International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 10, October- 2014

Effects of Temperature and Losses in Semiconductor Devices used in Automotive Applications

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***Abstract*—The advancement of semiconductors and its technologies has led to high performance switches. However, only certain switches can be used for automotive applications. MOSFETs and IGBTs are good candidate options for this purpose. These switches are able to operate at high frequencies while maintaining a good efficiency. Earlier for this purpose Si IGBTs were widely used but now with the improvement of technologies in this area, SiC MOSFETs give a much better performance in comparison. Thus with these advantages of SiC MOSFETs, here the article suggests to replace the primitive Si IGBTs with SiC MOSFETS**

Keywords—MOSFET, IGBT, SiC MOSFET, Si IGBT

I. INTRODUCTION

These days electric and hybrid electric vehicles are becoming more popular due to the fact that they are more ecological, efficient etc. So such vehicles can be made more efficient and reliable by making use of efficient semiconductor switches in its various parts like the motor drive system etc. These motor drive systems must operate at high temperature conditions as high as 105ºC or above. Hence it is required to have semiconductor technologies in these parts, which can withstand such high temperatures. Also the size of the cooling system is determined by the efficiency of the switches. Thus by using switches with higher efficiency, the power losses can be reduced, thereby reducing the size and weight of the cooling system required. Thus we can understand that switches with high temperature operating capability and high efficiency can result in the better performance of the vehicle.

II. DIFFERENT TYPES OF SWITCHES USED IN AUTOMOTIVES

Presently, Si IGBTs are used in most of the applications like the traction drive systems and other drive systems mainly due to its less complexity and ease of manufacture. In the case of SiC devices, Silicon Carbide cannot be melted to its liquid state under controllable pressures, instead it changes directly into the gaseous state (this process is known as the sublimation process). Therefore the crystal has to be cultivated from its gaseous phase which is a tedious and complex process. Another factor that discourages the use of SiC based switches is the lack of availability of the substrate . But there are no such constraints in case of Si IGBTs since it has a much more simpler construction and hence lower cost. Even though Si IGBTs are used now a days it has the drawback of higher switching losses. This is due to the fact that IGBTs being bipolar devices, consist of both the electrons and holes and so eventually during the turn off time both the carriers must be removed which is being accompanied with a reverse current. IGBT being a bipolar device more reverse current will be required because here both electrons and holes are to be removed. Higher the reverse current during the turn off time higher is the power dissipated and so higher the switching losses. The increase in losses leads to increase in the junction temperature of the device which thus calls for the need of cooling system with larger size and weight, making them bulky and finally less efficient. So usually IGBT modules are used at half the rated current so as to prevent larger switching losses and temperature rise.

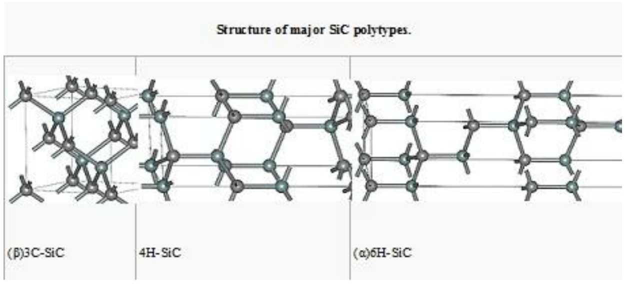
III. NEED FOR SILICON CARBIDE SWITCHES

In order to overcome these disadvantages researches are conducted all over the world since years for power electronic switch that is capable of blocking high voltages, conducting large currents in the on-state and capable of being switched from one state to the other with minimum energy loss or without any energy loss, thus making the whole system more efficient. Although an ideal switch with all these capabilities is not yet available SiC based switches possess properties close to the properties of an ideal switch. That is, they can withstand high breakdown voltages, can handle high temperatures, exhibit lower losses, reduce the size and weight of the coolant, have higher efficiency and also they are chemically inert.

SiC MOSFET devices have a larger band gap due to which SiC devices can be operated at higher temperatures, also due to the fact that MOSFETs are unipolar it requires only a lesser amount of reverse current during turn off time and hence its junction temperature rises only to a smaller extent. This in turn reduces the losses and thus again reducing the size of the coolant and thereby increasing the efficiency. Since SiC MOSFETs have a dielectric breakdown voltage field strength 10 times higher than Si, SiC devices can be made to have much thinner drift layer and higher dopping concentration and yet with a lower value of resistance. Higher dopping concentration implies higher breakdown voltage, almost 600V or above. Also the resistance of high voltage device is determined by width of the drift region.

IV. DISCOVERY, SYNTHESIS AND STRUCTURE OF SILICON CARBIDE

Silicon Carbide is one among the hardest of the ceramics which retains its hardness and strength even at high temperature conditions with a chemical formula SiC. It is also known as carborundum. Silicon Carbide is an extremely rare compound in nature but it is found in the mineral mossanite, first found in Arizona in 1893. Synthesis of SiC is carried out by the Acheson process, where silica sand and carbon are heated at elevated temperatures in a graphite resistance furnace. From this process it can be either obtained in the form of a fine powder or bonded mass; if once formed as powder the grains can be bonded together by sintering. There are basically 3 types of SiC used for commercial engineering purposes. They are Sintered silicon carbide, Nitride bonded silicon carbide and Reaction bonded silicon carbide. SiC has certain key properties like high strength and high hardness which is due to the strong bond between the silicon and carbon atoms, and the low thermal expansion which is because the compound directly moves on to its gaseous state from the solid state. It is also an excellent thermal shock resistor, it has a high elastic modulus and has a superior chemical inertness. Talking about the different structures of SiC, silicon carbide occurs in a large number of poly types (different structures of the same compound due to the different stacking sequence). There are about 150 to 250 poly types of silicon carbide. But among them the most famous poly types are hexagonal 4H and 6H, cubic 3C and rhombohedral 15R. Not all of these are easy to grow and among these only 4H and 6H are available as substrate materials. 4H is relevant for electronic applications than 6H due to its higher carrier mobility and wider band gap. About 3 inches of 4H SiC substrate is available since 2001. The structure of the important poly types of SiC are shown below:



V. SIC SWITCHES VS SI SWITCHES

A. *Switching frequency:*

An SiC MOSFET is capable of operating at higher switching frequency because of its lower switching losses and so it has a higher efficiency too. We know that $f \alpha 1/LC$, and therefore for higher switching frequency only a smaller sized energy device is required, thereby reducing the size of the power electronic converter circuits. This downsizes the passive components of the circuit. But with the increase in frequency and with lower switching times the chances for a higher electromagnetic interference (EMI) increases. For example, for a rise time of 100ns EMI is much lesser when compared to that of a rise time of 10ns. But these can be compensated to an extent by the use of snubber circuits, circuits used to prevent electrical spikes.

B. *Conduction and Switching losses:*

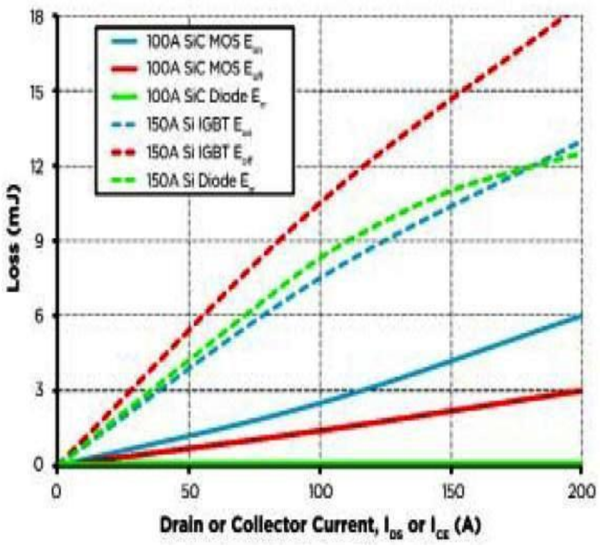
Comparing the conduction and switching losses of Si based switches(Si IGBTs) and SiC based switches(SiC MOSFET) one can find that Silicon Carbide based switches have a much lesser losses when compared to Silicon based switches. This can be explained from the various basic equations governing the power dissipation in a switch and also from the basic theory that unipolar switches like MOSFETs have a much lesser turn off time since only majority carriers have to be removed and so the reverse current during turn off is lesser when compared to bipolar switches like IGBTs due to which unipolar devices have a lesser amount of power loss and also a smaller turn off time. Similar is the case for turn on time also.

C. *Cost:*

Cost of Si IGBTs is much lesser than SiC MOSFETs due to the lack of SiC quality substrate and also manufacturing complexities of the unique properties of SiC. Due to this fact Si IGBTs have been used traditionally in spite of the various advantageous properties of SiC switches over Si switches.

VI. EFFECT OF TEMPERATURE AND LOSSES IN SEMICONDUCTOR SWITCHES

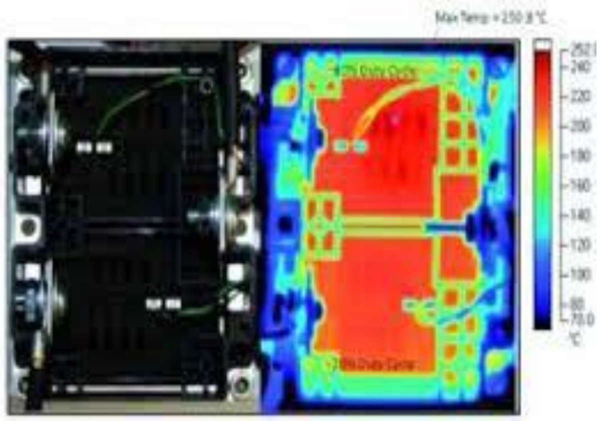
Although one can estimate the power losses for a switch from the basic equations, the actual dissipated power from the switch is different. It is observed from various experiments that there are variations from the theoretically obtained values. As the temperature of operation varies the power losses also vary. These variation of the switches under consideration are shown below :



The above graph is a plot of the power losses versus the current through the switches. It can be seen that even with the increase in current through the switch, for a SiC MOS switch the power loss remains more or less a constant or in simple words the power losses are low, whereas in a Si IGBT and Si diodes the power losses are found to increase dramatically with the increase in current flowing through the switch. Also the values of the power dissipated are more precise than that obtained from the theoretically obtained values.

VII. THERMAL IMAGING METHOD TO FIND THE TEMPERATURES IN THE VARIOUS PARTS

Thermal imaging is a non-contact type technique in which the image of an object is obtained by identifying the heat or the infrared energy emitted or transmitted or reflected from the object at temperatures above absolute zero. Here for more amount of accuracy the thermal image of a setup can be produced whereby we can clearly identify the regions or more precisely the spots with higher temperatures and precautions can be taken before hand, thereby preventing the setup or system. The figure below shows a SiC power module and its thermal image.



From the above figure the hot spots in a system can be easily identified thereby providing provision to replace them or take the necessary actions before hand.

VIII. VARIOUS APPLICATION OF SIC

Due to the strength of SiC at elevated temperature it is considered as one among the best wear resistors; also because of its hardness SiCs can be used in electrical machines such as heat exchangers, hot gas flow liners etc. Also it is used in abrasive machining processes like grinding, sand blasting etc. Its ability to withstand high temperatures without breaking makes it possible to use them in the manufacture of bulletproof vests as armour materials and in ceramic brake discs for sports cars etc.

It was first used to demonstrate the LED action in 1907. For this purpose 3C SiC was used for yellow LEDs and 6H SiCs for blue ones. It is also used in astronomy purposes like in telescopes etc. It is used in thin filament pyrometry and other heating elements also.

IX. CONCLUSION

Here the various properties, like the effects of variation of temperatures and power losses in semiconductor switches, its uses and applications have been discussed. It is concluded that the SiCs are one of the promising technologies of the coming days.

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