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Impact of *in situ* plasma enhanced atomic layer deposition on the electrical properties of $HfO_2/In_{0.53}Ga_{0.47}As$ MOSCAPs for low EOT and low interface state density

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Abstract

We report on the passivation of $HfO_2/In_{0.53}Ga_{0.47}As$ interface using *in-situ* plasma enhanced atomic layer deposition. Excellent electrical characteristics have been demonstrated on the InGaAs MOS structure with low interface state density and low leakage current density. It is found that pre and post PEALD passivation enable the down scaling of equivalent oxide thicknesses into sub-nanometer.

1. Introduction

InGaAs channel material is one of the most attractive III-V compound semiconductors for future downscaling of complementary metal oxide semiconductor (CMOS) devices beyond 10 nm technology node [1]. However, the requirement of high quality native oxides on the III-V surfaces as well as outstanding interfacial properties of high-k/III-V have never been accomplished, suppressing the performance of III-V based devices toward post-Si application. In this article, we present the influences of *in situ* plasma enhanced atomic layer deposition (PEALD) passivation on the electrical properties of the $HfO_2/In_{0.53}Ga_{0.47}As$ metal-oxide-semiconductor capacitors (MOSCAPs). It is shown that excellent quality of $HfO_2/In_{0.53}Ga_{0.47}As$ structures can be achieved by performing PEALD passivations including PEALD-AlN interfacial passivation layer prior to ALD-HfO_2 and post remote-plasma gas treatment. Sub-nanometer equivalent oxide thickness $HfO_2/In_{0.53}Ga_{0.47}As$ MOS devices with low interface state density and low gate leakage current density is illustrated.

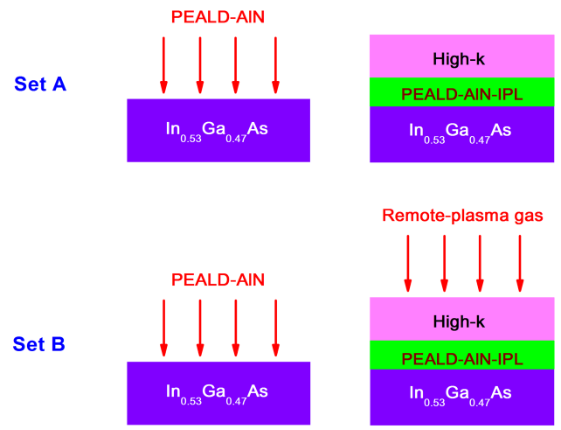

Fig.1. Passivation processes for $HfO_2/In_{0.53}Ga_{0.47}As$ structures

2. Experimental

The substrates used in this study are solid source molecular beam epitaxial grown 100 nm n-$In_{0.53}Ga_{0.47}As$ layer (5×10^{17} cm^{-3} doping) on n^+-InP substrates. After removing native oxides by HCl solution in 2 min, the samples were loaded into ALD chamber for high-k deposition. In ALD chamber, trimethyl-aluminum (TMA) and ammonia (NH_3) gas were used as precursors for PEALD-AlN at plasma power of 150 W [2]. Tetrakis-ethylmethylaminohafnium (TEMAHf) and water were used for thermal HfO_2 deposition, while the substrate temperature was kept at 250 °C during all processes. Two deposition processes were carried out as seen in Fig. 1. Set A consisted of PEALD-AlN (~ 1 nm) as interfacial passivation layer and various thicknesses of HfO_2. Samples of set B were further underwent post remote-plasma treatment with different plasma gases in order to improve not only the HfO_2 quality but also the interface quality. After ALD deposition, the post deposition annealing (PDA) were conducted at 450 °C in FG for 2 min. Ni/Au gate metal was formed via lift-off process. Finally, the ohmic metal was deposited and followed by post metal deposition annealing (PMA) at 250 °C, in N_2, for 30 s.

3. Results and discussion

Figure 2 shows the multi-frequency CV curves and the interface state density (D_{it}) distribution, extracted by the Terman method, for $HfO_2/AlN/In_{0.53}Ga_{0.47}As$ MOSCAPs with 85 cycles HfO_2 (left column) or 40 cycles HfO_2 (right column), respectively. Both samples have shown very nice C-V behaviors, clear accumulation/depletion/inversion regions, with strong inversion behavior as observed in terms of constant capacitance of a particular frequency at different negative gate voltages. Furthermore, the disappearance of weak inversion “hump” have also confirmed high quality of high-k/III-V interface (Fig. 2(a) and Fig. 2(c)).

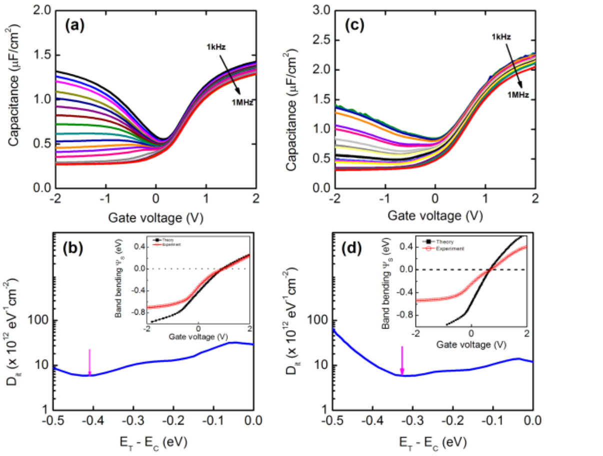

Fig.2. CV characteristics of $HfO_2/AlN/In_{0.53}Ga_{0.47}As$ structures and the D_{it} profiles within the band gap energy: (a) and (b) 85 cycles HfO_2; (c) and (d) 40 cycles HfO_2, respectively. Insets: (b) and (d) are the extracted band bending versus gate voltage.

An increase of the capacitance density without any further degradation of CV behaviors has been conducted for various HfO_2 thicknesses. Moreover, the similar minimum D_{it} results at the order of 10^{12} $eV^{-1}cm^{-2}$ along with efficient band bending through midgap are shown in Figs. 2(b) and 2(d). This strongly proves that the PEALD-AlN passivation prior to high-k deposition can provide promising interface quality for future down scaling oxide thickness.

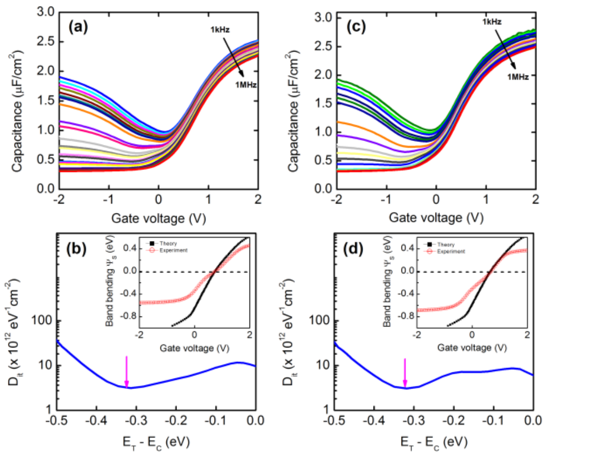

Fig.3. CV characteristics of $HfO_2/AlN/In_{0.53}Ga_{0.47}As$ structures and the D_{it} profiles within the band gap energy: (a) and (b) NH_3 gas plasma; (c) and (d) N_2/H_2 gas plasma, respectively. Insets: (b) and (d) are the extracted band bending versus gate voltage.

The impact of post remote-plasma gas treatment on $HfO_2/AlN/In_{0.53}Ga_{0.47}As$ structures is presented in Fig. 3. The left column shows the result of sample underwent post plasma treatment with NH_3 gas, and the right column shows the result of sample underwent post plasma treatment with N_2/H_2 gas. After performing post remote-plasma gas treatment, the accumulation capacitances have significantly enhanced for both types of gases treated MOSCAPs (Fig. 3(a) and Fig. (c)). It means that the post remote-plasma treatment can be beneficial in the improvement of HfO_2 quality in term of higher k value. From Fig. 3(b) and Fig. 3(d), the minimum D_{it} at approximately 0.33 eV below the conduction band are 3.5 x 10^{12} $eV^{-1}cm^{-2}$ and 3 x 10^{12} $eV^{-1}cm^{-2}$ for NH_3 gas treated and N_2/H_2 gas treated MOSCAP, respectively.

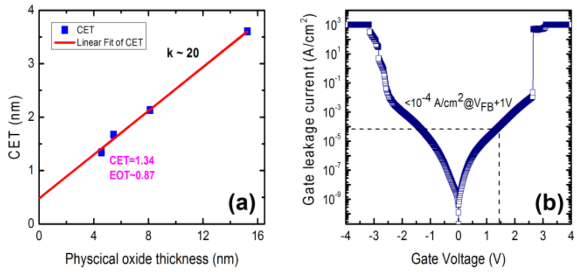

Fig.4. (a) CET as a function of physical oxide thickness and (b) the leakage current density versus gate bias (J-V) of $HfO_2/AlN/In_{0.53}Ga_{0.47}As$ MOSCAP with post N_2/H_2 plasma gas treatment

Figure 4(a) shows capacitance equivalent thickness (CET), estimated from accumulation capacitance at 500 kHz, as a function of physical total oxide thickness. From this, dielectric constant (κ) of 20 for the HfO_2 and the probable quantum-mechanical correction of 0.47 are obtained from the slope and y-axis intercept of the fitting line, respectively. An EOT is then estimated to be around 0.87 nm for the HfO_2 (~ 3.56 nm)/AlN (~ 1 nm)/$In_{0.53}Ga_{0.47}As$ structure with N_2/H_2 remote-plasma treatment. The leakage current density of this sample is also shown in Fig. 4(b). The gate leakage current smaller than 10^{-4} A/cm2 (at V_{FB}+1V) and breakdown field E_{BD} of 6 MV/cm are sufficient for the future logic devices application.

4. Conclusions

In summary, we have presented the influence *in situ* plasma enhanced atomic layer deposition (PEALD) passivation on the electrical characteristics of the $HfO_2/In_{0.53}Ga_{0.47}As$ MOS devices. The utilization of in situ PEALD treatments can be potential for better quality of high-k materials and high interfacial quality. Low interface state density and low leakage current have been achieved with sub-nanometer EOT $HfO_2/In_{0.53}Ga_{0.47}As$ structure.

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