gap (BG) i.e., 0.084 to get Table 17. Similarly all the other individual alternative comparison

matrix of each attributes are multiplied with its corresponding weights determined earlier (Refer Table 5).

Table 16. Alternative comparison matrix for band-gap (BG) A_1.

	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
Si	1	0	0	0	0	0	0
GaAs	1	1	0	0	0	0	0
3C-SiC	1	1	1	0	0	0	0
6H-SiC	1	1	1	1	0	0	0
4H-SiC	1	1	1	1	1	0	0
GaN	1	1	1	1	1	1	0
Diamond	1	1	1	1	1	1	1

Table 17. Weighted alternative comparison matrix for band-gap (BG).

	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
Si	0.084	0	0	0	0	0	0
GaAs	0.084	0.084	0	0	0	0	0
3C-SiC	0.084	0.084	0.084	0	0	0	0
6H-SiC	0.084	0.084	0.084	0.084	0	0	0
4H-SiC	0.084	0.084	0.084	0.084	0.084	0	0
GaN	0.084	0.084	0.084	0.084	0.084	0.084	0
Diamond	0.084	0.084	0.084	0.084	0.084	0.084	0.084

3. Once all the weighted individual alternative comparison matrices are obtained, the final performance matrix A_{PM} of all alternatives has to be determined using the following equations.

$$A_{PM_{ij}} = \sum_{n=1}^{N} A_{n_{ij}}$$

where N is the number of attributes (here BG, EM,....., CO.) i.e., 10 and i, j varies from 1 to 7. It can be noted that all the diagonal elements of the final performance matrix A_{PM} is equal to one as sum of all the weights determined is one. The final performance matrix A_{PM} is shown in Table 18.

4. Determine the row-wise and column wise matrices S_R and S_C as follows:

Table 18. Final performance matrix A_{PM}.

	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
Si	1	0.507	0.365	0.365	0.365	0.365	0.438
GaAs	0.493	1	0.516	0.516	0.516	0.516	0.493
3C-SiC	0.635	0.484	1	0.127	0.127	0.487	0.438
6H-SiC	0.635	0.458	0.722	1	0.046	0.461	0.438
4H-SiC	0.635	0.458	0.722	0.339	1	0.612	0.438
GaN	0.484	0.458	0.458	0.362	0.362	1	0.438
Diamond	0.562	0.507	0.562	0.562	0.562	0.562	1

$$S_R = [S_{R_1}\ S_{R_2}\ S_{R_3}\ S_{R_4}\ S_{R_5}\ S_{R_6}\ S_{R_7}]$$

$$S_C = [S_{C_1}\ S_{C_2}\ S_{C_3}\ S_{C_4}\ S_{C_5}\ S_{C_6}\ S_{C_7}]$$

where,

$$S_{R_1} = \sum_{j=1}^{7} A_{PM_{1j}}, S_{R_2} = \sum_{j=1}^{7} A_{PM_{2j}} \text{ and so on,}$$

and

$$S_{C_1} = \sum_{i=1}^{7} A_{PM_{i1}}, S_{C_2} = \sum_{i=1}^{7} A_{PM_{i2}} \text{ and so on,}$$

The final row-wise and column wise matrices S_R and S_C is shown in Table 19.

Table 19. Row-wise and Column wise matrices S_R and S_C.

	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
S_R	3.405	4.050	3.298	3.760	4.204	3.562	4.317
S_C	4.444	3.872	4.345	3.271	2.978	4.003	3.683

5. Determine the final performance scores P_i of each alternatives as follows:

$$P_{i_{ij}} = S_{R_{ij}} - S_{C_{ij}}$$

where, i=1 and j varies from 1 to 7.

Table 20. Final performance scores P_i and ranks using PROMETHEE method.

	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
P_i	-1.039	0.178	-1.047	0.489	1.226	-0.441	0.634
Rank	6	4	7	3	1	5	2

6. Arranging the final performance scores P_i in descending order gives the rank of the semiconductor materials according to which it can be chosen for power electronics devices. The score of all the alternatives and their ranks obtained using PROMETHEE method is shown in Table 20.
   The alternative having the highest Pi 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 whereas 3C-SiC turned out to be the least preferable using PROMETHEE method.

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 three multiple attribute decision making methods, namely Analytic Hierarchy Process (AHP) method, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method and PROMETHEE method . The ranks obtained using all the methods are shown in Table 21.

Table 21. Rank of each alternatives using AHP, TOPSIS and PROMETHEE methods.

Rank	Si	GaAs	3C-SiC	6H-SiC	4H-SiC	GaN	Diamond
AHP	2	6	3	5	4	7	1
TOPSIS	3	4	5	2	1	7	6
PROMETHEE	6	4	7	3	1	5	2

Using AHP method Diamond achieves the highest ranking whereas 4H-SiC secures the best position when TOPSIS and PROMETHEE methods are used. Even though Diamond has 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 at present. Si, even though being reached its technological limits and having a poor device performance compared to WBG semiconductor materials hasn't lost its significance due to its matured device technology and reduced cost and high availability. 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 cost of a GaAs wafer. Also, the toxicity of arsenic itself invites special handling to prevent adverse effects. 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. The applied MADM techniques suggests that 4H-SiC will be a better choice when it comes to selection of materials for fabrication of semiconductor switching devices in EV's when compared with its fellow material grades due to its superior performance and reduced cost.

Conflict of interest

The authors declare that there is no conflicts of interest in this paper.

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