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A COMPARISON OF SiC POWER SWITCHES FOR HI-REL DEFENSE APPLICATIONS (PREPRINT)

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14. ABSTRACT
SiC VJFETs are an ideal device for a number of power electronics applications, including, but not limited to, high temperature motor drives, switch modules, and DC-DC or DC-AC inverters/converters. These applications are relevant to a number of military applications, such as shipboard power systems, more electric vehicles (including hybrid vehicles), and power conditioning systems in hostile and/or high temperature environments. The SiC VJFETs combine the switching speed of Si MOSFETs with the voltage and current handling properties of IGBTs and the thermal properties of SiC material. Since the VJFET is a unipolar device, it can easily be paralleled over the entire operating temperature range of the device. The SiC VJFET has a lower specific on resistance than the best Si IBGT and lacks the gate oxide problems of the SiC MOSFET. Because of the thermal properties of SiC and the lack of a gate oxide, they are capable of higher temperature operation than either device. The vertical channel structures provide for excellent packing density on the wafer and low per-unit production costs.

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A COMPARISON OF SiC POWER SWITCHES FOR HI-REL DEFENSE APPLICATIONS

Jeffrey B. Casady and Michael S. Mazzola

Abstract

Three principal switch types based on silicon carbide have achieved a reasonable level of maturity for defense applications. They are the vertical junction field effect transistor (VJFET), the metal-oxide-semiconductor FET (MOSFET), and the bipolar junction transistor (BJT). The VJFET is principally valued for having demonstrated the highest current and voltage combinations, positive temperature coefficient over the entire applications range of -40 C to 300 C; and other features that are either inherent to the simplicity of the VJFET or to their somewhat greater technology readiness level, such as the lowest reported specific on-resistance, rugged radiation tolerance, and good reliability at operating temperatures well above 175 C. In principal, this makes the VJFET the preferred solution for high-reliability applications in the defense and the commercial sectors, but the perception remains that the VJFET is a normally on device that is not compatible with typical circuits and methods in power electronics. However, the large built-in potential of the SiC pn-junction gate, a liability in power diodes, is an asset for VJFET power switches for expanding the design options for threshold voltage to include positive threshold voltage (meaning normally off devices).

1. INTRODUCTION

It is now beyond question that silicon-carbide based electronics have a role in future defense and civilian power electronics. One key indicator is that the SiC Schottky barrier diode (SBD) is commercially available and is being adopted in power supplies. Another is that the most technologically ready SiC power switch, the vertical junction field effect transistor (VJFET), has been demonstrated in preproduction devices at all applicable voltage levels between 600 and 1800 V [1-2]. The fact that preproduction versions of the 600-V JFET can now claim "best in" class over the very best silicon 600-V MOSFETs means that commercial availability of a SiC switch is near at hand. The question remains, which of several competing device technologies will be adopted by the market? This question is an important consideration for the defense community because what happens in the commercial market place will ultimately drive adoption trends in the defense market as well. We assume that the viability of the VJFET and the MOSFET are sufficiently guaranteed that the only issue is between the two FET technologies. The BJT, while technically feasible, will face much greater challenges to adoption due to the preference for voltage control over current control in power electronics. In this paper, a brief comparison of the latest results of the two FET technologies is followed by a discussion of the core technical issue, that of "normally on" versus "normally off" switches (or depletion-mode versus enhancement-mode operation). As conventional wisdom goes, the SiC MOSFET is the only plausible winner in either the near or the long term, a conclusion often based on projecting the properties of a silicon JFET onto the SiC VJFET. We challenge the conventional wisdom based on an analysis of the features necessary for applications to economically adopt SiC devices of any type and of the true properties of the SiC VJFET.

2. PERFORMANCE COMPARISONS

Complicating the performance comparison of the SiC VJFET and the SiC MOSFET is the lack of well established commercial availability of either part. However, preproduction samples are becoming available for both types of parts, and combined with the most recent literature, a comparison is possible for an important figure of merit: the product of the absolute on-resistance R_{on} and the total gate charge Q_g required to change the state of the FET from blocking to conducting at R_{on} (or vice versa). It is widely accepted that the smaller the figure of merit (FOM) the better the FET technology is for use in switch mode power supply (SMPS) applications. This FOM is widely used to compare silicon FET technology. The advantage of this FOM is that it is independent of die area. Simply making the device larger does not solve the problems of the SMPS designer, because increasing the die size

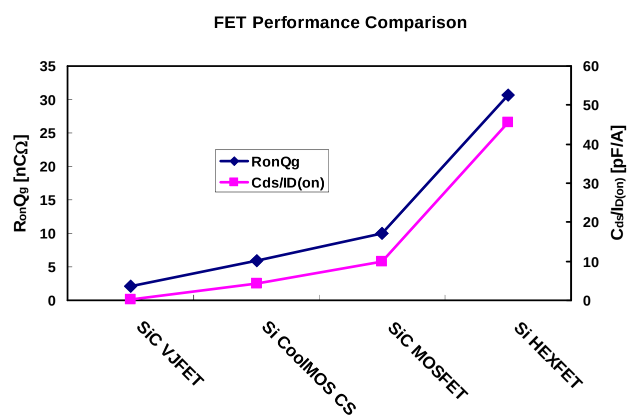

Figure 1. FET performance comparison. $I_{D(on)}$ is calculated from R_{on} at V_{DS} = 3 V.

may indeed lower the on resistance, but it also increases the capacitances which determine Q_g; which is known to be proportional to switching losses. In addition to the FOM, another device characteristic that is a problem in applications is the drain-source capacitance of the FET. C_{ds} in a high-voltage FET stores energy during blocking that is lost during the turn-on transition, a loss that is in addition to that predicted by the R_{on} Q_g FOM.

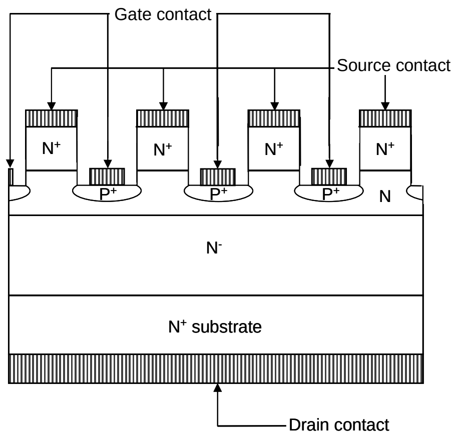

Fig. 2(a). A schematic cross-sectional view of a vertical-channel SiC VJFET.

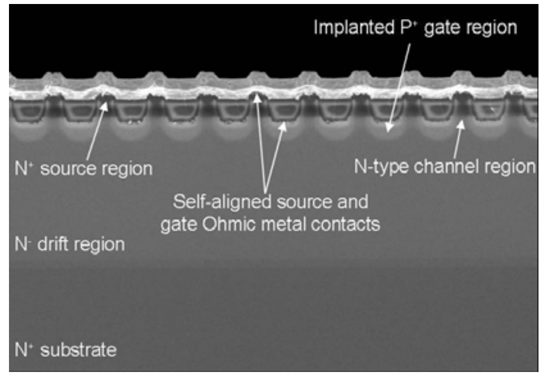

Fig. 2(b). Cross-sectional SEM image of the structure of a vertical-channel SiC VJFET.

Figure 1 compares the FOM and the C_{ds} relative to the current rating of a representative collection of field effect transistors. The SiC VJFET is the vertical-channel type being sampled by SemiSouth Laboratories, Inc. to various institutions with defense-related applications. This VJFET has a R_{on} = 0.37 Ω @ V_{GS} = 3 V. The SiC MOSFET parameters are estimated from data widely available from published and unpublished sources based on results from preproduction engineering samples with ratings similar to that of the SiC VJFET. The SiC MOSFET has a R_{on} = 0.5 Ω @ V_{GS} = 25 V. The International Rectifier HEXFET represents the conventional silicon MOSFET. The 600-V CoolMOS CS MOSFET from Infineon represents the current "best in class" for silicon. With respect to both the FOM and C_{ds} the SiC vertical-channel VJFET is significantly better than the Infineon CoolMOS CS, but the SiC MOSFET does not yet beat the "best in class" for silicon. The IR HEXFET is a distant fourth. In this performance comparison, the SiC VJFET is the near term leader. With such low R_{on}, Q_g, and C_{ds}, the SemiSouth VJFET has characteristically very fast switching performance. Switching transition times of less than 50 ns and $f_{t(max)}$ of 41 MHz have been reported [2].

3. SiC VJFET CONDUCTION MODES

Given the abundant literature on the SiC VJFET and the SiC MOSFET, it can hardly come as a surprise that the SiC VJFET is currently best in class among FETs in terms of performance. However, it is not as commonly understood that there is not really an issue with functionality. Wide-spread conventional wisdom says that the SiC VJFET is limited in applications because it is a "normally on" switch. This curious belief seems to have evolved from association with the silicon JFET. However, this is an erroneous comparison, if for no other reason than the cut-on voltage for the SiC pn junction in the 4H polytype is about 3 V, whereas it is only 0.7 V for the silicon pn junction. This is a fundamental difference between the two materials that makes the SiC VJFET a potentially disruptive device technology. Figures 2(a) and 2(b) show the cross section of a modern SiC vertical-channel JFET. With proper design of the channel structure, this device can have a threshold voltage $V_t \geq 1$ V, which means the device can block a significant drain voltage when V_{GS} = 0 V. By design, this SiC VJFET can only be switched into conduction by applying $V_{GS} > V_t$, which means this FET has enhancement-mode functionality, just like the silicon or the SiC MOSFET. However, the VJFET conductivity is "enhanced" by barrier reduction, as opposed to inversion of majority carrier type as in the MOSFET. Because conductivity inversion in the channel of the MOSFET occurs at the semiconductor-oxide interface, the MOSFET suffers from surface effects such as low channel mobility; in contrast the channel mobility is many times greater in the VJFET. Therefore, an acceptably low on-resistance is achieved with the VJFET while keeping V_{GS} < 3 V, the SiC pn junction threshold for significant minority carrier injection. Since minority carrier injection is avoided, the SiC VJFET remains a unipolar device. Because a threshold voltage of 1 V is not physically possible with a silicon JFET, it makes no sense to treat the SiC JFET as though it were a silicon JFET. This seems to be the source of the erroneous assumption that applications using the SiC JFET must accept a purely "normally on" device.

Figure 3 illustrates the properties of an enhancement-mode vertical-channel JFET with a threshold voltage equal to approximately 1.3 V. The figure illustrates the relationship between the applied V_{GS} and the drain-source voltage blocked by the device when the drain current equals the compliance level of 50 µA. The device blocks approximately 300 V at V_{GS} = 0 V, but will block 600 V at V_{GS} = -1.5 V. We call this remarkable feature "enhancement-mode functionality with enhanced blocking capability" which has no analogue in enhancement-mode MOSFETs. The enhancement-mode VJFET of Fig. 3 has a very large blocking gain of 290 (defined as the ratio of the incremental increase in drain-source blocking potential for an incremental decrease in V_{GS}, $\Delta BV_{DS}/\Delta V_{GS}$). Thus, a 600-V rated device can be switched with a total gate voltage swing of 4 V. Given the already small size of the SiC power VJFET, a very low gate-voltage swing is an additional advantage likely to be welcomed by power supply designers. Most SMPS impose two different levels of voltage stress on the switch: A lower dc value during start-up and stand-by, and a higher transient value during gated

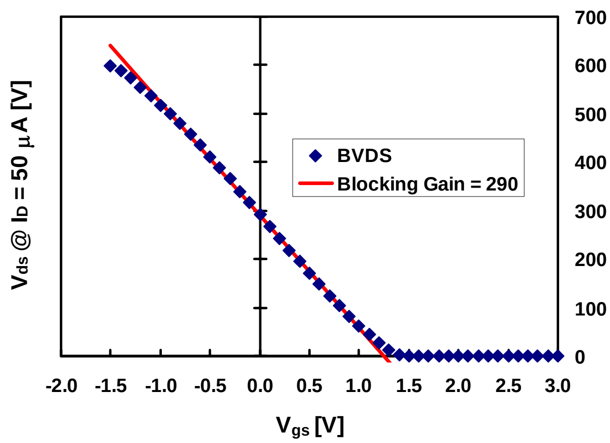

Figure 3. The blocking characteristics of an enhancement-mode vertical-channel SiC JFET.

operation. For example, a 200-V to 500-V, 1-kW dc-dc boost converter has been reported using the biased-enhanced blocking feature of an enhancement-mode SiC VJFET as an efficient way to fully utilize the available $R_{on}\,Q_g$ [3].

The VJFET shown in Fig. 2 is a conventional design. Non-conventional designs are under development that will have significantly increased blocking gain such that devices with voltage ratings of 600, 1200, or 1800 V will require no negative gate bias while continuing to achieve channel-limited on-resistance much lower than even the optimistic values projected for the SiC MOSFET. It is likely that the VJFET can be manufactured at lower cost and smaller size than the SiC MOSFET through any level of technical development. Such possibilities cast doubt on the long term viability of the SiC MOSFET with respect to the SiC VJFET in power supply applications.

4. THERMAL COMPARISON

In high-temperature applications, the VJFET will probably always be superior to the MOSFET. Multiple problems with the thermal stability and gate leakage of the SiC MOS structure limits the MOSFET for the foreseeable future to a junction-temperature $T_j \leq$ 175ºC. Since silicon IGBTs are nearing production with similar junction temperature ratings, it is not clear what the advantage of using SiC MOSFETs will be in important volume applications such as motor drives for hybrid electric vehicles (HEVs). In contrast, the junction temperature of the SiC VJFET is limited by packaging and metallurgy, and 500-hr reliability at 450ºC has been reported [4]. Near term SiC production VJFETs will be rated at T_j = 225ºC, which can ease the design and reduce the cost of HEV power trains by permitting high-power-density air-cooled motor drives. The devices also exhibit a positive temperature coefficient over the full range -55ºC $\leq T_j \leq$ 225ºC [5], which was recently exploited to demonstrate a 600-V, 150-A SiC VJFET switching device for potential IGBT replacement [6]. It is less likely that silicon switches will ever compete with SiC switches in compact, air-cooled HEV-class motor drives. The preference for air-cooled motor drives is well known, and this may be the most plausible entry point for SiC power devices in future HEV commercial production. Such a technical adoption path, while more speculative than for the switch mode power supplies, once again casts doubt on the long term viability of the SiC MOSFET with respect to the SiC VJFET.

5. CONCLUSIONS

The fundamental properties of the SiC VJFET have been shown to more closely achieve the features required by designers of both defense and civilian power electronics. In this analysis, the SiC VJFET is the truly disruptive technology, while the SiC MOSFET is a stopgap. However, the first generation of vertical-channel SiC VJFETs are sufficiently superior to both silicon and SiC MOSFETs that there may not be a need for a stopgap. With enhancement-mode performance demonstrated in SiC vertical-channel VJFET devices significantly beyond that of silicon, and given the technical problems of the SiC MOSFET, including performance that does not exceed that of silicon, it appears that conventional wisdom is incorrect: The SiC VJFET should become the preferred approach in both the near and the long term.

6. References

[1] Ållebrand, B. and H.-P. Nee, "On the Possibility to use SiC JFETs in Power Electronic Circuits," *Proc. European Conf. on Power Electronics and Appl. (EPE)*, Graz, Austria (August, 2001).

[2] Cheng, L., J. R. B. Casady, M. S. Mazzola, V. Bondarenko, R. L. Kelley, I. Sankin, J. N. Merrett, J. B. Casady, "Fast Switching (41 MHz), 2.5 mΩ·cm^2, high current 4H-SiC VJFETs for high power and high temperature applications," presented at *Inter. Conf. on SiC and Related Mat. (ICSCRM)*, Pittsburg, PA (2005).

[3] Kelley, R., M. S. Mazzola, and V. Bondarenko, "A Scalable SiC Device for DC/DC Converters in Future Hybrid Electric Vehicles," to be presented at *IEEE Appl. Power Electronics Conf. (APEC)*, Dallas, TX, (March, 2006).

[4] Mazzola, M. S., R. Kelley, J. Casady, V. Bondarenko, C. Wang, Y. Liu, and W. Johnson, "SiC Devices for Converter and Motor Drive Applications at Extreme Temperatures," to be presented at *IEEE Aerospace Conf.*, Big Sky, MT, (5-9 March 2006).

[5] Cheng, L., I. Sankin, J. N. Merrett, V. Bondarenko, R. Kelley, S. Purohit, Y. Koshka, J. B. Casady and M. S. Mazzola, "Cryogenic and High Temperature Performance of 4H-SiC Vertical Junction Field Effect Transistors (VJFETs) for Space Applications" *Proc. Inter. Symp. on Power Semi. Dev.* (ISPSD'05), Santa Barbara, CA (2005).

[6] Mazzola, M. S., L. Cheng, J. R. B. Casady, D. Seale, V. Bondarenko, R. Kelley, and J. B. Casady, "Scalable SiC Power Switches for Applications in More Electric Vehicles", presented at *6th Inter. All Electric Combat Vehicle (AECV) Conference*, Bath, England (June, 2005).

7. BIBLIOGRAPHY (IES)

Dr. Casady is a co-founder of SemiSouth and has served as President since January 2003. Since he assumed the leadership role for the Company, SemiSouth has doubled the revenue and embarked on transitioning the company toward commercialization. Dr. Casady has published over 60 technical publications, three book chapters, and received two patents, all in SiC device development. Dr. Casady worked for Northrop Grumman Science and Technology Center on several key projects, including the development of high-frequency S-band and L-band SiC SITs for pulsed, narrow-band, high-power radar applications (both ground-based and airborne). He also designed and fabricated some of the first SiC power switches; including thyristor/MOSFET based switches in the 1990s, and received marketing and project management training while there. Dr. Casady has a PhD in Electrical Engr. from Auburn University and a BS and MS in Electrical Engr. from the University of Missouri.

Dr. Mazzola is a co-founder of SemiSouth and is currently serving as Vice President for Technology. He received his PhD from Old Dominion University in 1990. He was previously employed at the Naval Surface Warfare Center as an Electronics Engineer in the Pulsed Power Research and Technology group. He joined the faculty at MSU in 1993 and moved to SemiSouth full-time in 2005. Dr. Mazzola has made engineering contributions in several technical areas including semiconductor devices and their applications in power electronics as well as pulsed power technology. He has conducted research in the areas of silicon carbide device prototyping and semiconductor materials growth and characterization for the last 12 years. Dr. Mazzola has published more than 70 papers and has been awarded four patents and is a member of the IEEE Electron Devices Society, IEEE Nuclear and Plasma Sciences Society, and the IEEE Power Electronics Society. Dr. Mazzola is a professional engineer registered in the state of Mississippi.