SiC Bipolar Devices for High Power and Integrated Drivers

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Abstract — Silicon carbide (SiC) semiconductor devices for high power applications are now commercially available as discrete devices. The first SiC device to reach the market was the unipolar Schottky diode. Active switching devices such as bipolar junction transistors (BJTs), field effect transistors (JFETs and MOSFETs) are now being offered in the voltage range up to 1.2 kV. SiC material quality and epitaxy processes have greatly improved and degradation free 100 mm wafers are readily available, which has removed one obstacle for the introduction of bipolar devices. The SiC wafer roadmap looks very favorable as volume production takes off. Other advantages of SiC are the possibility of high temperature operation ($> 300^\circ\text{C}$) and in radiation hard environments, which could offer considerable system advantages. Thanks to the mature SiC process technology, low-power integrated circuits are now also viable. Such circuits could find use in integrated drivers operating at elevated temperatures.

Index Terms — Silicon Carbide bipolar process technology, bipolar physics and simulation, power devices, analog/digital circuits, integrated drivers, high temperature, radiation hardness.

I. INTRODUCTION

The key figure of merit for power switches is the specific on-resistance $R_{\text{on,sp}}$. This parameter tells directly how much resistive loss a device generates in the forward conduction mode. Several of the published device data for diodes, JFETs and BJTs are very close to the theoretical limit. For MOSFETs the channel resistance in SiC dominates because of the low channel mobility, and experimental data therefore suffers. Although BJTs would be expected to perform better than the unipolar limit, high injection is seldom achieved. Therefore high injection devices such as IGBTs and GTOs are explored for the highest breakdown voltages.

SiC Rectifiers

In power circuits, rectifiers are continuously switched between the ON and OFF states. These devices are also required to demonstrate low power loss switching characteristics especially for high frequency applications. The main power rectifiers are PiN diodes and Schottky diodes. The advent of SiC with one order of magnitude higher critical electric field has made it possible to implement thinner drift layer with higher doping and lower ON-resistance compared to Si. Also these devices have demonstrated higher temperature capability compared to Si based devices. In this section, structure, characteristics and challenges of these devices are shortly discussed and recent breakthroughs of SiC rectifiers are highlighted.

PiN Rectifiers

Optimum performance of the Si PiN diode is limited by the maximum switching frequency and a trade-off between forward voltage drop and switching speed is needed. 4H-SiC PiN diodes can provide higher switching speed and lower voltage drop compared to Si PiN diodes because of a thinner drift layer. These diodes have also shown high-temperature operation that is desired in many high power applications. The main concern for fabrication of high voltage 4H-SiC PiN diodes is high quality growth of a lowly doped thick epitaxial layer with high minority carrier lifetime for optimum conductivity modulation. However, the performance of the SiC PiN diode can be degraded under forward voltage stress resulting in an increasing forward voltage drop. This phenomenon which is known as bipolar degradation is due to Shockley stacking faults (SSF) that originate from basal plane dislocations and this is discussed in more detail in the next sections. Table 1 summarizes recent reported high voltage SiC PiN diodes in terms of breakdown voltage, ON-resistance and forward voltage drop at 100 Acm^{-2} .

Table 1: Recent reported high voltage 4H-SiC PiN diodes

V_{br} (kV)	R_{ON} ($\text{m}\Omega\text{cm}^2$)	V_{F} @100 Acm^{-2}	Ref.
3.3	1.7	3.3	[1]
4.5	1.7	3.3	[2]
6.5	34	3.4	[3]
10	38	3.9	[4]
12-19	65	4.4-7.5	[5]

Schottky Barrier Diodes (SBD)

High voltage 4H-SiC SBDs have been introduced to the market since 2001. Compared to Si diodes, these rectifiers show faster switching due to the thinner drift layer at the expense of higher forward voltage drop across the junction. Therefore, SiC SBDs are interesting devices particularly when the switching power losses are dominant. At the moment, 300V/30A-1700V/25A SiC SBDs are commercially available and there is potential for fabrication of higher power rectifiers as the material quality improves further.

JBS and MPS diodes

To utilize the properties of the PiN diode and Schottky diodes, JBS and MPS have been introduced as monolithic combinations of both devices. Junction barrier controlled Schottky (JBS) is a Schottky diode with an integrated P⁺-N junction grid into the drift region. During reverse bias, the integrated P layer,

extend the depletion layer, shield the Schottky barrier and reduce the leakage current compared to conventional Schottky rectifiers. Merged PiN/Schottky (MPS) rectifiers employ the same approach for combining two conventional rectifiers and act like JBS in the blocking mode. However, the integrated P⁺ layers are forward biased at high current levels and inject high concentration of minority carriers into the lowly doped n-layer that results in conductivity modulation, thereby protecting the diode from overheating under surge current conditions. Due to the presence of Schottky contact, the total charge required for conductivity modulation is less compared to the PiN diode that results in better recovery during turn-off. SiC JBS diodes are regarded as an interesting candidate to replace SBDs in the relatively high voltage range. However material quality and process complexity are still the main concern for fabrication of these types of devices. Table 2 demonstrates recent reported JBS rectifiers in SiC.

Table 2: Recent reported high voltage 4H-SiC JBS diodes

V _{br} (kV)	R _{ON} (mΩcm ²)	V _F	Ref.
1.6	7.5	1.4 V @100 Acm ⁻²	[6]
2.8	6.2	2 V @100 Acm ⁻²	[7]
5	25.2	3.5 V @108 Acm ⁻²	[8]
10	100	3.37 V @20 Acm ⁻²	[9]

SiC BJTs

Silicon bipolar power transistors are available since 40 years. The potential of operating at relatively high current densities with low power loss and high voltage capability was regarded as the distinguishing features of high voltage power BJTs. For these switches, operation in the forward direction is beneficial for reaching low on-state loss since the two built-in pn-junctions cancel each other. Hence, the on-state loss is mostly dependent on the drift layer resistance and the substrate resistance. However, due to low current gain of power BJTs at typical operating current levels, they have been replaced with insulated gate bipolar transistors (IGBT) and power MOSFETs in many power electronics applications. Also, operation of Si power bipolar transistors is limited by two major destructive effects that are known as thermal runaway and second breakdown. The thermal runaway, in which the total current increases with a positive feedback mechanism, occurs at elevated temperatures. This phenomenon, can occur due to the positive temperature coefficient of the forward voltage drop in a Si BJTs, and is caused by an increasing carrier lifetime in the device at elevated temperatures. This leads to a higher carrier concentration, higher current density and even more local increase in the temperature which is escalated by an increase in the total current. Interesting properties of SiC as a wide band gap semiconductor and robustness to harsh environments has made it possible to consider the SiC BJTs as one candidate for high

power applications due to its low power on-state loss and fast switching capability.

These devices show negative temperature coefficient of the current gain in which, the current gain of the device is significantly decreased at higher temperatures due to the activation of deep level acceptors in the base that limit the emitter injection efficiency. Also the specific ON-resistance of the device is increased at elevated temperatures due to the decreasing electron mobility which causes an increase in the resistance of the collector layer. These characteristics are desired for parallel connection of BJTs for high temperature applications. Moreover, the high critical field strength of SiC made it possible to use higher doping in the collector layer. For this reason second breakdown occurs at a very high current density which is well outside the normal operation area of the device [10]. The BJT is also extremely robust with high surge current capability, high temperature performance and high cosmic-ray radiation hardness.

A main design concern is to optimize the lowly doped collector epitaxy to accommodate the high reverse voltage but not to yield any additional series resistance. Ultimately, high injection devices will be needed. The most crucial optimization from a practical point today is to increase the current gain at application temperature [11-13]. Typically a current gain of 100 is desired when designing efficient drive circuitry. It is clear that an optimized surface passivation in the sensitive base-emitter surface region is very important for minimizing the base current recombination. Therefore in 4H-SiC BJTs, thermal oxidation in N₂O or post oxide anneal in N₂O are used to form state-of-the-art surface passivation. An improved passivation layer in terms of lower interface state density can decrease surface recombination current at the exposed base surface and along base-emitter junction sidewall thus resulting in higher current gain. Recently, it has been shown that deposited oxides followed by optimized nitridation annealing can results in improved current gain of up to β ~ 257 in SiC BJTs [14].

II. EDGE TERMINATION

Normally, vertical power transistors apply mesa edges for isolation of the layers. At the mesa edges, and close to the surface of the device, the critical electric field can be increased due to the curvature of the electric field profile. Therefore junction termination has to be adopted to locally reduce the electric field. There are different junction termination techniques for SiC BJTs that can be adopted singularly or in combination with each other. The most common technique for BJTs is an implanted Junction Termination Extension (JTE) in which the collector layer is locally implanted by p-dopants with lower doping than the base layer close to the base mesa. The other technique is field ring (guard ring)

termination that includes implanting p-type field rings surrounding the entire base mesa. This technique can be combined with implanted JTE and called guard ring assisted JTE [15]. Another junction termination is mesa-etched JTE that requires etching of single or multiple zones in the implanted [16] or in the epitaxial p-base layer [17] close to the main isolation to the collector. All of these terminations should be designed in a way to achieve an accurate dose of charge that becomes completely depleted to the surface close to the desired breakdown voltage, thereby reducing the maximum electric field in the edge region. It was also shown that the passivation layer can provide effective oxide charge and this can affect the optimum doses of implanted dopants in the JTE area, resulting in reduced breakdown voltage. Therefore, modification of JTE implantation dose may be needed when applying new passivation layers to high voltage SiC devices [18]. Consequently, 2800V large area (3mm²) BJTs with a maximum dc current gain of 52 and $R_{ON} = 6.8 \text{ m}\Omega\text{cm}^2$ was reported (Figure 1) [19].

Figure 1: Room temperature IV characteristics of 3mm² BJT

III. SWITCHING

The switching characteristics of this device were investigated with a driver circuit that is schematically demonstrated in Figure 2. In this topology the passive network composed of a resistance R2 for DC biasing and a series connection of R1 and C1 for dynamic overshoot of the base current during turn on and off. A double pulse is fed to the gate driver of IXDN509 to ramp up the inductor current. The BJT acts as a switch for a 5 mH inductive load with a 1200V 8A Schottky diode from Infineon (IDH08S120) as a freewheeling diode.

The turn-on and turn-off transients for 400V switching are shown in Figure 3. The large area BJT shows a V_{CE} fall time of 18 ns during turn-on and a V_{CE} rise time of 10 ns during turn-off. The fast switching without the current tail shows the potential for significantly smaller power losses compared to a Si IGBT. For high frequency application, minimal conductivity modulation is desired for an efficient switching; however, for high voltage switches, the power BJT should demonstrate conductivity modulation in the saturation region for the lowest ON-resistance.

Figure 2: Schematic of the test circuit for switching high voltage BJT

Figure 3: Transient characteristics of large area BJT for 400V switch during a) Turn-on and b) Turn-off

Table 3 summarizes the recent reported values for 4H-SiC BJTs.

Table 3: Recent reported 4H-SiC BJTs

V_{br} (kV)	R_{ON} (m Ωcm^2)	Current Gain	Ref.
0.95	3.2	134	[20]
1	2.9	33	[21]
1.2	6.3	70	[22]
1.2	5.2	60	[23]
1.5	3.4	40	[12]
1.6	5.1	70	[24]
1.8	4.4	40	[25]
2.2	4.5	35	[12]
2.7	12	50	[17]
2.8	4.5	55	[19]
6	28	3	[26]
9.2	49	7	[27]

So far conductivity modulation, which is one potentially main advantage of bipolar devices compared to unipolar devices, has not been readily observed in 4H-SiC BJTs. Low carrier lifetime which is due to the various defects in the SiC structure and also higher doping of the drift layer compared to Si power BJTs are factors explaining the absence of conductivity modulation. Therefore, optimum growth condition in terms of less defects and higher carrier life time not only improves the current gain but it can be advantageous also for achieving conductivity modulation.

IV. DEGRADATION

The other challenge which is the main obstacle for commercialization of 4H-SiC BJTs is degradation of the forward voltage drop (V_{CESAT}) and degradation of the current gain, under forward bias stress at high current density. Like the PiN diodes, degradation of V_{CESAT} is mainly attributed to carrier trapping and recombination in the base and/or collector due to the SSFs. However, a current gain degradation mechanism with no significant decrease on the on-resistance has been observed for BJTs on BPD-free substrate, and for small-area BJTs on standard substrates. The reason for this gain degradation is not clear and three possible mechanisms have been proposed:

1. an increase of the interface trap density along the SiC/SiO₂ interface
2. recombination enhanced defect generation in the base emitter region
3. small size stacking faults in the base-emitter region [28]

V. DARLINGTON PAIR

Increasing the current gain by two cascaded BJTs in a Darlington configuration is a potential solution for high power applications at the expense of a higher forward voltage drop. The optimally-designed Darlington can provide higher current gain ($\beta_{Darlington} = \beta_{(Driver\ BJT)} \times \beta_{(Output\ BJT)}$) compared to a single BJT along with high voltage blocking characteristics. Hybrid SiC Darlington transistors with 500 V and current gain of 430 [29] and 10kV with current gain of 440 [30] have been previously reported. However, monolithic Darlington design is preferred due to simpler design, better control in fabrication process and reproducibility. Recently Zhang et al. demonstrated a 10 kV monolithic Darlington BJT with current gain of 1200 [31]. The dependence of the maximum current gain in a 4H-SiC BJT on the collector current, emphasizes the importance of the ratio between the area of the driver and the output BJTs. For the maximum current gain, the driver BJT should be designed in a way that it is not only biased for the maximum gain but also provides the required

current for the highest gain to the output BJT. In [32] an implantation free monolithic Darlington with a maximum current gain of 2900 at room temperature is reported and it is shown that the high current gain is related to an optimum design for the ratio of the active area of the driver BJT to the output BJT (approximately 1:10). The forward characteristic of the Darlington transistor is shown in Figure 4.

Figure 4: Room temperature I-V characteristics of the Darlington transistor [32].

Also, assemble and package a full power module based on SiC devices in order to take full advantage of the high potential of increasing power density is a very challenging issue. Several groups have demonstrated promising results that are summarized in [33] and references therein.

VI. EXTREME HIGH VOLTAGE - HIGH INJECTION DEVICES

Devices for extremely high voltage (>10 kV) require ultimate materials quality for two main reasons. Firstly, at these high voltages defects in the material will cause premature breakdown and secondly, in order to yield a reasonable low on-resistance the devices must operate during high injection which also calls for high quality SiC wafers with a minimum basal plane dislocation density to achieve long minority carrier lifetimes.

Si IGBTs, as a commercially successful power device, replaced bipolar transistors in medium power applications that require high switching frequency and excellent on-state characteristics. However, performance of Si IGBTs are limited by high switching losses due to presence of minority carriers. High critical electric field as well as high temperature capability of SiC has urged different groups to consider fabrication of high voltage SiC IGBTs as a potential candidate for higher power applications [34]. N-channel IGBT which is composed of n-channel MOS and a PNP transistor is a preferred structure compared to p-channel IGBT due to the improved n-channel MOS process conditions with low interface states. However, the n-channel IGBT requires a p-type substrate. P-type substrates are not available in large dimensions and production volumes and they also introduce high resistance in series to the device. Recently 13 kV, 22 mΩcm² n-IGBT have

been reported [35]. This device shows conductivity modulation during forward conduction that corresponds to higher current capability compared to a 10kV SiC DMOSFET. High quality thick epitaxial growth with a long carrier life time is still a major challenge for development of SiC IGBTs.

Si GTOs suffer from large switching loss especially during turn-off due to the large current tails. The SiC GTO with high voltage capability is considered as an interesting device due to better thermal conductivity and larger breakdown field. However, the requirement of a large gate drive current for turn-off and also material quality are regarded as the main challenges of SiC GTO for high power applications. Recently a record large $1 \times 1 \text{ cm}^2$ sized Gate Turn-Off (GTO) thyristor with a breakdown voltage of 9 kV and a 1 ms current pulse of about 3 kA has been demonstrated [36].

VII. INTEGRATED DRIVER CIRCUITS

For a power switching system such as a motor drive, being able to operate the switches close to the motor will reduce the inductive losses. Low voltage high temperature electronics for drivers close to the switches will further reduce the system losses. There have been several demonstrations of SiC integrated circuits, such as the work on TTL by Singh et al. [37]. We have recently [38] demonstrated small-scale integration of emitter-coupled logic gates for these applications, as illustrated by the chip photo in Figure 5. Operation of logic gates has been verified up to 300°C , as shown in Figs. 6 and 7. The circuit is built in a low-voltage SiC BJT process with a current gain of 45 at room temperature, (25 at 300°C), and operates from a 15 V supply. Logic levels are clearly defined and results closely match simulations, based on preliminary SPICE models. Measured noise margins are stable from room temperature up to 300°C and are about 0.9V for both OR and NOR output.

Figure 5: Chip photo of ECL OR/NOR gate in low-voltage SiC

Figure 6: SiC integrated ECL OR-NOR gate: OR output vs. temperature

Figure 7: SiC integrated ECL OR-NOR gate: NOR output vs. temperature.

Further, the possibility of analog applications such as OP-amplifiers will be explored using the same process technology.

VIII. COST ANALYSIS

At present the cost per ampere is still too high for a massive breakthrough on the commercial mass-market for active high voltage switch devices in SiC. However, the trend line and cost analysis of wafer substrates and epitaxial services show a very fast decrease. To date a substantial part of the total device cost is dependent on the wafer cost and it is likely that the price per ampere will meet the market demands of 10-20 US cents per ampere in just a few years.

IX. CONCLUSIONS

Recent advantages in SiC wafer quality and device process technology, has prompted a renewed interest in bipolar devices. Several high voltage BJT

demonstrators with optimized current gain ($\beta > 100$) and advanced termination structures for high blocking voltage have been demonstrated. Very low specific On-resistance ($< 2.7 \text{ m}\Omega\text{cm}^2$) have also been achieved for devices with $> 1200 \text{ V}$ breakdown voltage. SiC BJT's are also making their way into the area of integrated circuits for high-temperature applications. Recent progress for GTOs, and IGBT also indicates the potential for extremely high voltage ($>10 \text{ kV}$) devices.

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