Kink effect in current–voltage characteristics of a GaN-based high electron mobility transistor with an AlGaN back barrier*

Ma Xiao-Hua(马晓华)[a)b)†], Lü Min(吕 敏)[a)b)], Pang Lei(庞 磊)[c)], Jiang Yuan-Qi(姜元祺)[a)b)], Yang Jing-Zhi(杨靖治)[a)b)], Chen Wei-Wei(陈伟伟)[a)b)], and Liu Xin-Yu(刘新宇)[c)]

[a)] *School of Advanced Materials and Nanotechnology, Xidian University, Xi'an* 710071, *China*

[b)] *Key Laboratory for Wide Band-Gap Semiconductor Materials and Devices, School of Microelectronics, Xidian University, Xi'an* 710071, *China*

[c)] *Key Laboratory of Microelectronics Device & Integrated Technology, Institute of Microelectronics, Chinese Academy of Sciences, Beijing* 100029, *China*

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The kink effect in current–voltage (IV) characteristic s seriously deteriorates the performance of a GaN-based HEMT. Based on a series of direct current (DC) IV measurements in a GaN-based HEMT with an AlGaN back barrier, a possible mechanism with electron-trapping and detrapping processes is proposed. Kink-related deep levels are activated by a high drain source voltage (V_{ds}) and located in a GaN channel layer. Both electron trapping and detrapping processes are accomplished with the help of hot electrons from the channel by impact ionization. Moreover, the mechanism is verified by two other DC IV measurements and a model with an expression of the kink current.

Keywords: kink effect, deep levels, hot electrons, GaN-based HEMT

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1. Introduction

The GaN-based high electron mobility transistor (HEMT) has attracted worldwide attention due to its high-power application at high frequencies and such excellent properties as wide bandgap, high electron mobility, large electron saturation velocity and high breakdown voltage.[1–4] Although material growth and processing techniques have been greatly improved, the presence of inevitable traps results in current collapse, which reduces power densities and limits the performance of GaN-based devices.[5,6] The kink effect, an anomalous increase in the drain current at a relatively low drain source voltage (V_{ds}), is also a trap-related phenomenon which causes quite a serious current collapse.

Kink effects have been successfully reported in various kinds of semiconductor transistors, such as Si MOSFETs,[7] GaAs MESFETs,[8,9] AlGaAs/InGaAs HEMTs,[10] and InAlAs/InGaAs HEMTs.[11–13] The mechanisms of those kink effects are classified from three viewpoints and have been clearly summarized in Ref. [10]. They are 1) channel impact-ionization and subsequent hole accumulation, leading to change of surface or channel/substrate interface potential;[9,12,14] 2) field-dependent trapping/detrapping in deep levels;[15] 3) a combined effect of impact ionization and deep levels, thereby generating holes and modifying the occupation state of the surface, and the bulk or channel/substrate interface deep levels.[16]

The kink effect has also been discovered in GaN-based HEMTs.[17–22] Considering the large energy gap of GaN and the relatively low V_{ds} at which the kink effect occurs, the possibility of hole creation by band-to-band impact-ionization should be less likely. Thus in GaN-based HEMTs, deep levels are responsible for the kink effect in general.[17–21] Binari *et al.*[17] presented evidence that the occurrence of the kink effect was almost surface-state-independent by comparing the measured drain characteristics before and after SiN passivation. The kink effect can be assumed to be a signature of deep levels located in a GaN buffer layer.[17–21] Deep levels were negatively charged as a result of trapped electrons. The hot electrons removed the trapped electrons by impact ionization.[18–20] In this way, charges in deep-level traps can be modulated and the kink effect may occur.

However, the existing mechanisms cannot fully explain some of the previously investigated key kink-related phenomena of the GaN-based HEMT. In this paper, according to a series of DC current–voltage (IV) measurements, we expand our analysis and propose a novel and reasonable mechanism with electron-trapping and detrapping processes. What is different from the existing mechanisms is that both electron trapping and electron detrapping are accomplished with the involvement of hot electrons through impact ionization.

2. Device structure and fabrication

The GaN-based HEMT device employed in this work was grown on a semi-insulating 4H–SiC substrate as shown in Fig. 1. The epitaxial structure, including a 1-nm AlN nucleation layer, a 1-μm GaN buffer layer, a 1-μm $Al_{0.02}Ga_{0.98}N$ back barrier layer, a 150-nm GaN channel layer, 1-nm AlN

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†Corresponding author. E-mail: xhma@xidian.edu.cn

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interlayer, a 23.5-μm $Al_{0.224}Ga_{0.776}N$ barrier layer, and 2-nm GaN cap layer, is grown by metal–organic chemical vapor deposition (MOCVD). Ohmic contacts were formed by depositing the metals Ti/Al/Ni/Au (200 Å/1800 Å/550 Å/450 Å) followed by rapid thermal annealing at 870 °C for 50 s in a nitrogen atmosphere, resulting in a low Ohmic contact resistivity of 2×10^{-6} Ω·cm. After ion implantation, Si_3N_4 film used for passivation was grown by plasma enhanced chemical vapor deposition (PECVD), and a gate recess was etched by using a fluorine-based, and subsequent chlorine-based, inductively coupled plasma process. Then Ni/Au (400 Å/5000 Å) metals were evaporated for the T-shaped Schottky gate metallization. The gate length and width of the device are 0.25 μm and 1000 μm (100 μm×10), respectively.

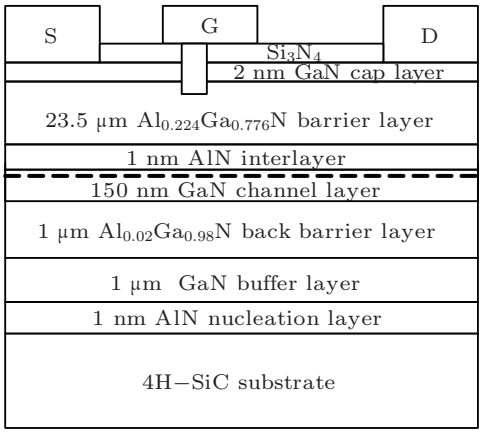


Fig. 1. Cross section of the GaN-based HEMT with AlGaN back barrier layer.

3. Experiments and discussion

DC current–voltage (IV) measurements below are carried out by an HP4142 parameter analyzer at room temperature.

In Fig. 2, four sets of DC IV output characteristics are shown for the same device. In order to guarantee that the subsequent measurements are not affected by the previous one, the interval between every two sets of sequential measurements is set at 2 hours. When $V_{ds,max}$ is restricted to 10 V, the kink effect does not occur, as shown in the dashed lines. The output characteristics indicated by the dotted lines are for $V_{ds,max}$ restricted to 20 V, and the kink effect is obvious. The higher the $V_{ds,max}$, the more remarkable the kink effect. So it can be concluded that the occurrence of the kink effect is strongly related to $V_{ds,max}$.

Figure 3 shows two sets of two identical consecutive measurements. The interval between the two sets of measurements is 2 hours. As shown with solid lines, the first sweep (curve 1) is under the same bias condition as the second sweep (curve 2) and the device is in an open state. It is observed that the kink effect does not appear in curve 1, but it does in curve 2. Thus it implies that after the open device is stressed by the prior DC IV sweep with a high enough $V_{ds,max}$, the kink effect will occur in the subsequent one. Moreover, after the device in pinch-off state is driven by high V_{ds}, the kink effect also appears in the subsequent sweep ($V_{gs} = -2$ V) as shown by the lines with symbols. It can be concluded that whether the kink effect occurs is unrelated to whether the device is in an on-state or pinch-off state in the first sweep. However, a comparison between the two sets of two consecutive measurements suggests that the magnitude of the kink effect appearing in the subsequent sweep is larger if the device is in an on-state in the prior sweep. It implies that the high drain voltage has a greater influence on the kink effect than the high drain current, which corresponds with the experiment results in Ref. [22].

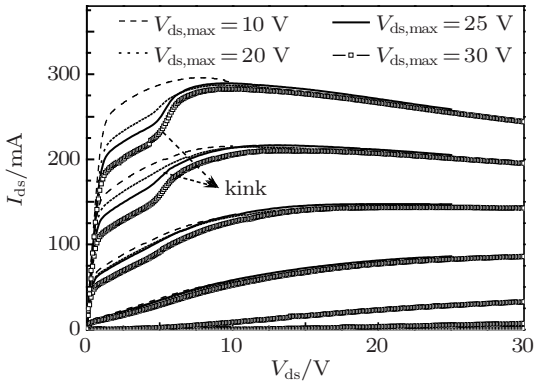


Fig. 2. DC IV output characteristics with different values of maximum drain bias ($V_{ds,max}$). The value of V_{gs} is from −3.75 V to −2 V in steps of 0.25 V and of V_{ds} is from 0 V to $V_{ds,max}$ in steps of 0.1 V.

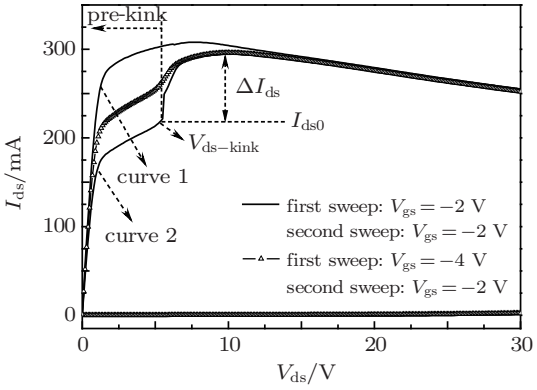


Fig. 3. Comparison between two consecutive measurements for two different first sweeps.

Here we define the drain source voltage at which the kink effect starts to appear as $V_{ds-kink}$, and then we know that $V_{ds-kink}$ of our device is about 6 V from Figs. 2 and 3. The region of $V_{ds} < V_{ds-kink}$ is defined as the pre-kink region, where I_{ds} is much lower than one without the kink effect, as shown in Fig. 3. Furthermore, under higher V_{ds} and higher V_{gs}, the kink effect is more obvious, as displayed in Fig. 2.

A novel mechanism will be presented to reasonably explain the kink-related phenomena above.

The kink is widely known as a trap-related effect. The trap may exist anywhere in the device. There are many surface states in the surface between the gate and drain space: interface states between every two layers, and traps in the AlGaN barrier layer, the GaN buffer layer, etc.[23] Meneghesso G *et al.*[18] demonstrated that traps which contributed to the kink effect probably existed in the GaN buffer layer by investigating the correlation between the kink effect and cathodoluminescence spectra in AlGaN/GaN HEMTs. Based on this discovery, a complete electron-trapping and detrapping mechanism is proposed as shown in Fig. 4. However, in the device investigated in this paper, kink-related deep levels are considered to be located in the GaN channel layer.

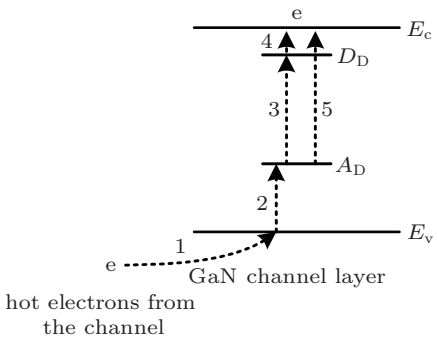


Fig. 4. Electron-trapping and detrapping mechanism of deep levels in GaN channel layer.

To the best of our knowledge, there is a shallow quantum well (called temporarily "back well") at the $Al_{0.02}Ga_{0.98}N$/GaN interface towards the SiC substrate. If a hot electron in the top channel (along the AlN/GaN) is pushed into the back well, it will spend more time and energy returning to the channel. But in general conditions it is difficult to inject the electron into the back well because of a back barrier.[24] Thus it is difficult for hot electrons to be transported beyond the back well and to be pushed into traps in the AlGaN back barrier layer or GaN buffer layer. So the kink effect is attributed to deep levels in the GaN channel layer (150 nm) in the GaN-based HEMT with an AlGaN back barrier. This is not the case in conventional GaN-based HEMTs. Kink-related traps in conventional GaN-based HEMTs with no back barrier are known in the GaN buffer layer.[17–21] But what is common is that the deep levels are located in the GaN layer which is below the channel.

In the first sweep, traps in the GaN channel layer are activated when $V_{ds,max}$ is high enough. Then, a subsequent sweep is conducted with V_{ds} ranging from 0 V to $V_{ds,max}$. The applied drain voltage, which results in a large lateral electric field, causes electrons in the channel to obtain energy and turn hot. For the energetic channel electron, it is possible to transfer to the valence band, and it is also likely to impact electrons in the valence band. If the energy of the hot electron from the channel is strong enough, it will activate the electron in the valence band to A_D above the valence band. Thus Steps 1 and 2 occur. With Steps 1 and 2, negative charges gradually accumulate in A_D, resulting in the decrease of the two-dimensional electron gas (2DEG) and reduction in I_{ds} in the subsequent DC IV sweep. So I_{ds} in curve 2 is lower than I_{ds} in curve 1 in the pre-kink region, as shown in Fig. 3. As V_{ds} increases, the electron obtains more energies from the electric field in the channel. With enough energy, it is possible for hot electrons to impact electrons in A_D and to activate them to D_D, as shown in Step 3. Then D_D releases the trapped electron, which is transferred to the conduction band, as shown in Step 4. There is also some probability that the electrons released by A_D will transfer to the conduction band directly, as shown in Step 5. The process of Step 3–Step 4 or Step 3 results in the removal of the negative charges accumulated in A_D. As a consequence, 2DEG and I_{ds} start to increase rapidly and the kink effect occurs.

Therefore it can be concluded that the kink effect is related to both V_{ds} of the prior sweep and V_{gs} of the subsequent sweep. The number of deep levels generated in the GaN channel layer is associated with V_{ds} of the prior sweep and the number of electrons activated from the valence band to A_D is related to V_{gs} of the subsequent sweep. This is exactly the reason for the more remarkable kink effect under higher V_{ds} and higher V_{gs}, as shown in Fig. 2.

According to the mechanism we presented above, in the first sweep (such as curve 1 in Fig. 3) the deep levels should already have been generated. However, the kink effect does not occur. This is due to the fact that, in the first sweep, the deep levels which lead to the kink effect are generated at high V_{ds}, and then electrons in the channel can obtain a great deal of energy from the large electric field in a very short time. As a result, the whole electron-trapping and detrapping process will take place quickly with the help of the hot electrons from the channel by impact ionization. In this case, negative charges cannot be accumulated in A_D or D_D. As a consequence, the kink effect cannot appear in the first sweep, even though deep levels have already been activated under high V_{ds}.

In order to verify the mechanism presented above, two further measurements are taken as follows. In Fig. 5, the DC IV curves are obtained from three sets of two consecutive measurements (measurements A, B, and C). The interval between every two sequential measurements is set at 2 hours. In the three measurements, the values of V_{gs} in the first sweeps are all -2 V and the values of V_{gs} in the second sweeps are -2.5 V, -2.25 V, and -2 V. As shown in Fig. 2, the kink effect does not occur when $V_{ds,max}$ is restricted to 10 V. However, after the device is stressed by the prior sweeps with high V_{ds} ($V_{ds,max} = 30$ V), the kink effect appears in the DC IV curves with $V_{ds,max} = 10$ V, as figure 5 shows. According to

the mechanism, the prior sweep with $V_{ds,max} = 30$ V leads to the generation of deep levels, which result in the occurrence of the electron-trapping and detrapping process in the subsequent sweep with $V_{ds,max} = 10$ V. The results correspond with the mechanism proposed in this paper.

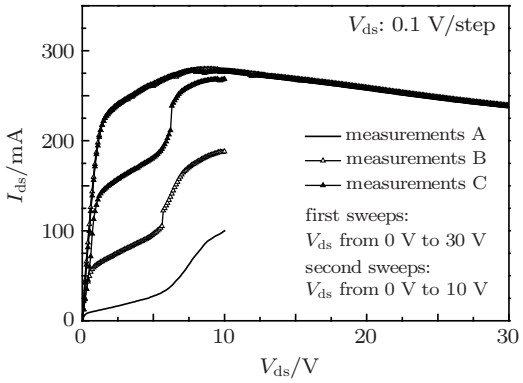


Fig. 5. DC IV output characteristics (I_{ds} versus V_{ds}) obtained from three measurements.

Figure 6 shows three sets of DC IV output characteristics. V_{ds} is swept from different values of minimum drain voltage ($V_{ds,min}$) to 30 V. The $V_{ds,min}$ of curve C is 2 V which is lower than $V_{ds-kink}$, and $V_{ds,min}$ of curve A is 7 V which is higher than $V_{ds-kink}$. The kink effect in curve C is obvious. If charge carrier trapping in deep levels can occur without the help of hot electrons by impact ionization,[18–20] the kink-related current collapse should also occur in curve A, of which $V_{ds,min}$ is high. However, the measurement result obtained is in exact opposition to this, and the kink effect does not appear. According to the mechanism proposed in this paper, this is mainly due to the fact that the applied minimum drain voltage is high enough to make the whole electron-trapping and detrapping processes occur almost at the same time with the involvement of hot electrons which impact electrons in the valence band or deep levels. As a consequence, negative charges cannot accumulate in A_D and D_D, and I_{ds} does not decrease in spite of the existence of deep levels.

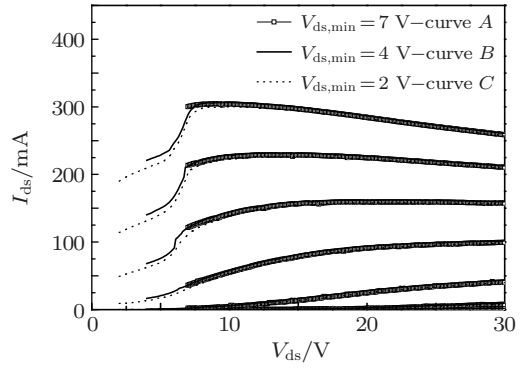


Fig. 6. DC IV output characteristics with different values of minimum drain bias $V_{ds,min}$. The value of V_{gs} is from −3.5 V to −2 V in steps of 0.25 V and V_{ds} is from $V_{ds,min}$ to 30 V in steps of 0.1 V.

A model with an expression of the kink current ΔI_{ds} versus V_{ds} (Eq. (1))[25] is used to demonstrate the consistency of the mechanism with previously observed kink-related behaviors. The expression is as follows:

$$\Delta I_{ds} = g_{m0}\frac{K_B T}{q}\ln\left[1 + AI_{ds}\exp\left(\frac{-B}{V_{ds} - V_{ds-kink}}\right)\right], \quad (1)$$

where A and B are the fitting parameters, can also be determined by

$$\Delta I_{ds} = I_{ds} - I_{ds0}, \quad (2)$$

with I_{ds0} being defined as I_{ds} at the point of minimum output conductance in pre-kink region. The kink current ΔI_{ds} increases exactly with the increase in I_{ds} over its "pre-kink" value I_{ds0} as shown in Fig. 3.

Four sets of two consecutive measurements (#1, #2, #3, and #4) are performed. The V_{ds} is swept from 0 V to $V_{ds,max}$ and V_{gs} is at a fixed-bias point in both the first and second sweeps. The interval between every two sets of sequential measurements is 2 hours. Table 2 shows the detailed sweeping conditions. In Applied Design System (ADS) software, adjust the fitting parameters A and B until I_{ds} extracted from the model fits I_{ds} obtained from the second sweep. The obtained values of A and B are shown in Table 1.

A comparison between #1 and #2 indicates that both A and B are highly related to V_{gs} of the first sweep. Moreover, it is obvious that the two fitting parameters are V_{gs} of the second sweep and $V_{ds,max}$ of the first sweep by comparing #3 with #2 and #4. Thus the kink current ΔI_{ds}, which represents the magnitude of the kink effect, is associated with V_{gs} and V_{ds} of both the first and second sweep. These are consistent with the previously proposed mechanism and observed kink behaviors.

Table 1. Sweeping conditions and fitting parameters.

	First sweep		Second sweep		Fitting parameter	
	$V_{ds,max}$	V_{gs}	$V_{ds,max}$	V_{gs}	A	B
#1	30	–4	30	–2	0.0278	1.10
#2	30	0	30	–2	0.0448	0.80
#3	30	0	30	–1	0.1440	0.74
#4	10	0	30	–1	0	–

4. Conclusions

GaN-based HEMTs display more and more advantages in both high power and high frequency. However, kink effect, a serious current collapse, is one of the trickiest issues which hinder the application and development of the GaN-based HEMT. In our research, based on a series of DC IV measurements, a novel mechanism with electron trapping and detrapping processes is proposed. Both electron trapping and electron detrapping are accomplished with the involvement of

hot electrons from the channel by impact ionization. We suggest that kink-related deep levels in the GaN-based HEMT with an AlGaN back barrier should be located in the GaN channel layer. According to the mechanism, the kink effect occurs at relatively low V_{ds} in the subsequent DV IV sweep only when $V_{ds,max}$ of the prior sweep is high enough. The number of deep levels is related to V_{ds} of the prior sweep, and the number of electrons activated from the valence band to deep levels is associated with V_{gs} of the subsequent sweep. Under higher V_{ds} and higher V_{gs}, the kink effect is more remarkable. These are highly consistent with the measurement results, which makes it meaningful for the mechanism to predict DC performance of GaN-based HEMTs.

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