Power loss analysis of silicon carbide devices

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Received 25 February 2000; accepted 14 December 2000

Power loss analysis has been performed for silicon and silicon carbide based power MOSFETs in terms of device electrical characteristics such as forward current, blocking voltage, gate voltage, operating frequency and material properties like mobility, critical electric field, dielectric constant, etc. It has been observed that minimum power losses in silicon carbide power MOSFETs are significantly less compared to silicon devices for same current, voltage (10 A, 500 V and 5 A, 1000 V) and operating frequency (1 kHz-10 MHz). Calculations have also been carried out for minimum device area corresponding to minimum power losses for silicon carbide and silicon power MOSFETs. Silicon carbide devices will need smaller area compared to silicon to operate at a given power level.

Advancements in crystal growth processes and fabrication technology have led to resurgence of interest in the device research based on silicon carbide material. It has wide energy band gap, higher breakdown electric field, higher thermal conductivity and higher electron saturation velocity. All these properties make silicon carbide a material of choice for devices for high power, high frequency and high temperature applications. During last few years a lot of research work has been carried out to develop various devices; p-n junction diodes, Schottky barrier diodes, and power MOSFETs in silicon carbide.

Silicon carbide exhibits a large number (more than 200) of polytypes with different structures; cubic, hexagonal and rhombohedral. Amongst these polytypes, 4H-SiC is attractive because of its favourable properties compared to others. Material properties of some semiconductor materials are given in Table 1. Higher band gap in SiC results in extremely low leakage currents even at higher temperatures. Higher breakdown field $E_b$ facilitates realisation of high voltage structures with less resistive and thin drift layers resulting in lower conduction power losses while higher thermal conductivity allows rapid removal of heat generated within device structure.

When a power (high voltage-high current) device operates in a system, power losses occur due to its internal resistance. At low operating frequency, these power losses can be assumed to be due to conduction only. But at higher frequency both conduction and switching losses must be taken into account. We have calculated minimum power losses in high voltage 4H-SiC power MOSFET structure shown in Fig. 1 at low and high frequencies. These results have been compared with same structure based on silicon. For 1000 V power MOSFET unit cell structure, products of minimum power losses and device area have been computed as a function of device current at an oper-

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Silicon</th>
<th>GaAs</th>
<th>GaN</th>
<th>6H-SiC</th>
<th>4H-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap (eV)</td>
<td>1.12</td>
<td>1.43</td>
<td>3.4</td>
<td>2.9</td>
<td>3.25</td>
</tr>
<tr>
<td>Breakdown electric field (MV/cm)</td>
<td>0.25</td>
<td>0.3</td>
<td>-3</td>
<td>-3</td>
<td>-3</td>
</tr>
<tr>
<td>Electron mobility @ $N_e=10^{16}$ (cm$^2$/V.s)</td>
<td>1200</td>
<td>6500</td>
<td>900</td>
<td>400</td>
<td>800</td>
</tr>
<tr>
<td>Thermal conductivity (W/cm-K)</td>
<td>1.5</td>
<td>0.5</td>
<td>1.3</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>11.9</td>
<td>12.8</td>
<td>9</td>
<td>9.7</td>
<td>9.7</td>
</tr>
<tr>
<td>Saturated electron velocity (10$^7$ cm/s)</td>
<td>1</td>
<td>2.0 peak</td>
<td>2.5 peak</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
Power Loss Analysis

The operation of a semiconductor power device is influenced by the power dissipation within the device structure, which determines the temperature rise,

$$\Delta T = T_j - T_A = P_0 R_0$$  \hspace{1cm} (1)

where $P_0$ is the power dissipation, $R_0$ is thermal resistance, $T_j$, $T_A$ are junction and ambient temperature respectively. Power loss in a device can arise during current conduction and blocking state as well as during switching between these states. The leakage current in power devices is generally very small so that power losses during forward blocking state can usually be neglected.

In systems operating at lower frequencies the power losses are mainly due to conduction process,

$$P = I^2_{\text{r.m.s.}} R_{ON}$$  \hspace{1cm} (2)

$R_{ON}$ is the resistance of the device structure to the current flow. In power MOSFETs it is the total resistance between source and drain terminals\(^15\). Conveniently, it is described in terms of device area and termed as specific on-resistance, $R_{ON SP}$ with units of ohm-cm\(^2\). Eq. (2) can be written in terms of device area and $R_{ON SP}$ as,

$$P = I^2_{\text{r.m.s.}} R_{ON SP} / A$$  \hspace{1cm} (3)

Further, $R_{ON SP}$ can be represented in terms of breakdown voltage and other material parameters\(^15\) and Eq. (3) can be written as,

$$P = \frac{I^2_{\text{r.m.s.}} 4(V_B)^2}{A \mu E_c^3}$$  \hspace{1cm} (4)

where $V_B$ is the device breakdown voltage, $E_c$ is the critical electric field at breakdown condition and $\mu$ is the electron mobility. Eq. (4) suggests that product of power loss and device area can be represented in terms of device current, breakdown voltage, $\varepsilon$, $\mu$ and $E_c$,

$$P A = \frac{I^2_{\text{r.m.s.}} 4(V_B)^2}{\varepsilon \mu E_c^3}$$  \hspace{1cm} (5)

Eq. (5) has been used to calculate power loss and area product for 1000 V power MOSFET with various current capabilities (5 to 20A) using material parameters of silicon and 4H-silicon carbide polytype.

In high-frequency systems, power loss calculation should take into account the switching losses during operation. For simplicity, we have assumed that switching losses are due to charging and discharging of the input capacitance of the power MOSFET. The total power losses are given by\(^16\),

$$P = I^2_{\text{r.m.s.}} R_{ON SP} / A + C_{IN SP} V_G^2 f$$  \hspace{1cm} (6)

$R_{ON SP}$ and $C_{IN SP}$ are device parameters determined by material properties and unit cell design. With increase in area, the first term decreases and second term increases. Hence, power loss exhibits a minimum at an area at which $dP/\text{d}A = 0$. This results in minimum power losses,

$$P_{min} = \frac{8I^2_{\text{r.m.s.}} V_G^{1.75} V_B^{1.5} f}{\mu E_c^3}$$  \hspace{1cm} (7)

at a device area given by

$$A_{min} = \frac{8I^2_{\text{r.m.s.}} V_B^{2.5}}{\varepsilon \mu E_c^4 V_G^{1.5}}$$  \hspace{1cm} (8)

Minimum power losses have been calculated for 500 V, 10 A and 1000 V, 5 A power MOSFET structure as a function of operating frequency using Eq. (7).
and material parameters of silicon and 4H-SiC, Table 1. Further, minimum device area corresponding to minimum power loss has been calculated using Eq. 8 for various materials; Si, GaAs, GaN, 4H-SiC and 6H-SiC for 1000 V, 5 A power MOSFET structure at operating frequency of 1 MHz.

Results and Discussion

For power loss calculations and analysis we have chosen high voltage power MOSFET structure because it is widely used in switching and motor control applications. In low operating frequency systems, conduction power losses have been calculated for 1000 V power MOSFET of varying current capabilities. As a measure of quality of device design, product of power loss and device area, \( P \cdot A \) has been calculated as a function of material parameters \( \mu, E_c \) and \( \varepsilon \) of silicon and 4H-SiC. Results are shown in Fig. 2. For 4H-SiC power MOSFET, power loss area product is 0.0018 W cm\(^{-2}\) compared to 1.125 W cm\(^{-2}\) for silicon. This is due to one order of magnitude difference in critical electric field in two materials. This difference even offsets lower electron mobility in 4H-SiC (800 cm\(^2\) V\(^{-1}\) s\(^{-1}\)).

For high frequency switching applications, conduction and switching power losses are considered. Power losses greatly depend upon the device area and hence exhibit a minimum value, Eq. (7), at minimum device area, Eq. (8). Calculated minimum power losses \( P_{l_{\text{min}}} \) as a function of operating frequency for 500 V, 10 A 4H-SiC power MOSFET structure are shown in Fig. 3 with gate bias voltage equal to 20 V. These values are compared with silicon for same current, voltage and bias values. As can be seen, minimum power losses in 4H-SiC are an order of magnitude lower than silicon case. Fig. 4 shows results for 1000 V, 5 A power MOSFET structure. At 1 kHz, \( P_{l_{\text{min}}} \) in 4H-SiC power MOSFET is 0.0129 W while in silicon it is 0.11 W. Similarly at 1 MHz, \( P_{l_{\text{min}}} \) (4H-SiC) = 0.41 W and \( P_{l_{\text{min}}} \) (Si) = 3.76 W. This means minimum power losses in 4H-SiC are significantly lower than in silicon. It improves efficiency and reliability of electronic systems using SiC devices in place of silicon devices.

Calculated minimum device area values corresponding to minimum power losses for different materials are given in Table 2. Minimum area values in other materials are normalised to the value of silicon (1.0). \( A_{\text{min}} \) for GaAs is 0.3046 but this material is not suitable for high temperature operations. In GaN, this value is 0.009 while for 4H-SiC, \( A_{\text{min}} = 0.009 \) and for 6H-SiC, \( A_{\text{min}} = 0.014 \). These values indicate that in
Table 2—Calculated minimum device area corresponding to minimum power losses for different materials for 1000 V, 5 A power MOSFET at operating frequency of 1 MHz

<table>
<thead>
<tr>
<th>Materials</th>
<th>Silicon</th>
<th>GaAs</th>
<th>4H-SiC</th>
<th>6H-SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\text{min}}$</td>
<td>1.0</td>
<td>0.3046</td>
<td>0.0099</td>
<td>0.014</td>
<td>0.0097</td>
</tr>
</tbody>
</table>

*The area values have been normalized to Silicon value for comparison.

Fig. 4—Variation of minimum power losses with operating frequency for 1000 V, 5 A power MOSFET designed in silicon and 4H-SiC

4H silicon carbide (4H-, 6H-), significantly smaller die size is required for same power handling capability. These results indicate that compact and reliable systems can be made employing silicon carbide based power MOSFETs and other devices.

Conclusions

Power losses have been calculated for 500 V and 1000 V power MOSFET structure designed in 4H-SiC and conventional material silicon. Calculations have revealed that minimum power losses in 4H-SiC are approximately one order of magnitude lower than in silicon in the frequency range 1 kHz-10 MHz. For low operating frequency systems, product of power loss and device area in 1000 V, 5A power MOSFET in silicon is 1.125 W·cm² while in 4H-SiC, it is 0.0018 W·cm². Minimum area corresponding to minimum power losses in 4H-SiC power MOSFET is roughly hundred times smaller compared to silicon. All these results suggest that silicon carbide is a superior material for devices for high power, high frequency and high temperature applications.

Acknowledgements

Authors are thankful to Director, CEERI for his keen interest and encouragement for this work.

References