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Neutron Irradiation Effect in Two-Dimensional Electron Gas of AlGaN/GaN Heterostructures *

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AlGaN/GaN heterostructures have been irradiated by neutrons with different fluences and characterized by means of temperature-dependent Hall measurements and Micro-Raman scattering techniques. It is found that the carrier mobility of two-dimensional electron gas (2DEG) is very sensitive to neutrons. At a low fluence of $6.13 \times 10^{15}\,cm^{-2}$*, the carrier mobility drops sharply, while the sheet carrier density remains the same as that of an unirradiated sample. Moreover, even for a fluence of up to* $3.66 \times 10^{16}\,cm^{-2}$*, the sheet carrier density shows only a slight drop. We attribute the degradation of the figure-of-merit (product of* $n_s \times \mu$ *) of 2DEG to the defects induced by neutron irradiation. Raman measurements show that neutron irradiation does not yield obvious change to the strain state of AlGaN/GaN heterostructures, which proves that degradation of sheet carrier density has no relation to strain relaxation in the present study. The increase of the product of* $n_s \times \mu$ *of 2DEG during rapid thermal annealing processes at relatively high temperature has been attributed to the activation of* Ge_{Ga} *transmuted from Ga and the recovery of displaced defects.*

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The most important advantages of GaN are its wide band gap, high saturation velocity and high thermal stability. Due to strong polarization effects, two-dimensional electron gas with density higher than $10^{13}\mathrm{cm}^{-2}$ is formed at the interface of AlGaN/GaN heterostructure without intentional doping. These properties, combined with a very high breakdown field, make gallium nitride-based devices superior to the traditional GaAs-based and InP-based devices when applied under circumstances of high power, high temperature and high frequency. In recent years, gallium nitride-based high electron mobility transistors (HEMTs) have attracted a great deal of research interest, and tremendous progress has been made in material growth and device fabrication.[1,2]

Another feature of gallium nitride-based devices is that they have the potential capability to exhibit extremely high radiation hardness. So far there have already been systems employing GaN devices designed for the use in outer space and other radiation environment, where devices must operate reliably when subjected to irradiations of protons, electrons, neutrons, or γ rays. Therefore, significance should be attached to the understanding of the radiation effect on GaN-based electronic devices. In this area, detailed studies[3−5] have been performed on the proton irradiation effect of AlGaN/GaN HEMTs. Gaudreau *et al.*[4] has reported temperature-dependent Hall measurements on 2 MeV proton-irradiated MBE-grown $Al_{0.3}Ga_{0.7}N$/GaN 2DEG structures. They found that the structure changes from a conductor to an insulator when the fluence increases from $3 \times 10^{14}\,\mathrm{cm}^{-2}$ to $3 \times 10^{15}\,\mathrm{cm}^{-2}$. Decreases of dc saturation current and transconductance of GaN HEMTs after the irradiation with 1.8 MeV protons have been reported by Cai *et al.*[3] A recent work of Sonia *et al.*[5] has demonstrated that the irradiation with high energy heavy ions (carbon and oxygen, 68 MeV) does not degrade the operation of AlGaN/GaN HEMTs, while low energy heavy ion irradiation (2 MeV) induces degradation in I_{DS} and g_m at a low fluence.

However, few works have been performed on neutron[6] and γ ray[7] irradiation effect on AlGaN/GaN HEMTs. Actually, a clear understanding of radiation effect in 2DEG of simple microstructures will provide important and necessary background knowledge for predicting the behaviour of AlGaN/GaN HEMTs. In the present study, the neutron irradiation effect on AlGaN/GaN heterostructure is studied by means of Hall measurements and Raman scattering techniques.

The AlGaN/GaN heterostructures were grown by metal organic chemical vapour deposition (MOCVD) on C-plane sapphire substrates. The structure in Fig. 1 was grown unintentionally doped. A 20 nm low temperature GaN nucleation layer was initially grown, followed by the deposition of a 3.6-μm-high resistant GaN buffer layer. Then a 100-nm-high quality GaN

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channel layer and a 20-nm $Al_{0.3}Ga_{0.7}N$ barrier layer were grown in sequence. To study the effect of neutron irradiation, the wafer was cut into small pieces with an area of about $5 \times 5\,mm^2$. The samples were irradiated at room temperature in the light water nuclear reactor at Tsinghua University. The fluences were respectively $6.13 \times 10^{15}\,cm^{-2}$ and $3.66 \times 10^{16}\,cm^{-2}$, with the thermal-fast neutron ($E > 1\,MeV$) ratio of 6.1:1.

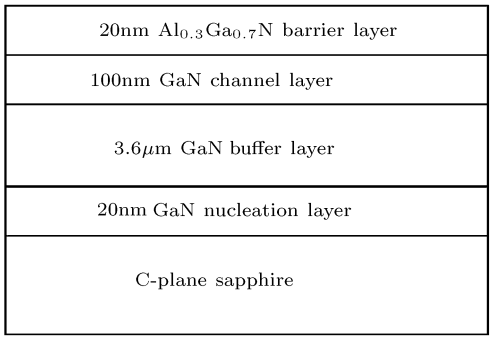


Fig. 1. Schematic cross-sectional diagram of the unintentionally doped AlGaN/GaN heterostructure

For Hall measurements, the samples were treated in a conventional cleaning process. After that, the Ohmic contacts were made by putting metal In onto the samples immediately. The Van der Pauw configuration was used in Hall measurements to estimate the 2DEG density and electron mobility of the samples from 80 K to 300 K.

The 632.8 nm line of a He-Ne laser with a power of 25 mW was used for Raman scattering. The laser beam was focused on the sample with a spot diameter of about $1\,\mu m$. The scattered light was collected and analysed by a Dilor Labram microscope with a CCD detector. The spectral resolution was better than $0.1\,cm^{-1}$, and the spatial resolution was below $1\,\mu m$. All the spectra were recorded in backscattering geometry at room temperature.

All samples were isochronally annealed for 60 s in a N_2 rapid thermal annealing system at different temperatures with the In ohmic contact retained. The annealing was followed by Hall measurements at room temperature.

Figure 2 shows the results of temperature-dependent Hall measurements. With the increase of incident fluence, the carrier mobility of 2DEG in the AlGaN/GaN heterostructure drops sharply. After being irradiated with a fluence of $3.66 \times 10^{16}\,cm^{-2}$, the carrier mobility at room temperature drops from $1200\,cm^2/Vs$ to $610\,cm^2/Vs$.

There are several mechanisms that play a role in limiting the mobility of 2DEG in the AlGaN/GaN heterostructure. Theoretical calculation[8] shows that interface roughness and alloy disorder scattering are the dominant scattering mechanisms at low temperature in unintentionally doped samples. However, for the irradiated samples, the influence of the irradiation induced charged defect centres are crucial. When the sample is subjected to neutron irradiation, the lattice is bombarded by fast neutrons and thermal neutrons. These processes not only cause the crystal structure to slightly distort, but also introduce charged defect centres into the AlGaN/GaN heterostructure, such as displacement defects and point defects (V_{Ga}, Ga_I and Ge_{Ga} transmuted from Ga).[9] These defect centres enhance the carrier scattering in the 2DEG through Coulomb interactions. The increased carrier scattering leads to the reduced mobility in the 2DEG. High level incident fluence produces a large number of defect centres. As a result, the carrier mobility is degraded seriously. The displaced atoms near interface form localized states. The existence of the localized states and distorted lattice increases interface roughness, which is another reason for the low carrier mobility of neutron irradiated sample. Moreover, variation of alloy disorder induced by the defect centres is also a possible reason.

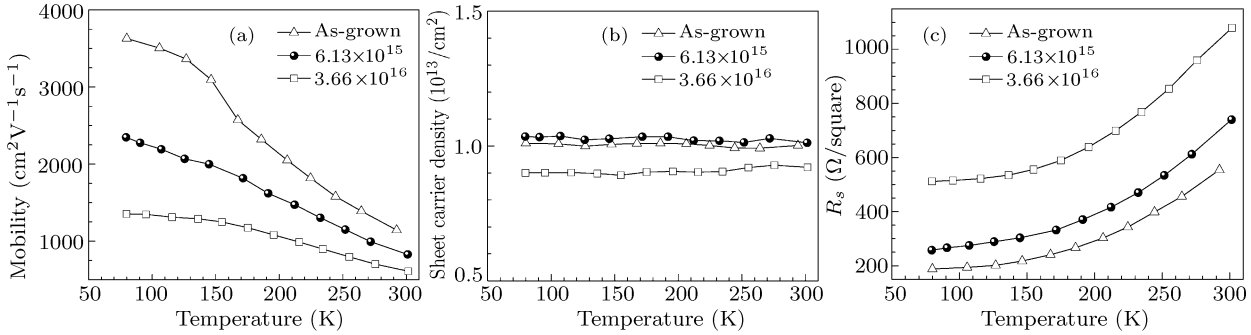


Fig. 2. Results of temperature-dependent Hall measurements for (a) carrier mobility, (b) sheet carrier density, and (c) sheet resistance with different neutron fluence.

The sheet carrier density is not affected greatly by neutron irradiation. Even with a fluence of up to $3.66 \times 10^{16}\,\mathrm{cm}^{-2}$, the sheet carrier density of 2DEG shows only a slight drop, but no increase, which is completely different from the results of Polyakov *et al.*[6] The mechanism of neutron irradiation induced sheet carrier density removal in Si-doped AlGaN/GaN heterostructure has been explained by the shift of the Fermi level.[6,10] In the proton irradiated AlGaN/GaN HEMTs, it has been attributed to the variation of strain state in the channel layer.[3] Figure 3 shows the Raman spectrum of the as-grown and irradiated samples in the present study. The E_2 peak of GaN centres at $569.6\,\mathrm{cm}^{-1}$ and the A_1 (LO) peak centres at $734.81\,\mathrm{cm}^{-1}$. However, it is noticed that there is no shift of peak E_2. This proves that in the present study, the strain state in the AlGaN/GaN heterostructure does not change under neutron irradiation at all, and the reduction of sheet carrier density is unrelated to the strain relaxation.

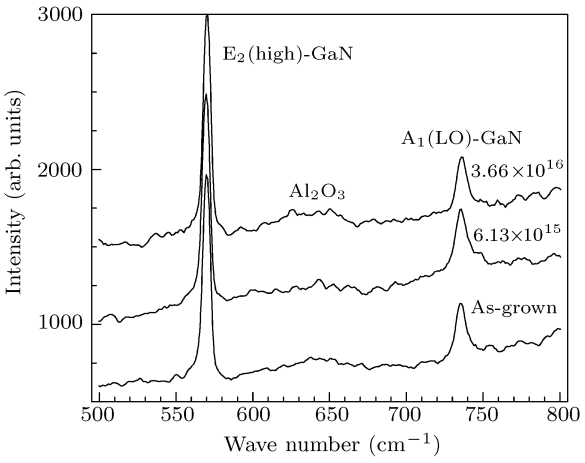


Fig. 3. Micro-Raman spectrum of samples.

Some of the charged defect centres play as carrier trap centres in the neutron irradiated AlGaN/GaN heterostructure.[6,9−11] At low fluence, there is only a small number of trap defects formed, which has no obvious impact on the carrier density. When the fluence is high enough, electrons in the channel layer will be trapped by the trap level and the sheet carrier density of 2DEG drops. The carrier removal through charge compensation also contributes.

At the low incident fluence of $6.13\times10^{15}\mathrm{cm}^{-2}$, only the carrier mobility degradation is responsible for the increase of the sheet resistance. With a fluence of up to $3.66\times10^{16}\mathrm{cm}^{-2}$, both the carrier mobility and sheet carrier density have been damaged by neutron irradiation, which increases the sheet resistance rapidly. In Fig. 2(c), no conductor-to-insulator transition[4] occurs.

Rapid annealing processes were performed at 500, 600, 700, and 800°C, with N_2 serving as the protective gas. Figure 4 shows the figure-of-merit (product of $n_s \times \mu$) at different stages of annealing. When the annealing temperature increases, $\mathrm{Ge_{Ga}}$, the shallow effective-mass donor in the neutron irradiated GaN,[9] will be activated. It is found that n-type doping increases the sheet carrier density of 2DEG at the interface of the AlGaN/GaN heterostructure, while ionized impurity degrades the carrier mobility through Coulomb interactions. These are consistent with the results of Hall measurements obtained in the present study. When annealed at over 600°C, carrier mobility of the irradiated samples shows only a slight increase, although the sheet carrier density has an obvious increase. After annealed at 800°C, the sheet carrier density is equal to that of the as-grown samples. Therefore, the variation of the product of $n_s \times \mu$ is mainly attributed to the increase of the sheet carrier density when annealing temperature changes from 600°C to 800°C.

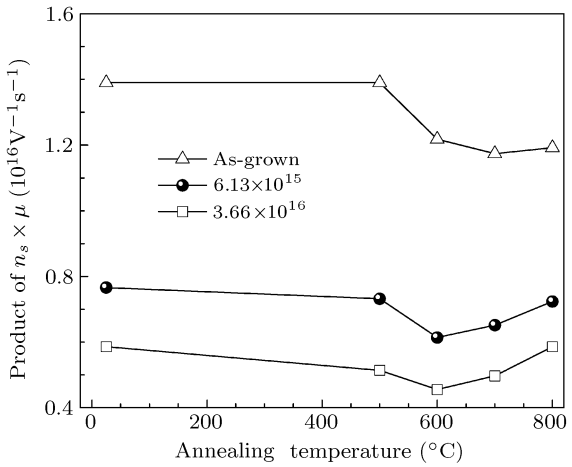


Fig. 4. Product of $n_s \times \mu$ versus annealing temperature.

It should be noted that in contrast with the irradiated samples, when the annealing temperature is above 600°C, the carrier mobility of unirradiated samples remains constant, the sheet carrier density drops continuously, and the product of $n_s \times \mu$ shows no increase. The annealing behaviour is very different from the irradiated samples, which proves that our postulation is right.

In summary, the influence of neutron irradiation on AlGaN/GaN heterostructure has been studied. It is found that the carrier mobility of 2DEG is strongly affected by neutrons, but the influence on the sheet carrier density is slight, even at high fluence. The strain state of the AlGaN/GaN heterostructure is not obviously changed by neutron irradiation, and the reduction of sheet carrier density is irrelevant to the strain relaxation. The neutron irradiation induced charged defect centres are used to explain these re-

sults. The figure-of-merit (product of $n_s \times \mu$) of 2DEG can be partially recovered by rapid thermal annealing processes at relatively high temperature, due to the recovery of displaced defects and the activation of Ge_{Ga}.

References

[1] Khan M A, Bhattarai A, Kuznia J N and Olson D T 1993 *Appl. Phys. Lett.* **63** 1214

[2] Wang X L, Cheng T S, Ma Z Y, Hu G X, Xiao H L, Ran J X, Wang C M and Luo W J 2007 *Solid State Electron.* **51** 428

[3] Cai S J, Tang Y S, Li R, Wei Y Y, Wong L, Chen Y L, Wang K L, Chen M, Zhao Y F, Schrimpf R D, Keay J C and Galloway K F 2000 *IEEE Trans. Electron Devices* **47** 304

[4] Gaudreau F, Fournier P, Carlone C, Khanna Shyam M, Tang H P, Webb J and Houdayer A 2002 *IEEE Trans. Nucl. Sci.* **49** 2702

[5] Sonia G, Brunner F, Denker A, Lossy R, Mai M, Opitz-Coutuieau J, Pensl G, Richter E, Schmidt J, Zeimer U, Wang L, Weyers M, Wurfl J and Trankle G 2006 *IEEE Trans. Nucl. Sci.* **53** 3661

[6] Polyakov A Y, Smirnov N B, Govokov A V, Markov A V, Pearton S J, Kolin N G, Merkurisov D I and Boiko V M 2005 *J. Appl. Phys.* **98** 033529

[7] Umana-Membreno G A, Dell J M, Parish G, Nener B D, Faraone L, Ventury R and Mishra U K 2005 *Phys. Status Solidi* C **2** 2581

[8] L Hsu and W Walukiewicz 2001 *J. Appl. Phys.* **89** 1783

[9] Kuriyama K, Tokumasu T, Takahashi Jun, Kondo H, and Okada M 2002 *Appl. Phys. Lett.* **80** 3328

[10] Polyakov A Y, Smirnov N B, Govorkov A V, Pashkova N V, Pearton S J, Zavada J M, and Wilson R G 2003 *J. Vac. Sci. Technol.* B **21** 2500

[11] Polyakov A Y, Smirnov N B, Govorkov A V, Markov A V, Pearton S J, Kolin N G., Merkurisov K I, Boiko V M, Lee Cheul-Ro, and Lee Ln-Hwan 2007 *J. Vac. Sci. Technol.* B **25** 436