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SiC based Technology for High Power Electronics and Packaging Applications

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Abstract: Silicon has been most widely used semiconductor material for power electronic systems. However, Si-based power devices have attained their working limits and there are a lot of efforts for alternative Si-based power devices for better performance. Advances in power electronics have improved the efficiency, size, weight and materials cost. New wide band gap materials such as SiC have now been introduced for high power applications. SiC power devices have been evolved from lab scale to a viable alternative to Si electronics in high-efficiency and high-power density applications. In this article, the potential impact of SiC devices for power applications will be discussed along with their Si counterpart in terms of higher switching performance, higher voltages and higher power density. The recent progress in the development of high voltage power semiconductor devices is reviewed. Future trends in device development and industrialization are also addressed.

Keywords: SiC, Packaging, Semiconductor, IGBT, JFET

1. Introduction

1.1. Wide Band Gap Semiconductors

It has been already established that the major breakthrough in Power Electronics comes from the development and use of Wide Band Gap (WBG) semiconductor devices. Most commonly used WBG semiconductors in power electronics are as SiC, GaN, and diamond. WBG show superior material properties can be operated at higher switching speed, high voltage and high temperatures.1) These unique properties provide a substantial change in their applications for power generation. The electrical power undergoes a number of conversion steps making the process highly inefficient, i.e., only 20% of the whole energy involved in energy generation reaches the end-user.2) Thanks to the WGB semiconductors which increase the conversion efficiency due to their outstanding material properties.

The WBG semiconductors generally includes all materials with a band gap starting at roughly 2.0 eV, including indium nitride (InN) and cubic phase silicon carbide (3C-SiC), up to materials such as aluminum nitride (AlN) and diamond, which have energy gaps on the order of 6.0 eV. The electronic band gap of gallium arsenide (GaAs) at room temperature is about 1.42 eV. The most important features of a semiconductor with a large band gap are the sustainability of a high breakdown voltage. It is generally believed that as the band gap increases, the breakdown voltage also increases accordingly. This is the most important advantage which enables the high voltage operation of devices. Moreover, the thermal leakage is drastically reduced, as compared to standard semiconductors. This allows devices to operate in high temperature environments or in systems where leakage current affects their performance, such as in photodetectors, charge-coupled devices (CCDs), and nonvolatile memories .1, 2)

1.2. SiC in Power Electronics

SiC is the potential reputed wide band gap semiconductor in advanced electronic applications Its unique properties allow the feasibility of easily growing a native oxide. The presence of numerous polytypes of SiC can potentially be used in a wide range of applications such as microwave and high-power devices. The use of SiC based devices is improving many aspects of current electronics due to the limitations of Si in region of high-frequency and high-power applications.3-5) For example, in wireless communication, there is always a demand for microwave transistors capable of high power densities. In addition, the data storage and optical communication systems markets have developed high frequency emitters and detectors.6) Therefore, the various transport properties and breakdown characteristics

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and the implications on the performance of SiC based electronic materials are of interest. These materials have great potential for a wide range of power applications; however there exists a lack of information about the wide band gap materials systems. The various obstructing factors include the lack of suitable substrates, difficulty in accurately monitoring the growth processes, and general inexperience with these new systems.

2. History and Motivation

During 1950s, first time the wide band gap and high temperature resistance of SiC is exploited in the USA for high-temperature electronic devices. Since then SiC is being researched and developed worldwide. In spite of the various advantages of SiC for high power applications, such as its high temperature stability, materials processing is very difficult. And further investigations proceeded at a slower rate until 1970. In late 1970, a major breakthrough is noticed in Russia where bulk crystals of SiC are grown using seeded sublimation technique.7, 8) Other researchers soon proposed step-controlled epitaxial growth of SiC in the late 1980s. These breakthroughs stimulated the research community to use SiC for power electronic devices in early 1990s. High voltage SiC Schottky diodes are fabricated in 1993 and 1995 in Japan.9) Research and development SiC devices are now conducted at a greater pace in various countries.

3. State-of-the Art of SiC Power Devices

High performance 4H-SiC Schottky diodes was fabricated in 1990s.7-9) The superior reverse blocking characteristics and higher breakdown voltages are achieved subsequently.9) Schottky diodes with a breakdown voltage of several kilovolts and a current above several tens of amps have been developed. The commercially available Schottky diodes now a days are of 600 V/2–12 A, 20 A, 300 V/10, 20 A, and 1.2 kV/10, 20 A. The SiC p-n junction diodes are fabricated by epitaxial growth or ion implantation. High breakdown voltages are often achieved the extension of the junction termination.10-12)

High power switching devices, trench U-shape MOSFETs and double-implanted MOSFETs have been demonstrated. Low channel mobility of MOSFETs, have been improved using accumulation FETs and epi-channel FETs.13, 14) A number of research works is done on improving channel mobility along with MOS interfaces. Various switching devices using junction FETs (JFETs) have been developed in place of MOSFETs to avoid low channel mobility. SiC IGBTs (Insulated Gate Bipolar Transistor)s were introduced on the market in 1988. IGBTs from 1.7 kV up to 6.5 kV with DC current ratings up to 3 kA are commercially available.15, 16) They have been optimized to satisfy the specifications of the high-power motor drives for industrial and traction applications. More recently a new type of thyristors has been inserted to the market, the IGCT (Integrated Gate Commutated Thyristors), representing the state of the art and probably opening a new era.

4. Merits of the SiC Technology

SiC possesses a number of unique properties that make it a potential candidate for power electronic applications. It is resistant to high temperature and radiation. It is characterized by low diffusion rates of dopants. Various polytypes of SiC have been recognized as more promising material systems for high-frequency and high-power devices. The high breakdown voltage of these polytypes allows the fabrication of metal-semiconductor field effect transistors (MESFETs) and metal-oxide semiconductor field effect transistors (MOSFETs) with high power densities that operates at very high frequencies.15-16)

Renewable energy system designers are always striving to achieve higher efficiency and lower cost systems. SiC devices offer, compared to silicon, a higher voltage devices with lower on-state resistance and faster switching speed. For example, photovoltaic inverters can achieve smaller size, lighter weight, and more cost-effective designs utilizing SiC. Inverter based on SiC JFET and Schottky diode has achieved efficiency up to 99%.17) With such developments, solar energy price can be brought to comparative price level with conventional energy source. The high efficiency and cost effective SiC-based solution also benefits other applications including wind power and hybrid vehicle. Silicon Carbide has a higher energy gap compared to Si, which gives it the advantage of significantly lower reverse leakage currents, especially important at high temperatures, compared to Si. Thus SiC can operate at higher junction temperatures. The higher energy gap of SiC compared to Si gives it the advantage of a much higher breakdown electric field compared to Si. Several SiC-based power devices have been successfully commercialized, however the SiC device market is still in its initial stage and its potential users are not aware of this technology.

4.1. SiC Properties

The development of SiC technology over the last few years has seen various ups and downs, with significant improvements in wafer growth technology, materials processing, electronic devices, and, sensors. The fundamental rationale for these investments in SiC technology is its excellent material properties coming from the high strength of the Si–C bond.

SiC exhibits polytypism, i.e., different crystal structures having same Si–C subunit but arranged into a variety of stacking sequences. Such polytypes are distinguished by the crystal lattice (i.e. hexagonal, cubic, or rhombohedral) and the number of layers making up the repeat pattern, e.g. 4H-SiC has a hexagonal lattice with a four-layer repeat structure. There are more than 100 polytypes of SiC. The most common polytype used frequently for research and development has been concentrated on three: 3C, 6H, and 4H. 4H polytype is the most common for electronic devices because of its overall superior material properties such as bandgap is 3.23 eV at room temperature.5-7) Thus the number of electron-hole pairs formed from thermal activation across the bandgap is reduced and allows high-temperature operation of SiC electronic devices. The 3C-SiC polytype is more common for micro electromechanical systems (MEMS) because it can be grown in polycrystalline form on Si wafers (thus reducing the overall wafer cost compared with pure SiC technology). Other material advantages for all forms of SiC include a high radiation and chemical tolerance, a high thermal conductivity (better than Cu), high hardness and Young's modulus (typically ~450 GPa compared with ~130 GPa for Si), and for some polytypes (notably 4H and 6H) a high critical electric field (in excess of 2 $\mathrm{MVcm^{-1}}$). This combination of excellent electronic and mechanical properties offers many possibilities for using SiC as a material for a wide range of devices and sensors-particularly in applications featuring high temperatures or power.18, 19)

4.2. Materials Processing Issues

SiC devices provide lower conduction and switching losses thus increases the converter efficiency. High switching speed ability with SiC tends to reduce weight and cost of conversion systems. Another unique advantage of SiC compared to other wide bandgap semiconductors, is its ability to oxidize and form SiO_2 exactly as in Si technology. The oxidation rates are much lower for SiC than for Si. The fabrication of high quality thermal oxides with low interface state and oxide trap densities has proven to be a great challenge. Finally, the reliability of oxides is a major issue for SiC devices since at high electric fields and high temperatures oxides have poor life expectancy.

Historically, the major difficulty with SiC is the presence of epilayers of micropipes in the substrates, which are essentially small holes (of diameter ~1 μm) throughout the wafer. However, material with essentially zero micropipe densities are now available (reduced from over 1000 $\mathrm{cm^{-2}}$ in just a few years), a further difficulty concerns the uniformity of epilayer doping and thickness across the wafer.20-22)

The breakdown and reliability properties of SiO_2 are crucial for all metal-oxide-semiconductor (MOS) devices, but unfortunately the situation is not as favorable as it is for Si. For simple MOS field-effect transistor (MOSFET) designs, the ratio of the dielectric constants of SiC and SiO_2 produces a surface electric field ~2.5 times higher in the oxide than in SiC.23) Hence, to gain the full benefit of the ~2.5 $\mathrm{MVcm^{-1}}$ breakdown field of SiC, the oxide must withstand 6.25 $\mathrm{MVcm^{-1}}$, which is higher than is reliably usable, even on SiO_2. However, this can be mitigated by the use of more complex structures or by careful device design. In addition, the barrier for injection of holes is much lower than in Si, which is unfortunate since holes are particularly damaging to oxides.24) The selective doping of a SiC wafer via ion implantation is of crucial importance for device fabrication and there have been extensive studies of ion implantation of a range of dopant atoms into SiC.25) To anneal defects out of a wafer and to activate the dopant, it is essential to anneal the wafer at high temperatures post-implant. This is typically carried out at temperatures as high as 1700°C and is technologically difficult because of the instability of the SiC surface at such temperatures. Si atoms sublime at temperatures above 1400°C, destroying the stoichiometry of the near-surface region and causing macro-step formation and introducing defects. This effect can be mitigated by using a Si over-pressure in the annealing furnace (typically introduced by using a silane atmosphere) or by capping the wafer with a robust material such as graphite.26, 27)

4.3. SiC versus Si

Compared to Si, Silicon Carbide (SiC) has a number of advantages including lower on-resistance for a given chip area at high voltage and 200°C capability. Silicon Carbide is a new semiconductor material with a much higher breakdown electric field than Si due to its higher energy gap and a material with a higher thermal conductivity than Si.28) A comparison of the electrical properties of SiC and Si is given in Table 1. The performance advantages of SiC over Si in power electronics applications include lower resistance devices for the same area due to its higher breakdown electric field, higher junction temperature operation, and thus higher case temperature operation.29)

Table 1. Electrical and material properties of Si, and SiC at room temperature unless otherwise noted.[29)]

Materials Property	Si	SiC
Electron Mobility at 150°C and 600 V (cm^2/V.s)	576	148
Breakdown Electric Field (V/cm)	3×10^5	1.9×10^6
Dielectric Constant	11.7	9.66
Built in Potential (Schottky) (V)	0.5	1.1
Built in Potential (Junction) (V)	0.7	2.1
Thermal conductivity (W/cm°C)	1.45	4.56

In power applications, an important consideration is the maximum junction temperature at which the device can operate. Figure 1 shows the maximum junction temperature of Si, SiC in the near (short) term, and SiC in the far (long) term. It indicates that SiC has the potential to operate at temperatures as high as 400°C. In the near term, packaging considerations will limit SiC device junction temperatures to values more like 250°C. This is a significant improvement over Si's maximum junction temperature of 150°C. In addition, a SiC device operating at a junction temperature of 250°C, which is significantly lower temperature than its theoretical maximum, should be more reliable than a corresponding Si device at operating at a junction temperature of 150°C.[29)] High thermal stress is a leading cause of semiconductor failures.

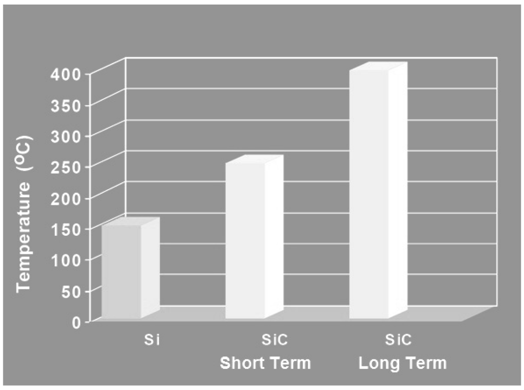

Fig. 1. Comparison of the Maximum Semiconductor Operating Junction Temperature for Si, Short Term SiC and Long Term SiC.

4.4. GaN versus SiC

Among the possible candidates to be the base materials for these new power devices, apart from SiC, GaN present the better trade-off between theoretical characteristics (high voltage blocking capability, high temperature operation and high switching frequencies), and real commercial availability of the starting material (wafers) and maturity of their technological processes. Table 2 summarizes the main material parameters of WBG semiconductors candidates to replace Si.[30)]

GaN and especially SiC process technologies are by far more mature and, therefore, more attractive from the device manufacturer's perspective, especially for high power and high temperature electronics (HTE). GaN can offer better high frequency and high voltage performances, but the lack of good quality bulk substrates is a disadvantage for vertical devices.

Nevertheless, GaN presents a lower thermal conductivity than SiC. At present time, SiC is considered to have the best trade-off between properties and commercial maturity with considerable potential for both HTE and high power devices. For this reason, SiC and GaN are the more attractive candidates to GaN and especially SiC process technologies are by far more mature and, therefore, more attractive from the device manufacturer's perspective, especially for high power and high temperature electronics (HTE).[30)]

In fact, some SiC devices, such as Schottky diodes, are already competing with Si power diodes. On the other hand, GaN allows forming hetero-junctions (InAlGaN alloys) that can be grown either on SiC or Si substrates. Currently, there is a sort of competition between SiC and GaN in a battle of performance versus cost. Recently SiC power devices reported in literature include high voltage and high temperature diodes, junction controlled devices (like JFETs and MESFETs), MOSFETs, Thyristors and IGBTs. Those based on GaN include diodes, HEMTs and MOSFETs; and advanced research on novel devices concerning low-losses digital switches based on SiC and GaN is also of main concern. Although GaN does not have as high a thermal conductivity as SiC, still it makes an attractive candidate for

Table 2. Approximate value of physical properties of some semiconductors.

Name	Band Gap (eV)	Maximum Electric Field (V/cm)	Dielectric Constant (ε)	Thermal Conductivity (W/cmK)	Carrier Mobility (cm^2/Vs)
Si	1.1	3×10^5	11.8	1.5	1350, 480
GaAs	1.4	3.5×10^5	10.9	0.8	8600, 250
SiC	3.3	2.5×10^6	9.8	4.9	980, 200
GaN	3.4	2×10^6	7.8	1.4	2000
Diamond	5.5	1×10^7	5.5	10-20	1800, 1600

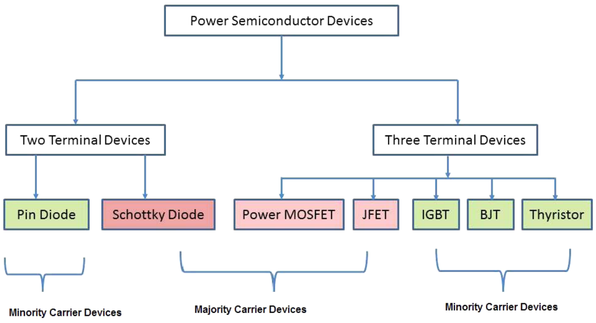

Fig. 2. Power devices family showing principal power switches.

high-power, high-frequency applications.

5. Power Semiconductor Devices

Power semiconductor can be divided into two main categories based on terminal numbers: two-terminal devices and three-terminal devices.[15] A second classification can be based on the device performance: majority carrier devices (Schottky Diode, MOSFET) and minority carrier devices (Thyristor, bipolar transistor, IGBT), as shown in Figure 2.

Recent technology advances in power electronics have been made by improvements in controllable power semiconductor devices. Metal Oxide Semiconductor Field Effect Transistors (MOSFET) and IGBTs have replaced Bipolar Junction Transistors (BJT) almost completely. Several SiC devices among unipolar devices Schottky didoes, JFETs, and MOSFETs are available. Schottky barrier diodes (SBDs) are made by utilizing the rectifying contact between a metal and device drift region. In case of silicon the high resistance of the drift region limits realizing high breakdown voltage devices and thus available devices are limited to 100 V. In the case of SiC, the higher breakdown field leads to lower drift region resistance. This enables higher breakdown voltages with lower losses making SiC-SBDs with breakdown voltage of 600-1700 V achievable. With the continuous development of the Schottky rectifiers, specific on-state resistance is already approaching the theoretical unipolar limit of SiC.[18]

5.1. SiC as Power Devices

The switching devices are free from reliability issues related to the gate oxide and temperature-dependent threshold voltages drifts. These reasons have made JFET one of the most successful devices within SiC technology.[31] The JFET is conventionally fabricated as a normally-on device. However, normally-off characteristic is achievable especially with the high built-in voltage (~3 V) observed at SiC pn junction. Recent reported JFETs with 1.2 kV breakdown voltage have specific on resistance of only 2.47 mΩcm^2 and 2.9 mΩcm^2 for normally-on and normally-off devices, respectively.[32] On the other hand, MOSFETs are preferred by designers due to high input impedance and voltage-controlled gate. So the efforts are continuing to realize a SiC-MOSFET with acceptable channel mobility and oxide reliability. Improving the interface between oxide and SiC is essential for increasing effective channel mobility and hence reducing device resistance. For high breakdown voltages, bipolar devices offer low forward voltage drop. For voltages higher than 3 kV, SiC P-i-N diodes offer, in addition to the low forward voltage drop, a faster switching speed making them a good candidate to replace silicon P-i-N diodes in this voltage class.

With current SiC MOS technology, a 4H-SiC IGBT would only be effective at voltage blocking levels exceeding 4 kV (in Si, IGBTs become effective at ~300 V). Finally, the presence of deep levels, associated with common p-type dopants such as Al and B, gives cause for concern about the integrity of voltage blocking structures under dynamic conditions. P-i-N diodes have been demonstrated with blocking voltages exceeding 10 kV and a current of 20 A and with die areas up to 40 mm^2 and current ratings of up to 40 A for inclusion in 2.5 kV power modules alongside Si IGBTs. Recently, some very promising results have been reported for BJTs. These devices exhibit a relatively high current gain (-20), and an effective on-resistance of just 0.8 mΩcm^2 (the lowest of any SiC power switch reported thus far) with a positive temperature coefficient. Note that the BJT structure does not suffer from the high forward voltage drop of other bipolar devices. Both conventional and gate turn-off (GTO) thyristors have been demonstrated at voltage levels between 400 V and 2.6 kV and recently a p-channel IGBT has been fabricated. There has also been considerable interest in high-voltage Schottky diodes as these offer very low stored charge – a great advantage for many power switching circuits. Schottky diodes with ratings up to 6 kV and operable at temperatures up to 500°C have been reported.[33, 34]

6. Latest Developments in High Power Devices

6.1. High Speed Switching Devices

Insulated gate bipolar transistors (IGBT), Integrated Gate Commutated Thyristor (IGCT) and MOS-Controlled Thyristor (MCT) are three new structures of power devices. IGBT is most common used power electronic devices nowadays, whose structure is shown in Figure 3. An IGBT is basically a hybrid MOS-gated turn on/off bipolar transistor that

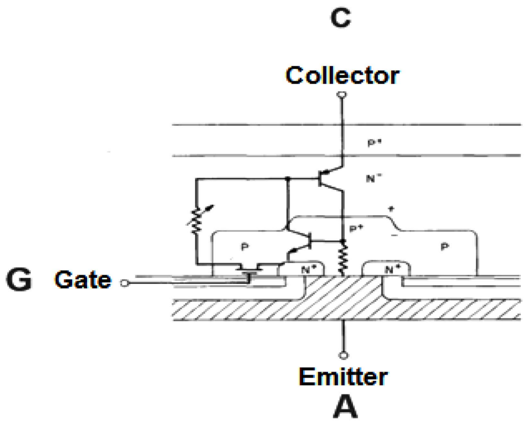

Fig. 3. Basic structure of IGBT.

combines the attributes of a MOSFET, BJT and thyristors.6-10)

The main advantages of the IGBT over a Power MOSFET and a BJT are explained as follows:

(1) It has a very low on-state voltage drop due to conductivity modulation and has superior on-state current density. So smaller chip size is possible and the cost can be reduced.

(2) Low driving power and a simple drive circuit due to the input MOS gate structure. It can be easily controlled as compared to current controlled devices (Thyristor, BJT) in high voltage and high current applications.31-33)

Since conductivity modulation is an essential factor which contributes towards the reduction of on state resistance of high voltage power devices (over 10 kV blocking voltage), significant research is going on in the development of silicon carbide IGBTs. Figure 4 shows the simplified cross section of a p-channel SiC IGBT rated for 12 kV blocking voltage.32)

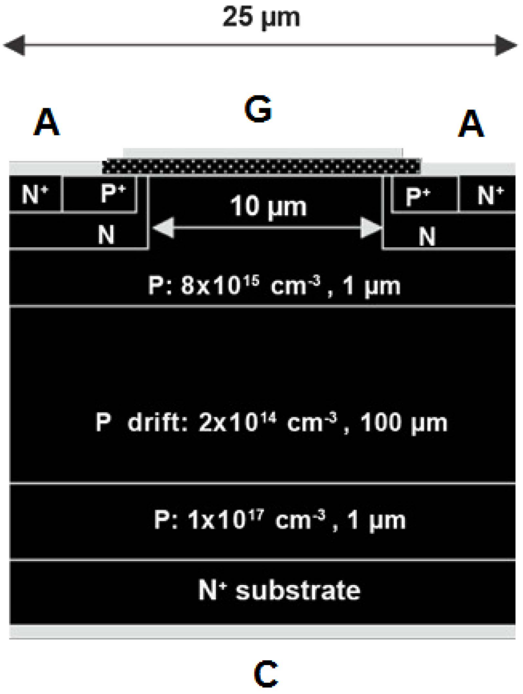

Fig. 4. 4H-SiC p-channel IGBT.

The device exhibited a low differential specific on-resistance of 18.6 mΩ cm^2, corresponding to a forward voltage drop of 5.3 V at 100 Acm^{-2} at room temperature. The superior DC and switching performance of SiC p-IGBTs make them promising candidates for high-power applications.32-34) With the introduction of the third IGBT chip generation, current density could be increased by 50%.

6.2. Die Attach Materials

Tin-based solder alloys (SnPb) and lead-free solder alloys (SnCu, SnAg, SnAgCu) and conductive fillers are used widely as die attach materials because of their ease of processing at temperatures below 300°C. Silicon carbide has been utilized as one of the potential semiconductor wafers for the next generation electronic devices. An advantage to the use of some wide bandgap materials that is often overlooked is that the thermal coefficient of expansion (CTE) is better suited to the ceramics used today in packaging technology.

From these thermo-mechanical arguments, the choices of desirable semiconductors are narrowed to SiC, GaN, and C (diamond). GaN and SiC are by comparison to C (diamond) very well suited to typical package materials35, 36), and in fact provide a better thermo-mechanical match than Si as shown in Figure 5.

6.3. SiC Materials Development

Silicon based power switching devices are reaching fundamental limits imposed by the low breakdown field of

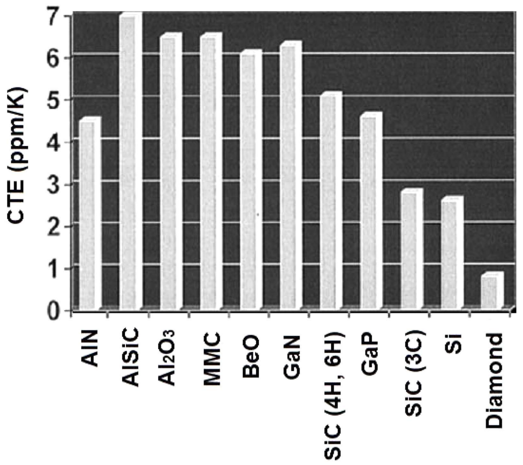

Fig. 5. Coefficient of thermal coefficients of expansion for package substrates and some semiconductors (ppm/K).

the material. Silicon carbide, with a higher field characteristic, is a promising choice for high power, high temperature and high frequency applications.25-27) Following factors led to the continuous development of even improved SiC material for high switching applications: (1) high electric breakdown property, (2) high carrier drift velocity, (3) high thermal conductivity realizing high temperature operation. SiC power devices can give a much on-resistance that can be seven hundred times lower compared to silicon devices.

7. Summary

New generation starts in SiC technology for power electronic devices. High-power high frequency devices and switching devices constitute the key technology that supports power electronics infrastructures in the 21st century. Reduced cost concerns and potential system-level advantages are likely to ensure that many of the early commercial applications of SiC technology will be in the next generation. The cost premium for SiC devices in comparison with those fabricated from traditional semiconductor materials, such as Si, will limit the deployment of these devices to markets where the material properties offer a unique advantage. The commercial prospects of SiC electronics are thus both enabled and also limited by material issues devices should not be delayed in light of their importance.

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