Proton irradiation effects on GaN-based epitaxial structures

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Abstract. Radiation hardness of different types of GaN based epitaxial structures which can be used as elements of electronic devices is studied by Hall effect, CV and IV measurements, as well as photoluminescence and Raman scattering. It is shown that proton irradiation leads to formation of deep acceptor states reducing conductivity of high electron mobility transistors (HEMTs) and Si-doped layers and is accompanied by a redistribution of the defect-related lines in the photoluminescence spectra. Our results demonstrate that proton irradiation increases conductivity for GaN:C, while decreases it for GaN:Fe and GaN:(Fe+C) layers.

1. Introduction

The development of semiconductor electronics has completely changed the world we live in and these devices are widely spread, working in harsh conditions. Electronic devices exposed to space and terrestrial radiation environment interact with the energetic particles, resulting in deterioration of their properties. For operation in such conditions, radiation hard materials, like GaN, that is several orders of magnitude more resistant to radiation damage than GaAs, are needed. Modern high-power electronic devices, e.g. HEMTs and Schottky barrier diodes (SBD) are based on wide band gap materials, such as SiC or III-nitride heterostructures. Polar nature of the wurzite crystalline structure of III-nitride materials leads to formation of two-dimensional electron gas (2DEG) at the heterointerfaces with carrier concentrations much higher than in traditional arsenide-phosphide HEMTs even without doping [1,2]. There exist several papers devoted to radiation stability of such devices [3,4] or GaN layers [5,6], but there is a lack of studies of highly insulating GaN layers used in power devices.

In this paper, we present the study of the proton irradiation effect on GaN based structures used as elements of electronic devices as well as HEMT structures.

2. Experimental

Samples were grown by metal-organic vapor phase epitaxy (MOVPE) on (0001) sapphire substrates using standard precursors. Silane, propane and ferrocene were used for silicon, carbon and iron doping, respectively. Several types of structures were grown. First, a set of 3-µm thick highly insulating GaN layers doped with C (I1), Fe (I2) or codoped with C+Fe (I3) [7] was grown on 2-µm
thick Si-doped GaN for the study of vertical conductivity. Second, lightly Si-doped 2-μm thick GaN was grown on unintentional doped (UID) GaN (N1). Si concentration was chosen below 2·10^{17} cm^{-3}, close to that used in SBD and appropriate to Hall and CV studies. Third, a complete HEMT structure consisting of 2-μm thick GaN layer codoped with C+Fe (identical to I3 structure) followed by 1.5-μm thick UID GaN and capped with 0.7 nm AlN and 23 nm Al_{0.23}Ga_{0.77}N was grown (H1). Schemes of the mentioned structures are shown in figure 1.

Samples were irradiated by 15 MeV protons using small-scale cyclotron MGTs-20 in pulsed regime [8]. Proton spot diameter was 30 mm, current density was 10 – 100 nA/cm², pulse duration and frequency – 2.5 ms and 100 Hz, respectively. Single cycle irradiation dose was set to 1·10^{14} cm^{-2}, some samples were exposed to several cycles. Path length for such protons calculated by using SRIM software [9] was 1 mm, indicating uniform irradiation damage over sample thickness.

Samples were studied by Hall effect, CV-, IV-, photoluminescence and Raman scattering measurements before and after irradiation. For the vertical conductivity measurements, Ni contacts were evaporated on I1-I3 samples surface, contact to n-type layer was made by melted indium using mechanical scribing. For Hall effect measurements, indium contacts were used for N1 and H1 structures. The epi-layers were irradiated prior to contact fabrication, followed by structure characterization.

![Schematic images of the investigated structures: (a) I1-I3, (b) N1, and (c) H1.](image)

**Figure 1.** Schematic images of the investigated structures: (a) I1-I3, (b) N1, and (c) H1.

### 3. Results and discussion

Below we present the results obtained for samples irradiated with a dose of 1·10^{15} cm^{-2}. Capacitance-voltage and Hall effect measurements for sample N1 show that carrier concentration decreases from 1.6·10^{17} to ~1·10^{17} cm^{-3} accompanied by mobility degradation from 250 to 130 cm²/Vs. These data are in good agreement with estimates of carrier concentration and mobility obtained from the analysis of coupled plasmon-phonon modes in Raman spectra (see below). Increase of irradiation dose up to 1·10^{15} cm^{-2} shows linear drop of carrier concentration with dose, indicating the formation of deep defects trapping carriers. DLTS measurements reveal formation of deep centers with ionization energies $E_c$–0.19 eV and capture cross-sections $\sim$ 5·10^{-16} cm². PL spectra measured using 325 nm CW excitation (figure 2a) shows 10-fold decrease intensity of band-edge (BE) related line. Defect-related blue (BL) and yellow (YL) line intensity also drops 3–5 times indicating reduction of material quality.

For the H1 structure, Hall effect measurements show room temperature electron concentration in two-dimensional channel and mobility drop from 1.14·10^{13} cm² and 1800 cm²/Vs to 1.0·10^{13} cm² and 1600 cm²/Vs, respectively. Low temperature (77K) mobility drop was more pronounced – from 12000 to 7000 cm²/Vs indicating strong increase in electron scattering. Mobility degradation can be
explained by intermixing of Al(Ga)N and GaN at the 2DEG interface caused by proton irradiation or by creation of charged traps serving as scattering centers. Last assumption is more favorable, because of the observed electron concentration decrease. PL spectra of a HEMT structure measured using 266 nm pulsed excitation (figure 2b) show 3-fold decrease of GaN BE and YL lines. Intensity decrease of the AlGaN BE line was small. The strongest intensity drop was observed for the GaN BL line. Similar effect after proton irradiation was reported in [10] and can be attributed to formation of deep defect states capturing carriers and hampering donor-acceptor recombination in undoped GaN.

![Figure 2](image1.png)

**Figure 2.** (a) Low temperature PL spectra of the N1 structure before and after irradiation. (b) Low temperature PL spectra of the structure H1 before and after irradiation.

In polar semiconductors, such as GaN, longitudinal optical phonons can interact via a macroscopic electric field with collective excitations of free carriers (plasmons). This leads to the formation of two coupled plasmon – LO phonon (PLP) modes. We will refer them below as PLP* and PLP+ with lower and higher eigenfrequencies, respectively. Studying the spectral parameters of PLP modes (their energy position and half width) makes it possible to estimate the concentrations of charge carriers in n-type semiconductors materials [11].

Raman spectra in the region of the $A_1(LO)$ phonon for as grown and proton irradiated (I1-I3) and for as grown and proton irradiated N1 samples are shown on figures 3a and 3b, respectively. It can be seen that the irradiation does not significantly affect the frequency and shape of the PLP+ mode of (I1-I3) samples. These results indicate a constant concentration of free charge carriers in these samples upon irradiation. However, the spectrum of the irradiated n-GaN sample demonstrates a low-frequency shift and narrowing of the PLP+ mode compared to the spectrum of the as grown sample, which indicates a decrease in the carrier concentration after proton irradiation.

The shape of the PLP+ mode was analyzed under the assumption that the electro-optic and deformation-potential mechanisms are responsible for scattering [12]

$$I_A = \frac{d^2S}{d\omega d\Omega} = \frac{16\pi\hbar n_2}{V_0} \frac{\omega_1^2}{\epsilon^4} \left( \frac{d\alpha}{d\epsilon} \right)^2 \left( n_\omega + 1 \right) \text{AIm} \left( -\frac{1}{\epsilon} \right),$$

where $V_0$ is the unit cell volume, $\omega_{1,2}$ are the incident and scattered photon frequencies, $n_{1,2}$ are the refractive indexes at $\omega_{1,2}$, $\alpha$ is the polarizability, $E$ is the macroscopic electric field, and $n_\omega$ is the Bose–Einstein factor. The function $A$ is defined by the Faust–Henry coefficient as well as by the plasmon and phonon damping constants. The dielectric function $\epsilon$ is given by

$$\epsilon = \epsilon_\infty \frac{\omega_{LO}^2 - \omega_\omega^2}{\omega_{LO}^2 - \omega^2 - i\omega\gamma} - \frac{\omega_\omega^2}{\omega^2 + i\omega\gamma},$$
Figure 3. (a) Experimental Raman spectra of as grown (open symbols) and proton irradiated (closed symbols) I1-I3 samples. (b) Experimental Raman spectra of as grown (open symbols) and proton irradiated (closed symbols) N1 samples. The fitting curves obtained by (1) are shown by dashed lines.

were \( \omega_p \) is the plasmon frequency

\[
\omega_p^2 = \frac{4\pi ne^2}{\varepsilon_\infty m^*},
\]

\( n \) is the free carrier concentration, \( m^* \) is the effective electron mass and \( \varepsilon_\infty \) is the high-frequency dielectric constant.

The plasmon frequency \( \omega_p \), plasmon damping \( \gamma \) and phonon damping \( \Gamma \) were used as fitting parameters in analysis of experimental spectra. In addition, some constants determined experimentally were put in calculations. Among them, the characteristic frequencies \( \omega[A_1(LO)] \) for the uncoupled longitudinal mode, \( \omega[A_1(TO)] \), and the Faust–Henry coefficient were taken to be 733, 532 cm\(^{-1}\) and 0.52, respectively.

The concentration of charge carriers in as grown and proton irradiated I1-I3 and \( n \)-GaN samples (see Table I) were found from the plasmon frequency \( \omega_p \) (3). We use \( m^*=0.2m_0 \) and \( \varepsilon_\infty=5.35 \), because PLP\(^+\) mode discussed here has \( A_1 \) symmetry where the electronic and lattice displacements are along \( c \) axis of GaN [13]. Note that the technique for estimating the concentration of charged carriers according to Raman data has a lower limit at the level of \( n \sim 6.0 \times 10^{16} \) cm\(^{-3}\).

Table I The frequency of PLP\(^+\)-modes and the concentration of charge carriers in the as grown and proton irradiated I1-I3 and \( n \)-GaN samples

| Sample | I1 (GaN:C) | I2 (GaN:Fe) | I3 (GaN:C,Fe) | N1 (\( n \)-GaN) |
|--------|------------|-------------|---------------|-----------------|
|        | as grown  | p-irrad.    | as grown      | p-irrad.        | as grown       | p-irrad.     |
| \( \omega (PLP^+) \), cm\(^{-1}\) | 735.3      | 735.4       | 735.3         | 735.4           | 735.5         | 735.4        | 737.1         | 736.1          |
| \( n(\pm 5\%) \), cm\(^{-3}\) | 7.2\( \times 10^{16} \) | 6.9\( \times 10^{16} \) | 6.3\( \times 10^{16} \) | 5.8\( \times 10^{16} \) | 6.1\( \times 10^{16} \) | 6.0\( \times 10^{16} \) | 2.0\( \times 10^{17} \) | 1.3\( \times 10^{17} \) |
For samples I1 - I3, measurements of the Hall effect and CV were not possible, which indicates a high resistivity of these structures due to deep-impurity doping. Measurements of current-voltage characteristics (figure 4) show that proton irradiation increases conductivity for GaN:C, and decreases it for GaN:Fe and GaN:(Fe+C) layers. It is known that current flow mechanisms are different for carbon and iron doped samples: for GaN:Fe, the dominant mechanism in high electric field is Fowler-Nordheim tunneling, while for GaN:C it is not true. The nature of this effect is to be studied separately, but it is clear that it makes iron doping (or codoping) more favorable for radiation-stable buffer layers used in HEMTs.

4. Conclusion
The effects of proton irradiation at room temperature on GaN-based epitaxial structures which can be used as elements of electronic devices have been investigated using combine electrical and optical measurements. A satisfactory correlation between the data obtained by different experimental techniques was found. It was established that compensation effects, accompanied by a decrease in the electron concentration and mobility, are dominant in doped n-GaN and HEMT structures subjected to proton irradiation. Luminescence studies revealed intensity drop after irradiation accompanied with redistribution of intensity between defect-related PL lines in GaN. Our results demonstrate that proton irradiation increases conductivity for GaN:C, while decreases it for GaN:Fe and GaN:(Fe+C) layers. The data obtained suggest that iron doping (or codoping) is more favorable for radiation-stable buffer layers used in HEMTs.

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References
[1] Ambacher O, Smart J, Shealy J R, Weimann N G, Chu K, Murphy M, Schaff W J, Eastman L F, Dimitrov R, Wittmer L, Stutzmann M, Rieger W and Hilsenbeck J 1999 Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGaN/GaN heterostructures J. Appl. Phys. 85 3222–33
[2] Khan M A, Hove J M V, Kuznia J N and Olson D T 1991 High electron mobility GaN/AlGaN heterostructures grown by low-pressure metalorganic chemical vapor deposition Appl. Phys. Lett. 58 2408–10
[3] Hu X, Choi B K, Barnaby H J, Fleetwood D M, Schrimpf R D, Lee S C, Shojah-Ardalan S, Wilkins R, Mishra U K and Dettmer R 2004 The energy dependence of proton-induced
degradation in AlGaN/GaN high electron mobility transistors *IEEE Transactions on Nuclear Science*, **51** 293–7

[4] Luo B, Johnson J W, Ren F, Allums K K, Abernathy C R, Pearton S J, Dwivedi R, Fogarty T N, Wilkins R, Dabiran A M, Wowchack A M, Polley C J, Chow P P, and Baca A G 2001 DC and RF performance of proton-irradiated AlGaN/GaN high electron mobility transistors *Appl. Phys. Lett.* **79** 2196–9

[5] Polyakov A Y, Pearton S J, Frenzer P, Ren F, Lu L and Kimd J 2013 Radiation effects in GaN materials and devices *J. Mater. Chem. C.* **1** 877–87

[6] Pearton S J, Ren F, Patrick E, Law M E and Polyakov A Y 2016 Review—Ionizing Radiation Damage Effects on GaN Devices *ECS J. Solid State Sci. Tech.* **5:2** Q35–60

[7] Lundin W V, Sakharov A V, Zavarin E E, Zakgeim D A, Lundina E Yu, Brunkov P N and Tsatsulnikov A F 2019 Insulating GaN Epilayers Co-Doped with Iron and Carbon *Tech. Phys. Lett.* **45** 723–26

[8] Zakharenkov L F, Kozlovski V V and Shustrov B A 1990 Transmutation Doping of Indium Phosphide and Gallium Arsenide Due to Protons and $\alpha$-Particles *Phys. Status Solidi A* **117** 85–90

[9] http://www.srim.org

[10] Khanal M P 2018 Impact of 100keV proton irradiation on electronic and optical properties of AlGaN/GaN high electron mobility transistors (HEMTs) *J. Appl. Phys.* **124** 215702

[11] Klein M V 1975 *Light Scattering in Solids IV* ed M Cardona Topic in Applied Physics (Berlin: Springer) Vol 8 p.147

[12] Irmer G, Toropov V V, Bairamov B H and Monecke J 1983 Determination of the charge carrier concentration and mobility in n-GaP by Raman spectroscopy *Phys. Status Solidi B* **119** 595–603

[13] Kozawa T, Kchi T, Kano H, Taga Y, Hashimoto M, Koide N and Manabe K 1994 Raman scattering from LO phonon-plasmon coupled modes in gallium nitride *J. Appl. Phys.* **75** 1098–1101