# Impact of stress in ICP-CVD $SiN_x$ passivation films on the leakage current in AlGaN/GaN HEMTs

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The impact of the stress in room temperature inductively coupled plasma chemical vapour deposited (ICP-CVD) $SiN_x$ surface passivation layers on off-state drain ($I_{DS\text{-}off}$) and gate leakage currents ($I_{GS}$) in AlGaN/GaN high electron mobility transistors (HEMTs) is reported. $I_{DS\text{-}off}$ and $I_{GS}$ in 2 µm gate length devices were reduced by up to four orders of magnitude to ~10 pA/mm using a compressively stressed bilayer $SiN_x$ passivation scheme. In addition, $I_{on}/I_{off}$ of $\sim 10^{11}$ and sub-threshold slope of 68 mV/dec were obtained using this strain engineered surface passivation approach.

*Introduction:* AlGaN/GaN HEMTs are a promising candidate for power and RF electronics due to the high breakdown voltage, high electron saturation velocity and good thermal stability of the GaN-based material system [1, 2]. Off-state drain to source ($I_{DS\text{-}off}$) and gate leakage ($I_{GS}$) currents must be minimised in these devices to improve the efficiency of their power switching. To reduce leakage currents, $Al_2O_3$ passivation deposited by atomic layer deposition, wet chemical or plasma surface treatment before passivation and annealing after gate metal deposition have been reported [3–6]. $SiN_x$ has been widely used for surface passivation between the transistor gate and drain and shown to be effective in reducing current collapse and DC-to-RF dispersion arising from the large density of surface states and trapped surface charge [7]. Optimisation of the properties of the $SiN_x$ passivation film has been reported, including the impact of stress in the $SiN_x$ film on the properties of an AlGaN/GaN HEMT by Gregušová *et al.* [8]. Fehlberg *et al.* [9] used Hall Bars to investigate the impact of stress in $SiN_x$ deposited films on the electrical transport properties of AlGaN/GaN heterostructures. To date, all reports on the impact of stressed $SiN_x$ films have been restricted to passivation layers deposited by plasma enhanced chemical vapour deposition (PE-CVD) techniques with a maximum compressive stress of 150 MPa. Moreover, the use of $SiN_x$ by PE-CVD as a surface passivant can result in increased $I_{DS\text{-}off}$ and $I_{GS}$ [10]. To mitigate these effects, in this Letter, we compare the impact of both tensile and compressive stress in the range of −1622 to +440 MPa in room temperature deposited ICP-CVD $SiN_x$ surface passivation films on AlGaN/GaN HEMTs. A significant reduction in $I_{DS\text{-}off}$ and $I_{GS}$ was observed for the optimally stressed films.

*Fabrication process:* The AlGaN/GaN heterostructure epi-layers of this study were grown on a silicon substrate by metal organic chemical vapour deposition. From the substrate, the layer structure comprised a 0.25 µm AlN nucleation layer; a $10^{18}$ $cm^{-3}$ carbon doped buffer layer comprising a graded 1.8 µm AlGaN layer, followed by a 0.8 µm GaN layer; a 0.25 µm undoped GaN channel; a 1 nm mobility enhancing AlN interlayer; a 27 nm $Al_{0.27}Ga_{0.73}N$ barrier and a 2 nm GaN cap layer. Transistors were fabricated by first performing an electron beam evaporation of 30/180/40/100 nm Ti/Al/Ni/Au source and drain ohmic contacts which were annealed at 770°C for 30 s in $N_2$, followed by a 600 nm mesa isolation etch in a $SiCl_4$-based plasma chemistry. Then, 2 µm length, 20/200 nm thick Ni/Au Schottky gate contacts were defined by photolithography between the source and drain contacts. At this point, the 'unpassivated' transistor characteristics were measured on all samples.

The stress of an ICP-CVD $SiN_x$ passivation film can be adjusted by changing the ICP and RF platen powers [11]. Initially, without any surface pre-treatments, single layers of $SiN_x$ of various stresses were deposited on device samples described above as shown schematically in Fig. 1*a*. The stress in the films of Table 1 was determined when deposited on silicon substrates. With the exception of films (I and V) in Table 1, referred to elsewhere as 'conventional $SiN_x$', all the other films (II to IV of Table 1) cracked or delaminated; an example is shown in Fig. 2*a*. It was discovered that this situation could be overcome by first depositing 70 nm $SiN_x$ films using process (I) in Table 1 followed by the higher stress films [(II) to (V) of Table 1]. 'A typical bilayer' films are shown in Figs. 1*b* and 2*b*.

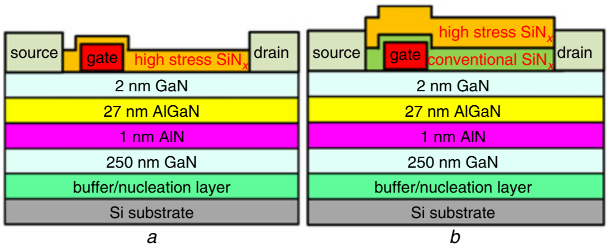


**Fig. 1** *Cross-section of surface passivation*

*a* 'High' stressed single layer surface passivation
*b* 'High/conventional' stressed bilayer surface passivation

**Table 1:** Stress conditions and type of $SiN_x$

| Ref. | ICP power, W | Platen power, W | Chamber pressure, mT | Stress, MPa | Refractive index |
|---|---|---|---|---|---|
| (I) | 200 | 0 | 5 | −280 (compressive) | 2.01 |
| (II) | 200 | 4 | 5 | −616 (compressive) | 1.99 |
| (III) | 300 | 4 | 5 | −1163 (compressive) | 1.93 |
| (IV) | 300 | 8 | 5 | −1622 (compressive) | 1.89 |
| (V) | 300 | 0 | 7 | +440 (tensile) | 1.72 |

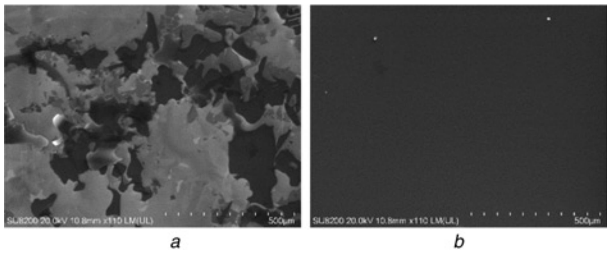


**Fig. 2** *SEM image of surface passivation*

*a* 'High' stressed single layer surface passivation
*b* 'High/conventional' stressed bilayer surface passivation

*Measurement results and discussion:* Fig. 3 shows room temperature electron mobility ($\mu_n$) and carrier concentration ($n_s$) as a function of various stress of $SiN_x$ bilayer as determined by Van der Pauw test structure measurement. Electron mobility is increased and carrier concentration is decreased as a consequence of highly compressive stress of $SiN_x$. This suggests either highly compressive stress of $SiN_x$ passivation schemes have reduction of net positive charge effect at the GaN surface and/or the presence of fixed positive charge in the $SiN_x$ films [12].

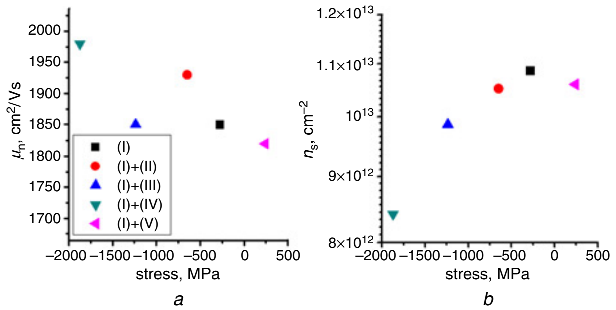


**Fig. 3** *Room temperature Van der Pauw evaluation*

*a* Stress–electron mobility by various passivation schemes
*b* Stress–carrier concentration by various passivation schemes

Fig. 4*a* shows semi-log scale $I_{DS}$–$V_{GS}$ and $I_{GS}$–$V_{GS}$ characteristics for the single and bilayer passivation schemes and are compared with unpassivated devices. The incorporation of passivations (I) + (II) and (I) + (V) result in three orders of magnitude increase in $I_{DS\text{-}off}$ and $I_{GS}$, when compared to unpassivated devices which have leakage currents of order 10 nA/mm. In contrast, devices with passivation (I) + (IV) have around four orders of magnitude reduction in $I_{DS\text{-}off}$ and $I_G$, when compared to unpassivated devices. Devices with passivation (I) + (IV) demonstrated $I_{on}/I_{off}$ ratio of $\sim 10^{11}$ and subthreshold slope of 68 mV/dec. Fig. 4*b* shows reverse Schottky gate leakage comparison of unpassivated and various stressed $SiN_x$ surface passivation schemes. The rank of Schottky reverse bias leakage is same as $I_{GS}$ leakage of Fig. 4*a*. Figs. 5*a* and *b*, respectively, show the $I_{DS}$–$V_{DS}$ three terminal off-state leakage current and $I_{GS}$–$V_{DS}$ lateral isolated leakage current ($I_{buffer}$) characteristics for the various passivation schemes. These clearly show the bilayer passivation (I) + (IV) is optimal in reducing these contributors to device leakage current.

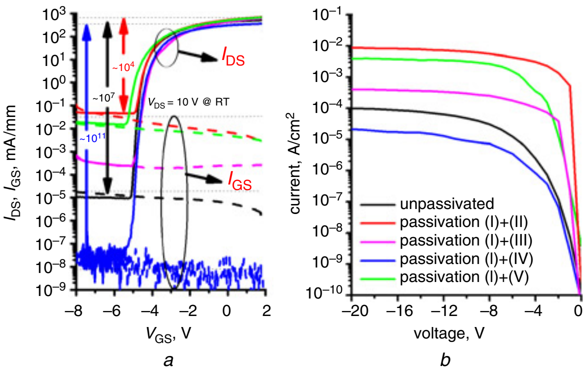


**Fig. 4** *Semi-log scale off-state and gate leakage comparison of unpassivated and various stressed $SiN_x$ surface passivation schemes*

*a* $I_{DS}$–$V_{GS}$ and $I_{GS}$–$V_{GS}$ comparison ($W_G$ = 100 µm, $L_{GS}$ = 2 µm, $L_G$ = 2 µm, $L_{GD}$ = 7 µm)
*b* Reverse Schottky gate leakage comparison

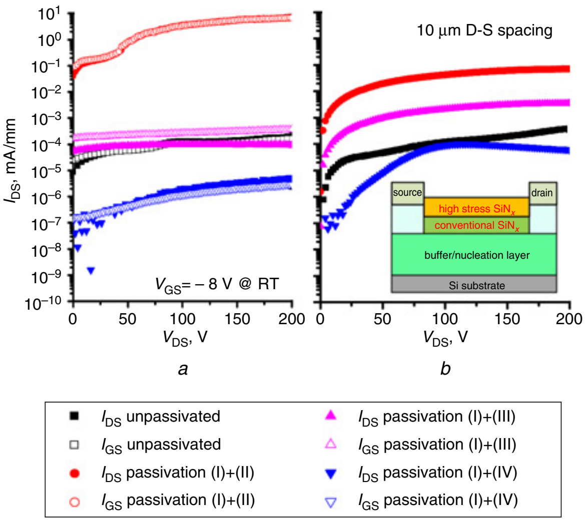


**Fig. 5** *Semi-log scale off-state and lateral isolated leakage comparison of unpassivated and various stressed $SiN_x$ surface passivation schemes*

*a* $I_{DS}$–$V_{DS}$ and $I_{GS}$–$V_{DS}$ off-state leakage current characteristics ($W_G$ = 100 µm, $L_{GS}$ = 2 µm, $L_G$ = 2 µm, $L_{GD}$ = 7 µm)
*b* Lateral isolated leakage current characteristics

*Conclusion:* In this Letter, the impact of stress in ICP-CVD $SiN_x$ surface passivation layers deposited at room temperature on $I_{DS\text{-}off}$ and $I_{GS}$ in AlGaN/GaN HEMTs is assessed. The use of a bilayer $SiN_x$ passivation scheme comprising 70 nm 280 MPa compressively strained film followed by a 150 nm 1.6 GPa compressively strained layer resulted in $I_{DS\text{-}off}$ and $I_{GS}$ reduction by up to four orders of magnitude when compared to unpassivated devices and up to seven orders of magnitude in comparison with devices with a single 70 nm 280 MPa compressively strained passivation layer. $I_{DS\text{-}off}$ and $I_{GS}$ of ~10 pA/mm, $I_{on}/I_{off}$ of ~$10^{11}$ and subthreshold slope of 68 mV/dec are obtained using the optimal process.

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One or more of the Figures in this Letter are available in colour online.

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