Effects of Low-Energy Proton Irradiation on AlGaN/GaN HEMTs

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Abstract

This study systematically investigates the effects of low-energy proton irradiation (70 keV and 100 keV) on the performance and reliability of AlGaN/GaN high-electron mobility transistors (HEMTs).Low-frequency 1/f noise analysis was employed to quantitatively assess the radiation-induced defect density, with a dominant activation energy of 0.8 eV identified and attributed to gallium vacancy-related complexes. Post-irradiation annealing at 600°C enables the recovery of up to 75% of the initial transconductance, demonstrating partial annihilation of the radiation-induced defects.These findings provide crucial insights into the proton irradiation damage mechanisms of AlGaN/GaN HEMTs.

Full Text

Preamble

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Abstract

study systematically investigates effects low-energy proton irradiation performance reliability AlGaN/GaN high-electron mobility transistors (HEMTs).

Low-frequency noise

analysis

employed quantitatively assess radiation-induced defect density, dominant activation energy identified attributed gallium vacancy-related complexes.

Post-irradiation annealing enables recovery initial transconductance, demonstrating partial annihilation radiation-induced defects.

These findings provide crucial insights proton irradiation damage mechanisms AlGaN/GaN HEMTs.

words gallium nitride (GaN), high-electron-mobility transistors (HEMTs), low-energy proton irradiation, low-frequency noise

Introduction

allium nitride (GaN) electron mobility transistors (HEMTs) attracted considerable interest their exceptional performance high-frequency high-power applications recent years.

These application areas include telecommunications, radar systems, power electronics, increasingly, aerospace industries AlGaN/GaN HEMTs particularly valued their electron mobility excellent radiation resistance. aerospace space exploration missions

continually limits technology, devices being considered application radiation environments, those encountered satellite systems, nuclear reactors, other space-based technologies However, harsh radiation conditions aerospace nuclear reactor environments cause significant degradation electrical properties semiconductor devices, thereby affecting their long-term reliability performance particular, proton irradiation, which commonly encountered space specific nuclear reactor environments, induce various defects GaN-based devices These defects degrade carrier mobility, threshold voltage, overall performance devices, ultimately limiting their lifespan efficiency While existing research radiation effects HEMTs focused high-energy proton irradiation, relatively little attention effects low-energy protons. research significant, low-energy protons, which prevalent certain environments, those encountered low-Earth orbit (LEO), induce different damage mechanisms compared their high-energy counterparts High-energy protons penetrate deeper material, while low-energy protons likely create defects surface within near-surface region semiconductor. damage caused low-energy protons

result

altered electrical characteristics often fully understood characterized.

Several studies contributed understanding impact proton irradiation GaN-based devices. early 2013, Abderrahmane studied effects proton irradiation mobility AlGaN/GaN heterojunctions.

After irradiation, sheet electron density significantly change, heterostructures displayed sharp decline electron mobility 2014, Hwang investigated effects protons irradiation Si-based AlGaN/GaN HEMTs demonstrated position defects affects effects proton irradiation AlGaN/GaN HEMTs Additionally, simulations proved defects channel improve off-state breakdown voltage weakening electric field margins while degrading performance. 2018, Khanal expanded these studies examining effects proton irradiation electrical properties AlGaN/GaN HEMTs 2024, Rasel investigated effects proton irradiation AlGaN/GaN HEMTs reported irradiation-induced defects primarily generated AlGaN barrier GaN/AlGaN

interface, where disturb transport Despite these efforts, specific impact low-energy proton irradiation especially context AlGaN/GaN devices remains underexplored, particularly terms effects device reliability space-based nuclear environments. address aforementioned issues, paper investigates effects low-energy proton irradiation reliability AlGaN/GaN HEMTs. focus

introduction

radiation-induced defects their subsequent impact electrical properties devices.

Low-frequency noise measurements primary characterizing radiation-induced defects noise widely recognized sensitive parameter detecting analyzing defects semiconductor devices, highly sensitive states other defects generated radiation exposure temperature dependence low-frequency noise under post-irradiation conditions investigated, contributing deeper understanding defect nature thermal stability. integrating these techniques, characterized types densities defects introduced low-energy proton irradiation assessed their impact device performance.

Additionally, explore possibility recovery device performance, performed high-temperature annealing experiments irradiated devices.

Annealing well-known technique repairing radiation-induced damage semiconductor devices. effect annealing proton-induced defects GaN-HEMTs investigated.

Specifically, annealing performed various temperatures, These tests evaluate thermal stability radiation-induced defects recovery potential devices exposed radiation-damaged environments.

results

study provide valuable insights radiation effects low-energy protons AlGaN/GaN HEMTs, which critical ensuring long-term reliability these devices radiation-rich environments aerospace applications nuclear reactors. findings contribute deeper understanding mechanisms radiation-induced degradation HEMTs offer guidance designing robust devices capable withstanding harsh radiation conditions.

Experiments AlGaN/GaN HEMTs processed Xidian University China.

Using metal organic chemical vapor deposition (MOCVD), nucleation layer, m-thick undoped buffer layer 20-nm-thick barrier layer sequentially deposited sapphire substrates. source drain regions formed ohmic contacts composed Ti/Al/Ni/Au nm/160 nm/55 nm/45 while employed Schottky contact consisting Ni/Au/Ni nm/100 nm/20 120-nm-thick passivation layer deposited between source gate, between drain gate. device features length width schematic structure HEMTs shown AlGaN/GaN HEMTs. current-voltage characteristics AlGaN/GaN HEMTs analyzed through offline testing using Agilent B1500A Keithley semiconductor parameter analyzer.

Additionally, noise characteristics HEMTs tested using FS-Pro multifunctional semiconductor parametric tester.

Low-frequency noise tests conducted within temperature range further characterize temperature dependence defects induced proton irradiation.

Subsequently, proton-irradiated devices underwent rapid thermal annealing minutes nitrogen atmosphere.

Under annealing condition, characteristics, low-frequency noise, photoluminescence properties HEMTs evaluated.

Discussion

characteristics characteristic curves AlGaN/GaN HEMTs before after irradiation low-energy protons under fluence level ranging observed electrical performance AlGaN/GaN HEMTs gradually degraded increasing proton fluence.

Particularly proton fluence reached degradation devices became significant. proton fluence increases, maximum saturation current decreases threshold voltage drifts toward positive direction.

These observations confirm low-energy proton irradiation significantly reduces density mobility HEMTs, which caused acceptor-like traps induced proton Output transfer characteristics AlGaN/GaN HEMTs irradiated protons different fluences.

Output transfer characteristics AlGaN/GaN HEMTs irradiated protons different fluences. shown variations threshold voltage maximum transconductance function proton fluence extracted.

Under condition identical proton fluence, damage devices caused proton irradiations severe induced

protons. Therefore, lower proton energies significant degradation device performance. observation agreement findings reported investigated effects proton irradiation devices energies Furthermore, compared MeV-level protons, keV-level protons cause severe damage HEMTs.

AlGaN/GaN HEMTs under different proton fluences. Protons collide lattice atoms, transferring sufficient energy displace latter their equilibrium lattice sites, forming vacancy-interstitial pairs (Frenkel defects). proton fluences, stable defect clusters easily formed.

High-energy protons exhibit “tunneling effect” allows penetrate active region substrate, their energy dispersed larger volume leading lower energy deposition. generated defects predominantly distributed non-critical areas (e.g., substrate), exerting relatively minor impacts performance.

Compared high-energy protons, low-energy protons deposit higher energy AlGaN/GaN heterojunction channel, their non-ionizing energy

(NIEL) is significantly higher, thus causing more severe damage.

density defects (e.g., vacancies vacancies) induced protons under AlGaN/GaN heterojunction channel higher induced protons.

Defects introduced proton irradiation reduce concentration through carrier removal effect, decrease mobility scattering, enhance off-state leakage current through trap-assisted tunneling.

defects, -related complexes, electrons. reduces concentration 2DEG, thereby affecting threshold voltage maximum transconductance irradiated devices. leakage current off-state drain-source breakdown characteristic curves under different proton energies fluences. leakage current under different proton energies fluences shown found reverse leakage current increases increasing proton fluence, while forward leakage current decreases.

Particularly protons, device performance exhibits severe degradation fluence reaches Proton irradiation causes damage introduces states gate, thereby affecting reverse forward currents HEMTs.

Under reverse bias, exhibits electron extraction behavior. levels AlGaN barrier generated proton irradiation assistant tunneling centers, ultimately leading significant increase device’ s reverse leakage current, shown Under forward bias, injects electrons channel, thermionic emission being dominant leakage mechanism, shown Proton irradiation introduces states interfacial charges AlGaN/GaN heterojunction metal/AlGaN interface, which effectively increases barrier height Schottky junction. suppresses efficiency thermionic electron emission, thereby reducing forward current.

Furthermore, lattice defects gallium vacancies induced proton irradiation electrons 2DEG, leading significant reduction concentration channel. decrease diminishes number carriers participating Schottky junction electron transport.

AlGaN/GaN HEMTs after proton irradiation under reverse forward biases. off-state drain-source breakdown voltage under different proton energies fluences shown extracted mA/mm observed fresh device about After irradiation protons, decreased approximately Meanwhile, observed off-state irradiated devices increase significantly increasing radiation fluence Proton radiation introduces defects critical regions HEMTs forms localized leakage current paths, thereby reducing devices breakdown voltage.

Photon emission measurement conduct in-depth investigation, photon emission measurement (PEM) technique carried shows photoemission signature AlGaN/GaN HEMTs before after proton irradiation, device conditions clearly observed number hotspots increases significantly after proton irradiation, indicating leakage paths within device.

Proton irradiation induces increase leakage current, which considered reasons degradation device electrical performance.

AlGaN/GaN HEMTs. frequency noise device function frequency under different irradiation fluences protons. found noise power spectral density gradually increases rising irradiation fluence overdrive voltage which indicates increase defect density induced proton irradiation. fluences.

Based McWhorter model, noise semiconductor devices mainly caused random mechanism carrier number, approximately represented

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where transconductance AlGaN/GaN HEMTs, flat-band voltage noise

power spectral density. primarily depends parameters charge channel interface structural dimensions, while independent channel current frequency.

Based model, defect density related generation noise extracted. relationship between expressed

2 S

q kT N WLfC = (2)

AlGaN where tunneling attenuation length AlGaN/GaN layer, width length respectively, frequency, AlGaN barrier capacitance AlGaN layer. function drain current measured under different irradiation fluences protons. carrier fluctuation model points noise originates capture release charge carriers traps channel interface, occurring tunneling processes.

These traps introduced proton irradiation interact carriers conduction valence band, resulting fluctuations manifest noise fitted extracted, shown Table irradiation fluence increases, values gradually increase. proton fluences.

before after proton irradiation Proton Energy maters Pre-irradaiton mobility fluctuation model proposed Hooge based empirical formulas. model points noise intrinsic effect device, characterized Hooge parameter larger Hooge parameter corresponds higher defect density semiconductor device.

Currently, widely recognized reflection intrinsic defects semiconductors. normalized drain-current noise mobility fluctuation model expressed where channel device, carrier concentration channel. device operates linear region under drain voltage, carrier concentration channel proportional voltage, described

1 ( ) CH AlGa S H N G T N C V V q = - (4)

Hooge parameters function overdrive voltage under different proton fluences protons. indicated Hooge parameters increase significantly proton fluence, demonstrating proton irradiation introduces defects HEMTs.

These defects predominantly associated states within space charge region beneath AlGaN/GaN HEMTs, which critical generation noise increase noise attributed modulation channel conductivity caused capture release carriers these traps.

Achouche suggest traps induce fluctuations channel conductance, thereby causing noise variations drain current

Temperature-dependent low-frequency noise excess drain-voltage noise power spectral density varies approximately inversely frequency. define frequency exponent

T ¶ = - ¶ (5)

Based Dutta-Horn model, frequency temperature dependence noise expressed

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Where temperature characteristic associated noise, which usually related defect scattering. frequency noise temperature range measured. shows experimental calculated values frequency exponent function temperature. suggests noise follows Dutta model accurately, which permits collaboration features temperature dependence noise changes defect-energy distribution

function temperature. Based temperature dependence noise amplitude, distribution defect energy estimated low-frequency noise measurements where Boltzmann constant. defect energy energy barrier between metastable charge states defect function temperature frequency.

AlGaN/GaN HEMTs under different proton energies fluences.

Peaks observed noise magnitude activation energies before after proton irradiation. irradiation fluence increases, defect energy gradually decreases temperature.

Furthermore, exhibits significant variation irradiated devices. noise likely associated complex defects related gallium vacancies consistent findings reported energy level complex located approximately above valence

under different proton energies fluences. Thermal annealing evaluate recovery AlGaN/GaN devices after radiation-induced degradation, thermal annealing performed sequentially annealing condition lasting minutes. shows transfer characteristic curves devices irradiated protons subsequently annealed different temperatures.

After annealing different temperatures, device' s recovered certain extent, recovery degree increasing annealing temperature rose.

After annealing protons fluence devices irradiated recovered their pre-irradiation levels, respectively. improvement attributed recovery Schottky control capability temperatures, thereby enhancing transconductance AlGaN/GaN HEMTs irradiated protons after different annealing temperatures.

annealing process demonstrated significant improvement device performance, indicating radiation-induced defects partially mitigated through thermal treatment.

Experimental

results

demonstrate radiation-induced traps affecting device performance permanent eliminated appropriate thermal annealing. frequency devices irradiated protons after annealing noise power spectral density decreases progressively increasing annealing temperature under overdrive voltage. trend indicates reduction density radiation-induced defects following annealing. finding consistent observed recovery device characteristics after annealing, confirming annealing process effectively mitigates radiation-induced defects reduces defect density. annealing temperatures.

Conclusion

bandgap nature confers inherent radiation tolerance superior silicon-based devices.

Nevertheless, damage mechanisms induced low-energy protons specifically target structures heterojunctions gates.

Consequently, investigating low-energy proton irradiation damage particular significance GaN-based devices employed space environments low-energy protons (e.g., near-Earth orbit) nuclear radiation environments. study investigates displacement damage effects low-energy proton radiation

AlGaN/GaN devices.

results

demonstrate proton radiation intensity increases,

introduction

defects leads degradation devices electrical characteristics.

Notably, lower proton energies

result

significant device performance deterioration, primarily radiation-induced damage proton incident region. defects characterized using low-frequency noise measurements, defect density increasing proportionally radiation exposure.

Temperature-dependent noise measurements revealed around energy attributed formation complexes.

High-temperature annealing showed partial recovery electrical properties irradiated devices, suggesting annealing removes radiation-induced traps damage.

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Figure 8

Figure 1: Figure 8

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Figures