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Corrosion-induced degradation of GaAs PHEMTs under operation in high humidity conditions

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\section*{ABSTRACT}

We have comprehensively investigated the degradation mechanism of AlGaAs/InGaAs pseudomorphic high-electron-mobility transistors (PHEMTs) under operation in high humidity conditions. PHEMTs degradation under high humidity with bias consists of a decrease in maximum drain current ($I_{\text{max}}$) caused by a corrosion reaction at the semiconductor surface at the drain side. The decrease in $I_{\text{max}}$ is markedly accelerated by the external gate-drain bias ($V_{\text{gd}}$). This originates from a reduction in the actual activation energy ($E_{\text{a0}}$) by $V_{\text{gd}}$. The degradation depends on the surface treatment prior to deposition of the SiNx passivation film. The reduction of As-oxide at the SiN$_x$/semiconductor interface suppresses the corrosion reaction.

\textbf{Keywords}

AlGaAs/InGaAs PHEMT, Reliability, High humidity, Surface degradation, Corrosion

\section*{INTRODUCTION}

AlGaAs/InGaAs PHEMTs are being widely used for high frequency applications such as automotive radars and satellite communications [1-3], direct broadcast satellite (DBS) and cellular phones. Recently,
the demand of low cost AlGaAs/InGaAs PHEMTs with keeping high frequency performance is emerging for these applications. In order to reduce the cost of the devices, there has been wide recent interest in the last few years in the use of non-hermetic packages. To survive in non-hermetic packages, GaAs devices must have resistance to humidity. Thicker passivation films and other polymer coatings (e.g., polyimide and benzo cyclo butane (BCB)[4-5]) on the devices without a hermetic sealing have conveniently been used as a primitive method to protect the device surface, despite the fact that these films and coatings degrade the high-frequency characteristics due to their parasitic capacitance. In order to simultaneously meet the demand for high performance and low cost, there is a need for a highly reliable high-power GaAs PHEMT technology under high humidity conditions.

We have previously reported a comprehensive study of the dependence of degradation in PHEMTs on bias ($V_{gd}$), ambient temperature ($T_a$), and relative humidity ($RH$) [6-7]. These experimental results of the degradation rate can be explained by a proposed mechanism that the degradation is caused by surface electrochemical corrosion reaction taking place at the drain surface between semiconductor and H$_2$O. It was found that the degradation rate is changed by $RH^3$, $\exp(V_{gd})$, and $\exp(-E_a/kT_a)$, where $E_a$ is activation energy and $k$ is Boltzmann constant [6]. According to the electrochemical corrosion reaction model, we showed theoretically that $V_{gd}$ lowers $E_a$. We also demonstrated that a surface treatment prior to deposition of a SiNx passivation film can effectively suppress the surface electrochemical reaction. The result shows that the surface electrochemical reaction strongly depends on the condition of semiconductor/SiNx interface.

In this paper, we experimentally confirm the dependence of $E_a$ on $V_{gd}$ in PHEMTs. We also present evidence behind the corrosion suppression mechanism of our surface treatment. We show through XPS analysis that a reduction of As-oxide at SiNx /semiconductor successfully suppresses the corrosion reaction.

**EXPERIMENTAL**

AlGaAs/InGaAs PHEMTs with around 0.2 µm gate length ($L_g$) were fabricated for this study. The T-shaped gate was patterned by electron beam lithography. The gate region was wet-chemically recessed to a desired drain current and metallized with Ti/Al. These devices were passivated with silicon nitride by plasma enhanced chemical vapor deposition (PECVD). The dependence of $I_{max}$ reduction on drain bias, temperature was determined by the DC stress test under high humidity condition. After the stress test, cross-sectional transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDX) analysis were also performed.

**RESULTS AND DISCUSSION**
A. Degradation model of PHEMT

Fig. 1 shows cross-sectional transmission electron microscopy (TEM) image of a typical degraded device under biased humidity test ($T_a=130^\circ C$, $RH=85\%$, $V_{gd}=5$ V). A degraded surface region was observed on the semiconductor surface in the proximity of the recess on the drain side of the device. A significant amount of oxygen is observed at the degraded region by energy dispersive X-ray spectroscopy (EDX) analysis as shown in Fig. 2. From these results, we proposed the mechanism of degradation under humidity, bias and temperature [6]. $I_{\text{max}}$ reduction is caused by the surface degradation attributed to a corrosion reaction of semiconductor surface with oxygen or $H_2O$ enhanced by electric field.

The GaAs corrosion reaction can be described by

$$\text{IIIAs} + 3H_2O + 3/2O_2 \rightarrow \text{III(OH)}_3 + \text{As(OH)}_3$$

$$\rightarrow 1/2 \text{III}_2\text{O}_3 + 1/2\text{As}_2\text{O}_3 + 3H_2O \quad \text{III: Ga, Al} \quad (1)$$

Consequently, the reaction rate ($v$) at which GaAs surface corrosion takes place is

$$v = k_0[H_2O]^3[O_2]^{3/2} \quad (2)$$

where $k_0$ is the rate constant.

The potential energy between the anode and outer Helmholtz plane (O.H.P.) with and without an external voltage ($\eta$) is shown in Fig.3, where $\beta$ is a contribution factor. The activation energy ($E_a$) depends on $\eta$. The increase of $\eta$ reduces $E_a$ [8]. When the reaction rate is dominantly controlled by the charge-transfer reaction, the rate constant ($k_0$) of the anode electrode is expressed by

$$k_0 = A \exp \left( \frac{-E_a(0)}{kT} \right) \cdot \exp \left( \frac{n\beta\eta}{kT} \right) = A \exp \left( \frac{-\left(E_a(0) - n\beta\eta\right)}{kT} \right) \quad (3)$$

where $\eta$, $\beta$, $E_a(0)$, A, k, e, and n are external voltage, contribution factor, the activation energy at $\eta$ = 0, frequency factor, Boltzmann constant, elementary charge, and the number of electrons contributing to the reaction, respectively[8-9].

Previous results that $I_{\text{max}}$ change increased by $RH^3$ and exp ($V_{gd}$) [6] agrees well with eq. (2) and eq.(3), respectively. As $\eta$ is determined by $V_{gd}$, eq.(3) shows higher $V_{gd}$ decreases resultantly the actual activation energy ($E_a(\eta)$).

B. $V_{gd}$ dependence of $E_a$

In order to confirm the $V_{gd}$ dependence of $E_a$ experimentally, we employed the humidity test under $T_a$ between 110$^\circ C$ to 130$^\circ C$, $RH=85\%$ with bias as a function of $V_{gd}$ = 3 and 5 V. $I_{ds}$ at $V_{ds} = 1V$, $V_{gs}=+0.5V$ was automatically measured every 30 minutes in the furnace in the course of the humidity test.
Fig. 4 shows the degradation of $I_{\text{max}}$ with stress time as a function of $V_{gd} = 3$ and 5 V during a humidity test with $T_e = 130\,^\circ\text{C}$ and $RH=85\%$.

The behavior of $I_{\text{max}}$ degradation ($\Delta I_{\text{max}}$) is distinctively separated in two modes in which $\Delta I_{\text{max}}$ is proportional to $t$ and $t^{0.5}$, respectively. According to the corrosion reaction of eq. (2), $k_g$ is a constant. Therefore, $\Delta I_{\text{max}}$ indicates the growth of corrosion which follows a linear law for short stress times. This reaction-limited corrosion is mainly observed in the initial stage in which $\Delta I_{\text{max}}$ ranges from 0 to around 30\%, as shown in Fig. 6. After this initial stage, a diffusion-limited corrosion reaction is observed mainly by a parabolic evolution in time ($t^{0.5}$). These results indicate that the initial reaction-limited corrosion reaction moves to a diffusion-limited corrosion reaction beyond a critical oxide thickness. The time at 10\% decrease in $I_{\text{max}}$ is used to extract the $V_{gd}$ dependence of $E_a$ that is shown in fig. 5. $E_a = 0.46$ eV at $V_{gd} = 5$ V, and $E_a = 1.53$ eV at $V_{gd} = 3$ V are observed, respectively.

All experimental results are consistent with our proposed corrosion mechanism, which is enhanced by temperature, humidity, and electric field.

C. Suppression mechanism by pre-deposition treatment

As reported previously [10], a surface treatment just prior to the deposition of SiN$_x$ effectively suppresses the degradation of PHEMT. In order to investigate this suppression mechanism, we employed an additional AlGaAs epitaxial wafer of the same composition as the barrier layer in the HEMT. This wafer had around 3 nm SiN$_x$ deposited on top. This sample was stored in $RH = 85\%, T_e = 130\,^\circ\text{C}$. We analyzed the semiconductor/SiN$_x$ interface by X-ray photoelectron spectroscopy (XPS) before and after the humidity test.

Fig. 6 shows relative intensity of XPS at the SiNx/AlGaAs interface as a function of storage time for the sample with (a), and without (b) surface treatment. The XPS intensity at time $=0$ indicates that the amount of all oxides on the sample with surface treatment is smaller than without surface treatment. Especially, As-oxide is not detected in the sample with surface treatment as shown in XPS spectra in Fig. 7.

For the samples without the surface treatment Ga-oxide, Al-oxide and As-metal of the sample increase significantly as a function of storage time, as shown in Fig. 6 (b). The change in As-oxide (As$_2$O$_3$) is relatively small. The increase of Ga-oxide and Al-oxide indicates that the corrosion reaction shown in eq. (1) is occurring. The increase of metal-As against small change of As-oxide indicates that As-oxide generated by eq.(1) changes to III-oxide and metal–As as followed by the reaction shown in eq. (4) [12].

$$\text{As}_2\text{O}_3 + 2\text{IIIA}_2 \rightarrow 2\text{IIIO}_3 + 4\text{As} \quad \text{III: Ga, Al} \quad (4)$$

As-Oxide react with Ga(Al)As, consequently change to metal–As as shown in eq. (4). Metal-As easily reacts with oxygen and H$_2$O diffused from ambient to As-oxide. These chain reactions might promote the corrosion reaction at the SiN$_x$/semiconductor interface. These chain reactions in the samples
with the surface treatment in which the As-oxide is not detected are suppressed. In order to suppress the corrosion reaction at the SiNx/AlGaAs the interface, reduction of As-Oxide might play an important role.

CONCLUSION

In summary, the AlGaAs/InGaAs PHEMTs degradation under high humidity condition with bias is caused by a corrosion reaction at the semiconductor surface on the drain side. $V_{gd}$ decreases the actual activation energy for corrosion. The degradation strongly depends on surface treatment prior to deposition of a SiNx passivation film. The reduction of As-oxide at SiNx/semiconductor might successfully suppress the corrosion reaction.

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REFERENCES


FIGURE CAPTIONS

Fig.1: TEM image of a degraded device under biased humidity test ($RH=85\%, T_a=130^\circ C, V_{gd}=5V$)

Fig.2: Energy dispersive x-ray spectroscopy (EDX) spectra of degraded region of Fig.1.
Fig.3: Schematics of corrosion mechanism at the semiconductor surface of PHEMTs: (a) Schematics of corrosion mechanism at surface region in the vicinity of the recess on the gate-drain portion of the device and (b) Potential change near the surface between the semiconductor surface and the outer Helmholtz plane (OHP)[6].

Fig.4: $\Delta I_{\text{max}}(V_{gd}=1\text{V}, V_{gs}=-0.5\text{V})$ as a function of stress time during humidity test ($RH=85\%, T_a=130^\circ\text{C}, V_{gd}=3.5\text{V}$) for $V_{gs}=3.5\text{V}$.

Fig.5: $V_{gd}$ dependence of $E_a$ of degradation. The $E_a$ is extracted from time of $-10\%$ decrease in $I_{\text{max}}$ during humidity test ($RH=85\%$) as a function of temperature.

Fig.6: Relative intensity of XPS as a function of storage time of humidity test ($RH=85\%, T_a=130^\circ\text{C}$). The sample is SiNx 3nm/AlGaAs (a) with and (b) without surface treatment.

Fig.7: As 3d XPS spectra for the AlGaAs/SiNx sample (a) with and (b) without surface treatment.
Drain side
Degradation region

100 nm

Fig. 1
Fig. 3
Fig. 4

Linear reaction
\[ \Delta I_{\text{max}} \propto t \]

Root reaction
\[ \Delta I_{\text{max}} \propto t^{0.5} \]

RH=85%
Ta=130°C
Fig. 5

RH=85%

$V_{gd}=3V$

$E_a=1.53eV$

$V_{gd}=5V$

$E_a=0.46eV$

$1000/T(K)$

Time (Hr)
(a) With surface treatment

(b) Without surface treatment
Fig. 6

(a) With surface treatment

(b) Without surface treatment

Fig. 7