Effects of Nitrided-InGaAs Interfacial Layers formed by ECR nitrogen plasma on Al_2O_3/InGaAs MOS Properties

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1. Introduction

III-V MOSFETs are attracting an interest as a solution for the performance limitation of scaled Si MOSFETs. Among various III-V compound semiconductors, InGaAs has been regarded as a promising n-MOSFET channel material owing to the high electron mobility and appropriate effective mass [1]. Previously, we have found that electron cyclotron resonance (ECR) plasma nitridation of InGaAs surfaces reduces D_b, SiO_x/InGaAs with the nitrided interfaces has yielded the minimum D_b value of 2 x 10^{11} cm^{-2}eV^{-1} with the CET increase of 1.3 nm [2] and ALD-Al_2O_3/nitrided-InGaAs MOS interfaces have exhibited lower D_b distribution with the CET increase of 0.65 nm [3]. Also, XPS studies on these interfaces have revealed that the D_b reduction is attributable to the formation of Ga-N bonds at the MOS interfaces due to the nitridation and successive annealing. In this study, the impact of plasma nitridation conditions on the MOS properties and the physical origins of the dependence are from the viewpoint of the MOS interface structures for further reducing D_b and decreasing CET.

2. Experiments

Fabrication process of MOS capacitors and XPS samples are illustrated in Fig. 1. A Si-doped n-InGaAs layer (N_d ~ 5 x 10^{17} cm^{-3}) was grown on a 2-inch (001) InP substrate at 610 °C by MOVPE. After surface oxide removal with 10% HCl, nitridation was performed by ECR plasma in Ar and N_2 ambient at ~1 x 10^{-3} Pa without heating the substrates. After nitridation, Al_2O_3 deposition using tri-methyl aluminum and H_2O as the liquid sources was performed with 8.8 nm for capacitors and 1 nm for XPS samples. After that, annealing was performed at 500 °C for 1 min under nitrogen ambient. As the nitridation conditions, the microwave power, P_{microwave}, for the ECR plasma generation and nitridation time, t_{nitridation}, were changed. The D_b values were evaluated by using the conductance method and the increased CET values associated with the nitridation were evaluated as the difference of the capacitance in accumulation region with and without nitridation. Also, the Ge 2p spectra were analyzed to study the physical origins of the D_b decrease and increase under nitridation. Here, the spectra were de-convoluted into four components of the bulk InGaAs, Ga_2O_3, InGaO_2 and Ga-N bonds. Here, the peaks of Ga_2O_3, InGaO_2 and Ga-N were assumed to locate at 1.1, 1.8 [4] and 0.8 eV [5] above that of the bulk Ga, respectively.

3. Result and Discussion

In order to confirm the nitrided layer, a HAADF image and an EELS profile, shown in Fig.2 (a) and (b), are taken for the cross section of a capacitor with nitridation using P_{microwave} of 250 W and t_{nitridation} of 420 s, which is the condition optimized for D_b reduction [3]. As shown in Fig. 2(c), the nitrogen signals in EELS is found to appear over ~1.6 nm thick region, confirming that plasma nitridation forms a nitrided layer at Al_2O_3/InGaAs interfaces.

It is found that the ECR plasma nitridation, t_{nitridation}, and P_{microwave}, strongly affects the amounts of D_b and CET. Fig. 3 shows the D_b distribution of the Al_2O_3/nitrided-InGaAs capacitors using P_{microwave} of 250 W as a parameter of t_{nitridation}. Also, Fig. 4(a) and (b) shows D_b at a surface Fermi energy, ϕ_F of 0.15 eV and CET, respectively, as a function of t_{nitridation}. It is found that D_b decreases first and increases with increasing t_{nitridation}. Fig. 4(c) shows D_b versus CET as a parameter of P_{microwave}. It is found from these results that higher P_{microwave} and shorter t_{nitridation} can provide thinner CET under a same degree of D_b.

The chemical structures at the MOS interfaces were evaluated to study the physical origins of these D_b change. Fig. 5(a) - (d) show the Ga 2p XPS spectra for the samples with nitridation using P_{microwave} of 250 W as a parameter of t_{nitridation}. Also, the spectra in Fig. 5(e) - (g) were taken from the interfaces with a D_b value of ~1 x 10^{12} cm^{-2}eV^{-1} at ϕ_F of 0.15 eV under different combinations of P_{microwave} and t_{nitridation}. Fig. 6(a) and (b) shows the t_{nitridation} dependence of the peak area ratios of Ga-N bonds and the sum of Ga_2O_3 and InGaO_2 bonds to the bulk peak taken from Fig. 5(a)-(d) and 5(e)-(g), respectively. The simultaneous increase in the ratios of Ga-N bonds and the sum of Ga_2O_3 and InGaO_2 bonds, shown in Fig. 6(a), means the formation of the InGaAs oxynitrided layers. Also, the saturation of the Ga-N bond ratio between 420 s and 900 s suggests that the nitridation of InGaAs surfaces almost stops around this t_{nitridation} period. Also, Fig. 6(b) shows that the peak area ratio of the Ga-N bonds is almost same for the interfaces with the same D_b fabricated under different P_{microwave} suggesting that D_b is uniquely controlled by the amount of Ga-N bonds. Thus, D_b was plotted as a function of the peak area ratio of Ga-N in Fig. 6(c). It is found that that D_b is universally represented by the amount of the Ga-N bonds before the stop of the growth of the nitrided layers, meaning that the D_b reduction by plasma nitridation is attributed to the increase in the Ga-N bonds at the interfaces [2]. On the other hand, D_b is found to increase, when the nitridation saturates. These results indicate that the decrease and increase in D_b are attributed to the formation of Ga-N bond and Ga oxides, respectively, and thus, the minimum D_b can be determined by the balance between the saturation of nitridation and the...
progress of oxidation. Also, higher $P_{\text{microwave}}$ is expected to have a higher rate of InGaAs nitridation, attributable to larger amount of activated nitrogen species [6].

4. Conclusion The impact of the ECR plasma condition on $\text{Al}_2\text{O}_3$/nitride layer/InGaAs interface properties was examined. It was found that the amount of Ga-N bonds at the InGaAs interfaces determines the $D_\text{t}$ reduction.

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**Fig. 1** Fabrication process of ALD-ALD-Al$_2$O$_3$/nitrided-InGaAs MOS capacitors and XPS samples.

**Fig. 2** (a) HAADF image and (b) EELS profile for nitrogen of an ALD-Al$_2$O$_3$/nitrided-InGaAs MOS capacitor using $P_{\text{microwave}}$ of 250 W and $t_{\text{nitridation}}$ of 420 s, and (c) the combined result of the line profiles of the brightness in the regions indicated by arrows in Fig. 2(a) and (b).

**Fig. 3** Energy distributions of $D_\text{t}$ of Al$_2$O$_3$/nitrided-InGaAs MOS capacitors.

**Fig. 4** (a) $D_\text{t}$ value at $\psi_r$ of 0.15 eV above the midgap and (b) CET of Al$_2$O$_3$/nitrided-InGaAs MOS capacitors versus $t_{\text{nitridation}}$ and (c) $D_\text{t}$ value versus CET of them.

**Fig. 5** Ga 2p XPS spectra for the Al$_2$O$_3$/InGaAs structures fabricated with (a)-(d) nitridation using $P_{\text{microwave}}$ of 250 W and (e)-(g) nitridation resulting in the $D_\text{t}$ of $\sim 1 \times 10^{10} \text{ cm}^{-2}\text{ eV}^{-1}$ at $\psi_r$ of 0.15 eV.

**Fig. 6** $t_{\text{nitridation}}$ dependence of peak area ratio for (a) spectra in Fig. 5(a)-(d) and (b) spectra in Fig. 5(e)-(g), and (c) $D_\text{t}$ versus the XPS peak area ratio of Ga-N. Each symbol corresponds to the samples shown in Fig. 5.