REVIEW PAPER

STATUS OF SILICON CARBIDE (SiC) AS A WIDE-BANDGAP SEMICONDUCTOR FOR HIGH-TEMPERATURE APPLICATIONS: A REVIEW

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Abstract—Silicon carbide (SiC), a material long known with potential for high-temperature, high-power, high-frequency, and radiation hardened applications, has emerged as the most mature of the wide-bandgap ($2.0\,\text{eV} \lesssim E_g \lesssim 7.0\,\text{eV}$) semiconductors since the release of commercial 6H-SiC bulk substrates in 1991 and 4H-SiC substrates in 1994. Following a brief introduction to SiC material properties, the status of SiC in terms of bulk crystal growth, unit device fabrication processes, device performance, circuits and sensors is discussed. Emphasis is placed upon demonstrated high-temperature applications, such as power transistors and rectifiers, turbine engine combustion monitoring, temperature sensors, analog and digital circuitry, flame detectors, and accelerometers. While individual device performances have been impressive (e.g. 4H-SiC MESFETs with f_{max} of 42 GHz and over $2.8\,\text{W mm}^{-1}$ power density; 4H-SiC static induction transistors with 225 W power output at 600 MHz, 47% power added efficiency (PAE), and 200 V forward blocking voltage), material defects in SiC, in particular micropipe defects, remain the primary impediment to wide-spread application in commercial markets. Micropipe defect densities have been reduced from near the $1000\,\text{cm}^{-2}$ order of magnitude in 1992 to $3.5\,\text{cm}^{-2}$ at the research level in 1995. Copyright © 1996 Elsevier Science Ltd

1. BACKGROUND

Most traditional integrated circuit technologies using silicon devices are not able to operate at temperatures above 250°C, especially when high operating temperatures are combined with high-power, high-frequency and high-radiation environments. Much attention has been given to SiC, currently the most mature of the wide-bandgap ($2.0\,\text{eV} \lesssim E_g \lesssim 7.0\,\text{eV}$) semiconductors, as a material well-suited for high-temperature operation. High-temperature circuit operation from 350°C to 500°C is desired for use in aerospace applications (turbine engines and the more electric aircraft initiative), nuclear power instrumentation, satellites, space exploration, and geothermal wells[1–6]. In addition to high-temperature applications, SiC has potential for use in high-power, high-frequency, and radiation-resistant applications[7–9]. Silicon carbide (SiC), aluminum nitride (AlN), gallium nitride (GaN), boron nitride (BN), diamond, and zinc selenium (ZnSe) are just some of the premier wide-bandgap semiconductors now being developed for use in the aforementioned applications. However, SiC has several advantages over other wide-bandgap semiconductors at the present time including commercial availability of substrates[10,11], known device processing tech-

niques, and the ability to grow a thermal oxide for use as masks in processing, device passivation layers, and gate dielectrics. In addition, SiC's high thermal conductivity (about 3.3 times that of Si at 300 K for 6H-SiC), high electric field breakdown strength (about 10 times that of Si for 6H-SiC), and wide bandgap (about 3 times that of Si for 4H-SiC and 6H-SiC) make it a material ideally suited for high-temperature, high-power, high-frequency, and high-radiation environments.

The availability of 6H-SiC and 4H-SiC polytypes in bulk wafer form[10,11] has helped SiC to emerge as one of the relatively mature wide-bandgap semiconductor technologies. Lattice mismatches of only 1% for AlN[12], and 3% for GaN[13,14], exist when these materials are grown on 6H-SiC substrates. Thus, SiC processing is often intimately linked with AlN and GaN electronic and optical device fabrication. Commercially available GaN LEDs manufactured on 6H-SiC substrates were released in 1995[10]. The small lattice mismatches with AlN and GaN, as well as the abundance of polytypes in SiC, combine to make SiC a material with an immense potential for use in heterostructure electronic devices which take advantage of the differing bandgaps, carrier mobilities, etc.

2. HISTORICAL DEVELOPMENT

With all the recent attention given to SiC, an often surprising fact is that growth of SiC crystals by the Acheson technique dates back to 1893. Discovery and identification of a SiC light emitting diode (LED) occurred in 1907 when Round published a short article entitled "A Note on Carborundum"[15]. Semiconductor pioneer Shockley, inventor of the bipolar junction transistor in 1947, recognized the potential of SiC in his now prophetic, introductory remarks at the First International Conference on Silicon Carbide in April 1959, as illustrated by the following quote.

"*Today, in the electronics field there are probably two areas of special interest. One of these is miniaturization, the process of making devices small, complicated and fast; the other has to do with problems of new environment, such as higher temperatures and radiation resistance . . .*

Now, the big question is this: How is the problem of high temperature going to be solved?

What are the horses to put one's money on? . . . One approach is the logical sequence we see here: Ge, Si, SiC, C in that sequence . . .

The SiC situation suffers from the very same thing that makes it so good. The bond is very strong and so all processes go on at very high temperature . . . Another aspect of the silicon carbide situation is similar to past situations in the semiconductor field. The lesson is that one should not give up too soon and one would not always look for gold at the ends of new rainbows . . .

The situation may be similar with silicon carbide. The material problem will have to be extensively worked on. Perhaps one day . . . large single crystals of silicon carbide will be grown easily . . . These are difficult questions."[16].

3. MATERIAL PROPERTIES

SiC is part of a family of materials which exhibit a one-dimensional polymorphism called polytypism. An almost infinite number of SiC polytypes are possible, and approximately 200 polytypes have already been discovered[17]. A listing of some of the more common polytypes includes 3C, 2H, 4H, 6H, 8H, 9R, 10H, 14H, 15R, 19R, 20H, 21H and 24R. SiC polytypes are differentiated by the stacking sequence of each tetrahedrally bonded Si-C bilayer. With the exception of 2H and 3C, all of the polytypes form one-dimensional superlattice structures[18]. Even though individual bond lengths are nearly identical, the crystal symmetry is determined by the stacking periodicity. The polytypes are divided into three basic crystallographic categories; cubic (C), hexagonal (H), and rhombohedral (R).

3.1. Cubic silicon carbide

Cubic SiC has only one possible polytype, and is referred to as 3C-SiC or β-SiC. Each SiC bilayer can be oriented into only three possible positions with respect to the lattice while the tetrahedral bonding is maintained. If these three layers are arbitrarily denoted A, B and C, and the stacking sequence is ABCABC . . ., then the crystallographic structure is cubic zinc blende. This arrangement is known as 3C-SiC or β-SiC. The number 3 refers to the number of layers needed for periodicity. 3C-SiC possesses the smallest bandgap (~ 2.4 eV)[19], and one of the largest electron mobilities (~ 800 cm^2 V^{-1} s^{-1} in low-doped material[20]) of all the known SiC polytypes. It is not currently available in bulk form, despite bulk growth of 3C-SiC having been demonstrated in a research environment[21]. Cubic SiC has been grown on Si with limited success and incorporated into heterostructure devices, despite the nearly 20% lattice mismatch between β-SiC and Si. Recent advances in heteroepitaxial growth of β-SiC include low temperature (750°C) CVD of β-SiC on silicon achieved by researchers at Allied Signal[22], and 3C-SiC has also been grown on 6H-SiC substrates[23,24].

3.2. Hexagonal and rhombohedral silicon carbide

If the stacking of the bi-layers is ABAB . . ., then the symmetry is hexagonal and referred to as 2H-SiC. All of the other SiC polytypes are a mixture of the zinc blende (cubic) and wurtzite (hexagonal) bonding. 4H-SiC consists of an equal number of cubic and hexagonal bonds. 6H-SiC is composed of two-thirds cubic bonds and one-third hexagonal bonds. The overall symmetry is hexagonal for both polytypes, despite the cubic bonds which are present in each. The hexagonal structures are collectively grouped as α-SiC. 6H-SiC and 4H-SiC are the only SiC polytypes currently available in bulk wafer form. Polytypes with rhombohedral symmetry have also been found, and are denoted by the letter R. 15R-SiC substrates have also been grown by Advanced Technology Materials, Inc. (ATMI)[25].

3.3. Electrical properties and impurity centers in 3C, 6H and 4H polytypes

Basic electrical properties obtained from the literature for the 3C, 6H, and 4H polytypes of SiC are shown in Table 1. The data cited is dependent upon the temperature, test methods used, quality of the material, as well as dopant concentrations and species. Accuracy of these material properties is extremely important for device modeling, yet often material properties are erroneously or improperly cited in the literature. To fully analyze the data provided in Table 1, the reader is encouraged to check the references given in the table. The properties of Si are also shown for reference. Three key categories where SiC enjoys inherent advantages over

Si for high-temperature operation are thermal conductivity, electric field breakdown strength, and bandgap. SiC also has a much (8 to 10 times) higher thermal conductivity ($\Theta\kappa$) than GaAs at 300 K[26], a bandgap of approximately twice the bandgap of GaAs, while still possessing a peak saturation velocity (v_{sat}) of 2×10^7 cm s^{-1}, just as in GaAs. Also, because of the saturation velocity overshoot in GaAs, SiC's v_{sat} at high electric fields is superior to that of GaAs.

All of the quantities shown in Table 1 are temperature dependent to differing extent. Electron mobility (μ_e) and hole mobility (μ_h) are carrier velocity per unit drift field, and are critically important device parameters, affecting the microwave performance, transconductance (g_m), output gain of FETs, on-resistance of power FETs (R_{on}), and other parameters. The low, anisotropic electron mobility in 6H-SiC is one of the primary reasons for the emerging popularity of 4H-SiC, which has a higher and much less anisotropic electron mobility. In fact $(\mu_\perp)/(\mu_\parallel)$ is about 0.7 to 0.83 at 300 K in 4H-SiC[34,35], while the same ratio is about 6 in 6H-SiC[35].

The intrinsic carrier concentration (n_i) is directly proportional to N_c and N_v, which are the conduction band and valence band density of states, respectively. However, as a result of thermal expansion of the lattice and electron–phonon coupling, n_i has an *exponential* dependence upon temperature, as well as E_g[36]. Intrinsic carrier concentration (n_i) is important in high-temperature device applications, because *pn* junction leakage currents in devices are normally proportional to n_i or n_i^2. Electron effective masses ($m_\perp^* = 0.42\, m_o$ and $m_\parallel^* = 0.29\, m_o$ in 4H-SiC[34]) have not been analyzed as a function of temperature, and work remains in that area.

Typical bandgap values are obtained from photoluminescence studies performed at liquid He temperatures (~ 4.2 K) under very low pressures ($\sim 10^{-11}$ T)[17,19,27]. High doping levels lead to band gap narrowing (BGN) effects in semiconductors, but have not been extensively studied in SiC, so the effective intrinsic carrier concentration (n_{ie}) relationship with doping has not been established.

Arrangement of next neighbors in the lattice is the same for all SiC polytypes, but crystallographically inequivalent lattice sites exist in different polytypes. Thus, electronic properties, such as effective mass, carrier mobility (μ), and bandgap, vary widely between different polytypes of SiC. Electrically active impurities in semiconductors are normally substitutional dopants, occupying vacant lattice sites. Dopants for SiC include N (*n*-type), and Al, B, Be, Ga, O, and Sc (*p*-type), with Al being the most common *p*-type dopant because it has the shallowest acceptor level[17]. Undoped SiC is typically *n*-type from residual nitrogen, and has a slight green tint in color for 6H-SiC. The color of the material depends upon the specific polytype, however. Donor activation energies are often found to vary over a wide range, depending upon the measurement technique, material quality, polytype and dopant concentrations. Activation energies also vary depending upon the substitutional site occupied in the lattice (cubic or hexagonal). For *n*-type 3C, Hall measurements have yielded nitrogen activation energies from 18 to 48 meV. In 6H-SiC, two donor levels have been found depending upon the occupancy site. Site 1 (hexagonal site) is from 84 to 100 meV, and site 2 (cubic site) is from 125 to 150 meV[17]. In 4H material, donor levels are 45 meV, and 100 meV for site 1 and site 2, respectively[17]. The fact that most dopant levels are deeper than those found comparably in silicon explains the partial carrier freeze-out found in SiC at room temperature, since the thermal energy (kT/q) is only ~ 25.9 meV at 300 K. Despite this, SiC junction field effect transistors (JFETs) have been operated to temperatures as low as 77 K, because of field ionization of dopants [39].

In contrast, for *p*-type Al doped SiC, an average acceptor energy level of approximately 200 meV is found for all polytypes[17]. Other *p*-type dopants such as boron have deeper acceptor levels (ranging from approximately 320 to 735 meV), and are not as commonly used.

4. SILICON CARBIDE PROCESSING, DEVICES AND CIRCUITS

Having illustrated a brief overview of SiC as a semiconductor for high-temperature, high-power, and high-frequency applications, it is now appropriate to discuss some classic SiC device technology

Table 1. Comparison of silicon carbide and silicon material properties

Quantity	3C-SiC	4H-SiC	6H-SiC	Silicon [28]
E_g (eV) ($T < 5$ K)	2.40 [19]	3.26 [27]	3.02 [27]	1.12
E_{crit} (MV cm^{-1})	2.12 [29]	2.2 [29]	2.5 [29]	0.25
$\Theta\kappa$ (W cm^{-1} K^{-1}) at 300 K†	3.2 [32]	3.7 [33]	4.9 [33]	1.5
n_i @ 300 K (cm^{-3})‡	1.5×10^{-1}	5×10^{-9}	1.6×10^{-6}	1.0×10^{10}
v_{sat} (cm s^{-1}) parallel to *c*-axis		2.0×10^7 [10]	2.0×10^7 [30]	1.0×10^7
μ_e (cm^2 V^{-1} s^{-1})	800 [20]	1000 [35]	400 [35]	1400
$(\mu_\perp)/(\mu_\parallel)$ at 300 K		0.7–0.83 [34]	6 [35]	
μ_h (cm^2 V^{-1} s^{-1})	40 [37]	115 [38]	101 [38]	471
ε_s	9.72 [40]		9.66 [40]	11.7

†Doped at $\sim 10^{17}$ cm^{-3}.
‡Effective mass values found in Refs [34, 35], and E_g with respect to T in Ref. [36].

developments achieved prior to 1996. As material quality and device processing in SiC continue to mature rapidly, no doubt improvements will be made on all of the following seminal references. Although not an inclusive list, much information can be obtained by meticulously reviewing the references pertaining to each section of interest.

4.1. Fabrication processes necessary for SiC devices

4.1.1. Growth.
Bulk growth of SiC has been perhaps the most significant problem limiting the usefulness of SiC in electronic applications[41–54]. Single-crystal wafers of 6H-SiC have been available commercially only since 1991 (from Cree Research, Inc.[10]), and 4H-SiC wafers have only been available since 1994 (from Cree in 1994 and ATMI in 1995[10,11]). 3C-SiC wafers[21] and 15R-SiC[11] wafers have been produced in research environments, but not commercially. An excellent review of commercial SiC boule growth by seeded sublimation is given by Tsvetkov et al.[41]. Micropipe defect density (MDD), found in densities of $1000 \ cm^{-2}$ only a few years earlier, were reported as reduced to $3.5 \ cm^{-2}$ at the research level on a 30 mm (1.18 inch) 4H-SiC wafer[41]. Micropipes are bulk defects (voids) which propagate the length of the boule from the seed crystal, and are also found to propagate through subsequent epitaxially grown SiC layers. Nucleating at the seed crystal, micropipes have hexagonal cross-sections with diameters from about 0.1 to $5 \ \mu m$[41,43]. Mechanisms causing the micropipes have not been clearly identified in the literature, but 13 possible thermodynamic, kinetic and technological mechanisms are listed in Ref.[41]. A good discussion of various defects (hexagonal pits, micropipes, screw dislocations, hillocks, etc.) and possible causes is found in Ref.[53]. Elimination of the micropipes found in bulk SiC is a very critical issue for development of SiC power devices and larger-area integrated circuits[42]. It should be noted that at least three different corporations in the U.S. (Northrop Grumman, Cree Research, and ATMI) are currently producing SiC wafers, with other companies in Russia, Japan and Europe also producing wafers. A brief, noninclusive listing of other outstanding references to bulk growth of SiC are listed for the interested reader[21,25,41–54]. Work by Hobgood et al.[44] and Barrett et al.[49,52], though somewhat dated, provide superb discussion of SiC bulk growth using a sublimation-source physical vapor transport system at Northrop Grumman, with results comparable to that of Cree's. Notable achievements include production of 6H-SiC boules up to 60 mm (2.36″) in diameter. Growth was done at $\sim 2300°C$, while the oriented SiC seed crystal was held at a lower temperature ($\sim 2200°C$). It is estimated that 100 mm, high-quality wafers of reasonable cost will be required for high-power commercial SiC device production, while 50–75 mm wafers should suffice for low-power commercial products[41]. One other recent advance of extreme importance for microwave applications is the development of semi-insulating SiC substrates[54].

4.1.2. Doping.
Doping in SiC for device fabrication is accomplished via epitaxially controlled doping and hot ion implantation. Temperatures required for diffusion are too high (greater than 1800°C) for standard device processing because of the very high bond strength possessed by SiC. The two most common dopants used in SiC are nitrogen (n-type) and aluminum (p-type), as discussed previously. In the absence of diffusion, epitaxial and ion-implanted control of dopants are critical for the development of devices and ICs. Numerous high-quality publications on epitaxial growth processes exist[22,23,38,54–66]. An invited paper from ICSCRM'95 by Larkin[56] provides an overview of a dopant control technique known as "site-competition epitaxy" growth of SiC on bulk SiC wafers, and is representative of the excellent, long-standing work done at NASA-Lewis Research Center. Doping is controlled from degeneratively doped ($> 1 \times 10^{19} \ cm^{-3}$) to lightly doped ($\sim 1 \times 10^{14} \ cm^{-3}$) as the Si and C source gas flow are varied. Silane and propane are typical source gasses of Si and C, respectively. Typical growth rates for 6H-SiC homoepitaxy layers on Si-face n-type substrates are $\sim 3 \ \mu m \ h^{-1}$. Site-competition epitaxy works by adjusting the Si/C source gas ratio in the growth reactor to control the amount of dopant incorporated into substitutional SiC crystal lattice sites[58]. The model is based upon N and C competition for C sites, with Al and Si competition for Si sites in the SiC lattice. The technique has also been used for boron and phosphorous[56]. Growth on C-face substrates has behaved quite differently, and more work is still needed to fully understand all growth mechanisms[56]. Numerous corporate and university laboratories now routinely produce homoepitaxial, device-quality growth of SiC.

Ion implantation is also proving to be a vital component of device processing in the absence of a usable diffusion process. Again, numerous papers are found in the literature concerning dopant ion implantation into SiC[67–83]. Finding the optimum high-temperature implant and subsequent high-temperature anneal (e.g. 500°C to 1700°C) to activate the dopants has proven challenging, with a flurry of recent progress reported. Two typical examples of recent work which contain information on nitrogen, boron, and aluminum implants are[68,79], although several other comparable papers exist. Of particular concern has been the p-type implant. Boron has proven easier to implant and activate than Al because Al is a great deal heavier than B, and causes much more lattice damage. High-temperature ion implantation is preferred, since room temperature ion implantation results in amorphized material, while high-temperature implants do not. In Ref.[78], Al and N implants were performed at 850°C and 700°C,

respectively, into Si-face, (100) 6H-SiC, followed by a 10–45 min anneal at 1100°C to 1650°C in argon. Si and C co-implantations were also performed in attempts to increase Al activation, but C had no affect and Si co-implantation decreased dopant activation[78].

Both ion implantation and epitaxial controlled doping should both prove vital processes for SiC device fabrication. Ion implantation has the advantage of selective doping, which is important for complementary logic structures, power device termination and isolation, etc., but epitaxial doping has the advantage of not inducing lattice damage which eliminates the need for a high-temperature anneal, as well as possible creation of defects.

4.1.3. Etching. Wet etching of SiC has proven to not be feasible from a practical device processing standpoint, as it requires molten salts (for example, NaOH-KOH at 350°C) to be used at high temperatures. The difficulty encountered in etching SiC is a result of the high bond strength, a property which makes SiC useful for high-temperature operation, but a hindrance in fabrication. Nonetheless, numerous dry etches (primarily focused on reactive ion etching (RIE) processes) have been developed for the various polytypes of SiC[85–104]. Electron cyclotron resonance (ECR) etching has also been employed[100,101]. Most published RIE etches all make use of fluorinated gases to etch SiC, although etch rates of 1900 Å min^{-1} have been obtained in 6H-SiC using a chloride-based ($Cl_2/SiCl_4/O_2$) etch with SiO_2 mask[97]. RIE etch rates of 6H-SiC and 4H-SiC are typically slow in comparison to Si (300 Å min^{-1} to 2000 Å min^{-1}), with residue-formation problems commonly found, although not prevalent in all etches. A good overview of SiC etching is also found in the text, *Properties of Silicon Carbide*[84]. Etching of silicon in fluorinated gas has been found to occur by the reaction mechanism below.

$$Si + 4F \Rightarrow SiF_4$$
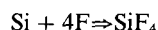
However, the removal of C has been debated in the literature, with some works indicating that addition of oxygen removes the C, while others claim that the C removal is via physical bombardment or reactive chemistry between the fluorine and carbon. Depending upon the etch chemistry and process parameters (RF power, chamber pressure, electrode area and spacing, etc.), any one of the three mechanisms may actually dominate. Three of the most common fluorinated RIE mechanisms for removal of C proposed in the literature are listed below.

$$C + xO \Rightarrow CO \text{ or } CO_2$$

$$C + xF \Rightarrow CF_4 \text{ or } CF_2$$
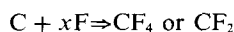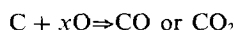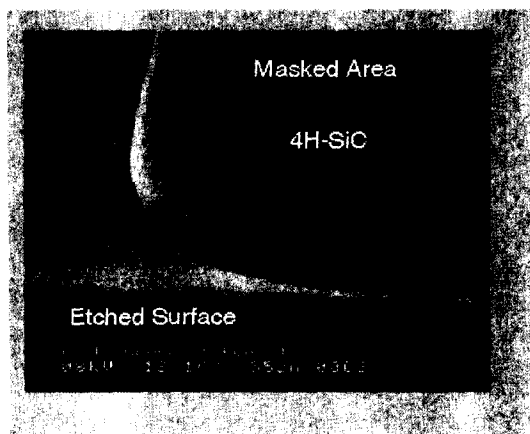
physical (ionic) bombardment.

Fig. 1. SEM (18.1 kX magnification) of etched 4H-SiC sample. Taken from Ref.[86].

Two recent papers summarizing work in residue-free RIE of 6H- and 4H-SiC are by Yih and Steckl[85] and Casady et al.[86], with Ref.[86] having higher etch rates (~ 1500 Å min^{-1}). An SEM of a typical sample after RIE is shown in Fig. 1[86]. Photoelectrochemical etching (PEC) of SiC has produced very high etch rates, and several quality papers can be found on PEC as well, but RIE and ECR etching currently appear more compatible with small-feature device processing[104].

4.1.4. Oxidation/passivation. The ability of SiC to oxidize and form SiO_2 has allowed compatibility with standard silicon-based fabrication processing. Obtaining a high-quality oxide with low interface state and oxide trap densities has proven to be challenging because of the carbon on the surface, as well as off-axis epitaxial layers which have rough surface morphologies. Numerous studies have been published about cleaning and oxidation procedures[105–135], and the goal of low (comparable with silicon) interface state densities is close to fulfillment. In SiC, unlike Si, it is important that C–V measurements be performed at high temperatures (> 300°C) to see the response time of interface states lying deep (> 0.6 eV) in the bandgap of SiC. Standard room-temperature C–V analysis will not reveal the true interface state density. Shenoy et al.[105] have reported interface state densities (D_{it}) near the 1×10^{11} cm^2 eV^{-1} order of magnitude, and fixed oxide charge (Q_{ox}) of 1×10^{12} (q cm^{-2}) in thermally grown SiO_2 on 6H-SiC. High-temperature, high-power operation and reliability issues remain to be addressed, however. For example, in vertical power devices, the high fields present in the device often breakdown the oxide. Also, the vertical sidewalls are a problem because oxide growth and quality vary substantially depending upon surface's orientation, and whether the surface is silicon-face or carbon-face[109,117,123]. Alternative insulators (such as nitrides and oxynitrides) are also being pursued for high-temperature

device applications, just as in the silicon industry. One example involves thermal oxidation of SiC in N_2O[134]. Diffusion of CO through the oxynitride was attributed to be the limiting factor in oxidation, and Q_{ox} was reported to be on the order of 1×10^{12} q cm^{-2}. The oxidation rate was found to be initially parabolic with time, eventually switching to linear after some time, just as the case for Si. It is believed that the introduction of nitrogen into the oxide (or oxynitride) should reduce the D_{it}, although no specific numbers were mentioned in this work.

4.1.5. Ohmic contacts. Low resistivity ohmic contacts are essential for high-frequency operation. Additionally, high-temperature and high-power requirements maintain that the contacts must be reliable under extreme conditions. Once seen as one of the primary impediments to SiC technological development, the ohmic contact area has now matured rapidly[136–159]. P-type ohmic contacts to SiC typically use some variation of Al/Ti alloys, and an example of such a contact with specific contact resistance measured at $1.5 \times 10^{-5} \Omega \cdot cm^2$ on Al-doped samples ($N_A = 2 \times 10^{19} cm^{-3}$) has been published by Crofton *et al.*[136]. Because Al is easily oxidized, other contacts such as boron carbide (for example, B_4C) may prove to be superior for high-temperature ohmic p-type contacts, but much more research is needed in this area. N-type contacts have been formed from a variety of silicides and carbides (such as Ni_2Si and $CoSi_2$). To our knowledge, the n-type contact based on nickel silicide (Ni_2Si)[137] currently has been reported to have the lowest specific contact resistance ($<5 \times 10^{-6} \Omega \cdot cm^2$ on 6H-SiC doped $7–9 \times 10^{18} cm^{-3}$), and has actually been reported to have lower contact resistance at 500°C than at room temperature. Other ohmic contacts using TiC to n-type 6H-SiC have also shown promise, but with somewhat higher contact resistances[138]. Reliability studies are only now taking place[139], and although preliminary results are encouraging, the best ohmic contact for high-temperature operation is still in question. Packaging issues and composite contact delamination at high temperatures must still be addressed. N-type ohmic contacts using NiCr may prove advantageous from contact delamination, reliability, and wirebonding issues[152]. Other work which may be advantageous from the point of post-oxidation device processing includes research on low-temperature annealing cycles, or even ohmic contacts which are ohmic as deposited[140]. High-temperature anneals (for instance of 1000°C[137]) could degrade the interface quality and reliability of thermally grown oxides[112].

4.1.6. Schottky contacts. Increasing the Schottky barrier height is extremely important for elevating the maximum operating temperature for metal semiconductor field effect transistors (MESFETs) and Schottky rectifiers. While MESFETs are discussed below, some recent work on Schottky diodes[159–174] is quite worthy of further review. One of the

primary uses of Schottky contacts on SiC, other than that of a gate metal in MESFETs, is for use in efficient, solid state, high-voltage switching applications[164], which could prove to be an important market for SiC electronics. Metals used for Schottky contacts to SiC include Ni, NiCr, Au, Pt, Ti, Mg, Co, Al, Hf and Pd. Actual Schottky barrier heights depend upon the surface quality of material, metal deposition process, polytype, conductivity (n-type or p-type), and whether the surface is Si-face or C-face. On Si-face, 6H-SiC, Au and Ni possess two of the highest Schottky barriers of ~ 1.47 and $1.27 eV$, respectively[162]. Many metals such as Ni and Ti, can form both ohmic and Schottky contacts[146,155,159], with short-term, high-temperature anneals ($\gtrsim 900°C$) converting the Schottky contact to ohmic.

4.2. High-temperature SiC devices

A myriad of devices in 3C, 6H and 4H SiC have been demonstrated including the bipolar junction transistor (BJT)[175–179,191], insulated gate bipolar transistor (IGBT)[180], MESFET[181–186], the JFET[7,39,187–196], the metal oxide semiconductor field effect transistor (MOSFET)[197–203], which has been operated up to 923 K[203], the static induction transistor (SIT)[204], power MOSFETs[205–209], thyristors[186,209–211], pn-junction diodes[201,212–215], and Schottky diodes[161,164,170,216,230]. Additionally, heterojunction devices such as the heterojunction FET (HFET) and heterojunction bipolar transistor (HBT) have been proposed and fabricated. Examples include 3C-SiC/Si HBTs[217–219], a 6H-SiC/3C-SiC HBT[175], and a GaN/6H-SiC HBT[220]. A summary of fabricated SiC devices along with the highest recorded temperature of operation and comments are summarized in Table 2.

Extracted mobility (μ_{eff}) in the channel of a 6H-SiC depletion-mode MOSFET is shown vs temperature in Fig. 2[199]. The channel mobility is lower than the bulk mobility, and the difference is attributed to interface states between the oxide and semiconductor, material defects, mobility anisotropy, and other factors. Channel mobility in 4H-SiC JFETs with $9 \mu m$ gate length have been reported at $340 cm^2 V^{-1} s^{-1}$ at 300 K[190], with a maximum transconductance (g_m) of $15 mS mm^{-1}$. Enhancement-mode JFETs have also been fabricated[192], opening up the possibility of complementary JFET-based logic in SiC, possibly reducing the need for a high-quality gate oxide which can withstand high-temperature, and possibly high-power and high-radiation environments. In the enhancement-mode JFET, the *pn* junction space charge region at zero gate bias fully depleted the drain-source channel, causing the device to be normally off. The extrapolated threshold voltage (V_{TH}) was measured to be 0.81 V at 300 K, with g_m of $1.5 mS mm^{-1}$ for a device with a gate length of $5 \mu m$[192]. The maximum gate voltage before forward biasing the gate *pn* junction diode fell from $\sim 2.5 V$ at 300 K, to $\sim 1.9 V$ at 723 K. A good

Table 2. Summary of SiC high-temperature device research with references prior to 1996

Device	Highest temp. operated	Comments	References
MOSFET	923 K	3C-, 6H- and 4H-SiC devices.	197–203
Power MOSFET	673 K	175 V, 2 A device and 600 V 1.8 A device fabricated	205–209
6H-SiC MESFET	673 K	f_{max} = 25 GHz; 8.5 dB @ 10 GHz	181–183, 185
4H-SiC MESFET	673 K	f_{max} = 42 GHz, 2.8 W/mm	181–187
6H-SiC JFET	873 K	Also enhancement mode	188–195
4H-SiC JFET	723 K	μ_{eff} = 340 cm^2 V^{-1} s^{-1} at 300 K	190, 196
BJT	673 K	$\beta \sim$ 5 to 15 for npn (comm. E)	175–179, 191
GaN/SiC HBT	808 K	Very high d.c. gain ($\beta > 1 \times 10^5$ at 300 K)	220
SIT	473 K	225 W output @ 600 MHz, 47% PAE, 200 V blocking and f_{max} of 4 GHz	204
Thyristor	773 K	2 kA cm^{-2} maximum switched current density	186, 208–211
pn junction diode	870 K	4.5 kV breakdown demonstrated at 300 K	212–215
Schottky diode	973 K	Over 1 kV breakdown demonstrated at 300 K	161, 164, 170–174 216, 232

discussion of I_{DSS} vs temperature can be found in the literature as well[192,193]. High-voltage JFETs have also been fabricated, with 6H-SiC JFETs capable of 450 V forward blocking voltage, although pinchoff-voltage was −400 V[195]. R_{on} was found to vary from 20 m$\Omega \cdot$cm^2 to 80 m$\Omega \cdot$cm^2.

Bipolar junction transistors in SiC typically have low d.c. current gain ($\sim$5–15) in the common emitter configuration, primarily as a result of minority carrier base recombination in npn structures[176], although with very heavily doped emitters, bandgap narrowing could also play an extremely important role in degrading the d.c. current gain. Heterostructure devices using wide bandgap emitters or narrow bandgap bases of different SiC polytypes of III–V nitrides will probably be needed to increase d.c. gain and improve the high-frequency response of the devices.

Power MOSFETs with 260 V blocking capability and R_{om} of 18 m$\Omega \cdot$cm^2 have been obtained[209] for vertical 4H-SiC UMOSFETs. Also, larger area devices, such as 175 V MOSFETs with a rated current of 2 A (200 A cm^{-2}) at a forward drop of

2.65 V were also demonstrated. Operation of similar devices had previously been demonstrated to 300°C with short lifetimes because of gate oxide failure, but no high-temperature data was reported for these later developments[209]. Because of SiC's superior electric field strength, R_{on} has been affected by channel resistance, and not simply the resistance of the lightly-doped drain-drift region, which is much thinner than that of comparable Si power MOSFETs. Improvement of channel mobility to lower R_{on} is critical. Poor channel mobility in SiC Power MOSFETs (e.g. $\sim$13 cm^2 V^{-1} s^{-1} in 4H-SiC UMOSFET[209]) has thus far been generally attributed to poor interface quality between oxide and SiC in the channel region. Additionally, long-term stability of the insulator has been shown to be the limiting factor in SiC power UMOSFET structures, although use of a p^+ polysilicon gate reduces Fowler–Nordheim injection from the gate electrode, thereby increasing breakdown voltage. An excellent discussion of these issues is found elsewhere[207]. Other high-temperature, high-power devices, such as thyristors have been demonstrated to 500°C[209]. At room temperature, this same device had a blocking voltage of 600 V with a 1.8 A forward current at a voltage drop of 3.7 V. A 10 A, 200 V thyristor with a forward voltage drop of −3.6 V, current density of 620 A cm^{-2}, and R_{on} of 1.2 m$\Omega \cdot$cm^2 was also demonstrated[209].

A promising device in SiC for use in a combination of high-power, high-frequency, and high-temperature applications is the SIT. Recently, a 225 W UHF 4H-SiC SIT was reported on[204], with the maximum output power of 225 W at 600 MHz, and a power added efficiency (PAE) of 47% and a gain of 8.7 dB for the packaged device. The maximum blocking voltage was 200 V, and maximum channel current density was 1 A cm^{-1} of source periphery. Maximum transconductance was 75 mS mm^{-1}, and a f_{max} of 4 GHz was measured on these devices. An SEM of the completed SIT devices is shown in Fig. 3, as taken
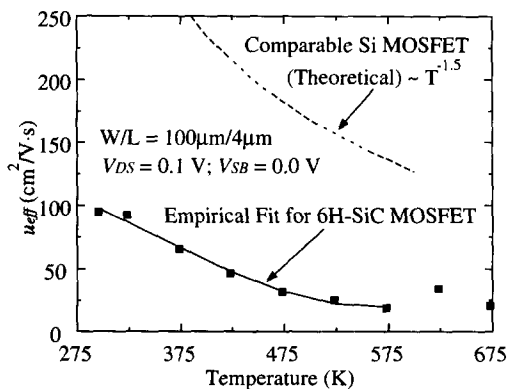

Fig. 2. Effective channel mobility vs temperature for a 6H-SiC depletion-mode MOSFET compared to a similar, theoretical device in silicon. Taken from Ref.[199].
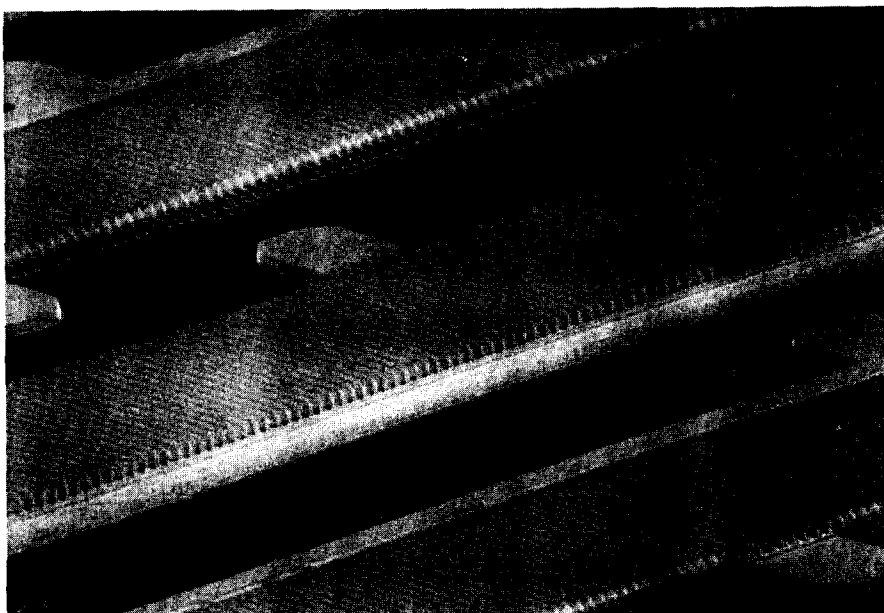
Fig. 3. SEM of completed 1.5 cm periphery SiC Static Induction Transistors (SITs). Gate and source
bonding tabs can be seen. Taken from Ref.[204].

from[204]. Aside from the impressive performance, also noteworthy is that 1.5 cm periphery devices are practical despite the micropipes present in the material, and that eleven good devices with output power of 225 W were obtained on the die shown in Fig. 3.

4.3. High-temperature SiC circuits and sensors

4.3.1. Operational amplifiers. The first SiC-based operational amplifier was assembled as a hybrid circuit on an alumina ceramic substrate, using thick-film resistors, gold conductor traces, and die containing 6H-SiC depletion-mode MESFET pairs[221,222]. The packaged circuit was demonstrated in 1992, with measured gain greater than 60 dB from 25°C to 350°C, and a gain bandwidth of 1.08 MHz at 25°C, and 0.91 MHz at 350°C. The first

monolithic op-amp was reported in 1994[223] by researchers at General Electric making use of depletion-mode, n-channel, 6H-SiC MOSFET technology. The conservatively designed, packaged op-amp had a gain of 49 dB at room temperature, and a gain bandwidth of 724 kHz at 25°C, falling to 269 kHz at 350°C. An enhancement-mode NMOS op-amp, with 12 V power supply, an input offset of 56 mV and open loop gain of 103 (40.3 dB) has also been fabricated[224], and was operated successfully to 350°C. Monolithic SiC CMOS op-amps have been recently reported with a room-temperature open loop voltage gain of 10,000[225], and hybrid, 4H-SiC JFET op-amps are currently under development[226].

4.3.2. Digital circuits. Another focus of SiC electronics research is to develop a high-temperature, high-speed logic family. Researchers at Purdue
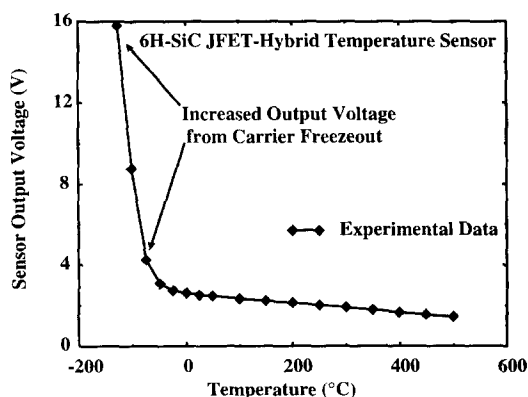

Fig. 4. Measured output voltage as a function of temperature from a 6H-SiC, hybrid temperature sensor from 500°C to ~ −150°C. Taken from Ref.[228].
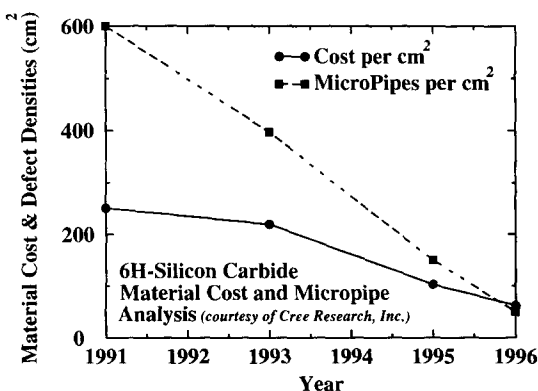

Fig. 5. Cost (in dollars) and micropipes per square centimeter of 6H-SiC bulk material from Cree Research Inc. as a function of time. Data furnished courtesy of Ref.[10].

University were the first to demonstrate these capabilities[227], demonstrating fabrication and operation of inverters, NAND, NOR, and XNOR gates, D-latches, RS flip-flops, binary counters, and half-adders with successful operation from room temperature to over 300°C. 17-stage ring oscillators have also been fabricated, with 40% yield for NMOS circuits on 30 mm (1.182 in) *p*-type 6H-SiC substrates, and 25% yield for PMOS circuits on 35 mm (1.379 in) *n*-type 6H-SiC substrates[224].

4.3.3. Sensors. A 6H-SiC, hybrid temperature sensor was designed, fabricated, and tested from −150°C to 500°C at Auburn University utilizing two 6H-SiC JFETs configured in a series-series feedback network, and a 6H-SiC diode formed using the gate-to-source junction in a third JFET[228]. Linear output with respect to temperature was measured from 500°C to about −50°C, where carrier-freezeout in the diode began to affect performance. The measured temperature sensor output voltage is shown in Fig. 4. Other temperature sensing applications have also been envisioned[229]. A SiC thermistor has been demonstrated as early as 1973[230], with sustained operation at 1050°C (1323 K) for over 2500 h. The thermistors were packaged in stainless steel housings, with logarithmic temperature response to temperature from −200°C to 700°C.

SiC u.v. photodiodes have also been demonstrated[1,231,232]. SiC u.v. detectors have the advantages of operation in hostile environments, insensitivity to longer wavelengths, and very small dark currents leading to sensitivity four orders of magnitude greater than that of Si detectors[191]. Flame-indication sensors utilizing 6H-SiC transistors[1,233] have been fabricated and tested at temperatures over 500°C. A flame indication sensor with an integral amplifier was operated for over 600 h in simulated engine environments with no degradation. Other applications for u.v. detectors include satellite-based missile plume detection, gas sensing (automobile exhaust systems, etc.), and u.v. dosimetry. SiC hydrocarbon sensors have been pursued as well, with a potentially large market in the automotive industry[234,235]. SiC MOS oxygen sensors, also with a potential large market development, have been developed with promising results[236].

A 3C-SiC accelerometer[237] fabricated via micromachining of 3C-SiC membranes on a silicon substrate has been demonstrated by Daimler-Benz. Free-standing 3C-SiC membranes were obtained by anisotropic etching of the Si wafer. The 3C-SiC membranes were able to withstand much higher temperature and pressure, as well as more corrosive environments than comparable Si membranes, indicating a much more robust accelerometer could be fabricated.

Although not a high-temperature application, high-speed nonvolatile random access memory (NVRAM) in SiC[238] is worth mention, because of

SiC's wide bandgap and subsequent long charge storage times (> 10 min at 623 K and projected to be over a million years at 300 K) may give rise to room-temperature memory chips which need no refreshing, thus eliminating hard drives in computers. This could open the commercial personal computer market to SiC, allowing economies of scale to occur and allow the cost of SiC to fall rapidly.

5. CONCLUSIONS

The interested reader should look to other reviews found in press and in the literature[17,84,239–242]. In addition, proceedings of past conferences relating to SiC research also prove helpful[243–256]. A brief overview of the electronic properties of SiC as relating to high-temperature electronics, as well as significant achievements involving high-temperature SiC electronics prior to 1996 has been given.

A broad overview of some of the high-temperature applications using SiC electronics has also been discussed, and excellent progress has been demonstrated by SiC devices and circuits to date. Still, despite impressive individual device performances, some key barriers remain. First, insulators capable of reliable high-temperature operation with high breakdown field strength and lower interface trap densities need further development. Of particular concern is the uniform growth/deposition of insulators on the different surfaces of SiC exposed in a typical vertical power UMOSFET configuration. Second, material defects (in particular, micropipes) and material cost must be decreased, while wafer-size must be increased substantially in order to facilitate commercial production of SiC based electronics. Much progress has been made towards these goals, as evidenced by Fig. 5[10], and should continue, making SiC an attractive semiconductor choice in the high-temperature electronics marketplace. Devices such as high-frequency MESFETs, which do not rely on large area or a high-quality dielectric may be the first SiC electronic devices (excluding optical devices) to hit the commercial market.

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