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Characteristics of SiN/GaAs interface under exposure to high-temperature and high-humidity conditions measured by photoreflectance spectroscopy

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Abstract: We investigated the changes in the electrical properties of a SiN/GaAs interface under high-temperature and high-humidity conditions, using photoreflectance (PR) spectroscopy and the electrical device characteristics. The PR spectra show the Franz-Keldysh oscillation (FKO); these spectra show that the period decreases after the sample is exposed to humidity. The electric field strength obtained from the FKO period indicates that the initial high electric field decreases with humidity exposure. Decomposed water molecules are supposed to diffuse into the SiN layer and react with the SiN/GaAs interface, causing a decrease in the interface states.

Keywords: reliability, photoreflectance, Franz-Keldysh oscillation, humidity, MESFET

Classification: Electron devices, circuits, and systems

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1 Introduction

Recently, it has been necessary to improve the humidity tolerance of GaAs compound semiconductor devices [1]. These components are commonly used in cellular phones and satellite receivers, which are often enclosed in non-hermetic packages in order to reduce the device cost [2]. Further, it should be noted that the thickness of a passivation film, which generally consists of a silicon nitride (SiN) layer, cannot be increased in high-frequency devices because this increase would degrade their high-frequency characteristics [3]. Therefore, to improve the humidity tolerance of these semiconductors, it is important to first investigate the mechanism that causes humidity to change their performance. Humidity tolerance has been evaluated using practical high-frequency devices under high-temperature and high-humidity conditions. Hisaka *et al.* reported that the maximum drain current ($I_{\mathrm{D(MAX)}}$) of AlGaAs/InGaAs pseudomorphic high electron mobility transistor (PHEMT) devices decreased when these devices were exposed to high-temperature and high-humidity with electrical bias condition [4]. Shiramizu *et al.* exposed a planar SiN/GaAs sample and observed that oxygen diffused from the surface of the sample; they identified the reaction that occurred between GaAs and moisture using secondary-ion mass spectrometry (SIMS) [5]. This pa-

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per describes the electrical characteristics of the SiN/GaAs interface after it is exposed to high-temperature and high-humidity. We use non-destructive photoreflectance (PR) spectroscopy to evaluate the electrical characteristics of this interface. In this paper, we introduce our experimental procedure and method of interpreting the PR spectra, following which we present our experimental results and discussions.

2 Experimental

We used an i-GaAs (200 nm)/n-GaAs (3000 nm, $3.0 \times 10^{18}\,\mathrm{cm}^{-3}$) epitaxial wafer. A 30-nm-thick SiN layer was deposited on the flat wafer surface by conventional plasma enhanced chemical vapor deposition (PECVD). The refractive index of the deposited SiN was $n = 1.98$. For the device exposure study, a single-recessed metal-semiconductor field-effect transistor (MESFET) with a square-shaped Ti/Al gate covered with a 30-nm-thick SiN layer was used, with a gate length L_g of 0.5 μm. The MESFET was fabricated using an n-GaAs (410 nm, $3.2 \times 10^{17}\,\mathrm{cm}^{-3}$) epitaxial layer grown on regular GaAs buffers and GaAs/AlGaAs superlattice buffers. The MESFET was subjected to high-temperature and high-humidity with no electrical bias in a chamber at a temperature, humidity, and pressure of 180°C, 100%, and 9.9 atm, respectively. To increase the sensitivity of PR measurement, we intentionally used i-GaAs in PR instead of n-GaAs; however, we think that the change mechanism is not much different between i-GaAs and n-GaAs within the scope of this experiment, because the carrier density of n-GaAs is not so high. The surface states or the effect of the SiN/GaAs interface states of the MESFET was examined by the gate voltage pulsing method, what is called gate lag measurement [6]. The gate pulse width, pulse period, monitored gate voltage, off-time gate voltage, and applied drain voltage were 1.0 ms, 100 ms, $V_{GS} = +0.4$ V, $V_{GS} = -3$ V, and $V_{DS} = 1.0$ V, respectively. The photon energy of the pumping laser used in the PR measurements was 2.33 eV. The source of the probe beam was a tungsten-halogen lamp, dispersed by a monochromator. The measurements were performed at room temperature. The measurement method is described in detail in the literature [7].

3 Results and discussions

Figure 1 (a) shows the PR spectra of the as-deposited SiN sample on the epitaxial wafer (initial) and after the sample was exposed for 72 h. The spectra show major oscillations at a band-gap region of GaAs and a subsequent large number of oscillations from 1.5 eV to 1.6 eV. Figure 1 (b) shows the measured spectra at high sensitivity to magnify the small oscillations shown in Fig. 1 (a). A comparison between the measured spectra of the initial and exposed spectra shows that there is no difference in the band-gap region in Fig. 1 (a); however, an apparent shift in the oscillation is observed in a higher energy region, and the extrema gradually make an obvious separation, as shown by arrows in Fig. 1 (b). If the oscillations are caused by Franz-Keldysh oscillation (FKO), the period of the extrema are expressed by

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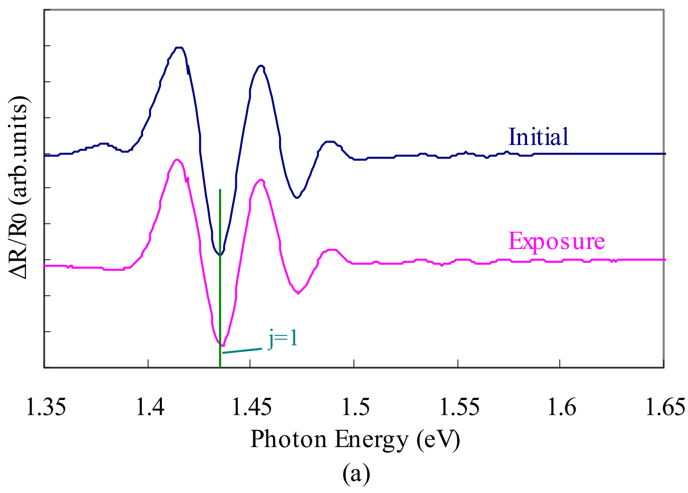

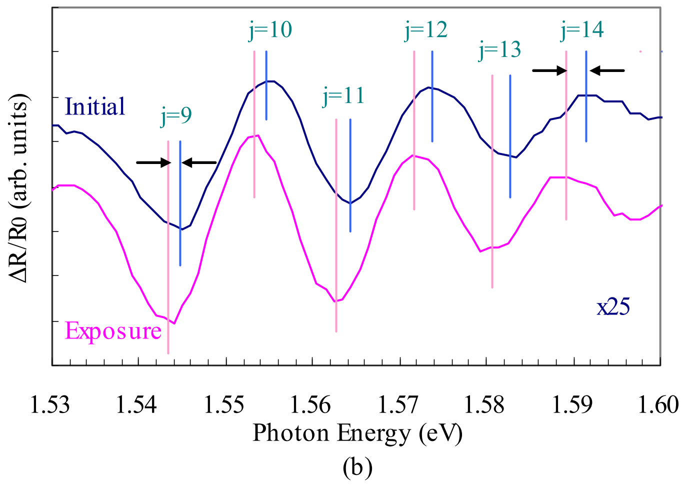

Fig. 1. (a) PR spectra from SiN/i-GaAs/n-GaAs of as-deposited SiN before and after 72 h of exposure to high temperature and high humidity. (b) Magnified PR spectra of (a). Vertical lines are the fitted J_{th} extrema calculated by Eq. (1).

the following relationship [7].

$$\hbar\omega_j = \hbar\Theta_{HH}\left[\frac{3\pi}{4}\left(j-\frac{1}{2}\right)\right]^{\frac{2}{3}} + E_G \tag{1}$$

Here, j is the extremum index, $\hbar\omega_j$ is the position of the j_{th} extremum, $\hbar\Theta_{HH}$ is the electro-optic energy associated with the Γ–HH transition, and E_{G} is the band gap of i-GaAs.

The relationship between the electro-optic energy and the electric field strength is given by [7],

$$(\hbar\Theta_{HH})^3 = \frac{e^2\hbar^2E^2}{2\mu_r} \tag{2}$$

Here, E is the electric field strength, and μ_{r} is the interband reduced mass in the direction of the electric field. The vertical lines shown in Fig. 1 are the calculated and fitted j_{th} extrema of the initial sample (28.02 kV/cm)

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Table I. DC and pulse characteristics of MESFET before and after 72 h exposure.

Exposure	Initial	72h
Pulse (I_{DS}) / DC(I_{DS}) (%)	70.8	88.7
$I_{DS(max)}$ (mA/mm)	259.7	261.8
Threshold voltage V_{TH} (V)	-0.98	-1.02
Ideality factor n	1.36	1.35
Schottky barrier height ϕ_B (eV)	0.59	0.59
Source resistance R_S (Ω·cm)	1.02	1.04
Drain resistance R_D (Ω·cm)	1.04	1.06

and the exposed sample (27.01 kV/cm). These lines are in good agreement with the experimental extrema. As shown in Fig. 1 (b), the period of the FKO decreases after the sample is exposed. This result indicates that the electric field strength of the SiN/GaAs interface decreases after exposure, as calculated in Eqs. (1) and (2).

In order to correlate the PR result with the actual device, we exposed the MESFET in a similar manner. Table I summarizes the changes in the electric characteristics of the MESFET. The ratio of pulse (I_{DS}) and DC (I_{DS}) increases from 70.8% in the initial sample to 88.7% in the exposed sample. Further, $I_{DS(max)}$ either slightly increases or does not change within the range of the experimental accuracy, and V_{TH} slightly shifts toward a negative voltage. Other characteristics such as Schottky characteristics (ideality factor (n), barrier height (ϕ_B)), R_S and R_D, do not show remarkable changes. These changes indicate that the main change caused by exposure is the decrease in the SiN/GaAs interface states.

Vittadini *et al.* indicated that the adsorbed water is dissociated on the Si surface, resulting in the generation of hydroxyl (OH) and atomic hydrogen (H) radicals [8]. Therefore, we think that part of the exposed water is dissociated at the SiN surface in the same manner. Because these dissociated species have a smaller molecular radius than the larger H_2O molecules, they can easily diffuse into the SiN film and reach the SiN/GaAs interface. This phenomenon can be estimated from the SIMS data [5]. The SIMS result shows that although the reaction at the SiN/GaAs interface begins, oxidation is observed only at the SiN surface; this implies that small species diffuse more rapidly in the SiN film. The initial SiN/GaAs interface contains many dangling bonds attributed to the plasma damage; thus, this interface has a certain number of interface states. We think that after the interface is exposed to high-temperature and high-humidity, the diffused H or OH species terminate the dangling bonds; next, the density of the interface states decreases, which in turn causes a decrease in the surface depletion layer or in the interface recombination velocity or relaxation of Fermi-level pinning. We also assumed that an initial oxidation of the interface and the relaxation of atomic stress occur. Hwang *et al.* demonstrated that oxide (Ga_2O_3) formation effectively passivated the GaAs film, decreasing the density of the

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interface states [9]. Although they described the initial stage oxidation, after exposure for a long period of time, the interface states and the oxidation layer may increase. The results of our study seem to correspond to an early stage of exposure. As a result, we assume that the decrease in the interface states causes the decrease in the electric field strength during exposure.

4 Conclusion

We used a non-destructive analytical technique of PR spectroscopy to characterize the electric field strength at the GaAs surface passivated by the SiN layer deposited by PECVD and found that the spectra changed during exposure under high-temperature and high-humidity conditions. The obtained PR spectra show a large number of oscillations, and the relationship between the oscillation period and the extrema of the probe photon energy confirms that this result can be attributed to FKO. The calculated electric field strength is decreased by the exposure. This decrease is attributed to a change in the dangling bond termination and/or interface reactions with diffused H or OH species supplied by dissolved water at the SiN surface that diffuses into the SiN/GaAs interface.

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