Institute of Physics Conf. Series 141: Compound Semiconductors 1994, pp. 1-6
Paper presented at 21st Int. Symp. Compound Semiconductors, San Diego CA, 1994

Progress towards high temperature, high power SiC devices

Philip G. Neudeck

NASA Lewis Research Center, M.S. 77-1, 21000 Brookpark Road, Cleveland, OH 44135 USA

Abstract. Silicon carbide's demonstrated ability to function under extreme high-temperature, high-power, and/or high-radiation conditions is expected to enable significant enhancements to a far-ranging variety of applications and systems. However, improvements in crystal growth and device fabrication processes are needed before SiC-based devices and circuits can be scaled-up and reliably incorporated into electronic systems. This paper surveys the present status of SiC-based semiconductor electronics within the context of identifying areas where technological maturation is most needed, and speculating on the prospects for resolution of crucial technological obstacles. Recent achievements include the monolithic realization of SiC integrated circuit operational amplifiers and digital logic circuits, as well as significant improvements to epitaxial and bulk crystal growth processes that will impact the overall viability of this rapidly emerging technology.

1. Introduction

Silicon carbide (SiC) based semiconductor electronic devices and circuits are presently being developed for advantageous use in high-temperature, high-power, and/or high-radiation conditions under which conventional semiconductors cannot adequately perform. Silicon carbide's demonstrated ability to function under extreme high-temperature, high-power, and/or high-radiation conditions is expected to enable significant improvements to a far-ranging variety of applications and systems. These range from improved high-voltage switching [1,2] for energy savings in public electric power distribution and electric vehicles to more powerful microwave electronics for radar and communications [3] to sensors and controls for cleaner-burning more fuel-efficient jet aircraft and automobile engines [4,5]. However, there are many crucial crystal growth and device fabrication issues that must be addressed before SiC-based devices and circuits are ready for scale-up and reliable incorporation into electronic systems. This paper surveys recent progress towards the realization of high temperature and/or high power SiC devices and circuits within the context of identifying specific performance-limiting areas where technological maturation is most needed. The prospects for resolution of crucial technological obstacles are also discussed.

Silicon carbide occurs in many different crystal structures (called polytypes) with each crystal structure having its own unique electrical and optical properties. The electrical properties of the more common SiC polytypes are compared to the properties of silicon and GaAs in Table 1. In many device applications, SiC's exceptionally high breakdown field (> 5 times that of Si), wide bandgap energy (> 2 times that of Si), high carrier saturation velocity (> 2 times that of Si), and high thermal conductivity (> 3 times that of Si) could enable substantial performance gains, greatly overcoming non-trivial low-field carrier mobility disadvantages. In the particularly attractive area of power devices, Bhatnagar and Baliga [2] indicate that SiC power MOSFET's and Schottky diode rectifiers would operate over higher voltage and temperature ranges, have superior switching characteristics, and yet have die sizes nearly 20 times smaller than correspondingly rated silicon-based devices.

Table 1. Comparison of selected semiconductor room temperature physical properties.

	Si	GaAs	6H-SiC	4H-SiC	3C-SiC
Bandgap (eV)	1.1	1.42	3.0	3.2	2.3
Breakdown Field @ 10^{17} cm^{-3} (MV/cm)	0.6	0.6	3.2	3	> 1.5
Electron Mobility @ 10^{16} cm^{-3} (cm^2/ V-s)	1100	6000	370	800	750
Saturated Electron Drift Velocity (cm/s)	10^7	8×10^6	2×10^7	2×10^7	2.5×10^7
Thermal Conductivity (W/cm-K)	1.5	0.5	4.9	4.9	5.0
Hole Mobility @ 10^{16} cm^{-3} (cm^2/ V-s)	420	320	90	115	40
Commercial Wafers	12"	6"	1.375"	1.375"	None

2. Crystal Growth

Although some of silicon carbide's advantageous electrical properties have been known for decades, until recently there was a lack of wafers with reproducible SiC of sufficient electrical quality to realize advantageous devices and circuits. Efforts to solve the material shortage problem through the heteroepitaxial growth of 3C-SiC on large-area substrate materials (primarily silicon wafers) have not proven successful to date, as the resulting SiC material still contains too many defects to be useful. Only with the development of the modified Lely seeded sublimation growth technique have acceptably large and reproducible single-crystal SiC wafers of usable electrical quality become available [6,7]. 1-inch 6H-SiC wafers first became commercially available in 1989 [8], and the vast majority of silicon carbide semiconductor device technology development has taken place since that time.

Of the numerous polytypic forms of silicon carbide, 4H- and 6H-SiC electronic devices presently exhibit the most promise due to the availability and quality of reproducible single-crystal wafers in these polytypes. The size of commercially available 4H- and 6H-SiC wafers has recently been increased from 1 inch to 1.375 inches in diameter, and further up-scaling to 2-inch and 3-inch wafer sizes is eventually expected. Although only one U.S. company is presently selling greater than 1-inch SiC wafers on the open market [8], at least three other companies are producing similar SiC wafers on a regular basis for internal purposes. Having been introduced commercially as recently as 1993, the 4H-SiC wafers are presently more expensive and slightly less developed than 6H-SiC wafers. However, 4H-SiC's substantially higher carrier mobility [9] should make it the polytype of choice for most SiC electronic devices, provided that all other device processing, performance, and cost-related issues play out as being roughly equal between the two polytypes. Furthermore, the inherent mobility anisotropy that degrades conduction parallel to the crystallographic c-axis in 6H-SiC [9,10] will particularly favor 4H-SiC for vertical power devices. The emergence of higher mobility 4H-SiC has largely overshadowed significant progress made in obtaining greatly improved 3C-SiC through heteroepitaxy on low-tilt-angle 6H-SiC substrates [11]. If on-going work ever solves the crystallographic defect problems associated with the heteroepitaxial growth of 3C-SiC on large-area silicon substrates, fabrication line compatibility and economic advantages would probably push 3C-SiC to the forefront.

The controlled growth of high-quality epilayers is a key issue in the realization of SiC electronics, especially given the fact that present-day commercial SiC wafers exhibit bulk resistivities no higher than 10 Ω-cm. Homoepitaxial growth of n-type (nitrogen-doped) or p-type (aluminum-doped) epilayers is primarily accomplished using chemical vapor deposition (CVD) [12]. Recently, a major advancement which greatly enhances the range and control of in-situ doping of SiC during CVD growth was reported by Larkin et. al. [13,14]. This technique, called site-competition epitaxy, has enabled reproducible doping concentrations low enough to enable the fabrication of the first 2 kV SiC rectifiers ever reported [15], as well as doping concentrations high enough that a wide variety of contact metals form ohmic contacts to SiC in their as-deposited state [16]. Despite this recent accomplishment, further reductions in background epilayer doping concentrations will be needed before experimental SiC devices will be capable of 5 to 10 kV standoff voltages. Improvements in epilayer uniformity and surface morphology will also be needed as SiC upscales from prototype devices towards production integrated circuits, but it is anticipated that technological maturation via refined CVD reactor designs and growth conditions will address these problems.

3. Discrete Devices

A variety of small-area prototype SiC devices have been reported in the literature in recent years [17-19], and some have already made their way into the marketplace. Blue light emitting diodes were the first silicon carbide based devices to reach high volume sales, while small signal diodes and JFET's rated to 350 °C and ultraviolet-sensitive photodiodes are more recently introduced commercial products [8]. For the most part, early SiC devices have been produced using nonoptimized device designs and fabrication procedures. Only limited investigations into fundamental SiC device processing techniques, such as contact metallization, ion implantation, surface passivation, oxidation, and etching, have been carried out to date [17-19].

In spite of the lack of optimized fabrication processes, some highly encouraging results, only some of which are specifically mentioned below, have been obtained from a variety of prototype SiC devices. The experimentally realized power performance of prototype X-band SiC MESFET's on highly parasitic low-resistivity substrates nevertheless exceeds the theoretical maximum power output density attainable in GaAs MESFET's at 1 GHz [20,21]. The first microwave MESFET's fabricated on high resistivity 6H-SiC substrates attained a measured RF gain of 8.5 dB at 10 GHz and an f_{max} of 25 GHz [22]. Despite the low mobility of 6H-SiC in the vertical (c-axis) direction, Kimoto et. al. [23] demonstrated high voltage (500 - 1100 V) 6H-SiC Schottky rectifiers whose specific on-resistances were more than 10 times smaller than the theoretical minimum on-resistances attainable in silicon Schottky diodes. Operation of SiC p-n junction diodes, MOSFET's, MESFET's, JFET's, BJT's, and thyristors at temperatures above 300 °C (and in some cases as high as 650 °C) has been well-established (Fig. 1) [17-19]. When these unpackaged devices are operated in atmospheric environments at temperatures near 600 °C, chemical degradation of the contact metallizations restricts the functional lifetime to less than a few hours [24], but much longer 600 °C contact lifetimes have been demonstrated in inert non-oxidizing environments [25]. Clearly, reliable interconnection, passivation, and packaging technologies remain to be developed and proven before SiC devices can become truly useful in extreme high-temperature environments.

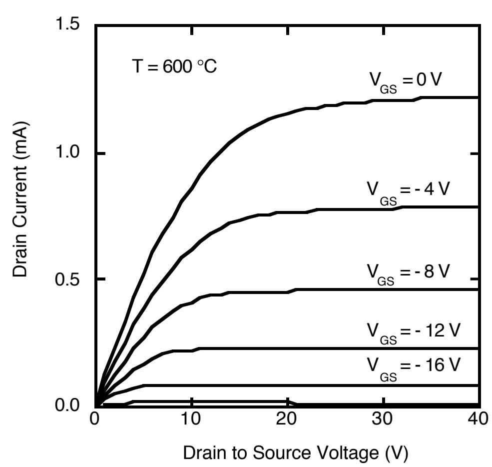

Figure 1. Drain characteristics of a 10 µm x 90 µm 6H-SiC buried-gate JFET at 600 °C.

Given the extreme usefulness and success of MOSFET-based electronics in silicon, it is naturally desirable to implement high-performance inversion channel MOSFET's in SiC. Research results to date indicate that the quality of the SiO_2 formed by thermal oxidation of n-type 6H-SiC is comparable to oxides used for silicon MOSFET's [26]. However, thermal oxides grown on p-type 6H-SiC are generally poorer, exhibiting higher fixed charge and interface state densities. This leads to low inversion channel electron mobilities that seriously degrade the performance of n-channel MOSFET's [27]. However, on-going work towards improving the electrical quality of oxides on p-type SiC [28,29] offers some encouragement that the predicted advantages of inversion channel SiC N-MOSFET's (especially vertical power SiC MOSFET's [2]) might be realized. Since SiC devices will be operating at higher electric fields and temperatures than their silicon-based counterparts, challenging oxide and other surface passivation reliability issues will undoubtedly be faced as the technology progresses forward.

Though many of the SiC devices described above exhibit very promising area-normalized performances, micropipe defects present in the SiC wafers (and propagate into subsequently grown homoepilayers) prevent small-area prototype power device results from being scaled-up into useful large-area (> 1 mm^2), multi-amp power devices [30]. The micropipe defects generally lead to junction breakdown at electric fields well below the known critical-field. Figures 2 (top view) and 3 (cross-sectional view) show optical micrographs of localized microplasmas associated with premature reverse-bias failure at micropipes in 6H-SiC devices. The origin of these defects is still very much a topic of current debate and research [31-34], but their density has been steadily decreasing at a roughly twofold rate every year to a present-day minimum density of 55 per square centimeter [35]. The density of dislocation defects has been measured on the order of 10,000 cm^{-2}, but these defects are apparently not nearly as detrimental (as evidenced by SiC prototype device performances) as micropipes. The fact that areas larger than 1 mm^2 within SiC Lely-platelet crystals (which are not considered suitable for mass production) have been observed to be totally free of dislocations and micropipes [31] suggests that these defects are perhaps preventable.

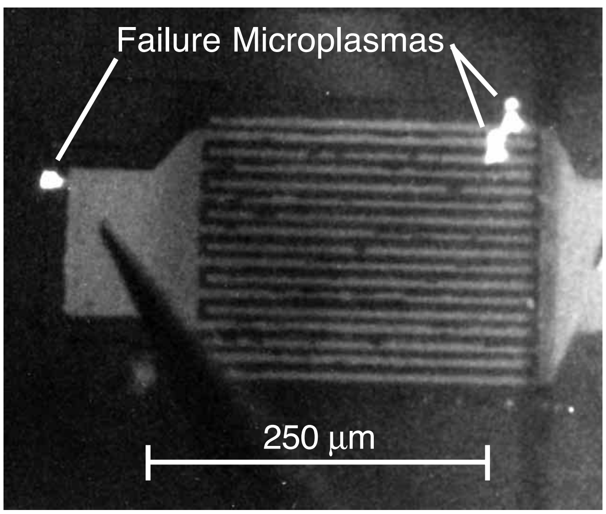

Figure 2. Top view of highly localized microp

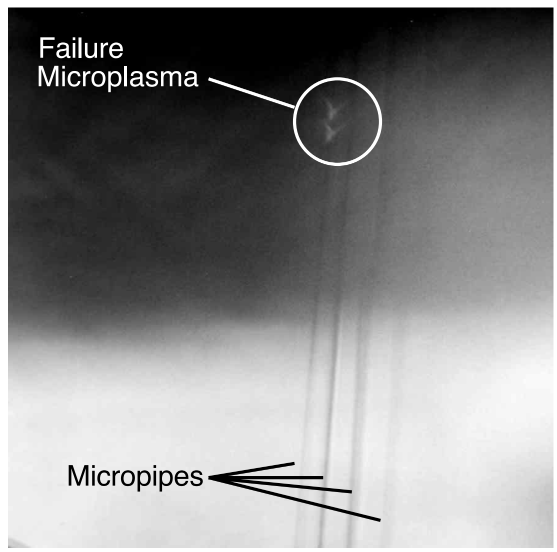

Figure 3. Cross-sectional view (~ 400X) of localized failure microplasma in micropipe running through a 6H-SiC p-n junction. After Ref. [30].

4. Integrated Circuits

Although they have a severe impact on high-field power devices, the micropipes appear to be less of a problem for signal-level electronics where devices are operated at much lower electric fields. This is evidenced by the recent achievement of Brown and co-workers at General Electric, who successfully fabricated the first complete monolithic integrated SiC operational amplifier chips [36]. The 1 mm x 2 mm op-amp chip shown in Figure 4 exhibited yields far higher than could be expected if micropipes were fatal to the active devices in this low-voltage circuit. Based on highly conservative 7 µm design rules, the circuit demonstrated 49 to 54 dB gains and bandwidths of 724 kHz to 269 kHz as temperature increased from 25 °C to 300 °C. The chip was based on depletion mode n-channel MOSFET technology, which alleviated the present difficulties associated with p-type SiC oxides needed to fabricate inversion channel N-MOSFET's [37].

An indication that the p-type oxide problems can be overcome somewhat can be found in the work of Xie and co-workers at Purdue University [38], who recently demonstrated SiC digital integrated circuits based on inversion channel N-MOSFET's. Basic digital logic gates, latches, flip-flops, binary counters, and half adder circuits with up to a dozen transistors were fabricated and successfully operated over the temperature range from 25 °C to 300 °C. These circuits are envisioned as first-generation prototypes for on-chip peripheral logic to drive 1-transistor non-volatile random access memory (NVRAM) arrays [39], but clearly demonstrate the present feasibility of small SiC digital integrated circuits. It is anticipated that increasingly larger digital circuits will be demonstrated in the near future, but the functional sizes and yields of such circuits will probably be influenced by the aforementioned crystal growth uniformity and defect issues.

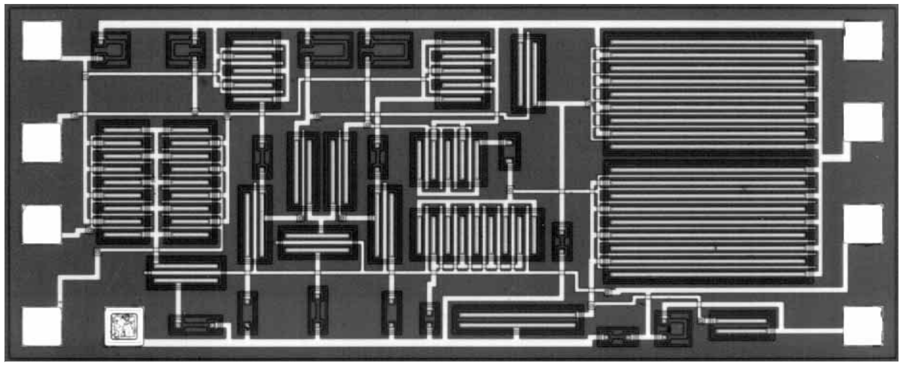

Figure 4. Photo micrograph of SiC MOSFET operational amplifier chip. The chip size is 1 mm x 2 mm. After Ref. [36]. (Courtesy of D. M. Brown, General Electric Company)

5. Conclusion

Although the advantageous properties of SiC have been known for decades, it was largely an enabling technical breakthrough in crystal growth that made mass production of useful SiC semiconductor devices and circuits seem possible. This, coupled with an acknowledged growing need for high temperature electronics, has led to SiC's accelerated development over the last half-decade. Although progress to date has yielded a few products and highly encouraging prototype results, some crucial technical obstacles remain to be solved before SiC can achieve its true potential. It is of paramount importance that crystal growth continue to improve, as larger wafers with far lower defect densities and improved epilayer doping and thickness control will be required for the majority of envisioned SiC electronic products. When combined with the continued maturation of device processing and high temperature packaging technologies, an increasingly capable variety of SiC devices and circuits will evolve to meet the system demands for hostile-environment electronics.

References

[1] Hingorani N G and Stahlkopf K E 1993 *Scientific American* **269** (5) 78-85

[2] Bhatnagar M and Baliga B J 1993 *IEEE Trans. Electron Devices* **40** 645-655

[3] Trew R J, Yan J-B and Mock P M 1991 *Proc. IEEE* **79** 598-620

[4] Nieberding W C and Powell J A 1982 *IEEE Trans. on Industrial Elect.* **29** 103-106

[5] Przybylko S J 1993 *American Institute of Aeronautics and Astronautics Report* AIAA 93-2581

[6] Tairov Y M and Tsvetkov V F 1978 *J. Cryst. Growth* **43** 209-212

[7] Barrett D L, Seidensticker R G, Gaida W, Hopkins R H and Choyke W J 1991 *J. Cryst. Growth* **109** 17-23

[8] Cree Research, Inc. (Durham, NC)

[9] Schaffer W J, Negley G H, Irvine K G and Palmour J W 1994 to appear in Diamond, SiC, and Nitride Wide-Bandgap Semiconductors *Materials Research Society Symposia Proceedings* (Pittsburgh, PA: Materials Research Society)

[10] Lomakina G A 1973 Silicon Carbide-1973 (Columbia, SC: University of South Carolina Press) 520-526
[11] Neudeck P G, Larkin D J, Starr J E, Powell J A, Salupo C S and Matus L G 1994 *IEEE Trans. Electron Devices* **41** 826-835
[12] Powell J A, Petit J B and Matus L G 1991 *Trans. 1st Int. High Temperature Electronics Conf.* (Sandia National Laboratories: Albuquerque, NM) 192-197
[13] Larkin D J, Neudeck P G, Powell J A and Matus L G 1994 to appear in *Appl. Phys. Lett.*
[14] Larkin D J, Neudeck P G, Powell J A and Matus L G 1994 Silicon Carbide and Related Materials *Institute of Physics Conference Series* **137** (Bristol, United Kingdom: IOP Publishing) 51-54
[15] Neudeck P G, Larkin D J, Powell J A, Matus L G and Salupo C S 1994 *Appl. Phys. Lett.* **64** 1386-1388
[16] Petit J B, Neudeck P G, Salupo C S, Larkin D J and Powell J A 1994 Silicon Carbide and Related Materials *Institute of Physics Conference Series* **137** (Bristol, United Kingdom: IOP Publishing) 679-682
[17] Davis R F, Kelner G, Shur M, Palmour J W and Edmond J A 1991 *Proc. IEEE* **79** 677-701
[18] Spencer M G, Devaty R P, Edmond J A, Khan M A, Kaplan R and Rahman M 1994 Silicon Carbide and Related Materials *Institute of Physics Conference Series* **137** (Bristol, United Kingdom: IOP Publishing) 465-690
[19] King D B and Thome F V 1994 Sessions X & XI*Trans. 2nd. Int. High Temperature Electronics Conf.* (Charlotte, NC) X-1 - XI-28
[20] Sriram S et al 1994 Silicon Carbide and Related Materials *Institute of Physics Conference Series* **137** (Bristol, United Kingdom: IOP Publishing) 491-494
[21] Weitzel C E, Palmour J W, Carter C H Jr. and Nordquist K J 1994 *this volume*
[22] Sriram S et al 1994 *52nd Annual IEEE Device Research Conference* (Boulder, CO)
[23] Kimoto T, Itoh A, Urushidani T, Jang S and Matsunami H 1994 *this volume*
[24] Neudeck P G, Petit J B and Salupo C S 1994 *Trans. 2nd. Int. High Temperature Electronic Conf.* (Charlotte, NC) X-23-28
[25] Crofton J, Williams J R, Bozack M J and Barnes P A 1994 Silicon Carbide and Related Materials *Institure of Physics Conference Series* **137** (Bristol, United Kingdom: IOP Publishing) 719-722
[26] Brown D M, Ghezzo M, Kretchmer J, Downey E, Pimbley J and Palmour J 1994 *IEEE Trans. Electron Devices* **41** 618-620
[27] Sheppard S T, Melloch M R and Cooper J A Jr. 1994 *IEEE Trans. Electron Devices* **41** 1257-1264
[28] Ouisse T, Becourt N, Templier F and Jaussaud C 1993 *J. Appl. Phys.* **75** 604-607
[29] Shenoy J, Lipkin L A, Chindalore G, Pan J, Cooper J A Jr., Palmour J W and Melloch M R 1994 *this volume*
[30] Neudeck P G and Powell J A 1994 *IEEE Electron Device Lett.* **15** 63-65
[31] Fazi C, Dudley M, Wang S and Ghezzo M 1994 Silicon Carbide and Related Materials *Institute of Physics Conference Series* **137** (Bristol, United Kingdom: IOP Publishing) 487-490
[32] Wang S, Dudley M, Carter C Jr., Asbury D and Fazi C 1993 Applications of Synchrotron Radiation Techniques to Materials Science *Materials Research Society Symposia Proceedings* **307** (Pittsburgh: Materials Research Society) 249-254
[33] Stein R A 1993 *Physica B* **185** 211-216
[34] Yang J-W 1993 Case Western Reserve University Ph. D. thesis (Cleveland, OH)
[35] Palmour J W 1994 personal communication
[36] Brown D M, Ghezzo M, Kretchmer J, Krishnamurthy V, Michon G and Gate G 1994 *Trans. 2nd. Int. High Temperature Electronics Conf.* (Charlotte, NC) XI-17-22
[37] Krishnamurthy V, Brown D M, Ghezzo M, Kretchmer J, Hennessy W, Downey E and Michon G 1994 Silicon Carbide and Related Materials *Institute of Physics Conference Series* **137** (Bristol, United Kingdom: IOP Publishing) 483-486
[38] Xie W, Pan J, Cooper J A Jr. and Melloch M R 1994 *this volume*
[39] Xie W, Johnson G M, Yang Y, Cooper J A Jr., Palmour J W, Lipkin L A, Melloch M R and Carter C H Jr. 1994 *this volume*