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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_{it}. SiO_2/InGaAs with the nitirided interfaces has yielded the minimum D_{it} value of 2×10^{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_{it} distribution with the CET increase of 0.65 nm [3]. Also, XPS studies on these interfaces have revealed that the D_{it} reduction is attributable to the formation of Ga-N bonds at the MOS interfaces due to the nitiridation 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_{it} and decreasing CET.

2. Experiments Fabrication process of MOS capacitors and XPS samples are illustrated in Fig. 1. A Si-doped n-$In_{0.53}Ga_{0.47}As$ layer (N_D ~5×10^{15} cm^{-3}) was grown on a 2-inch (001) InP substrate at 610 ºC by MOVPE. After surface oxide removal with 10% HCl, nitridation was performed by ECR plasma in Ar and N_2 ambient at ~1×10^{-1} 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 ºC 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_{it} 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_{it} decrease and increase under nitridation. Here, the spectra were de-convoluted into four components of the bulk InGaAs, Ga^{3+}, $InGaO_x$ and Ga-N bonds. Here, the peaks of Ga^{3+}, $InGaO_x$ 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_{it} 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_{it} and CET. Fig. 3 shows the D_{it} 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_{it} at a surface Fermi energy, ψ_f, of 0.15 eV and CET, respectively, as a function of $t_{nitridation}$. It is found that D_{it} decreases first and increases with increasing $t_{nitridation}$. Fig. 4(c) shows D_{it} 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_{it}.

The chemical structures at the MOS interfaces were evaluated to study the physical origins of these D_{it} 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_{it} value of ~1×10^{12} $cm^{-2}eV^{-1}$ at ψ_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^{3+} and $InGaO_x$ 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^{3+} and $InGaO_x$ 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_{it} fabricated under different $P_{microwave}$, suggesting that D_{it} is uniquely controlled by the amount of Ga-N bonds. Thus, D_{it} was plotted as a function of the peak area ratio of Ga-N in Fig. 6(c). It is found that that D_{it} 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_{it} reduction by plasma nitridation is attributed to the increase in the Ga-N bonds at the interfaces [2]. On the other hand, D_{it} is found to increase, when the nitridation saturates. These results indicate that the decrease and increase in D_{it} are attributed to the formation of Ga-N bond and Ga oxides, respectively, and thus, the minimum D_{it} can be determined by the balance between the saturation of nitridation and the progress of oxidation. Also, higher $P_{microwave}$ 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 Al_2O_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_{it} reduction.

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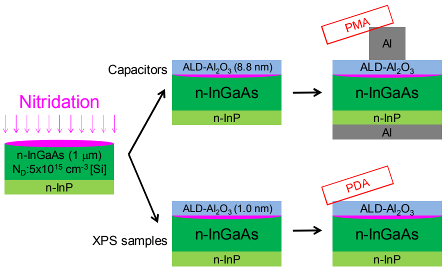


Fig. 1 Fabrication process of ALD-Al_2O_3/nitrided-InGaAs MOS capacitors and XPS samples.

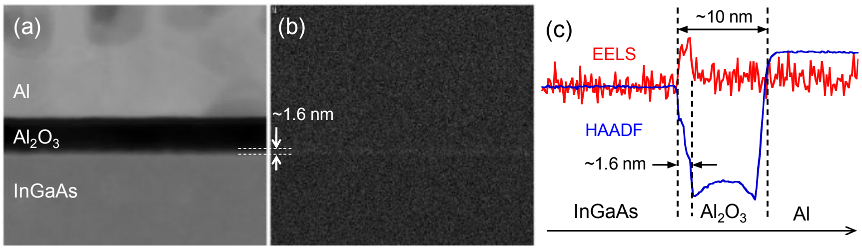


Fig. 2 (a) HAADF image and (b) EELS profile for nitrogen of an Al_2O_3/nitrided-InGaAs MOS capacitor using $P_{microwave}$ of 250 W and $t_{nitridation}$ of 420 s, and (c) the combined result of the line profiles of the brightness in the regions indicated by arrows in Fig. 2(a) and (b).

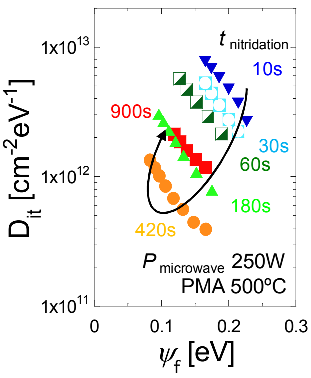


Fig. 3 Energy distributions of D_{it} of Al_2O_3/nitrided-InGaAs MOS capacitors.

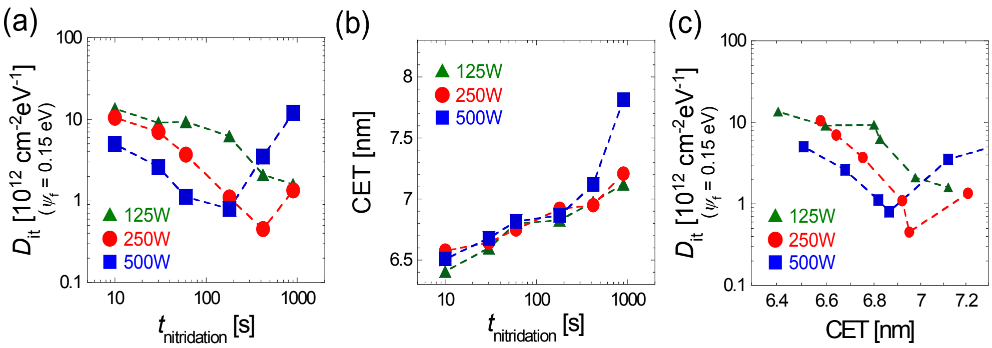


Fig. 4 (a) D_{it} value at ψ_f of 0.15 eV above the midgap and (b) CET of Al_2O_3/nitrided-InGaAs MOS capacitors versus $t_{nitridation}$, and (c) D_{it} value versus CET of them.

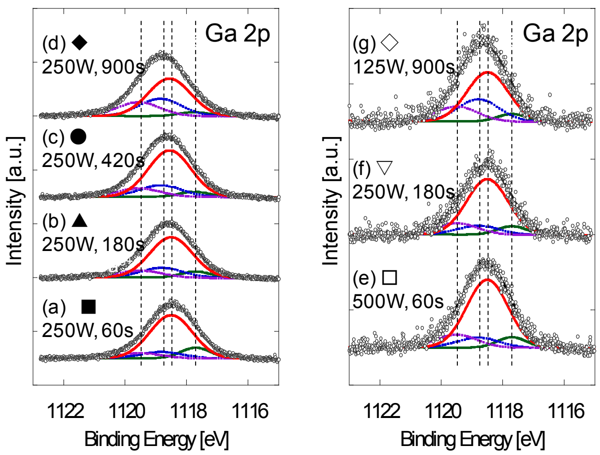
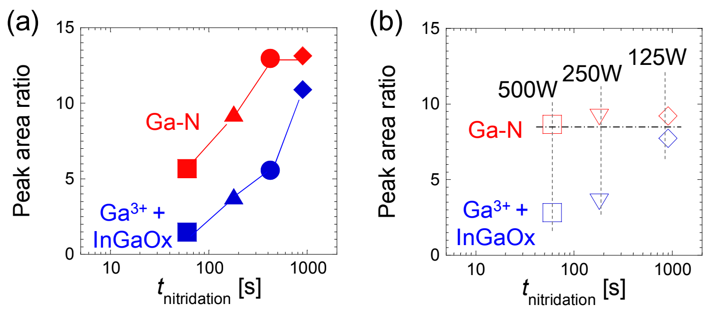


Fig. 5 Ga 2p XPS spectra for the Al_2O_3/InGaAs structures fabricated with (a)-(d) nitridation using $P_{microwave}$ of 250 W and (e)-(g) nitridation resulting in the D_{it} of ~1×10^{12} $cm^{-2}eV^{-1}$ at ψ_f of 0.15 eV.



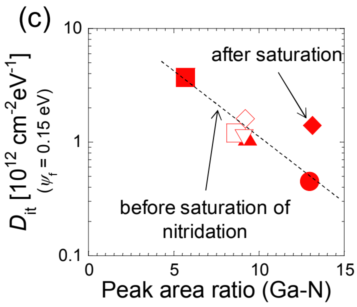


Fig. 6 $t_{nitridation}$ dependence of peak area ratio for (a) spectra in Fig. 5(a)-(d) and (b) spectra in Fig. 5(e)-(g), and (c) D_{it} versus the XPS peak area ratio of Ga-N. Each symbol corresponds to the samples shown in Fig. 5.