Effects of SiN_x on two-dimensional electron gas and current collapse of AlGaN/GaN high electron mobility transistors*

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SiN_x is commonly used as a passivation material for AlGaN/GaN high electron mobility transistors (HEMTs). In this paper, the effects of SiN_x passivation film on both two-dimensional electron gas characteristics and current collapse of AlGaN/GaN HEMTs are investigated. The SiN_x films are deposited by high- and low-frequency plasma-enhanced chemical vapour deposition, and they display different strains on the AlGaN/GaN heterostructure, which can explain the experiment results.

Keywords: SiN_x passivation, plasma-enhanced chemical vapour deposition, AlGaN/GaN heterostructure, current collapse

PACC: 7360H, 7360L, 7340N, 7360Q

1. Introduction

During the last decade, AlGaN/GaN high electron mobility transistors (HMETs) have aroused great interest due to their high-power and high-frequency applications.[1] However, there are still some important issues by which their practical applications are hampered: one of them is the so-called current collapse. Many methods have been developed to avoid current collapse, including optimizing the epi-layer structure as well as crystal quality[2] and coating passivation films.[3,4]

SiN_x deposited by plasma-enhanced chemical vapour deposition (PECVD) is one of the commonly used passivation materials to reduce surface electron traps, and can decrease current collapse observably. However, SiN_x films deposited under different PECVD conditions will display different strains, which can be very critical especially for strained GaN-based materials. Chang and Lee[5] reported on the effects of tensile stress of SiN_x passivation film, but they did not discuss the relationship between the effects and the SiN_x deposition conditions. Tan *et al.*[6] mentioned that SiN_x film deposited by dual-frequency PECVD could improve the static characteristics of AlGaN/GaN HEMTs, but no results of AC performance were given. Also, they measured the stress of SiN_x on a Si wafer, which is not accurate for GaN-based material. In the present work, the effects of the stress of SiN_x films deposited by high- and low-frequency PECVDs on the 2DEG characteristics and current collapse of HEMT devices are studied in detail.

2. Experiment

The AlGaN/GaN HEMT wafers were grown by an AIXTRON 2000HT metal-organic vapour phase epitaxy (MOVPE) system. A low temperature GaN nucleation layer was grown on (0001) sapphire substrate, followed by a 3 μm thick GaN buffer layer, and finally capped by a 30 nm thick AlGaN layer with an Al content of 30%. SiN_x thin films were deposited on as-grown samples by an Oxford Instrument Plasma-lab 80 plus PECVD system. For samples A_1 and B_1, the thicknesses of SiN_x were 30 and 100 nm, respectively, and the RF source power was 20 W at 13.56 MHz. For sample C_1, the SiN_x thickness and RF source power were 30 nm and 50 W at 100 kHz, respectively. The

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SiN_x films deposited under these two different conditions are hereafter referred to as HF- and LF-SiN_x. The stresses of these SiN_x films on 2-inch (5.08 cm) GaN wafer on (0001) sapphire substrate were calculated from the change of the wafer bending before and after the deposition of SiN_x film, which had been measured by using a Dektak 150 stylus profiler. The 2DEG properties of the samples were characterized by van der Pauw Hall measurement before and after SiN_x deposition at room temperature.

HEMT device samples A_2, B_2 and C_2 were fabricated with SiN_x passivation by using the same PECVD conditions as samples A_1, B_1 and C_1, respectively. The device structure is shown in Fig. 1. Ti/Al/Ti/Au was deposited by e-beam evaporation as source and drain electrodes, followed by annealing at 900 °C for 3 min in an N_2 atmosphere, and Ni/Au was deposited by e-beam evaporation as gate electrode. The source–drain separation is 5 μm, and the gate length is 1 μm. On each sample, the SiN_x films on some devices were removed in order to make a comparison.

Then gate- and drain-lag current–voltage (I–V) characteristics were measured by an Agilent 4155C semiconductor parameter analyser. The pulse frequency and width were 200 Hz and 500 μs. The base voltages were –8 V and +10 V, respectively, for gate and drain signals. The details of the measurement can be found in our previous work.[7]

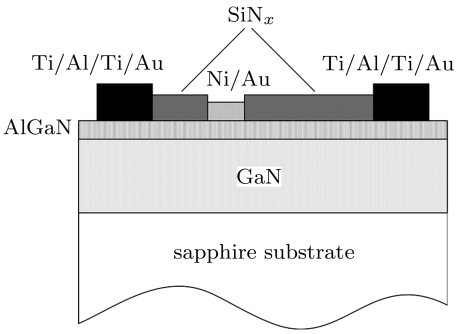


Fig. 1. HEMT device structure with SiN_x passivation.

3. Results and discussion

Table 1 shows the Hall measurement results of samples A_1, B_1 and C_1 before and after SiN_x film deposition. For sample A_1 with 30-nm HF SiN_x, the 2DEG density (n_s) increases slightly, and sheet resistivity (ρ_s) decreases by 5.5%. As for sample B_1 with 100 nm HF SiN_x, n_s shows an increase of 33%, and ρ_s decreases by about 22%. The 2DEG mobility (μ) changes little for these two samples. However, for sample C_1 with 30 nm LF SiN_x, both n_s and μ significantly decrease, thus ρ_s reaches as high as 2610 Ω/□.

Table 1. Hall measurement results on A_1, B_1 and C_1.

	A_1		B_1		C_1	
	as grown	w/30 nm HF SiN_x	as grown	w/100 nm HF SiN_x	as grown	w/30 nm LF SiN_x
n_s	1.14×10^{13}	1.18×10^{13}	1.07×10^{13}	1.42×10^{13}	1.25×10^{13}	7.71×10^{12}
μ	1118	1146	1193	1152	1161	311
ρ_s	491	464	489	382	431	2610

The devices on samples A_2 and B_2 exhibit normal static characteristics. However, since the 2DEG n_s and μ severely decrease, all devices on sample C_2 are failed regardless of whether they are with or without LF SiN_x films, which shows that LF SiN_x has a non-reversible effect on AlGaN/GaN heterostructure. Typical I–V curves for the devices without and with 100 nm HF SiN_x passivation on sample B_2 are shown in Fig. 2. It is obvious that the maximum drain current at $V_G = +1$ V for the devices with 100 nm HF SiN_x is about 53% larger than that for the devices without SiN_x, which is consistent with the Hall measurement results.

From the I–V curves, since the maximum drain currents under pulsed measurement are smaller than those under static measurement, thermal effects can be ruled out. The gate-lag and drain-lag measurement results on samples A_2 and B_2 are summarized in Table 2. A normalized current collapse parameter, $\Delta I = \Delta I_{DCpulsed}/I_{DSS}$,[8,9] is used, where $\Delta I_{DCpulsed}$ is the maximum reduction of drain current between static and pulsed measurements, and I_{DDS} is the corresponding static drain current at the V_{DS} where $\Delta I_{DCpulsed}$ is observed. The results show that HF SiN_x films can suppress current collapse, and the current reduces less with the increase of HF SiN_x thickness. Moreover, this effect is more evident during gate-lag measurement.

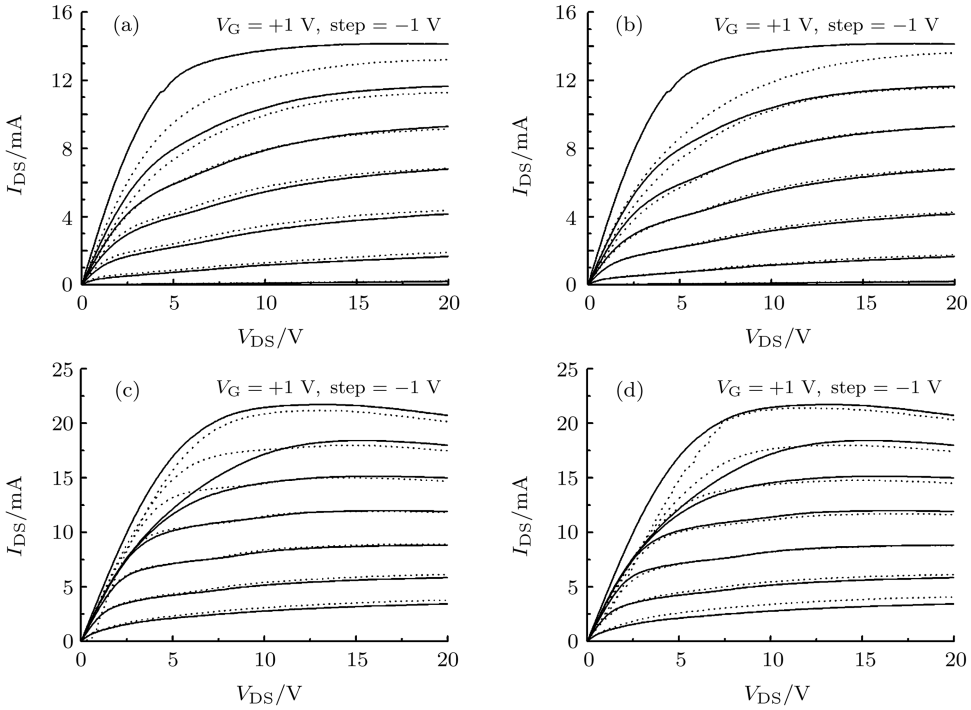


Fig. 2. Typical I–V curves for the devices with 100 nm thick HF SiN_x passivation on sample B_2. (a) and (b), (c) and (d) are gate-lag and drain-lag results for the devices without and with SiN_x, respectively. Solid and dotted curves are for static and pulsed measurements, respectively.

Table 2. Gate-lag and drain-lag measurement results.

ΔI	A_2		B_2	
	w/o 30 nm HF SiN_x	w/ 30 nm HF SiN_x	w/o 100 nm HF SiN_x	w/100 nm HF SiN_x
gate lag	21.25 %	14.42 %	14. 86 %	5.21 %
drain lag	20.47 %	16.03 %	12.8 %	9.07 %

The stresses of the HF SiN_x and LF SiN_x films are measured to be about +0.62 GPa and –1.08 GPa, respectively. A positive value represents tensile stress, while a negative value indicates compressive stress. According to these, the HF SiN_x film will impose an extra tensile strain on the AlGaN layer, and the strain becomes greater with the increase of SiN_x thickness. The tensile strain plays a critical role in 2DEG formation at the AlGaN/GaN interface. In this sense, HF SiN_x can enhance the tensile strain in the AlGaN layer, and thus increase the piezoelectric polarization, leading to a greater total polarization in the AlGaN barrier and a deeper triangle well in the conductive band as illustrated in Fig. 3. The consequence is that more free electrons can be induced and the potential well can supply better confinement, which improves the 2DEG characteristics.

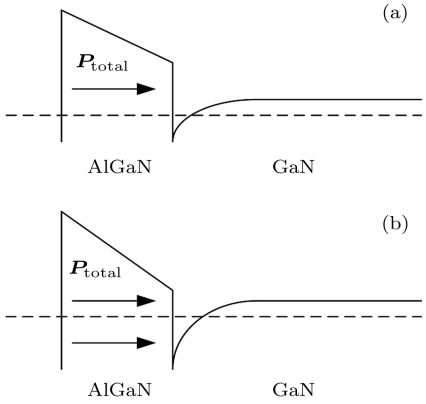


Fig. 3. Band diagram of AlGaN/GaN heterostructure before (a) and after (b) HF SiN_x deposition, on the assumption that the Schottky barrier does not change.

To explain the reduction of the drain-lag current collapse which is related to the traps in the GaN buffer[10] and the AlGaN capping layer, a better 2DEG

confinement can prevent electrons in the channel from scattering into the AlGaN and GaN layers. As for the gate-lag current collapse which is usually attributed to surface state charging,[11,12] besides the surface state passivation effect of SiN_x, the extra tensile strain in the AlGaN layer can prevent the residual surface state from being charged, because the electrical field induced by the negative polarization charge on the AlGaN surface can be enhanced. For LF SiN_x, on the other side, a strong extra compressive force will be imposed on the AlGaN layer, which will compensate the original tensile strain in the AlGaN layer and degrade the 2DEG properties. In addition, at lower frequencies (below 1 MHz) of the PECVD RF source, ion bombardment becomes more significant, causing low-energy ion implantation (< 300 eV), which may cause damage to the AlGaN epi-layer and even destroy the 2DEG.[13,14] This could be the reason why the devices are still failed after removing LF SiN_x films.

4. Conclusion

The effects of HF SiN_x and LF SiN_x films deposited by PECVD on AlGaN/GaN 2DEG characteristics are investigated. HF SiN_x can enhance the 2DEG by inducing extra tensile strain in the AlGaN layer. In contrast, LF SiN_x weakens 2DEG greatly due to an extra compressive strain and ion bombardment damage. The gate-lag and drain-lag measurements on HEMT devices with and without HF SiN_x are also performed. Reduced current collapse can be explained by the extra tensile strain in the AlGaN layer.

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