Silicon Carbide Merged PiN Shottkey [MPS] Diode Power Electronic Control Devices

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Abstract
Silicon carbide is a physically robust semiconductor whose crystal lattice is a cross between pure silicon and pure diamond. Silicon is the foundation of the modern microelectronics industry, and the most highly developed manufacturing technology in the history of mankind. Semiconducting diamond has electronic properties far superior to silicon, but, it has not been developed commercially, because its extreme material stability makes ordinary semiconductor fabrication techniques impractical. In this paper work, SiC is used for high temperature environments because of its high bandgap energy to create electron-hole (e-h) pairs in the material. The bandgap of SiC is about three times higher than silicon, but, since the e-h pair generation rate decreases exponentially with bandgap, the average density of e-h pairs in SiC at room temperature (the intrinsic carrier concentration) is sixteen orders-of-magnitude lower than silicon.
Keywords
Silicon Carbide(SiC), Power Electronics Control Device, Wide bandgap semiconductors (WBS), Merged pin shottkey(MPS) diode.

1. Introduction

Silicon carbide (SiC) is the perfect cross between silicon and diamond. The crystal lattice of SiC is identical to silicon and diamond, hut exactly half the lattice sites are occupied by silicon atoms and half by carbon atoms. Like-diamond SiC has electronic properties superior to silicon, but, unlike diamond it is also manufacturable. The thermal leakage current (dark current) in SiC is sixteen orders-of magnitude lower as well. As temperature increases, the leakage current increases, but, the temperature where the leakage current would disrupt circuit operation is over 1000 °C in SiC, compared to about 250 °C in silicon. The SiC electronic revolution began in the early 1990's when single-crystal wafers became commercially available for the first time. During the intervening years, many different electronic devices have been demonstrated in SiC, with performance often exceeding the theoretical limits of silicon. These include pn diodes, MOS field-effect transistors (MOSFETs), metal-semiconductor field-effect transistors (MESFETs), and bipolar transistors (BJTs), as well as specialized devices such as CCD imagers, Schottky diodes, static induction transistors (SITS), and impact-ionization-avalanche-transit-time (MATT) microwave oscillators. These early digital logic gates and linear elements are based on n-channel MOS technology, but, quickly followed by more sophisticated CMOS integrated circuits.

2 Applications of SiC

2.1 SiC – a widely used material

The material qualities of SiC have great potential, before the emergence of microelectronics applications based on SiC, to unique mechanical properties, so SiC is used as an abrasive in sand, in polishing agents or in cutting tools. SiC is one of the hardest materials known to man, only diamond and boron nitride are harder. The short bond length of 1.89 Å between 'Si' and 'C' atoms result is in high bond strength and excellent hardness. However, this makes SiC wafers difficult to cut and polish. The strong bonds do also create a large bandgap that gives SiC's high refractive index accompanied by a broad transparency over the visible spectrum, optical brilliance, and resistance to chemical and abrasive attack. Recently high-purity, almost colorless Moissanite crystals become available, leading to the development of SiC gemstone that have a beneficial influence on SiC semiconductor. Due to relatively low density, SiC can be used even in space applications, e.g. for ultra-lightweight mirrors. It is also appropriate for bearings with the hardness and toughness.

2.2 Wide bandgap semiconductors

The wide range applications of SiC, is the most promising area is semiconductor processing. The wide bandgap materials are in many respects superior to silicon due to their physical and electrical properties. The properties of different wide bandgap semiconductors, selected from the viewpoint of microelectronics applications. For e.g. in SiC the probability of thermal excitation of an electron over the bandgap is 10^{-26} at room temperature, i.e. there are no thermally excited electrons in the conduction band. The wide bandgap is also accompanied by considerably higher

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breakdown voltage as compared to silicon. This means that for power devices with similar blocking voltage capabilities, the one made of silicon must have about 100 times lower doping level in a 10 times thicker layer, as compared to a SiC device.

2.3 SiC for microelectronics applications

The wide bandgap semiconductor having silicon dioxide (SiO2) as native oxide, similarly to silicon is studied in SiC. SiO2 as a dielectric is needed for surface passivation of SiC devices, as well as for a gate material in metal-oxide-semiconductor field-effect transistors (MOSFETs) and related structures. Silicon dioxide can be formed by simple wet or dry oxidation of SiC.

2.4 High voltage devices

SiC high voltage devices can be realized on much thinner drift layers then for Si and GaAs diodes, achieving high breakdown voltage as well as lower on-resistance and good results have been demonstrated with a steady improvement in performance. SiC junction Schottky barrier diodes (JBS) are interesting in the 600 – 3300V blocking voltage regime. SiC Schottky diodes suffer from a rather high reverse leakage current, which is suppressed in JBS diodes. Moreover, in JBS diodes, the switching frequency and the blocking voltage/surge current capabilities are promising features compared to PiN and Schottky diodes.

2.5 RF power devices

SiC devices have shown considerable improvement and superior RF power performance to those available in Si or GaAs devices. The RF power available from an impact ionization avalanche transit time (IMPATT) diode in SiC is ~100 times higher than in Si or GaAs. The high temperature and/or high power SiC electronic devices would enable revolutionary improvements to aerospace systems, even without cooling systems. Replacement of hydraulic controls and auxiliary power units with distributed smart electro-mechanicals controls capable of harsh-ambient operation enables substantial jet-aircraft weight savings, and reduced maintenance.

3. Crystal Structure and Polytypism

The SiC's crystalline structure and its polytypic nature influence of polytypism on the physical properties of SiC. Silicon carbide is a binary compound containing equal amount of 'Si' and 'C', where, Si-C bonds are nearly covalent, with an ionic contribution of 12% (Si positively, 'C' negatively charged). The smallest building element of any SiC lattice is a tetrahedron of a Si (C) atom surrounded by four C (Si) atoms in strong sp^3-bonds. Therefore, the first neighbor shell configuration is identical for all atoms in any crystalline structure of SiC. The basic elements of SiC crystals is shown in Figure 1.

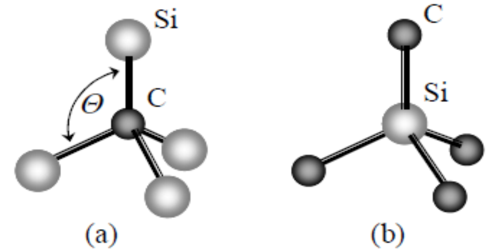

Fig. 1 Basic elements of SiC crystals: Tetrahedrons containing (a) one C and four Si (b) one Si and four C atoms

4. Semiconductor switching devices

The ideal switch should have: very high blocking voltage in off-state, very low on-state resistance, very short (zero) turn-on and turn-off times, very low turn-on and turn-off power dissipation. The switch should have only one gate, easy control and it should be in the off-state without a controlling signal. In real power semiconductor device structures, described in details in e.g. in [1],[2], the high blocking voltage is connected with the existence of a thick space charge region (depletion layer) at the PN junction that spreads with increasing voltage into a low doped area of the structure. A PN junction breakdown occurs if the electric field in the depletion layer reaches its critical value *Ecrit*. From simple theory, the breakdown voltage *VBR* depends on donor concentration *ND* in a low doped area, as

$$V_{BR} = \varepsilon_o \varepsilon_r E^2_{crit} / 2eN_D \qquad \dots (1)$$

The breakdown voltage may also be expressed as,

$$V_{BR} \xi W_D E_{crit} \qquad \dots (2)$$

where *w*D is the thickness of the high resistivity (low doped) region and $0.5 < \xi < 1$ ($\xi = 0.5$ for the non punch through case, $\xi = 1$ for an ideal PIN structure). Therefore, the thickness of the structure increases with increasing blocking voltage, as shown in Figure.2. Perfect junction surface termination is necessary in order to obtain a high breakdown voltage.

A common design objective of power semiconductor switches is to optimize the combination of conduction losses and switching losses (in the form of heat), because the maximum operating temperature *Tjmax* is limited to prevent thermal breakdown. The maximum power losses are limited by,

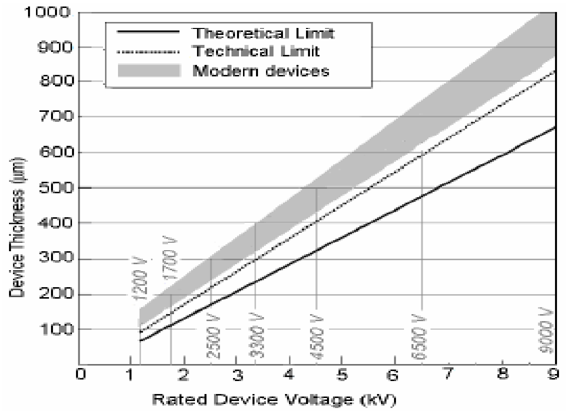

Fig.2 Comparison between the minimum device thickness and breakdown voltage

$$\mathbf{P_{AVmax} \leq (T_{jmax} - TA)/R_{thja}} \qquad \dots (3)$$

Tj max is the maximum junction temperature, *Ta* is the temperature of the ambient, and *Rthja* refers to the thermal resistance between the semiconductor junction and the ambient. Thus, the maximum current in a particular application is influenced not only by the characteristics of the device but also by the thermal resistance of the encapsulation and the thermal resistance of the heat sink. The maximum operating temperature *Tjmax* decreases with the device blocking voltage [3][4], as shown in Figure 3.

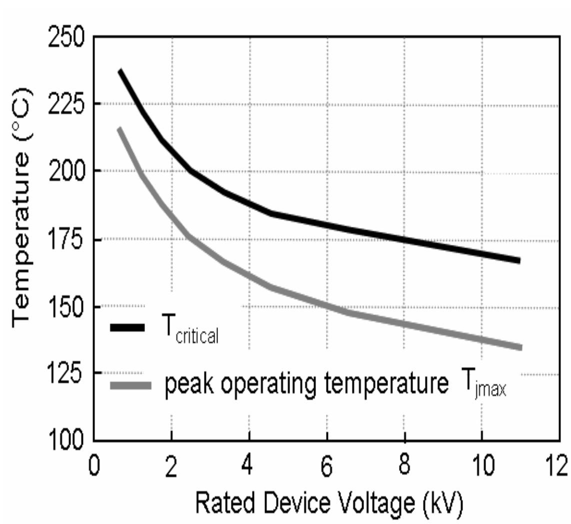

Fig.3 Critical thermal runaway temperature and the estimated maximum safe operating temperature *Tjmax* of silicon devices

The power losses of a hard switching device operating at frequency *f* can be expressed by

$$\mathbf{P_{AV} = \Psi I_{on} V_{on} + f(W_{on} + W_{eff}).} \qquad \dots (4)$$

where, *Ion* is on-state current, *Von* is on-state voltage, *Won* are onstate losses, *Woff* are off-state loses and ψ represents the duty cycle. Eqs. (3) and (4) provide limits for device application, as demonstrated in Figure 4. Some important features of the most important types of switching devices are discussed bellow.

The current and future power semiconductor devices developmental direction is shown in Figure 5. High temperature operation capability and low forward voltage drop operation can be obtained if silicon is replaced by silicon carbide material for producing power devices. The silicon carbide has a higher band replaced by silicon carbide material for producing power devices. The silicon carbide has a higher band gap than silicon. Hence, higher breakdown voltage devices could be developed. Silicon carbide devices have excellent switching characteristics and stable blocking voltages at higher temperatures. But, the silicon carbide devices are still in the very early stages of development.

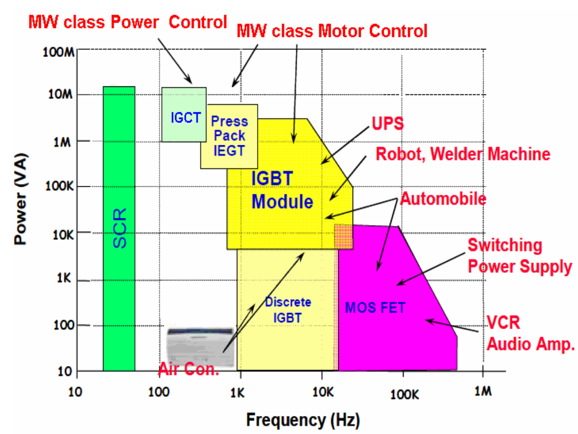

Fig.4 Application fields of power devices

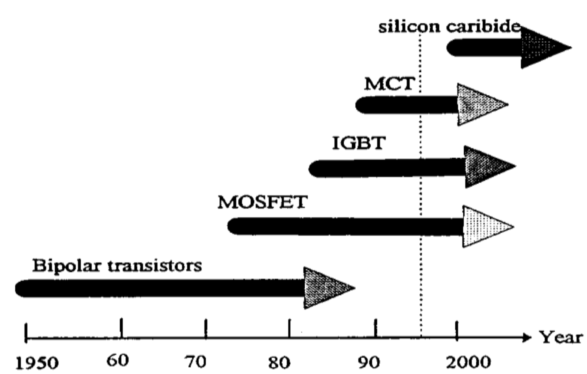

Fig. 5 Current and future power semiconductor devices development direction

5. SiC Electronic Properties

The electronic parameters of SiC are superior to silicon, thereby offering advantages in terms of electronic performance. For high temperature operation, the most important parameter is the intrinsic carrier concentration i.e. the background density of holes and electrons in the material caused by thermal generation. The generation rate of hole-electron pairs decreases exponentially with the bandgap energy, and the wide bandgap of SiC makes the background carrier concentration orders-of-magnitude smaller than that of silicon, because the maximum operational temperature of a semiconductor device is limited by the temperature where the background density of holes and electrons becomes comparable to the minimum doping in the device. The intrinsic carrier concentration of silicon and 4H-SiC **as** a function of temperature. Assuming that the minimum doping in the device is 10^{15} cm^{-3}, the maximum junction temperature of a silicon device would he only about 250 ℃. In contrast, the maximum junction temperature of the same device made in 4H-SiC would be above 1000 ℃. This does not mean that SiC devices can actually be operated at 1000 ℃**,** because other mechanisms will impose lower limits. However, imply that the semiconductor does not impose any electronic limits to the maximum temperature.

Another important electronic parameter is the critical electric field for avalanche breakdown. The critical field in 4H-SiC is almost ten times higher than in silicon. An important figure of merit figure-of-merit, $\mu_n \boldsymbol{\varepsilon_s}$ Ec^3. Because of the high critical field, the Baliga figure of merit in 4H-SiC is about 400 times higher than in silicon. The specific on-resistance (i.e. the resistance-area product) of unipolar devices such as power MOSFETs is inversely proportional to the Baliga figure-of merit. Since this figure-of-merit is 400x higher in SiC, the specific on-resistance in SiC can he up to 400 times lower than in silicon for the same blocking voltage. Results approaching this figure have recently been achieved in actual SiC power devices. Another important advantage of SiC is its high thermal conductivity, 3.3 W/cm K, approximately twice as high as silicon. This facilitates efficient heat removal from the device during high power operation. The electron saturation drift velocity in SiC is also about twice as high as silicon, but the electron mobility is only about 60% of the silicon value. SiC has the distinction of being the only compound semiconductor whose native oxide is silicon dioxide, $Si0_2$. This makes it possible to fabricate the entire range of MOS devices in the material. However, as an insulator, $Si0_2$ is not suitable for high temperature operation (i.e. T > 250℃), since it is subject to charge injection at high temperatures and high electric fields. Consequently, SiC devices for high-temperature operation will need to avoid the use of $Si0_2$ insulating films in parts of the device where electric fields are also high.

Power electronic converters process giga watts of power at some point between where it is generated and where it is ultimately utilized; this emphasizes the need for highly efficient power electronic converters and systems in these utility applications. Figure 6 shows a typical cost structure for the converter station [3]. 20% of the converter station cost is due to valves. Presently, thyristors are used in the valves. For high voltage rating of converters of the order of tens and hundreds of KV, many silicon-based power electronic devices are connected in series. With the high voltage capability of wide band-gap semiconductors, replacing the many Si devices by a few wide band-gap semiconductor based power devices is desirable. This will decrease the device count, size, cost of the converter, erection and civil work/maintenance costs, and T&D losses.

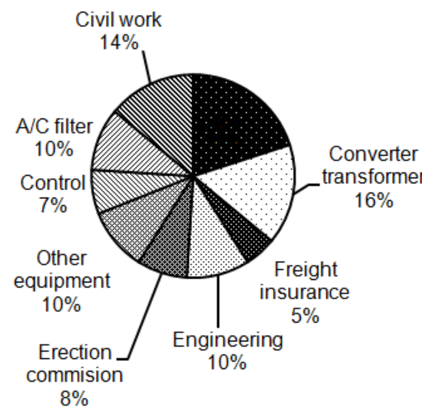

Fig. 6 Cost structure for the converter station

6. Results and Discussion

In this work, Silicon Carbide discussed some of the results in that MPS diode charges shows different voltage levels in Figure 10 shows the structure of MPS diode. The substrate is selected as Silicon carbide material. The boron and phosphorus is used impurities to form mps diode. Aluminum contact is used as electrode. Thickness of the device is made 80 µm and height is taken as 10µm. This is shown in Figure 7.

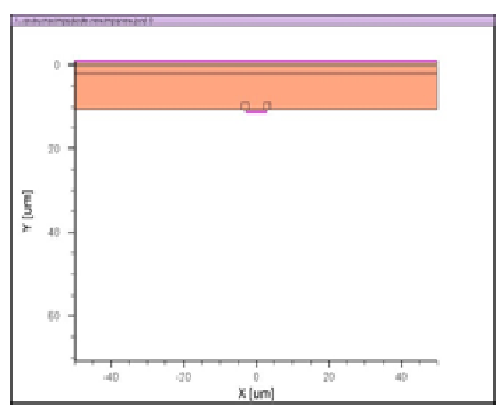

Fig. 7 Structure of Silicon Carbide mps diode

Figure 8 shows the characteristics of MPS diode total current in amperes verses maximum temperature. Figure 9 shows the characteristics obtained for MPS diode anode charge v/s anode outer voltage. Here, the mps diode forward voltage drop is around 3 volts.

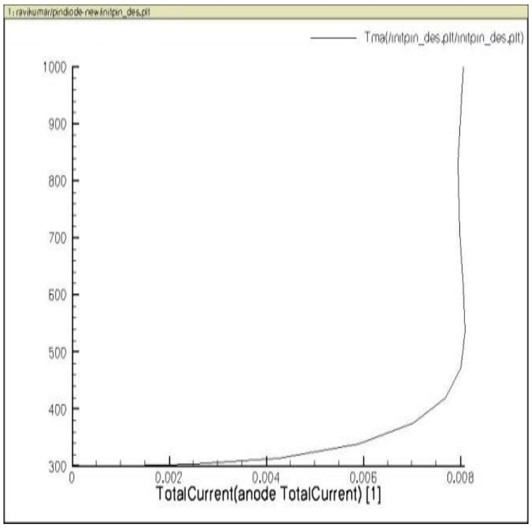

Fig. 8.MPS diode total current in amperes verses maximum temperature.

The MPS diode charge verses anode inner voltage is obtained by varying the anode outer voltage and recording the charge. The anode voltage is minimum the charge and charge increases with increase in the anode outer voltage is shown in Figure 10.

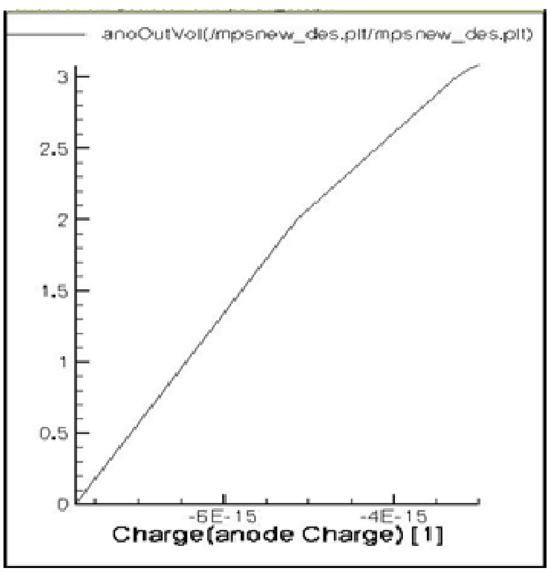

Fig. 9 MPS diode charge verses anode outer voltage

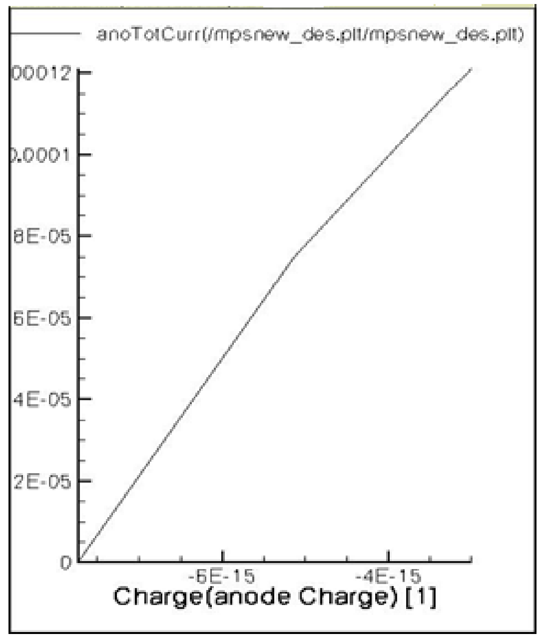

Fig. 10. Shows the characteristics of MPS diode charge verses total anode inner voltage

7. Conclusion

In this work, it devoted to realization of an industrial process for the fabrication of SiC diodes for high power and high temperature. To date, there has been no concerted effort to optimize SiC integrated circuits for high-temperature operation, primarily because a strong commercial driver (system pull) has not been present. However, the basic high-temperature capability of the technology is undeniable, and the material quality and fabrication technology have been maturing rapidly. With proper optimization, discrete devices and integrated circuits in SiC should be able to operate reliably at junction temperatures in the 300 -600 ℃ range. Because of their wide bandgap energy and extreme physical stability, certain classes of SiC devices are also expected to be highly radiation tolerant.

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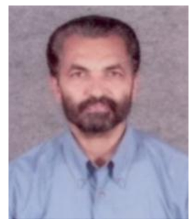

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