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Cryogenic and High Temperature Performance of 4H-SiC Vertical Junction Field Effect Transistors (VJFETs) for Space Applications

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Abstract

In this paper, we present an investigation on the different aspects of the performance of a 600V, 3A 4H-SiC vertical-trench junction field effect transistor (VJFET) at cryogenic and high temperatures. Some critical device physics related factors that affect the DC characteristics and switching performance of the device are explored. In particular, the experimental low-temperature performance of 4H-SiC VJFETs (down to 30K or -243°C) is presented for the first time to our knowledge.

Introduction

Applications of switching of electronic circuits and systems for use in earth orbiting and deep space missions require high-power operations under extremely low temperatures and high radiation environment. In order to reduce the weight and improve the efficiency and reliability of power systems used in these systems, the power electronics need to be able to operate over a wide temperature range with a high radiation tolerance. Silicon carbide (SiC) power switches are logical candidates for these applications due to the excellent material physical properties of SiC such as wide energy band-gap, high dielectric breakdown strength and high thermal conductivity. VJFETs in SiC are especially attractive for high power applications thanks to the inherent stability of their p-n junction gate, which is free from gate oxidation problems concerning channel mobility in MOS structure and high-temperature reliability issues in MESFETs having metal-semiconductor Schottky barrier. To date, the operation of SiC power FETs at extremely low temperatures has not been thoroughly investigated. Previously, operation of 4H-SiC VJFETs has been demonstrated at junction temperatures over 300ºC (1) and shown promise under high radiation (2). Performance of the 4H-SiC bipolar junction transistor at 100K has been also studied (3).

In 4H-SiC VJFETs, the specific on-resistance is a primary device performance parameter. Both free electron density and electron mobility in the nitrogen-doped channel and drift regions are temperature-dependent (4) and play important roles in determining the on-resistance hence forward drop of the device. Above the temperature at which the nitrogen donors are almost fully ionized, the on-resistance is defined mostly by the electron mobility. With decreasing temperature below a certain point, ionization percentage of the nitrogen donors (free electron concentration) starts dropping down dramatically (carrier freezeout) and becomes the dominant factor that limits device on-state conduction, leading to an increase of the channel resistance. Freezing of the nitrogen donor results not only in conductivity degradation of n-type SiC layers, but also causes narrowing down the device channel until it becomes fully depleted. A change of the channel depletion width with temperature results in a change in the threshold voltage of the SiC VJFET. On the other hand, the freeze-out of free holes in the gate region occurs at significantly higher temperatures due to the energy position of the Al acceptor level. However, we did not observe significant indications of this effect influencing the device performance. Furthermore, the temperature dynamics of the switching frequency is similar to that of the threshold voltage. In this paper, we have investigated experimentally the effects of temperature on the DC and switching performance of the 4H-SiC VJFET fabricated in house from temperatures as low as 30K for the first time to 473K.

Device structure and fabrication

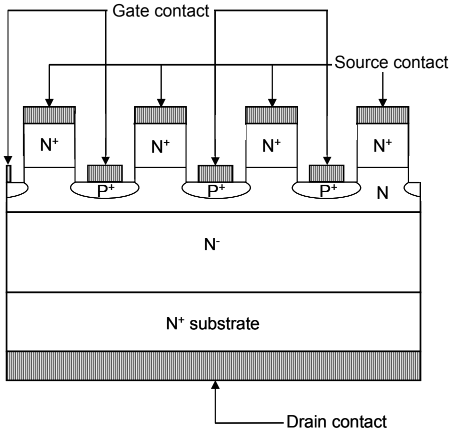

Fig. 1 A schematic of cross-sectional view of SiC VJFET.

A schematic of the cross-sectional device structure of the 4H-SiC VJFET are shown in Fig.1. In this structure, the n-type drift, channel and source regions are epitaxially grown on n^+, 8 °-off, Si-faced, 4H-SiC substrate. Trenches are then etched and implanted with Al to form p-type gates, followed by the formation of metal contacts. The spacing between the Al implanted region is the vertical channel region. The drain to source conduction is regulated by the channel depletion width, which is temperature-dependent and controlled by the gate bias at each operating temperature. Fig. 2 shows a packaged 4H-SiC VJFET with a chip size less than 1 mm^2 and an active area of 0.5 mm^2 fabricated in house.

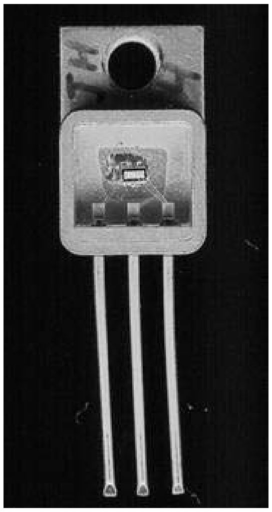

Fig. 2 A packaged 4H-SiC VJFET fabricated in house.

Temperature dependence of the static electrical characteristics

At temperatures above ~ 200K, almost all the nitrogen donors are ionized (4) and the device on-resistance is defined mostly by the electron mobility that increases with decreasing temperature, resulting in a decrease of the specific on-resistance (ρ_{on-sp}) and an increase of the drain-to-source forward current (I_{ds}). As shown in Figs. 3 and 4, when temperature decreases from 390K to 190K, the specific on-resistance reduces by a factor of ~ 2 while the forward current I_{ds} in the linear region at drain-to-source voltage (V_{ds}) of 0.12V raises by a factor of ~ 2 under all positive gate bias applied from 0.5V to 3V, resulting a negative temperature coefficient. The ρ_{on-sp} at V_{ds} of 0.12V and gate bias of 3V has been measured less than 35 $m\Omega\text{-cm}^2$ for the 4H-SiC VJFET at the temperatures above 70K, while reaching its minimum value of 6.06 $m\Omega\text{-cm}^2$ at 190K. Within the range of temperatures varied from 210K to 390K, the negative temperature coefficient approximated by a simple regression is about -0.62 ± 0.1 %/K for all positive gate bias applied and shows no clear trend of dependence on the gate bias. At zero gate bias, the dependence of ρ_{on-sp} and I_{ds} on temperature is different from those under positive gate bias. The ρ_{on-sp} slightly decreases while I_{ds} slightly increases with decreasing temperature from 390K to 310K under zero bias, showing a negative temperature coefficient.

Meanwhile, with decreasing temperatures below ~ 200K, the effect of freezing of the nitrogen donors, i.e.: reduction of the free electron concentration, on the device forward conduction becomes dominant (4). As also shown in Figs. 3 and 4, the ρ_{on-sp} starts increasing while I_{ds} starts decreasing with decreasing temperature from 210K to 30K, giving a positive temperature coefficient under all gate bias applied. At 30K, SiC becomes semi-insulating although the gating effect still exists and the on-state I_{ds} increases from 1.4E-11A to 2.4E-9A with increasing the gate bias from 0.5V to 3V. Under

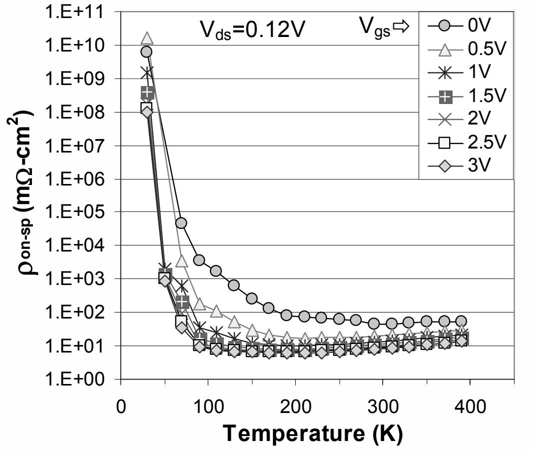

Fig. 3 Dependence of specific-on resistance, ρ_{on}, of the SiC VJFET on temperatures ranging from 30K to 390K.

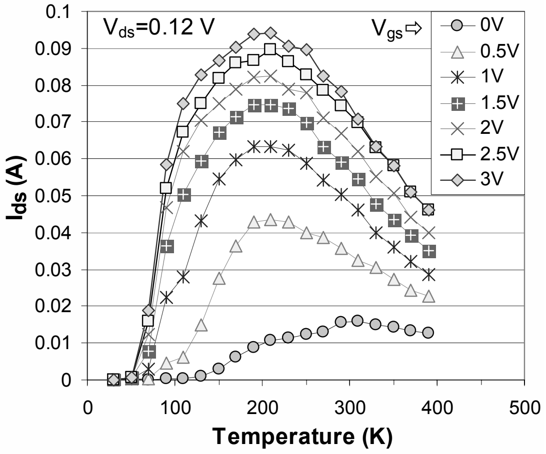

Fig. 4 Forward currents, I_{ds}, at V_{ds}=0.12 V of SiC VJFET as a function of temperature at zero and positive gate bias, V_{gs}, up to 3V.

zero gate bias, the $\rho_{on\text{-}sp}$ starts increasing while I_{ds} starts decreasing with decreasing temperature from 310K to above 110K. When temperature continuously decreases to 110K and below at zero gate bias, the forward I_{ds} becomes negligible, indicating that device channel of the SiC VJFET is fully depleted at 110K. This is also confirmed by measuring the threshold voltage as a function of temperature.

In Fig. 5, the threshold voltage (V_{th}) measured at V_{ds} of 0.2V monotonically increases with decreasing temperature from 390K down to 30K. When temperature decreases from 130K to 110K, the V_{th} changes from negative to positive and the SiC VJFET turns from a "normally-on" device into a "normally-off" device. Therefore, freezing of the nitrogen donor at temperatures below 130K causes the device channel fully depleted as well as a dramatic degradation in conductivity of the n-type SiC drift and channel layers. On the other hand, the narrowed channel width due to reduction of ionization ratio of the nitrogen donor at the low temperatures enhances the blocking capability of the SiC VJFET.

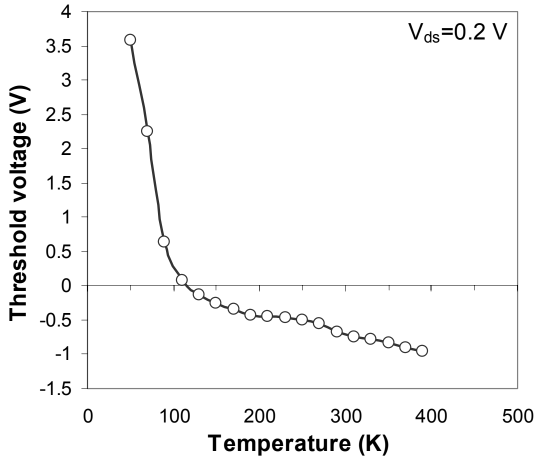

Fig. 5 Temperature dependence of threshold voltage, V_{th}, at V_{ds}=0.2 V for the SiC VJFET.

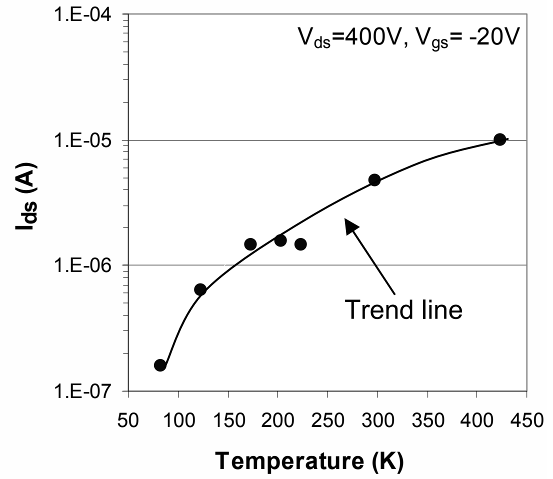

Fig. 6 Measured off-state leakage current I_{ds} as a function of temperature at V_{ds}=400 V and gate bias of -20 V for the SiC VJFET.

As shown in Fig.6, the off-state leakage current measured at gate bias of -20V on the SiC VJFET was found to decrease with decreasing temperature. This is also explained by the increase of channel resistance with decreasing temperature, which is defined by the electron mobility at temperatures above ~ 200K and ionization ratio of the nitrogen donors at temperatures below ~ 200K. It is interesting that 200K seems to be the optimum temperature that gives the lowest on-state resistance, highest forward conduction, and moderately low off-state leakage current or high blocking capability for the SiC VJFET. At ~ 200K, the SiC VJFET also acts as a "quasi-on" device that is not fully pinched off at zero gate bias but has the on-resistance high enough to protect the device and circuit by limiting the forward I_{ds} low enough in the event of abnormal operating conditions such as a delay or failure in gate control (1).

Temperature dependence of the dynamic electrical characteristics

Temperature dependence of the switching speed has been also studied. In Fig.7, the total switching frequency (sum of t_{rise}, t_{fall}, $t_{d(on)}$, and $t_{d(off)}$) was measured at the rated on-state I_{ds} of 2A and 3A with V_{ds} set at 300V and gate bias of 3V/-20V. With decreasing the case temperature from 473K to 200K, the total switching frequency decreases

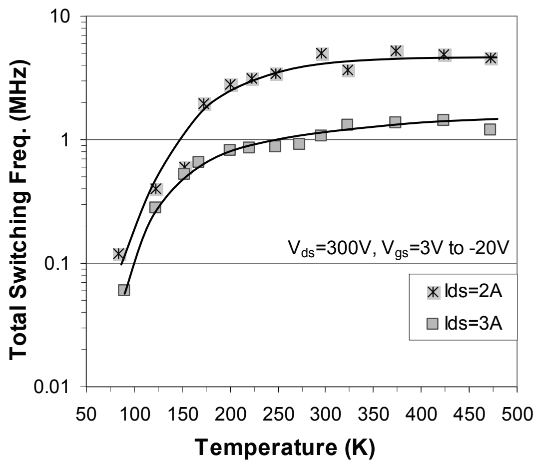

Fig. 7 Temperature-dependence of total switching frequency as a function of temperature for the 4H-SiC VJFET.

gradually from 5.2 MHz down to 2.8 MHz and from 1.42 MHz down to 0.82 MHz then it experiences a steep reduction down to 120 KHz and 60 KHz with continuously decreasing temperature to 84K for the I_{ds} of 2A and 3A, respectively. The temperature dynamics of the switching frequency is similar to that of the threshold voltage. The specific on-resistance calculated from the switching measurement decreases from 37.4 $m\Omega\text{-}cm^2$ at 473K to 2.7 $m\Omega\text{-}cm^2$ at 200K for I_{ds} of 2A and 70.3 $m\Omega\text{-}cm^2$ at 473K to 6.17 $m\Omega\text{-}cm^2$ at 200K for I_{ds} of 3A, then increases to 107.9 $m\Omega\text{-}cm^2$ for I_{ds} of 2A and 63.4 $m\Omega\text{-}cm^2$ for I_{ds} of 3A at 84K.

Conclusion

In summary, we have demonstrated the performance of the 4H-SiC VJFET at temperatures from 473K down to as low as 30K for the first time. The competing factors that affect both DC on-state/off-state behaviors hence switching performance of the 4H-SiC VJFET at different temperature regimes are discussed based on the experimental high and low temperature characteristics. In particular, the 4H-SiC VJFET is found to be functional and can be switched under a current stress of 3A at temperature as low as 84K. By reducing the current stress, the 4H-SiC VJFET can be switched faster at such cryogenic temperature. It is important that this study explores the opportunities of using SiC VJFET in the power electronic systems at extremely low temperatures for the deep space and earth orbiting missions, such as International Space Station, Space Shuttle, Mars Science Laboratory, and other low temperature applications.

Acknowledgment

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