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ACTIVE IN-CORE IRRADIATION OF SIC JFETS AT 300°C IN A TRIGA NUCLEAR REACTOR

James McGarrity, Charles Scozzie, James Blackburn, and Merle DeLancey
U. S. Army Research Laboratory
Attn: AMSRL-PS-PD
2800 Powder Mill Road
Adelphi, MD 20783-1197
(301) 394-3828 voice
(301) 394-4576 fax

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Abstract

In this paper we demonstrate that SiC transistors have the potential to operate in the severe high temperature and radiation environments of commercial and space nuclear power sources. 6H-SiC FETs were exposed to neutron fluxes and gamma dose rates as high as 1.6×10^{12} n/cm^2/sec and 3.8×10^4 rad(Si)/sec while they were maintained under bias at both 300°C and room temperature within the core of a TRIGA reactor operated at 200 kW power level. The radiation exposure was continuous and the bias on the devices was interrupted only to record the current-voltage characteristics at various accumulated neutron fluences from 10^{13} to 5×10^{15} n/cm^2. No significant degradation in the device characteristics was observed until the total neutron fluence exceeded 10^{15} n/cm^2 for irradiation at 25°C, and no significant changes were observed even at 5×10^{15} n/cm^2 at 300°C.

INTRODUCTION

Silicon carbide (SiC) is a very promising semiconductor material for the development of electronics that will operate at high temperature (Davis et al. 1991 and Ivanov and Chelnokov 1992); it has the additional advantage that for some applications it should be less sensitive to radiation than Si or GaAs. There will be advantages to eventually using SiC to build very radiation-resistant, high-temperature circuits, which could be located near or within severe radiation environments. System benefits would come from development of amplifier and multiplexer circuits for sensor and control functions which operate at 500° to 600°C. The goal of our research is to demonstrate that high-temperature radiation-hardened devices can be developed and ultimately to demonstrate circuit operation in these severe environments (Scozzie et al. 1994 and Blackburn et al. 1994)

In this paper we report on the in-situ operation of state-of-the-art SiC junction field-effect transistors (JFETs) at high temperature within the core of an operating nuclear reactor. These devices represent the current state-of-the-art but do *not* represent the limits of operation of SiC semiconductor devices.

SIC DEVICE DESCRIPTION

The design of the JFET devices, fabricated by Cree Research, Inc. (see cross-section in fig.1), have been described elsewhere (McGarrity et al. 1992). Each device was mounted on a TO-46 header. The devices were "scrubbed" to the heated header with a AuGe preform. Scrubbing ensured a good mechanical contact for the gate connection. Device contacts were then connected to their pins using a eutectic wire bonder and a 1-mil Au wire. The devices were hermetically sealed in a dry nitrogen atmosphere so as to help prevent oxidation of the source/drain electrodes during high-temperature operation. The present packaging and metallization limit long term testing to 300°C.

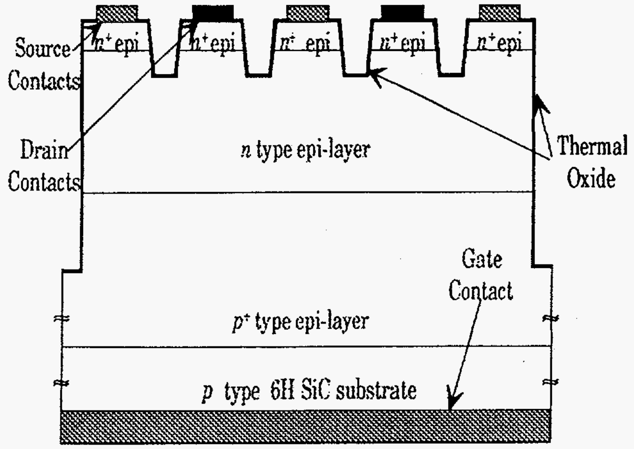

Figure 1. Cross-sectional design of 6H-SiC FET.

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DISCLAIMER

DEVICE ELECTRICAL CHARACTERIZATION

The drain current (I_{ds}) versus drain-to-source (V_{ds}) and gate (V_{gs}) voltages were measured before, during, and after the active reactor irradiation for a series of temperatures between room temperature (RT) and 300°C. From these measurements, values for the threshold voltage (V_t), transconductance (G_m), and drain saturation current (I_{dss}) were obtained.

The typical room temperature (RT) current voltage characteristics for the depletion-mode JFETs used in this study are shown in Fig. 2 for several values of gate voltage. Figure 3 illustrates the results of our temperature characterization. This figure shows I_{ds} versus V_{ds} curves at $V_{gs} = 0$ V for a series of temperatures between 23° (RT) and 400°C. The RT threshold voltage for this device was -8.8 V, with a corresponding pinch-off voltage of 11.5 V, transconductance of 8.0 mS/mm, and saturated drain current of 39 mA. We note that I_{dss} (as measured well above threshold, e.g., at $V_{ds} = 20$ V) decreases monotonically from 39 mA at 23°C to 17 mA at 400°C, a drop by a factor of a little over two. However, it is clear that good, clean transistor action is obtained throughout the temperature range of RT to 400°C for these SiC JFETs; these devices have been shown to demonstrate near-ideal behavior throughout this temperature range (McLean et al. 1994 and McLean et al. 1996).

DESCRIPTION OF NUCLEAR REACTOR EXPERIMENT

A series of active SiC JFET radiation experiments was performed at the Maryland University Training Reactor (MUTR), where measurements of in-situ device radiation response were made during continuous reactor operation. The MUTR is a 250-kW open-pool TRIGA reactor that has five test facilities which includes a 1-in. ID delivery tube, which is part of a pneumatic sample transfer system that allows in-core sample irradiation. This tube was used to gain access to the reactor core for this set of active experiments. The typical fast (>10 keV) neutron flux and gamma dose rate at the in-core rabbit test location are 8.0×10^9 n/cm^2-kW-s and 19 rad (Si)/kW-s, respectively, which at full power (250 kW) provides an environment of 2.0×10^{12} n/cm^2-s and 4.7 krad (Si)/s gamma.

To achieve our key objective of making in-situ measurements at high temperature, we developed a test fixture that could maintain the devices at temperatures of greater than 300°C while providing electrical insulation currents of only a few nanoamps. This fixture also had to slip easily within the 1-in. ID delivery tube for insertion into the reactor core. Figure 4 is a schematic of the 0.98-in. OD by 6.25-in. long test fixture. A cylindrical high-temperature ceramic Globar® power resistor was used as the heater. This resistor is encased in an aluminum silicate insulation and pressed into a thin-walled aluminum tube. Although thin, the insulation is effective; about 40 W of power

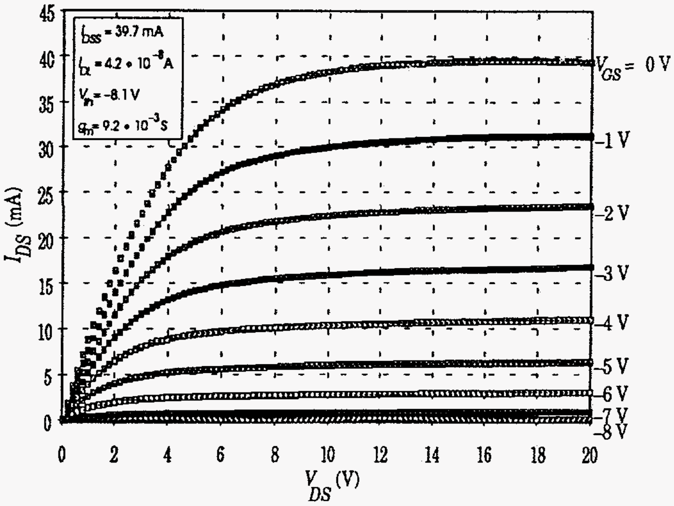


Figure 2. *I-V* characteristics of the JFET described in figure 1.

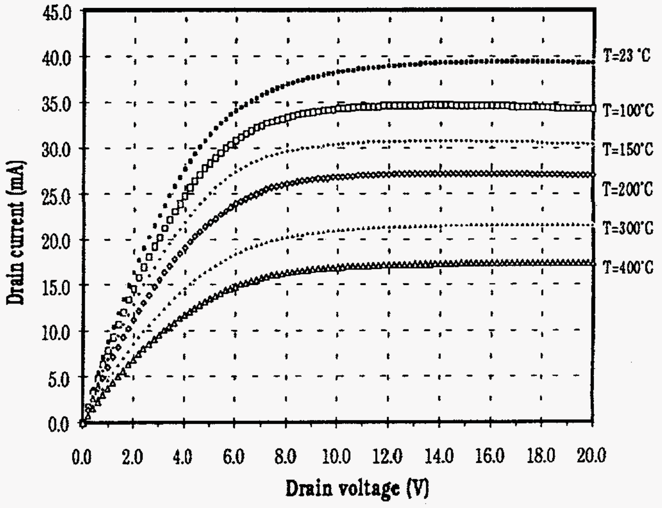


Figure 3. Id-Vd as a function of temperature for Vg = 0 V for SiC JFET described in figure 1.

maintains an internal temperature of 300°C with the outer tube at RT. The transistor sockets/insulators are made from Macor®, a glass-ceramic, which is machineable with ordinary metal working tools, into which are inserted high-temperature (non corroding) plug-in receptacle pins (Gryzbowski 1991). Electrical connections to the sockets are made via a high-temperature wire obtained from BRIM Electronics (Fair Lawn NJ); the wire is spot welded to the pins. Although the electrical insulating materials were carefully selected on the basis of tests, they provided only a small margin in regard to leakage currents at 300°C; we monitored leakage during the tests by measuring the current to a transistor header pin that was not connected within the transistor package but was otherwise connected to and instrumented the same as the "active" pins. This pin suffered the same header leakage, socket leakage, and connecting wire leakage as the transistor pins. Note that signal wires could not be allowed to electrically contact the interior of the heating resistor because the ceramic from which it is made has considerable electrical conduction at high temperature. The thermocouple was connected to a typical commercially available temperature indicator/controller, which switched the dc power applied to the 18-ohm resistor to maintain a temperature of 300° ± 3° C during the high-temperature irradiation.

Eight devices were used in these active experiments; four devices were irradiated at the same time at each of two temperatures, ambient and 300°C. The test-fixture geometry for both the ambient and 300°C irradiations was identical and contained a device package with the spare pin instrumented, as discussed above, which also provided a measure of the radiation induced-current along the instrument cable and within the device package during the exposure.

The devices in both the ambient and 300°C test groups were biased at $V_{ds} = 5$ V and a V_{gs} value that would provide an I_{dss} of about 300 μA. This is a typical bias that would be applied to devices during use as logic gates in a high-temperature multiplexer circuit. Before the test, all devices were subjected to a 200-hour unbiased prestabilization bake at 300°C followed by a 160-hour burn-in (at 300°C) under the same bias condition as was applied to the devices during the active irradiations.

Device measurements were made at logarithmic intervals of accumulated fluence between 1×10^{13} and 5×10^{15} n/cm^2 with the reactor under continuous operation see fig. 5). So that the exposure times would be long enough for accurate measurements to be made at each neutron fluence, the nuclear reactor power level was changed several times

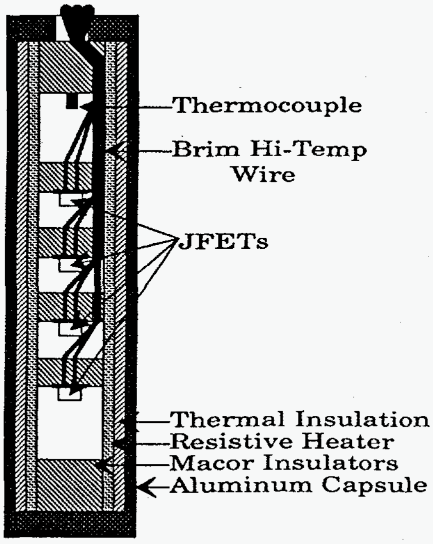


Figure 4. Schematic of irradiation test fixture.

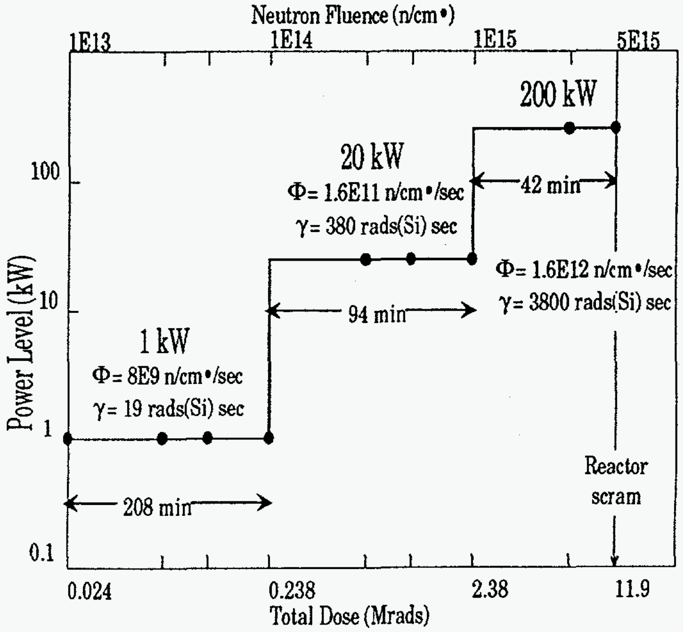


Figure 5. MUTR Experimental Sequence. Solid circles on chart denote device measurement periods and are plotted against irradiation time at each power level with the associated accumulated neutron fluence and total dose.

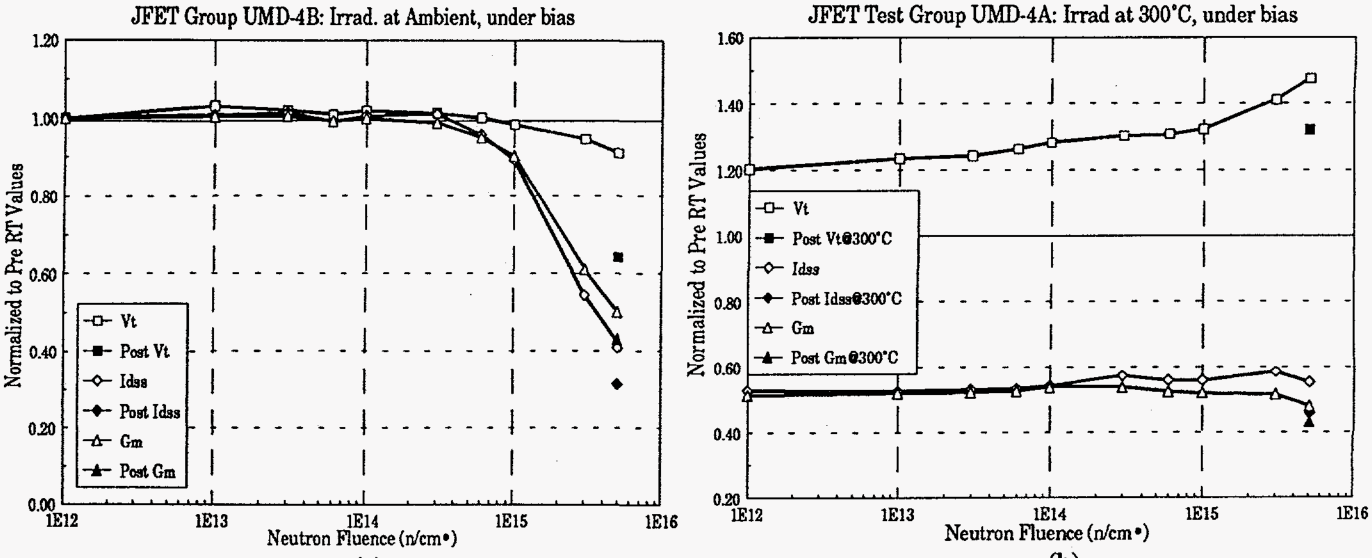
during the experiment. The final maximum power level at which most of the neutron fluence was accumulated was 200 kW. The devices in the ambient temperature test group experienced irradiation temperatures ranging from 22° to 40°C depending on the reactor power level.

Device characteristics were measured by PC-controlled HP 4145A semiconductor analyzers, one for each of the four devices being simultaneously tested. The control program kept the devices under a dc bias most of the time, periodically "sweeping" the bias conditions (gate-to-source voltage, drain-to-source voltage) and measuring gate and drain currents. The sweeps covered a limited number of data points in the operating regions of interest, both to limit electrical stress on the test devices and to avoid substantial differences in time (and accumulated dose) between first and last points of a set. I_{ds} vs V_{ds} sweeps with $V_g = 0$ V, including higher source currents, were made for parameter extraction. Frequently, we manually inspected the accumulated data to identify trends in device characteristics (as a result of accumulated dose and temperature); and we made adjustments, when necessary, to keep the devices in the desired region of operation.

RESULTS

Figure 6a and 6b gives analyses of the in-situ measurements for the device test groups irradiated at ambient and 300°C. This figure presents the relative group average change in extracted device parameters as a function of fluence and normalized to the pretest RT values, for the four devices tested at each temperature. Also included in this figure are the extracted parameters from post test measurements made the day after the reactor exposure with the devices at their respective test temperatures. The devices were stored at RT in the reactor pool away from any significant radiation field after termination of the active irradiation, until the posttest measurements were made.

For the active irradiation at RT, figure 6a shows very little change in device characteristics out to 1×10^{15} n/cm^2 accumulated fluence, at which point the I_{dss} and G_m have degraded about 10 percent; these values are in reasonable agreement with previous passive irradiations. But the end-point measurements made at 5×10^{15} n/cm^2 with the reactor still under power show significantly less degradation in the device characteristics than expected based on previous passive irradiations at RT (McLean et al. 1994). However, the posttest measurements made 24 hours later after the irradiation was terminated show a significant decrease (25 percent) in V_t with the corresponding decreases in the I_{dss} and G_m to values that are in very good agreement with our previous passive radiation experiments. To explain the result that there is less degradation in device parameters with the reactor operating, we suggest that there is a positive charging of the passivation oxide, which is in contact with the back of the conducting channel, arising



(a) (b)

Figure 6. Relative group average change in extracted device parameters as a function of fluence and normalized to the pretest RT values for the four devices irradiated under bias at RT (a) and at 300°C (b). In-situ and post test measurements are presented.

from ionizing radiation effects; but this a much larger effect than noted in earlier passive irradiations because of the applied fields in the active devices. The final values after 24 hours we believe agree because these ionizing effects anneal over time.

The characteristic initial increase in V_t and decrease in I_{dss} and G_m resulting from raising the device temperature from RT to 300°C is shown in Figure 6b at the 1×10^{12} n/cm^2 fluence. This figure shows degradations in I_{dss} and G_m of less than 20 percent as opposed to the greater than 60-percent degradation shown in figure 6a for the devices irradiated and measured at RT. From our previous analysis (McLean et al. 1994) for device operation at 300°C you would expect to see considerably less degradation in I_{dss} and G_m characteristics as a result of neutron irradiation than you would for device operation at RT. We conclude that since the carrier mobility is already so severely degraded due to the thermal phonon scattering at 300°C, the additional scattering due to the neutron-induced charged trap states has very little impact on mobility. (Therefore, carrier removal should be the primary effect from the neutron irradiation observed for device operation at this temperature; the effect of carrier removal is also less severe at 300°C because of the additional ionization of carriers at this temperature.)

Figure 6b also shows a continuing slow increase in V_t with the neutron fluence, resulting in a maximum end-point value at 5×10^{15} n/cm^2 that is about 25 percent larger than the pretest value. As suggested previously (McLean et al. 1994), the pinch-off voltage (V_p) should be constant with neutron fluence at 300°C, since we concluded that at that temperature, thermal detrapping of electrons trapped in the neutron-induced deep-level traps in the depletion region completely empties these traps. There should be no effect on V_p which depends on the channel doping density (N_D) and the physical characteristics of the device and we recall that V_p is related to V_t by the relation $V_p = |V_t| + V_{bi}$ where V_{bi} is the built-in potential at the p^+n junction. During the exposure we believe that with the applied bias between the source and drain and a competition between charge generation in the 200Å oxide and annealing of charge at 300°C, the balance between the two competing processes increases the net positive charge until the reactor is turned off. This could explain the continued increase in V_t with gamma dose and neutron fluence shown in Fig. 6b while under reactor power and the decrease in V_t (and the associated decreases in I_{dss} and G_m) in the posttest with the reactor power off.

It is important to note here that the post test parameter values shown in Fig. 6b, for the devices irradiated at 300°C, indicate less degradation from the reactor exposure than noted in our previous experiments, where devices were passively irradiated at RT and measured at 300°C. Further, when the temperature on these devices was decreased to room temperature (where we would have expected the results to agree with the posttest measurements in figure 6a for the devices irradiated at ambient temperature), we found that the devices irradiated at 300°C show significantly less degradation. These results, given in table 1, would imply that the damage was less severe for devices irradiated at 300°C than at ambient temperature. We also note that the posttest V_t measurement in figure 6b may indicate the presence of some permanent trapped charge within the passivation oxide, which would tend to increase the device parameters, as discussed previously. But at most this effect would account for less than half the difference between the parameter degradations that are shown in table 1 for the two JFET test groups.

Table 1

Group average change in parameters measured at RT for 6H-SiC JFETs after accumulated fluence of 5×10^{15} n/cm^2 and gamma dose of 12 Mrad. Values are normalized to the pretest RT measurements.

Device Parameters	Posttest /Pretest ratio after Irradiation, measured at RT			
	Irradiated at Ambient		Irradiated at 300C	
	Avg	Stdev	Avg	Stdev
V_t	0.64	0.03	0.88	0.03
G_m	0.43	0.09	0.66	0.05
I_{dss}	0.31	0.05	0.57	0.01

SUMMARY

This preliminary study has clearly shown that SiC FETs offer advantages over Si or GaAs FETs for nuclear applications at high temperature. The transistors used in this study were limited in application to 300°C because of the particular metallizations used for source and drain contacts. In the nuclear reactor environment, the devices (and circuits, we expect) are less sensitive to radiation when operated at high temperature.

Acknowledments

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