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Effect of SiN:H_x passivation layer on the reverse gate leakage current in GaN HEMTs

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This paper concentrates on the impact of SiN passivation layer deposited by plasma-enhanced chemical vapor deposition (PECVD) on the Schottky characteristics in GaN high electron mobility transistors (HEMTs). Three types of SiN layers with different deposition conditions were deposited on GaN HEMTs. Atomic force microscope (AFM), capacitance–voltage (C–V), and Fourier transform infrared (FTIR) measurement were used to analyze the surface morphology, the electrical characterization, and the chemical bonding of SiN thin films, respectively. The better surface morphology was achieved from the device with lower gate leakage current. The fixed positive charge Q_f was extracted from C–V curves of Al/SiN/Si structures and quite different density of trap states (in the order of magnitude of 10^{11}–10^{12} cm^{-2}) was observed. It was found that the least trap states were in accordance with the lowest gate leakage current. Furthermore, the chemical bonds and the %H in Si–H and N–H were figured from FTIR measurement, demonstrating an increase in the density of Q_f with the increasing %H in N–H. It reveals that the effect of SiN passivation can be improved in GaN-based HEMTs by modulating %H in Si–H and N–H, thus achieving a better Schottky characteristics.

Keywords: SiN passivation, the gate leakage current, Q_f, FTIR

PACS: 73.61.Ey, 73.61.–r, 72.80.Ey, 73.40.Qv **DOI:** 10.1088/1674-1056/27/9/097309

1. Introduction

GaN-based high electron mobility transistors (HEMTs) have gained increasing attention as a key component especially in wireless communication systems to produce high output power and efficiency.[1–3] Silicon nitride (SiN)[4] deposited by plasma-enhanced chemical vapor deposition (PECVD) is extensively used as a surface passivation layer, playing an important role in mitigating current collapse and DC-to-RF dispersion,[5] and thus results in good power efficiency. However, the employment of SiN as a surface passivation layer leads to severe issues with increased off-state drain and gate leakage currents. This is a critically sensitive issue to meet high operating voltage and power transistors. On this basis, a significant amount of effort has been devoted to improve the Schottky characteristics in GaN HENTs with SiN thin films deposition. Quite recently, it has been explored that the trap states in SiN layer and the interface are the main reasons for the large gate leakage current and the poor Schottky characteristic.

In recent years, extensive work has been conducted to investigate the role of SiN thin films composition on surface passivation,[6–10] which concluded that chemical bonds play a crucial role in the density of trap states. Chen *et al.*[6] proposed that the passivation degradation has a crucial role in the dissociation of bonded hydrogen at the SiN/Si interface and effusion out of the Si. When SiN layer has a dense structure, hydrogen from the SiN film cannot be able to diffuse through the film and replace the lost hydrogen at the interface. Garcia *et al.*[11] and Romero *et al.*[12] found a linear relationship between the N–H bond density and the minimum interface trap density (D_{it}). A large proportion of works focus on the effect of SiN film composition on the passivation characteristic of metal/SiN/Si structure and scarce research[13,14] on the Schottky characteristic in GaN HEMTs with SiN layer. Meyer *et al.*[13] and Yue *et al.*[14] pointed out that the chemical bonds Si–H and N–H have an effect on the passivation, but no detail analysis on the relation between the gate leakage current and Si–H and N–H have been exhibited.

This article presents the impact of chemical bonds of SiN on the leakage current in GaN HEMTs using Fourier transform infrared (FTIR) spectroscopy on GaN substrate, and explores the relationship between the Schottky leakage current and these chemical bonds. Three different types of SiN layers are deposited on GaN HEMTs and the leakage current mechanism is revealed by capacitance–voltage (C–V) measurement and FTIR analysis.

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2. Sample preparation

Figure 1 displays the schematic cross section of AlGaN/GaN HEMTs with SiN passivation. In this experiment, the heterostructure layers were grown on sapphire substrate by metal–organic chemical vapor deposition (MOCVD). For GaN HEMTs, device processing starts with source and drain Ohmic contact formed by electron beam evaporation of Ti/Al/Ni/Au. After rapid thermal annealing at 870 °C for 50 s, the Ohmic contact resistance of 0.35 Ω·mm and sheet resistance of 488 Ω/□ were derived from transmission line models. Device isolation was achieved by reactive ion etching using Cl_2 plasma. T-shaped gate of 0.15-μm length and 50-μm width was adopted in this paper. After gate lithography, a Ni/Au electrode was evaporated and then splited into four pieces. Exactly the same surface treatments were applied to the samples 1, 2, 3 before SiN passivation, except the sample 4 which was without passivated. Not less than 100 nm SiN layer was introduced to study the passivation effect. However, the thicker SiN layer resulted in larger trap states and parasitic capacitance. In this work, considering the process conditions, 120-nm SiN thin films were subsequently deposited with a 790+ system on GaN surfaces. SiH_4He and NH_3 were used as the Si and N precursors, respectively, and N_2 was used as the carrier gas as well as the purge gas. SiN thin films were deposited under different process conditions as listed in Table 1.

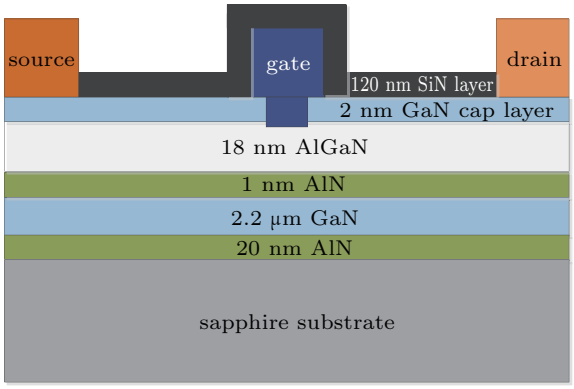


Fig. 1. (color online) Schematic cross section of AlGaN/GaN HEMTs.

Table 1. Range of process parameters used for the PECVD SiN depositions.

	Power	SiH_4He	NH_3	T/°C
Sample1	30	250	100	250
Sample 2	30	250	100	270
Sample 3	50	250	100	270

3. Results and discussion

Firstly, the Schottky characterization of 50-μm width GaN HEMTs with SiN passivation was performed with a Keithley 4200 semiconductor characterization system. The off-state gate leakage currents I_g of HEMTs at gate–source voltage $V_{gs} = -20$ V and $V_{ds} = 0$ V are shown in Fig. 2(a). The gate leakage currents of HEMTs (samples 1, 2, 3, and 4) are -1.121×10^{-2} A/mm, -1.45×10^{-3} A/mm, -2.258×10^{-5} A/mm, and -6.07×10^{-6} A/mm, respectively, which unveils that the reverse leakage current increases by about one–four orders of magnitude with different SiN film passivation. The increased gate leakage current is attributed to the damage from the active plasma sources in PECVD. Exposure of AlGaN&GaN surface to the aggressive plasmas in PECVD could lead to degradation of the SiN dielectric/AlGaN&GaN interface, causing a higher density interface traps and further increase in leakage current.[15] Then a part of SiN dielectric of sample 1 was removed and the reverse gate leakage current was analyzed. Figure 2(b) depicts that the gate leakage current decreases by three orders of magnitude after removing a part SiN layer and is close to the reverse gate current of GaN HEMT sample 4 without SiN passivation. This demonstrates that the reverse gate leakage current increases with SiN passivation.

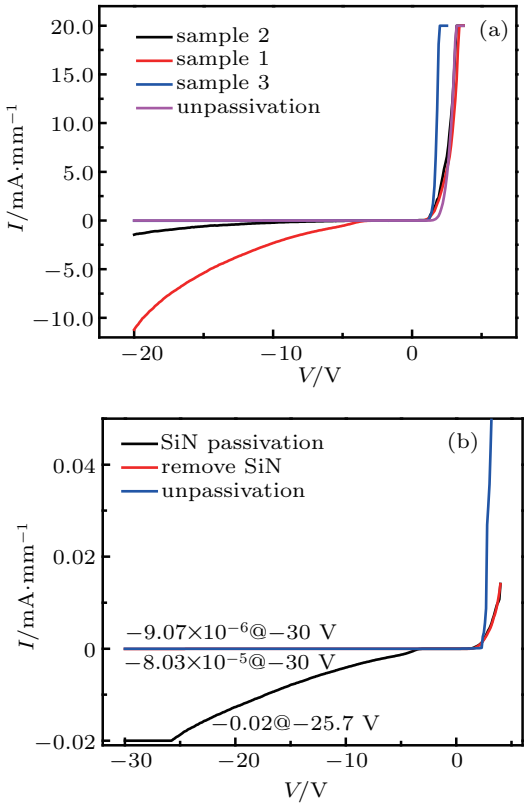


Fig. 2. (color online) (a) The Schottky characterization of samples. (b) The reverse gate leakage current of sample 1 removed SiN passivation layer.

3.1. AFM measurement

Agilent N9451A atomic force microscope (AFM) was used to analyze the surface microstructures of GaN HEMTs with SiN passivation layer. As shown in Fig. 3, the surface morphology within 5×5 μm^2 area of three samples was ob-

served. The morphology of sample 1 showed some large-scale grains with diameter larger than 200 nm. At fast deposition rate and lower temperature, three-dimensional island growth mode might take place, so the root mean square (RMS) roughness and maximum undulation of SiN thin films are largest for sample 1 device, as shown in Fig. 3(a). Excellent surface morphology was obtained for sample 2 and sample 3 thin films, and the less surface pits of SiN film for sample 3 led to a smaller maximum undulation compared to sample 2. Compared with the Schottky characterization, the superior surface morphology was in accordance with the minimal leakage current.

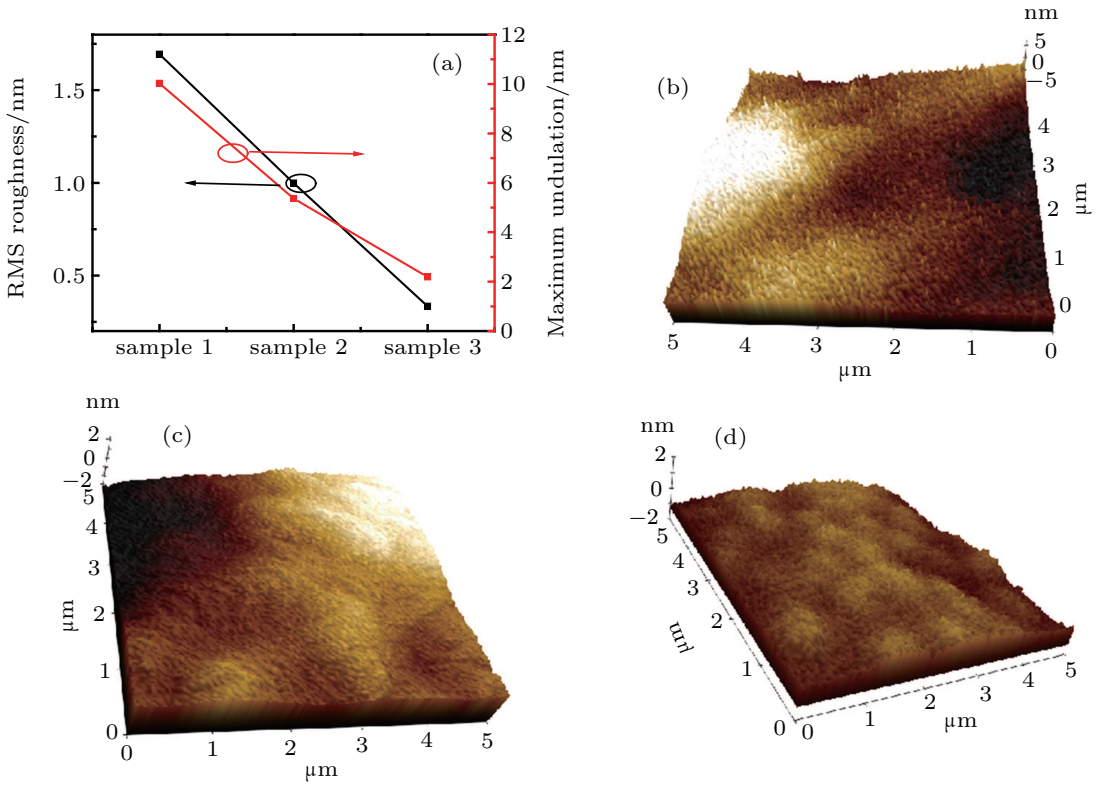


Fig. 3. (color online) (a) RMS roughness and the maximum undulation of SiN thin films for three HEMTs. The AFM morphology of samples (b) 1, (c) 2, and (d) 3.

3.2. *C–V* measurement

Metal–insulator–semiconductor (MIS) structures were prepared to perform the *C–V* characterization. For the three samples, aluminum contact of 300 nm was thermally evaporated to produce Al/SiN/Si devices and to stress that SiN layer on Si substrate was deposited together with the SiN passivation of GaN HEMT devices. The area of *C–V* circular ring was about 7.85×10^{-5} cm^2. The frequency of ac signal was set at 1 MHz, with amplitude of 30 mV. The *C–V* curves of SiN samples on Si were measured with a Keithley B1500 analyzer.

The hysteresis *C–V* curves for three samples shown in Fig. 4(a) depicts a hysteresis loop in an anti-clockwise direction due to the trap states and the charge exchange mechanism. The trapped charge quality (N_t) in SiN film could be calculated by using

$$N_t = \frac{C\Delta V}{q}.$$

In the curves, the hysteresis decreases gradually from sample 1 to sample 3. The hysteresis (ΔV) of curves for samples 1, 2, and 3 are 5.8 V, 4.4 V, and 1.2 V, respectively. The large hysteresis in sample 1 (5.8 V) indicates that the SiN film has excellent charge storage characteristics and there are more trapped centers in the dielectric films. In addition, the fixed charges Q_f (silicon dangling bond because of the large lattice and thermal mismatch to GaN) in SiN thin films were investigated by sweeping the voltage from accumulation region to depletion region in order to eliminate the attribution of trapped charges, as shown in Fig. 4(b). The calculated fixed charge densities for samples 1, 2, and 3 are 1.573×10^{12} cm^{-2}, 1.054×10^{12} cm^{-2}, and 7.43×10^{11} cm^{-2}, respectively. For the sample 3, the *C–V* curve shows positive shift due to a decrease in fixed charges.[16,17] The fixed charge density in SiN thin films grown at sample 1 condition is much higher than that of other ones, which is in agreement with the poor microstructural characteristics. Furthermore, so many charges can also cause serious reverse leakage current, presented by a decrease in capacitance.[18] In one word, the charge density Q_f is not only related to the surface microstructures but also the gate leak current, contributed by K-center defects presenting in the SiN films.

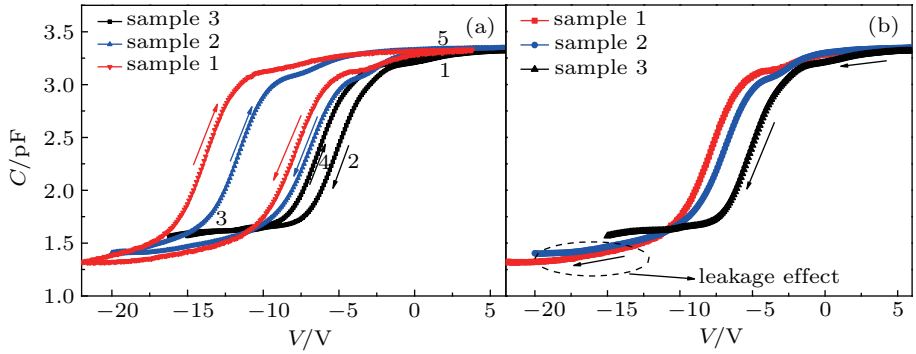


Fig. 4. (color online) (a) Hysteresis *C*–*V* curves of SiN thin films. (b) Capacitance versus voltage curves by sweeping biased voltage from 8 V to −25 V.

3.3. FTIR spectroscopy measurement

FTIR spectroscopy was used to determine the composition of the SiN films and explore the role of specific chemical bonds on surface passivation. The absorption spectra of the SiN films in GaN HEMTs were measured using a Varian 3100 FTIR by taking 64 scans of each sample over a range of wavenumbers between 600 cm^{-1} and 4000 cm^{-1}. Figure 5 displays the FTIR spectra of the different types of SiN film. Film thicknesses were approximately 120 nm. The Si–H and N–H stretching modes were observed at 2160 and 3350 cm^{-1}, respectively. The methods[17,19,20] of calculating the bonds densities were compared, and the peak wavenumber of the Si–H and N–H bonds were extracted from the absorption spectra, shown in Table 2. The ratio of Si–H and N–H bonds and the relative content of hydrogen of the films were also calculated. Exact quantitative analysis of the bonds was not performed. However, an interesting trend was observed in the relative amount %H bonded as Si–H or N–H in the three samples of devices, illustrated in Table 2. The trend was not different compared with that obtained in the gate leakage current data and trap charges density, after passivation, shown in Figs. 2 and 4.

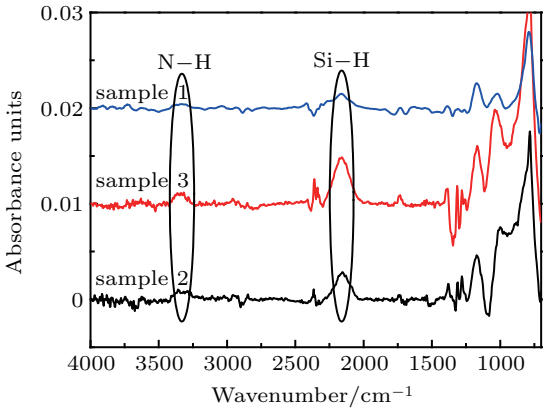


Fig. 5. (color online) FTIR absorption spectra of the SiN films on GaN HEMTs.

So what is the relation between the relative content of H incorporated as Si–H or N–H bond and the gate leak current? It is considered that the effect of fixed positive charge Q_f in SiN layer was the potential mechanism accounting for this characteristic. At present, many researchers have confirmed that there is a great propensity of defects to occur in the SiN material due to the relatively low deposition temperatures.[21–23] Krick *et al.*[24] observed the presence of a silicon dangling bond, termed as "K-center". Robertson *et al.*[25] discussed the dangling bond effect on a nitrogen atom in PECVD SiN and demonstrated that the net fixed charge would change if the nitrogen dangling bond was passivated with hydrogen. This characteristic is significantly relevant to our study in this paper. It was observed that increasing passivation of nitrogen dangling bonds with hydrogen could lead to a net increase in fixed positive charge Q_f and further increase in the gate leak current. Previous results have suggested that N–H bonds act as precursors of the K^+ centers creating a positive charge Q_f.[26,27]

Table 2. FTIR peak integration areas for SiN films on GaN HEMTs device.

	Si–H	N–H	Si–H/N–H	%H bonded	
				Si–H	N–H
Sample1	0.12	0.076	1.58	61.22	38.78
Sample 2	0.28	0.11	2.59	71.8	28.2
Sample 3	0.466	0.124	3.75	79	21

Recalling the data that was observed in our FTIR measurement, the relative contents of hydrogen in N–H of the three devices (samples 1, 2, and 3) were 38.78%, 28.2%, and 21%, respectively. This trend resembles the effect observed in the trap charges density and the gate leakage current, indicating increase in the gate leak current, correlated well with the relative amount of %H in N–H bonding present in the film. It is consistent with the theory discussed in the previous paragraph. In addition, Prabhakaran *et al.* also confirmed that the N–H bonds in films were inferior to Si–H bonds for surface passivation.[28] We can get better Schottky characterization of devices depending on the details of the film stoichiometry and different deposition conditions to decrease the relative amount of H% in N–H, the populations of fixed charge defects.

4. Conclusion

We explored the feasible mechanism linking the reverse gate leakage current of GaN HEMTs with SiN passivation film, analyzing through AFM, C–V, and FTIR measurement. The results demonstrate that the relative amount of H in N–H bonding is the key factor that can affect the gate leakage current. Most importantly, there is a linear relationship between the relative amount H in N–H bonding and density of the fixed positive charge $Q_{\rm f}$ in SiN layer measurement from FTIR. In addition, an increase in the $Q_{\rm f}$ density leads to the increasing gate leakage current, shown in C–V measurement. It also demonstrates that the worst RMS roughness of 1.694 nm is the base for largest gate leakage current of -1.121×10^{-2} A/mm at $V_{\rm gs} = -20$ V.

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