Vol 18 No 7, July 2009
1674-1056/2009/18(07)/2912-08

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

Degraded model of radiation-induced acceptor defects for GaN-based high electron mobility transistors (HEMTs)*

Fan Long(范 隆)[a)†], Hao Yue(郝 跃)[b)c)d)], Zhao Yuan-Fu(赵元富)[a)],
Zhang Jin-Cheng(张进城)[b)c)d)], Gao Zhi-Yuan(高志远)[b)c)d)], and Li Pei-Xian(李培咸)[b)c)d)]

[a)] *Beijing Microelectronics Technology Institute, Beijing* 100076, *China*
[b)] *The School of Microelectronics, Xidian University, Xi'an* 710071, *China*
[c)] *Key Laboratory of Fundamental Science for National Defense of Wide Bandgap Semiconductor Technology, Xidian University, Xi'an* 710071, *China*
[d)] *Key Laboratory for Wide Band-gap Semiconductor Materials and Devices of Ministry of Education, Xidian University, Xi'an* 710071, *China*

(Received 15 April 2007; revised manuscript received 5 November 2008)

Using depletion approximation theory and introducing acceptor defects which can characterize radiation induced deep-level defects in AlGaN/GaN heterostructures, we set up a radiation damage model of AlGaN/GaN high electron mobility transistor (HEMT) to separately simulate the effects of several main radiation damage mechanisms and the complete radiation damage effect simultaneously considering the degradation in mobility. Our calculated results, consistent with the experimental results, indicate that thin AlGaN barrier layer, high Al content and high doping concentration are favourable for restraining the shifts of threshold voltage in the AlGaN/GaN HEMT; when the acceptor concentration induced is less than 10^{14}cm^{-3}, the shifts in threshold voltage are not obvious; only when the acceptor concentration induced is higher than 10^{16}cm^{-3}, will the shifts of threshold voltage remarkably increase; the increase of threshold voltage, resulting from radiation induced acceptor, mainly contributes to the degradation in drain saturation current of the current–voltage (I–V) characteristic, but has no effect on the transconductance in the saturation area.

Keywords: GaN-based high electron mobility transistor (HEMT) radiation, acceptor, defects
PACC: 6180, 7280E, 7360L , 7320

1. Introduction

In general, it is well known that radiation can induce both donor defects and acceptor defects in semiconductor materials.[1−3] The deep acceptor centre will result in compensation in n type material, while the deep donor centre will do so in p type material. Therefore, regardless of whether the material has n or p type conduction originally, its electrical resistivity will inevitably increase after it is irradiated, unless by a very low radiation dose. The deep donor centre in n type material and the deep acceptor centre in p type material both hardly have an effect on conductive electrons, because their ionization energies are too high to contribute free electrons.

Most GaN materials grown by using the metal-organic chemical vapour deposition (MOCVD) technology possess n-type conduction, and so does the AlGaN in the modulated doped AlGaN/GaN heterostructures, consequently, the radiation induced defects in these materials and structures are primarily deep acceptor defects. The GaN buffer, acting as the conductive channel in the AlGaN/GaN heterostructures, is generally of n type or weak n type, hence only the deep donor state in this material is of real use. Even though an intrinsic GaN layer can be achieved in the ideal technological condition, the Fermi level in it will approach to the conduction band of GaN near the heterojunction, due to the n type modulated doping, the big polarization electrical field and the conduction band offset. In other words, the surface of the GaN near the interface of the heterojunction is inversed, so only the acceptor state defect could remove the charge carrier and all these induced defects will reduce the conductivity of the material, i.e. make the material more intrinsic, and the two dimensional electron gas

*Project supported by the National Defense Scientific and Technical Pre-Research Program of China (Grant Nos 51311050112, 51308040301 and 51308030102), the National Defense Fundamental Research Program of China (Grant No A1420060156), and the National Basic Research Program of China (Grant No 513270407).
†Corresponding author. E-mail: meilfan@yahoo.com.cn

(2DEG) concentration in the heterostructures, resulting in the retarding current. For these reasons, we study the radiation induced acceptor defects in the present paper for a good understanding of the micromechanism of the radiation damage in AlGaN/GaN high electron mobility transistor (HEMT).

Concerning the electrical character of AlGaN/GaN HEMT, the radiation induced acceptor defects will produce two basic radiation effects, i.e. the effective doping concentration variation in each layer of the structure which results from the removing of current carrier and the degradation of mobility which originates from the scattering centre of additional defects. Moreover, it will also cause threshold voltage shifts, the decrease of drain current and transconductance, as well as the increase of parasitic resistance between source and drain. Since the 2DEG in the AlGaN/GaN heterostructure is localized in a small region (in a thick range of 0.5–2 nm) and it is close to the heterojunction, which is regarded as a characteristic of the 2DEG distribution in the AlGaN/GaN HEMT, even though the concentration of the radiation induced defects in GaN is as high as 10^{17} cm^{-3}, assuming the defect distribution is uniform, the effective areal density of charged defects in the channel that could cause the mobility degeneration is only about 10^{10} cm^{-2}, whose effect is weaker than that of a low interface state density of 10^{11} cm^{-2}. Therefore, the effect of the channel charged defects on the mobility radiation degeneration can be integrated into the scattering effect of the effective interface state charge. In our model, the damage effect which can cause the threshold voltage shifts is primarily regarded as the essential one, and then the threshold voltage shifts can further lead to the reduction in drain current and transconductance.

2. Threshold voltage shift model with depletion approximation

Threshold voltage is an important electrical parameter in the electronic devices. In the present paper, we construct a model where the effect of radiation induced acceptor on the threshold voltage of AlGaN/GaN HEMT is described, by referring to the method used to analyse the depletion layer in the charge control model of depletion approximation, constructed by Krantz and Bloss for AlGaAs/GaAs HEMT.[4]

When a device turns on at a threshold voltage, in general, the effect of the acceptor defects introduced in the AlGaN layer is to reduce the effective doping concentration in the barrier region, however the effect of the acceptor defects induced in the GaN channel is to change the depletion width and the conduction shape on the side of GaN channel. Nevertheless both effects ultimately cause the AlGaN/GaN HEMT threshold voltage shifts.

On the assumption that after radiation, a number of acceptor defects with a concentration of N_a are induced, and under the GaN depletion approximation condition, using the charge control principle, the threshold voltage shift model can be established by solving the Poisson equation near heterojunction interface when the device turns on under the threshold voltage condition.

Adopted in the device model to be analysed is the normal AlGaN/GaN HEMT structure, which has a classic AlGaN/GaN heterojunction, a Schottky barrier at the gate, and an isolating layer at the interface. Its energy band structure under bias is shown in Fig.1, where d_d, d_i and W are the thickness of doping AlGaN, the space isolating region and the depletion layer respectively, N_d is the doping concentration of the AlGaN potential barrier, Φ_{ms}, ΔE_C, E_g and ϕ_{bulk} denote the Schottky barrier height, the offset of the conduction band, the GaN band gap and the GaN bulk barrier respectively. The dielectric constants of GaN and AlGaN in our analysis are $9.5\varepsilon_0$ and $9.35\varepsilon_0$ respectively, and the intentional doping concentration of GaN buffer is assumed to be zero for the convenience of calculation.

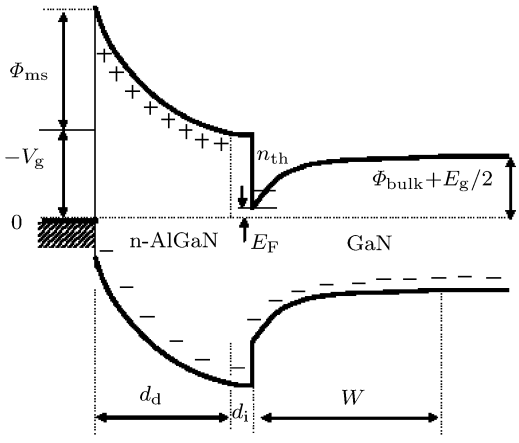


Fig.1. Energy band structure of AlGaN/GaN HEMT, used to calculate threshold voltage, affected by radiation induced acceptor.

Firstly, under the charge equilibrium condition, when a threshold voltage is achieved, the Poisson

equation concerning the gate voltage and the charge density in the doping AlGaN layer, the spacer and the GaN depletion layer $\rho_{\rm d}$, $\rho_{\rm a}$, and $\rho_{\rm w}$ can be established as follows:

$$\begin{aligned} V_{\rm g} =& \Phi_{\rm ms}(m) - \Delta E_{\rm C} - E_{\rm g}/2 - \Phi_{\rm bulk} - \frac{\sigma_{\rm pol}}{\varepsilon_{\rm AlGaN}}\left(d_{\rm d}+d_{\rm i}\right) \\ & - \left(1/\varepsilon_{\rm AlGaN}\right)\left[\int_0^{d_{\rm d}} \rho_{\rm d}\cdot z\cdot {\rm d}z - \int_{d_{\rm d}}^{d_{\rm d}+d_{\rm i}} \rho_{\rm d}\cdot z\cdot {\rm d}z\right] \\ & - \left(q/\varepsilon_{\rm GaN}\right)\cdot\int_{d_{\rm d}+d_{\rm i}}^{(W+d_{\rm d}+d_{\rm i})} \rho_{\rm w}\cdot z\cdot {\rm d}z, \end{aligned} \tag{1}$$

where $\sigma_{\rm pol}$ is the sheet (area) density of polarization charge at AlGaN/GaN heterojunction interface. Assuming that all of the defects induced in the AlGaN/GaN heterostructure by radiation are the uniformly distributed acceptor defects, the charge density $\rho_{\rm d}$ of AlGaN layer is given by the difference between donor density and radiation induced acceptor density, i.e. $q(N_{\rm d}-N_{\rm a})$. The spacer charge density $\rho_{\rm a}$ equals the negative acceptor density $-qN_{\rm a}$. Owing to the threshold voltage condition, the GaN charge density $\rho_{\rm w}$ is dominated by the charge in the depletion layer, $-qN_{\rm a}$. Consequently, the last item in expression (1) represents the band bending in GaN dominated by the charge in the depletion layer.

By dint of Fig.1, the band bending in GaN is given by the following expression:

$$\phi_{\rm bb} = E_{\rm g}/2 + \Phi_{\rm bulk} - E_{\rm F}, \tag{2}$$

where $E_{\rm F}$ is the difference in electrical potential between the 2DEG channel bottom and the Fermi level. Under the depletion approximation condition, by integrating Poisson equation the threshold voltage expression can be obtained as

$$\begin{aligned} V_{\rm th} =& \Phi_{\rm ms} - \Delta E_{\rm C} - E_{\rm F} - \left(qd_{\rm d}^2/2\varepsilon_{\rm AlGaN}\right)\cdot\left[N_{\rm d}-N_{\rm a}\right] \\ & + \left(q/\varepsilon_{\rm GaN}\right)\cdot N_{\rm a}W\left(d_{\rm d}+d_{\rm i}\right) \\ & - \left(\sigma_{\rm pol}/\varepsilon_{\rm AlGaN}\right)\left(d_{\rm d}+d_{\rm i}\right). \end{aligned} \tag{3}$$

The items containing $d_{\rm i}/d_{\rm d}$ and $d_{\rm d}/W$ have been ignored in expression (3) above. Under the threshold voltage condition and in the single sub-band triangle potential trap approximation, $E_{\rm F}$ is related to the channel charge density $n_{\rm th}$ by the following expression:

$$\begin{aligned} E_{\rm F} =& -\left(kT/q\right)\ln\left[\pi\hbar^2 n_{\rm th}/m_{\rm t}kT\right] \\ & - \left(9\hbar^2/8m_{\rm t}\right)\left(4qN_{\rm a}Wm_{\rm t}/\hbar^2\varepsilon_{\rm GaN}\right)^{2/3}, \end{aligned} \tag{4}$$

where k, T, q and $\hbar$ are the Boltzmann constant, the temperature, the quantity of electron charge, and the Plank constant respectively, and $m_{\rm t}$ is the transverse effective mass of carrier.

In order to use the physical constant, the HEMT geometric parameter and the doping density to evaluate the threshold voltage, the relation among the channel charge $n_{\rm th}$, the depletion layer width W and $N_{\rm a}$ needs to be established under the threshold voltage condition.

When a device turns on at the threshold voltage, letting the channel charge density equal the doping density of the channel $N_{\rm a}$ multiplied by the average channel width $z_{\rm ave}$, leads to the following expression:

$$n_{\rm th} = 3N_a^{2/3}/\left(4qm_{\rm t}W/h^2\varepsilon_{\rm GaN}\right)^{1/3}. \tag{5}$$

The band bending $\phi_{\rm bb}$ of GaN is obtained by integrating the last item of expression (1) to be $\left(q/2\varepsilon_{\rm GaN}\right)N_{\rm a}W^2$. Rearranging the terms on the right-hand side of expression (2), we can obtain the depletion width expressed as

$$\begin{aligned} W =& \left\{\left(4\varepsilon_{\rm GaN}\cdot\Phi_{\rm bulk}/qN_{\rm a}\right)\right. \\ & \left.\times\left[1+\left(\frac{E_{\rm g}}{2}-\Phi_{\rm bulk}-E_{\rm F}\right)/2\Phi_{\rm bulk}\right]\right\}^{1/2}. \end{aligned} \tag{6}$$

The bulk electrical potential of GaN is

$$\Phi_{\rm bulk} = \left(kT/q\right)\cdot\ln\left(N_{\rm a}/n_{\rm i}\right), \tag{7}$$

where the intrinsic carrier density n_i is

$$n_i = \left(\frac{2\left(2\pi kT\right)^{3/2}\left(m_p m_n\right)^{3/4}}{h^3} \right) \cdot \exp\left(\frac{q \cdot E_g}{2kT} \right). \quad (8)$$

Except for the second item in the parentheses on the right-hand side of expression (6), this depletion layer width equals the strong inversion layer width in the MOSFET threshold theory, where MOSFET stands for metal oxide semiconductor field effect transistor, however, the evaluation from expressions (7) and (8), shows that for the high acceptor density ($\sim 10^{17}$ cm^{-3}), the former is about 2% higher than the latter, and for the acceptor density below 10^{17} cm^{-3}, the former is about 18% higher than the later. When the acceptor density is below 10^{13} cm^{-3}, the contribution of depletion charge to the threshold voltage is smaller than that of the other factors, and when the density is high, the depletion width difference is small, so the depletion width could be approximated to be

$$W = 2\left\{ \left(\varepsilon_{GaN} kT/q^2 N_a \right) \cdot \ln\left(N_a/n_i \right) \right\}^{1/2}. \quad (9)$$

From expression (9), the relation between depletion width and radiation induced acceptor concentration can be obtained, and the relationships among n_{th}, E_F and N_a can be further obtained from expressions (4) and (5). Substituting them into expression (3) we can obtain the relation between threshold voltage and acceptor density N_a.

3. Results and discussion

3.1. Effect of acceptor defect on HEMT threshold voltage

Figure 2 shows the curve for the threshold voltage of $Al_{0.3}Ga_{0.7}N$ /GaN HEMT with AlGaN doping density N_d of 1×10^{18} cm^{-3}, of which the structure is as shown in Fig.1 versus radiation induced acceptor defects density N_a. In calculation, the width of the doping layer AlGaN in HEMT is 150 Å, the spacer width d_i is 30 Å, and the GaN layer is assumed to be semi-infinite. The results shows that the threshold voltage positively shifts with the acceptor concentration increasing, which means after introducing the radiation induced defects, the 2DEG depletion voltage of HEMT falls down, which is consistent with the experimental results[5] obtained in the case where the threshold voltage of AlGaN/GaN HEMT varies after being irradiated, which demonstrates that the model we have used here is reasonable. It is also shown that when the acceptor concentration is below 10^{16} cm^{-3}, the threshold voltage shift is smaller than 0.36 V, with the increase of acceptor concentration, the threshold voltage shifts faster, resulting in the increase of the interface electrical field, and accordingly the change of the triangle potential trap shape. The electrical field sign in the interface is inversed by the Schottky potential barrier, so the net potential difference is reduced. Secondly, the increased interfacial electrical potential can improve the quantization energy level of the triangle potential trap. All these factors make the threshold voltage increase correspondingly.

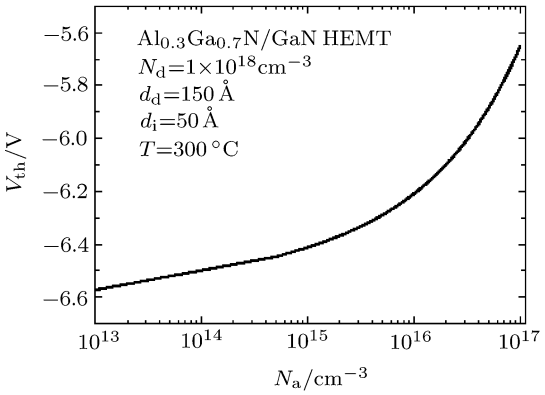


Fig.2. Effect of radiation induced acceptor on threshold voltage.

For a low acceptor density, threshold voltage is determined by the Fermi energy level determined by the Schottky potential barrier, the conduction offset, the polarization charge, the potential layer thickness, the doping concentration and the channel charge, the first quantum trap energy level, and the second term of expression (4), and it is directly proportional to $qN_aW(d_d + d_i)/\varepsilon$ in the depletion width expression, which is close to zero when the acceptor defect density is below 10^{14} cm^{-3}. With acceptor density increasing, all of the nonconstant terms that can contribute to the threshold voltage shift will increase.

As the depletion charge $-qN_aW$ increases with the acceptor density increasing, the interface electrical field is enhanced. The energy level in the two dimensional quantum trap increases as the 2/3 power of depletion layer charges, and contributes to the threshold voltage as well.

Figure 3 shows the difference in threshold voltage shift among the acceptor defects introduced into different regions.

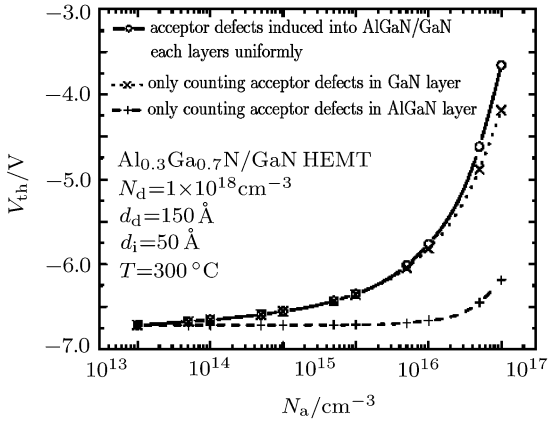


Fig.3. Effect of uniformly induced acceptor defects introduced into each layer of AlGaN/GaN on threshold voltage.

From the comparison among the threshold voltage shifts when acceptor defects are introduced uniformly into each layer, we can find that for single heterojunction of AlGaN/GaN HEMT, the acceptor defects introduced into the GaN layer primarily contribute to the voltage shift, and only when the concentration is very high, will the acceptor defects introduced into the AlGaN layer have an effect on the voltage shift. This result is consistent with the radiation experimental result of AlGaAs/GaAs HEMT in the same structure observed by Krantz *et al.*[6] This result implies that in order to improve the radiation-harden level for single heterojunction HEMT devices, it is necessary to overcome the sensibility of channel to the induced acceptor defects, and this aim can be achieved in a single quantum well structure, i.e. double heterojunction structure, which has been confirmed by the radiation experiment of GaAs single heterojunction and single quantum well HEMT.[7] Because the additional energy level offset isolates the 2DEG from GaN buffer in the single quantum HEMT, i.e. AlGaN/GaN/AlGaN or AlGaN/InGaN/GaN structure, and the potential well in this structure is similar to the square potential well, which is insensitive to the acceptor defects, the quantized energy level of this structure is insensitive to the acceptor defect energy level. Nawaz and Jensen have also found in their theoretical research that the threshold voltage shift of AlGaAs–GaAs–AlGaAs single quantum well HEMT is very small (about 0.1 V), when the acceptor doping concentration increases from 10^{13} to 10^{16} cm^{-3}.[8]

3.2. Effect of acceptor defects on HEMT threshold voltage with different Al compositions

In $Al_mGa_{1-m}N$/GaN HEMT devices, the most important device parameter that determines the 2DEG concentration is the Al composition in the barrier layer. In Fig.4, the dependences of the threshold voltage of HEMTs with three commonly used Al compositions on acceptor defect density have been given.

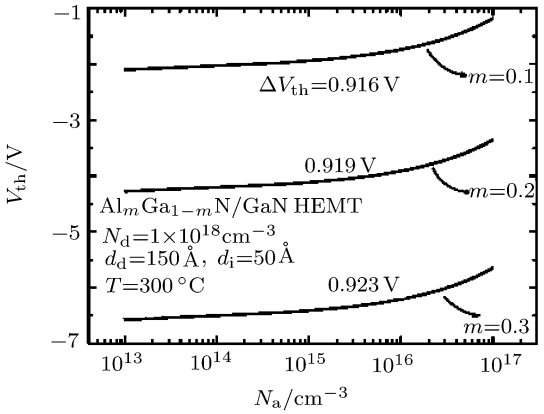


Fig.4. Relations between threshold voltage of device and the radiation induced acceptor defect concentration for three different Al compositions.

The result shows that the threshold voltage shifts of HEMTs with different Al compositions toward increasing acceptor defect density are nearly the same when m increases from 0.1 to 0.4. In other words, the sensibilities of HEMT devices with different Al compositions to acceptor defect are the same, therefore the increase of Al composition could not enhance the effect of acceptor defects on the device threshold voltage shifts. So an Al composition as high as possible can be adopted in order to improve $Al_mGa_{1-m}N$/GaN HEMT performance in device design.

3.3. Effect of AlGaN barrier thickness on relationship between threshold voltage and acceptor defect

The barrier thickness (d_d+d_i) of $Al_mGa_{1-m}N$/GaN HEMT is another structure parameter as important as Al composition in determining a 2DEG concentration. Figure 5 shows the variations of threshold voltage with acceptor defect concentration under different barrier thicknesses. It is obvious that the thicker the barrier is, the more the shifts of the threshold voltage will be, and for the HEMTs with d_d = 150 and 400 Å, the threshold voltage shifts are, respectively, 2.769 and 6.950 V within a calculated acceptor concentration range ($10^{13} - 10^{18}$ cm^{-3}), which means the thin barrier could restrain the threshold voltage shift to some extent.

Figure 6 shows the curves for the variations of threshold voltage with acceptor concentration under different barrier spacer thicknesses. The thinner the spacer is, the smaller the shift of threshold voltage

caused by acceptor defects will be, which is similar to the behaviours given in Fig.5. It can be explained as follows: a thicker spacer will introduce more acceptor defects into the barrier, thereby increasing the charge areal density $-qN_a(d_d+d_i)$ that could affect threshold voltage, and finally leading to a larger forward threshold voltage shift.

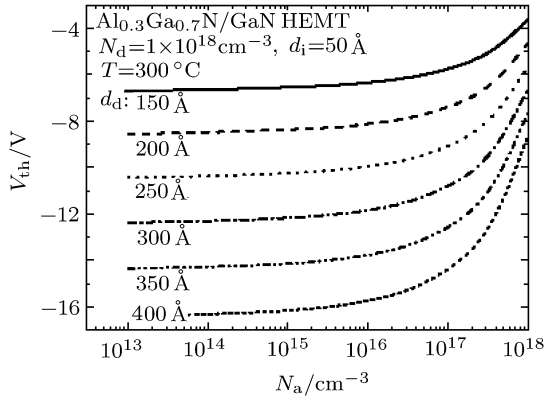


Fig.5. Curves for threshold voltage versus acceptor defect concentration with different $Al_mGa_{1-m}N$ modulated doping layer thicknesses.

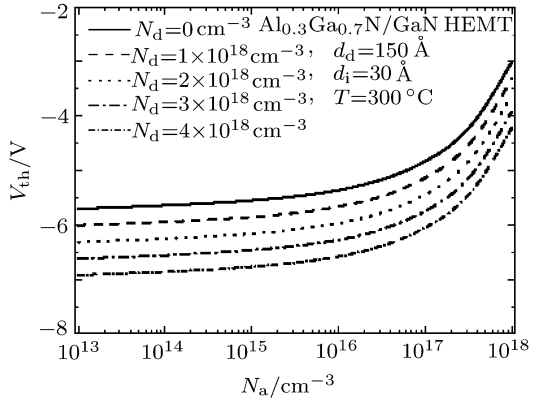


Fig.6. Curves for threshold voltage versus acceptor defect concentration with different $Al_mGa_{1-m}N$ spacer thicknesses.

3.4. Effect of AlGaN barrier doping concentration on relationship between threshold voltage and acceptor defect

The contribution of modulated doping concentration to 2DEG concentration in AlGaN/GaN HEMT is different from that in traditional AlGAs/GaAs HEMT. The latter primarily depends on doping concentration, while the former depends little on doping when Al composition ($m > 0.2$) is a bit higher.

Figure 7 shows the curves for threshold voltage shift versus acceptor concentration with different barrier doping concentrations. It can be seen that the variations of threshold voltage with radiation-induced acceptor concentration have the same trends, no matter whether it is the HEMT only with polarity induced 2DEG ($N_d = 0$) or affected by modulated doping. The absolute threshold voltage shifts of HEMTs with different modulated doping concentrations are also the same (2.700 V) within the calculated acceptor concentration range, which means that the donor in the barrier layer has no effect on the relationship between threshold voltage shift and acceptor concentration.

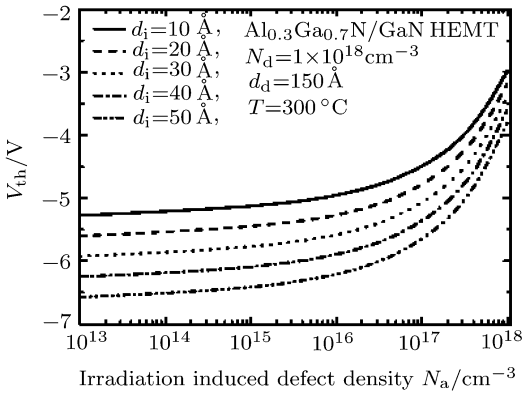


Fig.7. Curves for threshold voltage versus acceptor defect concentration for different $Al_mGa_{1-m}N$ doping concentrations.

3.5. Drain current and transconductance degradation

Based on the AlGaN/GaN HEMT I–V characteristic model, the degradation effect of radiation induced acceptor on HEMT I–V characteristic has been investigated here. Figure 8 shows the effect of acceptor concentration on output characters, and for the convenience of calculation, the output characters are illustrated only in the case of $V_G = 0$. As can be seen, the drain saturation current obviously decreases with the increase in acceptor concentration, but only a little in the linearity range.

Figure 9 shows the effect of radiation induced acceptor on the transfer characteristic and transconductance. It can be seen that with acceptor concentration increasing, the transfer characteristic curves shift toward the increasing of V_{GS}, without obvious changes in slop and transconductance extreme value. This result also illustrates that the transconductance is only affected by carrier mobility, independent of threshold

voltage.

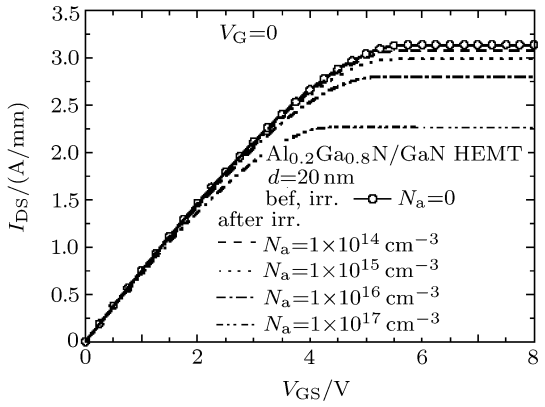


Fig.8. Effects of radiation induced acceptor concentration on the $Al_mGa_{1-m}N$/GaN HEMT output character, with $V_G = 0$.

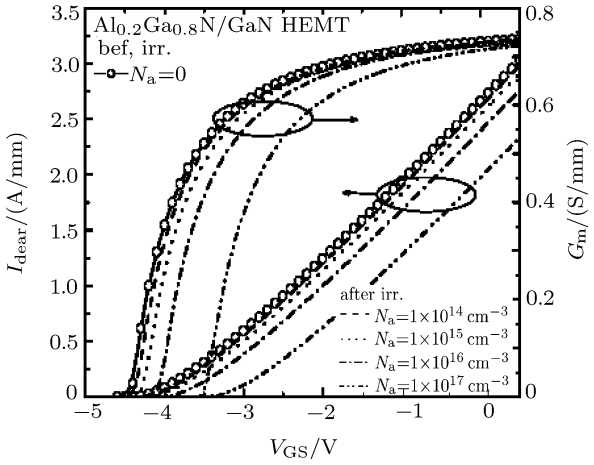


Fig.9. Effects of radiation induced acceptor concentration on $Al_mGa_{1-m}N$/GaN HEMT transfer characteristic and transconductance.

Concerning the long gate HEMT, the drain saturation current, of which the saturation is caused by drain pinch off, is generally given by the following expression:[9]

$$I_{d,sat} = \left(\frac{\beta}{2}\right)(V_g - V_{th} - V_0), \tag{10}$$

where $V_0 = I_{d,sat} \cdot R_s$ is the difference in voltage across the parasitic series resistances of source and drain nodes, and β is given as

$$\beta = (W/L) \cdot \frac{\mu_0 \cdot \varepsilon_{GaN}}{(d_d + d_i + \Delta d)}, \tag{11}$$

where μ_0 is the carrier mobility in GaN channel under low electrical fields, ε_{GaN} and $(d_d + d_i)$ are the dielectric constant of GaN and the doping AlGaN thickness respectively, Δd is the correction term including the variation of Fermi energy level with 2DEG concentration in the interface of AlGaN/GaN,[10] and W/L is the width/length ratio of the device gate.

Expressions (10) and (11) evidently show that the variation of radiation induced drain current is governed by the combination of threshold voltage, channel mobility, parasitic series source and drain resistances, in other words, the radiation can cause not only the saturation current to decrease, but also the linear drain current to reduce in output characteristic, which is the effect related to threshold shift, mobility decrease, parasitic series source and drain resistance increase, and these changes shall be embodied in the curve translation and slope fall in the transfer characteristic, as well as in the transconductance decrease. Consequently, compared with the case where the I–V characteristic variation is caused only by the threshold voltage shift, it can be expected that the linear drain current decrease, the slope fall in the transfer characteristic curve and the transconductance decrease are mainly due to the decrease in mobility and the increase in parasitic series source and drain resistance induced by radiation, and those micro-variations are related to the increase of the radiation induced interface state charge.

Te the model of radiation induced acceptor effect is primarily based on the threshold voltage shift, and it does not involve the mobility degradation effect. However, as one of the primary radiation effects, the radiation degradation of threshold voltage involves contributions of almost primary radiation mechanisms, such as the radiation induced interface state charge , the polarization charge variation and radiation-induced deep level. Hence by using this degraded model, many of the main radiation effects can be simulated and analysed.

4. Summary

In summary, we have constructed a degradation model of radiation induced acceptor defects for GaN-based HEMTs, which regards the introduced effective acceptor defect as the radiation effect. The calculated results show that with the increase in induced acceptor defect concentration, the threshold shifts toward the increasing of V_{GS}, and it becomes more prominent at a higher acceptor concentration. This result is consistent with the experimental result of threshold voltage variation of AlGaN/GaN HEMT after being irradiated, which confirms that this degradation model we have adopted here are reasonable. The calculated

results also show that the increase in AlGaN/GaN HEMT threshold voltage is primarily due to the acceptor defect introduced into the GaN channel.

Using this model, we investigate the effects of acceptor defect on threshold voltage shift, for different device structure sizes, Al compositions and modulation doping concentrations. The results show that thin barrier layer, high Al composition and doping concentration could help to restrain the effect of radiation induced acceptor defects on threshold voltage. Meanwhile, according to the threshold voltage shift, the I–V characteristics show that radiation induced acceptor defects can result in the degradation of drain saturation current.

Analysis indicates that this model of radiation induced acceptor effect is able to reflect many main radiation effects on AlGaN/GaN HEMT devices.

References

[1] Fang Z Q, Hemsky J W, Look D C and Mack M P 1998 *Appl. Phys. Lett.* **72** 448

[2] Look D C, Reynolds D C, Hemsky J W, Sizelove J R, Jonrs R L and Molnar R J 1997 *Phys. Rev. Lett.* **79** 2273

[3] Goodman S A, Auret F D, Koschnick F K, Spaeth J M, Beaumont B and Gibart P 1999 *MRS Internet J. Nitride Semicond. Res.* 4S1, G6.12–15

[4] Krantz R J and Bloss W L 1989 *IEEE Trans. on Electron Devices* **36** 451

[5] Muri Annul Review Vanderblit University Nashvile, TN, October 10-11, 2000 Eicke Weber University of California, Berkeley (http://jaspers.vuse.vanderbilt.edu/muri/presentations/October_10-11_00/EickeWeber.PDF).

[6] Krantz R J, Bloss W L and O'Loughlin M J 1988 *IEEE Trans. on Nucl. Sci.* **35** 1438

[7] Jun B, Subramanian S and Peczalski A 2001 *IEEE Trans. on Nucl. Sci.* **48** 2250

[8] Nawaz M and Jensen G U 1997 *Solid State Electron.* **41** 851

[9] Delagebeadeuf D and Linh N T 1982 *IEEE Trans. on Electron Devices* **ED 29** 955

[10] Lee K, Shur M S, Drummond T J and Morkoc H 1983 *IEEE Trans. Electron Devices* **ED-30** 207