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SiC Devices

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SiC AND GaN HIGH-VOLTAGE POWER DEVICES

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ABSTRACT

The present status of development of SiC and GaN devices for high-voltage power electronics applications is reviewed. Device structures that are particularly applicable to these two wide bandgap semiconductors are considered and compared to those commonly used in silicon. The simulated and experimental performance of two-terminal rectifiers and three-terminal transistors and thyristors are compared. The effects of material parameters (mobility, ionization coefficients, lifetimes) and defects on device characteristics are pointed out. Similarities and differences between electronic and photonic device development in these semiconductors are discussed.

INTRODUCTION

Silicon has long been the dominant semiconductor of choice for high-voltage power electronics applications [1,2]. However, recently, wide bandgap semiconductors, particularly SiC and GaN, have attracted much attention because they are projected to have more than 100 times better performance than silicon [3-6]. The superior physical properties that these semiconductors offer include a lower intrinsic carrier concentration (10 to 35 orders of magnitude), a higher electric breakdown field (4-20 times), a higher thermal conductivity (3-13 times), a larger saturated electron drift velocity (2-2.5 times), when compared to silicon (See Table I). Two more important material properties may also be noted. First, SiC possesses higher minority carrier lifetimes than GaN because SiC has an indirect bandgap. Second, the hole impact ionization coefficient (α_p) is larger than the electron one (α_n) in both SiC and GaN, unlike silicon (see Figs. 1 and 2). Several figures of merit, specifically to quantify the intrinsic performance potentials of unipolar and bipolar power switching devices, have been proposed [3-6]. Another figure of merit has been developed for HBTs, but it is intended for high-frequency amplifying applications [7]. Also, GaN has clearly established itself commercially in the display and photonic applications and blue LEDs and lasers made of InGaN are currently available. Furthermore, SiC MESFETs and SITs, GaN MESFETs and AlGaN HEMTs have been experimentally demonstrated at increasingly higher frequencies for microwave applications.

In this paper, the device structures suitable for power switching device demonstrations in SiC and GaN will be presented. Simulated or experimental characteristics of selected two- and three-terminal devices will be described. The material and processing issues that are relevant for power device commercialization will be comparatively discussed.

DEVICE CHOICES AND STRUCTURES

One of the basic building blocks of a power circuit is the half bridge (Fig. 3), in which two parallelly connected pairs of a three-terminal switch and a two-terminal anti-parallel rectifier are connected in series.

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Rectifiers

High-voltage power Schottky rectifiers offer fast switching speed but suffers from high on-state voltage drop and on-resistance because mostly majority carriers participate in its forward conduction. By contrast, the pin junction rectifier has low forward drop and high current capability due to conductivity modulation, but has slow reverse recovery characteristics due to minority carrier storage. To combine the best features of these two rectifiers, hybrid rectifier structures, such as the Junction Barrier Schottky (JBS), Merged Pin/Schottky (MPS) and MOS Barrier Schottky (MBS) rectifiers have been proposed and have been demonstrated in silicon [2]. GaN rectifiers can only utilize quasi-vertical or lateral structures (Fig. 4) when they are grown on insulating substrates like sapphire. Furthermore, whether a unipolar or a bipolar rectifier is preferred depends on many device parameters, such as reverse blocking voltage, forward current density, maximum allowable reverse current density, operating temperature and switching frequency. We estimate the practical upper reverse blocking voltage limit for 4H-SiC Schottky rectifiers is about 2000V [8].

(a) Schottky Rectifiers -

Fig. 5 illustrates the $R_{ON,sp}$ vs. BV relationship calculated for n-type Schottky rectifiers on silicon, 6H-SiC and 4H-SiC. The substrate thickness and resistivity are assumed to be 300 μm and 0.01, 0.03 and 0.015 Ω-cm for Si, 6H-SiC and 4H-SiC, respectively. Also, the electron mobility in the drift layer is taken to be 450 and 1000 cm^2/ V-sec for 6H-SiC and 4H-SiC, respectively. At low values of BV (< 500V for SiC), the specific on-resistance is dominated by the substrate resistance. When the BV exceeds 1000V, the drift resistance starts to be the main limiting factor and the increase in R_d is a direct consequence of the increase in drift layer thickness and reduction in drift layer doping. We have also included recent published experimental results [9-13] in Figs. 5 and 6. As seen in the figure, experimental SiC Schottky rectifiers have achieved significant improvement over Si counterparts, but they are still far from the theoretical predictions (Figs. 5-7). The highest reverse blocking voltage reported so far for a 4H-SiC Schottky rectifier is 5000kV [10]. Experimental GaN Schottky rectifiers also block up to 4000V [13] but their performances are still significantly inferior to those of SiC devices at present.

(b) Junction Rectifiers -

Due to the small diffusion lengths in GaN [14,15], bipolar power junction rectifiers are only attractive in SiC. To achieve sufficient conductivity modulation of the lightly doped drift region, a minority carrier lifetime of >1μs is needed for 10kV devices in 4H-SiC [8]. Calculated curves and experimental data on forward drop vs. breakdown voltage in various epi-grown and ion-implanted 6H- and 4H-SiC pin junction rectifiers are shown in Fig. 8. The highest BV reported for a 4H-SiC junction rectifier is 12.3 kV, with a forward drop of 4.9 V at 100A/cm^2 [32]. We have demonstrated a planar, implanted-anode pin rectifier with a BV of ~5000 V and V_F < 4.5V [17].

Besides the difficulties in lightly doped p-type epi growth, the drift region doping is preferred to be n-type in SiC due to the effect of the mid-region on the switching characteristics. Because of the asymmetry in electron and hole mobility, the electron-hole plasma extraction and recombination leads to a more abrupt turn-off when the mid-region is p-type. We have demonstrated that the p+/p-/n+ rectifier is more susceptible to cause current oscillation in the power circuit than the p+/n-/n+ counterpart [9,18]. Such a behavior has been observed

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previously in silicon rectifiers also [1]. The reverse peak current and reverse recovery charge are generally smaller in SiC rectifiers than in Si rectifiers because of a lower level of carrier injection and 10x shorter drift region thickness [9,17].

Transistors/Thyristors

Silicon MOS, voltage-controlled power devices (such as MOSFET and IGBT) have generally replaced current-controlled transistors (BJT and Darlington) in low to medium power electronics. We have also previously suggested that the IGBT is not the best MOS-gated bipolar transistor for SiC due to the ionization coefficient asymmetry [8]. Besides, the SiC MOS process tehcnology is not as mature as Si MOS technology at present. In particular, the electron inversion layer mobilty has been found to be very low in 4H-SiC (<10 cm^2/V-s), attributed to a very high interface state density near the conduction band edge [19]. Another concern is the hot electron effect, particularly at temperatures >200°C, due to the low barrier height bewteen SiO_2 and 4H-SiC [20]. Also, there is a gate reliability concern since the electric field in the SiO_2 gate insulator is higher than conventional silicon devices due to the higher SiC avalanche field. For these reasons, BJTs and thryistors are also under active development. Further, among the three-terminal bipolar device structures, the BJT is the only one that can have the forward drop less than the diode turn-on voltage (~2.7V for 4H-SiC and ~2.9V for 2H-GaN) because of junction voltage cancellation in the saturation region [8]. Consequently, the BJT can compete with the MOSFET or JFET for low frequency applications (<1 MHz), even at blocking voltages below 3000V. In GaN, due to short carrier lifetimes, heterojunction bipolar transistors (HBTs) are preferred to improve current gain and AlGaN/GaN HBTs with aluminum mole percentage typically at ~10% have been explored to enhance the emitter injection efficiency [21,22]. However, the increase in bandgap offset increases the on-state voltage drop because of a larger difference between the emitter-base voltage and collector-base voltage.

(a) SiC BJT -

SiC BJTs have been explored in 6H-SiC over five years ago [23]. Fairly low current gain (β < 10) and low BV (<200V) have been reported and these devices were fabricated with epitaxially grown emitter and base regions. Recently, we have found that ion-implanted phosphorus to be a very good n-type dopant in 4H-SiC for concentrations of ~10^{20} cm^{-3} with significant activation at annealing temperatures as low as 1200°C [24].

The schematic cross-sections of the epi-grown and implanted-emitter BJTs are shown in Fig. 9(a) and (b) respectively. The forward I-V characterisitcs of our implanted-emitter BJT [25] is shown in Fig. 10, demonstrating a peak common-emitter current gain of ~40 with a nominal base width of 0.5µm. The current gain is sensitive to collector and base current density and decreases rapidly at collector current density above ~2A/cm^2, attributed to base widening with increasing current density. Another interesting feature of this BJT is the temperature dependence of the current gain. The current gain decreases with increasing temperature, from ~40 at room temperature to <10 at temperatures above 150°C (Fig. 11). This feature is actually attractive in that local increase in temperaure from current density fluctuations among parallel emitter fingers will be stablized and, consequently, SiC BJTs will have less thermal runaway problems than Si BJTs. The reason for such temperature dependence is attributed to the increased activation of acceptors in the p-base with increasing temperature, thus increasing the base charge. The current gain can be further enhanced with a two stage Darlington configuration and the resulting I-V characteristics are shown in Fig. 12 [25]. A current gain of over 300 was observed. An all epi-

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grown BJT in 4H-SiC has also been recently reported [26]. A maximum current gain of 22 with BV_{CEO} of 1800V and BV_{CBO} of 2200V are the salient features.

(b) AlGaN/GaN HBT -

As mentioned earlier, the AlGaN/GaN HBT is the bipolar transistor structure that is worth exploring. The design of AlGaN/GaN HBT is similar to that of AlGaAs/GaAs in that the base width is kept to a minimum and set by the punchthrough voltage so as to maximize the base transport factor. The emitter injection efficiency is enhanced with the bandgap offset and increases with increasing alumnium mole fraction. One recent experimental result has shown a current gain (β) of ~3 and BV_{CEO} of ~30V but the large turn-on voltage results in a forward drop of ~5V at a collector current density of 250A/cm^2 [21]. Another group reported a higher curernt gain (15-20) but a lower coomon-base breakdown voltage (BV_{BCB}) of ~8V [27].

To assess the high-voltage AlGaN/GaN HBT, we have designed a 3000V $Al_{0.3}Ga_{0.7}N$/GaN HBT and compared it to a Si BJT. The structural and material parameters of these transistors are summarized in Table II. A simple one-dimensional analysis has yielded a forward drop of <1V for the AlGaN/GaN but 22V for an equivalent Si BJT, despite the much shorter base minority carrier lifetime (5ns vs. 1 µs) (See Table III). However, a higher base current density (60 vs. 0.5 A/cm^2) is needed to conductivity modulate the base region due to the short lifetime. The AlGaN is mostly base transport limited while the Si BJT is emitter injection limited. This simple analysis clearly showes the feasibility of AlGaN/GaN HBT at higher blocking voltages. Experimentally, the most challenging task is clearly the doping of the p-base to lower the extrinsic base sheet resistance as well as the base contact resistance [21].

(c) SiC GTOs -

Since thyristors have a very higher level of conductivity modulation, their minority carrier lifetime requirement is similar to that of the pin junction rectifier. GaN thyristors are not attractive due to the high forward drop resulting from short diffusion lengths [8,28]. Recent progress on 4H-SiC GTOs mainly emphasizes all epi-grown structures [29,30] (Fig. 13) and BV over 3kV has been reported [29]. The schematic cross-section of the SiC GTO is shown in Fig. 12. The forward I-V characteristics of our GTOs [30] indicate a forward drop of ~6V at 100°C but decreases to ~4V at 300°C, as shown in Fig. 14. Interestingly, unlike silicon devices, the SiC thyristor turns on faster with increasing temperature (Fig. 15) because an increase in acceptor activation improves hole injection from the p+ emitters. The turn-off characteristics are shown in Fig. 16 and the turnoff time increases with temperature because of an increase in recombination lifetime. A maximum turn-off current density of over 100A/cm^2 is possible at 190°C.

MATERIAL AND PROCESSING CHALLENGES

For high voltage devices, total epitaixal layer thickness of at least up to 30µm with acceptable surface flatness, doping uniformity and minimum compensation is needed. To minimize parasitic substrate resistance and maximum carrier concentration, a doping of 10^{19} cm^{-3} would be desired. Such a high doping level seems to be difficult with p+ substrates. A micropipe density of less than 1/cm^2 is needed to realize devices of current ratings larger than 100A with reasonable yield. Other structural defects, such as elementary screw dislocations, appear to correlate with excessive leakage current in 4H-SiC pn junctions [31]. At present, it is generally agreed that the interface state density is much higher near the conduction band than that near the

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valence band in 4H-SiC and 15R and 6H polytypes offer lower MOS D_{it}'s. Unfortunately, a process that can significantly reduce D_{it} (like the hydrogen annealing step at 400°C in silicon) has not been developed. Recent advances in n-type implantation in 4H-SiC [24] yield sheet resistance values approaching those in silicon but p-type implanted layers still have too high a sheet resistance (> 5 KΩ/square).

AlGaInN materials have been mostly optimized for photonic devices. Low leakage current density is necessary for power devices but lack of large-area GaN substrates still impede progress in this area. An electrical conducting heterojunction between GaN epi and SiC substrate would allow vertical device structures for minimum active area. P-type Ohmic contacts with low contact resistivities (< 10^{-6} Ω-cm^2) is particularly challenging in GaN due to low hole concentrations. Activation of ion-implanted p-type dopants in GaN is still very difficult and needs to be developed.

At present, commercialization of SiC power switching devices is clearly ahead of GaN ones. However, the cost leverages of these devices in power electronics systems need to be assessed and emphasized before there is a widespread adoption by system and circuit designers.

SUMMARY

We have reviewed the present status of SiC and GaN devices for high-voltage power electronics applications. In particular, we have presented the choice and design of device structures, major recent device achievements, and material and processing challenges.

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REFERENCES

1. S.K. Ghandhi, Semiconductor Power Devices (Wiley, 1977, republished 1998).
2. B.J. Baliga, Physics of Semiconductor Power Devices (JWS Publishing, 1996).
3. K. Shenai, R.S. Scott, and B.J. Baliga., IEEE Trans. Electron Devices **36**, 1811 (1989).
4. B.J. Baliga, IEEE Electron Device Lett. **10**, 455 (1989).
5. T.P. Chow and R. Tyagi, IEEE Trans. Electron Devices **41**, 1481 (1994).
6. A. Bhalla and T.P. Chow, Paper 6.13, Proc. 6th International Symp. Power Semiconductor Devices and ICs, pp.287-292, May 31-Jun 2 (1994).
7. G.-B. Gao and H. Morkoc, IEEE Trans. Electron Devices **38**, 2410 (1991).
8. T.P. Chow, et al., Solid-State Electronics, **44** (2000).
9. V. Khemka, et al., Solid-State Electronics, **43**, 1945 (1999) and references therein.
10. J. Cooper, et al. Device Research Conference, 1999 (unpublished).
11. Z.Z. Bandic, P.M. Bridger, E.C. Piquette, T.C. McGill, R.P. Vaudo, V.M. Phanse, and J.M. Redwing, Appl. Phys. Lett., 74, 1266 (1999).

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12. G.T. Dang, A.P. Zhang, F. Ren, X.A. Cao, S.J. Pearton, H. Cho, J. Han, J.-I. Chyi, C.-M. Lee, C.-C. Chuo, S.N.G. Chu, and R.G. Wilson, IEEE Trans. Electr. Dev. **47**, 692 (2000).
13. S.J. Pearton, et al. (unpublished).
14. Z.Z. Bandic, P.M. Bridger, E.C. Piquette, and T.C. McGill, Appl. Phys. Lett. **72**, 3166 (1998).
15. R. Hickman, J.M. Van Hove, P.P. Chow, J.J. Klaassen, A.M. Wowchak, C.J. Polley, D.J. King, F. Ren, C.R. Abernathy, S.J. Pearton, K.B. Jung, H. Cho, and J.R. LaRoche, Solid-State Electronics, **44**, 377 (2000).
16. R. Singh, et al. (unpublished).
17. J. Fedison, et al., Device Research Conference, 1999 (unpublished).
18. T.P. Chow (unpublished).
19. R. Schorner, et al., Electron Device Letters, **20**, 241 (1999).
20. A.K. Agarwal, et al., Electron Device Letters, **18**, 592 (1997).
21. L.S. McCarthy, P. Kozodoy, M.J.W. Rodell, S.P. DenBaars, and U.K. Mishra, Electron Device Letters, **20**, 277 (1999).
22. D.J.H. Lambert, D.E. Lin, and R.D. Dupuis, Solid-State Electronics, **44**, 253 (2000).
23. J.W. Palmour, 1992 (unpublished).
24. V. Khemka, et al., J. Electronic Materials, **28**, 3 (1999).
25. Y. Tang, et al., Device Research Conference, 2000 (unpublished).
26. J. Ryu, et al., Device Research Conference, 2000 (unpublished).
27. X.A. Cao, et al., Electrochemical and Solid-State Letters, **3**, 144 (2000).
28. Z.Z. Bandic, P.M. Bridger, E.C. Piquette, and T.C. McGill, Solid-State Electronics, 44, 221 (2000).
29. A. Agarwal, et al., Proc. International Conference on Silicon Carbide and Related Materials (1999).
30. J. Fedison, et al., Proc. International Conference on Silicon Carbide and Related Materials (1999).
31. P. Neudeck, Proc. International Conference on Silicon Carbide and Related Materials (1999).
32. Y. Sugawara, ULD-2000, June, 2000.

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Table I: Physical properties of important semiconductors for high-voltage power devices.

Material	E_g eV	n_i cm^{-3}	ε_r	μ_n $cm^2/V\cdot s$	E_c 10^6 V/cm	v_{sat} 10^7 cm/s	λ $W/cm\cdot K$	*Direct Indirect*
Si	1.1	1.5×10^{10}	11.8	1350	0.3	1.0	1.5	I
Ge	0.66	2.4×10^{13}	16.0	3900	0.1	0.5	0.6	I
GaAs	1.4	1.8×10^{6}	12.8	8500	0.4	2.0	0.5	D
GaP	2.3	7.7×10^{-1}	11.1	350	1.3	1.4	0.8	I
InN	1.86	$\sim 10^{3}$	9.6	3000	1.0	2.5	-	D
GaN	3.39	1.9×10^{-10}	9.0	900	3.3	2.5	1.3	D
3C-SiC	**2.2**	**6.9**	**9.6**	**900**	**1.2**	**2.0**	**4.5**	**I**
4H-SiC	**3.26**	$\mathbf{8.2\times10^{-9}}$	**10**	**720**[a] **650**[c]	**2.0**	**2.0**	**4.5**	**I**
6H-SiC	**3.0**	$\mathbf{2.3\times10^{-6}}$	**9.7**	**370**[a] **50**[c]	**2.4**	**2.0**	**4.5**	**I**
Diamond	5.45	1.6×10^{-27}	5.5	1900	5.6	2.7	20	I
BN	6.0	1.5×10^{-31}	7.1	5	10	1.0*	13	I
AlN	6.1	$\sim 10^{-31}$	8.7	1100	11.7	1.8	2.5	D

Note: *a* — mobility along a-axis, *c* — mobility along c axis, *— estimate.

Table II: Structural and material paramters used for the design of 3000V transistors.

	AlGaN/GaN HBT	Si BJT
Emitter	$Al_{0.3}Ga_{0.7}N$/GaN $N_D = 10^{18}$ cm^{-3}	$N_D = 10^{19}$ cm^{-3}
Base	GaN, 0.4 μm $N_A = 5 \times 10^{17}$ cm^{-3} $\tau_n = 5$ ns	0.4 μm $N_A = 5 \times 10^{17}$ cm^{-3} $\tau_n = 1$ μs
Collector	GaN, 22.5μm $N_D = 7 \times 10^{15}$ cm^{-3}	210 μm $N_D = 9 \times 10^{13}$ cm^{-3}

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Table III: Electrical characteristics of the 3000V transistors.

	AlGaN/GaN HBT	Si BJT
Emitter Injection Efficiency (γ)	1	0.9833
Base Transport Factor (α_T)	0.9888	0.9999
Common-Emitter Curent Gain (β)	80	60
V_{CE} (V) at J_C = 100A/cm^2	0.7	22V
Base Current Density (A/cm^2) (J_B)	60	0.5

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