RADIATION PERFORMANCE OF GaN AND InAs/GaAs QUANTUM DOT BASED DEVICES SUBJECTED TO NEUTRON RADIATION

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(Received: 18th Mar. 2016; Accepted: 4th Dec. 2016; Published online: 30th May 2017)

ABSTRACT: In addition to their useful optoelectronics functions, gallium nitride (GaN) and quantum dots (QDs) based structures are also known for their radiation hardness properties. With increasing demand for such semiconductor material structures, it is important to investigate the differences in the reliability and radiation hardness properties of these two devices. For this purpose, three sets of GaN light-emitting diodes (LED) and InAs/GaAs dot-in-a well (DWELL) samples were irradiated with thermal neutron of fluence ranging from 3×10^{13} to 6×10^{14} neutron/cm^2 in a PUSPATI TRIGA research reactor. The radiation performances for each device were evaluated based on the current-voltage (I-V) and capacitance-voltage (C-V) electrical characterisation method. Results suggested that the GaN based sample was less susceptible to electrical changes due to the thermal neutron radiation effects compared to the QD based sample.

ABSTRAK: Selain daripada kegunaanya sebagai bahan optoeletronik, struktur berasaskan galium nitrida (GaN) dan kuantum dot (QD) juga dikenali atas sifatnya yang teguh daripada kesan radiasi. Dengan permintaan yang kian meningkat, adalah amat penting bagi kedua-dua bahan ini diuji bagi melihat tahap prestasi dan keteguhannya terhadap kesan radiasi. Bagi tujuan ini, tiga set sampel daripada diod pemancar cahaya (LED) dan dot-dalam-takungan (DWELL) di dedahkan kepada radiasi neutron haba dengan jumlah fluens dari 3×10^{13} hingga ke 6×10^{14} neutron/sm^2 di reaktor nuklear PUSPATI TRIGA. Prestasi bagi setiap bahan ujikaji kemudian di uji dengan menggunakan kaedah arus elektrik-voltan (I-V) dan kapasitan-voltan (C-V). Hasil daripada ujian berkenaan mencadangkan bahawa sampel dari GaN kurang mengalami perubahan apabila didedahkan kepada radiasi neutron berbanding dengan sampel QD.

KEYWORDS: *GaN; InAs/GaAs; quantum dots; neutron; electrical characteristics*

1. INTRODUCTION

Semiconductor based devices find many applications in harsh radiation environments such as space, for satellite optocouplers, and radiation physics laboratories, for particle detectors [1; 2]. Serious damage due to the radiation effects such as increment in the leakage current [3; 4] and reduction in the charge collection efficiency [5] may occur in such devices if proper shielding is not well integrated. However, to some devices such as sensors and radiation detectors, direct shielding may hinder the device‘s useful function which, at length, will result in precision and accuracy deterioration. To other devices, shielding could increase the payload of the system and consequently the cost of operation. For this reason, the reliability of these devices is greatly dependent on the material composition and material structure. The search for a radiation-hard semiconductor material and material structure has long been performed and the effort continues to progress along with the development of new semiconductor technology. To date, some of the materials and material structures deemed radiation-hard include; SiC *pn*-junction, III-V nitride-based heterostructure, InAs/GaAs quantum dot (QD) and InGaAs quantum well (QW) [6-8]. For optoelectronics purposes, it was reported that GaN and InAs/GaAs QD based diodes are less susceptible to radiation damage compared to other structures [9-11]. These two materials could hold the key for future free-space communication technology which highlights the importance of studying their reliability against the effects of radiation.

This paper was written to evaluate the tolerance of two of the most radiation-hard material structures known in optoelectronics applications; the InAs/GaAs quantum dot-in-well (DWELL) structure and the GaN/SiC double heterojunction light emitting diode (LED) structure. All samples were subjected to thermal neutron radiation to assess their radiation hardness properties against the displacement damage. The investigations were carried out through two electrical characterisation methods; the current voltage (I-V) and capacitance-voltage (C-V) which yield information of the current density, series resistance, doping profile and the carrier removal rate of both samples.

2. EXPERIMENTAL DETAILS

2.1 Sample Specifications

For this study, two different types of diodes were used; commercial off-the shelf GaN LEDs manufactured by Vishay GmbH and mesa InAs/GaAs DWELL diodes fabricated by the University of Sheffield. The GaN LED samples were fabricated on SiC grown by the metal-organic chemical vapour deposition (MOCVD) technique with an approximate active area value of 0.09 cm^2. Further details on the GaN LED layers will not be disclosed due to the confidentiality policy of the manufacturer. The InAs QDs samples, on the other hand, were grown using Stranski-Krastanov (S-K) method where the QDs were sandwiched between 2 nm thickness of $In_{0.15}Ga_{0.85}As$ and 6 nm thickness of $In_{0.15}Ga_{0.85}As$ to develop a DWELL structure. The active region consists of InAs/GaAs DWELLs separated by 50 nm GaAs spacer layers. Enclosing the active region are undoped 150 nm GaAs/AlGaAs waveguides with the *n*-type $Al_{0.4}Ga_{0.6}As$ deposited on the lower cladding layers and the *p*-type on the upper layers. The growth process was completed with 300 nm p^+-GaAs ohmic contact.

2.2 Neutron Irradiation Process

All samples were exposed to thermal neutron radiation via pneumatic transfer system (PTS) of the PUSPATI TRIGA MARK II research reactor at the Malaysian Nuclear Agency. Throughout the irradiation process, the power level of the reactor was kept at 750 kW with maximum thermal neutron flux rate peaked at 1×10^{12} neutron/cm^2.s and the reactor core temperature maintained at an average of 300 ºC. Each set of samples contains three devices with nominally identical I-V and C-V characteristics, prepared in separate polyethylene vials. The QDs and GaN samples were exposed to two different thermal neutron fluence range; with 3×10^{13} to 9×10^{13} neutron/cm^2 for the QDs samples and 6×10^{13}

to 6×10^{14} neutron/cm^2 for the GaN samples. The higher fluence range used on the GaN samples is to produce new findings since the report on the lower fluence has been justified by Li and Subramanian [12] where there were no changes in the electrical characteristics observed. The electrical characterizations of all samples were conducted in the dark at room temperature (≈300 K) using Keithley 42000 SCS parameter analyzer connected to a probe station and 8101-4TRX test fixture. Measurements were consecutively repeated three times to achieve reproducibility on the obtained results.

3. RESULTS AND DISCUSSION

The reverse-bias and forward-bias current densities of the GaN samples and QDs samples plotted with respect to the voltage before and after neutron irradiation are shown in Fig. 1 and Fig. 2 respectively.

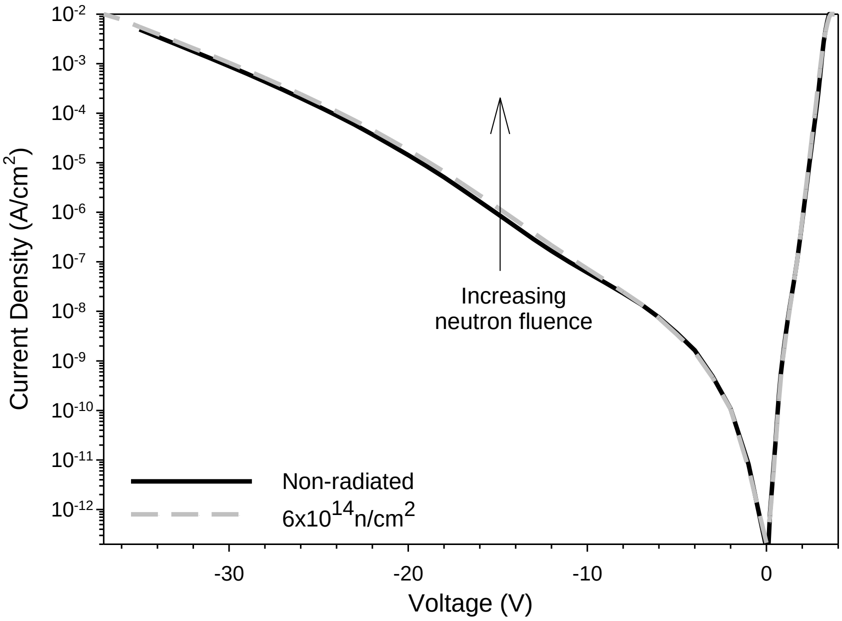

Fig. 1: Reverse-bias and forward-bias I-V characteristics of GaN samples before and after neutron irradiation of 6×10^{14} n/cm^2.

Based on Fig. 1 above, there are no significant changes observed neither in the forward bias nor in the reverse bias characteristics of the GaN samples. Similar trends were also observed in other tested models of GaN/SiC LEDs. Increment in the leakage current however is observed for neutron fluence larger than 1×10^{15} neutron/cm^2 which is in agreement with Grant et al., Lorenz et al. and Qiu et al. [13-15]. Some of the properties suggesting the radiation hardness of GaN/SiC based diode include; wide bandgap energy [11; 16], high thermal stability and self-annealing property [16; 17], as well as small thermal neutron capture cross section of the nitride [18]. Additionally, due to the presence of SiC (the polymer type is not disclosed by the manufacturer), it is believed that the bandgap of the heterostructure is altered to become much wider reducing the rate of generation-recombination of carriers [19].

A perfect fit of the forward-bias I-V characteristics with the ideal diode equation yield the value of the ideality factor, n of 3.5 and series resistance, R_s of 0.5 Ω. According to the Sah-Noyce-Shockley (SNS) analysis, as the value of n approaches 2, the dominant current in the device may largely be contributed by the generation-recombination process [20].

However, since the ideality factor obtained in the GaN sample is greater than 2, the SNS analysis is therefore unaccountable for the current behavior. Such behavior is reported to be either due to an excessive contact resistance between metal and the *p*-type layer of the sample or the deep-level trap-assisted tunneling mechanism [21]. Figure 2 shows the I-V characteristics of the QDs samples, indicating a significant increment in the reverse-bias leakage current densities of up to 2 orders of magnitude under the maximum neutron irradiation of 9×10^{13} n/cm^2. The reverse-bias current densities are observed to increase proportionally with the increase in neutron fluence. A similar trend is also observed in the forward-bias I-V characteristics of the QDs samples with maximum increment in the leakage current density of about 4.5 times.

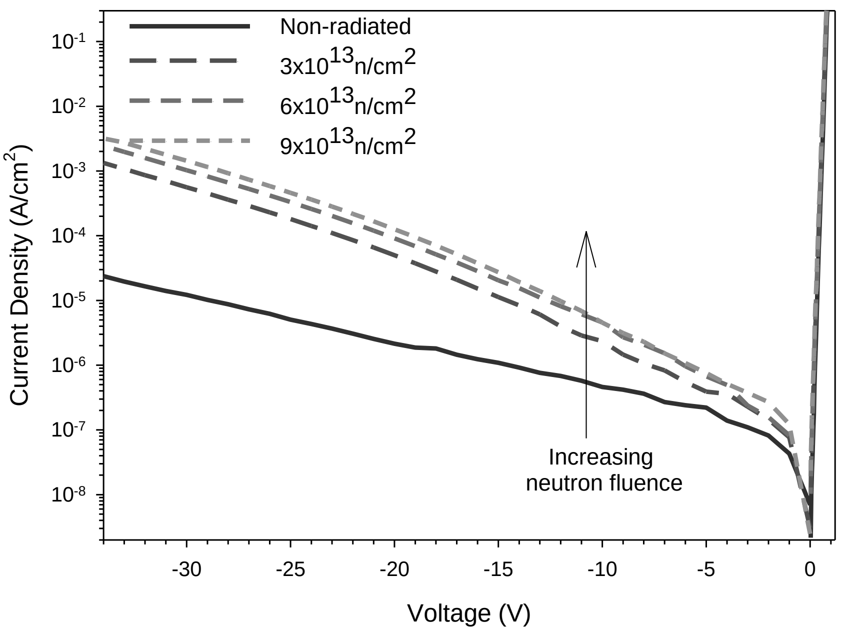

Fig. 2: Reverse bias and forward bias I-V characteristics of QDs samples before and after neutron irradiation of up to 9×10^{13} n/cm^2.

Based on the fitting of the ideal diode equation on the forward bias I-V characteristics (illustrated in Fig. 3), it is noted that the QDs device ideality factor increases from 1.77 (before irradiation) to 1.86 (after being irradiated with 9×10^{13} neutron/cm^2) while the measured series resistance increases from 0.02 Ω to a maximum value of 0.05 Ω. The parameters and results of the fittings are tabulated in Table 1. Increment in the leakage current densities is highly believed to be associated with the neutron induced trap-assisted generation-recombination (TAGR) process [4; 22] which can be modelled as in [23]. These charge carrier traps or non-radiative recombination centers are known to be the result of the displacement damage effect which can be instigated by the incident neutron particles as well as recoil atoms through secondary events known as primary knock-on-atoms (PKAs) [4]. Additionally, it is also believed that the formation of in situ traps due to growth defects may also assist in the propagation of further traps giving rise to the leakage current density values.

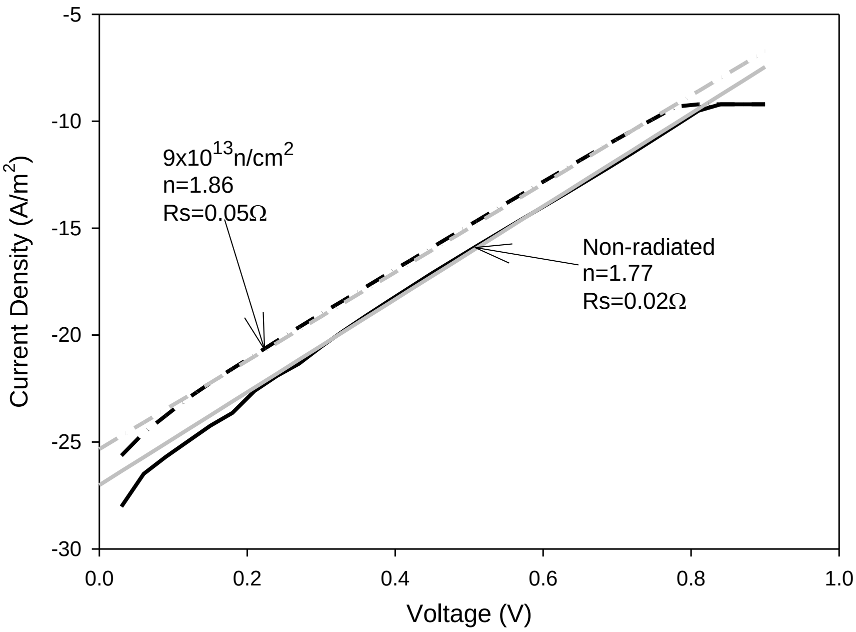

Fig. 3: Forward bias I-V fittings of the QD samples before and after neutron irradiation.

Table 1: Fitting parameters of the QDs forward bias I-V characteristics

Fluence (n/cm^2)	**n±0.01**	**R_s±1m (Ω)**
Unirradiated	1.77	0.02
3×10^{13}	1.81	0.03
6×10^{13}	1.84	0.04
9×10^{13}	1.86	0.05

Neglecting the minimal effect of gamma radiation, the linear increment in the leakage current can be explained by the relation of the saturation current (A) with the neutron fluence, ϕ_n (n/cm^2) given by equation (1) [12]:

$$I_o\{\phi_n\} = I_o\{0\} + k\phi_n \tag{1}$$

where $I_o\{0\}$ is the pre-exponential term before neutron irradiation, and k is the damage factor (Acm^2/n). The saturation current is further defined as $I_o = q\ n_i\ w\ \sigma\ \upsilon_{th}\ N$ with q being the electron charge, n_i the intrinsic concentration, w the width of depletion region, σ the electron and hole capture cross section, υ_{th} the electron's thermal velocity, and N_t the trap density. The damage factor for the 3, 6 and 9×10^{13} neutron/cm^2 irradiated samples are 3.52×10^{-22}, 3.49×10^{-22} and 3.24×10^{-22} Acm^2/n respectively. Based on these results, it is worthy to note that the damage incurred in the QD samples are reduced with increasing neutron fluence. This, to our knowledge, could be either a sign of a series resistance effect or the thermal annealing of defects initiated by the high temperature of the reactor core.

With regard to the increment in the series resistance or the series resistance effect, review suggested that it may be caused by any of these three major reasons; thermal annealing effect [24], carrier removal through deep carrier trapping [4; 25] and neutron transmutation doping (NTD) effect [4]. The thermal annealing effect facilitates the curing of defects, hence causing the diode to behave like it is intrinsic. Alternatively, the deep carrier trapping and NTD effects change the resistance by altering the carrier concentration of the device. The carrier trapping reduces the concentration of carriers while the NTD changes the concentration type from *p*-type to *n*-type when the thermal neutron undergoes inelastic interaction with the lattice. To prove the existence of such effects after neutron irradiation, the samples are further characterized using a C-V characterisation technique. However, prior to the C-V characterisation of the samples, it is important to investigate the reverse bias leakage current mechanism to better understand the carrier transport of neutron irradiated QDs. An attempt to fit the TAGR model alone on the reverse-bias characteristics of the QD sample came to no avail. Therefore, aside from the TAGR process it is believed that there could be another mechanism that contributed to such I-V characteristics after the neutron irradiations. Although some claimed that the extra contributing mechanism is due to tunnelling [9; 10; 22], our further analysis indicates that the viable mechanism in the high field region is due to the Frenkel-Poole mechanism [23] .

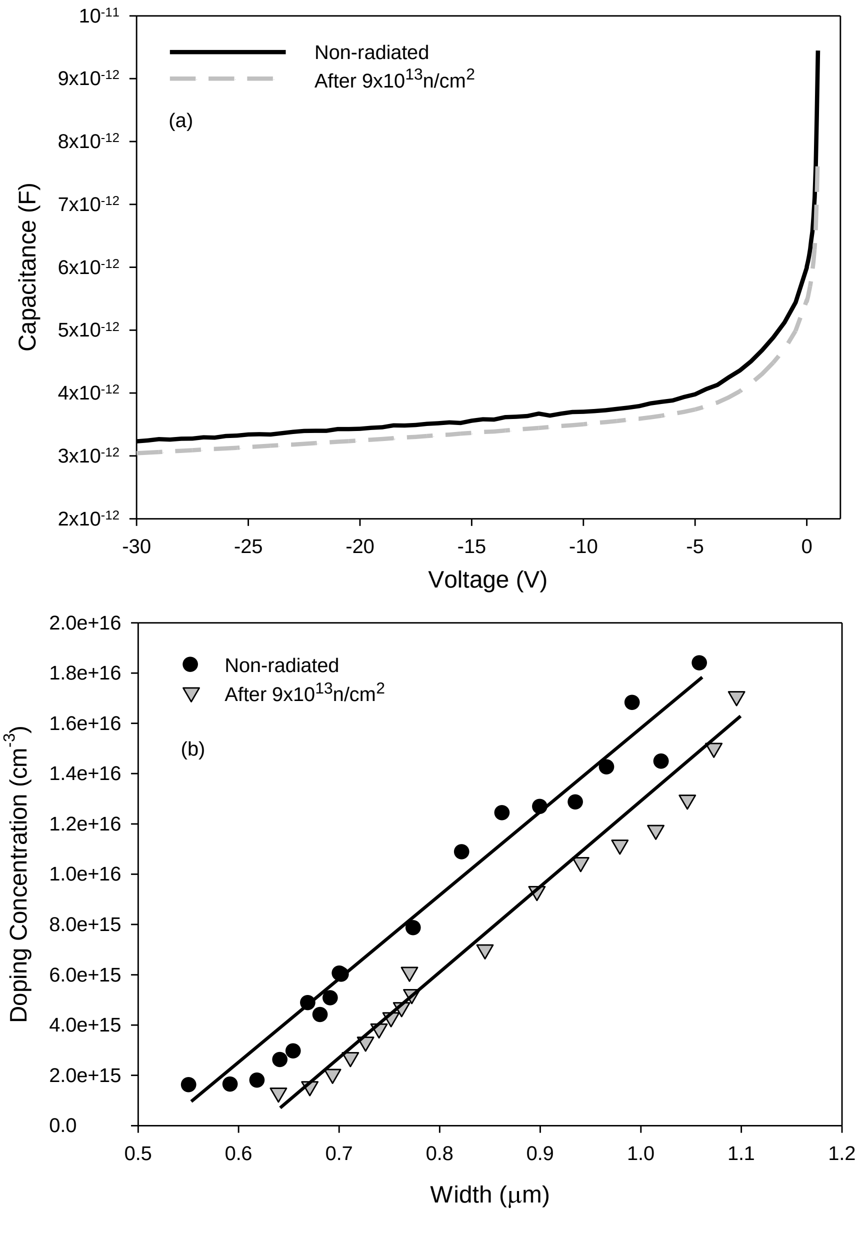

Fig. 4: Top (a): The C-V characteristics and bottom (b): the doping profile of the QD samples before and after neutron irradiation of 9×10^{13} n/cm^2.

The room-temperature C-V measurements conducted for both GaN and QD samples were done at a frequency of 1 MHz to eliminate the effect of built-in charge near the interface [26]. As expected, there are almost no changes observed in the C-V characteristics of the GaN samples before and after neutron irradiation. Instead, the QD samples show decrement in capacitance of about 6.4% as shown in Fig. 4(a). The doping profile for the QD samples is derived based on the linear graded region as illustrated in Fig. 4(b). Based on the guide lines, it is observed that there is a reduction in the doping concentration of the QD sample after being exposed to thermal neutrons of up to 9×10^{13} n/cm^2. It is understood that the observed trend is due the carrier removal effect which explains the increment in the value of the series resistance. Based on other work, it is discovered that the cause of carrier removal is attributable to the NTD effect [23]. It has been suggested that among the key measures that can be taken to improve the susceptibility of the QD samples towards radiation damage include, increasing the number of QDs stacks [27] and improving the growth condition [28].

4. CONCLUSION

This paper presents the discussion of the radiation hardness of two different semiconductor material structures; GaN/SiC double heterojunction LED and InAs/GaAs QDs based diode against thermal neutron radiation of fluence ranging from 3×10^{13} to 6×10^{14} n/cm^2. Based on the I-V and C-V measurement analysis, the GaN samples showed no significant changes to neutron fluence as high as 6×10^{14} n/cm^2. Conversely, the QD samples showed considerable increment both in the leakage current density and series resistance, even at a much lower fluence of 9×10^{13} n/cm^2. We believe that the main reason causing the degeneration of the QD samples' radiation hardness is the inherited defects incurred during the growth process. Better growth of QDs samples could be investigated in the near future to compare with current results.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Malaysian Ministry of Higher Education for the research fund under FRGS12-081-0230 grant.

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