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Effects on the Forward Bias Characteristics of Neutron Irradiated Si and GaAs Diodes

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Abstract: The aim of this study is to investigate the effects on forward bias characteristics of neutron radiation on various commercially available silicon and GaAs diodes. The diodes were irradiated using the Pneumatic Transfer System (PTS) facility in Malaysian Nuclear Agency with neutron fluences up to 10^{12} neutron/cm^2.s for an exposure time of 1, 3 and 5 min. The Forward Bias (FB) current-voltage (I-V) characteristics and doping profiles of the diodes were recorded before and after irradiation. It is observed that the FB leakage current of the silicon and GaAs diodes increases after irradiation. The increase in leakage current is interpreted as being due to an increase of generation-recombination traps created in the band gap after radiation. The doping concentration of GaAs diodes in FB is observed to decrease while the series resistance increases after irradiation which may be attributed to changes in doping concentration due to carrier removal by the defects produced.

Keywords: Commercial diode, doping concentration, electrical characterization, ideality factor, leakage current, neutron radiation

INTRODUCTION

Diodes such as solar cells, laser diodes and light emitting diodes are being used routinely in military, research reactor and outer space applications as auxiliary power sources and detectors. Technology development in the semiconductor industry has led to continuous testing of the reliability and radiation hardness of these devices. Studies over recent years on commercial silicon photodiodes (Korde *et al*., 1989) and light emitting diodes (Kim *et al*., 2010; Li and Subramanian 2003; Lischka *et al*., 1993; Stanley, 1970) under neutron irradiation have shown measurable changes in the device parameters and characteristics. Silicon (Si) and Germanium (Ge) are the most common elemental semiconductor materials used in semiconductor fabrication. While, group III-V compounds such as Gallium Arsenide (GaAs) are widely used for applications in areas such as nuclear instrumentation and outer space where radiation levels are high. The electronic devices are exposed to high-energy particles such as neutron and proton which may give rise to radiation-induced defects. The primary damage mechanism in semiconductors is the introduction of displacements defects identified as vacancies and interstitials (Khamari *et al*., 2011; Weatherford and Anderson, 2003). This study presents experimental results on changes of Si and GaAs commercial diode's Forward Bias (FB) current-voltage (I-V) characteristics including leakage current, ideality factor and series resistance as a function of neutron fluence up to 10^{12} neutron/cm^2.s.

Table 1: Diodes specifications

No.	Part no.	Material	Manufacturer
1	1N4148	silicon	NTE electronics
2	1N4150	silicon	Fairchild semiconductor
3	TSKS5400S	GaAs	Vishay semiconductor

The study was carried out between 1st of January and 30th of March 2012.

EXPERIMENTAL DETAILS

Samples specifications and neutron source: Commercial devices used in this investigation are standard GaAs diodes with molded plastic packages and two Si diodes 1N4148 and 1N4150 encapsulated in sealed leaded glass packages. Table 1 summarizes the diodes specifications.

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The diodes were irradiated with neutron fluences up to 10^{12} neutron/cm^2.s in the Reactor TRIGA PUSPATI with power level at 750 kW using the Pneumatic Transfer system in Malaysian Nuclear Agency, Bangi, Malaysia. Irradiation was performed on three devices of each part number to ensure reproducibility of the measurements. All diodes were labeled accordingly and inserted one by one into capped Polyethylene (PE) vials before irradiation to avoid contamination. The exposure times for each type of diode were 1, 3 and 5 min. The PTS system is meant for short irradiation purposes with a maximum exposure time of 5 min. For each exposure time, three vials were inserted into a particular capsule for the transmission into ring G20 of the reactor core.

Measurements: The electrical measurements were carried out in the Electronics Systems laboratory at International Islamic University Malaysia. FB I-V measurements were performed at room temperature in a dark enclosure using Keithley 4200 Semiconductor Characterisation System (SCS) before and after irradiation. For each sample, the measurements were repeated three times to ensure reproducibility. FB I-V characteristics of 1N4148 (Si) and 1N4150 (Si) diodes were measured three days after irradiation while measurements on TSKS5400S (GaAs) diodes were performed one week later to allow radioactivity to reach acceptable safety level.

RESULTS AND DISCUSSION

In this study we present some results which are representative for the selected devices. The cross sectional areas for all devices are unknown although requested from manufacturers. Figure 1 consist of three graphs where Fig. 1a shows semi-log FB I-V characteristics of the 1N4148 (Si), Fig. 1b for 1N4150 (Si) diodes and Fig. 1c for the TSKS5400S (GaAs) diodes. All devices show an increase in FB leakage current after neutron irradiation. This is expected as radiation-induced defects are introduced in the diodes. This will cause an increase of Generation-Recombination (GR) current in the devices and increase the leakage current of the devices (Hajghassem *et al*., 1992; Horváth *et al*., 1999; Weatherford and Anderson, 2003). Figure 1 a and b show that the increase of leakage current for the Si diodes are minimal compared to the GaAs diodes in Fig. 1c. Figure 2 further illustrates the differences in current increment where the percentage current increment is plotted against exposure time.

Figure 2 shows a semi-log plot of percentage current increment plotted with respect to exposure time taken at reference voltage of 0.5V. The percentage current increment is obtained by calculating the percentage difference in FB leakage current magnitude before and

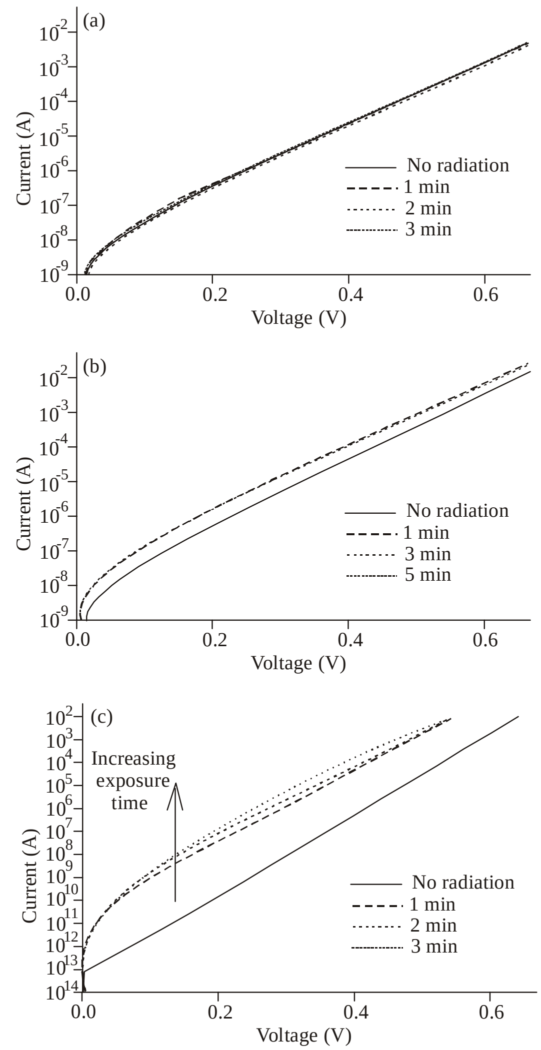

Fig. 1: FB leakage currents for unirradiated devices and irradiated devices exposed for 1, 3 and 5 min for (a) 1N4148 silicon diodes, (b) 1N4150 silicon diodes and, (c) TSKS5400 GaAs diodes, respectively

after irradiation. Generally, it can be seen that there is a linear increase in the diode FB leakage current for all devices as the exposure time increases. This is expected as the rate of reaction induced by neutrons is defined as $\phi(r)\Sigma$ where, $\phi(r)$ is the neutron flux (length^{-2} time^{-1}) and Σ is the macroscopic cross section (Knoll, 2000). Thus, an increase in exposure time increases the reaction rate and radiation-induced defect density. This is manifested by the increase of leakage currents in the devices. As exposure time increases the rate of GR also increases because there are more defects in the semiconductor lattice. Several studies (Chih-Tang *et al*., 1957; Hasbullah *et al*., 2011; Sanchez *et al*., 2009) suggested that FB leakage current correlates with defect density where GR leakage current, I_{GR} is proportional to $qW\sigma v_{th}N_t n_i$ with q being the

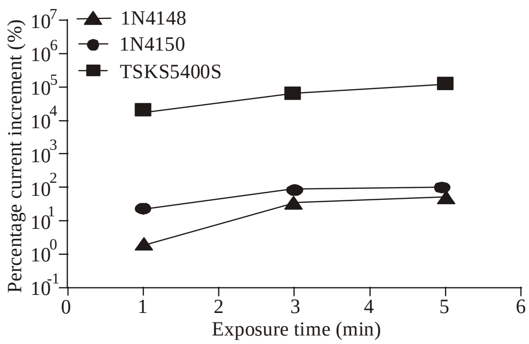

Fig. 2: Percentage current increment of all diodes at 0.5 V bias with different neutron exposure time. The solid lines are a guide to the eyes

electronic charge, W is the thickness of the intrinsic region, σ is the electron and hole capture cross section, v_{th} is the thermal velocity, N_t the defect density and n_i is the intrinsic carrier concentration.

Results from Fig. 2 indicates that the GaAs diodes suffer more degradation compared to the Si diodes. This is unusual compared to other studies reported where Wysocki (1963) discovered that GaAs cells to be superior to Si cells in a radiation field of high-energy particles. It was also reported that GaAs devices are more resistant to defects due to neutron irradiation compared to Si devices (Weatherford and Anderson, 2003).

This may be explained by the fact that the silicon diodes used in this experiment are switching diodes. It is known that gold (Au) doping is used in switching diodes to improve its speed (Streetman and Banerjee, 2010; Sze and Ng, 2007). A recent technical report by Sandia National Laboratories states that gold doping is used in 1N4148 (Si) diodes (Loubriel *et al*., 2012). It was reported by McPherson *et al*. (1997) that gold doping in silicon may reduce the effects of neutron irradiation. Present vacancies in the silicon lattice are believed to be occupied by the gold atoms thus restricting the formation of other energy levels in the bandgap. A similar effect was obtained by Cappelletti *et al*. (2009) on gold-doped silicon photodiodes comparing simulated results with experimental data. They suggested that gold atoms filling the vacancies prevent formation of neutron-induced defect levels near the midband gap. Thus, we believe that the gold-doping in our silicon diodes is the possibility that suppresses the increase in leakage current after irradiation.

Further analysis can be done by studying the ideality factor, n where it is a measure of the deviation from the ideal diode characteristics. The diode is considered ideal if n = 1 where the dominant mechanism is diffusion and if n = 2 the dominant mechanism is GR. Both diffusion and GR processes may occur simultaneously in the device when the values of n are between 1 and 2. The diode

Table 2: Parameters for TSKS5400 GaAs diode

Exposure time (min)	Irradiation	Is (pA)	n	Rs (Ω)
1	before	0.0676	1.732	0.68
1	after	14.200	1.820	6.92
3	before	0.0543	1.693	6.87
3	after	53.100	1.872	7.82
5	before	0.0516	1.709	1.12
5	after	101.50	1.898	15.98

ideality factor, n and saturation current, I_S can be extracted from the FB I-V characteristics by fitting the linear region of the plot to the approximated ideal diode equation.

$$I \approx I_s \left[\exp\left(\frac{qV}{nkT} \right) \right] \tag{1}$$

where, I is the forward current, q is the electronic charge, V is the voltage applied, k is the Boltzmann's constant and T is the temperature. The I_s and n extracted from a representative fit of the TSK5400S GaAs diode irradiated for 5 min are 1.015x10^{-10}A and 1.898, respectively. Values of the saturation current and ideality factor for all exposure time recorded for TSK5400S GaAs diodes are shown in Table 2. There appears to be a systematic increase in the ideality factor and the saturation current as the exposure time increases.

The increase in FB leakage current, I_s and n may be attributed to the introduction of recombination centres introduced by the creation of defects in the semiconductor structure by radiation-induced displacement damages (Weatherford and Anderson, 2003). Displacement damages occur when neutron particles collide with an atom of a nucleus and displace the atom from their normal position in the lattice thus creating interstitial or vacancy defects. These defects act as effective recombination and trapping centres which create additional levels within the band gap assisting emission of electrons and holes thus increasing the leakage current.

The high current region of the FB I-V characteristics in Fig. 1c shows substantial changes with exposure time. This is interpreted as a change in the series resistance of the material. The series resistance, R_s of GaAs diodes before and after 1, 3 and 5 min neutron irradiation is obtained by fitting the high injection region of the FB I-V curve to the ideal diode equation, where thermal voltage, V_t, is equal to kT/q.

$$I = I_s \left[\exp\left(\frac{V - I.R_s}{nV_t} \right) - 1 \right] \tag{2}$$

The values of n and I_s previously obtained in Table 2 were used by fitting only the value of R_s. The values of series resistance of the GaAs diodes are tabulated in Table 2 where R_s is observed to increase after irradiation.

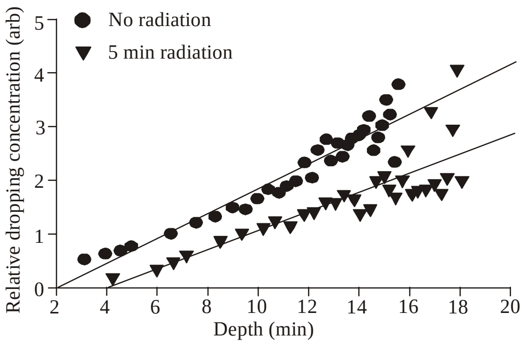

Fig. 3: The doping concentration against depletion width of GaAs diodes before and after 5 min irradiation. The solid lines are a guide to the eye

Previous studies have discussed such effects where a study by Korde *et al*. (1989) reported that the increase in R_s was due to the increase in bulk resistivity of the device caused by a decrease in the doping density due to carrier removal after neutron exposure. The increase in R_s can be further explained by the changes in the doping profile of the GaAs diodes. Harris *et al*. (2005) stated that series resistance of a diode is inversely proportional to the dopant density where $R_s = C/N_D$ (Sze and Ng, 2007). N_D is the dopant density and C is a constant depending on the relation of N_D and R_s. The doping concentration and width of depletion region are extracted from the Capacitance-Voltage (C-V) measurements with one sided abrupt junction assumption. The values of doping concentration are represented as relative doping concentration since the cross sectional area of the diodes were not provided by the manufacturer.

Figure 3 shows at a fixed depletion width, the relative doping concentration halves after irradiation. This is interpreted due to changes in the effective doping concentration known as carrier removal (Czerwinski *et al*., 2003; Williams *et al*., 1991). Carrier removal is one of the effects of displacement damage in the diode after neutron irradiation. Another effect of displacement damage is type conversion or carrier compensation where after irradiation the samples become intrinsic observed after neutron irradiation due to carrier removal (Moscatelli *et al*., 2006; Weatherford and Anderson, 2003). The fluence of up to 10^{12} neutron cm^2.s is insufficient to make the material of the diodes intrinsic.

CONCLUSION

The results presented in this study show that both silicon and GaAs diodes experienced increase in FB leakage current after neutron irradiation. This is interpreted due to the neutron-induced defects creating more mid band traps hence the increase of the FB leakage current. Silicon diodes shows less degradation compare to GaAs diodes due to gold doping in the diode which suppresses neutron-induced defects. The saturation current, ideality factor and series resistance increases in all devices suggest that defects increase in devices after irradiation. It is also found that series resistance increase with exposure time due to carrier removal induced by displacement defects. Diodes may continue to evolve in the near future and there will always be a need to do basic evaluations of new diode types as radiation effects may differ for other types of diodes.

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