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PROTON IRRADIATION INDUCED DEFECTS IN GaN SINGLE CRYSTAL FILM

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Abstract

The proton irradiation induced defects in GaN are studied by combining elastic recoil detection analysis (ERDA), thermally stimulated current (TSC) and Rutherford backscattering spectroscopy (RBS) measurements. The proton irradiation into GaN single crystal films with a thickness of 3 μm is performed using a 500 keV implanter. The carrier concentration decreases three orders of magnitude to 10^{15} cm^{-3} by the proton irradiation. ERDA measurements using the 1.5 MeV helium beam can evaluate hydrogen. The hydrogen concentration at ~220 nm is ~8.3×10^{13} cm^{-2} and ~1.0×10^{14} cm^{-2} for un-irradiated and as-irradiated samples, respectively, suggesting that electrical properties are almost not affected by hydrogen. TSC measurements show a broad spectrum at around 110 K which can be divided into three traps, P_1 (ionization energy 173 meV), P_2 (251 meV), and P_3 (330 meV). These traps are related to the N vacancy and/or complex involving N vacancy (P_1), neutral Ga vacancy (V_{Ga}) (P_2), and complex involving V_{Ga} (P_3). The Ga displacement concentration evaluated by RBS measurements is 1.75×10^{19} cm^{-3} corresponding to 1/1000 of the Ga concentration in GaN.

I. Introduction

Gallium nitride exhibits unique electrical, optical, and thermal properties. For space-based applications, these devices will have to operate in a radiation environment.

Proton irradiation induced defects in GaN were studied by combining elastic recoil detection analysis (ERDA), thermally stimulated current (TSC) and Rutherford back scattering (RBS) measurements. We carried out ERDA and TSC measurements to clarify the hydrogen concentration and the ionization energies related to the defects induced by the proton irradiation. The Ga displacement concentration in the proton irradiated GaN was evaluated using RBS/ channeling measurements.

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II. Experimental

GaN single crystal films with 3 μm-thick grown on the sapphire (0001) substrate by metalorganic vapor phase epitaxy were used in this study. Proton irradiations were carried out by using a Tandem accelerator of Hosei University. A 500 keV proton irradiation was performed with a dose of 1×10^{15} cm^{-3} at room temperature. Since the proton concentration by a TRIM simulation is maximum at 3600 nm in depth, the proton beam almost passes through the GaN films. The electrical properties of un-irradiated and as-irradiated GaN films were evaluated by the Van der Pauw technique. Hydrogen in GaN was evaluated by ERDA using a 1.5 MeV $^4He^+$ beam. The recoiled H-ions were detected with a solid-state detector located at 15 °. An aluminum film with 7.5 μm in thickness was placed in front of the ERDA detector in order to stop all the recoiled atoms heavier than hydrogen. The ERDA measurements using 1.5MeV $^4He^+$ ion can evaluate hydrogen until about 300 nm in depth. This beam energy has been used for the evaluation of hydrogen in the proton irradiated ZnO bulk single crystals [1)].

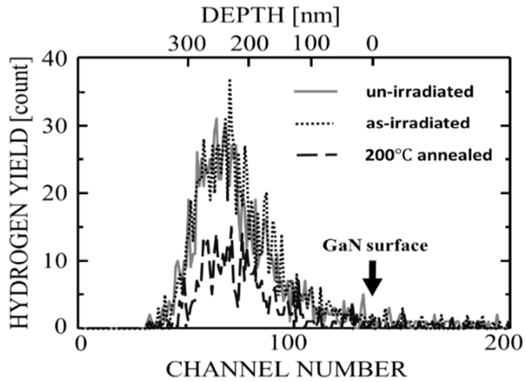

FIG. 1 Hydrogen in un-irradiated, as-irradiated and 200°C annealed GaN evaluated by ERDA.

The TSC technique is applied without the fabrication of Schottky contacts or *p-n* junctions. The bias voltage of 20 V was applied to the indium electrodes for the TSC measurements. TSC studies were performed at 100 K using LEDs with various wavelengths. The sample was initialized by illumination for 20 min with an ultraviolet LED (a peak wavelength of λ=375 nm) for the excitation above the band gap. The measurements using blue (λ = 475 nm), green (λ = 525 nm), and red (λ = 645 nm) LEDs for the excitation near or below the band gap were also performed. RBS/channeling measurements were performed using a 1.5 MeV $^4He^+$ beam. The backscattered He-ions were detected with a solid-state detector located at 150 °.

III. Results and Discussion

The resistivity, electron mobility, and carrier concentration were 1.3×10^{-1} Ω cm, 8.0 cm^2/V s, and 6.1×10^{18} cm^{-3} for un-irradiated GaN, and 4.1×10^{1} Ω cm, 48 cm^2/V s, and 3.2×10^{15} cm^{-3} for as-irradiated one. The carrier concentration decreased three orders of magnitude to 10^{15} cm^{-3} by the proton irradiation, suggesting the existence of the proton irradiation-induced defects.

Figure 1 shows the result of ERDA measurements. The hydrogen concentration can be calculated by the equation[2)], $N = Y \sin\theta / [Q (d\sigma / d\Omega) \Delta\Omega]$, where Y is the yield of Recoil, Q number of incident ion, $(d\sigma / d\Omega)$ recoil differential scattering cross-section (cm^{-2}), $\Delta\Omega$ solid angle of the detector, θ angle of incidence (15 º). In un-irradiated, as-irradiated and 200°C annealed samples, the hydrogen concentrations observed at 220 nm were 8.3×10^{13}, 1.0×10^{14}, 5.0×10^{13} cm^{-2}, respectively. The hydrogen concentration did not change much after the proton irradiation and the subsequent annealing. Therefore, the carrier concentration would not be affected by the hydrogen concentration.

Figure 2 (a) shows the TSC spectra of proton irradiated GaN initialized by various LEDs. A broad peak was observed at a temperature ranging from 100 K to 300 K using blue and ultraviolet LEDs illumination. TSC peaks were not observed for excitation using red and green LEDs. This indicates only a small carrier trap effect for LED illumination below the band gap. As shown in Figs. 2 (b) and (c), a broad peak taken for the excitation using blue and violet LEDs were resolved to optimum Gaussian curves, leading to three traps, P_1 ($T_m = 104$ K), P_2 (141 K), and P_3 (178 K). According to the approximate relationship [3] $E_i \approx kT_m ln(T_m^4/\beta)$, where E_i is the ionization energy, k Boltzmann's constant, T_m the TSC peak temperature, β the heating rate for the thermal scan. The ionization energies for these traps were calculated to be E_i (P_1) = 173 meV, E_i (P_2) = 251 meV, and E_i (P_3) = 330 meV. E_i values estimated by the present TSC study contain an uncertainty of ±20 meV. The origin of the P_1 trap has been attributed to the N vacancy (V_N) and/or complex involving V_N [4,5]. The TS current for P_2 and P_3 traps was also assigned to the defect complex involving Ga vacancy (V_{Ga}) [4] rather than the isolated neutral V_{Ga}. The peak intensity of P_1 is much larger than that of P_2 and P_3, suggesting that mainly produced defect by the proton irradiation are the V_N related defects.

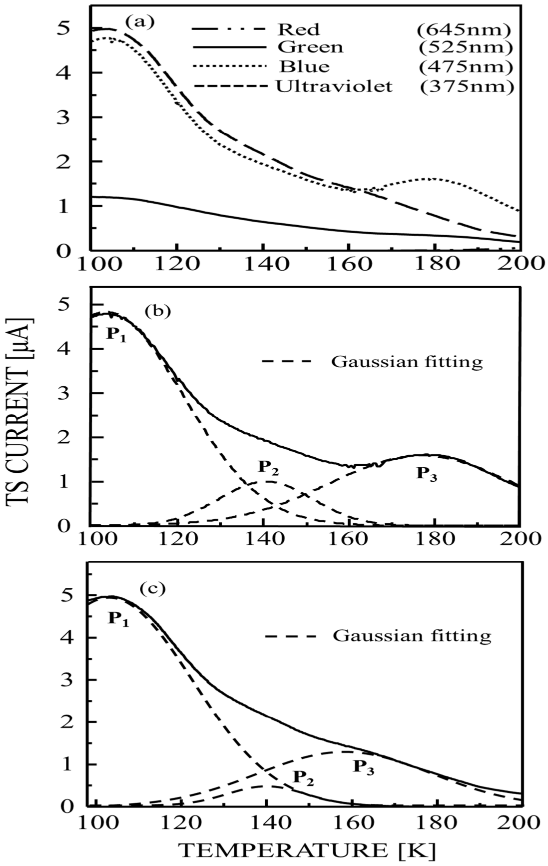

FIG. 2 TSC spectra (a) taken using LEDs with various wavelengths. Spectra (b) and (c) were measured using blue and ultraviolet LEDs.

Figure 3 shows random and aligned RBS spectra for un-irradiated and as-irradiated GaN. The aligned spectra were obtained from scattering along the <0001> channeling direction. The minimum yield χ_{min} (the ratio of aligned and random yields) was evaluated using a width of about 20 channels (~90 nm) from the crystal surface behind the surface peak. Near the surface, the number of atoms displaced into channels is approximately related to the minimum yield by [6,7],

$N_D = N_{Ga} (\chi_{min} - \chi^0_{min}) / (1 - \chi^0_{min})$, where N_{Ga} is the Ga density (4.38×10^{22} cm^{-3}) of the crystal, χ_{min}^0 is the minimum yield for the un-implanted sample, and χ_{min} is the observed minimum yield for implanted one. χ_{min} value was calculated only for Ga atoms because for Ga were $\chi_{min}{}^{0}$ = 2.00 % for un-irradiated samples and χ_{min} = 2.04 % for as-irradiated ones, respectively. The Ga displacement concentration estimated from these χ_{min} values is 1.75 × 10^{19} cm^{-3}. This value is about 1/1000 of the Ga concentration in GaN. The slight displacement concentration would be related to P_2 and P_3 traps observed in TSC measurements.

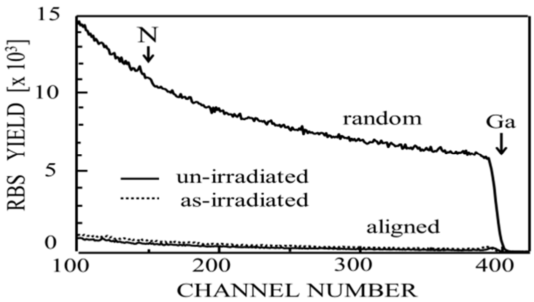

FIG. 3 Aligned and random RBS spectra for un-irradiated and as-irradiated GaN using 1.5 MeV He^{+} ions.

IV. Conclusion

The carrier concentration decreased three orders of magnitude to 10^{15} cm^{-3} by the proton irradiation. This result was related to the proton irradiation induced defects. The hydrogen concentration did not change much after the proton irradiation, suggesting that the carrier concentration is not affected by hydrogen. Three traps, P_1 (ionization energy 173 meV), P_2 (251 meV), and P_3 (330 meV) were observed by TSC measurements. The peak intensity of P_1 is much larger than that of P_2 and P_3, suggesting that V_N related defects are mainly introduced and V_{Ga} related defects are slightly introduced by the proton irradiation. The Ga displacement concentration of 1/1000 of Ga in GaN was observed by RBS / channeling measurements, corresponding to P_2 and P_3 traps.

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