Effects of Gamma Irradiation on AlGaN-Based High Electron Mobility Transistors

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The influence of various radiations on the performance and carrier transport properties of AlGaN/GaN HEMTs has been observed at length over the previous few decades. Gamma irradiation has been shown to have little influence on carrier density but has significant effects on device performance. The effects of gamma irradiation have proven non-monotonic in nature, dividing results into low and high doses with an inflection point near 300 Gy. Low doses of gamma irradiation have a tendency to improve device characteristics, while high doses lead to device degradation. The differences in low versus high doses are highlighted by electron beam induced current and dc characterizations. The variance in behavior originates from irradiation-induced trap generation and subsequent trap occupation from Compton scattering. AlGaN/GaN-based HEMTs have shown carrier transport enhancement for low doses.

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III-Nitride devices have long been an attractive solution to the ever-increasing high power and speed demands of industry. Of note, AlGaN/GaN high electron mobility transistors (HEMTs) have emerged as a contender for these industrial applications investigated due to their high power and speed capabilities. Further, AlGaN/GaN HEMT devices do not require additional doping in contrast to AlGaAs/GaAs. Attention to AlGaN/GaN-based devices for potential space and military applications has incited numerous investigations into device radiation hardness. Particularly, the effects of high energy radiations on AlGaN/GaN HEMTs have been investigated, as well as p-i-n diodes for solar blind light detectors.

Studies of radiation-induced defects in GaN-based devices have attracted significant interest, and much insight exists into the behavior of III-Nitride-based transistors after exposure to energetic ionizing radiation. Investigations of the radiation effects in AlGaN/GaN-based devices employing energetic protons have consistently reported that proton-irradiation results in a decrease in two-dimensional electron gas (2DEG) sheet carrier concentration and a positive threshold voltage shift with increasing proton dose. Negatively threshold voltage shifts and increase in 2DEG sheet concentration have been observed in AlGaN/GaN HEMT structures exposed to 1-MeV neutron irradiation with doses up to $2.5 \times 10^{15}$ cm$^{-2}$. In contrast to the behavior observed in proton-irradiated HEMTs, negative threshold voltage shifts are also observed in gamma-irradiated devices.

Even at low altitudes, the fluences of high energy protons, electrons, and photons may be non-negligible and depend on many factors including the local solar weather. The interaction of highly energetic particles with matter tend to lead to the generation of secondary radiation. Such investigations have shown that the lower energy levels of the irradiation induced defects were found at 89 and 132 meV. The lower energy was related to VN defects while the higher energy was possibly due to coupled neighboring defects. The model predicts that VN will present as s-like, or A1, donor levels and p-like, or T2, levels. For Al concentrations from 0 < x < 0.5, the T2 level remains above the conduction band edge while the A1 level remains in the forbidden band. While nitrogen interstitials, NI, form deeper acceptor levels near 1 eV below the conduction band edge. For gallium vacancies, VGa, a half-occupied p-like T2 level forms just above the valence band, which can act as a trap for both electrons and holes. When charged, VGa can form acceptor states near 1 eV above the valence band, while gallium interstitials, GaI, form donor levels with 3/2+ charge transition level located near 1 eV below the conduction band.

Energy levels induced by 60Co gamma irradiation have been detected in GaN by deep level transient spectroscopy (DLTS). The energy levels of the irradiation induced defects were found at 89 and 132 meV. The lower energy was related to VN defects while the higher energy was possibly due to coupled neighboring defects. The coupling of an interstitial and nearby vacancy is known as a Frenkel pair. These defects have been observed experimentally in GaN after being subjected to 0.7–1.0 MeV electron irradiation. The Hall mobility was observed to decrease after irradiation with $5 \times 10^{16}$ 1 MeV electrons/cm$^2$, and introduced new donors with ionization energy of 0.06 eV. However, there was only a slight change in majority carrier concentration. This is significant because VGa acts as a triple acceptor in n-type GaN, while GaI is a single donor. Therefore, with Ga lattice Frenkel pairs there is a marked change in majority carrier concentration. While for Frenkel pairs generated in the N lattice, VN tend to behave as shallow donors, and NI as deep acceptors yielding no net change in carrier density. The effects of irradiation by 60Co gamma-rays in GaN are charge compensated suggesting that the primary defects generated are N lattice Frenkel pairs.

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The energy threshold for atomic displacement is notably higher for Ga than that of N in GaN. As revealed by molecular dynamics calculations, the lowest displacement energies for Ga and N are 39 and 17 eV, respectively. The weighted average displacement energies taking into account wurtzite crystal orientation are 73.2 for Ga and 32.4 eV for N. When irradiated by high energy (0.7 – 1.0 MeV) electrons, Frenkel defects are generated far less in the Ga lattice for electron energies below 400 keV, while for the N lattice the Frenkel pair generation rate is nearly constant after 150 keV. With gamma-rays from $^{60}$Co of energy above 1 MeV, the dominant process, Compton scattering, imparts an average energy of 600 keV to scattered electrons. The generation of Frenkel defects at 600 keV is more than twice as frequent as for the N lattice as compared to the Ga lattice. For GaN, the impact of internal electron irradiation was found to be equivalent to $^{60}$Co gamma irradiation.

**Carrier transport properties.** — The generation of point defects introduces traps throughout the material leading to alterations in charge transport properties in the 2DEG channel. The direct current (dc) properties are among the most widely investigated, including drain-source I-V characteristics, transconductance, gate leakage current, and threshold breakdown voltage. Several investigations have shown that there is a significant improvement for dc device performance characteristics for lower doses of $^{60}$Co gamma irradiation. $^{7,8,20}$-23

Vitusevich et al. irradiated HEMT devices with doses of 0.1 to 10 MGy and observed the drain-source current, $I_{DS}$, and transconductance. At higher doses, the same device parameters exhibited a deteriorating trend which was attributed to extended defect generation in both the AlGaN channel and the GaN buffer layer. The current noise spectral density was also observed and showed a shift from $1/\nu^2$ to $1/\nu$ after 2 MGy suggesting an increase in the number of deep levels. They claimed that for doses up to 1000 Gy, transconductance and $I_{DS}$ were enhanced and was assumed to be due to relaxation of film strain found at the SiNx passivation layer interface or restructuring of native defects. $^{24-27}$

Kurakin et al. further explored the carrier enhancement effects of gamma irradiation through X-ray diffraction (XRD) and magnetotransport spectroscopies. This study included HEMT devices with differing Al concentration, layer thicknesses, and passivation materials. Hall measurements showed there was a marked increase in mobility after gamma irradiation up to 10 kGy. Magnetotransport spectroscopy, when considered with the mobility increase, suggested a reduction in the short-range carrier scattering in the 2DEG. By observing the shift in the peak corresponding to the AlGaN (0004) plane through XRD, they claimed the strain relaxation to be the cause of increased mobility. $^{28}$

The effects of a very low dose of 40 Gy gamma radiation on unpassivated HEMTs were later explored by Berthet et al. where an increase in $I_{DS}$ was again observed. The Schottky characteristics and gate leakage current remained unchanged, which is not unexpected for such a small dose. In that study, the increase of $I_{DS}$ was described as a decrease of trap density from structural reordering of native defects. The conclusion of this study was that enhanced $I_{DS}$ induced by gamma irradiation could be realized for much lower doses in unpassivated AlGaN HEMT devices. $^{29}$

In addition to dc characteristics, recent studies have investigated the effects of gamma irradiation on more fundamental carrier transport properties including carrier diffusion length. The minority carrier diffusion length, $L$, may be measured by collecting the electron beam induced current (EBIC) as a function of distance from a p-n junction or Schottky barrier, or in this case the gate electrode. $^{30,31}$ This reveals information about the recombination behavior of excited carriers in the material, and the temperature dependence of $L$ is described a single component exponential decay. Temperature dependent EBIC measurements allowed obtaining activation energies for the levels in the material’s forbidden gap, which (levels) are responsible for carrier recombination. Fig. 1 shows that while the diffusion length decreases significantly with increasing irradiation dose, the activation energy, associated with carrier recombination, gets larger. This fact indicates generation of new deep levels caused by gamma-photon irradiation. The energy determined by this method is regarded a defect level difference from the conduction or valence band edge, with the limiting process for recombination being the thermally activated escape of trapped carriers. $^{26}$

Lately, more studies have included investigations of lower doses, one such study conducted by Hwang et al. showed that mobility increased for doses from 50 to 700 Gy. Gate pulse measurements showed slight dispersion in the drain current at 10 kHz after all doses which suggested again strain relaxation and the introduction donor type defects. $^{32}$ This was coupled with EBIC for determination of L and its associated activation energy as a function of gamma irradiation dose in Ref. 29. The thermal activation energy found initially near 80 meV reduced for doses of 50 and 300 Gy while L was increased, while the opposite trend is observed for doses greater than 300 Gy. This behavior of low dose gamma irradiation increasing L and decreasing activation energy presented in other similar studies found in Refs. 21, 30, 31.

The experimental results from Ref. 21 particularly highlight the effects of incremental low doses of gamma irradiation on AlGaN HEMT device properties. In that study, the same device was cumulatively exposed from 100 to 600 Gy with analysis after each dose. As presented in Fig. 2, L tended to increase for doses of less than...
300 Gy while the trap activation energy simultaneously decreased. The dc device properties improved as well, including a near 40% increase in peak transconductance while gate leakage current decreased as presented in Fig. 3a. The variation of these parameters was attributed to the generation and subsequent occupation of trap levels during irradiation. This is because, during irradiation, Compton scattering of electrons leads to occupation of the trap levels introduced by displacement defects. When such a meta-stable trap level becomes occupied, it can no longer participate in recombination processes resulting in longer minority carrier lifetime and diffusion length. A decrease in recombination events for excited carriers leads to an increase in L.

The explanation of the effects of low dosages involves the occupation of interband traps, limiting the recombination pathway. Trap levels are constantly generated during irradiation with high energy photons, and Compton scattering leads to their subsequent occupation. Once a trap level becomes occupied, it limits recombination events by screening acceptor sites below the conduction band. The occupation of these trap levels contributes to increased values of L, transconductance, and IDS magnitude. This is of course occurring for the larger doses as well, however, the generation of extended defects contributes to much larger effects on the AlGaN system, including alterations to local carrier density through introduction of non-compensated donors.

At higher doses, device properties tend to degrade, realized as higher gate leakage currents, reduced diffusion lengths, and increased activation energies. For doses higher than 300 Gy, the value of L tended to decrease with increasing dose. This occurs due to the increasing density of gamma induced defects. The activation energy revealed that for extended doses, the energy of the trap increased—dropped further below the conduction band—suggesting an increase in the population of defects which couple with nearby Vg. The increased density of deeper trap levels increases scattering leading to shorter L. The extended defects generated in the buffer layer can be responsible for changes in dc properties including increases in gate leakage current.

The effectiveness of annealing for gamma induced defect mitigation has been explored in Ref. 33. The EBIC technique was used to monitor the value of L and corresponding activation energy as well as dc properties including leakage current, transconductance, and breakdown voltage threshold. HEMT devices were exposed to radiation and annealed for 25 minutes at 200 °C. Exposure to gamma radiation showed device degradation for all doses above 300 Gy, while annealing proved most effective when applied to devices damaged with lower doses. The recovery of device properties after annealing was due to a reduction in the population of trap related defects, resulting in higher L, lower activation energy. For higher doses annealing had a limited effect, this is due to the generation of extended defects which cannot be repaired by simple low temperature annealing. The EBIC determined value of L and activation energy serve as evidence of mitigation of some defects and suggest further the differing effects of low and high doses in AlGaN/GaN HEMT devices.

Conclusions

The effects of defect mitigation by annealing have been explored and found to be moderately successful. The influence of defects generated by gamma irradiation were found to reduce after an annealing step, and is likely due to the low energy of defect generation during 60Co gamma irradiation. This is especially evident when observing the effects of annealing as a function of dose. Since the displacement energy of N atoms is generally lower than that of Ga atoms, the population of displaced N atoms may increase more rapidly than that of Ga. The evolution of extended defects after higher doses lead to a reduction in the effectiveness of defect mitigation by annealing, since only certain defects may be reproducibly altered in this way.

The effects of gamma irradiation on AlGaN HEMTs has been observed in numerous studies. The impacts have shown to depend on dose, device structure, and film strain. The investigations referenced in this report show two distinct regimes of dosage: low dose effect leads to dc device property and transport characteristic improvement, and high dosages show general device degradation. Earlier studies of the influence of gamma irradiation tend to overlook the enhancement found at lower doses, and generally considered them to be related primarily to strain relaxation effects, and focus on the effects of larger doses. This is likely because the effects of large doses are of higher interest when considering space borne device applications.

In numerous dc and EBIC experiments, L and the related thermal activation energy have been measured in AIGa1-xN/GaN HEMTs after exposure to 60Co gamma rays. The activation energies observed from EBIC studies were regarded as due to VN for low doses. The enhancement of device function at low doses extended to dc properties as well, including transconductance, IDS magnitudes, and gate leakage currents. They found that for lower doses, up to 300 Gy, device properties were enhanced, but for higher doses the opposite trend was observed. The threshold of device enhancement can differ due to variances in native, or as-grown, defect population as well as lattice mismatch induced strain.

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Figure 3. HEMT dc properties including (a) transconductance at drain-source voltage 4 V with inset showing peak transconductance value by dose and (b) gate leakage current as a function of dose at gate voltage −1 V. Results of Ref. 21.
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