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Advances in Power Electronic Devices with the Emergence of Wide Bandgap Materials

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Abstract— *Silicon is a predominant semiconductor material which has been used in the field of electronics and Power Electronics for the past half century. To enhance the performance of power electronic devices, Silicon is being replaced by various wide bandgap materials due to its inherent material properties like low thermal conductivity, low bandgap energy, and switching frequency limitations. The most popular among them are Silicon Carbide and Gallium Nitride. Such materials have superior electrical and thermal properties like high thermal conductivity, high breakdown electric field, high operating temperatures, etc making them most viable for power electronic devices. This paper discusses various Wide Band Gap materials with main focus on silicon carbide, its polytypes and its exceptional properties. Further, silicon carbide based power device 'Power MOSFET' has been enlightened. The power MOSFET is extensively used in low-voltage switch, power supplies, DC to DC converters, low voltage motor controllers etc. This review paper also briefs about the various structures of Power MOSFETS like UMOSFET, VMOSFET, Vertical DMOSFET and their characteristics.*

Keywords: *Wide Bandgap,silicon carbide, Power MOSFET*

1. INTRODUCTION

Advancement in semiconductor materials has always been one of the most significant steps towards the progression of electronic devices. Upon such advancements relies the future of electronic devices. The long term reliability of such devices revolve around what materials can be used, how dense such devices can be made to be energy efficient and lastly how easy would be the interface between the user and such devices. From the device physics point of view, the main advantages of SiC when compared to Si are larger bandgap (3.25eV for 4H SiC); higher thermal conductivity (700 W/m-K); higher electronic breakdown field (4 MV/cm for 6H SiC) [1]. Such properties make SiC an appropriate option to be used by the designers of power semiconductor devices for higher blocking voltages.

2. WIDE BANDGAP MATERIALS

A wide bandgap material is a material which has a band gap greater than generally used semiconductors. They exhibit a bandgap of 2.2eV or higher. The different categories of wide bandgap materials have been derived from the combination of oxygen, nitrogen, carbon with materials of different groups of periodic table, for example, II-O, II-S, III-N, SiC in various polytypes, diamond and alloys of these materials [2]. At present the power devices are based upon the well established technology using silicon but silicon exhibits quite a number of limitations regarding blocking voltage capability, operating temperatures, switching frequencies and many more which limits the performance of the power devices like current power convertor which requires complex and costly cooling systems. As a result, a new generation of power devices based on wide bandgap semiconductor materials would replace the conventional Si power devices [3].

The very first advantage of wide bandgap material is the significantly high thermal conductivity than that of conventional semiconductors which is efficacious in both high power amplifiers and in LASERS where systems get heat up very fast. Secondly, the wide bandgap reduces the thermally generated leakage by 10-14 times which makes it suitable to be used in CCDs, non metallic high speed memories and for appreciably reduced dark currents in photo detectors. Also, its high dielectric strength makes it efficient in high power amplifiers, switches and diodes. Wide bandgap materials also exhibit a lower relative dielectric constant and this property is of great use where lower parasitic capacitances are required. Saturated velocity which is electron velocity at high electric field is also considerably higher than the commonly used semiconductors. This makes it a good contender for millimetre wave amplifier [2].

3. MATERIAL CONTENDERS AMONG WBG MATERIALS

There are number of materials bearing a wide bandgap which find application in the field of power electronics.

3.1 Silicon Carbide

SiC exhibit a high dielectric strength and thermal conductivity which are 10 times and 5 times that of silicon respectively.

The combination of these two properties and its easy availability make it feasible for use as high power amplifiers, switches and diodes. It is the only material which can grow a viable native oxide, hence, making itself useful in an enhancement/ depletion transistor configuration [2]. SiC can withstand high temperature and high power density as electrons in SiC requires more energy to be pushed into the conduction band. Hence, devices based on SiC can resist 10 times the voltage as compare to that of Si [4].

Nitrides

GaN, InN and AlN are generally used in alloy or heterojunction combination. Their most stable polytype (hexagonal) are direct bandgap, hence making them suitable for sharp cut-off photo detectors [2]. GaN offers better high-frequencies and high-voltage performances but the lack of good quality bulk substrates required for vertical devices and lower thermal conductivity makes SiC a better option for high voltage devices[3]. The lattice mismatch between GaN and substrates introduces defects and thus, limits the operational characteristics and degrades the reliability [5].

3.2 Diamond

It is considered as the best material for future power devices since; its large bandgap (5.45ev) makes it viable for its use in power devices. It has highest thermal conductivity (22W/cm-K). Also the carrier mobility for both holes and electrons is very high. But there are issues which make diamond not an ideal material. The fabrication technology for material and device is not so developed as for SiC and GaN. Also it requires large activation energy for dopant impurities like boron and phosphorus which leads to highly resistive diamond material [5].

4. SILICON CARBIDE

Silicon carbide is becoming very famous among the researchers and designers for the development of radiation hardened electronic devices working at high temperature, appreciably high power and high frequency.

4.1 Structure

Si and C atoms are tetrahedrally bonded to each other in primitive unit cell. A very peculiar property of silicon carbide is polytypism which means a material can adopt different crystal structures which vary in one dimension (that is, in stacking sequence) without changes in chemical composition. SiC is available in more than 200 polytypes but only few are commercially useful like 2H 3C, 4H, 6H, 15R. The sequence of stacking of the hexagonally closed packed double layers of Si and C atoms along the cubic [111] or the hexagonal [0001] directions bring about different crystal structures and hence is the reason for the existence of various polytypes.

In Ramsdell's notation, polytypes are represented by the number of Si-C bilayers in the unit cell and the crystal system (C-cubic, H-hexagonal, and R-rhombohedral). 3C-SiC is often called β-SiC, and other polytypes are referred to as α-SiC.

The simplest among all the structures is 3C-SiC which is a zinc blende structure is having a lattice constant 0.436 mm. SiC polytypes (except 3C-SiC) are uniaxial (hexagonal or rhombohedral) and denoted as α-SiC [6-8]. The various structures of SiC polytypes is shown in fig.1.

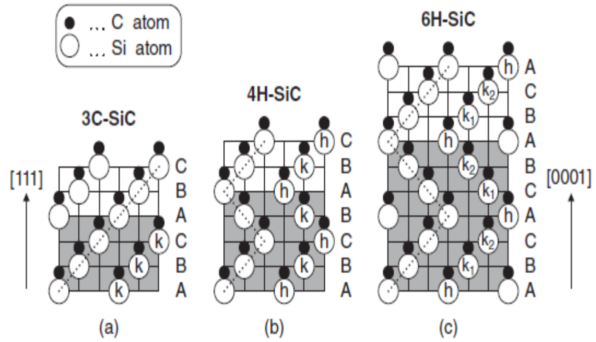
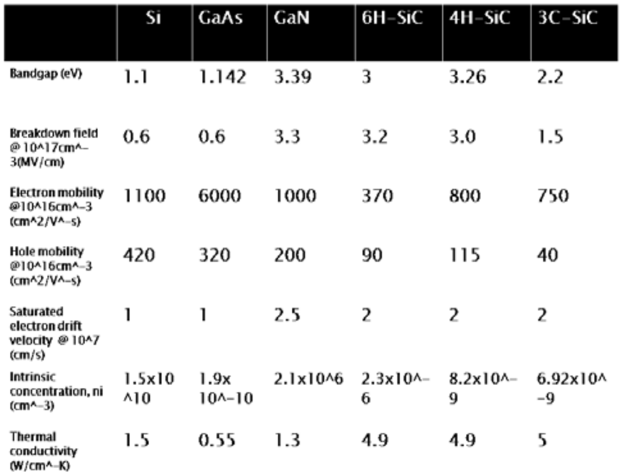


Fig. 1: Schematic structures of popular SiC polytypes; (a) 3C-SiC, (b) 4H-SiC and (c) 6H-SiC. A, B, and C are the occupied sites in a hexagonal close-packed structure. [9]

4.2 Properties

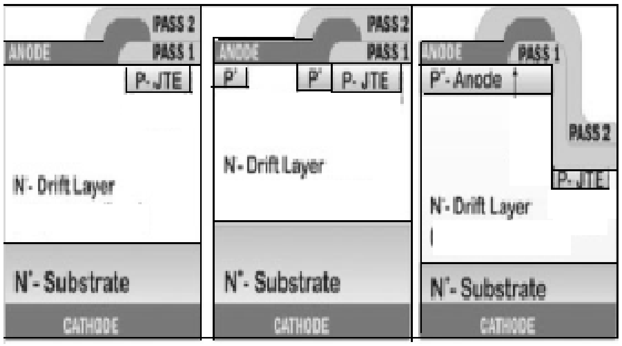
With properties such as large breakdown electric field, large saturated drift velocity, wide bandgap, small dielectric constant, appreciably high electron mobility and high thermal conductivity silicon carbide has become a satisfactory material for fabricating high power devices with reduced power losses and die sizes.

Table 1: Comparision of parameters of various semiconductors at 300K [1,11,4,10]



	Si	GaAs	GaN	6H-SiC	4H-SiC	3C-SiC
Bandgap (eV)	1.1	1.142	3.39	3	3.26	2.2
Breakdown field @10^17cm^-3(MV/cm)	0.6	0.6	3.3	3.2	3.0	1.5
Electron mobility @10^16cm^-3 (cm^2/V^-s)	1100	6000	1000	370	800	750
Hole mobility @10^16cm^-3 (cm^2/V^-s)	420	320	200	90	115	40
Saturated electron drift velocity @ 10^7 (cm/s)	1	1	2.5	2	2	2
Intrinsic concentration, ni (cm^-3)	1.5x10^10	1.9x 10^-10	2.1x10^6	2.3x10^-6	8.2x10^-9	6.92x10^-9
Thermal conductivity (W/cm^-K)	1.5	0.55	1.3	4.9	4.9	5

SiC as compared to Si has wide bandgap which is considered as the major benefit for high power devices resulting in larger critical electric field and higher temperature handling. Its high breakdown fields makes it possible to work on drift regions that are eight to ten times thinner than Silicon high voltage devices, with lower leakage currents and less resistance at elevated temperatures for desired breakdown voltage. Due to this reason silicon carbide becomes high power devices practicable even in kilovolt range and beyond. Hence, the high current handling capacity of these devices is achieved. The table given below gives a comparison between various semiconductor materials employed in power electronic devices. [10]



SBD **JBS** **PIN**

Fig. 2: Cross section of various power diodes [3]

Continuous efforts have been made to develop SiC material and device technology which resulted in number of breakthroughs. SiC Schottky barrier diodes (SBDs) were presented in 2001which have been employed in numerous power systems, like photovoltaic convertors, switch mode power supplies and motor controls for elevators and subways. Production of SiC based JFETs and MOSFETs began in 2006-2010 which are primarily used in power switching devices [9].

5. SIC POWER DEVICES

There are huge number of devices using SiC as the base material including power rectifiers like Schottky Barrier diode (SBD), Junction Barrier Schottky and PiN diode, Junction Field Effect Transistor (JFET), MOSFET, MOSHFET, MESFET, IGBT, GTO and MCT. This paper gives a brief overview of JBS, MOSFET, JFET and BJT.

5.1 SiC Diodes

There are three types of diodes which are commonly used as power rectifiers.

a) Schottky Barrier Diodes have extremely high switching frequency due to the absence of reverse recovery currents [12].

b) PiN diodes can operate at high voltages with very low leakage currents [3].

c) Junction Barrier Schottky diodes combines the advantages of schottky, i.e., low voltage drop in on state and that of PiN diode , i.e., low leakage current and high breakdown voltage in off state [12].

Figure. 2 shows cross section of three types of SiC diode.

5.2 SiC JFET

SiC JFET has extremely low specific on resistance and hence is reliable as high power switch at high temperatures. It is a normally-on device and therefore, requires a negative Vgs for turn off. The saturated currents have been improved and have reached up to 700A/cm^2 . JFETs are considered to be quite promising as it relies on P-N junction operation and is independent of gate control dielectrics [4]. The physical structure has been shown below in Fig. 3.

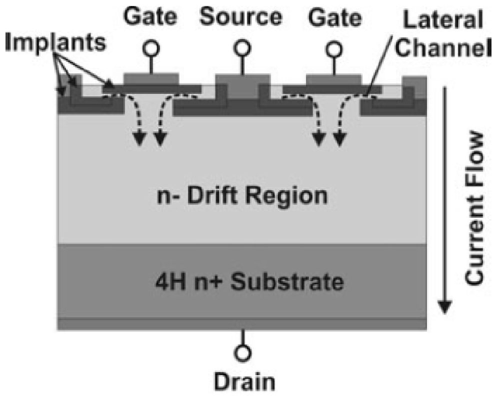


Fig. 3: Cross sectional view of power JFET [13]

5.3 SiC BJT

It is a normally-off device having a low on state power loss (0.32V at 100A/cm^2) owing to the reason that two in-built P-N junctions exist which cancel each other. This also indicates that loss is dependent on drift region resistance only.

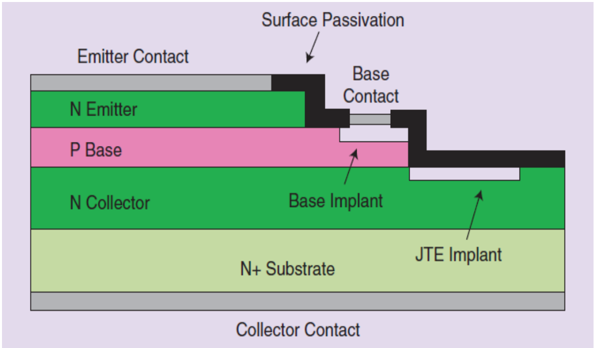


Fig. 4: Cross sectional view of power BJT [13]

Such devices have fast switching capability and can operate under temperature variation between -80^{0}C to 250^{0}C. [4].SiC BJTs can have high current gains more than 70 [13]. They do not exhibit a quasi-saturation region as is typical in Si power bipolar transistors. Due to the presence of stacking faults in the base-emitter regions, there arises degradation in both current gain and forward voltage drop under forward stress. This drawback hinders the commercial production of these devices [16].

5.4 SiC Power MOSFET

SiC has the capability to form its own native oxide, SiO$_2$, thus becoming an attractive semiconductor material for MOSFET [4]. It operates in normally off, i.e. enhancement mode. Also it provides a high input impedence. The main drawback of SiC MOSFET is low channel mobilities resulting in higher On-state resistance. Also the question arises on reliability and stability due to the sensitive gate oxide layer [13].

5.5 SiC IGBT

Insulated gate bipolar transistors are voltage controlled switching devices. It combines best characteristics like high input power, large input impedence and fast switching response of MOSFETs and low turn-on resistance and large conducting currents of bipolar devices. With the use of 4H-SiC as material, it was observed that for the same breakdown voltage, IGBTs have thinner epitaxial layer thickness resulting in lower epitaxial layer resistance when compared to Si IGBTs [14, 15].

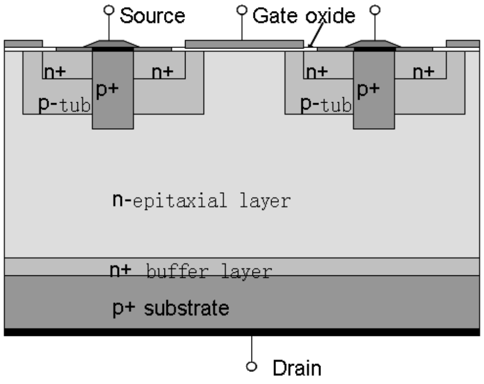


Fig. 5: Structure of vertical power MOSFET [14]

6. SIC POWER MOSFETS

SiC is becoming a attractive choice for the implementation of efficient Power MOSFETs. The advent of power MOSFET was driven by limitations posed by BJTs mainly being their low current gain when designed for high voltage operations. Also power Bipolar transistors work at low frequencies due to large storage time of injected charge in drift regions [15]. In late 1980s first SiC mosfet was reported [17].

There exist two structures for Power MOSFET- Vertical and Lateral. Vertical Power MOSFETs in SiC include trench U-shaped Mosfet or UMOS and DMOS structures. Fig. 6 shows basic trench and vertical double diffused MOSFET (VDMOSFET) structures.

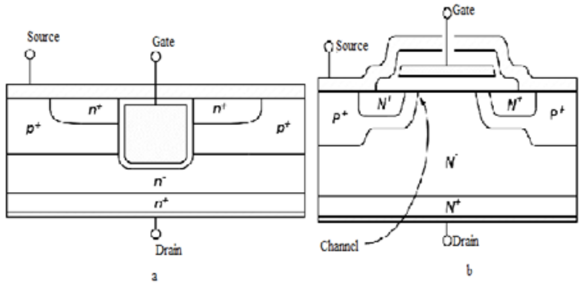


Fig. 6: Cross sectional view of power MOSFETs a) Trench b) VDMOSFET [18]

The highest blocking voltage stated in 4H-SiC UMOSFET is 5KV with specific on resistance $R_{on(sp)}$ of 105 mΩ-cm^2. The highest blocking voltage for VDMOSFET in 4H-SiC is reported to be 10KV with $R_{on(sp)}$ of 123 mΩ-cm^2[19]. Trench U-shaped MOSFETs find applications for <200V voltage ratings because of their higher channel density leading to lower-on resistance. Planar MOSFETs are better for higher voltage ratings as on-resistance depends mainly on drift region resistance [20]. When a lightly doped n-type epitaxial is grown on the side walls of the trench, the device changes into accumulation-layer UMOSFET or ACCUFET increasing the electron mobility and thus decreasing the on-resistance [21].

Lateral power MOSFETs which were studied long before trench MOSFETs are popularly used in smart power ICs or RF devices. They offer quite low gate capacitance and gate charge but suffers from high on-resistance [22]. Unlike vertical MOSFETs, 6H-SiC is more efficacious than 4H-SiC in lateral MOSFETs due to greater inversion channel and high avalanche field.

7. RELIABILITY

The silicon carbide material has around thousands of defacts per cm^2 which cause high amounts of leakage currents in off state and leads to switching failures and thermal runaway while operatig at high frequencies. A method to delimit the device facing such problem is reverse bias stress test circuit with a reactive load [23].The poor quality of SiO$_2$-SiC interface afflicted with high interface state density and poor mobility is one of the main challenges of SiC power devices. This leads to much lower mobility due to coulomb scattering from interface charges and surface roughness scattering [24].

SiC MOSFETs can hold up lower short circuit owing to the reason that it has smaller chip area and large current densities. To ensure SiC MOSFET operate within safe operating area (SOA) limits, the response time of the protection circuit must be very fast. In this regard, three measures for overcurrent protection have been acknowledged which are the solid state circuit breaker (SSCB), the desaturation technique with the use of sensing diode and lastly the fault current evaluation scheme [25].

8. PACKAGING

In addition to specific on-resistance, $R_{on(sp),}$ die area and package types are key factors in thermal stability of power devices. Among 40V power MOSFETs, DirectFETs having no heat sink has enhanced thermal performancethan D2PAK package [26]. Thermal management can also be done by employing double sided liquid convection with embedded power packaging [27].

9. CONCLUSION

This paper has reviewed the ecent materials which can be used for the power devices. Wide Bandgap materials, especially SiC with its suitable properties has made itself the finest option for latest power devices like Power MOSFET, SBD, IGBT,etc. It is a clear indication that much developments in the SiC technology can overpower the well established Si technology for the high power, high temperature and raduiation hardened systems.

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REFERENCES

[1] Jerry L, Grigory S.Simin, Enrico Santi, and M. Asif Khan, “An Assessment of wide bandgap semiconductors for power devices” *IEEE transactions on power electronics*, Vol. 18, No.3, May 2003, pp. 907 – 914.

[2] Max N. Yoder, “wide bandgap semiconductor materials and devices,” *IEEE Transactions on Electron device*, vol. 43, no. 10, October 1996, pp. 1633 – 1636.

[3] Jose Millan, Philippe Godignon, Xavier Perpina, Amador Perez-Tomas, and Jose Rebollo, “A Survey of Wide Bandgap Power Semiconductor Devices,” *IEEE transactions on power electronics*, Vol. 29, No.5, May 2014, pp.. 2155 – 2163.

[4] Jennifer Najjar, Rita Khalil, Paul Akiki and Hadi Y. Kanaan, “Modern Power Switch: Silicon Carbide Technology,” *2nd International Conference on Advances in Computational Tools for Engineering Applicaions*, 2012, pp. 225 – 230.

[5] Jerry L. Hudgins, “Power Electronic Dsevices in the Future,” *IEEE Journal Of Emerging And Selected Topics In Power Electronics*, Vol. 1, No. 1, March 2013

[6] F Nava, G Bertuccio, A Cavallini and E Vittone, “Silicon carbide and its use as a radiation detector material,” *Measurement Science and Technology*,2008, pp. 1-25

[7] H. Matsunami, “Current SiC technology for power electronic devices beyond Si” *Microelectronic Engineering* 83 (2006) 2–4

[8] M. Treu, R. Rupp, P. Blaschitz, J. Hilsenbeck, “Commercial SiC device processing: Status and requirements with respect to SiC based power devices,” *Superlattices and Microstructure,s* 40, 2006, pp. 380–387

[9] Tsunenobu Kimoto and James A. Cooper, “Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices, and Applications,” 2014 by John Wiley & Sons Singapore Pte Ltd.

[10] Mohit Bhatnagar and B. J. Baliga, “Comparison of 6H SiC, 3C-SiC, and Si for Power Devices, *IEEE Transactions on Electron Devices*, Vol. 40, No. 3, March 1993, pp. 645 – 654.

[11] Roya Maboudian and Carlo Carraro, “Advances in silicon carbide science and technology at the micro- and nanoscales,” *American Vacuum Society*, june 2013, pp. 050805-1 – 050805-18.

[12] Mikael Ostling, Reza Ghandi and Carl-Mikael Zetterling, “SiC Power devices – present stauts, applications and future perspective,” *in Proc. Int. Symp. Power Semicond. Devices ICs*, 2011, pp. 10 – 15

[13] Jacek RaBkowski, Dimosthenis Peftitsis and Hans-Peter Nee, “silicon Carbide Power Transistors” June 2012 IEEE Industrial Electronics Magazine

[14] Shoucai Yuan and Yi Zhang, “Breakdown Voltage and On-Resistance Comparison of IGBTs Based on 4H-SiC and Si,” *Symposium on Photonics and Optoelectronics (SOPO), IEEE*, 2011 , pp. 1-3

[15] B. Jayant Baliga, “Fundamentals of Power Semiconductor Devices” *Springer science and Business Media*,2010

[16] Mikael Ostling, “Silicon Carbide Based Power Devices,” *International Electron Devices Meeting (IEDM), IEEE*, 2010, pp. 13.3.1 – 13.3.4.

[17] S L Rumyantsev, M S Shur, M E Levinshtein, P A Ivanov, J W Palmour, A K Agarwal, B A Hull and Sei-Hyung Ryu, “Channel mobility and on-resistance of vertical double implanted 4H-SiC MOSFETs at elevated temperatures” *Semiconductor Science and Technology*,2009 pp. 1-6

[18] http://en.wikipedia.org/wiki/Power_MOSFET

[19] T. Paul Chow, “High-voltage SiC and GaN power devices” *Microelectronic Engineering*, 83, 2006, pp- 112-122

[20] www.aosmd.com/res/application.../mosfets/Power_MOSFET_Basics

[21] Morteza Fathipour, Negin Peyvast and Negar Shoaazar, *IEEE, COMMAD* 2008, pp140-143

[22] Z. John Shen, , David N. Okada, Fuyu Lin, Samuel Anderson, and Xu Cheng,”Lateral Power MOSFET for Megahertz-Frequency,High-Density DC/DC Converters” *IEEE Transactions On Power Electronics*, Vol. 21, No. 1, January 2006, pp- 11-17

[23] Krishna shenai, “Reliability of wide bandgap semiconductor power switching devices,” *National Aerospace and Electronics Conference (NAECON), Proceedings of the IEEE, 2010* , pp 322-327

[24] Vinayak Tilak, "inversion layer electron transport in 4H-SiC metal-oxide-semiconductor-field-effect-trasistors" *Physica Status Soli A*,206, No. 10, 2009, pp 2391-2402

[25] Zhiqiang Wang, Xiaojie Shi, Yang Xue, Leon M. Tolbert, Fei Wang, and Benjamin J. Blalock, "Design and Performance Evaluation of Overcurrent Protection Schemes for Silicon Carbide (SiC) Power MOSFETs," *IEEE Transactions On Industrial Electronics*, Vol. 61, No. 10, October 2014,pp 5570-5581

[26] Namagerdi, H.A, Shah, H and Oknaian, S, "Evaluating dynamic reliability of power MOSFETs in low voltage hard-switched applications," *Applied Power Electronics Conference and Exposition (APEC)*, 2012 Twenty-Seventh Annual IEEE, pp. 2380-2483

[27] Bryan C. Charboneau, Fei Wang, Jacobus Daniel van Wyk, Dushan Boroyevich, Zhenxian Liang, Elaine P. Scott, and C. Wesley Tipton, "Double-Sided Liquid Cooling for Power Semiconductor Devices Using Embedded Power Packaging," *IEEE Transactions On Industry Applications*, Vol. 44, No. 5, September/October 2008, pp. 1645-1655s