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Study of Static and Dynamic Characteristics of Silicon and Silicon Carbide Devices

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***Abstract*—There is a rising demand for more efficient, high power density, high frequency and high temperature operation in the power electronic industry. Nowadays Silicon (Si) devices reaches its maximum possible theoretical values due to its material properties. Silicon Carbide (SiC) based power semiconductor electronic devices have been being presently developed for high-temperature, high-power, and high-radiation conditions under which Si based semiconductors cannot perform efficiently. The large band-gap and high breakdown electric field of SiC power switching devices enable them to perform much better than Si devices. This project aims to study and simulate dynamic and electric behavior of Si and SiC devices in LTspice IV platform.**

***Keywords*—Silicon Carbide; Wide Band Gap material; high power density; IGBT; MOSFET**

I. INTRODUCTION

At present Si based semiconductors are not suitable for our increasing future demands, especially in high voltage, high efficiency, high temperature operations. As we know that, Si IGBT can handle a voltage upto 5000V, but due to the bipolar nature, its switching frequency is restricted to 100KHz. Si MOSFET can handle switching frequency upto several MHz, but due to its high ON state resistance, the use of MOSFET is restricted to low voltage applications and also, the operating temperature of Si based power semiconductor devices is restricted to 150°C. This is because silicon has narrow bandgap, i.e., 1.1eV. So when the temperature rises, there is an exponential increase in intrinsic carriers. This causes high undesired leakage currents and at higher temperatures, the intrinsic carriers make uncontrolled conductivity and it will overcome the semiconductor device operation. Si devices have reached their maximum theoretical limits with respect to temperature, operating frequency and voltage blocking capabilities. Theoretically, wider bandgap devices like SiC, GaN and Diamond have the potential to overcome the above mentioned issues. Nowadays, Silicon Carbide (SiC), has emerged as an alternative semiconductor to fulfill power electronics requirement.

Because of the high electric breakdown field, wide bandgap (WBG) semiconductor-based power devices have high breakdown voltages. WBG semiconductor-based unipolar devices are thinner and have lower on-resistances (Ron). Lower Ron also means lower conduction losses. Therefore, higher overall converter efficiency is attainable. Because of the high thermal conductivity, WBG power semiconductor devices have low junction to case thermal resistance. Therefore, heat can easily be transferred out from the device. WBG power semiconductor devices is projected to operate at high junction temperatures up to 600°C. Where, Si based power semiconductor operation is restricted to 150°C. Forward and reverse characteristics of WBG power semiconductor devices vary slightly with temperature and time. Therefore, they are more reliable. WBG semiconductor-based bipolar devices have excellent reverse recovery characteristics. With less reverse recovery current, switching losses and electromagnetic interference (EMI) are reduced, and there is less or no need for snubbers. As a result, there is no need to use soft-switching techniques to reduce switching losses. Because of low switching losses, WBG semiconductor-based devices can operate at higher frequency.

The main objective is to study the fundamentals of SiC material properties and compare the static and dynamic behavior of SiC and Si device.

TABLE I. WBG SEMICONDUCTOR MATERIAL PROPERTIES.

Property	Si	SiC	GaN	Diamond
Bandgap, E_g (eV)	1.12	3.26	3.45	5.45
Dielectric Constant	11.9	10.1	9	5.5
Electric Breakdown Field, E_c (KV/cm)	300	2200	2000	10000
Thermal Conductivity (W/cm.K)	1.5	4.9	1.3	22
Saturated Electron Drift Velocity (*10^7 cm/s)	1	2	2.2	2.7

II. SIC STRUCTURES

Silicon carbide is a non-oxide ceramic having high hardness and strength, and it is chemically and thermally stable. Silicon carbide has different polytypes; among this 200 are found in mainly cubic, hexagonal and rhombohedral crystallographic categories. SiC polytypes with a cubic crystal structure is 3C-SiC, also known as β-SiC. 4H-SiC and 6H-SiC are the SiC polytypes with a hexagonal crystal structure and 15R-SiC is the SiC polytypes with rhombohedral crystal structure. The electrical semiconductor properties of each SiC polytype are distinct.

A. *Material properties*

Here we are comparing the characteristics of Si with other important wide bandgap semiconductor materials. From the table I, we can infer that the wide energy band gap semiconductor materials like SiC, Galium Nitride (GaN) and diamond have good potential to overcome the limitation of silicon devices. Being a wide bandgap material, SiC offers a critical electric field of 2.0×10^6 V/cm – an order of magnitude higher than Si. This increases the blocking capability of SiC power devices. To reduce the on-state resistance, the drift layer should be thin and highly doped. This is how the Wide bandgap material fabricate. The high thermal conductivity of SiC enhances heat dissipation and, coupled with the wide bandgap energy (3.3 eV), allows high temperature operation above 300 °C. All of the above advantages make the SiC power devices an ideal substitution for Si counterparts in future high-voltage and high-power converter systems.

B. *Advantages of SiC over Si*

- The electric breakdown field of SiC is almost ten times greater than that of Si. Therefore SiC has ten times greater breakdown voltage than Si.
- SiC has high thermal conductivity, i.e., low junction to case thermal resistance. So heat can be easily transferred from the device. It helps to reduce the heat sink size and other thermal management system. As we know that the heat sink and thermal management system in a power electronics system constitutes most of its size. So by using SiC devices, overall system size and weight is reduced.
- Wide energy bandgap and high electric breakdown field features helps SiC devices to operate at higher switching frequency. Therefore, switching losses are reduced due to faster turn ON and turn OFF of the devices.
- High switching frequency operations in power converters are highly desirable because it reduces the size of the reactive components like capacitors, inductors and transformer.
- SiC can be operated theoritically at a junction temperature of 600°C.
- Compared to Si, SiC has lower reverse recovery time current and recovery time. This reduces losses and noise emission. This characteristic doesn’t change with over current and operating temperature ranges so SiC allows system designers to improve efficiency and reduce the cost.
- Transformer less operation is possible by using Silicon carbide devices.

III. DYNAMIC CHARACTERISTIC OF SIC DEVICE

It is important to study the device characteristics due to various parasitic inductances. To characterize the device due to change of parasitic inductance, simulation study is carried out. Parasitic inductances are DC Bus inductance, capacitor (ESL), drain side, source side and gate side inductance. Fig. 1, is used as the circuit for simulating and studying the effects of parasitic inductances on the switching performance of SiC devices.

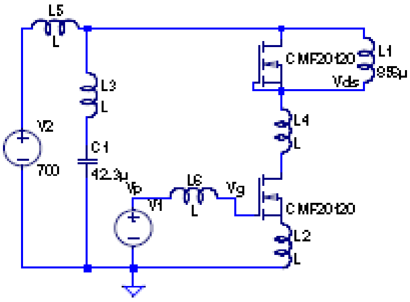


Fig. 1. Clamped Inductive switching waveform test circuit.

Each parasitic inductance is included individually in the circuit to study their effects. The spice equivalent circuit model of CREE make, 1200V,42A CMF20120 is used to study the effect of parasitic on the switching behavior.

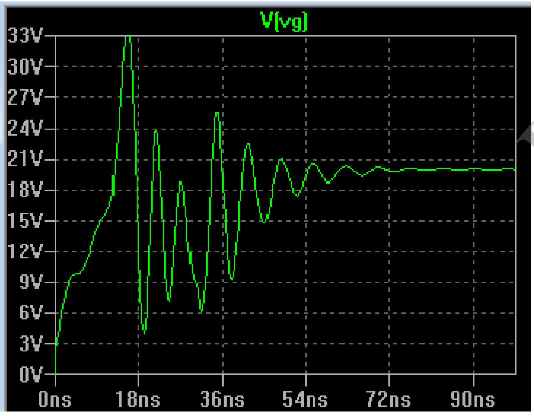


Fig. 2. Gate voltage at 35nH.

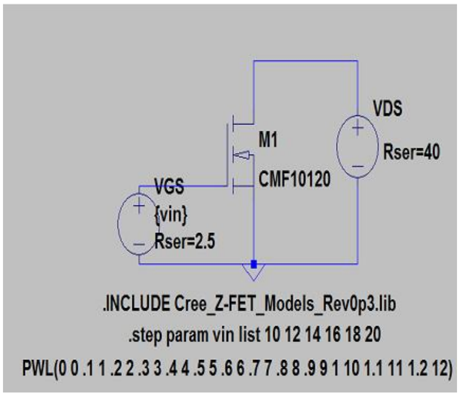
Graphical results for different conditions are simulated and analyzed. It is interesting to look at the results obtained for the effect of parasitic inductances on gate side, drain side and source side of the switching device. When these inductance varied, it affects switching performance intensively. Fig. 2, shows the waveform of gate voltage when gate side parasitic inductance is varied to 35nH. Here we can see that the gate voltage is oscillating and even at one point it is coming below the threshold voltage (4V) i.e., the device will turn OFF instead of turn ON. Bus bar inductance and equivalent series inductance of capacitor does not seem much effect on the switching performance. So, for the proper operation of the device, layout should be done in such a way that parasitic inductances (drain side, source side and gate side inductance) must be kept as minimum as possible.

IV. COMPARSION BETWEEN SIC AND SI DEVICE

LTspice model of CREE make SiC MOSFET, 1200V, 24A, CMF10120D, and STMicroelectronics make Si MOSFET, 800V,11A STW11NM80 are used in the comparative study.

A. Electrical characteristics

Fig. 3, shows the circuit diagram to plot the typical output i-v characteristics V_{DS} versus I_D of SiC MOSFET CMF10120D at 25ºC and 135ºC. V_{DS} is varied from 1V to 12V and corresponding I_D is plotted for different values of V_{GS} (10V, 12V,14V, 16V, 18V, 20V).



```
.INCLUDE Cree_Z-FET_Models_Rev0p3.lib
.step param vin list 10 12 14 16 18 20
PWL(0 0 .1 1 .2 2 .3 3 .4 4 .5 5 .6 6 .7 7 .8 8 .9 9 1 10 1.1 11 1.2 12)
```

Fig. 3. Circuit used to find typical i-v Characteristics.

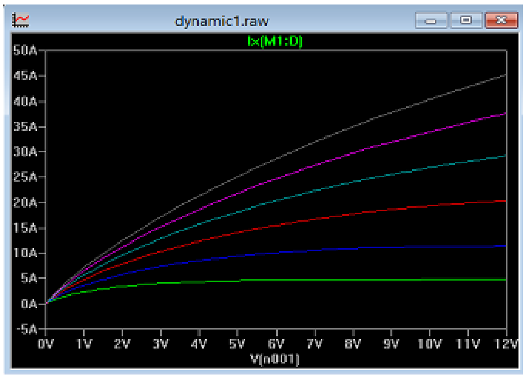


Fig. 4. Typical i-v Characteristics of SiC MOSFET.

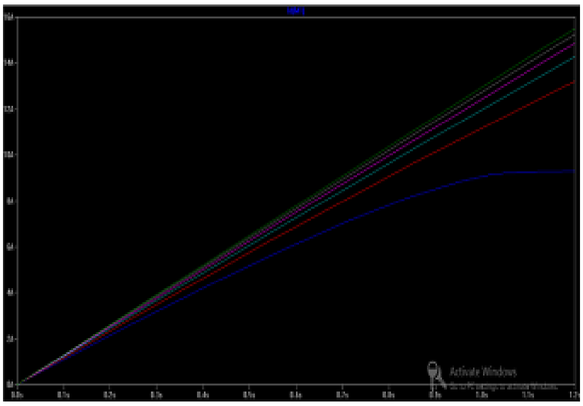
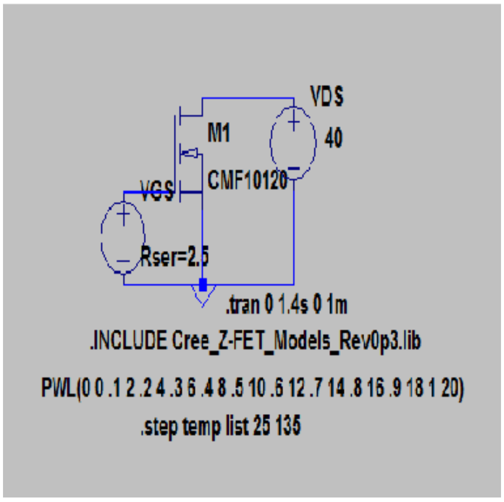


Fig. 5. Typical i-v Characteristics of Si MOSFET.

From the obtained output characteristics of SiC and Si MOSFETS, we can infer that the slope of the output characteristic curve of SiC MOSFET is very low compared with Si MOSFET. i.e., SiC MOSFET has a low value of ON time resistance. It is evident that the SiC MOSFET has low conduction loss compared to Si MOSFET.

Fig. 6, shows the circuit diagram to plot the typical transfer characteristics V_{GS} versus I_D of SiC and Si MOSFET at 25ºC and 135ºC. SiC MOSFET CMF10120D and Si MOSFET STW11NM80 are used for plotting the transfer characteristics. The transconductance can be calculated from the transfer curve, which increases with temperature, from 25°C to 135°C.



```
.tran 0 1.4s 0 1m
.INCLUDE Cree_Z-FET_Models_Rev0p3.lib
PWL(0 0 .1 2 .2 4 .3 6 .4 8 .5 10 .6 12 .7 14 .8 16 .9 18 1 20)
.step temp list 25 135
```

Fig. 6. Circuit used to find Transfer Characteristics.

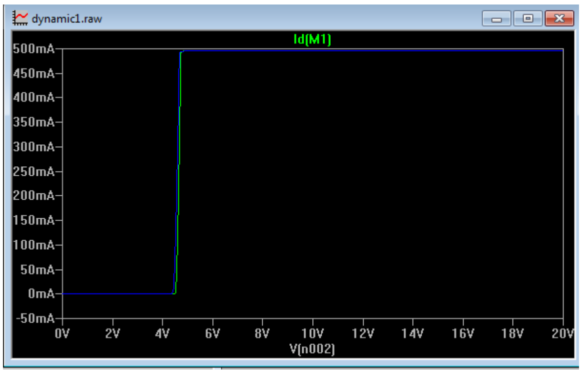


Fig. 7. Transfer Characteristics of Si MOSFET at 25ºC and 135ºC.

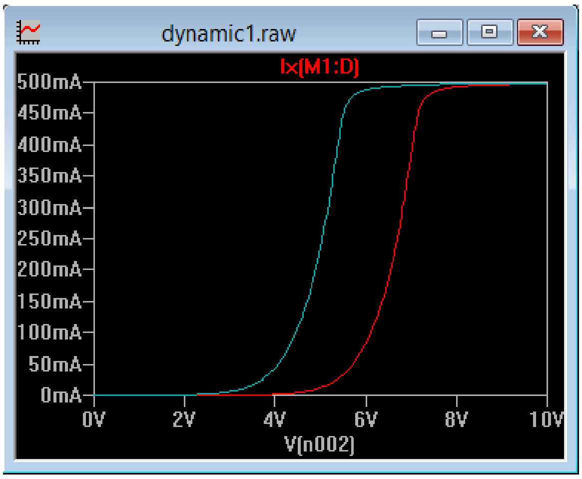
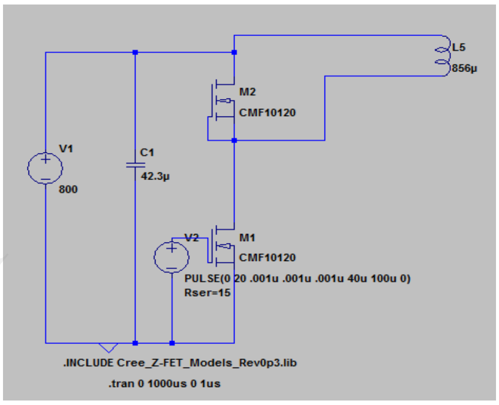


Fig. 8. Transfer Characteristics of SiC MOSFET at 25ºC and 135ºC

B. *Calculation of Switching Loss*



```
.INCLUDE Cree_Z-FET_Models_Rev0p3.lib
.tran 0 1000us 0 1us
```

Fig. 9. Circuit used to find switching losses.

TABLE II. PERCENTAGE DEVICE LOSSES AND INVERTER EFFICIENCY OF SILICON CARBIDE DEVICES AT DIFFERENT FREQUENCIES

			Temperature = 27°C				Temperature = 135°C			
Fs (kHz)	Ts (s)	Ton (s)	Switching Loss (W)	Load Power (kW)	Percentage Loss@27°C(%)	3 phase inverter efficency (%)	Switching Loss (W)	Load Power (kW)	Percentage Loss@135°C (%)	3 phase inverter efficency (%)
1	1.000E-03	4.000E-04	7.8173	4.3401	0.180118	98.9	9.1919	4.3374	0.211922	98.7
5	2.000E-04	8.000E-05	8.9493	4.3387	0.206267	98.7	10.382	4.3361	0.239432	98.5
10	1.000E-04	4.000E-05	8.8217	4.3398	0.203274	98.7	10.169	4.3377	0.234433	98.5
20	5.000E-05	2.000E-05	12.333	4.3347	0.284518	98.2	13.699	4.3332	0.31614	98.1
50	2.000E-05	8.000E-06	13.727	4.3372	0.316495	98.1	14.728	4.3386	0.339464	97.9
100	1.000E-05	4.000E-06	15.396	4.33339	0.355288	97.86	16.164	4.3358	0.372803	97.7
200	5.000E-06	2.000E-06	26.057	4.3409	0.600267	96.3	26.969	4.3529	0.619564	96.2

TABLE III. PERCENTAGE DEVICE LOSSES AND INVERTER EFFICIENCY OF SILICON DEVICES AT DIFFERENT FREQUENCIES

			Temperature = 27°C				Temperature = 135°C			
Fs (kHz)	Ts (s)	Ton (s)	Switching Loss (W)	Load Power (kW)	Percentage Loss@27°C(%)	3 phase inverter efficency (%)	Switching Loss (W)	Load Power (kW)	Percentage Loss@135°C (%)	3 phase inverter efficency (%)
1	1.000E-03	4.000E-04	42.437	4.8654	0.87222	94.7	80.299	4.7836	1.678631	89.9
5	2.000E-04	8.000E-05	42.968	4.8699	0.882318	94.7	80.382	4.788	1.678822	89.9
10	1.000E-04	4.000E-05	43.527	4.8595	0.895709	94.6	81.68	4.7938	1.703867	89.7
20	5.000E-05	2.000E-05	44.732	4.8756	0.917467	94.4	81.611	4.7783	1.707951	89.7
50	2.000E-05	8.000E-06	49.072	4.886	1.004339	93.9	85.707	4.804	1.784076	89.2
100	1.000E-05	4.000E-06	54.338	4.8979	1.109414	93.3	90.757	4.815	1.884881	88.69
200	5.000E-06	2.000E-06	62.278	4.9175	1.266457	92.4	98.244	4.8341	2.032312	87.8

Simulation of SiC MOSFET CMF10120D and Si MOSFET SPW17N80C3 are carried out in LT SPICE to compare the percentage of switching losses. The switching losses (turn on loss + turn off loss) are calculated at different test conditions. The switching losses are computed from a double pulse test circuit as shown in Fig.9.

Table II shows the percentage device losses and efficiency of a three phase inverter using SiC MOSFET at different frequencies and temperatures. Table III shows the percentage device losses and efficiency of a three phase inverter using Si MOSFET. Here the frequency is varied from 1 KHz to 200 KHz. SiC MOSFET gives an efficiency of above 96% in these frequency ranges and doesn't show much difference in temperature. But Si MOSFET is giving high switching losses and very low efficiency and efficiency is also reduced, when temperature increases.

From Fig. 10, we can see that at 5 kHz switching frequency SiC MOSFET based inverter shows efficiency more than 98.9% compared to 94.7% efficiency with Si MOSFET. At 100 kHz switching frequency, the SiC inverter efficiency is still above 97%, but with Si MOSFET the efficiency falls below 95%. From Fig. 11, we can see that when temperature is increased to 135ºC SiC MOSFET based inverter efficiency does not show much difference, but the efficiency of Si based inverter falls below 90%. It can be concluded that the SiC MOSFET has better switching characteristics than Si MOSFET. The efficiency of an inverter is more with SiC MOSFET.

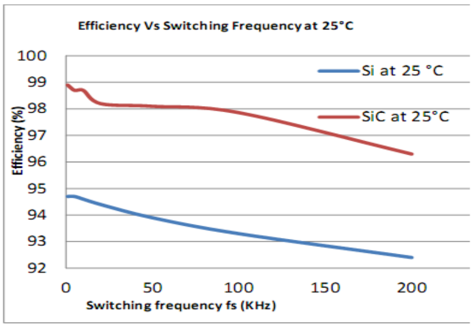


Fig. 10. Efficiency of an inverter with Si & SiC MOSFET at different switching frequency & at 25ºC.

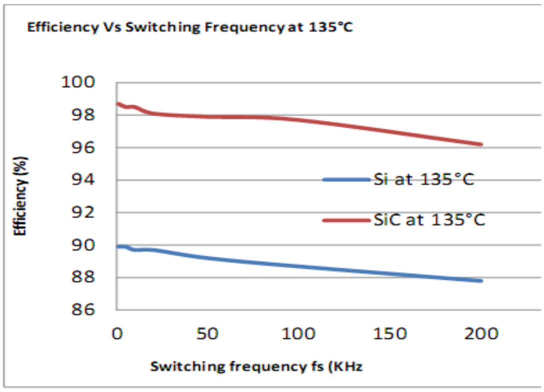


Fig. 11. Efficiency of an inverter with Si & SiC MOSFET at different switching frequency & at 135ºC.

C. *Switching Losses Vs Load Current and Frequency*

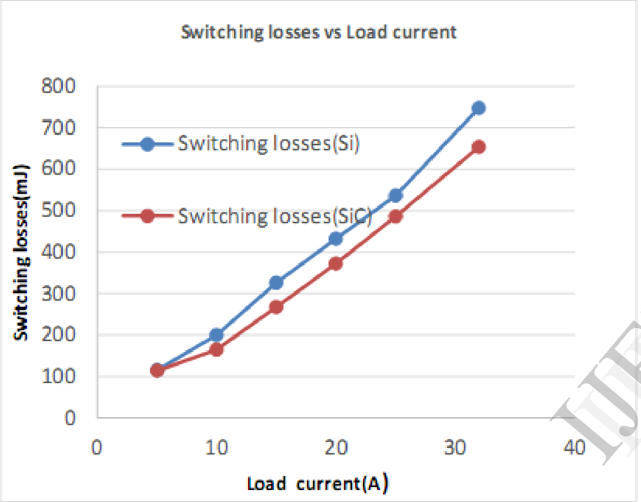


Fig. 12 Switching losses Vs load current

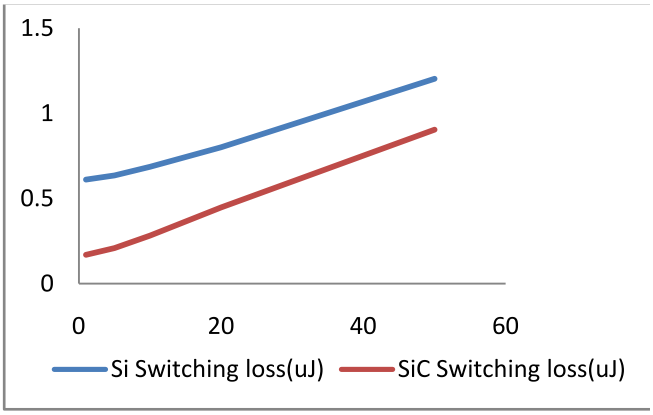


Fig. 13. Switching losses Vs Frequency

Switching loss versus frequency and switching loss versus load current are plotted in fig. 12 and 13. The switching losses of SiC MOSFET are low, when comparing with Si MOSFET. So, SiC MOSFET can operate at higher switching frequency compared to Si MOSFET. High switching frequency operations in power converters are highly desirable because it reduces the size of the reactive components like capacitors, inductors and transformer in the system. So, by using SiC device we can reduce the size and weight of the system.

V. CONCLUSION

This paper presents a comparative study of Silicon Carbide and Silicon MOSFET in LT-spice platform. SiC and Si MOSFET have been simulated to get output i-v characteristics and transfer characteristics and also studied about the effect of parasitic inductance in devices switching behavior. Percentage switching losses and inverter efficiency using SiC and Si devices are tabulated. From the simulation results, it can be concluded that SiC has low ON time resistance, low conduction loss, low switching loss compared to Si device. The SiC based inverter has high efficiency compared to Si. Overall, SiC device has better switching performance compared to Si.

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