

# Impact of gamma-ray irradiation on dynamic characteristics of Si and SiC power MOSFETs

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## ABSTRACT

Power electronic devices in spacecraft and military applications requires high radiation tolerant. The semiconductor devices face the issue of device degradation due to their sensitivity to radiation. Power MOSFET is one of the primary components of these power electronic devices because of its capabilities of fast switching speed and low power consumption. These abilities are challenged by ionizing radiation which damages the devices by inducing charge built-up in the sensitive oxide layer of power MOSFET. Radiations degrade the oxides in a power MOSFET through Total Ionization Dose effect mechanism that creates defects by generation of excessive electron-hole pairs causing electrical characteristics shifts. This study investigates the impact of gamma ray irradiation on dynamic characteristics of silicon and silicon carbide power MOSFET. The switching speed is limit at the higher doses due to the increase capacitance in power MOSFETs. Thus, the power circuit may operate improper due to the switching speed has changed by increasing or decreasing capacitances in power MOSFETs. These defects are obtained due to the penetration of Cobalt60 gamma ray dose level from 50krad to 600krad. The irradiated devices were evaluated through its shifts in the capacitance-voltage characteristics, results were analyzed and plotted for the both silicon and silicon carbide power MOSFET.

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## 1. INTRODUCTION

Power Metal-Oxide Semiconductor Field-Effect Transistors (MOSFETs) play a significant role in space, power plant, military and harsh environment applications [1], [2]. Semiconductor devices present in radiation harsh environment would be exposed to different types of radiations which lead to malfunctions of the devices [3]. The space radiation environment is mainly classified into particle and proton radiation. The radiation effects of power MOSFETs mainly includes ionizing radiation and single event effects [4], [5]. Power MOSFET exposed to ionizing radiation cause an accumulation of charges in interface and gate oxide layer, thereby degrading the performance of devices. Assessing the radiation hardness of a device with one radiation on the ground and anticipating its reaction to a diverse radiation in space could be an intricate task. In this way, it is exceptionally fundamental to assess the radiation hardness of a device to diverse radiations from the application perspective.

Several studies have shown the changes in static electrical characteristics of commercially available silicon (Si) and silicon carbide (SiC) power MOSFET under radiation [6], [7]. The results show that the ionizing total dose damage of power MOSFETs mainly appears as changes in I-V characteristics, especially the decrease of threshold voltage and the increase of current drive [8]. Neutron irradiation can cause functional failure of the

commercial grade SiC power MOSFETs devices, mainly due to the ionizing effect caused by the recoil nucleus the obtained from collision of the neutron and the lattice atoms so to make the devices fail [9]. The results of heavy ion and proton radiation test report that the permanent damage caused by ion irradiation at high LET values will lead to increase in the gate and source leakage of the device. The study [10], [11] demonstrated that the safe working voltage of the device was significantly reduced and the current was attenuated after the heavy ion irradiation test on SiC power MOSFETs of 1200 V. The decrease of safe working voltage will directly affect the device's reliability index as well as the device's space applications. Akturk et al. detailed that SiC MOSFETs irradiated with gamma-rays under gate voltage biasing condition showed the negative voltage shift in threshold voltage ( $V_{th}$ ), though in their examinations the aggregate measurement of gamma-ray dose level was limited to kGy [12]. The investigation of threshold voltage shift and drain current degradation was conducted for both N-channel and P-channel Si MOSFET subjected to electron beam radiation and gamma ray irradiation [13], [14]. However, it is necessary to consider the dynamic electrical characteristics on power MOSFETs during the total ionizing radiation. Therefore, this work aims to investigate the capacitance voltage shifts of commercial Si (TOSHIBA 2SK2662) and SiC (ROHM SCT2H12NZ and SCT3160KL) power MOSFETs subjected to radiation by analysing its C-V characteristics before and after cobalt-60 gamma ray radiation.

In this study, the relation between variable drain voltage and gamma-ray irradiation response of Si and SiC power MOSFETs was investigated by applying a constant or variable bias to gate terminal. The experiments indicate that Si and SiC MOSFETs operate within specification up to 100 krad, and may reliably operate after receiving doses up to 300 krad, provided that a gate bias of 0V, which is specified as the lowest recommended gate bias in the datasheet, is used to turn off the power MOSFET. In addition it clears that SiC power MOSFET capacitance value changes is less compared to silicon power MOSFET. Furthermore, experiments indicate that the switching applications such as buck and boost converters will be more affected due to increases and decreases in interface state densities and device capacitances such as output ( $C_{oss}$ ), input ( $C_{iss}$ ) and reverse transfer ( $C_{rss}$ ) capacitances, than changes in threshold voltage and device current drive.

The remaining part of the article is structured as follows, Section 2. presents the theoretical concepts of radiation effects on power MOSFET. Section 3. details the experimental test set-up for the investigation of dynamic characteristics due to gamma ray irradiation, Section 4. discuss about the results and comparative analysis, Section 5. provides Conclusion.

## 2. RADIATION EFFECTS ON POWER MOSFET

Power MOSFET is a three terminal device Gate (G), Source (S) and Drain (D), which used in DC-DC converter, power amplifier and switching electronic signals. In addition, Power MOSFET is a superior switching speed with very low current required to turn on gate drive, due to the rate of charge removed or supplied from capacitance. In high voltage power MOSFET, only electrons are flowing during forward conduction. This is the reason that it can switching fast at high switching frequency with low switching loss. Many studies have been carried out to investigate the radiation effects on silicon based power MOSFET. SiC replaces a silicon material due to their realistic advantages such as wide band gap, high critical field and high thermal conductivity. 4H-polytype SiC material is most promising semiconductor for power MOSFETs compared to other polytypes 6H-SiC and 3H-SiC. The SiC power MOSFETs reduces the specific on-resistance, which are more suitable for high voltage, high temperature and harsh radiation environment. The design process used for SiC power MOSFETs as similar as silicon power MOSFETs [15].

Radiation is a transmission and emission of energy that travel in a form of particles or waves through space or material. The radiation is categorized as ionizing and non-ionizing radiation based on the type of particle. The ionizing radiation induced the ionization mechanism in the device which tends to device degradation and performance failure by changing the electrical characteristics. During the radiation exposure, the highly charged particle such as electrons, protons and gamma rays passing through the oxide layer that ionize atom to creates the electron-hole pairs in the power MOSFET. The generated electrons are much more mobile than the holes and they will move out of the oxide in a very fast times. However, some electrons and holes that escape initial recombination and they are immobile and remain behind in oxide. Trapped charge at the SiO<sub>2</sub>/ Si interface induces an inversion layer during the off-state that is responsible for increasing leakage current and threshold voltage shifts. The ionizing radiation of the space environment mainly causes Total Ionizing Dose (TID) [16].

The cumulative effect of ionizing radiation is referred as TID. Dose is defined as the quantitative measure of accumulated energy absorbed from ionizing radiation per unit mass as given in equations (1).

$$d = \phi \frac{1}{\rho} \frac{dE}{dx} \quad (1)$$

where,  $d$  is the dose,  $\phi$  is the flux of incident particles. The SI unit for radiation dose is the radiation absorbed dose (rad) or Gray [Gy] i.e. 1 Gy = 100 rad. The units are material-specific, it consists of accumulation of charges over time in different materials such as silicon or silicon carbide.

The SiC power is the leading high voltage technology in current market and there are number of research on going for analysis of radiation hardness. There is compulsion to investigate impact on dynamic characteristics of Si and SiC power MOSFET during radiation for using in space applications. Hence in this work the investigation of gamma ray irradiation on silicon carbide power MOSFETs by measuring the capacitance-voltage (C-V) characteristic as a function of drain-source voltage and radiation dose level and also compared with silicon power MOSFET.

### 3. EXPERIMENTAL TEST SET-UP FOR ANALYSIS OF RADIATION EFFECTS

The goal of this experiment is to investigate and analysis the cobalt-60 gamma ray effects on the dynamic characteristics of both Si and SiC power MOSFETs. Commercially available Si (TOSHIBA 2SK2662) and SiC (ROHM SCT2H12NZ and SCT3160KL) power MOSFETs were investigated and compared. The power MOSFETs details are collected from the data sheet. A sample size of five devices for each radiation level in total twenty devices used for this experiment. First, the capacitances including output capacitance ( $C_{oss}$ ), input capacitance ( $C_{iss}$ ) and reverse transfer capacitance ( $C_{rss}$ ) were characterized prior to the radiation exposure by varying the Drain-Current Voltage ( $V_{ds}$ ) in the Electrical characterization laboratory at University Teknologi PETRONAS, Malaysia. The capacitances of power MOSFET calculated by using equation, as in (1).

$$\begin{aligned} C_{iss} &= C_{gs} + C_{gd} \\ C_{oss} &= C_{ds} + C_{gd} \\ C_{rss} &= C_{gd} \end{aligned} \quad (2)$$

where the  $C_{gs}$ ,  $C_{ds}$  and  $C_{gd}$  are gate-to-source, drain-to-source and gate-to-drain respectively. Next, the cobalt-60 gamma ray irradiations were performed at Agency Nuclear Malaysia, Bangi for a dose level of 50krad to 600krad. The devices are measured at pre-rad, 50krad, 100krad, 300krad and 600krad for variable bias condition using Agilent E4980A LCR meter. To achieve the analysis of radiation effects on dynamic characteristics of power MOSFET, Funaki et al method is used to measure the inter electrode capacitance values. In this method the LCR meter with external power source and simple circuit configuration to measure the capacitance value. However, the LCR meter has a limited of up to 40V for  $V_{ds}$  biasing. Hence, the circuit is connected to the extra high voltage source with resistance and dc-blocking capacitance in order to measure the capacitance of the higher voltage in  $V_{ds}$ . A schematic of the test circuit for different capacitance measurement is shown in Figure 1. To achieve accurate measurement value of the internal capacitance different electrical test schematic circuits were used in this experiment.

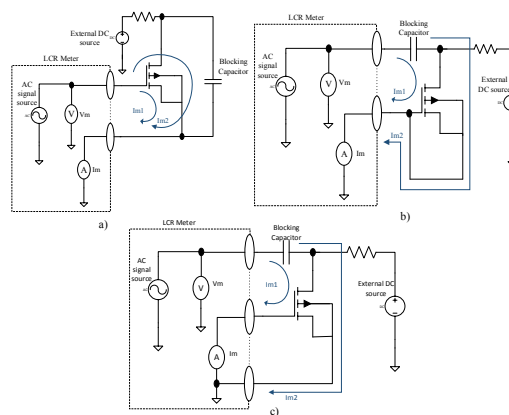


Figure 1. Experiment electrical schematic for a)  $C_{iss}$ , b)  $C_{oss}$  and c)  $C_{rss}$  measurement

#### 4. RESULT AND ANALYSIS

Previous related studies have shown that after gamma irradiation, the power MOSFET threshold voltage ( $V_{th}$ ) shifts negative and the drain current ( $I_{ds}$ ) was increased. However, the changes in dynamic electrical characteristics are neglected, yet the internal capacitances are introduce leakage current effects. Therefore, the analysis of capacitance voltage curves as a function of radiation dose is necessary to reflect reliable circuit operation. The measurement includes input ( $C_{iss}$ ), output ( $C_{oss}$ ) and reverse transfer ( $C_{rss}$ ) capacitances of both Si and SiC power MOSFETs. Table 1 shows the result of total ionizing dose dependent changes in leakage characteristics of Si and SiC MOSFETs irradiated at room temperature. Here the power MOSFETs capacitance-voltage characteristics measured at  $V_{gs} = 0V$  and  $V_{ds}$  changes from 0 to 30 V for before and after 50krad, 100krad, 300 krad and 600 krad.

The measured capacitances are related to the terminal capacitances of power MOSFET, refer (2). According to the formula  $C_{gd}$  is the key of these capacitances its depends on equation (3),

$$C_{gd} = \frac{C_{ox} \times (C_{inv} + C_{dp})}{C_{ox} + (C_{inv} + C_{dp})} \quad (3)$$

where,  $C_{dp}$  is a depletion capacitance which is inversely proportional to the depletion width of MOSFETs neck region under the oxide layer,  $C_{ox}$  is a oxide capacitance and  $C_{inv}$  is an inversion capacitance. During off state and low  $V_{ds}$ , the threshold voltage increase  $C_{inv}$  due to the radiation and this gives rise to larger  $C_{gd}$ . The increased capacitance as a function of low  $V_{ds}$  and lateral shift during high drain-source voltage for pre and post radiation plotted in Figure 4. In expansion to the change in  $C_{gd}$ , the measurements subordinate changes in  $C_{oss}$  and  $C_{iss}$  moreover incorporate the changes in  $C_{ds}$  and  $C_{gs}$ , separately. Primarily, the gate-source capacitance  $C_{gs}$  is included fringe capacitance between gate and source, overlap, depletion, oxide and interface trap capacitances. Especially, the interface trap capacitance will change due to changing interface trap levels. Moreover, the drain-source capacitance  $C_{ds}$  will change less with gamma irradiation it also includes the power MOSFET structure junction capacitance. Figure 2 shows input capacitances ( $C_{iss}$ ) of Si and SiC power MOSFETs as a function of  $V_{ds}$  and dose level.

Hence, the result clear that the shifts in capacitances  $C_{iss}$ ,  $C_{oss}$ , and  $C_{rss}$  due to radiation dose level is primarily due to the variations in  $C_{gd}$ . Whereas in the case at 300 krad and 600krad, the dose dependent shift of  $C_{rss}$  and  $C_{oss}$  are considerably larger than pre radiation but contrariwise  $C_{iss}$  is decreases than pre radiation. The  $C_{oss}$  of Si MOSFETs have increased 25.9% at 600krad and 2.6% at 300krad for 0 to 30V after irradiation compared to the pre radiation which is shown in Figure 3. In addition,  $C_{rss}$  of Si MOSFETs have a significant increment which is more than 26.17% at 300krad while at 600krad the increment is more than 6% from 0 to 30V. In the  $C_{iss}$  measurement of Si MOSFETs, which is up to 5.61% at 600krad but at 300krad the decrement is up to 6.5% from 0 to 30V. This is because the  $C_{iss}$  determines driving condition while  $C_{rss}$  and  $C_{oss}$  are dictated switching speed. Hence, the  $C_{oss}$  is the key factor component of switching loss to affect the power loss due to the discharging and charging in switching mode. In addition, the  $C_{rss}$  and  $C_{oss}$  have voltage dependency due to the device depletion region modulating with applied varying operating voltage.

The capacitance of Rohm SiC 1200V and Rohm SiC 1700V power MOSFETs have a significant influent by the radiation at 300krad and 600krad. The  $C_{oss}$  of Rohm SiC 1200V has decrease up to 17.36% at 600krad while at 300krad the decrement is up to 45.47% from 0 to 30V whereas it slightly increase after 30V at 600krad compared to preradiation. However, the  $C_{oss}$  of Rohm SiC 1700V has increased significantly which is up to 50% at 600krad while at 300krad the increment is up to 48% from 0 to 30V. In addition, the  $C_{rss}$  of Rohm SiC 1200V has increased up to 24.5% at 600krad while at 300krad has significant increased and slightly decrease at 300krad from 0 to 30V. However, the  $C_{rss}$  of Rohm SiC 1700V has significant increased which is up to and around 80% at 300krad and 600krad. Also, the  $C_{iss}$  of Rohm SiC 1200V and Rohm SiC 1700V have decrement trends after irradiation gamma-ray. Rohm SiC 1200V has small decreased up to 7.85% whereas the Rohm SiC 1700V has significant increased which up to 29.8% at 600krad while at 300krad the Rohm SiC 1200V has decreased up to 10.15% and Rohm SiC 1700V has decreased up to 26.40%.

It concluded that the switching speed is limit at the higher doses due to the increase capacitance in power MOSFETs. Thus, the power circuit may operate improper due to the switching speed has changed by increasing or decreasing capacitances in MOSFETs. For instance, the larger  $C_{iss}$  in the MOSFET which requires more gate charge that supply by gate driver, so the  $C_{iss}$  is changed, this required to redesign the gate driver in order to turn on the device channel. Also, the larger output switching losses due to the larger  $C_{oss}$ . Power MOSFETs are used to in high switching application due to the changes of the terminal capacitance. The power circuit has to redesign

in order to reduce the unwanted transients in the circuit due to the gate driver or switching speed is changed.

Table 1. Experimental Results of Pre and Post Irradiated Power MOSFETs

Capacitance (pF)	Power MOSFETs	Radiation Dose (krad)	Drain-Source Voltage Vds (V)							
			0	1	2	8	10	20	30	
Ciss	Toshiba Si 500 V	Pre-Rad	1230.00	1230.00	1220.00	1210.00	1210.00	1190.00	1215.00	
		Post 50	1230.00	1230.00	1220.00	1210.00	1210.00	1190.00	1215.00	
		Post 100	1228.00	1229.00	1220.00	1212.00	1211.00	1189.00	1214.00	
		Post 300	1150.00	1151.00	1159.00	1161.00	1162.00	1162.00	1175.00	
		Post 600	1161.00	1161.00	1163.00	1163.00	1167.00	1168.00	1170.00	
		Pre-Rad	745.00	720.29	617.63	519.00	484.99	461.866	415.50	
	Rohm SiC 1200V	Post 50	745.00	720.29	617.63	519.00	484.99	461.866	415.50	
		Post 100	744.55	721.39	618.66	518.00	487.00	460.90	450.30	
		Post 300	705.58	647.16	609.68	493.10	478.84	475.42	447.32	
		Post 600	706.05	663.75	619.54	499.98	479.24	455.98	445.07	
		Pre-Rad	398.00	363.40	359.64	289.20	216.15	210.89	210.35	
		Post 50	398.00	363.40	359.64	289.20	216.15	210.89	210.35	
	Rohm SiC 1700V	Post 100	399.12	365.30	358.64	287.5	218.15	210.91	211.32	
		Post 300	359.91	356.16	349.70	212.84	209.85	207.29	206.90	
		Post 600	340.00	311.7	261.87	203.03	201.81	200.10	200.10	
		Pre-Rad	795.38	765.38	534.0	268.00	200.00	85.11	70.00	
Post 50		795.38	765.38	534.0	268.00	200.00	85.11	70.00		
Post 100		794.14	764.28	535.4	268.2	199.01	84.22	69.8		
Coss	Toshiba Si 500 V	Post 300	1610.0	1610.0	1238.0	280.27	205.26	105.23	77.69	
		Post 600	1724.0	1724.0	1724.0	437.97	314.28	119.83	88.13	
		Pre-Rad	777.66	737.66	531.92	272.02	244.49	173.92	133.89	
		Post 50	777.66	737.66	531.92	272.02	244.49	173.92	133.89	
		Post 100	776.89	736.96	514.12	272.08	244.23	173.81	133.72	
		Post 300	647.15	565.53	460.96	181.62	133.32	168.94	133.08	
	Rohm SiC 1200V	Post 600	747.66	609.59	492.22	272.02	237.96	170.00	134.53	
		Pre-Rad	281.00	266.87	152.37	80.00	57.12	42.145	36.528	
		Post 50	281.00	266.87	152.37	80.00	57.12	42.145	36.528	
		Post 100	283.53	267.87	153.37	80.80	57.43	42.183	36.534	
		Post 300	333.00	288.00	226.25	67.41	58.91	42.78	36.65	
		Post 600	338.00	297.00	229.21	68.4	59.016	43.21	36.80	
	Crss	Toshiba Si 500 V	Pre-Rad	612.10	542.34	542.34	320.11	210.00	83.34	69.50
			Post 50	612.10	542.34	542.34	320.11	210.00	83.34	69.50
			Post 100	611.56	541.40	543.30	322.19	211.12	83.87	69.50
			Post 300	1723.00	1710.00	1328.00	410.27	305.26	115.23	87.69
Post 600			1147.60	1106.2	1071.8	491.00	345.20	95.12	73.90	
Pre-Rad			435.00	400.00	395.80	286.31	220.53	174.50	133.00	
Rohm SiC 1200V		Post 50	435.00	400.00	395.80	286.31	220.53	174.50	133.00	
		Post 50	435.00	400.00	395.80	286.31	220.53	174.50	133.00	
		Post 50	435.00	400.00	395.80	286.31	220.53	174.50	133.00	
		Post 50	435.00	400.00	395.80	286.31	220.53	174.50	133.00	
		Post 50	435.00	400.00	395.80	286.31	220.53	174.50	133.00	
		Post 100	434.98	400.00	396.20	287.21	220.43	175.50	133.00	
		Post 300	505.50	473.06	421.26	254.10	229.95	174.83	143.98	
		Post 600	541.56	473.68	421.00	250.19	225.65	174.8	143.00	
		Pre-Rad	150.00	140.00	137.00	78.00	53.00	40.00	35.28	
		Post 50	150.00	140.00	137.00	78.00	53.00	40.00	35.28	
Rohm SiC 1700V	Post 100	150.62	140.50	136.8	77.80	52.60	39.70	35.16		
	Post 300	271.13	246.12	213.34	64.54	57.48	41.65	35.60		
	Post 600	275.5	252.03	218.30	78.10	63.40	43.50	37.30		

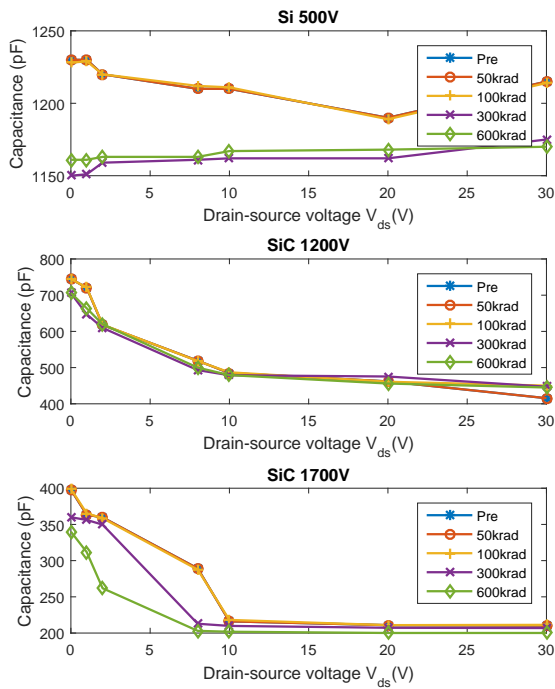


Figure 2.  $C_{iss}$  for Si and SiC power MOSFETs

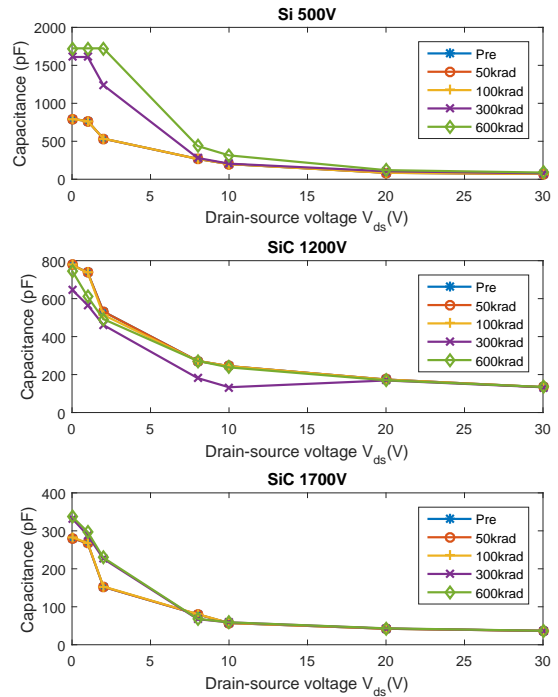


Figure 3.  $C_{oss}$  for Si and SiC power MOSFETs

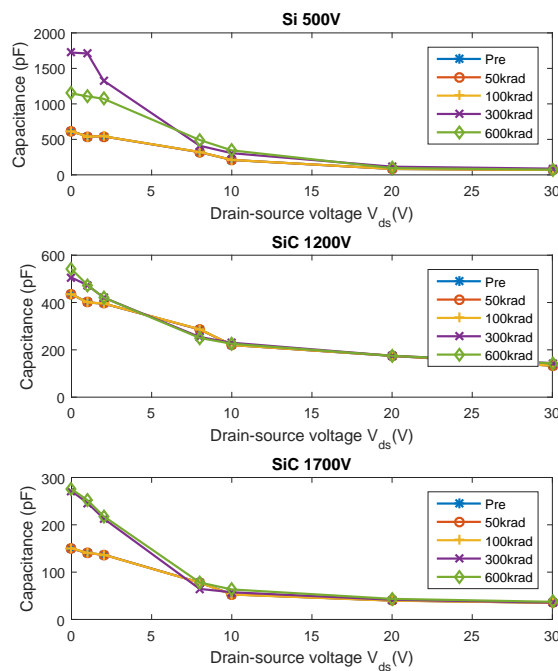


Figure 4.  $C_{rss}$  for Si and SiC power MOSFETs

## 5. CONCLUSION

The gamma ray induced total dose effects on Si (TOSHIBA 2SK2662) and SiC (ROHM SCT2H12NZ and SCT3160KL) MOSFETs have resulted in dynamic characteristics as a function of variable drain bias and dose level. These power MOSFETs perform well after a total dose of 100 krad, and may operate up to 300 krad. From the preceding results, it is very clear that changes in device capacitances are accounted for switching operations. Increase in oxide and interface trap densities is found to be the main degradation mechanism of gamma irradiated transistors. The measurements confirm the fact that gamma rays seriously degrade the device performance to a greater extent. Additionally, the failure modes in SiC power MOSFETs can differ depending on the component and the vendor for similar values of bias normalized by rated voltage. Therefore, the research and development is continuing to investigate SiC power MOSFETs in order to make high switching and high current device that available operate normally at radiation region.

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