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Improvement of interfacial and electrical properties of Al_2O_3/ n-$Ga_{0.47}In_{0.53}As$ for III-V impact ionization MOSFETs

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Abstract. In this work, Metal – Oxide – Semiconductor Capacitors (MOSCaps) based on *Al_2O_3/ n-$Ga_{0.47}In_{0.53}As$* interface have been studied. In order to have high MOSFETs performance, it is necessary to improve the semiconductor – oxide interface quality. It is observed that the $(NH_4)_2S$ passivation shows lower interface trap density in the order of $6\times10^{11}cm^{-2}.eV^{-1}$. Also, it is observed that O_2 plasma densification after a passivation in a NH_4OH solution improves the electrical behaviour of the charge control. Low interface trap density in the order of $1\times10^{12}cm^{-2}.eV^{-1}$ was obtained for different treatments presented in this work.

1. Introduction

During the past few years, the size reduction of the Metal – Oxide – Semiconductor Field Effect Transistor (MOSFET) was the key for the development of performant Integrated Circuits (ICs). One of the main issues is the reduction of power consumption related to the lowering of supply voltage V_{DD}. Today the decrease of V_{DD} is limited by the subthreshold swing SS. New device architectures are being investigated in order to have SS less than the 60mV/dec limit. I-MOSFET (Impact ionization MOSFET) is one candidate to obtain SS of few mV/dec [1]. Silicon I-MOSFET showed steep subthreshold swing in the order of 5mV/dec [2] with I_{ON} current in the range of 400mA/mm [2] however it requires large V_{DD}. III-V materials and engineering of bandgap energy is envisaged to reduce V_{DD}. In III-V I-MOSFET, gate oxide with high quality is an issue. Large majority of works used Al_2O_3 oxide deposited by ALD (Atomic Layer Deposition) to have low interface trap density D_{it} in the order of $10^{12}cm^{-2}.eV^{-1}$ [3] and very few report less D_{it} [4]. Recently, paper [5] reports an O_2 plasma treatment of the Al_2O_3 oxide to decrease the formation of oxide during the post-deposition annealing (PDA). In this paper, we present improvement of interfacial and electrical properties of Al_2O_3/ n-$Ga_{0.47}In_{0.53}As$ using O_2 plasma treatment during the formation of the oxide by ALD.

2. Device structure and experimental details

MOSCAPs were realised from a structure of n-doped $Ga_{0.47}In_{0.53}As$ lattice matched on InP wafer as shown in figure 1. The structure is made of a high n-doped GaInAs layer (N: $1\times10^{19}cm^{-3}$) to have a low resistance n-type ohmic contact and a low n-doped GaInAs layer (N: $2\times10^{16}cm^{-3}$) close to the oxide – semiconductor interface. The first step of fabrication process consist on cleaning, degreasing

the surface and passivation before oxide growth by ALD. Then the thermal Al_2O_3 is deposited at 250°C from trimethylaluminium (TMA) and water (H_2O) precursors. Three samples were prepared. For the sample I, the native oxide was etched with a HCl solution diluted in deionized water (EDI) with a volume ratio of 1:3 during 2min. Then a 5% dilute $(NH_4)_2S$ solution was used to passivate the surface during 10min [3]-[6]. For the sample II, a 4% dilute NH_4OH solution was used to passivate the surface during 10min. Then 4nm Al_2O_3 was deposited by ALD at 250°C. For a third sample III, an O_2 plasma was used after 2nm oxide deposition on a sample treated with a dilute NH_4OH solution. Then 2nm oxide was deposited to have an oxide thickness of 4nm. On each sample, a PDA at 600°C during 1min under N_2H_2 atmosphere was used to stabilize the oxide. All treatments are resumed in table 1. The gate contact was realised with the evaporation of a sequence of Ni/ Au (100nm/ 250nm). The source n-type ohmic contact was realised with the evaporation of a sequence of Ti/ Pt/ Au on the highly n-doped GaInAs layer. The cross section of MOS gate stack was observed by the means of transmission electron microscopy showed in figure 2. We can observe in the middle the 4nm of non-densified Al_2O_3 surrounded by GaInAs at left and Ni metal at right.

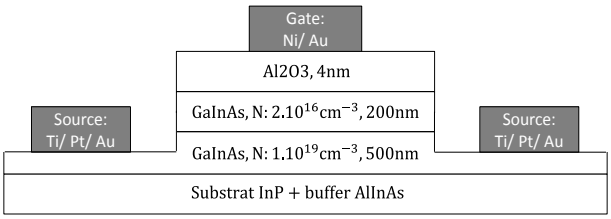

Figure 1. Structure of MOSCaps device at the end of the fabrication process.

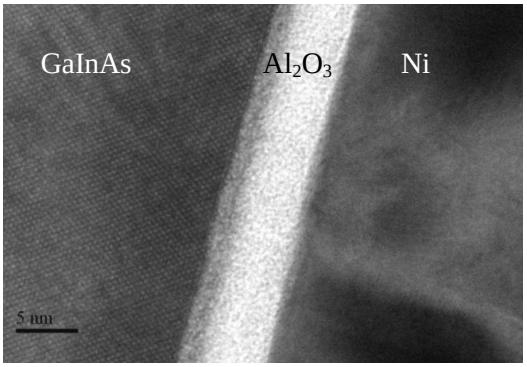

Figure 2. TEM picture of the MOS structure, we can see in the middle of Al_2O_3 with a uniform thickness of 4nm.

Table 1. Summary of different treatments and oxide deposition.

Sample	Surface treatments	Oxide Thickness (nm)	Densification	Post Deposition Annealing (°C)
I	HCl + $(NH_4)_2S$	4	no	600
II	NH_4OH	4	no	600
III	NH_4OH	4	yes	600

3. Results and discussion

3.1. Passivation effect

We compared dilute $(NH_4)_2S$ solution to passivate the surface of the sample I and dilute NH_4OH solution to passivate the surface of the sample II. To that purpose, capacitance – voltage (C – V) measurements were done at ambient temperature in function of gate voltage V_{gs} for various frequencies of the dynamic signal applied on the gate (figure 3). In figure 3(a), we represent C-V measurements for sample I and C-V measurements for sample II in figure 3(b). We can notice in both samples a high frequency dispersion in accumulation between V_{gs}=1V and V_{gs}=2V due to leakage current [7]. The sample I treated with the $(NH_4)_2S$ solution has showed around depletion, between V_{gs}=-0.75V and V_{gs}=0.25V, a lower frequency dispersion in comparison with sample II treated with the NH_4OH solution, indicating a lower interface trap density. However the identical stretch-out

between V_{gs}=-0.75V and V_{gs}=0.25V on both samples has showed no significant modification in charge control. Furthermore, we can notice a "bump" in inversion, between V_{gs}=-2V and V_{gs}=-0.5V which indicates inversion assisted by interface trap states [8].

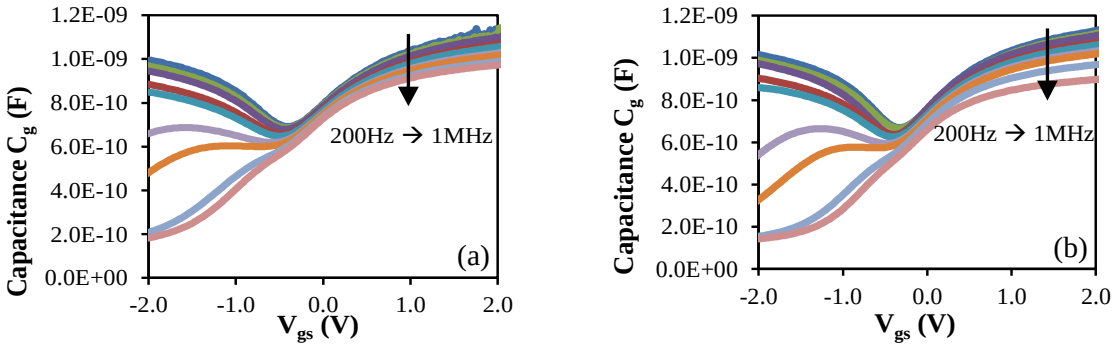

Figure 3. C – V characteristics of the MOS structure Al_2O_3/ n-GaInAs for sample I passivated with $(NH_4)_2S$ solution (a), and for sample II passivated with NH_4OH solution (b).

3.2. Oxide densification effect

We studied the densification effect using O_2 plasma in the sample III passivated with a dilute NH_4OH solution to improve the oxide – semiconductor interface quality. The post deposition O_2 plasma was used on the structure Al_2O_3/ Ge by Zhang et al. in order to improve GeO_x oxide [9]-[10], they succeed to have low value of D_{it} in the range of $10^{11}cm^{-2}.ev^{-1}$. In our case, the treatment consists on a densification of the oxide near interface by the mean of an O_2 plasma across 2nm of oxide. This treatment decreases the quantity of mobile charges in the oxide and fills dangling bonds after oxide deposition. Then 2nm of Al_2O_3 were added to have a total thickness of 4nm. C – V characteristics at ambient temperature in function of V_{gs} are showed in figure 4. We can notice at low frequency the minimum capacitance value is lower for the sample III than for sample II even though both are passivated with NH_4OH solution. Furthermore, the small stretch-out between V_{gs}=-0.5V and V_{gs}=0.5V for sample III indicates that the O_2 plasma improves the charge control by the gate and might improve the subthreshold swing SS of I-MOSFETs. And as for sample II, the large frequency dispersion in accumulation could be due to the high leakage current [7].

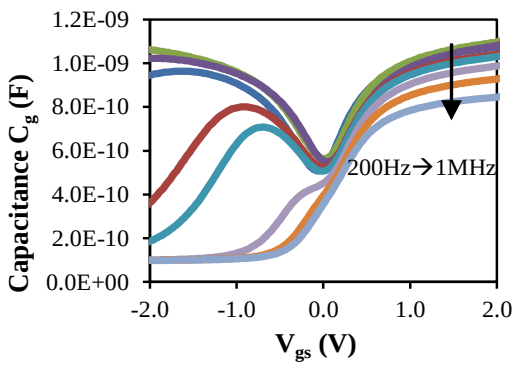

Figure 4. Capacitance measurements of the MOS structure Al_2O_3/ n-GaInAs with an oxide densification treatment (sample III).

3.3. Interface trap density

We extracted the interface trap density calculated by High frequency – Low frequency (HF-LF) method for each sample shown in figure 5 in function of gate – source voltage V_{gs}. All samples show D_{it} with the same order of magnitude, in the range of $1\times10^{12}cm^{-2}.eV^{-1}$. However, we can notice a low D_{it} of $6.5\times10^{11}cm^{-2}.eV^{-1}$ for the sample I passivated with $(NH_4)_2S$ solution compared to D_{it} of about $9.2\times10^{11}cm^{-2}.eV^{-1}$ and $1.5\times10^{12}cm^{-2}.eV^{-1}$ for samples II and III respectively. But the extraction of D_{it} in samples II and III may not be accurate because of the large frequency dispersion in accumulation.

Moreover, we have extracted flatband voltage V_{FB} in order to calculate the charge density Q_f in the oxide from $Q_f=(V_{FB}-\Phi_{MS})/C_{OX}$ (Table 2) where C_{OX} is oxide capacitance and Φ_{MS} ideal metal-semiconductor workfunction difference. We observed a decrease of charge density for sample III with densification and a shift of flatband voltage to its theoretical value (1).

$$\Phi_{MS} = \Phi_M - X - \frac{E_g}{2.q} - \frac{K.T}{q}.\ln(\frac{N_D}{n_i}) \quad (1)$$

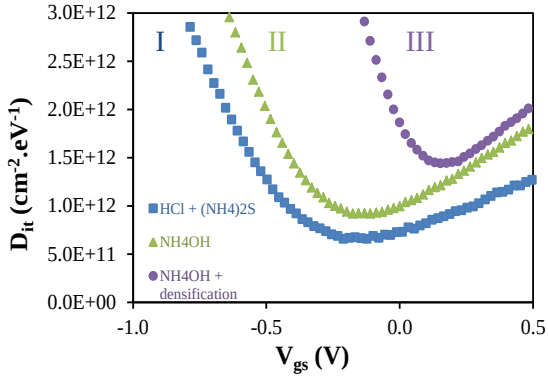

Figure 5. Extraction of the interface trap density D_{it} in function of the applied voltage V_{gs} from HF – LF method.

	HCl + $(NH_4)_2S$	NH_4OH	NH_4OH + densif.	Theory
Qf ($x10^{11}cm^{-2}$)	64	45.1	1.14	-
V_{FB} (V)	-1,27	-0,96	-0,15	-0.13

Table 2. Calculated oxide charge density in function of the flatband voltage for each sample.

4. Conclusion

In summary, we studied effect of surface treatment on Al_2O_3/ n-$Ga_{0.47}In_{0.53}As$ interface. We have demonstrated a low D_{it} of about $6.5\times10^{11}cm^{-2}.eV^{-1}$ for sample treated with dilute $(NH_4)_2S$ solution as surface treatment before oxide deposition. We have reported improvement in charge control by the gate using an O_2 plasma after oxide deposition, even if we obtained large interface trap density. This process needs to be optimized in order to build I-MOSFETs using higher dielectric permittivity oxide like HfO_2.

5. Acknowledgments

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6. References

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