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Mechanism of mobility increase of the two-dimensional electron gas in AlGaN/GaN heterostructures under small dose gamma irradiation

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The effect of a small dose of gamma irradiation on transport characteristics of the two-dimensional electron gas (2DEG) in AlGaN/GaN heterostructures was investigated. It is shown that the carrier concentration remains practically unchanged after an irradiation dose of 10^6 rad, while the 2DEG mobility exhibits a considerable increase. The results are explained within a model that takes into account the relaxation of elastic strains and structural-impurity ordering occurring in the barrier layer under irradiation. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2903144]

I. INTRODUCTION

The wide band gap AlGaN/GaN heterojunction structures appear to be very promising for high power and radiation resistant microwave devices, including high electron mobility transistors (HEMTs). In order to utilize the excellent potential of group III-nitride compound semiconductors and to improve their characteristics for a variety of applications, there is a need for physical models to describe the device performance and reliability. Recent advances in the development of the AlGaN/GaN heterostructure technology have led to the extensive improvement in their electrical properties. However, it has been reported that high-frequency excitation of the AlGaN/GaN HEMT structure causes the drain current to drop below the steady state values.[1] It is believed that this current degradation is a result of the trapping effect of the electrons by surface states. Therefore, different kinds of passivation materials[2–7] (mainly concentrated on more effective Si_3N_4 passivation) or cap layers[8–10] were investigated to decrease surface trap effect on the formation of two-dimensional electron gas (2DEG) at the heterostructure interface. In spite of temporary stabilization of surface properties, an additional surface layer causes stress-induced changes in the barrier layer[11–14] and changes the conditions for the formation of 2DEG as a result of piezoelectric and spontaneous polarization effects. Therefore, additional methods, such as plasma pretreatment,[15,16] were used before passivation to improve the electrical properties of 2DEG. The authors of Ref. 16 have deduced that the electrical traps are located not only at the surface of the structure, but also in the AlGaN layer and/or at the AlGaN/GaN interface. These, in turn, induce fluctuations in 2DEG; hence, new treatments for improving device performance should be developed.

One of the treatments that produce uniformly redistributed defect centers throughout the multiplayer structure is gamma radiation treatment, which can positively influence the carrier's transport and recombination processes in such devices due to different radiation-stimulated mechanisms.[17] Recently,[18–20] we reported on enhanced radiation hardness of GaN-based HEMTs that have good prospects for the application in a radiative environment. Moreover, an improvement of the principal parameters of the HEMTs, such as the saturation current and transconductance, was registered after a dose of 1×10^6 rad. An even more remarkable finding was the observation of a considerable decrease of dispersion of the transfer characteristics measured on a set of the transistors patterned on the same wafer. It has been assumed that the effects are related to the relaxation of strains existing in mismatched heterostructures and structural ordering of native defects.[17] To verify this suggestion, we performed the structural characterization of the as-grown heterostructures before and after irradiation. Additionally, the electrical properties of irradiated devices were compared with those measured on the same devices before gamma radiation treatment. In this Communication, we report comparison results of different AlGaN/GaN heterostructures with Si_3N_4 as well as GaN cap covered passivation layers. The obtained results demonstrate an irreversible improvement in the transport characteristic of the structures after small doses of gamma irradiation treatment.

II. EXPERIMENTAL DETAILS

The structures under study were grown by metal organic chemical vapor deposition on (0001) *c*-plane sapphire substrates and have the following sequence of layers: Sample 1-undoped GaN buffer, 1.1 μm; undoped $Al_{0.33}Ga_{0.67}N$ barrier, 23 nm; Si_3N_4 passivation layer, 320 nm. Sample 2-undoped GaN buffer, 3.0 μm; undoped $Al_{0.30}Ga_{0.70}N$ barrier, 30 nm; GaN cap layer, 4 nm. Sample 3-GaN nucleation layer, 28 nm; GaN insulating buffer, 7.5 μm; undoped AlN spacer, ~1 nm; undoped $Al_{0.25}Ga_{0.75}N$ barrier, 25 nm; GaN cap layer, 1.3 nm.

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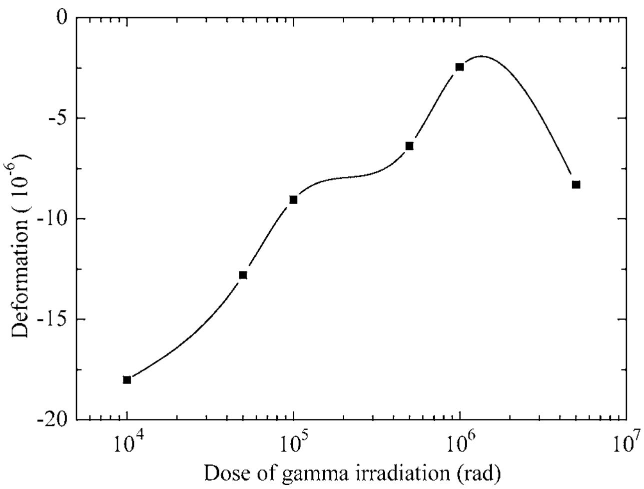

FIG. 1. Irradiation dose dependence of elastic strains in the AlGaN layer of AlGaN/GaN heterostructure 1 with the Si_3N_4 passivation layer.

The termination of the heterostructures with GaN capping layers provides a stable surface for processing. Following the growth procedure, the Hall bar mesas ($140 \times 700\ \mu m^2$) were fabricated with Ti/Al/Ni/Au contact metallization annealed for 40 s at 800 °C.

The structural characterization of the heterostructures was performed by x-ray diffraction (XRD) and secondary ion mass spectroscopy. The gamma irradiation was provided by ^{60}Co gamma rays at room temperature with doses in the range of 10^4-10^6 rad and a flux of 10^2 rad/s. The gamma-quanta average energy was about 1.2 MeV. We investigated several samples processed from different parts of each wafer. The samples are systematically studied with an increased step-by-step dose of gamma radiation treatment.

III. RESULTS AND DISCUSSION

To gain insight into the structural transformation of the heterostructures during irradiation, the angular distribution of the XRD corresponding to the (0002), (0004), $(10\bar{1}2)$, and $(\bar{1}\bar{1}24)$ reflections of GaN and AlGaN layers was measured by means of triple-crystal differential diffractometry (PANalytical X'Pert MRD) under conditions of symmetrical and asymmetrical Bragg and Laue geometries.

The shift of the peak corresponding to the (0004) plane of the AlGaN layer to the lower angle is observed after irradiation. It should be noted that a significant decrease in dispersion in the transport properties of AlGaN/GaN HEMTs has been observed[20] after gamma irradiation with the optimal dose. Additionally, the surface morphology was analyzed by scanning electron microscopy. It was established that the morphology is not affected by small doses of gamma radiation. The changes in XRD spectra clearly indicate a strain relaxation in the AlGaN layer after irradiation. To prove this statement, direct measurements of the elastic strain in the heterostructures were carried out. An integrated method for measuring surface curvature was used.[21] The results of these measurements for sample 1 are presented in Fig. 1. A negative sign corresponds to tensile stress in the AlGaN layer. It is seen that strain relaxation occurs up to doses of 1×10^6 rad. It should be noted that strain relaxation in the HEMT structure can result in the generation of additional defect or native defect structural ordering. The observed room temperature mobility improvement from 1380 $cm^2/V\,s$ (in the nonirradiated sample) to 1460 $cm^2/V\,s$ (in the irradiated sample at a dose of 1×10^6 rad) indicates that the latter process is dominating in the radiation-stimulated relaxation of sample 1. It is important to note that similar changes in mobility were registered also for two other structures. Moreover, as it will be demonstrated below, the low-temperature mobility exhibits more considerable increase after a gamma radiation treatment at a dose of 1×10^6 rad. The magnitude of carrier mobility is a very important parameter in the design and optimization of AlGaN/GaN heterostructures, and an understanding of the origin of mobility variation is crucial. Magnetotransport spectroscopy is a powerful method of study transport at the heterointerface, which is used for a detail analysis of the evolution of interface phenomena during a gamma radiation treatment.

Magnetotransport measurements were performed in a wide temperature range $T=0.3-300$ K and in magnetic fields up to 10 T using standard low-frequency (17 Hz) lock-in techniques. Measurements are typically made with a current modulation of 100 nA to prevent heating effects. From a Shubnikov–de Haas (SdH) oscillation period, a sheet concentration of the 2DEG was determined. The effective mass was calculated from the temperature dependence of the amplitude of the SdH oscillations. The parameters of samples 2 and 3 required for further analysis are summarized in Table I, where E_F is the Fermi energy measured starting from the quantization energy E_0, n_S is the carrier concentration, m_E^* is the effective mass at the Fermi energy, τ_t is the transport lifetime, τ_q is the quantum lifetime, and μ is the carrier mobility. There is no significant difference in the carrier concentration of different samples measured at low (Hall effect) and high (SdH oscillations) magnetic fields. This result indicates that the electrons occupy only the lowest subband. This fact is also confirmed by the calculation of the potential profiles and electron density of states for the investigated structures by self-consistently solving Schrödinger and Poisson equations, taking into account polarization effects in the structures. Figure 2 illustrates the energy band diagram at the AlN/GaN interfaces of heterostructure 3 and demonstrates that only the lowest level is occupied (which is typical of our samples presented in this work).

Results, presented in Table I, quantitatively demonstrate the radiation-stimulated improvements in transport properties and characteristics extracted from magnetotransport measurements. Moreover, the comparison of the magnetoresistance behaviors before and after irradiation enables us to reveal the physical origin of the improvements. The observed transformation in the magnetic field dependence of the dc component of magnetoresistance reflects the change in the scattering mechanism in the 2DEG channel[22] as well as the manifistation of electron-electron interaction (EEI).[23]

The decrease in magnetoresistance due to EEI can be described[24] by

TABLE I. Experimentally obtained parameters of 2DEG for samples 2 and 3 before and after gamma irradiation.

Sample	E_F (meV)	n_s (10^{13} cm^{-2})	m_E^* (m_0)	τ_q (fs)	μ (cm^2/V s) (0.35 K/300 K)
2 before irradiation	131	1.02	0.20 ± 0.01	79	5100/1260
2 after irradiation	128	1.0	0.20 ± 0.01	410	28 700/1350
3 before irradiation	129	1.01	0.19 ± 0.01	90	11 500/1850
3 after irradiation	123	0.96	0.19 ± 0.01	350	19 600/2000

$$\rho_{xx}(B) = -\rho_0^2 \delta\sigma_{xx}[1-(\omega_c\tau_0)^2], \qquad (1)$$

where ρ_{xx} is the diagonal component of the transverse magnetoresistivity, ρ_0 is the dissipative Drude resistivity, $\delta\sigma_{xx}$ is the correction to the diagonal component of conductivity due to EEI, $\omega_c = eB/m^*$, and τ_0 is the Drude scattering time. In Eq. (1), the correction factor can be estimated by using:[25–27]

$$\delta\sigma_{xx} = -\sigma_{00}\left[4 - 3\frac{2+F}{F}\ln\left(1+\frac{F}{2}\right)\right]\ln\left(\frac{\hbar}{k_B T \tau_{im}}\right), \qquad (2)$$

where $\sigma_{00} = e^2/2\pi^2\hbar$, F is the Hartree factor, τ_{im} is the impurity scattering time, and k_B is the Boltzman constant.

It should be noted that the temperature dependence of magnetoresistance and Eq. (2) enables a way of estimating such crucial parameters as impurity and Drude scattering times.

In the case of scattering of electrons on randomly distributed scatters in the presence of a long-range correlated random potential, the longitudinal component of magnetoresistance can be written in the form[28,29]

$$\rho_{xx}(B) - \rho_0 = \frac{\Delta\sigma_{int}}{\sigma_0^2}[(\omega_c\tau_{tr})^2 - 1], \qquad (3)$$

where $\Delta\sigma_{int}$ is the quantum interaction correction to the conductivity,[30] $\sigma_0 = n_s e^2 \tau_{tr}/m^*$, τ_{tr} is moment relaxation time, and n_s is the 2DEG sheet concentration.

It should be noted that both Eqs. (1) and (3) describe parabolic components of magnetoresistance. As it was previously found in Ref. 31, the scattering interplay mechanism plays a major role in the negative parabolic magnetoresistance effect in high-density 2DEG AlGaN/GaN heterostructures.

Our experimental results in investigating the magnetoresistance behavior (shown in Fig. 3 for nonirradiated AlGaN/GaN heterostructure 3) are in good agreement with theoretically predicted magnetoresistance dependence on B^2. The weak temperature dependence of slopes of curves in Fig. 3 indicates a strong short-range scattering of electrons in 2DEG. In samples measured after gamma irradiation treatment, the minimum in the dc component of magnetoresistance is observed (Fig. 4). According to the theoretical model,[22] the minimum position reflects changes in the con-

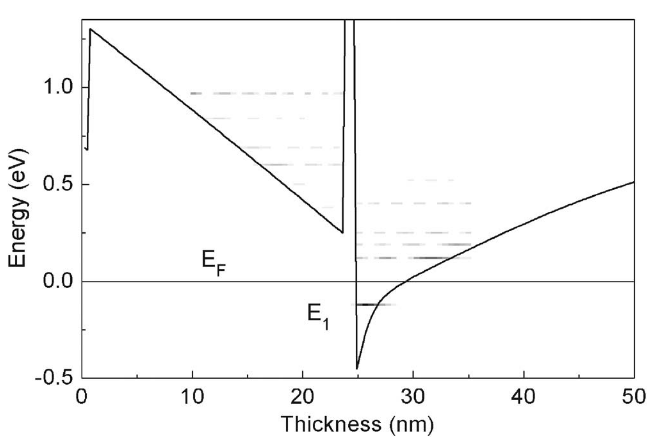

FIG. 2. Self-consistently calculated conduction band profile and electron density of states for sample 3. Only one level with the energy of E_1 is occupied.

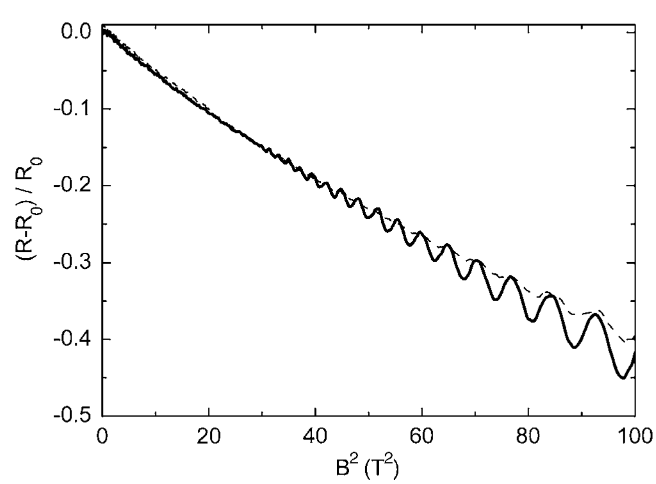

FIG. 3. The magnetoresistivity $(R-R_0)/R_0$ as a function of B^2 of nonirradiated sample 3 (R_0 is the resistance at $B=0$) measured for two temperatures T (K): 0.4 (solid line) and 13 (dashed line).

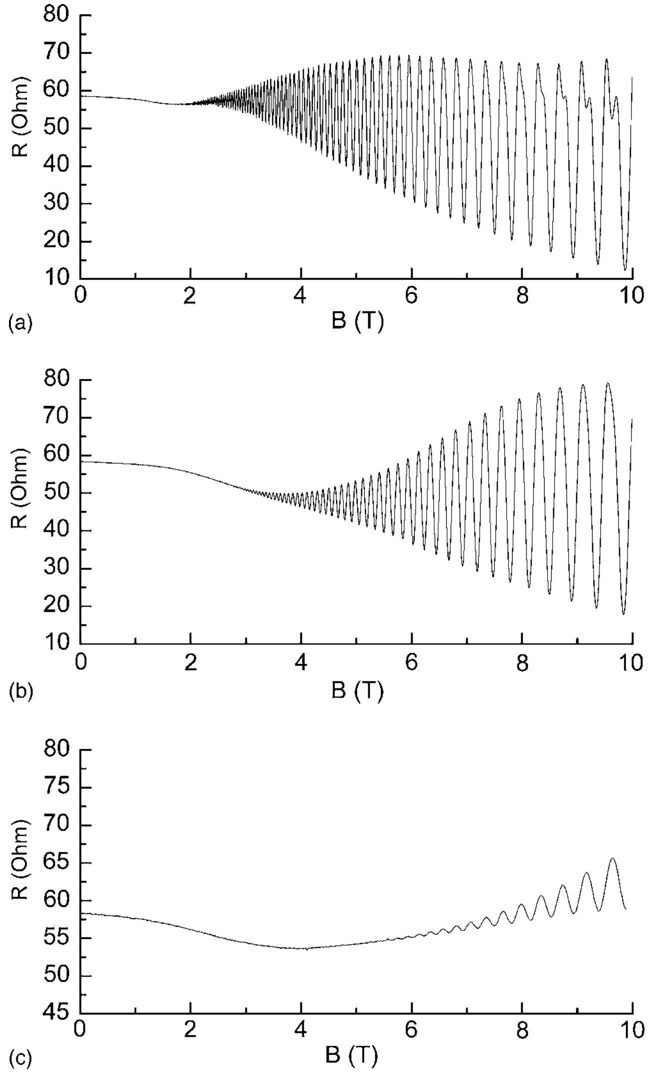

FIG. 4. The magnetoresistance R of irradiated sample 3 with a dose of 1×10^6 rad, measured at different temperatures T (K): (a) -0.4, (b) -4.0, and (c) −12.5.

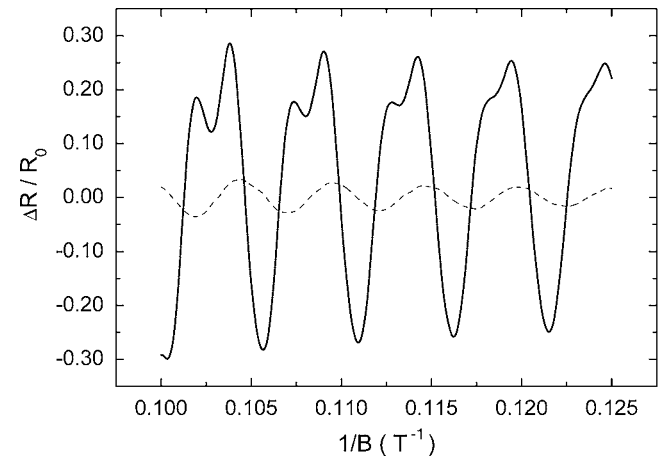

FIG. 5. High magnetic field part of the magnetoresistance R for sample 3 measured at T=0.35 K (R_0 is the resistance at B=0). Solid and dashed lines correspond to irradiated with a dose of 1×10^6 rad and the nonirradiated sample, respectively.

tribution of short- and long-range scatterings in the 2DEG system. In our case, this reflects a significant decrease in short-range carrier scattering, which is also confirmed by a registered increase in mobility.

The results of the electrical characterization of the structures obtained before and after irradiation can be resumed as follows: the carrier concentration is slightly decreased after an irradiation dose of 1×10^6 rad, while the 2DEG mobility measured at low temperatures exhibits a considerable increase. The latter is consistent with the above-mentioned decrease in strain accompanied by structural ordering of defects. The changes should improve the conditions for charge transfer that is reflected by an increase in mobility and the quantum lifetime. On the other hand, a small change in carrier concentration observed under visible relaxation of the AlGaN layer is less expected. It is known that the most peculiar feature of nitride heterostructures is the presence of huge spontaneous and piezoelectric polarization fields.[32–34] As a consequence, a high-density 2DEG appears at the AlGaN/GaN interfaces even without doping. Any changes in polarization fields will cause changes in 2DEG concentrations. If the expected decrease in the piezoelectric contribution does not affect the carrier concentration, two reasons should be considered. The first, the decrease in the piezoelectric field, is minor under the observed strain relaxation. The second, the variation in surface charge, compensates the decrease in the piezoelectric field to provide the same carrier concentration before and after irradiation.

The most striking result obtained for samples 2 and 3 is the gigantic amplification of the SdH oscillation amplitude after irradiation with a dose of 1×10^6 rad. Moreover, spin-split SdH oscillations become well resolved at a magnetic field $B > 8$ T, as seen in Fig. 5. The oscillations are well resolved up to a temperature of 2 K (Fig. 6). The onset of oscillations as well as their amplitude is determined by the degree of disorder broadening of the developing Landau levels (LLs) and, in addition to zero-field mobility, can be used for the estimation of material quality. Thus, the observed amplification of the SdH oscillation amplitude, together with the increase in the average time between scattering events, known as the quantum scattering time τ_q, strongly supports

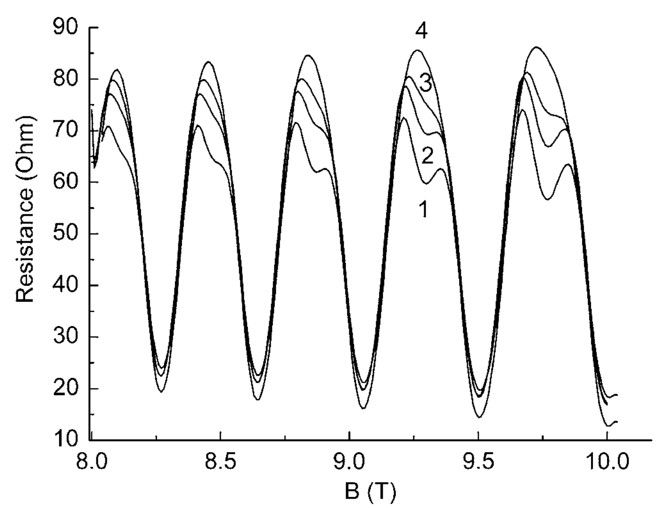

FIG. 6. High magnetic field part of the magnetoresistance R for sample 3 irradiated with a dose of 1×10^6 and measured at different temperatures T (K): (1) -0.30, (2) -1.17, (3) -2.00, and (4) -3.

the conclusion concerning the carrier mobility enhancement due to native defect ordering, as supported by the structural characterization.

From the observed LL spin splitting, we estimated the g-factors at different LL indices. We did not observe any beating patterns in the magnetoresistance trace. Thus, as an approximation, the effective g-factor g^* can be obtained by the standard equation[35,36]

$$g^* = \left(n + \frac{1}{2}\right) \frac{2\hbar e}{m^* \mu_B} \frac{(B_{n-} - B_{n+})}{(B_{n+} + B_{n-})}, \qquad (4)$$

where B_{n+} and B_{n-} are the experimental values of the magnetic field when spin-up and spin-down levels of the nth LL pass through the Fermi level, respectively. Here, we used the relation of the effective g-factor to the spin-splitting energy Δ_{ss} in the form $\Delta_{ss} = g^* \mu_B B$, where μ_B is the Bohr magneton.

By using Eq. (4), we calculated values of g^* for LLs with $n=20$, 21, and 22 equal to 3.7, 3.3, and 2.8, respectively. These results might be explained by the enhancement of g^* for the many-body exchange interaction.[37] The higher effective electron mass of $m^* = 0.185m_0$ than $m^* = 0.067m_0$ in GaAs and the lower dielectric constant of 9 than 13 in GaAs make EEls in GaN materials more significant. The enhancement of the effective g-factor allows us to effectively characterize the many-body exchange interaction in 2DEG systems with magnetic fields.

IV. CONCLUSIONS

In summary, we described the improvement of the transport properties of the 2DEG in AlGaN/GaN heterostructures after the treatment with small doses of gamma radiation. The samples displayed a considerable increase of mobility and quantum lifetime at $T = 0.3$ K. The revealed improvement of transport properties of AlGaN/GaN HEMTs after gamma irradiation is irreversible in time. Our experimental results on the magnetoresistance behavior of AlGaN/GaN heterostructures are in good agreement with theoretically predicted results. Magnetotransport spectroscopy results reflect a significant decrease in short-range carrier scattering, which is also confirmed by a registered increase in mobility. Moreover, spin splitting has been registered after a gamma radiation treatment of 1×10^6 rad, allowing us to estimate the value of the effective g-factor as high as 3.7 for LLs with $n=20$. The results suggest that improvements in transport characteristics can be achieved by using gamma-quanta irradiation in processing technology.

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