Effects of Neutron on Reverse Bias Characteristics of Commercially Available Si and GaAs Diodes

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Abstract: This study investigates the effects of neutron radiation on reverse bias characteristics of commercial silicon and gallium arsenide diodes. Reverse bias current-voltage and capacitance-voltage characteristics of the diodes were measured at room temperature before and after irradiation. The diodes were irradiated using Pneumatic Transfer System facility at PUSPATI TRIGA reactor with neutron fluences up to \((6.038 \pm 3.067) \times 10^{12} \text{ n/cm}^2\text{s}\) for a period of 1, 3 and 5 minutes. The results showed an increase in leakage current for all diodes which may be due to the existence of neutron-induced displacement defects introduced into the semiconductor lattice. The doping concentration of gallium arsenide diodes is observed to decrease after irradiation which is attributed to carrier removal process.

Key words: electrical characterisation, carrier removal, displacement damage, leakage current, doping profile

INTRODUCTION

Applications of diodes in extreme radiation environments are common nowadays which includes solar cells in outer space, light emitting diodes in research reactors and lasers for military purposes. Defects in semiconductor lattice of a diode may produce significant changes to the properties of the diodes hence their reliability. This has led to continuous testing and experimentation of the latest and available off-the-shelf diodes (Kim, Kim, Ren and Jang, 2010; Korde, Ojha, Braasch and English, 1989; Li and Subramanian, 2003; Stanley, 1970). Study of defects in diodes through various characterizations (Kim et al., 2010; Osborne, Hobson and Watts, 2000) such as electrical, optical and simulation play an important role in the development of diodes. Silicon (Si) and germanium (Ge) are the most common semiconductor material used in producing diodes. This work aims to investigate the effects of neutron on commercially available 1N4148 (Si), 1N4150 (Si) and TSKS5400S GaAs diodes by analysing their reverse bias (RB) current-voltage (I-V) and capacitance-voltage (C-V) characteristics before and after neutron irradiation, respectively.

MATERIALS AND METHODS

Samples Specifications And Neutron Irradiation:
The samples used for this experiment are Si and GaAs commercial diodes with the silicon diodes part number 1N4148 and 1N4150, manufactured by NTE Electronics and Fairchild Semiconductor. They are high-speed switching diodes encapsulated in a sealed leaded glass package. For GaAs diode, the part number is TSKS5400S, an infrared GaAs emitting diode manufactured by Vishay Semiconductor is also used for this experiment. Neutron irradiation was carried out for 1, 3 and 5 minutes using the Pneumatic Transfer System (PTS) facility in the PUSPATI TRIGA Reactor with power level of 750kW and thermal neutron fluences up to \((6.038 \pm 3.067) \times 10^{12} \text{ n/cm}^2\text{s}\) at the Malaysian Nuclear Agency, Bangi, Malaysia. The PTS facility has the advantage of rapidly transferring irradiation samples within short time, to and from the reactor core with high neutron fluxes. The diodes were prepared in a capped polyethylene vials and labelled accordingly. The vials were then inserted into PTS tubing before transferred into the reactor core.

Measurements:
RB I-V characteristics of the diodes were measured at room temperature before and after radiation. All measurements were performed in a metal enclosure connected to the Keithley 4200 semiconductor characterisation system (SCS) supplemented with a C-V analyser to measure C-V characteristics. The
measurements were carried out in the dark to ensure no contribution of photocurrent. Electrical measurements of 1N4148 and 1N4150 were performed three days after the radiation. The measurements on TSKS5400S diodes were performed a week later to allow adequate cool down period to minimize exposure of personnel to residual radiation. Three diodes of each part number are used and the I-V measurements were repeated three times for each sample to observe reproducibility.

**Results:**
Selected results which are representatives for the diodes are presented in this study. Figures 1 (a), (b), (c) and 2(a), (b), (c) show the semilog RB I-V characteristics for both 1N4148 and 1N4150 Si diodes before and after irradiation for 1, 3 and 5 minutes, respectively. It appears that the RB leakage current increases after radiation however no change in the breakdown voltage of the silicon devices. Only one diode irradiated for each exposure time is shown here to illustrate leakage current increment for both Si and GaAs diodes. Figure 3 shows the semilog plot of the RB I-V characteristics for TSKS5400S GaAs diodes before and after 1, 3 and 5 minutes irradiation. It is clearly seen that TSKS5400S GaAs diodes experienced a significant current increment when compared to both Si diodes after irradiation. Results from Figure 1, 2 and 3 are further illustrated in Figure 4 where the current increment ratio is plotted against exposure time.

![Fig. 1: RB I-V characteristics of 1N4148 Si diodes exposed to (a) 1, (b) 3 and (c) 5 minutes of neutron irradiation.](image1)

![Fig. 2: RB I-V characteristics of 1N4150 Si diodes exposed to (a) 1, (b) 3 and (c) 5 minutes of neutron irradiation.](image2)
Figure 3: Semilog RB I-V characteristics of TSKS5400S GaAs diodes exposed to (a) 1, (b) 3 and (c) 5 minutes of neutron irradiation.

Figure 4 (a) and (b) show the ratio of current increment before and after irradiation plotted against exposure time for all diodes exposed for 1, 3 and 5 minutes, respectively. In Figure 4, current increments for all diodes were taken at reference voltage of 30% before the breakdown voltage. Generally, there appears to be an increment in RB leakage current with respect to exposure time in both Si and GaAs diodes. This effect is expected as the longer the devices are exposed to radiation the higher the number of defects introduced in the lattice structure of the diodes. Neutron reaction rate density is expressed as φ(r) where φ(r) is the neutron flux (length^-2 time^-1) and σ is the macroscopic cross section (Knoll, 2010). Thus, an increase in exposure time increases the reaction rate and radiation-induced defect density thus an increase in leakage currents. Further analysis is done by plotting the linear RB I-V characteristics of TSKS5400S GaAs diodes as shown in Figure 5.
Figure 5 (a), (b) and (c) show the linear RB I-V plots of TSKS5400S GaAs diodes irradiated for 1, 3 and 5 minutes. \( \Delta V_{br} \) is the difference in breakdown voltage, \( V_{br} \), before and after irradiation. It clearly shows that breakdown voltages, \( V_{br} \), of all GaAs diodes shift and also \( \Delta V_{br} \) is increasing with exposure time. At reference current of 5mA, the percentage \( \Delta V_{br} \) increment is 2.65%, 4.90% and 9.72% after 1, 3 and 5 minutes irradiation, respectively. In contrary, the breakdown voltages for the silicon diodes show no obvious change. The RB leakage current and breakdown voltage changes in the I-V results for TSKS5400S GaAs diodes are further explained by C-V analysis.

Discussion:

From Figures 1, 2 and 3, both silicon and GaAs diodes showed increment in RB leakage current after neutron irradiation for all exposure time. It is known that RB leakage current increment in semiconductor diodes is prominent after neutron radiation due to the effects of displacement damage (Srour, Marshall and Marshall, 2003). Displacement damage is initiated by the collision of neutron particle with atoms in the semiconductor lattice causing the atom to displace from their normal position (Messenger, 1992; Srour et al., 2003; Weatherford and Anderson, 2003). Displacement damage introduces defect states into the semiconductor bandgap that can act as efficient generation centers. The generation of carriers through midband traps gives rise to RB leakage current in diodes (Srour et al., 2003) with the most effective defects level is located near the middle of the bandgap. This is due to equal probability of electrons and holes excitation mechanism in the diode. Lemeilleur et al. (Lemeilleur, Glaser, Heijne, Jarron and Occelli, 1992) reported that an increase of the diode reverse current is interpreted due to neutron-induced defects at the bulk of the diode where displacement damage is dominant. However, the source of leakage current in our diodes could not be determined whether from bulk, surface or side due to non-availability of diode chip of different sizes.

It can be seen from Figure 4, that the TSKS5400S GaAs diodes experienced a significant increase of RB leakage current compared to both silicon diodes, indicating more degradation in GaAs diodes which is unexpected. Previous works reported that Si devices are more prone to defects due to neutron irradiation compared to GaAs devices (Weatherford and Anderson, 2003; Wysocki, 1963). 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 to improve the speed of switching diodes (Streetman and Banerjee, 2006; Sze, 1981). A technical report by Sandia National Laboratories confirmed gold doping were used in 1N4148 (Si) diodes (Loubriel, Vigliano, Coleman, Williams, Wouters, Bacon et al., 2012). Furthermore, an experiment on the Si diode was conducted using a high-purity germanium detectors (HPGe) has shown the presence of gold in the material. Studies reported that gold doping in silicon may reduce the effects of neutron irradiation by restricting the formation of other energy levels in the bandgap, thus suppressing the increase of leakage current in the Si diodes (Cappelletti, Cedola, Baron, Casas and Peltzer, 2009; McPherson, Sloan and Jones, 1997). Therefore, we believe that the gold-doping in our Si diodes possibly suppresses the increase in leakage current after irradiation.

The shift in breakdown voltage after neutron irradiation for GaAs diodes can be explained by neutron-induced traps in diode depletion region. Hasan et al. (Hasan, Kosier, Schrimpf and Galloway, 1994) reported that trap centers inside the depletion region affects the electric field across the region, thus increases the breakdown voltage. To further analyze the I-V results, C-V measurements were performed for TSKS5400S GaAs diodes. From the C-V measurements, the doping profile can be extracted to analyse changes in doping concentration before and after irradiation. Assuming a diameter of 60μm, the depletion width, \( w \) and doping concentration, \( N_d \) of the TSKS5400S GaAs diode are calculated from the C-V measurements using one sided abrupt junction assumption. Figure 6 shows the extracted doping profile of TSKS5400S GaAs diode before and after 5 minutes exposure.
Fig. 6: Doping profile of TSKS5400S GaAs diode before and after 5 minutes irradiation.

From the figure, doping concentration is observed to decrease while the depletion width appears to increase after irradiation. A study by EerNisse et al., (EerNisse and Chaffin, 1970) reported that the shift in breakdown voltage may occur due to carrier removal at the edges of the depletion region. Carrier removal involves compensation of donors or acceptors by radiation-induced centers resulting in a reduction in the majority-carrier concentration (Khamari, Dixit, Ganguli, Porwal, Singh, Kher et al., 2011; Srour et al., 2003), which is clearly shown in Figure 6. In silicon diodes, the breakdown voltage has no significant change.

Conclusion:
The results of this study show that both silicon and GaAs diodes experienced an increase in RB leakage current after neutron irradiation due to defect centers formed by displacement defects. Other effects of displacement damage in GaAs diodes include increase in breakdown voltage which is interpreted due to carrier removal induced by displacement defects in the diodes after irradiation. The Si diodes however do not show significant changes in RB leakage current, breakdown voltage or doping concentration. It is believed that gold doping used in the Si diodes suppresses neutron-induced defects thus exhibit less degradation compare to GaAs diodes.

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REFERENCES


