

## Silicon carbide schottky diodes forward and reverse current properties upon fast electron radiation

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### Article Info

#### Article history:

Received Dec 18, 2018

Revised Feb 1, 2019

Accepted Mar 9, 2019

#### Keywords:

Electrical characterization

Electron radiation

Schottky diode

Silicon carbide

Wide bandgap semiconductor

### ABSTRACT

This paper investigates on the reaction of 10 and 15MGy, 3MeV electron irradiation upon off-the-shelves (commercial) Silicon Carbide Schottky diodes from Infineon Technologies (model: IDH08SG60C) and STMicroelectronics (model: STPSC806). Such irradiation reduces the forward-bias current. The reduction is mainly due to the significant increase of the series resistance (i.e. Infineon:  $1.45\Omega$  at before irradiation  $\rightarrow 121 \times 10^3 \Omega$  at 15MGy); STMicroelectronics:  $1.44\Omega$  at before irradiation  $\rightarrow 2.1 \times 10^9 \Omega$  at 15MGy). This increase in series resistance gives 4.6 and 8.2 orders of magnitude reduction for the forward-bias current density of Infineon and STMicroelectronics respectively. It is also observed that the ideality factor and the saturation current of the diodes increases with increasing dose (i.e. ideality factor- Infineon: 1.01 at before irradiation  $\rightarrow 1.05$  at 15MGy; STMicroelectronics: 1.02 at before irradiation  $\rightarrow 1.3$  at 15MGy | saturation current- Infineon:  $1.6 \times 10^{-17}A$  at before irradiation  $\rightarrow 2.5 \times 10^{-17}A$  at 15MGy; STMicroelectronics:  $2.4 \times 10^{-15}A$  at before irradiation  $\rightarrow 8 \times 10^{-15}A$  at 15MGy). Reverse-bias leakage current density in model by Infineon increases by one order of magnitude after 15MGy irradiation, however, in model by STMicroelectronics decreases by one order of magnitude. Overall, for these particular samples studied, Infineon devices have shown to be better in quality and more radiation resistance toward electron irradiation in forward-bias operation while STMicroelectronics exhibit better characteristics in reverse-bias operation.

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## 1. INTRODUCTION

The demanding market of high-reliability electronics which capable or working under extreme conditions such as harsh environment, high temperature (above 300°C), high pressures, encountering strong vibrations, or high radiations e.g. in space or nuclear plant, has motivated researchers to find the alternatives to Silicon (Si). Among materials, wide-bandgap semiconductors have attracted ample attention because of their distinguished electrical, mechanical, and chemical properties. Presently, the wide-bandgap semiconductor that demonstrates a more sophisticated manufacturing technology is Silicon Carbide (SiC). The contemporary advancement in SiC material growth which enables low defect concentration has allowed fabricating reliable SiC-based electronics devices [1]. These certainties have grant SiC to be the most appropriate alternative in establishing high-reliability converters and high-power electronics [2, 3].

Schottky diodes are devices of choice due to their multiple advantageous. Schottky diodes are dissimilar from P-N junction diodes in a way that the current movement requires only one type of carrier. For example, in n-type Schottky diodes, forward-bias current is driven from electrons flowing from the n-type semiconductor into the metal; while in p-type, holes are the major carrier. Therefore, when the voltage source is removed, current will stop immediately and reverse-bias voltage can be established in such a very short time (picoseconds) because there is no delay effect due to the stored charge. Schottky SiC-based devices are a compulsive resolution for the ever-escalating demand needed by space applications because power electronic devices in spacecraft or military applications need to be high radiation tolerant [4]. The premature death of satellites is suggested to be due to the degradation of the electrical characteristics of the satellites electronics devices when exposed to space radiation [5]. One type of radiation that is abundant in space is the fast electrons which can harm the semiconductor devices intensely. Some major effects of radiation include ionization damage: high-energy particles bombard the semiconductor material and remove orbital electrons from atoms, thus generate free charges which lead to extra unnecessary leakage current; and displacement damage: high-energy particles hit atoms in the lattice of a semiconductor material thus displacing individual atoms from their lattice (generate state level or traps) as the particle moves through the material hence increasing the series resistance.

It is often that, the degradation of Schottky diodes is characterized in term of their major electrical parameters i.e. ideality factor, saturation current, and series resistance. Schottky diodes performance is limited by the various factors which can be measured by the ideality factor ( $n$ ).  $n$  is a measure of how efficiently an applied bias is delivered to the junction of the device. Whereas, saturation current is a small leakage current flows due to the thermally excited electrons in the metal during reverse bias. Finally, the series resistance means the sum of the resistance due to the epi layer and the resistance due to the substrate [6].

In this context, the aim of this paper is to study the degradation of the electrical properties of the recent technology of commercial SiC Schottky diodes and to compare the device performance between two well-established and world-leading manufacturers in the field of semiconductor electronics i.e. Infineon Technology and STMicroelectronics under fast electron irradiation. The knowledge from the research is important for the building of expertise in radiation hard electronic devices which can be used in high-radiation environment.

## 2. RESEARCH METHOD

The devices studied were 4H silicon carbide Schottky diodes manufactured by Infineon Technology and STMicroelectronics. The devices part number and characteristics are given in Table 1. The device areas were determined by decapsulating the plastic packaging of the devices as shown in Figure 1 and measuring the area under microscope. Devices were irradiated at Malaysia Nuclear Agency (MNA), using Electron Beam Machine (EPS-3000) with 3 MeV electrons and were irradiated with two different doses of 10 and 15MGy (equivalent fluence of  $3.3 \times 10^{16}$   $4.95 \times 10^{16} \text{ cm}^{-2}$  respectively [7]). The specification of EPS-3000 is shown in Table 2.

Total of 6 devices from each manufacturer were labelled accordingly and unbiased during the irradiation. To ensure repeatability, each irradiation dose was performed on three different individual devices. The effects of irradiation were examined through current density-voltage (J-V) characterization which was made with two different instruments. Keithley 4200 Semiconductor Characterization System (SCS) was used to characterize the forward bias and lower currents in reverse bias and Keithley 2410 SourceMeter was used to supplement the 4200 SCS in order to extend the reverse bias measurement range to -600V. All measurements were done at room temperature  $\sim 300\text{K}$ .

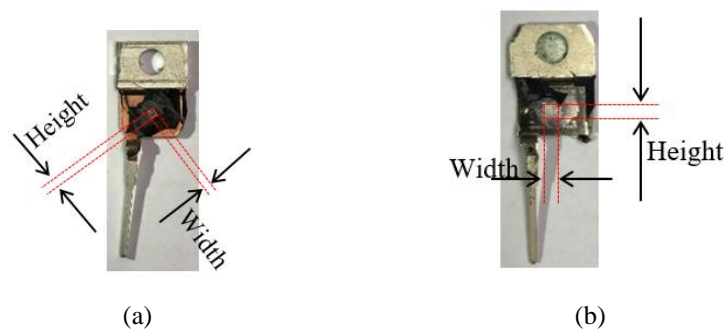


Figure 1. Devices semiconductor active area, (a) Infineon, (b) STMicroelectronics

Table 1. Characteristics of the studied schottky power diodes

Model	DC blocking voltage (V)	Forward voltage at room temperature (V)	Current rating (A)	Area (cm <sup>2</sup> )
Infineon (IDH08SG60C)	600	1.8-2.1	8	0.01335
STMicroelectronics (STPSC806)	600	1.4-1.7	8	0.02605

Table 2. Specification of EPS-3000

Generated electron energy (MeV)	Beam current (mA)	Maximum beam power (kW)	Beam width/area (cm)	Conveyor speed (m/min)	Fluence rate/Flux (kGy/pass)	Temperature during irradiation (°C)
0.5–3.0	1–30	90	30, 60 and 120	1–20	50	Room temperature

3. RESULTS AND ANALYSIS

In almost all datasets, only one characteristics from the three devices is shown due to them having similar characteristics before and after irradiation, and also to improve the figure clarity. However, the quantitative data of the diode-to-diode parameter variation are shown in Figure 2 and 3 for Infineon and STMicroelectronics respectively. As displayed, we can see that diode-to-diode parameters are relatively consistent in term of current density-voltage characteristics before and after electron irradiation.

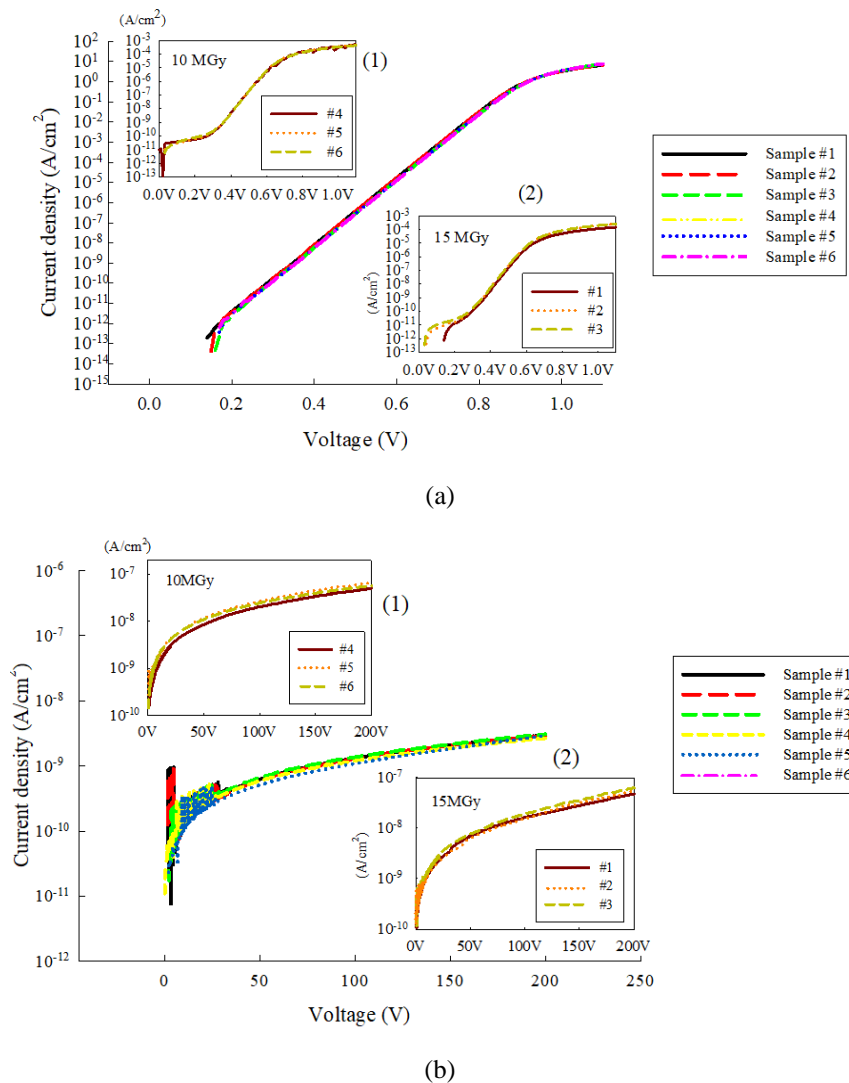
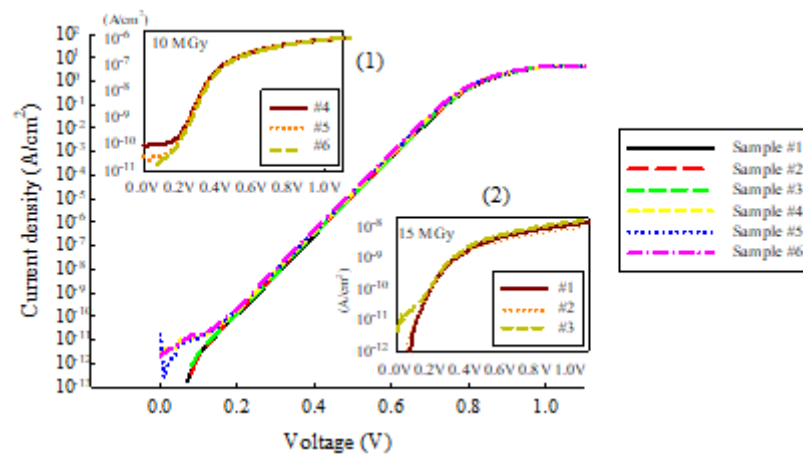
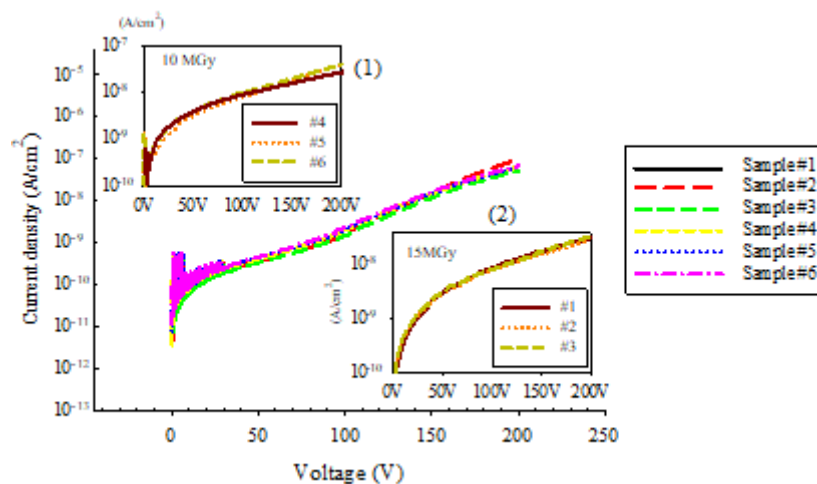


Figure 2. Diode-to-diode parameter variation of Infineon (IDH08SG60C) SiC Schottky diodes for, (a) Forward-bias, (b) Reverse-bias. Inset (1) and (2) show the parameter variation at 10 and 15MGy respectively



(a)



(b)

Figure 3. Diode-to-diode parameter variation of STMicroelectronics (STPSC806) SiC Schottky diodes for, (a) Forward-bias, (b) Reverse-bias. Inset (1) and (2) show the parameter variation at 10 and 15MGy respectively

### 3.1. Forward bias current density-voltage characteristics

Representative semi-logarithmic forward-bias current density-voltage characteristics are shown in Figure 4(a) and (b) for 600V SiC Schottky diodes from Infineon (IDH08SG60C) and STMicroelectronics (STPSC806) respectively. The fast electrons exposure caused a decrease in forward-bias current density in both diodes' models. However, the current density increment of 15MGy is less as compared to the increment to the 10MGy. To compare, at the highest irradiation dose, the forward-bias current density of Infineon (IDH08SG60C) decreases by approximately 4.6 orders of magnitude while STMicroelectronics (STPSC806) decreases by approximately 8.2 orders of magnitude.

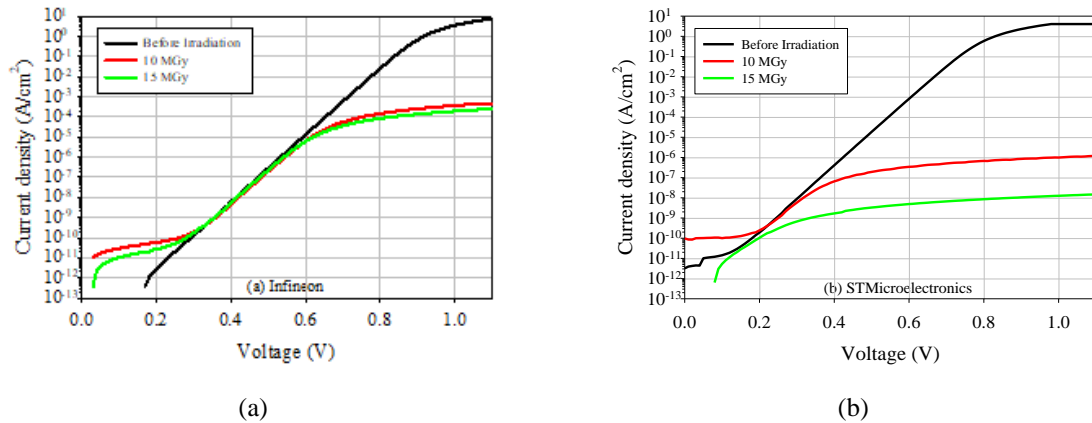


Figure 4. Experimental forward-bias current density-voltage characteristics of, (a) Infineon (IDH08SG60C), (b) STMicroelectronics (STPSC806) at room temperature before and after irradiation respectively

To analyze further, this study has determined the value of the devices ideality factor, saturation current, and series resistance. All of the parameters were determined by fitting the forward bias current-voltage characteristics with ideal diode (1) and thermionic emission model (2);

$$I = I_s \left[ e^{\left(\frac{qV}{n kT}\right)} - 1 \right] \quad (1)$$

$$I = I_s \left[ e^{\left(\frac{V-IR_s}{n \left(\frac{kT}{q}\right)}\right)} - 1 \right] \quad (2)$$

The ideality factor and the saturation current were determined by fitting the low current region of the current-voltage plot to (1), where  $I$  is the current,  $I_s$  is the saturation current,  $q$  is the electronic charge,  $V$  is the applied voltage,  $n$  is the ideality factor,  $k$  is Boltzmann's constant, and  $T$  is the temperature. The series resistance of the device was determined by fitting the high current region of current-voltage plot to the (2), where  $R_s$  is the series resistance. All of the obtained parameters are summarized in Table 3.

Table 3. Electrical parameters of the tested schottky diodes before and after irradiation

Model	Dose (MGy)	Ideality factor	Saturation current (A)	Series resistance ( $\Omega$ )
Infineon (IDH08SG60C)	0	1.01	$1.6 \times 10^{-17}$	1.45
	10	1.04	$2.1 \times 10^{-17}$	$60 \times 10^3$
	15	1.05	$2.5 \times 10^{-17}$	$121 \times 10^3$
STMicroelectronics (STPSC806)	0	1.02	$2.4 \times 10^{-15}$	1.44
	10	1.05	$2.5 \times 10^{-15}$	$21.5 \times 10^6$
	15	1.3	$8 \times 10^{-15}$	$2.1 \times 10^9$

From Table 3, we can see the significant changes in the properties of the Schottky diodes at 300K as a result of electron irradiation. Both models experienced an increment in the ideality factor where the increment is very significant for STMicroelectronics devices at 15MGy. The increment is approximately 1.3 times from the before irradiation; compared to Infineon, the increment at the highest dose to the before irradiation is only about 1 time. The 1.35 ideality factor of 15MGy STMicroelectronics devices indicates that the current transportation inside the diodes is no longer depend solely on the thermionic emission mechanism [8, 9]. On top of that, the saturation current also shows an incrementing behavior and this is rather expected and has been reported by several other researchers due to the irradiation-induced defects at the metal-semiconductor interface which caused tunneling of the free carrier through the barrier [8], [10], [11].

Furthermore, as mentioned earlier, it is proven by Table 3 that Infineon devices have a lower saturation current value compared to STMicroelectronics. The trend after irradiation is similar to the ideality factor where the saturation current of 15MGy STMicroelectronics devices experienced the highest increment. The increment from before irradiation to 15MGy of Infineon and STMicroelectronics is 1.5 and 3.3 respectively.

Besides that, new irradiation-induced defects have originated in the bulk of the SiC crystal and caused an increase in the series resistance as observed in Table 3 which at the same time caused the decrease in the forward bias current density-voltage characteristics observed earlier [11, 12]. There might be another mechanism which could also contribute to the increase in the series resistance, which is the contact quality after the irradiation between each element that form the Schottky diode; either the contact between the metal and semiconductor, or the contact of the wire bond has been damaged. Comparing the two models, the significant increase of series resistance from before irradiation to 15MGy is roughly 5 orders of magnitude for Infineon and 9 orders of magnitude for STMicroelectronics, which clearly show that Infineon (IDH08SG60C) has a better toleration toward the irradiation. The significant increase in the resistant means that, in real application, extra unnecessary heat will be dissipated and there will be much more energy losses in term of heat.

For a better visualization of both manufacturers diodes properties, the following Figure 5(a) to (c) is plotted. The semi-logarithmic forward-bias current density-voltage plots compare the two models on top of each other for all irradiation dose. During before irradiation as in Figure 5(a), it is clear that Infineon (IDH08SG60C) has a lower leakage current density for a given voltage (0–1.1V) compared to STMicroelectronics (STPSC806) by two orders of magnitude at 0.6V. Whereby at 10MGy (Figure 5(b)), before the series resistance is dominant, again, Infineon (IDH08SG60C) show a lower leakage current by 11 times difference to STMicroelectronics (STPSC806) at 0.4V. The difference of the leakage current of both manufacturers diodes become less significant at 15MGy (Figure 5(c)) whereby only small portion of STMicroelectronics (STPSC806) is showing the true leakage current; only up to around 0.35V. These facts clearly show that, the forward-bias characteristics of Infineon (IDH08SG60C) devices are more resistant to electron irradiation.

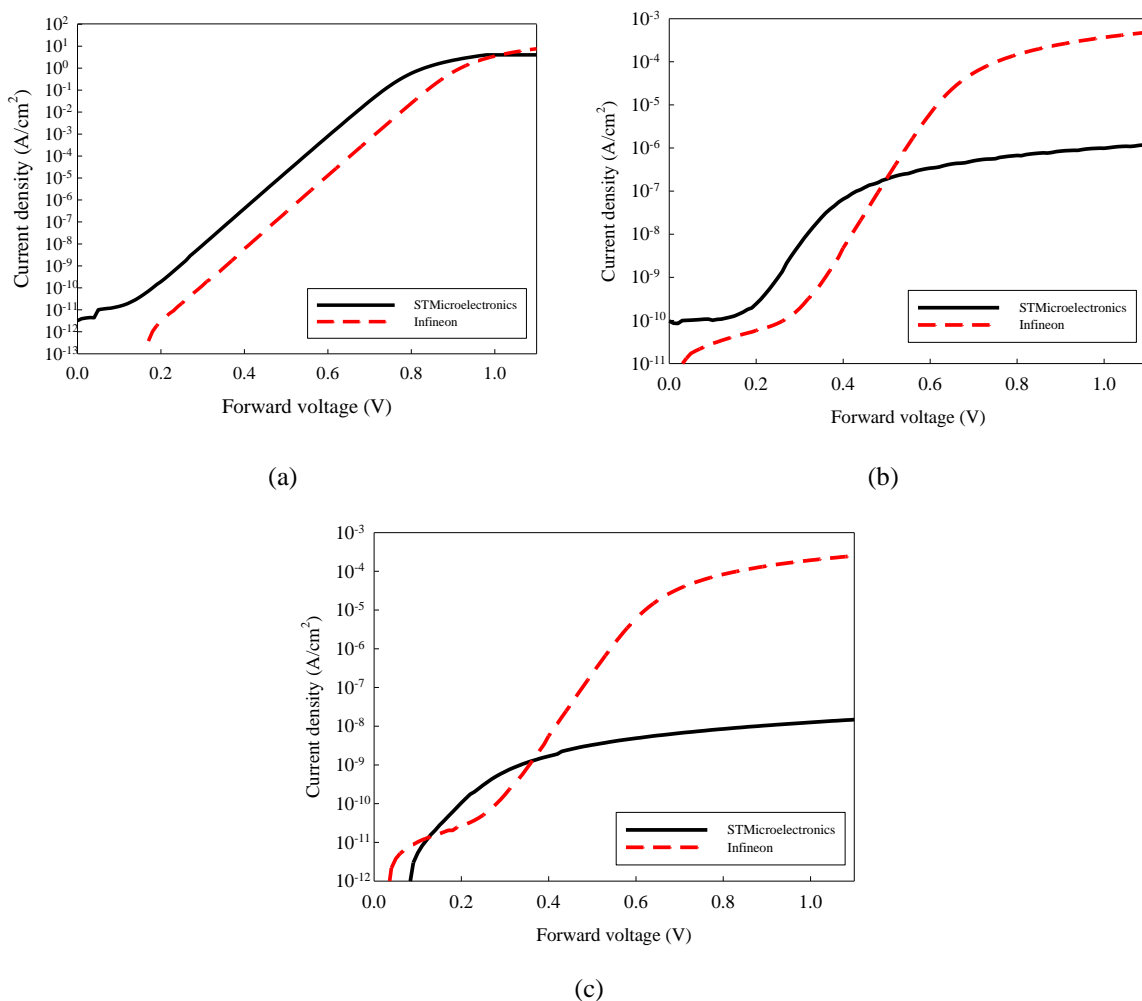


Figure 5. Properties of forward-bias current density-voltage characteristics of, (a) Before irradiation, (b) 10MGy, (c) 15MGy

### 3.2. Reverse bias current density-voltage characteristics

Figure 6(a) and (b) shows the Schottky diodes semi-logarithmic reverse-bias current density-voltage characteristics of Infineon (IDH08SG60C) and STMicroelectronics (STPSC806) respectively; while Figure 7(a) to (c) shows the semi-logarithmic reverse-bias current density-voltage of Infineon and STMicroelectronics plotted on top of each other for every irradiation dose.

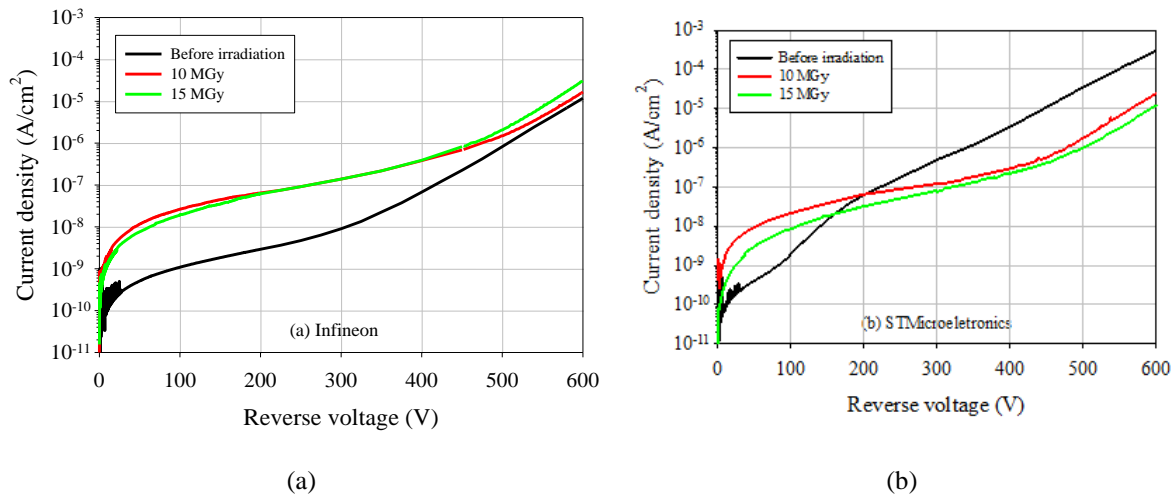


Figure 6. Experimental reverse bias current density-voltage characteristics of, (a) Infineon (IDH08SG60C), (b) STMicroelectronics (STPSC806) at room temperature before and after irradiation respectively

In Figure 6, it was observed that, the magnitude of the leakage current density in both manufacturers devices increases with increasing voltage which is believed to be related to the lowering of the Schottky barrier height [9]. Apart from that, the effects of 10 and 15MGy irradiation on the reverse bias characteristics can also be observed clearly in both models based on Figure 6. For Infineon (IDH08SG60C) devices, the same behaviour as in forward-bias discussed earlier has been observed where very little changes in the characteristics of 15MGy as compared to the 10MGy. It is suggested that several doses higher than 15MGy should be applied in the future to confirm such behaviour. Besides that, the leakage current density of Infineon (IDH08SG60C) devices is always higher after the irradiation as compared to before irradiation. At -300V, the leakage current magnitude increases approximately 1 order of magnitude. The increment can be reasoned by the emission of the free carriers thermally from the irradiation-induced defects [8]. For STMicroelectronics (STPSC806), the irradiation has also caused the reverse leakage current to increase at low voltages ( $V \leq -200V$ ). In particular, at -50V, the current density magnitude increases about 16 times at 10MGy and 9 times at 15MGy. The reason is believed to be attributed to the increase in the density of the irradiation-induced defect which caused the increase in the saturation current observed earlier in Table 3 hence enhance the free carriers flow at the interface thus excess in the reverse current at low voltage. Just to note that, the reverse-bias characteristics for STMicroelectronics (STPSC806) before and after irradiation show different shape which may correspond to different current transport mechanism that occur in the devices. However more study need to be done in order to investigate the difference in the current mechanism. Another hypothesis is that, the decrease is probably due to the annealing effects of the high irradiation doses which removed the radiation-induced defects observed during before irradiation [13-16].

Additionally, we can also see in Figure 7(a) that the magnitude of the leakage current density of before irradiation devices is higher in STMicroelectronics (STPSC806) as compared to Infineon (IDH08SG60C); for example, at -200V, the difference of the leakage current density between the two models is 13 times. This somehow indicates that Infineon (IDH08SG60C) devices have better rectifying attributes especially at high voltages, and STMicroelectronics have already many defects, to begin with [17].

However, after the irradiation of 10MGy as shown in Figure 7(b), the magnitude of the reverse-bias current density between the two models seems to be roughly similar, and as the dose increases, the leakage current of Infineon (IDH08SG60C) devices also seems to grow (Figure 7(c)). This means that, despite the superior properties as compared to STMicroelectronics (STPSC806) observed earlier in the previous analysis, Infineon (IDH08SG60C) devices still have their drawback which is they are likely to be more sensitive to the irradiation in the reverse-bias mode. It is safe to conclude that, based on the accumulated

facts, the best choice of devices still depends on how the user want to use the device. If the application requires more on the forward-bias properties, Infineon should have the advantage; but if the application need to perform better in reverse-bias mode, the user should select STMicroelectronics (STPSC806).

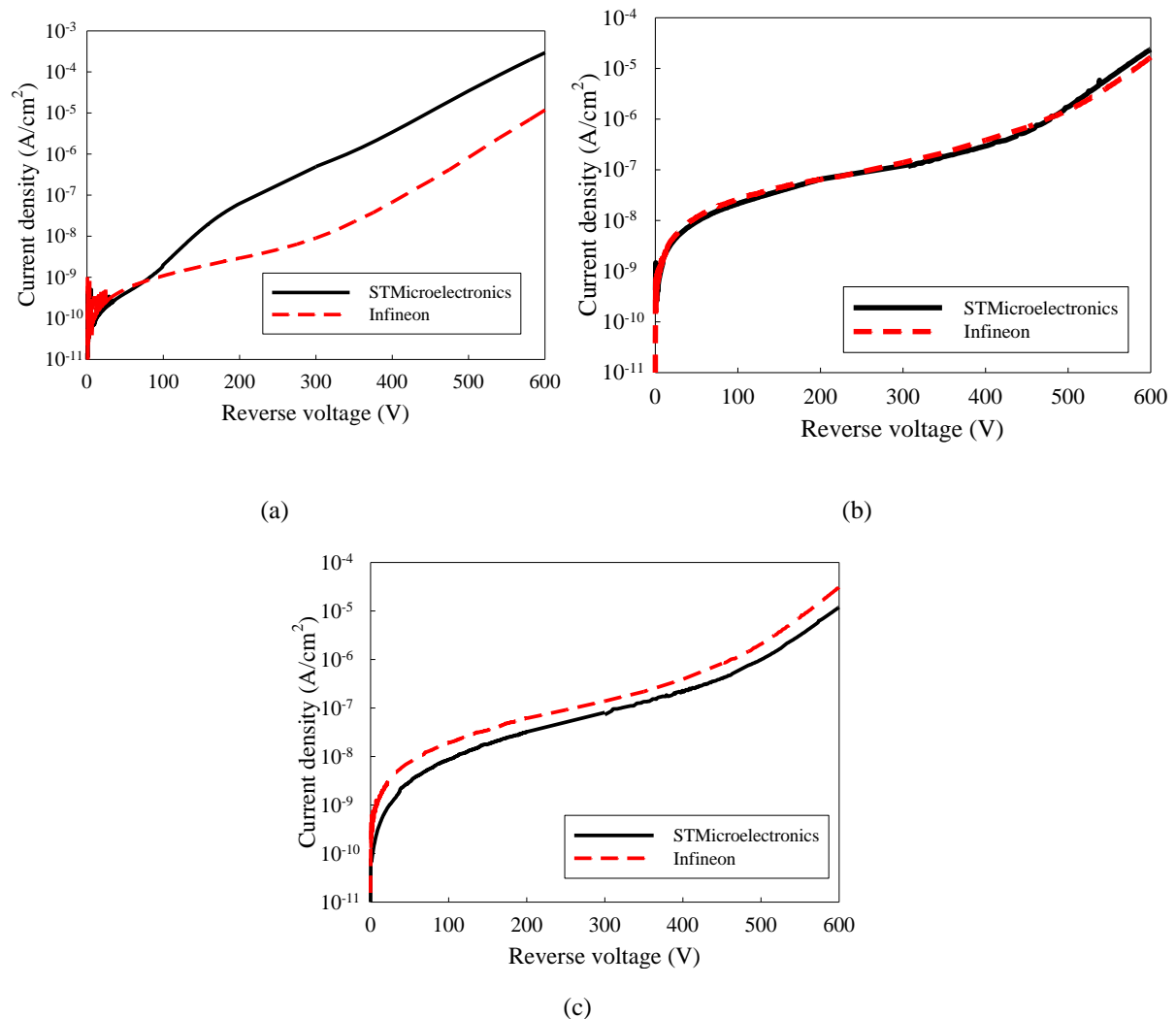


Figure 7. Properties of reverse-bias current density-voltage characteristics, of (a) Before irradiation, (b) 10MGy, (c) 15MGy

#### 4. CONCLUSION

This study shows the degradation of the electrical properties of commercial SiC Schottky diodes produced by Infineon (IDH08SG60C) and STMicroelectronics (STPSC806) upon the exposure fast electron. It was observed that, before irradiation, both forward and reverse-bias current density of Infineon (IDH08SG60C) is lower for a given voltage as compared to STMicroelectronics (STPSC806). This indicates that the Infineon devices has less defect density as compared to the STMicroelectronics. After irradiation of both 10 and 15MGy, significant increase of series resistance for all devices has been shown. However, the increase of the series resistance is more significant in STMicroelectronics (STPSC806) which is 9 orders of magnitude after 15MGy irradiation as compared to Infineon (IDH08SG60C) which is only 5 orders of magnitude. This series resistance is probably due to the defects induced during the irradiation or probably due to the damages occurred at each of the elements contact that form the diodes. Only a small portion of the forward-bias characteristics of STMicroelectronics (STPSC806) can be used to measure the ideality factor. Ideality factor is observed to be increases with increasing irradiation dose, i.e. 1.3 times increment for STMicroelectronics (STPSC806) and 1 time increment for Infineon (IDH08SG60C). In conclusion, for forward-bias operation, Infineon (IDH08SG60C) devices show a better radiation hardness compared to



STMicroelectronics (STPSC806) due to the less significant increase in the series resistance. However, for reverse-bias operation, at the high irradiation dose i.e. 15MGy, Infineon (IDH08SG60C) give a higher leakage current as compared to STMicroelectronics (STPSC806). Comparing to the before irradiation leakage current density of both models, Infineon (IDH08SG60C) clearly has a higher rate of degradation as compared to STMicroelectronics (STPSC806). Hence STMicroelectronics (STPSC806) is a much better and preferred choice for rectifying application.

#### ACKNOWLEDGEMENTS

This work was supported by Ministry of Education, Malaysia under Research Grant RIGS16-338-0502.

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