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Improved reliability of AlGaN/GaN-on-Si high electron mobility transistors (HEMTs) with high density Si₃₆N₆₄ passivation

W.A. Sasangka^a, G.J. Syaranamual^{a,b}, Y. Gao^{a,b}, R.I Made^a, C.L. Gan^{a,b,*}
and C.V. Thompson^{a,c}

^a *Low Energy Electronic Systems, Singapore-MIT Alliance for Research and Technology, Singapore 138602*

^b *School of Material Science and Engineering, Nanyang Technological University, Singapore 639798*

^c *Department of Material Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

Abstract

We have systematically studied the effects of Si_xN_{1-x} passivation density on the reliability of AlGaN/GaN high electron mobility transistors. Upon stressing, devices degrade in two stages, fast-mode degradation and followed by slow-mode degradation. Both degradations can be explained as different stages of pit formation at the gate-edge. Fast-mode degradation is caused by pre-existing oxygen at Si_xN_{1-x}/AlGaN interface. It is not significantly affected by the Si_xN_{1-x} density. On the other hand, slow-mode degradation is associated with Si_xN_{1-x} degradation. Si_xN_{1-x} degrades through electric-field induced oxidation in discrete locations along the gate-edges. The size of these degraded locations ranged from 100 to 300 nm from the gate edge. There are about 16 degraded locations per 100 μm gate-width. In each degraded location, low density nano-globes are formed within the Si_xN_{1-x}. Because of the low density of the degraded locations, oxygen can diffuse through these areas and oxidize the AlGaN/GaN to form pits. This slow-mode degradation can be minimized by using high density ($\rho = 2.48 \text{ gr/cm}^3$) Si₃₆N₆₄ as the passivation layer. For slow-mode degradation, the median time to failure of devices with high density passivation is found to increase up to 2X as compared to the low density ($\rho = 2.25 \text{ gr/cm}^3$) Si₄₃N₅₇ passivation. A model based on Johnson-Mehl-Avrami theory is proposed to explain the kinetics of pit formation.

Corresponding author

*clgan@ntu.edu.sg

Tel: +6567906220, +65 6790 6821

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W.A. Sasangka^a, G.J. Syaranamual^{a,b}, Y. Gao^{a,b}, R.I Made^a, C.L. Gan^{a,b,*}
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1. Introduction

The ability to monolithically integrate AlGaIn/GaN high electron mobility transistors (HEMTs) with Si complementary metal-oxide semiconductor (CMOS) circuits would be cost-effective and would open up new applications [1]. However, market adoption of this technology is still limited by the HEMT device reliability [2].

Upon on-state and off-state bias stressing, drain saturation current decreases over time. The decrease of the drain saturation current correlates well with physical degradation in the form of cracks [3], grooves [4], or pits [5]. The formation of these physical defects strongly depends on the applied voltage [4], temperature [6], threading dislocations [5,7], stressing duration [8], environment [9] and electron flow [10], in ways that are consistent with electrochemical oxidation [11].

One critical condition for such oxidation to take place is the presence of an oxidant. The oxidant can be in the form of water[11] or oxygen [9]. These oxidants are usually present at the passivation/AlGaIn interface depending on processing technology [12].

In this work, we found that Si_xN_{1-x} degrades through electrochemical oxidation during stressing. Oxidants (oxygen) is then able to diffuse through degraded locations Si_xN_{1-x} passivation layer, and eventually causes degradation of HEMT performance. We show that a possible solution to limit this degradation mechanism is to use high density Si₃₆N₆₄ as the passivation layer.

2. Experimental details

Figure 1. High angle annular dark field (HAADF) image of a fresh device

Figure 1 shows the layer structure of the devices used in this work. The epitaxial layers were grown using metal organic chemical vapor deposition (MOCVD). Device fabrication was carried out using conventional device

processing. Si_xN_{1-x} passivation was deposited using plasma enhanced chemical vapor deposition (PECVD). By varying the deposition conditions, we could produce different compositions of Si_xN_{1-x} and therefore different films with different densities, as seen in Table 1. Further details on device dimensions and process parameters can be found in [13].

Table 1. Comparison of material properties of low density vs. high density Si_xN_{1-x}.

Parameters	Low Density	High Density
Refractive Index	2.0229	2.0063
Thickness (nm)	120.6	117.9
Composition (EELS)	Si ₄₃ N ₅₇	Si ₃₆ N ₆₄
Density (XRR) (gr/cm ³)	2.25	2.48
Breakdown field of capacitor (MV/cm)	3.3	7.2

Figure 2. Electrical performance (direct current, static) of fresh devices with different passivation, measured at room temperature. a) I_D - V_G , V_D was fixed at 10 V. b) I_D - V_D .

We characterized the initial performance of both types of devices at room temperature. As seen in figure 2, passivation density does not significantly affect the electrical performance of the devices. Upon metallization removal, we also did not observe any pits in both types of devices

We stressed a total of 28 devices under constant reverse bias at 225°C, $V_G = -10$ and -20 V, and $V_D = 20$ V, for 500 hours. During stressing, we monitored the gate leakage current and recorded measurements every 4 seconds. We also measured the I_D - V_G characteristics of each sample every 5 hours. Further details of the stressing parameters and electrical analysis can be found in [5].

Various techniques were used to characterize material properties of the device. X-ray reflectometry (XRR) was used to measure the absolute density of the $\text{Si}_x\text{N}_{1-x}$. Transmission electron microscopy (TEM) was used to characterize microstructural defects. Electron energy loss spectroscopy (EELS) was used to measure chemical composition and relative density, especially near the defects.

3. Results and discussion

Figure 3 shows a cross-sectional transmission electron microscope image of a stressed device along the gate-edge of the drain side. One critical observation from figure 3a is that the $\text{Si}_x\text{N}_{1-x}$ passivation degrades at discrete locations (16 locations per 100 μm gate-width), instead of uniformly along the gate-edge. This is likely the reason we did not observe such passivation degradation when cutting samples at 90° with respect to the gate [5]. As seen in figure 3b, each degraded location has a very high concentration of oxygen. We observed nano-globes within these degraded locations. These nano-globes have much lower density as compared to the $\text{Si}_x\text{N}_{1-x}$ in the non-degraded locations.

Figure 3. Transmission electron microscopy image and EELS of a stressed device along the gate-edge on the drain side. a) Bright field view of a degraded location. b) Line scan chemical analysis along AA' using EELS, superimposed with local density

measurements.

At high temperatures (1100° – 1400°C), crystalline Si_3N_4 can react with oxygen to form SiO_2 , through the following reaction [14] :

Although our stressing temperature is only 225°C, a similar reaction may have occurred in this study due to the high electric field (1-3 MV/cm) at the gate-edge of the drain side. It has been reported that in the presence of a high electric field, Si_3N_4 can oxidize even at room temperature [15].

We believe that $\text{Si}_x\text{N}_{1-x}$ degrades through an electrochemical oxidation process. This suggests that the number of degraded locations is a function of V_{DG} stress. The higher the V_{DG} stress, the more degraded locations are likely to form

Once the $\text{Si}_x\text{N}_{1-x}$ degrades, oxygen from the ambient would easily diffuse through these low-density degraded locations and eventually react with the AlGaIn/GaN layer to form pits. This also explains the observation of Gao *et al* [9] that passivated devices degrade faster in air than under vacuum stressing.

Figure 4. Typical electrical characterizations of a device during stressing. a) $|I_g|$ vs V_G . b) $|I_D|$ vs V_G . Inset: Same graphs with vertical axis in log scale.

Figure 4 shows typical electrical characterizations of a device upon stressing. There is no significant change in the gate-leakage current (I_g), threshold voltage (V_{th}) and transconductance (g_m) over time. On the other hand, we consistently saw that the drain saturation current ($I_{D-saturation}$) decreased over time.

Figure 5 shows a $I_{D-saturation}$ profile over a 500 h stressing time. It can be seen that $I_{D-saturation}$ decreases over time in two stages. Initially, $I_{D-saturation}$ decreases quickly (fast mode/FM), then it slows down at a later stage (slow mode/SM).

Figure 5. Typical electrical degradation of a device during stressing for devices with different passivation. There are two stages of degradation, a fast mode (FM) and a slow mode (SM).

We hypothesize that the FM is associated with pit formation due to pre-existing oxygen at the $\text{Si}_x\text{N}_{1-x}/\text{AlGaIn}$ interface. As the oxygen is readily available at the interface, it is expected that transport and reaction at the gate edge would be fast. This is also supported by our EELS measurements at the $\text{Si}_x\text{N}_{1-x}/\text{AlGaIn}$ interface of a fresh device (not shown), in which oxygen is readily detected at the interface. On the other hand, the SM is likely associated with pit formation due to oxygen diffusion through degraded $\text{Si}_x\text{N}_{1-x}$.

Mode	V_{DG} (V)	$ DegFM $ (%)	t_{50} (h)	σ	ρ
FM-LD	30	14.2±10.8	95.2	0.70	0.98
FM-LD	40	15.2±8.8	74.6	0.78	0.90
FM-HD	30	8.8±2.3	93.2	0.75	0.99
FM-HD	40	11.8±4.3	77.5	0.48	0.95
SM-LD	30	-	200.8	0.40	0.93
SM-LD	40	-	148.0	0.60	0.98
SM-HD	30	-	408.4	0.63	1.00
SM-HD	40	-	182.7	0.52	0.97

(b)

Figure 6. Comparison of statistical reliability data of devices with low density passivation (LD) and high density passivation

(HD), stressed at two different voltages. a) Statistical plot of the device failure times analysed separately for each degradation mode, fit with lognormal distributions (lines). b) Table summarizing the statistical parameters for different test conditions and failure modes.

With the FM-SM degradation hypothesis in mind, we plot the statistical reliability of the devices as shown in figure 6. The FM's failure time (t_{FM}) is taken at the transition point from FM to SM (see figure 5). The failure time of the SM (t_{SM}) is defined as the time required for $I_{D-saturation}$ to degrade an additional 3% from its value determined at t_{FM} . It appears that the data is better fitted with a lognormal rather than a Weibull distribution function.

The key parameters for the lognormal distribution (the median time to failure t_{50} , deviation in the time to failure σ , and correlation coefficient ρ) are computed and shown in the table in figure 6. As seen, the applied drain-gate voltage has a strong correlation with t_{50} , regardless of the density of the $\text{Si}_x\text{N}_{1-x}$ for both FM and SM degradation. This is consistent with the electrochemical oxidation model. For the SM, high density $\text{Si}_{36}\text{N}_{64}$ leads to a higher t_{50} (up to ~2X) than low density $\text{Si}_{43}\text{N}_{57}$. The oxidation of silicon nitride (Si_3N_4) is known to be controlled by oxygen diffusion [14]. We expect that high-density $\text{Si}_{36}\text{N}_{64}$ has a lower oxygen diffusivity and therefore lower oxidation rate. This is likely the reason that higher density $\text{Si}_{36}\text{N}_{64}$ has a higher t_{50} . For the FM, the density of the $\text{Si}_x\text{N}_{1-x}$ has no correlation with t_{50} . This suggests that the amount of pre-existing oxygen for both types of passivation is similar. These observations are consistent with our FM-SM degradation hypothesis.

Figure 7. Schematic drawings of a proposed kinetic model for pit growth based on a Johnson-Mehl-Avrami analysis. a) A hemispherical shape of single pit is assumed. b) Top view: oxygen diffuses toward the gate-edge where it leads to pit nucleation and growth. c) Oxygen concentration profile across the diffusion field of width (δ) that changes over time t at the $\text{Si}_x\text{N}_{1-x}/\text{AlGaIn}$ interface (adapted from [16]).

For the FM degradation, we propose a kinetic model to explain how pits grow over time upon stressing, as illustrated in figure 7. The model is based on a Johnson-Mehl-Avrami (JMA) analysis of the combined effects of nucleation and growth [17]. First, we will assume that

pits nucleate only at dislocations, and that these sites are "saturated" early during the pit formation and growth process. This assumption is reasonable as we have shown that all pits are associated with threading dislocations [5] and the devices used in this work have very high threading dislocation densities ($\sim 10^9/\text{cm}^2$). This also follows from our observation that the sizes of the pits after coalescence are relatively uniform (not shown). In this model, we also assume that pits nucleate and grow only at the gate-edge near the drain, which is consistent with our previous results [10].

We consider three possible scenarios that may give different values of the Avrami constant (n). In scenario I, we consider the case that the rate of pit growth is limited by diffusion of oxygen toward the gate-edges at the $\text{Si}_x\text{N}_{1-x}/\text{AlGaIn}$ interface, and that the diffusion flux is constant over time. In scenario II, the oxygen diffusion flux is taken to decrease over time (figure 7c). In scenario III, we consider the case that the rate of pit growth is limited by the reaction at the perimeter of the pit at the surface.

In the model, we assume that all pits have a hemispherical shape with a radius (r), as shown in Figure 7a. The volume of a single pit (V) is then given by

$$V = \frac{2}{3}\pi r^3. \quad (2)$$

The pits are filled with an oxide that is a result of a reaction between oxygen and the AlGaIn layer [5]. In a single pit, we can represent the number of oxide molecules, N_r as

$$N_r = \frac{2}{3}\pi r^3 \Omega^{-1}, \quad (3)$$

$$\text{so} \quad \frac{dN_r}{dt} = 2\pi r^2 \Omega^{-1} \frac{dr}{dt}, \quad (4)$$

where Ω is the volume of an oxide molecule.

For scenario I, the number of arriving oxygen molecules per unit length of gate-edge, N_a^I , is constant over time,

$$\frac{dN_a^I}{dt} = \alpha_1 = \frac{dN_r}{dt} = N_p 2\pi r^2 \Omega^{-1} \frac{dr}{dt}, \quad (5)$$

where N_p is the number of pits per unit length of gate-edge and α_i is a constant. Re-arranging equation (5) gives,

$$\alpha_2 dt = N_p r^2 dr, \quad (6)$$

$$\text{so} \quad \int_0^t \alpha_2 dt = \int_0^r N_p r^2 dr, \quad (7)$$

$$\text{and} \quad r^I = \alpha_3 N_p^{-1/3} t^{1/3}. \quad (8)$$

For the case of one dimensional growth and nucleation site saturation, following the derivation of the JMA equation [17] gives the fraction of gate-edge length that is oxidized to form pits, L^I , as

$$L^I = 1 - \exp\left(-\alpha_4 N_p^{2/3} t^{1/3}\right). \quad (9)$$

As seen in equation (8), the Avrami exponent for scenario I is $n^I = 1/3$.

For scenario II, the oxygen diffusion flux decreases

over time. As the pre-existing oxygen is consumed, the diffusion field width $\delta(t)$ grows as shown in figure 7c. In this case, the rate at which oxygen molecules arrive at the gate-edge varies as $t^{-1/2}$,

$$\frac{dN_a^{II}}{dt} = \alpha_5 t^{-1/2}. \quad (10)$$

Following the derivation of equations (2) to (7),

$$r^{II} = \alpha_6 N_p^{-1/3} t^{1/6}. \quad (11)$$

Substituting equation (11) into JMA derivation,

$$L^{II} = 1 - \exp\left(-\alpha_7 N_p^{2/3} t^{1/6}\right). \quad (12)$$

As seen in equation (12), the Avrami exponent for scenario II is $n^{II} = 1/6$.

Scenarios I and II assume that the pit growth rate is limited by oxygen diffusion toward the gate-edge. In scenario III, we assume that the pit growth rate is limited by the reaction at the perimeters of the pits. With this assumption, the rate at which oxide molecules are formed can be represented as,

$$\frac{dN_a^{III}}{dt} = N_p 2\pi k r, \quad (13)$$

where k is the rate constant for the reaction of oxygen molecules with AlGaIn. Under steady state conditions,

$$\frac{dN_a^{III}}{dt} = \frac{dN_r}{dt}. \quad (14)$$

Substituting (4) and (13) into (14),

$$r^{III} = \alpha_9 N_p^{-1/2} t^{1/2}. \quad (15)$$

Using equation (15) in the JMA derivation,

$$L^{III} = 1 - \exp\left(-\alpha_{10} N_p t^{1/2}\right). \quad (16)$$

As seen in equation (16), the Avrami exponent for scenario III is $n^{III} = 1/2$.

Table 2. Avrami exponents describing pit formation for devices with different passivation densities and stressed at different voltages.

Mode	V_{DG}	t_{50} (hours)	Sigma	Avrami constant (n)
FM-LD	30	95.24	0.70	0.72 ± 0.36
FM-LD	40	74.55	0.78	0.237 ± 0.14
FM-HD	30	93.15	0.75	0.472 ± 0.18
FM-HD	40	77.46	0.48	0.215 ± 0.10

We have computed Avrami exponents for each set of device degradation data and the results are shown in Table 2. It appears that under high voltage stressing ($V_{DG} = 40$ V), the Avrami exponents for both low and high density $\text{Si}_x\text{N}_{1-x}$ are between 1/6 and 1/3. For devices stressed at low voltage ($V_{DG} = 30$ V), the Avrami exponent is closer to 1/2. These results suggest that at high voltages, the pit growth rate is limited by oxygen diffusion toward the gate-edge. At low voltages, the reaction at the pit perimeter is so slow that it becomes the rate limiting.

4. Conclusion

This work advances the state-of-the-art understanding of physical degradation in AlGaIn/GaN HEMTs in three key areas. First, we provide evidence that pre-existing oxygen is detrimental to device reliability. Its presence can decrease device lifetimes by $(2/3)X$, regardless of the passivation density. Device fabrication processes should be optimized to minimize this effect. We have also shown that $\text{Si}_x\text{N}_{1-x}$ passivation degrades through electrochemical oxidation upon stressing under high temperature reverse bias. Once the $\text{Si}_x\text{N}_{1-x}$ degrades, oxygen from the ambient diffuses through the passivation to electrochemically oxidize the AlGaIn surface to form pits at the gate edge. High density $\text{Si}_{36}\text{N}_{64}$ slows down this mode of degradation and leads to an improved device reliability of about $2X$. Finally, based on Johnson-Mehl-Avrami theory, we have proposed a model to explain the pit growth kinetics at the gate-edge. The model reveals a strong dependence of the reaction rate at the pit perimeters on the stressing voltage. Our work suggests that oxygen-free $\text{Si}_x\text{N}_{1-x}$ /AlGaIn interfaces and high-density passivation are essential to achieve long-lifetimes for AlGaIn/GaN HEMTs.

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