University of Warwick

School of Engineering

Progress Report

“Transformation of the Top and Tail of Energy Networks”

Authors: Dr. Yogesh Sharma and Hua Rong*
(*Equal contribution)

Supervisor: Prof. Phil Mawby

Contents:

1 Introduction

Top climate researchers have warned that global greenhouse gas emissions need to be reduced by at least sixty percent below the present levels by 2050 to avoid catastrophic climate change [1]. But such a radical reduction looks very challenging as the world's energy needs is increasing day by day. One of the ways is to upgrade our power distribution system. In this new technology high-voltage semiconductor devices are very crucial as they play a key role in power electronic systems. Most of these applications today are enabled by silicon. However, wide bandgap (WBG) semiconductors, such as silicon carbide (SiC) possess material properties which make it a prudent choice for power devices. The superior properties of SiC power devices compared with Si are expected to have a significant impact on the next-generation power systems.

There are two particular places in energy networks where existing network technology and infrastructure needs a radical change to move us to a low carbon economy and to meet the UK greenhouse emission reduction target by 2050 [2]. The very "top" of the energy network is formed by the expected emergence of a transcontinental energy exchange in Europe (and elsewhere) that is driven by exploitation of diversity in renewable sources and diversity in load. And the very Tail of the network is the so-called "last mile" and "behind the meter" wiring into customer premises. In this project the University of Warwick is working in Top of the network which investigates new approaches for super-scale capacity converters using novel semi-conductors materials, silicon carbide in particular.

Silicon carbide (SiC) is an excellent candidate for power devices comparing with the traditional Si due to its unique intrinsic properties which are discussed in greater details in the forthcoming sections. Power device with higher critical field strength will have much lower losses than conventional silicon based devices both for on-state losses and reduced switching losses. Cooling requirements are also reduced in direct proportion to the reduction in losses. 4H-SiC is particularly suited for vertical power devices compared with other polytypes of SiC because of its higher mobility along the c-axis, higher critical electric field, and a mature growth technology [3]. Silicon carbide semiconductor devices technology has matured greatly over the past few decades and gone from research to commercial production. In particular, 4H-SiC Schottky barrier diodes, junction field-effect transistors, and metal-oxide-semiconductor field-effect transistors (MOSFETs) are commercially available, mainly for 600- to 1700- V applications [4-6]. However, for the advanced electric power network such as HVDC transmission, ultrahigh-voltage (UHV) power devices with blocking capability of 10kV or more are expected. These high voltage power devices based on silicon carbide will be a critical component in building the microgrid with distributed and fluctuating sources of power generation, which would result reduction in greenhouse gas emissions and imported energy. 4H-SiC bipolar devices, such as p-i-n diodes, BJTs and thyristors, can achieve lower static power loss than the unipolar devices in UHV area due to their large concentration of holes and electrons (conductivity modulation) [7-10].

Substrate and epitaxial material quality and the number of detrimental defects are the biggest challenges for the realization of UHV 4H-SiC bipolar devices; these include design of the edge termination and growth of pure thick epitaxial layers with lower defect density and sufficiently long carrier lifetimes. Over the years this has been one of the limiting factors for a commercial success of the high voltage and high current device market. Much effort has been dedicated to the development of the technique of the fast epitaxial growth (> 100 µm/h) [11,12] and the post processes to improve the carrier lifetimes, such as reducing the interface state density using high temperature post-oxidation annealing techniques [13-15]. Many companies today can now offer high quality commercial SiC wafers and epitaxy on 4H-SiC with wafer diameter 100mm [16]. The main SiC power device products are still rectifiers based on Schottky or junction barrier didoes, the main advantage is the elimination of the reverse recovery charge which is present in the conventional Si fast recovery PiN diodes, and subsequent low switching losses as well as the ability to handle large current density at higher temperature [16, 17].

2 Progress in semiconductor devices

The first solid state amplifier was fabricated using germanium (Ge) which was seen as the semiconductor material of the future. But later on, silicon (Si) turned out to be more suitable for several reasons [18-21]. Silica, the source of Si is widely available, and it is easier to get high purity Si from it. Si can easily be doped to produce n-type, p-type and semi-insulating material [5]. Another very important reason is that a native oxide SiO_2 can be formed on Si using thermal oxidation at the relatively low temperature of around 900^oC [22-24]. These characteristics make Si semiconductor industry favourite.

At present, the semiconductor industry total is more than $300 billion [25]. Around 10% of this worth is in smart integrated circuits and electronic power devices [26,27]. More than 50% of our electricity is conditioned by electronic power devices [28,29]. These devices are important because they determine the cost and efficiency of electronic systems. Hence they have a greater impact on the economy of a country. The arrival in the 1950s of solid state devices like the bipolar transistor led to the replacement of vacuum tubes [30,31], and these improvements made possible the Second Electronic Revolution with silicon as the material of choice. Power devices had an important place in this revolution. During the 1970s, there were bipolar devices with blocking voltage capacity of 500V and high current capabilities. Also in 1970, International Rectifier Inc. launched the first metal-oxide-field effect transistor (MOSFET) [32]. The idea was to replace bipolar devices with MOSFETs for high power use. The MOSFET is a unipolar device and thus has a high switching speed. The MOSFET is also a voltage controlled device where the junction transistor is a current controlled device. Higher switching speed means operation at higher frequency where other system components such as inductors can be made smaller, and voltage control instead of current control means less internal energy loss in the device.

3 Why wide band gap semiconductor devices?

In order to save energy on the national electric power grid, the idea of redesigned 'micro-grids' has been proposed [33,34]. For this we need power devices which can operate at higher switching speeds and block voltages of up to 20kV [35]. A potential solution for this problem is to employ power devices fabricated using a wide band gap semiconductor material such as silicon carbide [36]. For a power device, the Baliga figure of merit (BFOM) is given by

$$BFOM = \mu_N \varepsilon_S E_C^3$$

μ_N = bulk mobility of SiC

ε_S = permittivity of SiC

E_C = critical electric field of breakdown for SiC

The higher the BFOM, the more suitable the semiconductor for high power operation.

4 Diode and transistor

In power electronics, we need both a rectifier and a transistor [37]. The characteristics of an ideal rectifier and a transistor are shown in figures 1 (a) and (b). For an ideal rectifier, there is no voltage drop in on state and no current flows while the diode is not conducting (off state). So there is no power loss during operation. Similarly, in the case of an ideal transistor, there is no power dissipation in the on/off states. Figure 1 shows that the transition from the on to off state is instantaneous, meaning there is no power loss during switching. The waveforms of an ideal power switching system are shown in figures 2 (a) and (b). For an ideal switch, there is a zero voltage drop in on state. In the off state there is no leakage current, and again there is no power loss. But in reality, this is not the case, and the characteristics of a non-ideal rectifier / transistor are shown in figures 3 (a), (b) and the

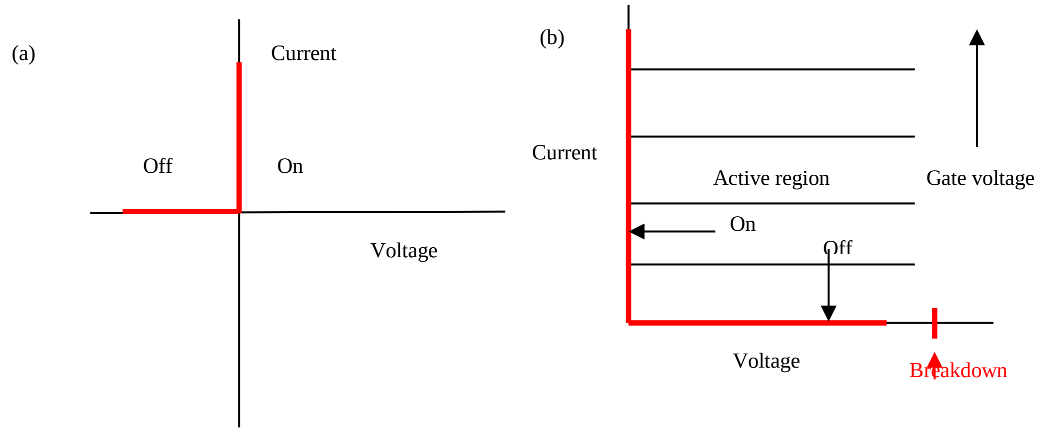


Figure 1: Ideal current-voltage characteristics of a diode (a) and transistor (b) [37].

corresponding waveforms of the power system are shown in figures 4. Total power loss in a switch is P_{total} and is given by

$$P_{total} = P_{turn\text{-}on} + P_{turn\text{-}off} + P_{on} + P_{off}$$

At high frequencies, the switching power loss is very large, so fast switching power devices are desirable. At low frequencies, on-state power loss dominates, so we need power devices with low on-state resistance.

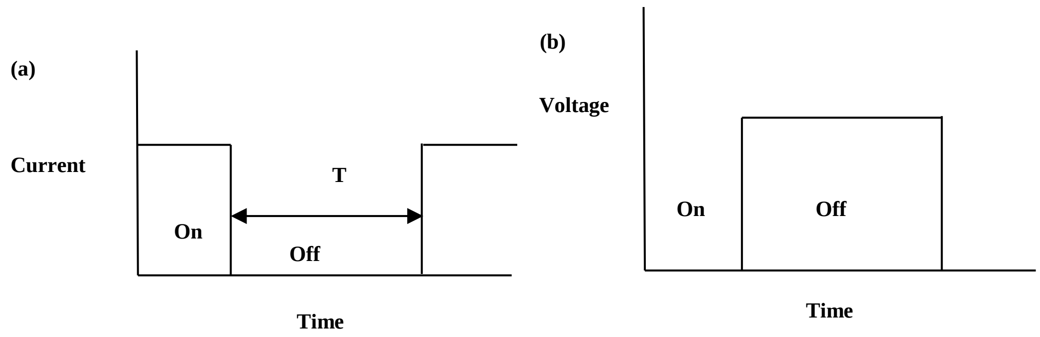


Figure 2: Switching waveforms of an ideal power system.

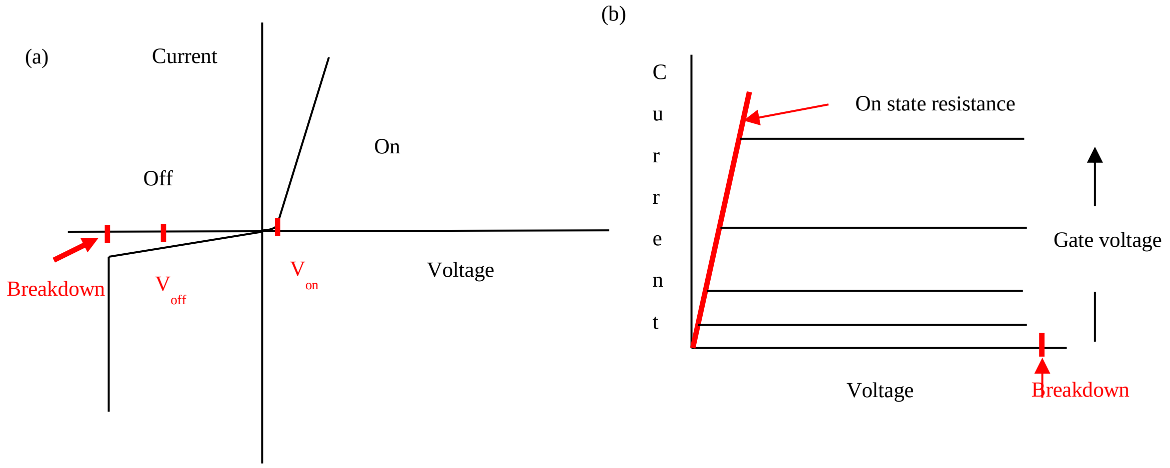


Figure 3: Real (non- ideal) current-voltage characteristics of a diode (a) and transistor (b). On sate resistance is ΔV/ΔI [37].

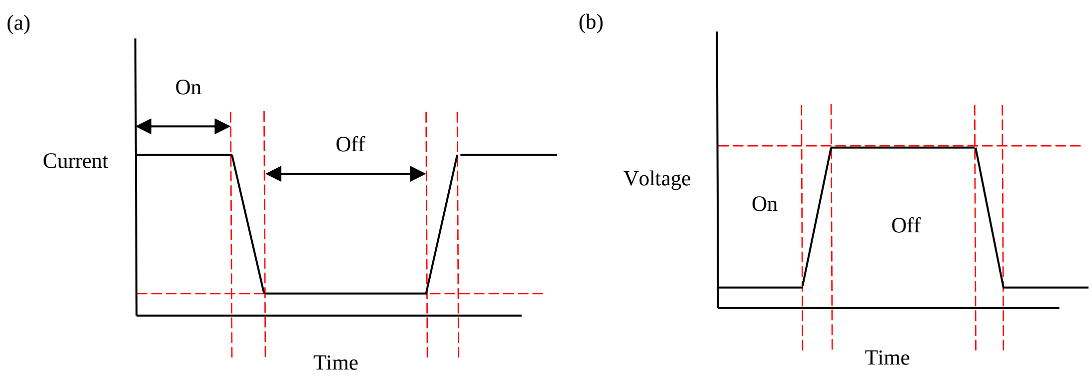


Figure 4: Switching waveforms in a real (non-ideal) power system [37].

5 Advantages of unipolar devices

Power devices mainly fall in two categories - unipolar and bipolar. Schottky diodes and MOSFETs are examples of unipolar devices. In a unipolar device, only one type of carrier (either a majority electron or a majority hole) is responsible for current flow. The device can operate at higher frequencies which results in lower switching losses [38]. There is a flow of both majority and minority carriers in bipolar devices. The slower minority carriers have to be injected and removed to get the device to turn on and off, so in bipolar devices there is power loss due to switching and leakage current.

The n-channel Si-MOSFET is a good choice for low voltages (around 100V), and it can operate at high switching speed, 100 kHz. But as the blocking voltage increases, the on-state resistance increases drastically. The SiC-MOSFET enables us to go to higher operating voltages (order of kilo volts) with higher switching speed. This is possible because SiC has a high critical breakdown field, almost 7 times that of Si. The specific on résistance of the MOSFET is given by [37]

$$R_{ON} = 4V_B^2 / \mu_N \varepsilon_S E_C^3$$

V_B is the desired blocking voltage, μ_N is the bulk electron mobility and ε_S is the semiconductor permittivity. Bulk electron mobilities are similar for lightly doped Si and SiC (900-1200cm^2/V-s) [24]. However, $E_C^{SiC} \sim 7E_C^{Si}$, so that for a given blocking voltage, the specific on-resistance can be a factor of 7^3 or 343 times lower for SiC. Another way to think of this advantage is that at higher critical field of SiC means a much thinner drift region can support the source-drain voltage in blocking state. A thinner drift region means lower drift resistance and thus lower on-resistance. Moreover, due to unipolar nature of the device we do not have to deal with stored charge and hence MOSFET will have higher switching speed.

6 Properties of silicon carbide

Silicon carbide exhibits the material characteristic of polytypism [38,39]. The tetrahedron is the building block of the SiC crystal with silicon (Si) at the center of tetrahedron and carbon (C) at the four corners as shown in figure 5.

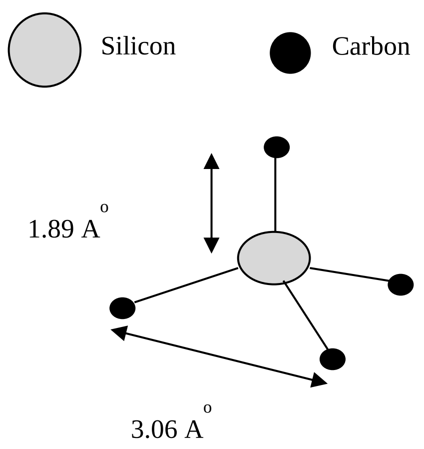


Figure 5: Building block of SiC [39].

The distance between Si and C is 1.89A°, and the distance between C and C is 3.06A°.There exists a second type of tetrahedron which is rotated by 180°. Silicon carbide has more than 200 polytypes. Among all polytypes, the technologically important are 3C-SiC, 4H-SiC and 6H-SiC. Depending upon the polytype SiC shows different electrical and physical properties. All polytypes of SiC have a hexagonal arrangement of SiC bilayers. Close packing of three bilayers (A, B and C) is shown in figure 6. In the 3C-SiC, the cubic polytype, the stacking sequence is ABCABC…….. The simplest hexagonal polytype is 2H-SiC having a stacking sequence ABAB…....... For 4H-SiC and 6H-SiC stacking sequences are ABCBABCB……………..and ABCACBABCACB…………… respectively. In notation for SiC, the letter designates the crystal structure of that particular sacking sequence and the number in the notation gives the periodicity of the sequence.

For an electronic device a high purity material is required. Initially in SiC it was very difficult to get large size polytype crystal. But then modified Lely process (1978) which is bulk crystal growth using seeded growth change the picture. And now SiC

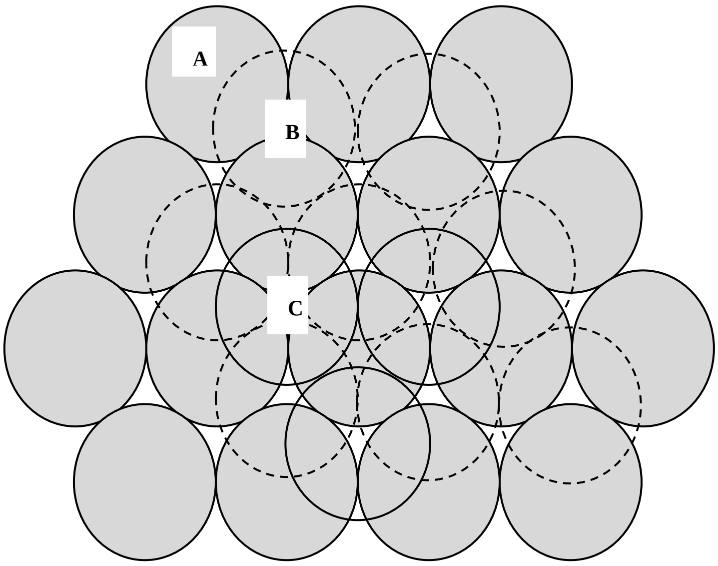


Figure 6: Close packing of three planes of spheres, one plane above the other. Each plane represents Si-C bilayers.

crystal with four inch (s00n six inch) diameter is available commercially. Even though the modified Lely process makes the growth of bulk SiC wafer possible still it is not flawless. There are two types of defects seen in the crystal after growth-micropipes and low-angle grain boundaries.

6.1 Electrical and physical properties of silicon carbide

SiC is a robust material with a Young's modulus of 424GPa, and is inert at room temperature. As a semiconductor, silicon carbide has a number of advantages as compare to silicon. Important electrical properties are compared in Table 1 for both semiconductors.

Table 1: Electrical properties of Si and several SiC polytypes [39].

Semiconductor	Si	3C-SiC	6H-SiC	4H-SiC
Bandgap (eV)	1.12	2.4	3.03	3.26
Breakdown Field (MV/cm)	0.25	>1.5	2.4 parallel to c-axis > 1, perpendicular to c-axis	2.2 parallel to c-axis
Intrinsic Carrier Conc.(cm^{-3})	1.45e10	1.5e-1	1.6e-6	5e-9
Electron Mobility @ n_d $=10^{16}$ cm^{-3}	1430	800	60 parallel to c-axis 400 perpendicular to c-axis	900 parallel to c-axis 800 perpendicular to c-axis

Hole Mobility @ n_a $=10^{16}$ cm^{-3}	480	40	90	115
Saturated Electron Vel (10^7cm/s)	1	2.5	2	2
Thermal Conductivity (W/cm-K)	1.5	3.2	3.0-3.8	3.0-3.8

SiC devices can withstand higher temperature as compare to Si The intrinsic carrier concentration of a semiconductor is given by [40]

$$n_i = \sqrt{N_C\, N_V}\; e^{(-Eg/2kT)}$$

where

N_C = effective density of states in conduction band;

N_v = effective density of states in valance band;

E_g = band gap energy;

k = Boltzmann's constant;

T = absolute temperature.

Due to low band gap of Si, the intrinsic carrier concentration n_i of Si increases rapidly with increasing temperature. If n_i becomes equal to the doping concentration, a material loses its semiconductor characteristics and behaves as a simple resistor. If we want to use a Si device at temperatures >150^{o}C, then we have to increase the doping. But there is a problem with this approach. Increased doping results in a higher internal electric field in the device and which leads to electrical breakdown. The much larger band gap of SiC (x3 Si) leads to lower intrinsic carrier concentration and a theoretical operating temperature of up to 500^{o}C.

SiC is best suited for high power devices due largely to its large band gap, high breakdown field and high thermal conductivity. However, it would not be fair to say that power devices are not fabricated using Si. Silicon thyristors are used for high voltage DC transmission. Bipolar junction transistors (BJTs) are used for medium power conditioning and moderate speeds. But in order to use BJTs at higher voltages, one must use complicated control circuits and which leads to additional power dissipation. The invention of the MOSFET circumvented some of these problems. This unipolar device in Si is very good for low voltage (less than a few hundred volts) and high frequencies (>100 kHz). Because of low critical field of Si, these devices are not used at higher voltages. Then there is the invention of the Si IGBT (insulated gate bipolar transistor) that can be used at higher voltages compare to the MOSFET. As minority carriers play an important role during its operation of bipolar devices, the switching speed of the IGBT devices is lower. For higher voltage, high current and low switching frequencies, the IGBT is good choice, while for lower voltage, high current and high switching speed, the MOSFETs is better.

SiC has three times the thermal conductivity of Si, and this is very important for the power devices. It makes heat dissipation much easier during device operation. Material properties can change with rising temperature that is the result of poor heat dissipation. High saturated electron velocity also makes SiC a good choice for microwave and radio frequency applications. SiC Schottky diodes have been on the market for a few years, and they are proving to be reliable replacements for better than silicon junction diodes.

7 Ultrahigh-Voltage SiC Devices

The specific on-resistance $R_{on,sp}$ is the key figure of merit for power switches. It tells directly how much resistive loss a device generates in the forward conduction mode. To compare between different materials, unipolar action is assumed. $R_{on,sp}$ can be calculated from the following equation

$$R_{on,sp} = \frac{4V_B^2}{\varepsilon \mu_n E_c^3}$$

where VB denotes the breakdown voltage, ε is the permittivity of the semiconductor, μ_N is the electron mobility perpendicular to the surface and Ec the critical electrical field. Since the electric field E_c of 4H-SiC is about 10 times higher than that of Si,

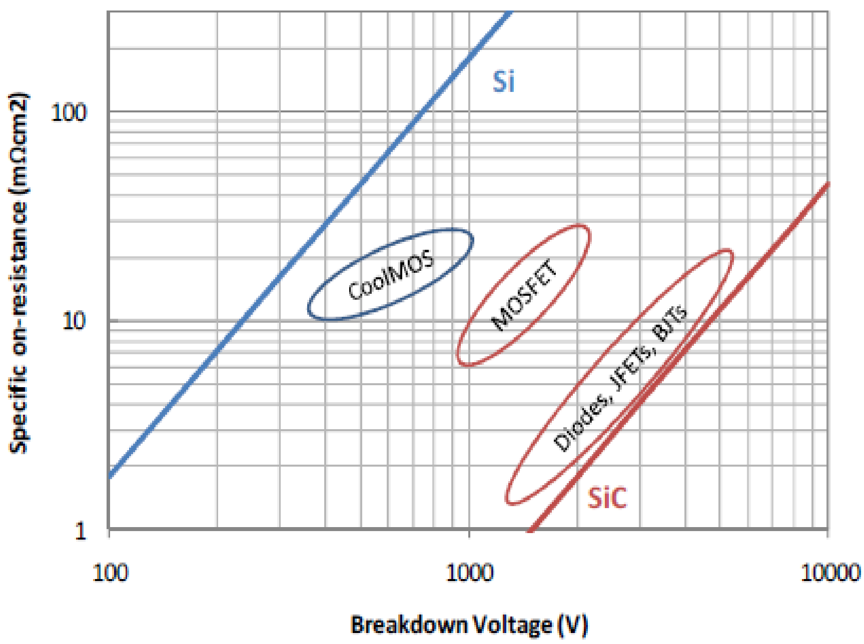


Figure 7: Comparison of unipolar limit of specific on-resistance versus blocking voltage for device types in Si and SiC.

even allowing for the lower electron mobility, the specific on-resistance in SiC at a given blocking voltage is about 400 times lower than in Si. Such improvement is significant as silicon devices are approaching their theoretical limits of performance. Relationship between the breakdown voltage and the specific on-resistance $R_{on,sp}$ for diodes, JFETs and BJTs is shown in figure 7.

Application for ultrahigh voltage (>10kV) power devices are usually in the electricity power network, such as HVDC transmission for distributed energy and other electric systems which require high-voltage and high-frequency. Only few papers are found on SiC power devices specifically for high voltage electricity network application.

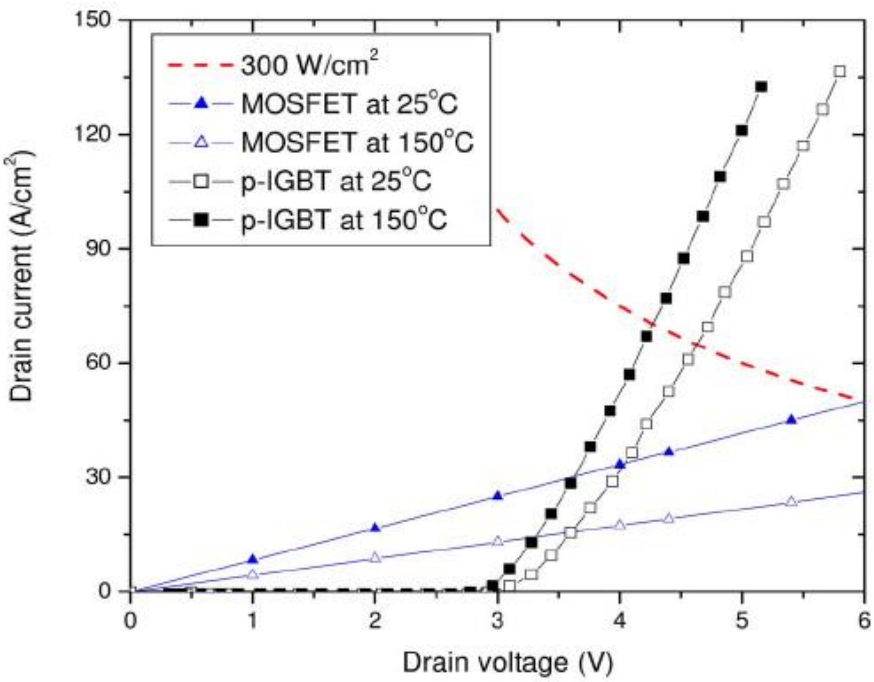


Figure 8: Comparison of 10-kV SiC MOSFET and IGBT conduction characteristics at 25℃ and 150℃.

One of the papers published in 2010 [41] illustrated the designs and results for ultrahigh voltage (10-15kV and 15-25kV) using 4H-SiC power devices for microgrid using a distributed and fluctuating sources for power generation. Figures 8 and 9 from paper [41] has shown the conduction characteristic for 10kV and 20kV MOSFETs and IGBTs. It is seen that the SiC IGBT exhibits a much lower forward voltage drop at typical operation current density (>30A/cm^2) than SiC MOSFET, but at lower operation current density (<10A/cm^2) SiC MOSFET has lower voltage drop than IGBT.

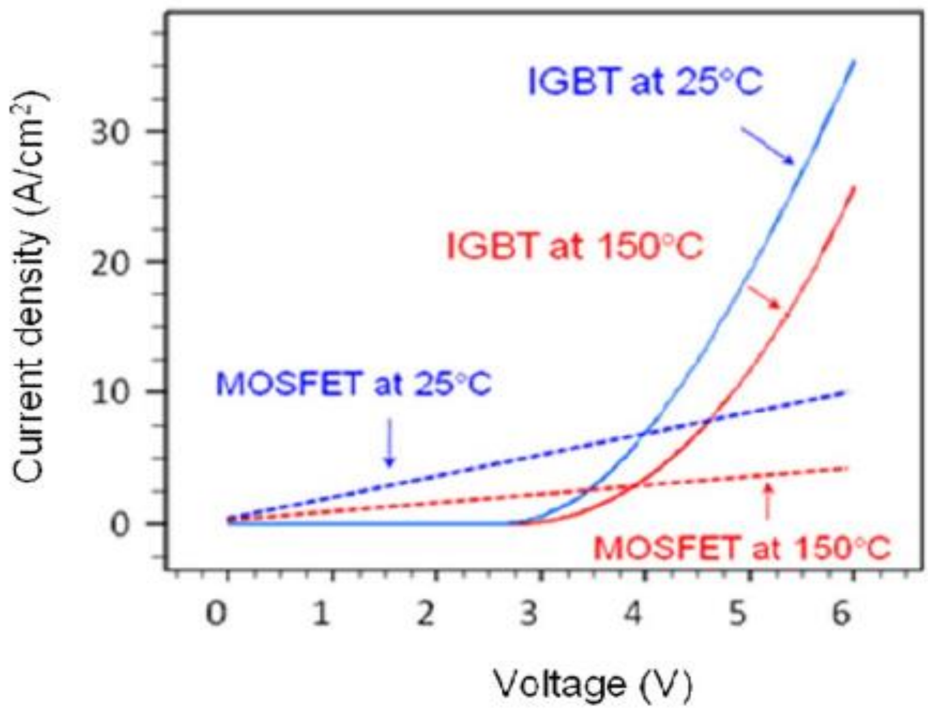


Figure 9: Comparison of 20-kV SiC MOSFET and IGBT conduction characteristics at 25℃ and 150℃ from numerical simulations.

The results described above have shown that MOSFETs exhibit the fastest turn-off speed, thus the lowest switching loss, while IGBTs have lower forward voltage drops at high current density (>30A/cm^2) with slower turn-off times. The trade-off between the ON-state power and switch energy losses makes it complicated to pick the right device for power grid applications. Furthermore, SiC MOS-based power devices such as MOSFETs and IGBTs are limited in size due to the gate yield and epitaxial material quality as mentioned before. Therefore, for high-voltage blocking rating SiC power devices, the optimum device is the one that produces the highest forward conduction current density at a given switching frequency under the condition that the total power loss is at the package power dissipation limit.

8 Benefits of SiC Technology in terms of Harmonics and Losses

Silicon Carbide Technology provides an extensive opportunity in power electronics field in terms of efficiency improvement. Silicon Carbide switches can operate at a faster speed than IGBT (due to their FET spec), can tolerate higher temperatures and can block at least the same level of conventional IGBTs, if not more. Their faster switching characteristics will reduce the filter size needed to eliminate the harmonics generated during the operation of power converters which could be a revolution for the power industry. Silicon Carbide switches proved to have at least 25% of losses of IGBTs in the same rating levels. Some studies show for the same rating SiC

MOSFET/Schottky Barrier Diode Modules have 85% losses reduction compared to Silicon IGBT/PiN Diode Modules.

Simulations of multilevel power converters have been done to compare SiC devices with Silicon IGBTs in terms of harmonics and losses. Converters have been tested under different switching schemes know as Pulse-Width-Modulation (PWM) drives. Although PWM techniques can be of different types, the main ones to be studies here are Sinusoidal PWM (SPWM) and Selective-Harmonic-Elimination PWM (SHE-PWM). The aim of SHE-PWM is to reduce the level of harmonics generated by converter on its output and it is expected to reduce the level of harmonics compared to SPWM. Different levels of converters have also been studied through to check the validity of the model. The models are from 2 up to 23 level converters as shown in figure.10. The Si IGBTs normally operate whithin10-20 kHz range while SiC FETs have the possibility of going to up to 1 MHz of switching. This is mainly due to the

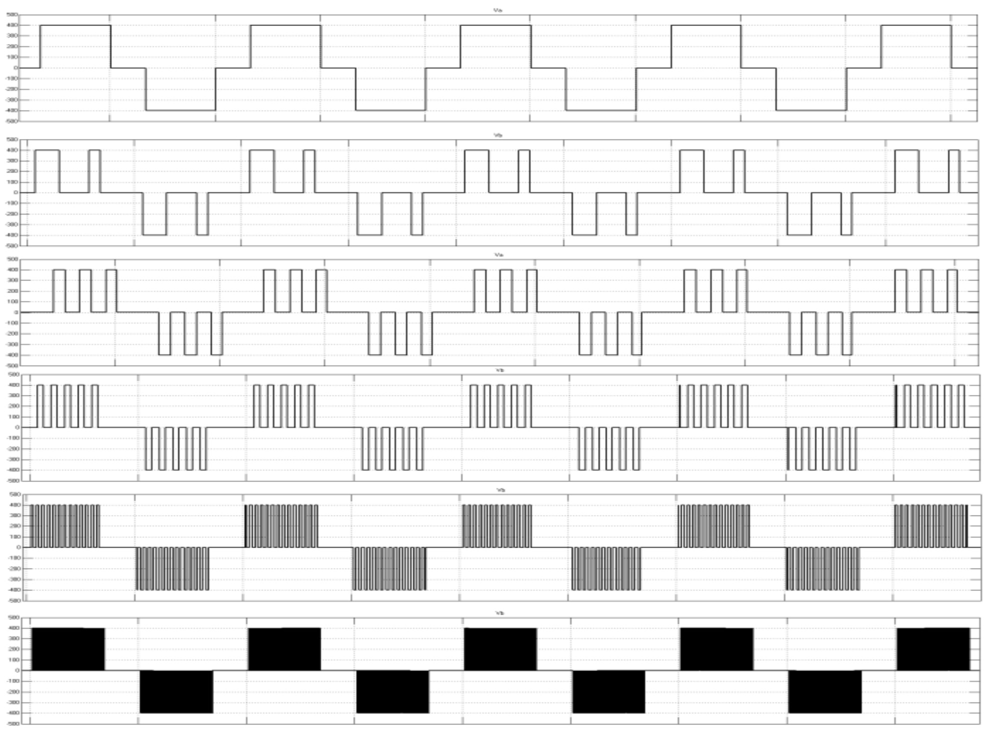


Figure 10: Increase in switching Frequency solidates the waveform generated

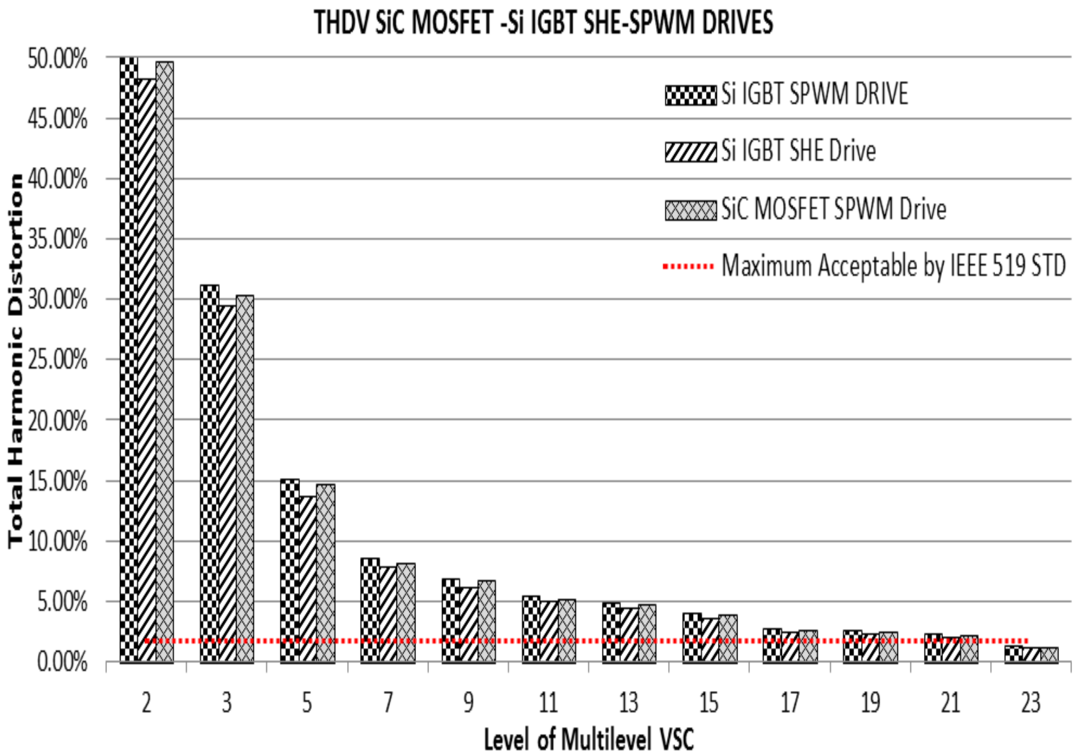


Figure 11: Reduction in Total Harmonic Generated by increase in level of converter.

limitation of its high switching losses in IGBTs, especially at Turn-On which is achievable in SiC FETS. Hence higher frequency is possible in 4H-SiC MOSFETs. Figure.11 shows that by increasing the level of converter, the total generated harmonics will decrease significantly; however this is not easily accessible in many applications as increased level will increase the complexity on gate driver side. It is also observed that using a different PWM technique such as SHE-PWM instead of an ordinary sinusoidal PWM provides less harmonic (THD) but this should be configured in each application based on the requirements of the output. In a 2-level converter the ordinary amount of harmonics generated is around 50% and decrease to 49.5% if SiC MOSFET is used and further to 48% if SHE drive is used. Although the difference looks very small at first, but can contribute significantly in energy-saving if used on high voltage systems. As it is seen, the acceptable level of Total Harmonics Distortion Generated by IEEE Standard 519 is only 2% which is accessible only via

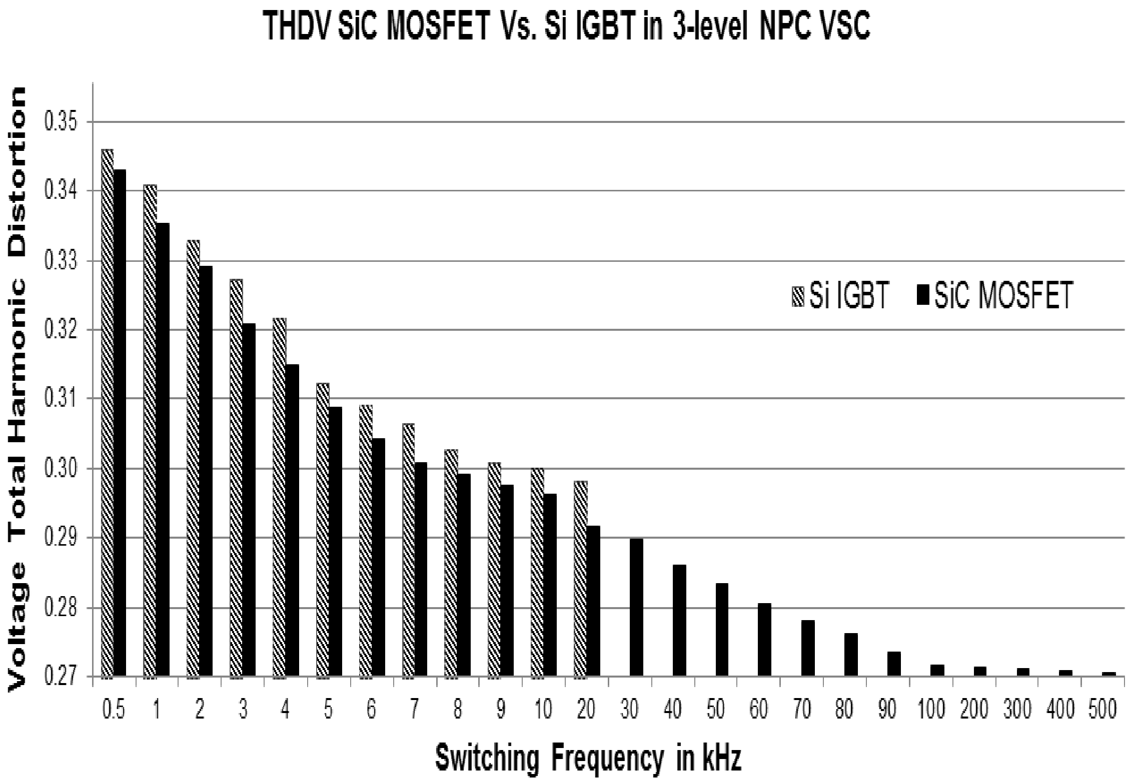


Figure 12: Reduction in harmonics generated by 4H-SiC-MOSFET compared to Si IGBT in high frequencies

increasing the level of converter top to 23 levels (which is not accessible in most cases) or using Filters in front which bring us the disadvantage of energy loss and huge sizes of passives. Reduction of THD, although small, will save us money/room in terms of filter sizes (passive elements sizes and capacities of inductors and capacitors in line) and reduction of energy loss in filtering. Figure 12 shows the total harmonic distortion versus switching frequencies for both Si IGBTs and SiC MOSFETs. It is seen that the amount of harmonics generated in a 3-level converter decreased from initial level of 34% to 31% if frequency range increased from 500 Hz to 20 kHz which is usually the maximum operating point of IGBTs. This fall increased to 27% in 0.5 MHz frequency, where only SiC MOFETs can operate normally. Clearly doing a simple calculation, the amount of switching losses at 120 kHz of a SiC MOFET is approximately of the same level as of IGBT operating at 20 kHz switching condition.

9 Current Status of Commercial SiC Devices

Today the main SiC power device products are still rectifiers based on Schottky or junction barrier diodes. Table 2 shows most of the manufacturers and current state-of-art of commercial SiC Schottky barrier diodes. 15kV SiC Schottky diodes have been developed in R&D laboratories but not yet commercialized.

Manufacturer	Part numbers	V_{RRM}	$I_{F(AVG)}$	Q_c	V_F@25 °C	V_F@125°C	I_R@25 °C	I_R@25 °C
Unit		V	A	nC	V		uA	
Cree	C4D40120	120	40	26	1.8	3	400	800

	D	0		0				
Infineon	IDH15S120	1200	15	54	1.8	2.55	360	1500
Microsemi	MSiCSS10120	1200	10	Na	1.88	Na	100	200
SemiSouth	SDP60S120D	1200	60	260	1.8	2.9	600	1200
ST Microelectronics	STPSC2006CW	600	20	24	1.7	2.1	300	3000
Rohm	SCS120AG	600	20	35	1.7	Na	400	Na

Table.2. Manufacturers and current status of commercial SiC Schottky Barrier Diodes

Few companies are offering active power switches as engineering samples based on MOSFETs, JFETs and BJTs. Commercially available 1200V SiC MOSFETs are recently released by Cree and a recent publication showed impressive performance of SiC devices [42]. Table 3 shows some basic information about the SiC devices that some companies have been offering. By comparison of different types of switches we can see that JFETs exhibit a small capacitance and can thus be operated at high switching speed. SiC JFETs also provide excellent high temperature operation. The main drawback with VJFETs is that they are usually normally-on devices, which are considered unsafe in power applications. Recently SemiSouth has demonstrated normally-off VJFETs, while the performance still remains some limitations.

	$V_{(BR)DSS}$	I_D	$R_{DS(on)}$	A_{Chip}
JFET(SiCED)	500 V	~5 A	0.2 Ω	5.76 mm^2
JFET(SiCED)	1.2 kV	~5 A	0.33 Ω	5.76 mm^2
JFET(SiCED)	1.2 kV	~17 A	0.12 Ω	17.3 mm^2
JFET(SiCED)	6.5 kV	~5 A	3.3 Ω	5.76 mm^2
JFET(SemiSouth)	1.2 kV	>15A	0.125 Ω	4 mm^2
MOSFET(Cree)	1.2 kV	>20 A	0.075 Ω	16.6 mm^2
MOSFET(Cree)	10 kV	~10 A	0.5 Ω	65.8 mm^2

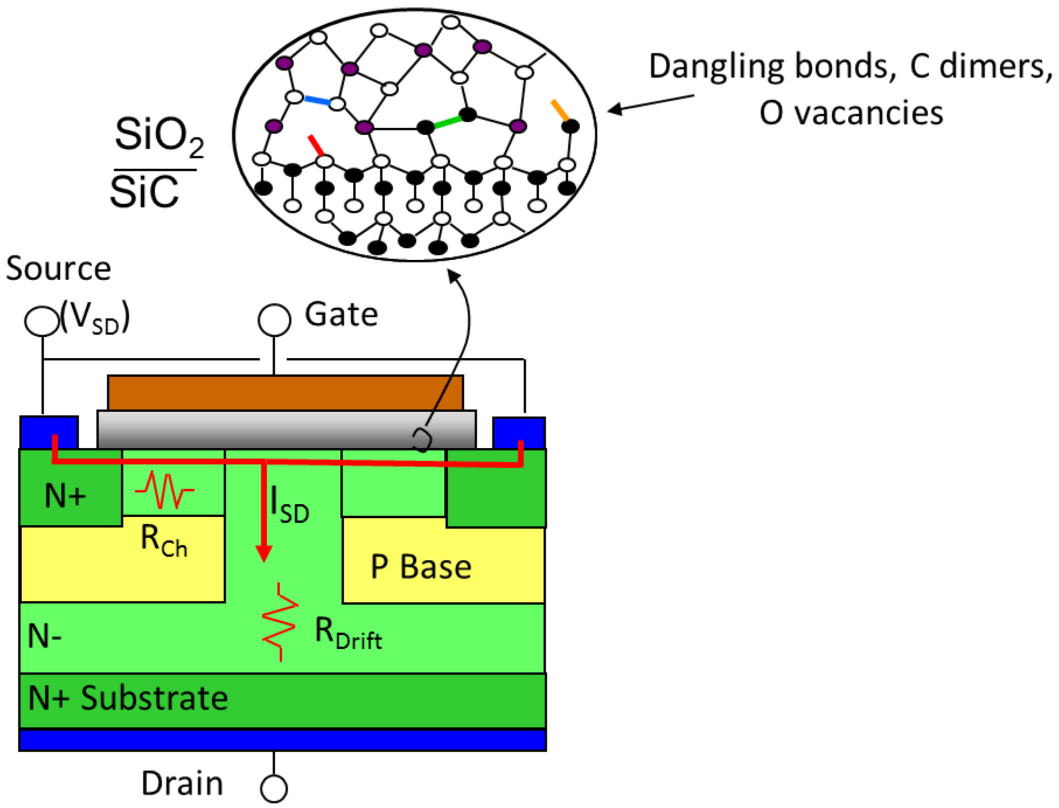
Table. 3. Current status of relatively mature SiC switches

10 Issues with SiC-MOSFET technology

Electrically imperfect 4 H-SiC/SiO2 interfaces compare with Si/SiO2

SiC exists in different polytypes. 4H-SiC polytype has the highest bandgap energy. It has higher and more isotropic mobility compared to other polytypes and hence is used to fabricate MOSFET devices [43,44]. To use SiC to its full potential, we must continue to work to improve the electrical characteristics of the SiO_2/SiC interface by developing more efficient processes to passivate defects at the interface that form during the oxidation process. These defects trap carriers (electrons) from the channel to become charged, thereafter acting as Coulomb scattering centers that scatter other channel electrons. The result of trapping and scattering is lower effective channel mobility. At present there is a standard passivation process based on post-oxidation annealing in nitric oxide (NO) or nitric oxide followed by hydrogen annealing ($NO+H_2$) [45,46]. These passivations increase the inversion electron channel mobility of a SiC-MOSFET from single digits (~ 8cm^2/V·s) to around 30cm^2/V·s. Although these processes have made the commercialization of SiC MOSFETs a reality, there is still room for significant improvement. This inversion channel mobility value is only around 4% of bulk mobility value of SiC. In case of Si, the inversion channel mobility can be as much as 50% of bulk mobility [47]. Remember that both Si and SiC have similar bulk mobilities of around 900-1100cm^2/V·s.

In addition to interface passivation, some groups have tried oxide growth in presence of sodium and have reported mobility values as high as 250 cm^2/V·s [48]. But as sodium moves under stress (high electric field of high temperature), devices fabricated with it are highly unstable and are of no practical use.



Although recent reports on Phosphorus/Nitrogen-plasma passivations are very impressive and increase the mobility (of the 4H-SiC-MOSFET) to $80 cm^2/V$, there is still room for improvement [49-51]. It is important to note that this value is two times higher than the state of the art Cree's MOSFETs. These initial results are very significant and encouraging for the SiC MOSFET technology, although more work is needed to be done before these processes can be used for commercial purposes.

References

[1] Global Warming 101: Costs, William Yeatman (2009).

[2] C. C. Committee, "Building a low carbon economy - the UK's innovation challenge," ed. http://www.theccc.org.uk/reports/low-carbon-innovation (2010).

[3] J. S. a. T. K. Gan Fengm, IEEE transactions on electron devices, **59** (2012).

[4] http://www.cree.com/products/power_docs2.asp].

[5] http://www.infineon.com/.

[6] http://www.rohm.com/products/discrete/sic/.

[7] K. A. Y. Sugawara, R. Singh, and J. W. Palmour, Mater. Sci. Forum, 1371 (2000).

[8] J. J. S. M. K. Das, B. A. Hull, J. Richmond, S. Krishnoswami, and A. R. Powell, vol. 483-485, ed: Mater. Sci. Forum, 965 (2005).

[9] S. H. R. A. Agarwal, R. Singh, O. Kordina, and J. W. Palmour, vol. 338-342, ed: Mater. Sci. Forum, 1387 (2000).

[10] B. H. L. L. H. Cao, and J. H. Zhao,Solid State Electronics, **44,** 347 (2000).

[11] M. Ito, L. Storasta, and H. Tsuchida, Applied Physics Express, **1 (**2008).

[12] H. Pedersen, S. Leone, A. Henry, F. C. Beyer, V. Darakchieva, and E. Janzen, Journal of Crystal Growth, **307**, 334-340 (2007).

[13] L. Storasta and H. Tsuchida, Applied Physics Letters, **90** (2007).

[14] T. Hiyoshi and T. Kimoto, Applied Physics Express, **2** (2009).

[15] J. Rozen, A. C. Ahyi, X. G. Zhu, J. R. Williams, and L. C. Feldman, IEEE Transactions on Electron Devices, **58**, 3808 (2011).

[16] M. Ostling, R. Ghandi, C.-M. Zetterling, IEEE 23rd International Symposium on Power Semiconductor Devices and ICs (ISPSD), San Diego, CA, 10-15 (2011).

[17] A. Agarwal, S.-H. Ryu, Ed., ed. CS MANTECH conference (2006).

[18] W. G. Pfann and J.H. Scaff, Proceedings of the I.R.E, **38**, 1151, 1950.

[19] L. B. Valdes, Proceedings of the I.R.E, **40**, 445 (1952).

[20] J. A., Proceedings of the I.R.E. **40**, 1314 (1952).

[21] Chrisrophe Lecuyer, Making Silicon Valley: Innovation and the Growth of High Tech, 1930-1970 (The MIT Press, 2007).

[22] William C. ÓMara, Robert B. Herring, and Lee P. Hunt, Handnook of Semiconductor and Silicon Technology (Willam Andrew, 1990).

[23] B.E. Deal and A.S. Grove, Journal of Applied Physics, **36**, 3770 (1965).

[24] N. F. Mott, S. Rigo, F. Rochet, A. M. Stoneham,PHIL. Mag. B. 60, 189 (1989)

[25] http://www.sia-online.org/news/2012/02/06/global-sales-report-2012.

[26] http://www.icinsights.com.

[27] http://www.electroiq.com/articles/sst/print/volume-54/issue-7.html.

[28] http://www.power-mag.com/news.detail.php?NID=38.

[29] B. J. Baliga, Fundamentals of Power Semiconductor Devices, (Springer, 2008).

[30] R. M. Warner, IEEE Transactions on Electron Devices, **48**, 2457 (2001).

[31] http://www.irf.com/60anniversary/index.html#1970s.

[32] R. H. Lasseter, P. Paigi, IEEE 35th Annual Conference on Power Electronics Specialists **6**, 4285 (2004).

[33] N. Hatziargyriou, IEEE Power and Energy Magazine**, 5**, 78 (2007).

[34] Q. Zhang, R. Callanan, M. K. Das, S. H. Ryu, A. K. Agarwal, and J. W. Palmour, IEEE Transactions on Power Electronics, **25**, 2889 (2010).

[35] S. E. Saddow, A. Agarwal, Advances in Silicon Carbide and Applications, (Artech House 2004).

[36] M. Bhatnagar and B. J. Baliga, IEEE Transactions on Electron. Devices, **3**, 645 (1993).

[37] B. J. Baliga, Silicon Carbide Power Devices, (World Scientific, 2005).

[38] S. H. Vanger, Silicon Carbide: New Materials, Production Method, and Applications, (Nova Science, Inc. 2011).

[39] G. L. Harris, Properties of Silicon Carbide, (IET, 1995).

[40] S. Dhar, S. Wang, J. R. Williams, S. T. Pantelides, and L. C. Feldman, MRS Bulletin, **30**, 288 (2005).

[41] Q. C. Zhang, R. Callanan, M. K. Das, S. H. Ryu, A. K. Agarwal, and J. W. Palmour, IEEE Transactions on Power Electronics, **25**, 2889 (2010).

[42] M. Ostling, R. Ghandi, C.-M. Zetterling, and Ieee, "SiC power devices - present status, applications and future perspective," in IEEE 23rd International Symposium on Power Semiconductor Devices and ICs (ISPSD), San Diego, CA, 10-15 (2011).

[43] F. Bechstedt, P. Kackell, A. Zywietz, K. Karch, B. Adolph, K. Tenelsen, and J. Furthmuller,Phy. Sta. Sol. (b), **202**, 35 (1997).

[44] S. E. Saddow and A. Agarwal, Advances in Siliocn Carbide Processing and Applications, (Artech House 2004).

[45] G. Y. Chung, C. C. Tin, J. R. Williams, K. McDonald, R. K. Chanana, Robert A. Weller, S. T. Pantelides, Leonard C. Feldman, Member,O. W. Holland, M. K. Das, and John W. Palmour, IEEE Electron Device Letters, **22**, 176 (2001).

[46] J. Senzaki, K. Kojima, S. Harada, R. Kosugi, S. Senzaki, and K. Fukuda, IEEE Electron. Device Letters. **23**,13 (2002).

[47] J. Welser, J. L. Hoyt, J. F. Gibbons, IEEE Electron. Device Letters, **15**, 100 (1994).

[48] E,O. Sveinbjornsson,F. Allerstam, G. Gudjónsson, H.Ö. Ólafsson, D. Dochev, T. Roddle,and R. Jos, Mater. Sci. Forum **556-557**, 487,(2007)

[49] Y.K. Sharma, A. C. Ahyi, T. Isaac-Smith, A. Modic, M. Park, Y. Xu, E.L. Garfunkel, S. Dhar, L. C. Feldman and J. R. Williams, IEEE Electron Device Letters, **34,** 175, (2013).

[50] Y. K. Sharma, A. C. Ahyi, T. Issacs-Smith, X. Shen, S. T. Pantelides, X. Zhu, J. Rozen, L.C. Feldman, Y. Xu, E. Garfunkel, and J.R. Williams, Solid-State Electronics, **68,** 103, (2012)

[51] A. Modic, Y. K. Sharma, Y. Xu, G. Liu, et al., “Nitrogen plasma processing of SiO_2/4H-SiC interfaces” (submitted)