Improvement of interfacial and electrical properties of Al$_2$O$_3$/ 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$_2$O$_3$/ 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$_4$)$_2$S passivation shows lower interface trap density in the order of $6 \times 10^{11}$ cm$^{-2}$eV$^{-1}$. Also, it is observed that O$_2$ plasma densification after a passivation in a NH$_4$OH solution improves the electrical behaviour of the charge control. Low interface trap density in the order of $1 \times 10^{12}$ 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$_2$O$_3$ 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$_2$O$_3$ 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$_2$O$_3$/ 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: $1 \times 10^{19}$ cm$^{-3}$) to have a low resistance n-type ohmic contact and a low n-doped GaInAs layer (N: $2 \times 10^{16}$ 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$_2$O$_3$ is deposited at 250°C from trimethylaluminium (TMA) and water (H$_2$O) 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$_4$)$_2$S solution was used to passivate the surface during 10min [3]-[6]. For the sample II, a 4% dilute NH$_4$OH solution was used to passivate the surface during 10min. Then 4nm Al$_2$O$_3$ 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$_4$OH 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$_2$H$_2$ 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$_2$O$_3$ surrounded by GaInAs at left and Ni metal at right.

![Figure 1. Structure of MOSCaps device at the end of the fabrication process.](image1)

![Figure 2. TEM picture of the MOS structure, we can see in the middle of Al$_2$O$_3$ with a uniform thickness of 4nm.](image2)

### Table 1. Summary of different treatments and oxide deposition.

| Sample | Surface treatments       | Oxide Thickness (nm) | Densification | Post Deposition Annealing (°C) |
|--------|--------------------------|----------------------|---------------|-------------------------------|
| I      | HCl + (NH$_4$)$_2$S      | 4                    | no            | 600                           |
| II     | NH$_4$OH                 | 4                    | no            | 600                           |
| III    | NH$_4$OH                 | 4                    | yes           | 600                           |

3. Results and discussion

3.1. Passivation effect

We compared dilute (NH$_4$)$_2$S solution to passivate the surface of the sample I and dilute NH$_4$OH 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$_4$)$_2$S 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$_4$OH 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](image-url)

**Figure 3.** C – V characteristics of the MOS structure Al$_2$O$_3$/ n-GaInAs for sample I passivated with (NH$_4$)$_2$S solution (a), and for sample II passivated with NH$_4$OH 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$_4$OH solution to improve the oxide – semiconductor interface quality. The post deposition O$_2$ plasma was used on the structure Al$_2$O$_3$/ 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$_2$O$_3$ 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$_4$OH 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](image-url)

**Figure 4.** Capacitance measurements of the MOS structure Al$_2$O$_3$/ 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$_4$)$_2$S 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 $\Phi_{MS}$ 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).

$$\Phi_{MS} = \Phi_M - X - \frac{E_x}{2q} - \frac{K.T}{q} \ln \left( \frac{N_D}{n_i} \right)$$

(1)

| $Q_f/(x10^{11}cm^{-2})$ | $V_{FB}$ (V) |
|--------------------------|--------------|
| HCl + (NH$_4$)$_2$S       | 64           | -1.27 |
| NH$_4$OH                 | 45.1         | -0.96 |
| NH$_4$OH + densif.       | 1.14         | -0.15 |
| Theory                   | -            | -0.13 |

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

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$_2$O$_3$/ n-Ga$_{0.47}$In$_{0.53}$As interface. We have demonstrated a low $D_{it}$ of about $6.5 \times 10^{11}cm^{-2}.eV^{-1}$ for sample treated with dilute (NH$_4$)$_2$S 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$_2$.

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6. References
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