SIMULATIONS OF A HIGH POWER 4H-SiC VJFET AND ITS GaAs COUNTERPART [*]

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Abstract

In this paper, the 2-D simulator ATLAS is used to investigate and compare the voltage blocking capability, the current rating and the switching characteristics of VJFET's based on SiC and GaAs materials. As a part of this study, simulations and analysis of a normally-off 4H-SiC VJFET with 8kV blocking voltage are presented, along with similar results for its GaAs counterpart. This structure is optimized to achieve a high blocking voltage and a high current density. The goal of this work is to compare the performance of a SiC VJFET with that of a similar GaAs VJFET, and to provide guidelines for pulsed power applications.

I. INTRODUCTION

Pulsed power applications require semiconductor switches to have a large breakdown voltage, a large current handling capability, a low on-state resistance and a high switching speed. In addition, for high temperature switch operation, thermal stability is also essential [1]. It is commonly recognized that Si power devices are reaching their theoretical performance limit. For example, the use of Si power MOSFET's has been limited to breakdown voltages of the order of 1000 V.

GaAs power switches offer an alternative to those made from Si. For example, the larger bandgap of GaAs (1.43 eV compared to 1.12 eV for Si) permits higher breakdown voltages and operating temperatures [2-3]. Additionally, GaAs has much higher electron mobility than Si, so that the on-state resistance of GaAs devices can be significantly lower than that of Si devices. Lower on-state resistance means lower conduction and switching power losses [4-5].

Due to their potentially superior material properties, SiC devices are also attractive alternatives to those based on Si. For example, because the SiC bandgap is about three times larger than that of Si, the intrinsic temperature is higher, which means higher junction operating temperatures [1,6]. Also, because the breakdown field of SiC is about 10 times that of Si, thinner and higher doped drift regions can be fabricated, which lowers the on-state resistance [7]. In addition, the thermal conductivity of SiC is more than three times higher than that of Si, which permits better heat dissipation [2,7].

In recent years, 3-inch 6H-SiC and 4H-SiC wafers have become commercially available, and the quality of the substrates and epitaxial layers has been improved considerably. These provide the basis for the design and fabrication of high power SiC devices.

In this paper, we present results of simulations that compare the performance of a SiC VJFET with that of a GaAs VJFET with the same structure. A novel, normally-off VJFET structure is used for this purpose. This structure is employed to achieve a high breakdown voltage and a high current density. A comparison is presented of the voltage blocking capability, the I_d-V_d waveforms and the switching characteristics of the two devices. The two-dimensional simulations were carried out using the ATLAS simulator from Silvaco International. The parameters chosen in implementing the physical models we used in the simulations were generated by fitting experimental data [8-13]. In these simulations, the effects of deep level defects have been neglected.

II. DEVICE DESIGN AND STRUCTURE

In the VJFET design process, a high blocking voltage, a high current density, and minimization of the specific on-state resistance were the main properties considered.

The structure of the normally-off 4H-SiC VJFET we assumed for our simulations is shown schematically in Figure 1. A $50\mu m$-thick drift region, with a doping concentration of $5\times10^{14}cm^{-3}$ is assumed to be epitaxially grown on a heavily doped n substrate. An n- epilayer (lateral channel) is sandwiched between the source and the gate. A vertical channel is on the right of the gate. The lateral and vertical channel thicknesses (0.6 μm and 1.0 μm, respectively) are the critical parameters needed to achieve high blocking voltages and current densities.

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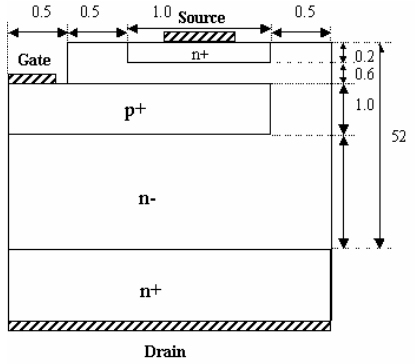

Figure 1. Schematic of a half-cell of the 4H-SiC VJFET. (Distances are in µm).

At the same time, the channel thicknesses and widths are chosen so that, at zero gate bias, the depletion regions are extended into the vertical and lateral channels by the junction built-in potential [14]. By forward biasing the gate, the depletion regions shrink and currents flow from the drain to the source when a reverse bias is applied between the drain and the source.

The GaAs VJFET we have considered uses the same structure. The dimensions and doping concentrations are carefully chosen so that we can get the best performance of a normally-off GaAs VJFET.

III. SIMULATION RESULTS

The temperature in the simulations was 300K. Figure 2 shows, for the SiC and GaAs devices, a plot of the predicted I_d vs. V_d when the drift region thickness is 50 µm. This shows that the breakdown voltage of the 4H-SiC VJFET is 8 kV. The leakage current density is 1×10^{-13} A/µm, which is equivalent to 1×10^{-5} A/cm^2. For the same leakage current level and drift region thickness, it can be seen from Figure 2 that the predicted breakdown voltage is 700 V for the GaAs VJFET. This value is about 0.09 of that for the 4H-SiC device.

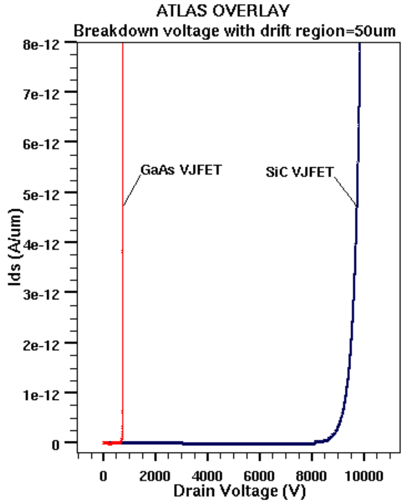

Figure 2. Predicted blocking voltage of the 4H-SiC VJFET at zero gate bias at 300K.

Figures 3(a) and 3(b) show the predicted gate current density as a function of gate voltage for the 4H-SiC and GaAs VJFET's, respectively. For the SiC device, at a gate bias of 2.9 V (V_{ds} = 10 V), the gate current density is 1×10^{-6} A/µm, which is comparable to the drain current density. However, when the gate bias is 2.8 V, the gate current density is 5×10^{-8} A/µm, which is about two orders of magnitude lower than the drain current density. In this case, the maximum gate voltage that can be applied is 2.8 V. This is controlled by the junction built-in potential. Similarly, the maximum gate voltage in the GaAs VJFET is 1.2 V with a gate current density of 2×10^{-7} A/µm.

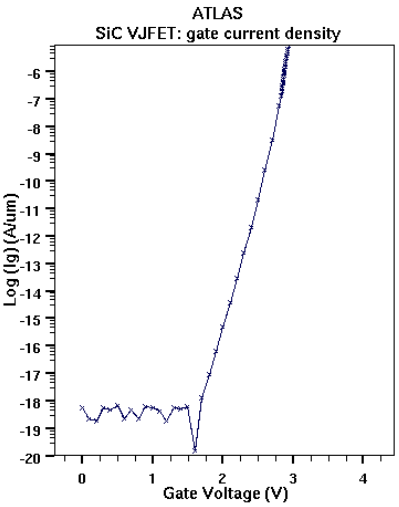

Figure 3(a). Predicted gate current density as a function of gate voltage for the 4H-SiC VJFET at 300K.

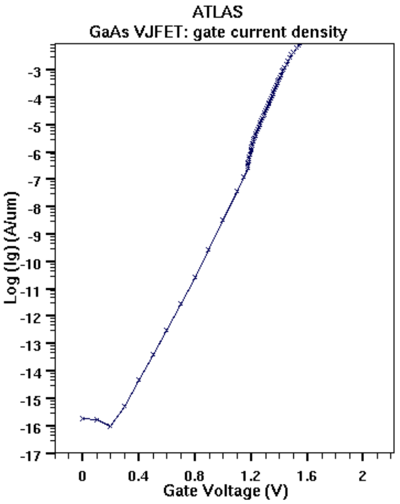

Figure 3(b). Predicted gate current density as a function of gate voltage for the GaAs VJFET at 300K.

Figures 4(a) and 4(b) show the predicted I_d-V_d characteristics of the SiC and GaAs VJFET's, respectively. At a V_{ds} of 5 V, the SiC VJFET can handle a current density of 185 A/cm^2, while the GaAs VJFET can handle 1475 A/cm^2. At a V_{gs} of 2.8 V, the current density level of the GaAs VJFET at a V_{gs} of 1.2 V is about eight times larger than that of the SiC VJFET.

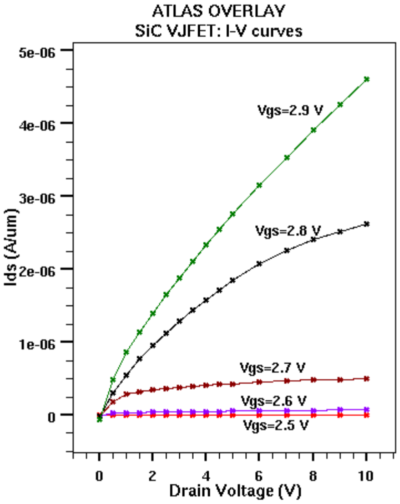

Figure 4(a). Predicted I-V characteristics of the 4H-SiC VJFET at 300K.

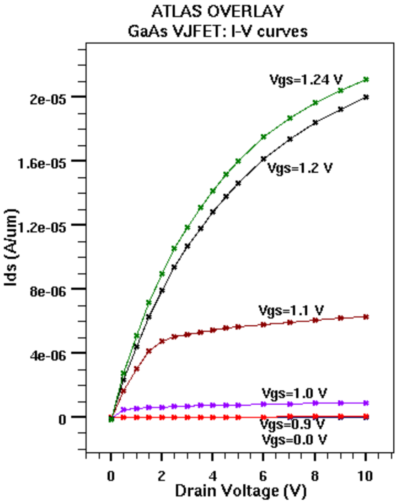

Figure 4(b). Predicted I-V characteristics of the GaAs VJFET at 300K.

The switching characteristics of the SiC VJFET with a resistive load have been simulated with a drain current density of 117 A/cm^2. The magnitude of the applied gate pulse was 2.75 V; the rise and fall times were both 2 ns. In simulations for the GaAs VJFET, the pulse magnitude on the gate was 1.2 V. Figures 5(a) and 5(b) show the predicted switching characteristics of the two VJFET's. From these figures, it can be seen that the VJFET's are predicted to have almost the same switching speeds, although the GaAs device is slightly faster. The rise and fall times are both 2 ns for the SiC VJFET. The rise time of the GaAs VJFET is less than 1 ns, and the fall time is about 1.5 ns.

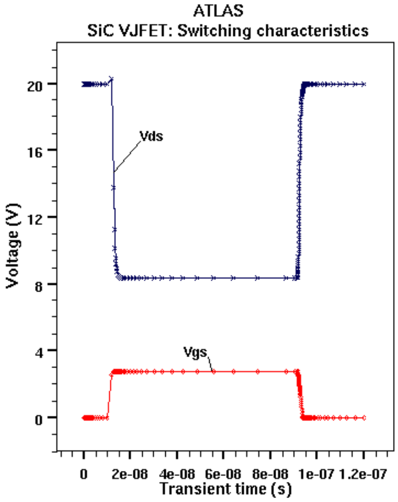

Figure 5(a). Predicted switching characteristics of the 4H-SiC VJFET at 300K.

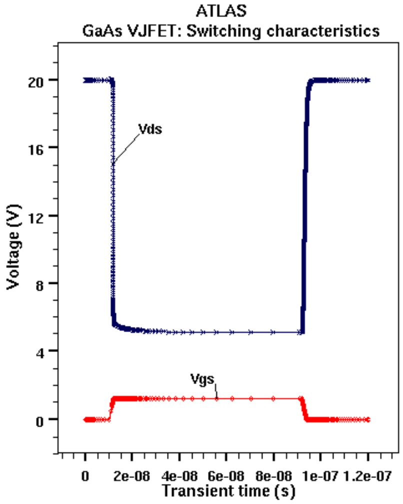

Figure 5(b). Predicted switching characteristics of the GaAs VJFET at 300K.

Our simulation results show that the predicted current density of the GaAs VJFET is about eight times higher than that of the SiC VJFET with the same structure. However, because the thermal conductivity of GaAs (0.46 W/cm-K) is about 0.1 that of SiC (4.9 W/cm-K), thermal runaway is a major concern for GaAs devices. Also when the electric field is more than about 4 kV/cm, GaAs devices exhibit negative differential resistance and can become inherently unstable.

These simulations thus show that, for the particular VJFET structure we have used, due to predicted better overall performance, SiC VJFET's are a potentially attractive alternative to those made from Si and GaAs.

IV. CONCLUSION

A novel, normally-off 4H-SiC VJFET structure with a blocking voltage of 8 kV has been described and simulated. Its characteristics have been compared with those of its GaAs counterpart. The simulations were performed using the 2-D ATLAS simulator. The results show that, with the same drift region thickness of 50 μm, the voltage blocking capability of the 4H-SiC VJFET is about 11 times larger than that of the GaAs VJFET, although the current density of the GaAs device is about eight times larger than that of the SiC device.

These simulations and our analysis suggest that SiC power devices are potential alternatives for Si and GaAs devices in pulsed power applications. However, in practice, their use requires considerable improvements in SiC materials growth and device fabrication techniques.

Issues related to the effects of deep level defects on VJFET's are considered in a separate paper [15].

V. ACKNOWLEDGEMENTS

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V. REFERENCES

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