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Numerical Explanation of Slow Transients in an AlGaN/GaN HEMT*

Zhang Jinfeng† and Hao Yue

(Key Laboratory of the Ministry of Education for Wide Band-Gap Semiconductor Materials and Devices, Microelectronics Institute, Xidian University, Xi'an 710071, China)

Abstract: A series of slow drain current recovery transients at different gate biases after a short-term stress are observed in an AlGaN/GaN HEMT. As the variation of the time constants of the transients is small, the working trap is determined to be electronic. A numerical simulation verifies this conclusion and reproduces the measured transients. The electron traps at different spatial positions in the device-on the ungated surface of the AlGaN layer, in the AlGaN barrier, and in the GaN layer are considered; corresponding behaviors in the stress and the transients are discussed; and for the simulated transients, agreement with and deviation from the measured transients are explained. Based on this discussion, we suggest that the measured transients are caused by the combined effects of a deep surface trap and a bulk trap in the GaN layer.

Key words: AlGaN/GaN HEMT; slow transients; virtual gate; surface trap; bulk trap
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1 Introduction

Current collapse (CC) phenomena limit the application of AlGaN/GaN high electron mobility transistors (HEMT). It has been shown that their slow transients are directly related to CC effects[1,2]. The theoretical explanation of such slow transients is generally based on the trap effects in the access region of the device surfaces. The suppression or even elimination of CC effects and slow transients by passivation have been widely observed and strongly support the surface trap model. Klein et al.[3] suggested that the bulk trap in the GaN buffer layer may also cause CC effects in GaN MESFETs. Thus the slowness of the transients may be the result of bulk traps.

In this paper, according to a series of slow drain current recovery transients measured after a short-term stress in an AlGaN/GaN HEMT, we determine that the working trap is electronic. Based on this finding, an effort is made to reproduce the measured transients by numerical simulation. The electron traps at the ungated surface of the AlGaN layer, in the AlGaN barrier, and in the GaN layer are considered, and corresponding simulated transients and behaviors are discussed.

2 Principles for judging the trap properties

The rate equation for trap charging is expressed in Shockley-Read-Hall statistics as follows (in the form of electron traps)[4].

$$\frac{dF_n}{dt} = -n_1 C_n F_n + nC_n(1-F_n) + p_1 C_p(1-F_n) - pC_p F_n \qquad (1)$$

The four terms on the right correspond to electron emission, electron capture, hole emission, and hole capture, respectively. F_n is the trap occupancy factor, and C_n is the electron capture coefficient. $C_n = \sigma_n v_n$, where σ_n is a capture cross section and v_n is the electron thermal velocity. n is the free electron density, and n_1 is a constant defined by the trap energy level. The quantities for the hole terms carry analogous meanings.

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† Corresponding author. Email: jfzhang@xidian.edu.cn

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According to the above trap rate equation, the capture rate for a trap ($C_n n$) is proportional to the free carrier density, and the emission rate ($C_n n_1$) is always constant. This means that when the overall behavior of a trap is capturing (releasing) carriers, the time constants of the resulting transients are variable (constant). Therefore, similar transients with different biases are good indicators of trap behavior. The transient simulations of an AlGaAs-GaAs HJFET with electron traps illustrate this fact in Ref. [5].

In the drain current recovery (collapse) transients of an AlGaN/GaN HEMT, the electron traps release (capture) electrons, while the hole traps capture (release) holes. So the trap property can be determined from the dependence of the time constants of drain current transients on the bias conditions.

3 Measured transients

The structure of the measured device is shown in Fig. 1. The heterostructure is grown in our laboratory, and the room-temperature Hall effect shows that its two-dimensional electron gas (2DEG) density and mobility are $1.1\times10^{13}cm^{-2}$ and $949cm^2/(V\cdot s)$, respectively. The device was processed in the No. 13 Research Institute of the China Electronics Technology Group Corporation.

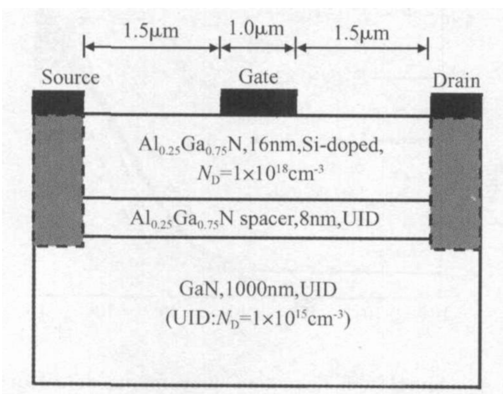

Fig. 1 Device structure The gray regions are taken to be GaN in the simulation.

The measured drain current transients at $V_d = 1V$ under different V_g are shown in Fig. 2. The transients are obtained immediately after a 10s stress of $V_d = 10V$ and $V_g = -4V$. Accompanied by a very large gate current, the curve at $V_g = 1V$ is quite different from the other curves, which are almost parallel to each other. The average distance between two adjacent curves increases as V_g decreases.

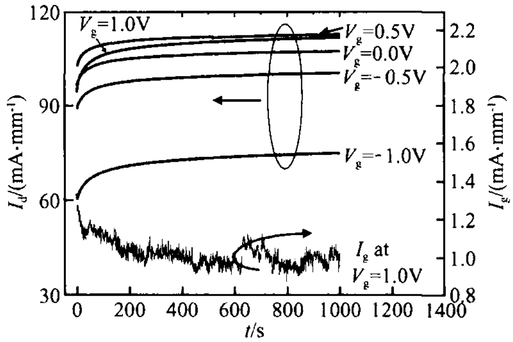

Fig. 2 Measured drain current transients at $V_d = 1V$ under different V_g The gate current at $V_g = 1V$ is also shown.

We take a fitting procedure for these transients similar to that described in Ref. [6], or

$$I_d(t) = \Delta I_{d,fast} + \Delta I_{d,slow}(t)$$
$$\Delta I_{d,slow}(t) = I_{on}(1 - \exp(-(t/\tau_{on})^{\beta})) \quad (2)$$

The time constant τ_{on} and stretching parameter β are listed in Table 1. For $V_d = 1V$, the fitting parameter values for the source current transient are also shown in Table 1 to account for the influence of the gate current. It can be seen that the time constants show a very weak reduction with the increase of gate bias. Meanwhile the time constants of the drain-on transients of the same device change significantly with V_d. Therefore the traps causing the above transients are electron traps.

Table 1 Time constant τ_{on} and stretching parameter β of drain current transients For $V_g = 1V$, the source current transient is also fitted, and the fitting parameter values are shown in parentheses.

V_g/V	1	0.5	0	-0.5	-1
τ_{on}/s	94.03(82.65)	86.56	100.71	117.24	171.19
β	0.47(0.43)	0.52	0.52	0.56	0.67

4 Numerical simulation

To verify our finding, two-dimensional drift-diffusion simulations of the AlGaN/GaN HEMT were carried out using the code ATLAS-SILVACO[7]. We used the nominal values of thickness and doping for all layers (see Fig. 1). To avoid the contact resistance problem at the heterostructure, we extend the GaN layer to the source and drain electrodes through the AlGaN layer (shown in

Fig. 1 as the gray regions). The thermionic model is used for the gate. The material parameters used for the nitrides involved are taken from the built-in libraries of ATLAS[7]. A 5nm thick channel layer with a low field mobility of $1100cm^2/(V\cdot s)$ is defined under the AlGaN/GaN hetero-interface to account for the 2DEG properties. Trapping effects are modeled in the simulator by supplementing the semiconductor transport equations with the Shockley-Read-Hall trap rate equation and by including the contribution of traps to the space-charge density and to the time change of electron and hole densities into the Poisson and carrier-continuity equations, respectively. Simulations were carried out assuming $T = 300K$.

Since the positions of the traps in the device are unknown, three possibilities are considered: on the ungated surface of the AlGaN layer (surface trap), in the AlGaN barrier (AlGaN bulk trap), and in the GaN layer (GaN bulk trap). All traps are defined to be acceptor traps. The polar charge definition for each situation is made combining the transfer characteristics as follows.

Figure 3 shows the measured transfer characteristic curves (thick solid lines). The absolute value of the threshold voltage $|V_{th}|$ is small. In an AlGaN/GaN HEMT, $|V_{th}|$ depends on the Schottky barrier height of the gate, the material, the doping and thickness of the barrier layer, the conduction band offset, and the polar charge at the AlGaN/GaN heterointerface. All these factors are easily determined except for the polar charge, which depends on the strain relaxation. So in the simulation the polar charge at the AlGaN/GaN heterointerface (σ_{pol2}) is adjusted to give a reasonable $|V_{th}|$, and the polar charge at the AlGaN surface (σ_{pol1}) is adjusted to give a reasonable surface potential. The polar charge definition and the calculated transfer characteristics for each trap model are also shown in Fig. 3.

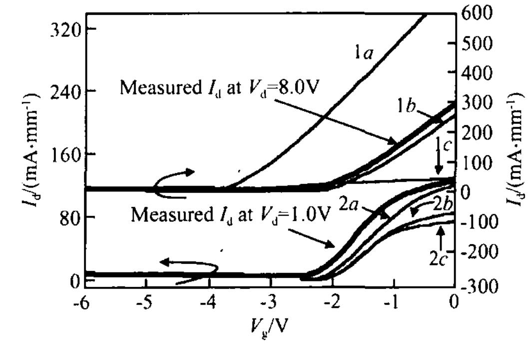

Fig. 3 Measured and simulated transfer characteristics The thick solid lines are measured curves, and the other curves are simulated ones. Traps are only added in the device for simulation of curves 2a (surface trap); 2b (AlGaN bulk trap) and 2c (GaN bulk trap). The polar charges at the AlGaN surface (σ_{pol1}) and at the AlGaN/GaN heterointerface (σ_{pol2}) are defined for the simulations as 1a: $\sigma_{pol1} = 0$, $\sigma_{pol2} = 8.86\times10^{12}cm^{-2}$; 1b, 2a: $\sigma_{pol1} = 0$, $\sigma_{pol2} = 4.8\times10^{12}cm^{-2}$; 1c: $\sigma_{pol1} = \sigma_{pol2} = 8.86\times10^{12}cm^{-2}$; 2b: $\sigma_{pol1} = 3.0\times10^{12}cm^{-2}$, $\sigma_{pol2} = 4.8\times10^{12}cm^{-2}$; 2c: $\sigma_{pol1} = 3.75\times10^{12}cm^{-2}$, $\sigma_{pol2} = 7.0\times10^{12}cm^{-2}$

4.1 Surface trap

It is assumed that the surface traps are uniformly distributed within 1nm under the surface over the ungated gate-source and gate-drain regions. The trap density is $N_T = 4.8\times10^{12}cm^{-2}$, and the capture cross section is $\sigma_n = 1\times10^{-14}cm^2$. We first investigate how the trap energy influences the transients; the simulation results of the transient at $V_g = 0V$ are shown in Fig. 4. When $E_c - E_T$ is larger, the transient is slower. Fitting the simulation curves in Fig. 4 by Eq. (2), and letting $E_c - E_T = 0.835eV$, we find $\tau_{on} = 98.34s$, which agrees well with the measured value. So the trap energy is set at 0.835eV below the conduction band for the surface trap model.

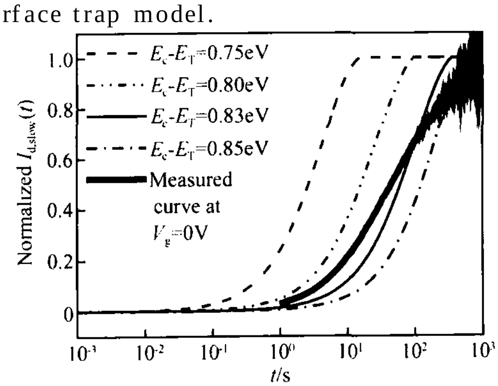

Fig. 4 Simulated $I_{d,slow}(t)$ waveforms at different trap energy levels

To show the trap behavior in the transients, the transient simulations are carried out for the whole measurement process, which includes three stages. The first is a 10s stress of $V_d = 10V$ and $V_g = -4V$, the second is a transition interval from stress to transient measurement, a zero bias state about 2s long, and the third is a 1000s transient at

$V_d = 1V$.

During the stress, the change of the trap occupancy factor F_n with time at the surface is shown in Fig. 5(a). In this stage there is no significant current in the channel, and the trap captures electrons. Since the Schottky barrier height of the gate is not high (about 0.3eV, determined from the I-V curve of gate-drain diode), the electron density n is higher under the gate than that at the ungated surface (less than $10^5 cm^{-3}$). We find in the simulation that for the AlGaN/ GaN heterostructure under the gate when the gate is negatively biased, the electronic quasi-Fermi level is not level, but is bent with the conduction band in the AlGaN layer. In the deep depletion state of $V_g = -4V$, though the peak electron density in the channel is greatly reduced to about $10^{16} cm^{-3}$, the electron density in the whole AlGaN layer under the gate is almost constant and not very low (about $10^{14} cm^{-3}$). As a result, n is higher under the gate than that at the ungated surface. Thus the trap captures more electrons near the gate, thereby changing F_n more.

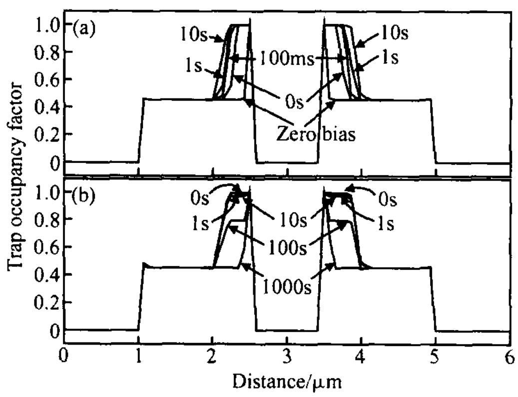

Fig. 5　Change of the trap occupancy factor F_n with time at the surface in the stress (a) and in the slow transient (b)　The time reference is the moment immediately after the respective rise edge, and zero bias means the stable state.

In the interval, the trap state tends to recover to that before the stress, but the time is too short and there is almost no change.

In the slow transient, the trap state transits to the stable state of $V_d = 1V$, and the trapped electrons are released steadily. Figure 5(b) shows the change of F_n. In this current transient the applied bias is constant so the recovery of the current is mainly caused by the change of the channel electron density, which results from not only the release of electrons from the trap but also the recovery of the drift regions depleted by the virtual gates formed by the negatively charged trap. The virtual gate effect is shown more clearly in the transients at different V_g, for which the simulated curves are shown in Fig. 6.

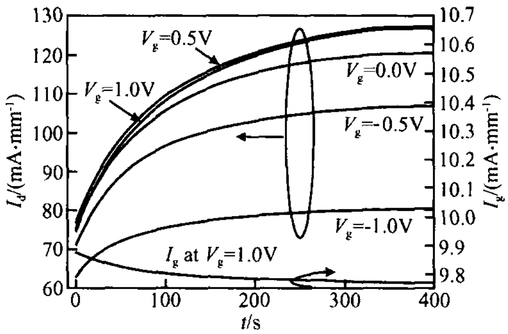

Fig. 6　Simulated transient curves at different V_g

Comparing Fig. 6. and Fig. 2, an obvious difference is that the simulated curves are not parallel but closer at the start of the transients. As for the change of the average distance between two adjacent curves with V_g and the specific curve at $V_g = 1V$ with its gate current, the simulated curves reproduce them well.

Since the electron emission rate ($C_n n_1$) of the trap is independent of V_g, the nonparallel property could only be related to the virtual gate effect. Figure 7 shows the surface conduction band edge at different times for $V_g = 0.5V$ and $V_g = -1.0V$. The difference between the two bias states is small at 0s but increases over time. The negatively charged surface trap is in almost the same state immediately after the rise edge ($t = 0s$)

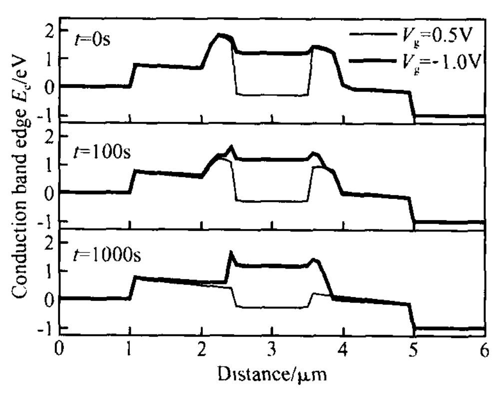

Fig. 7　Surface conduction band edge at different times for $V_g = 0.5V$ and $V_g = -1.0V$

for each transient, since the rise edge is too short (1ms used in simulation) compared to the time constant of the trap (~100s). The small difference of the drain currents at t = 0s in Fig. 6 reflects the weak control of the gate bias. In the transient, electrons are released constantly from the trap, the depletion of the virtual gates is weaker and the control of the gate bias is stronger. At the end of the transients, the virtual gates have almost disappeared and the final states at different gate biases are reached. So the nonparallel property of the transients results from a competition between the virtual gates and the real gate.

The drain current transient at $V_g = 1V$ with its gate current is also worth being mentioned. At the other gate bias the gate current is small. But at $V_g = 1V$, the gate is opened, the current is large and shows a falling transient. When the trap is releasing electrons, some of them go into the gate current, and the others go into the channel. As the virtual gate effect gets weaker, the lateral electric field driving the released electrons into the gate gets smaller, and thus the gate current is weakened and the channel current is recovered.

4.2 AlGaN bulk trap

The traps are assumed to be uniformly distributed within the AlGaN barrier layer with $N_T = 4.0 \times 10^{17} cm^{-3}$, $\sigma_n = 1 \times 10^{-14} cm^2$, and $E_c - E_T = 0.835eV$. A surface polar charge of $3.0 \times 10^{12} cm^{-2}$ is defined to keep the trap partially empty at zero bias. Figure 8 shows the simulated transients, which show similar characteristics to those of the

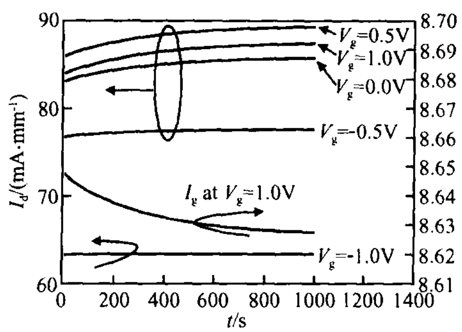

Fig. 8 Simulated transient curves at different V_g

surface trap model, but the relative change of the current magnitude is smaller. The smaller change is ascribed to the smaller trap density. At 5nm below the surface, the change of F_n during the stress and the transient at $V_g = 0V$ is shown in Fig. 9. The traps capture (release) electrons in a way is similar to the surface trap model, and changes mainly take place in the region under the source and drain edges of the gate.

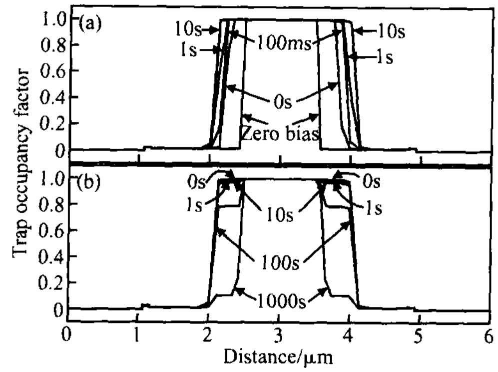

Fig. 9 Change of the trap occupancy factor F_n with time at 5nm below the surface in the stress (a) and in the slow transient (b)

4.3 GaN bulk trap

The traps are assumed to be uniformly distributed within the GaN layer, $N_T = 5.0 \times 10^{17} cm^{-3}$, $\sigma_n = 1 \times 10^{-14} cm^2$. The trap energy is set at 0.625eV below the conduction band and is also obtained by adjusting E_T to show a τ_{on} (123.97s) close to the measured value. Since the trap density influences the threshold voltage $|V_{th}|$, the polar charge definition is quite different from the above models. A surface polar charge of $3.75 \times 10^{12} cm^{-2}$ is defined so that $E_c - E_F = 1.53eV$ at the surface. A light p type doping of $1.0 \times 10^{15} cm^{-3}$ (same as the UID density) is added under the channel layer to keep the trap partially empty at zero bias.

Figure 10 shows the simulated transients. Unlike the surface trap model and the AlGaN bulk

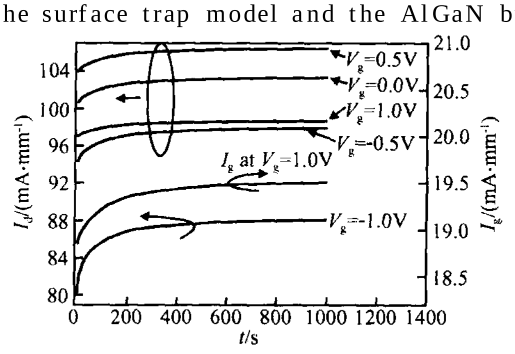

Fig. 10 Simulated transient curves at different V_g

trap, the curves are almost parallel, and the gate current at $V_g = 1V$ shows an increasing transient, so the gap between the drain current transient curves at V_g = 1V and V_g = 0.5V widens over time.

It is necessary to show the trap behavior in a single transient, for example at V_g = 0V. As the trap is in the GaN channel and buffer layers, the spatial complexity of the trap behavior should be noted. At the drain edge of the gate in the longitudinal direction, the change of F_n in the stress and in the transient at V_g = 0V is shown in Fig. 11. During the stress, the trap captures electrons. In the slow transient, the trap behavior is different at different depths. From the AlGaN/ GaN heterointerface to 10nm below it (34nm), the trap state shows no change as the electron density is very high and stable. From 34 to 48nm, the traps weakly release from t = 0s to t = 1s, and then capture for the rest of the transient. From 48 to 160nm, the traps release electrons the whole time. Below 160nm, the traps capture electrons from t = 0s to t = 100s, and then release them for the rest transient. No obvious change is observed below 220nm. In all these changes, the trap release process is relatively strong in magnitude and spatial range, so the overall trap behavior is release. A similar spatial complexity of the trap behavior is also observed at the other longitudinal profiles in the device, and the trap state change takes place mainly in the region under the drain edge of the gate.

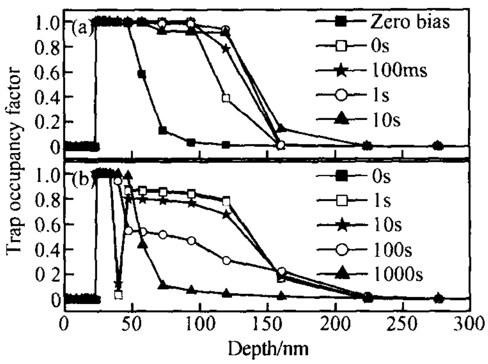

Fig. 11　Change of the trap occupancy factor F_n with time at drain edge of the gate in the stress (a) and in the slow transient (b)

The simulated transients at different V_g are almost parallel since the traps influence the channel electron density from below the channel, and the gate control is not affected. The gate current at V_g = 1V is a pure component of the channel current formed by thermionic emission, so its transient takes on a shape similar to that of the drain current transient.

5 Summary

A series of drain current recovery transients at different gate biases after a 10s high voltage stress are observed in an AlGaN/ GaN HEMT. The working trap is determined to be electronic, and an effort is made to explain the measured transients by numerical simulation. The electron traps at different positions in the device are considered, corresponding behaviors are discussed, and none of them can reproduce all the characteristics of the measured transients.

As the most significant deviation of the simulated transients from the measured one, the nonparallel property of the surface trap model is determined to be caused by competition of the virtual gates and the real gate, and the increasing transient of the gate current at V_g = 1V for the GaN trap model is similar to the drain current transient. Though it is not clear whether the nonparallel property is inherent in the surface trap model, it is observed in simulation that when $E_c - E_T$ is quite low so as to give a time constant comparable to the length of the rise edge, or is quite high so as to give a time constant much larger than 1000s, the 1000s transient would be almost parallel. It is also noted that the simulated transients of the GaN trap model show much smaller spans in the current magnitude than the measured ones in spite of quite a high trap density. So there is a possibility that the measured transients are caused by the combined effects of a deep surface trap and a bulk trap in the GaN layer with the latter's time constant shown in the measured transients. To verify this prediction, both longer transient measurements and trap characterization experiments should be done in future work.

There are still two problems to be solved. The first is that the time constants of the measured transients show a very weak reduction with the increase of gate bias. This seems abnormal. In the three trap models considered here, the time constants of the simulated transients show a weak increase as V_g increases. This can be explained as follows. The electron density is higher under the gate (the first two trap models) or in the channel

(GaN bulk trap model) when V_g increases, so the traps capture more electrons, the overall electron emission rates are reduced, and the transient is slower. The second is that there are two virtual gates that appear at the source and drain edge of the gate respectively in the simulation, and they are almost equally important. In the stress when the virtual gates are formed, $V_{gs} = -4V$ but $V_{gd} = 14V$, so the virtual gate effect should be much more serious between the gate and the drain. Both problems may result from some unknown mechanisms and need further consideration.

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AlGaN/GaN HEMT中慢瞬态的数值解释*

张金凤† 郝 跃

(西安电子科技大学微电子学院 宽禁带半导体材料与器件教育部重点实验室, 西安 710071)

摘要: 观察了 AlGaN/GaN HEMT 器件在短期应力后不同栅偏置下的一组漏极电流瞬态,发现瞬态的时间常数随栅偏压变化很小,据此判断这组瞬态由电子陷阱的释放引起.为了验证这个判断,采用数值仿真手段计算了上述瞬态.分别考虑了在器件中不同空间位置的电子陷阱,分析了应力和瞬态中相应的陷阱行为,对比和解释了仿真曲线与测量结果的异同.基于上述讨论,提出测量的瞬态可能是表面深陷阱和 GaN 层体陷阱的综合作用的结果.

关键词: AlGaN/GaN HEMT; 慢瞬态; 虚栅; 表面陷阱; 体陷阱

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† 通信作者. Email: jfzhang@xidian.edu.cn

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