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High-electric-field-stress-induced degradation of SiN passivated AlGaN/GaN high electron mobility transistors*

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AlGaN/GaN high electron mobility transistors (HEMTs) are fabricated by employing SiN passivation, this paper investigates the degradation due to the high-electric-field stress. After the stress, a recoverable degradation has been found, consisting of the decrease of saturation drain current $I_{\rm Dsat}$, maximal transconductance $g_{\rm m}$, and the positive shift of threshold voltage $V_{\rm TH}$ at high drain-source voltage $V_{\rm DS}$. The high-electric-field stress degrades the electric characteristics of AlGaN/GaN HEMTs because the high field increases the electron trapping at the surface and in AlGaN barrier layer. The SiN passivation of AlGaN/GaN HEMTs decreases the surface trapping and 2DEG depletion a little during the high-electric-field stress. After the hot carrier stress with $V_{\rm DS} = 20\,{\rm V}$ and $V_{\rm GS} = 0\,{\rm V}$ applied to the device for 10^4 sec, the SiN passivation decreases the stress-induced degradation of $I_{\rm Dsat}$ from 36% to 30%. Both on-state and pulse-state stresses produce comparative decrease of $I_{\rm Dsat}$, which shows that although the passivation is effective in suppressing electron trapping in surface states, it does not protect the device from high-electric-field degradation in nature. So passivation in conjunction with other technological solutions like cap layer, prepassivation surface treatments, or field-plate gate to weaken high-electric-field degradation should be adopted.

Keywords: AlGaN/GaN high electron mobility transistors, surface states, traps in AlGaN, passivation

PACC: 7320, 7280E, 7360L

1. Introduction

AlGaN/GaN HEMTs (high-electron-mobility transistors) may be promising for high-voltage switching applications due to wide bandgap, high critical field, high electron mobility, high saturation velocity and low intrinsic carrier generation.[1−4] The surface passivation is critical for AlGaN/GaN HEMT because the electron trapping at surface states depletes two-dimensional electron gas (2DEG) and induces the surface leakage current. AlGaN/GaN HEMTs are currently adopted for power microwave amplifiers, with very high drain-source voltage $V_{\rm DS}$. At these high bias levels, the electric stress should be applied to devices.[5,6] The high field during the switching operation increases the electron trapping at surface states and in AlGaN barrier layer of AlGaN/GaN HEMTs. All these effects demonstrate the presence of high energetic carriers and surface states which can trigger device degradation. Recently, the degradation of AlGaN/GaN HEMTs by electric stress and the reliability have been reported.[6−13] The applied stress to AlGaN/GaN HEMTs degrades the electric characteristics of devices such as the saturation drain current $I_{\rm Dsat}$, the maximal transconductance $g_{\rm m}$, and the threshold voltage $V_{\rm TH}$.[6,12,13] Moreover, Coffie *et al*[10] found that the electric stress increased the gate current. And the work of Joh *et al*[13] has showed that the electric stress not only increased the trapping of the intrinsical defects but also created the new traps in devices.

The purpose of our work is to report the effect of the high-electric-field stress on AlGaN/GaN HEMTs by employing SiN passivation. Indeed, a recoverable

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degradation has been found after different electrical stress. After the hot carrier stress with the drain bias $V_D = 20\,V$, the gate bias $V_G = 0\,V$ and the source bias $V_S = 0\,V$ are applied to AlGaN/GaN HEMTs for 10^4 sec, the I_{Dsat} of an unpassivated and passivated device decreases by 36% and 30% respectively. AlGaN/GaN HEMTs after SiN passivation exhibit less degradation due to the hot carrier stress because the SiN passivation layer suppresses the electron trapping at surface states and the depletion at 2DEG charge. And the direct current analyses under different stress conditions demonstrate that the degradation mechanism consists of the high field increasing the trapping at the surface and in AlGaN barrier layer.

2. Devices and experiments

AlGaN/GaN HEMTs studied in the present work were grown by metallorganic chemical vapour deposition developed by ourselves on (0001) sapphire substrates, and employed a 300 Å (1 Å = 0.1 nm) thick AlN buffer layer on sapphire substrates at 550 °C. Then 1.5 μm of undoped GaN was grown up to 1040 °C, as well as 230 Å thick $Al_{0.3}Ga_{0.7}N$ barrier layer. It was composed of 60 Å undoped $Al_{0.3}Ga_{0.7}N$, 100 Å doped $Al_{0.3}Ga_{0.7}N$ (Si concentration = $2 \times 10^{18}\,cm^{-3}$) and 70 Å undoped $Al_{0.3}Ga_{0.7}N$. The samples contain an additional 10 Å AlN interlayer located between the $Al_{0.3}Ga_{0.7}N$ barrier and GaN channel to reduce alloy scattering. The processing involved lift off of electron beam evaporated Ti/Al/Ni/Au (20 nm/120 nm /55 nm/45 nm) for Ohmic contacts or Ni/Au for Schottky gates. The Ohmic metallization was annealed under N_2 at 830 °C for 30 s. The gate lengths (L_g) were 1 μm, with gate width (W_g) of 25 μm. The 50 nm SiN passivation was performed by employing PECVD.

The direct current characteristics were measured at room temperature with an HP 4156B parameter analyser. First, the samples were stressed using the high-electric-field stress at $V_D = 20\,V$, and various fixed values of V_G (0, –10 V, pulse: (–10 V & 0 V), period = 10 ms). During the stress, the source was grounded ($V_S = 0\,V$). Then in order to investigate the origin of the electrons trapped in AlGaN barrier layer, we floated source and gate respectively, with $V_D = 20\,V$. $I_{DS} - V_{GS}$ and $I_{DS} - V_{DS}$ characteristics were measured before and after stresses. All transfer characteristics were measured at $V_{DS} = 5\,V$.

3. Results and discussion

When the high-electric-field stress is applied to AlGaN/GaN HEMTs, the channel is turned on and a high field exists in the gate-drain region. When the kinetic energy of electron which is accelerated by a high field is larger than the lattice thermal energy, the electrons are trapped in the surface states, interface states and AlGaN barrier.[6] Figure 1 is the schematic diagram of the degradation mechanism in AlGaN/GaN HEMTs under the high-electric-field stress.

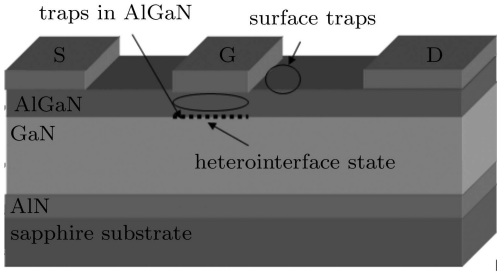


Fig.1. Schematic diagram of the degradation mechanism in AlGaN/GaN HEMTs under the high-electric-field stress.

Figure 2 shows the measured transfer (a), output (b) and off-state (c) characteristics of SiN passivated device before and after the hot carrier stress with $V_{DS} = 20\,V$ and $V_{GS} = 0\,V$. The period of the stress is 10^4 sec. After the stress, the transfer curves are shifted to a more positive direction and the degradation is more serious with the increased gate voltage. The I_{Dsat} decreases obviously by 30.92% (measured at $V_{DS} = 5\,V$, $V_{GS} = 1\,V$), the g_m decreases by 18.36%, while the V_{TH} is positively shifted by 9.3% after 10^4 sec stress. The change of a threshold voltage may be evidenced that the electrons are trapped in AlGaN near Schottky gate at both stress conditions. From Fig.2(b), we can find that the output characteristic degrades obviously. The higher the gate voltage is, the more degradation the devices have, and the primary change concentrates on the time before the drain current becomes saturated. The electric-field stress increases the resistance of the low electric-field region, and then decreases the drain current. With the increase of gate voltage, the channel is on, the resistance of the low electric-field region turns low, and the change of resistance induced by the high-electric-field stress increases, and then more obvious degradation of the drain current is resulted in. However, when the drain voltage is higher, the low electric-field region is

reduced, and the change of drain current also becomes less. Figure 2(c) shows the off-state characteristics of SiN passivated device before and after the hot carrier stress. The off-state leakage current decreases after the stress. In the reverse bias condition, the stressed devices increase depletion regions due to the trapped electrons in surface states.

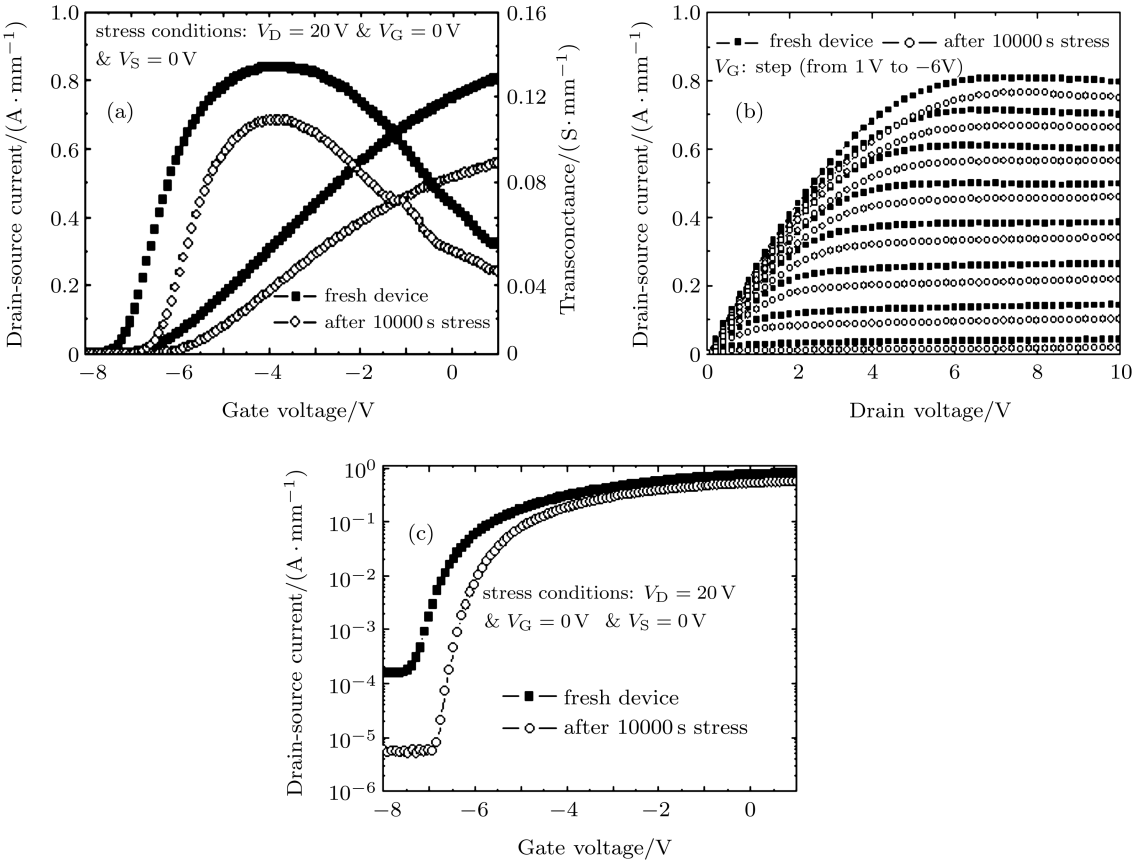


Fig.2. Transfer (a), output (b) and off-state characteristics (c) for $1 \times 25\,\mu m^2$ SiN passivated AlGaN/GaN HEMTs before and after 10^4 sec of hot electron stress test at $V_D = 20\,V$, $V_G = 0\,V$, $V_S = 0\,V$.

Stressed AlGaN/GaN HEMTs are relaxed for 48 hours without any light and electric signals, and the transfer characteristics of SiN passivated AlGaN/GaN HEMTs are nearly recovered to their initial values, which is different from the previous report.[10] In their studies, it is found that the permanent defects are generated after the high-electric-field stress. Figure 3 shows the I_{DS}–V_{GS} characteristics before and after the on-state stress of 10^4 sec with $V_D = 20\,V$, $V_G = 0\,V$, $V_S = 0\,V$ (a), and the static recovery characteristics (b) of SiN passivated AlGaN/GaN HEMTs. In Fig.3(b), the transfer characteristics recover completely after 48 hours relaxation. Generally, the damage induced by heterointerface states is permanent, so we think that the heterointerface states do not change enough to degrade devices under this stress condition, and we should almost lose sight of this factor.

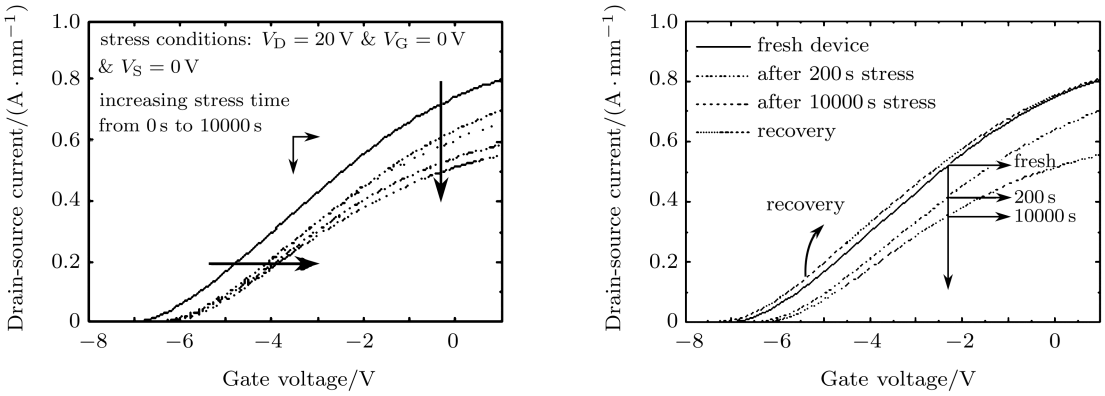
The Schottky barrier height can be determined from the forward I–V characteristics. The saturation current I_S is calculated from the gate I–V characteristics by plotting $\log(I)$ versus V. The intercept of this plot gives the saturation current I_S. The barrier height is given by

$$\Phi_B = \frac{KT}{q} \ln\left(\frac{AA^*T^2}{I_S}\right), \qquad (1)$$

where $A^* = 4\pi q k^2 m^*/h^3$ is Richardson's constant, A is the diode area, and T is the temperature.

Figure 4 shows the forward gate Schottky characteristics before and after an on-state stress of 10^4 sec with $V_D = 20\,V$, $V_G = 0\,V$, $V_S = 0\,V$. The forward

gate leakage current decreases after stress because of gate-drain surface degradation and reduced gate electron injection which is completely different from the results of Coffie *et al.*[10] In their study, the forward gate leakage current significantly increases. It can also be seen the intercept of the forward gate Schottky characteristics is almost unaffected after stress, and this suggests that the barrier height shows only a minor decrease. As increased defects at metal/thin-film interface can result in significant changes in the Schottky barrier height, increased defects at metal/thin-film interface should not be a very significant degradation mechanism. Moreover, most researchers have proved that the Ohmic contact plays an insignificant role in overall device degradation. Therefore, it can be ignored.



(a) on-state stress (b) recovery characteristics

Fig.3. I_{DS}–V_{GS} characteristics (a), and the static recovery characteristics (b) for $1 \times 25\,\mu m^2$ SiN passivated HEMTs before and after stress 10000 s of stress test at $V_D = 20$ V, $V_G = 0$ V, $V_S = 0$ V (the stress time from top to bottom, from left to right are followed by 0 s, 200 s, 1000 s, 5000 s, 10000 s).

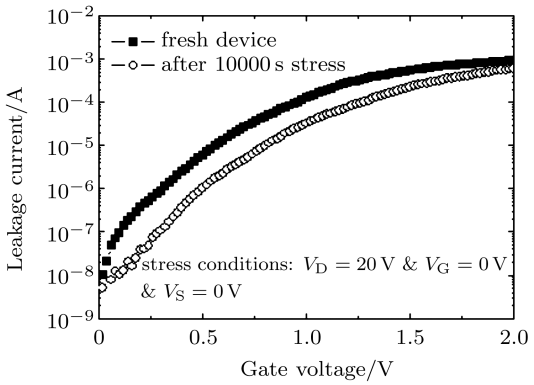


Fig.4. Forward gate characteristics for $1 \times 25\,\mu m^2$ SiN passivated HEMTs before and after stress 10000 s of stress test at $V_D = 20$ V, $V_G = 0$ V, $V_S = 0$ V.

Generally, the interface states are nearly most active to degrade the devices, and through the above analysis, we have almost ignored this factor. Moreover, because of the high chemical bond energy of GaN and AlGaN,[15] we believe that the new traps are difficult to produce after so short stress time. Thereby we think that the increased trapping at the surface and in AlGaN barrier layer should be the dominating degradation mechanism. When the kinetic energy of the electrons accelerated by a high field is larger than the lattice thermal energy, the electrons are trapped in the surface states and AlGaN barrier. However, Joh *et al*[13] have shown that the electric stress not only increased the trapping of the intrinsical defects but also created the new traps in devices. The stress time in their experiment is as long as 3000 hours. Through these comparisons, it is believed that the trapping of the intrinsical defects and the generation of new traps are closely related to the stress time, and we will describe it in details in subsequent studies.

In Fig.3(a), the V_{TH} is positively shifted obviously within 2×10^2 sec of high-electric-field stress, while the I_{Dsat} decreases by 12.75%; after 2×10^2 sec of stress the V_{TH} is relatively unaffected, but the I_{Dsat} continuously decreases. We know that V_{TH} is just affected by the traps in AlGaN barrier layer beneath the gate, and is almost unaffected by the surface states. So we think that the change of V_{TH} may be evidenced

that the electrons trapped in AlGaN near Schottky gate play a primary role from 0 sec to 2×10^2 sec, and the traps in AlGaN barrier layer especially under the gate are saturated basically within 2×10^2 sec. However, after 2×10^2 sec, the electrons filled in surface states at high gate-drain electric fields should be the dominating reason. It has been proved that the trapped electrons in surface states at high gate-drain electric fields are mostly from gate,[15] but the origin of the trapped electrons in AlGaN barrier layer remains controversial.[6,15,16]

Figure 5 shows the I_{DS}–V_{GS} characteristics of HEMTs before and after stress ($V_D = 20\,V$, $V_G = 0\,V$, source floating) (a) and ($V_D = 20\,V$, $V_S = 0\,V$, gate floating) (b) respectively, and the stress time is 2×10^2 sec. In Fig.5(a), the V_{TH} is positively shifted by 3.1% and the I_{Dsat} decreases only by 5.2%, which is much smaller than the on-state stress condition; While in Fig.5(b), the V_{TH} is positively shifted by 19.1% and the I_{Dsat} decreases by 17.2%, which is more than the on-state stress condition because gate floating corresponds to the positive V_G. From the above different degradations, we believe that the trapped electrons in AlGaN barrier layer mostly come from the hot carriers in channel, while a relatively few of them come from gate electrode. Once source is floated, the channel should have few electrons, and the hot electrons in channel would be so few that they could hardly affect devices degradation. So the shift of parameters is caused by the electrons filled in surface states at high gate-to-drain electric fields. However, when the gate electrode is floated, the channel turns on, and the hot electrons in channel would be more, while the impeditive electric fields (induced by high V_{DG}), which suppress increasing trapping in AlGaN barrier layer, would become lower because of gate floating corresponding to V_G being positive. And then the trapping in AlGaN barrier layer becomes active.

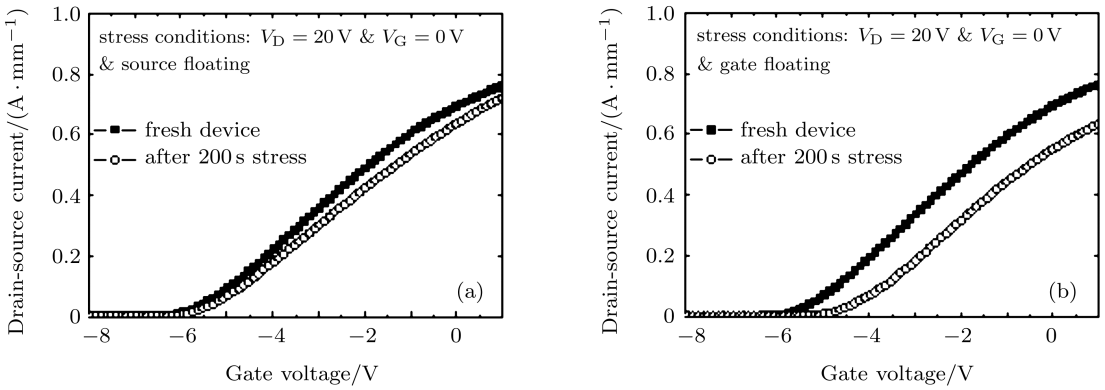


Fig.5. I_{DS}–V_{GS} characteristics for $1 \times 25\,\mu m^2$ SiN passivated HEMT's before and after 200 s of stress test at $V_D = 20\,V$, $V_G = 0\,V$, source floating (a) at $V_D = 20\,V$, $V_S = 0\,V$, gate floating (b).

Figure 6 shows the measured I_{DS}–V_{GS} characteristics of SiN passivated (a) and unpassivated (b) device before and after the hot carrier stress with $V_D = 20\,V$, $V_G = 0\,V$, $V_S = 0\,V$. The period of the stress is 10^4 sec. After the hot carrier stress, the transfer curve of SiN passivated and unpassivated AlGaN/GaN HEMTs is shifted to a positive direction. The V_{TH} of SiN passivated and unpassivated AlGaN/GaN HEMTs after the hot carrier stress is positively shifted by 9.3% and 7.4% respectively. The change of a V_{TH} may be evidenced that the electrons are trapped in AlGaN near Schottky gate of both SiN passivated and unpassivated AlGaN/GaN HEMTs. However, the change of V_{TH} in unpassivated AlGaN/GaN HEMT is equivalent to that of V_{TH} in SiN passivated one, so that the SiN passivation does not suppress the increase of a V_{TH} after the hot carrier stress. The V_{TH} shifts to a positive direction and the forward drain current of AlGaN/GaN HEMTs decreases after the hot carrier stress. The electron trapping into surface states depletes 2DEG charges and also decreases the forward drain current of the device. The I_{Dsat} of SiN passivated and unpassivated AlGaN/GaN HEMTs after the hot carrier stress de-

creases by 30% and 36% respectively. This experimental result shows that SiN passivated AlGaN/GaN HEMT is slightly more tolerable to the hot carrier stress than unpassivated one because the SiN passivation suppresses the electron trapping into the surface states during the hot carrier stress, and it also decreases the depletion of 2DEG charges due to the hot carrier stress. Although the passivation is effective in suppressing electron trapping in surface states, because of a little different degradations between the SiN passivated and unpassivated AlGaN/GaN HEMTs after the same stress, the passivation does not protect the device from high-electric-field degradation in nature, and we should adopt passivation in conjunction with other technological solutions like cap layer, prepassivation surface treatments, or field-plate gate to weaken high-electric-field degradation.[17−19]

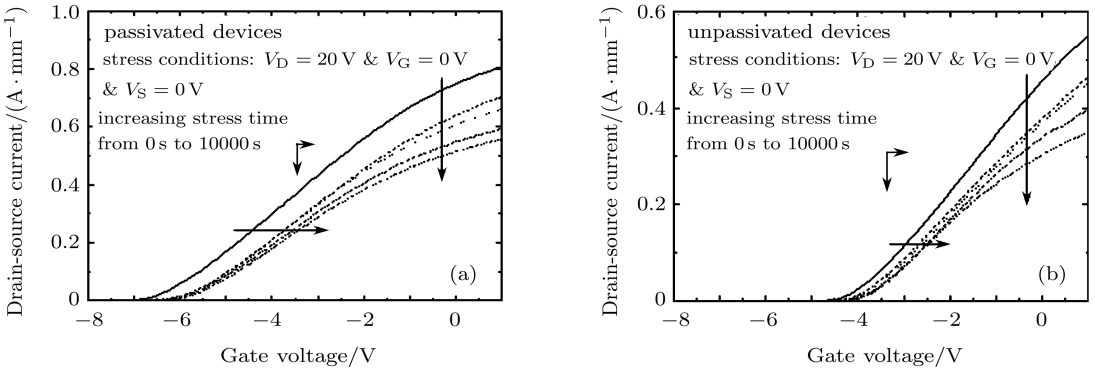


Fig.6. I_{DS}–V_{GS} characteristics for SiN passivated (a) and unpassivated (b) HEMTs before and after stress 10000 s of stress test at $V_D = 20\,V$, $V_G = 0\,V$, $V_S = 0\,V$ (the stress time from top to bottom, from left to right are followed by 0 s, 200 s, 1000 s, 5000 s, 10000 s).

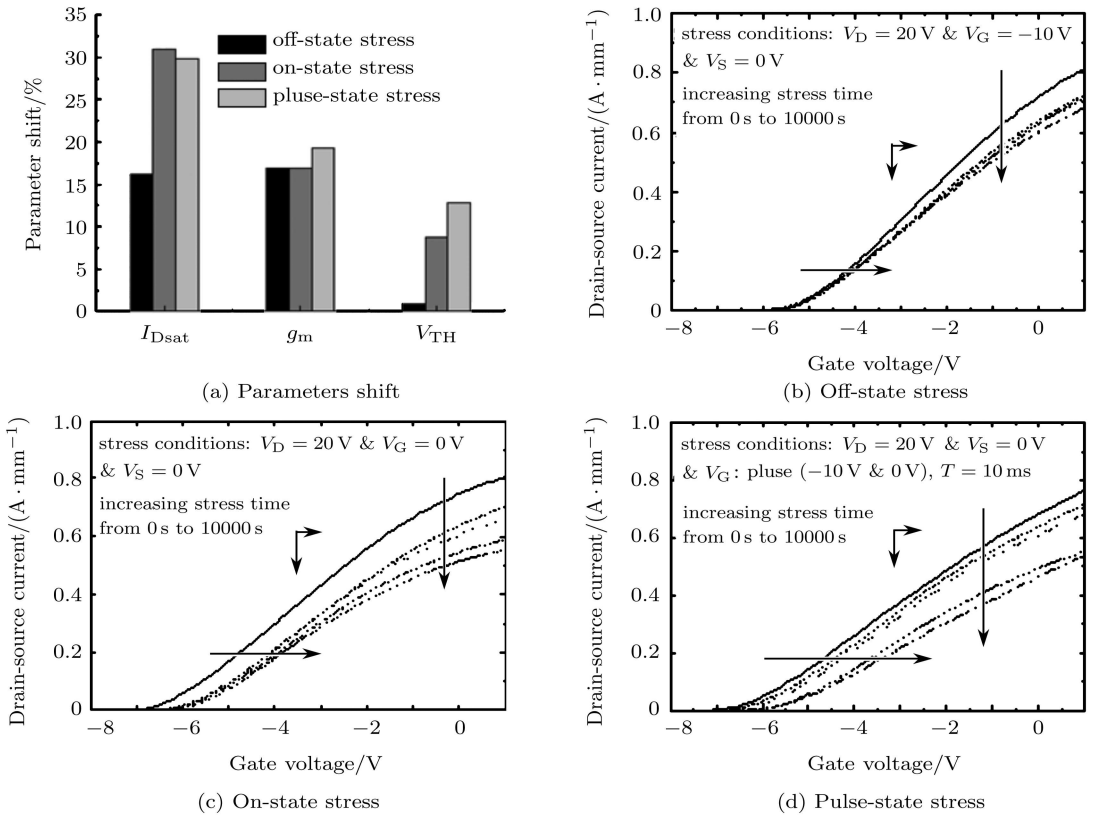
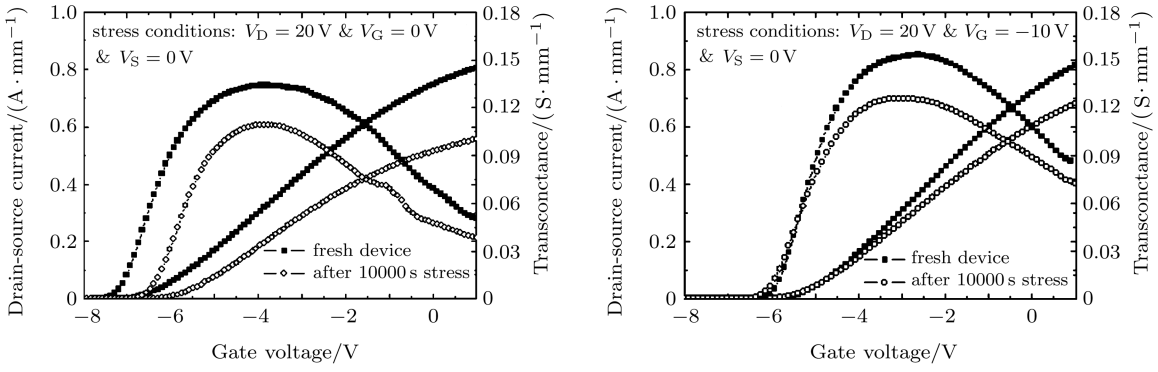


Fig.7. Parameters shift (a) and I_{DS}–V_{GS} characteristics of SiN passivated HEMTs after three different hot carrier stresses: (b) off-state stress ($V_D = 20\,V$, $V_G = -10\,V$, $V_S = 0\,V$); (c) on-state stress ($V_D = 20\,V$, $V_G = 0\,V$, $V_S = 0\,V$); (d) pulse-state stress ($V_D = 20\,V$, $V_S = 0\,V$, V_G: pulse (–10 V & 0 V), $T = 10$ ms), above stress time from top to bottom, from left to right are followed by 0 s, 200 s, 1000 s, 5000 s, 10000 s.

When a device works in on-state condition, both thermally-induced and hot-electron-related degradation can occur. In order to separate these two kinds of degradation mechanisms, both on-state and off-state stresses are carried out. Under off-state conditions, the electric field between gate and drain is the maximum, but the low current level prevents self heating. In order to evaluate the stability of these devices, 10^4 sec hot carrier stress is performed on SiN passivated AlGaN/GaN HEMTs.

Figure 7 shows the parameters shift (a) and I_{DS}–V_{GS} characteristics of the SiN passivated HEMTs after three different hot carrier stresses: (b) off-state stress ($V_{\mathrm{D}} = 20\,\mathrm{V}$, $V_{\mathrm{G}} = -10\,\mathrm{V}$, $V_{\mathrm{S}} = 0\,\mathrm{V}$); (c) on-state stress ($V_{\mathrm{D}} = 20\,\mathrm{V}$, $V_{\mathrm{G}} = 0\,\mathrm{V}$, $V_{\mathrm{S}} = 0\,\mathrm{V}$); (d) pulse-state stress ($V_{\mathrm{D}} = 20\,\mathrm{V}$, $V_{\mathrm{S}} = 0\,\mathrm{V}$, V_{G}: pulse (–10 V & 0 V), $T = 10\,\mathrm{ms}$). All the period of the stresses is 10^4 sec. After the off-state stress, the I_{Dsat} decreases by 16.39%, but the V_{TH} is almost unaffected within 10^4 sec. The I_{Dsat} decreases fast within 2×10^2 sec and the speed of decrease tends to slow down after 2×10^2 sec. Therefore, we believe that the electrons trapped in surface states play a dominating role under the off-state stress. Comparing Fig.7(c) with Fig.7(d), we find out that the degradation under pulse-state stress is smaller than that under on-state stress within 2×10^2 sec, while after 10^4 sec, the degradations of pulse-state stress and on-state stress are comparative on the whole. So we believe that the effect of passivation for this HEMT is not rather perfect. Passivation just increases the time constant a little, which means that trapping time becomes larger, but not interdicts the channel through which surface states are filled by electrons. Therefore, under pulse-state stress, only the degradation speed is slower than on-state stress. When the stress time is long enough, all the traps are filled. Therefore, the degradation either under pulse-state stress or under on-state stress is almost comparative, and the passivation does not protect the device from high-electric-field degradation in nature.

Figure 8(a) presents the transfer characteristics measured under on-state stress ($V_{\mathrm{D}} = 20\,\mathrm{V}$, $V_{\mathrm{G}} = 0\,\mathrm{V}$, $V_{\mathrm{S}} = 0\,\mathrm{V}$). Three degradation modes are presented after the stress: i) a V_{TH} shift appears, together with ii) a decrease in the g_{m}, and iii) a drop of the transconductance value at both low and high V_{GS}. In order to separate the thermally-induced degradation from the hot-electron one, we carry out hot-electron stress under closed channel conditions, named off-state stress ($V_{\mathrm{D}} = 20\,\mathrm{V}$, $V_{\mathrm{G}} = -10\,\mathrm{V}$, $V_{\mathrm{S}} = 0\,\mathrm{V}$) for 10^4 sec (b). The same degradation modes induced by on-state stress are observed, i.e., a decrease in the drain current and a decrease in the transconductance. The only exception is the V_{TH} shift, which is not presented after off-state stress. Although the degradation of drain current under off-state stress is less than that under on-state stress as a whole, the transconductance also degrades obviously at high V_{GS} bias, while at low V_{GS}, the transconductance hardly degrades. In order to explain simply, we call the channel under gate as internal channel and the channel beyond gate as outside channel. In on-state stress, the electrons in internal channel are trapped, which decrease the transconductance at low V_{GS} bias, and the trapped electrons of outside channel increase the drain series resistance, then reduce the transconductance at high V_{GS} bias. While under off-state stress, although the internal channel is pinched off, there are electrons in outside channel,



(a) On-state stress (b) Off-state stress

Fig.8. Transfer characteristics of SiN passivated HEMTs after (a) on-state stress ($V_{\mathrm{D}} = 20\,\mathrm{V}$, $V_{\mathrm{G}} = 0\,\mathrm{V}$, $V_{\mathrm{S}} = 0\,\mathrm{V}$); and (b) off-state stress ($V_{\mathrm{D}} = 20\,\mathrm{V}$, $V_{\mathrm{G}} = -10\,\mathrm{V}$, $V_{\mathrm{S}} = 0\,\mathrm{V}$).

and because of the negative V_{GS} bias, the electric field between the internal channel and outside channel will increase remarkably, and then the induced hot electrons could increase the drain series resistance, and reduce the transconductance at high V_{GS} bias.

Two degradation mechanisms could explain this behaviour: i) degradation of the surface in the gate-drain access region which attenuates the gate-edge electric field, this decreases gate electron injection and the gate-drain leakage current; ii) the electrons trapped in AlGaN barrier which degrades the V_{TH} and decreases 2DEG depletion a little during the high-electric-field stress.

4. Conclusion

In conclusion, a recoverable degradation has been found after high-electric-field stress, which consists of the decrease of I_{Dsat} and g_m, and the positive shift of V_{TH} at high V_{DS}. Direct current analyses under different stress conditions demonstrate that the degradation mechanism consists of the increased trapping at the surface and in AlGaN barrier layer. The trapped electrons in surface states at high gate-drain electric fields are mostly from gate, the trapped electrons in AlGaN barrier layer mostly come from the hot carriers in channel, while a relatively few of them come from gate electrode. Generally, the long-time degradation has the same physical mechanism to the short-time current collapse, and the SiN passivation of AlGaN/GaN HEMTs just decreases the surface trapping and 2DEG depletion a little during the high-electric-field stress. After the hot carrier stress with $V_{DS} = 20\,V$ and $V_{GS} = 0\,V$ applied to AlGaN/GaN HEMTs for 10^4 sec, the SiN passivation decreases the degradation of I_{Dsat} from 36% to 30%. Both on-state and pulse-state stresses produce comparative decrease of I_{Dsat}, which shows that although the passivation is effective in suppressing electron trapping in surface states, it does not protect the device from high-electric-field degradation in nature. So we should adopt passivation in conjunction with other technological solutions like cap layer, prepassivation surface treatments, or field-plate gate to weaken high-electric-field degradation.

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