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Preparation of InAs Surface by Hydrogen Plasma Pre-treatment for Low Interfacial Trap Density MOS Capacitors

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Abstract

Hydrogen plasma surface pre-treatment is used to obtain a desirable InAs surface for preparing high-κ/InAs capacitors. Using the conductance method, low interfacial trap density of 5.9×10^{11} near the mid-gap and 3.8×10^{11} $eV^{-1}cm^{-2}$ near the conduction band has been achieved on Au/Pt/ HfO_2/InAs capacitors.

1. Introduction

InAs-based materials, which have high electron mobility as well as narrow bandgap, attract great interest for applications in future high-speed low-power complementary metal-oxide-semiconductor (CMOS) integrated circuits.[1] They could also play a key role in devices beyond the CMOS technology, such as Ga(As)Sb/In(Ga)As hetero-junction tunneling field-effect transistors (TFETs), which have a type-II band alignment and allow inter-band tunneling to reach a subthreshold swing below 60 mV/decade.[2] However, the residual native oxides (AsO_x, InO_x) that lead to Fermi-level pinning and high interfacial trap density (D_{it}) remain to be the obstacles to realizing high quality MOS devices.

To dates, wet etching in a solution has been the most common ways of removing the native oxides prior to high-κ deposition.[3-6] While chemical surface treatments are viable, the native oxides form rapidly after the removal before dielectric deposition. To cope with this issue, an *in-situ* technique, i.e. epitaxial InAs film being transferred to the dielectric deposition system without exposure to air, has been employed to obtain a low D_{it} interface.[7] In this study, an alternative is proposed so as to lessen the stringent requirements on the process equipment used in the *in-situ* approach. We investigate the process parameters for hydrogen plasma pre-treatment on InAs surface prior to high-κ dielectric deposition. The results of this work demonstrate the feasibility of hydrogen plasma treatment on InAs as evidenced by the low D_{it} measured on HfO_2/InAs MOS capacitors (MOSCAPs).

2. Experiments

The samples used in this work were n-type InAs (100) (S doped, 5×10^{17} cm^{-3}) substrates. They were subject to hydrogen plasma treatments prior to dielectric deposition. The plasma was generated by a 13.56 MHz 100 W rf-power source with an H_2 flow of 0.2 sccm and an Ar flow of 0.3 sccm. The plasma exposure time was varied from 2 minutes to 10 minutes. To avoid the generation of In clusters, the substrate temperature was kept at room temperature during the plasma treatment because InAs decomposed easily and the melting point of In is 156 °C only.[8] After the hydrogen plasma treatment, samples were directly transferred into the atomic layer deposition (ALD) system without further exposure to air.

The dielectric deposition processes were started with a 50-cycle trimethylaluminum (TMA) pretreatment for all the samples to mediate the surface for subsequent deposition. Samples with Al_2O_3 (120 cycles), Al_2O_3/HfO_2 (12 cycles/65 cycles) and HfO_2 (65 cycles) gate dielectrics were prepared at 150 °C. Pt/Au metal stack was used as the gate electrode through a shadow mask. A post-metal annealing (PMA) process in forming gas was performed at 300 °C to reduce the traps in the dielectric films and the border traps near the oxide/semiconductor interface. Capacitance-voltage (C-V) measurements were carried out with frequencies ranging from 1 kHz to 500 kHz. The D_{it} distribution within the bandgap of InAs was extracted using the conductance method.

3. Results and discussion

The removal of InAs native oxides by hydrogen radicals (H*) is based on the reaction mechanisms shown below. [9]

$$As_2O_3 + 2InAs + 12H^* \rightarrow In_2O_3 + 4AsH_3\uparrow,$$

$$In_2O_3 + 4H^* \rightarrow In_2O\uparrow + 2H_2O\uparrow$$

Since AsH_3 is much volatile than indium oxides, one would expect an arsenic oxide-free surface after the hydrogen plasma treatment. However, prolonged treatment will deteriorate the surface. The effect of hydrogen plasma exposure time on surface morphology measured by atomic force microscopy (AFM) is depicted in Fig. 1. Fig.1 (a) shows the InAs surface conditioned by TMA only and its RMS roughness is about 0.70 nm. The RMS roughness decreases to 0.60 nm when sample is treated by hydrogen plasma for two minutes. As the exposure time is increased further, the RMS roughness increases as shown in Fig. 2(c)-(d). This could be attributed to the enhanced loss of arsenic atoms by hydrogen radicals.

Fig. 2(a) and 2(b) show the multi-frequency C-V characteristics of Al_2O_3/InAs MOSCAPs. The accumulation of C-V curve does not saturate to the oxide capacitance even with a strong bias due to the low conduction band effective density of states of InAs (8.7×10^{16} cm^{-3} at 300 K).[5] As shown in Fig. 2(a), the InAs MOSCAP with only TMA pre-treatment exhibits small dispersion in accumulation but large stretch-out in inversion region, while the H_2-plasma treated InAs MOSCAP shows small frequency dispersion as well as suppressed inversion stretch-out. This implies the reduction of trap states at the dielectric/semiconductor boundary.

Based on the surface treatment processes above, MOSCAPs with HfO_2/Al_2O_3 and HfO_2 gate dielectrics are also fabricated and studied. As shown in Fig. 3(a), the HfO_2/Al_2O_3/InAs MOSCAP exhibits small dispersion, high capacitance and large modulation depth. As for the HfO_2/InAs MOSCAP, its multi-frequencies C-V curves are depicted in Fig. 3(b). The absence of an upturn peak in inversion at high frequencies implies that the charge traps are reduced significantly near the valence band of InAs. [6, 10, 11] The C_{min} reaches 0.35 uF/cm^2 and the modulation depth reaches 70 %. The interface trap density of the HfO_2/InAs MOSCAPs estimated by the conductance method is 5.9×10^{11} near mid-gap and 3.8×10^{11} eV^{-1}cm^{-2} near the conduction band, respectively. [12]

3. Conclusions

Hydrogen plasma surface pre-treatment has been successfully used to obtain a desirable InAs surface for preparing high-κ/InAs capacitors as evidenced by their multi-frequency C-V characteristics. This method applies to both HfO_2/Al_2O_3 and HfO_2 MOSCAPs, which exhibit good modulation behavior and small frequency dispersion in the C-V characteristics. Low D_{it} of 5.9×10^{11} near mid-gap and 3.8×10^{11} eV^{-1}cm^{-2} near the conduction band have been realized on HfO_2/InAs MOSCAPs.

Acknowledgements

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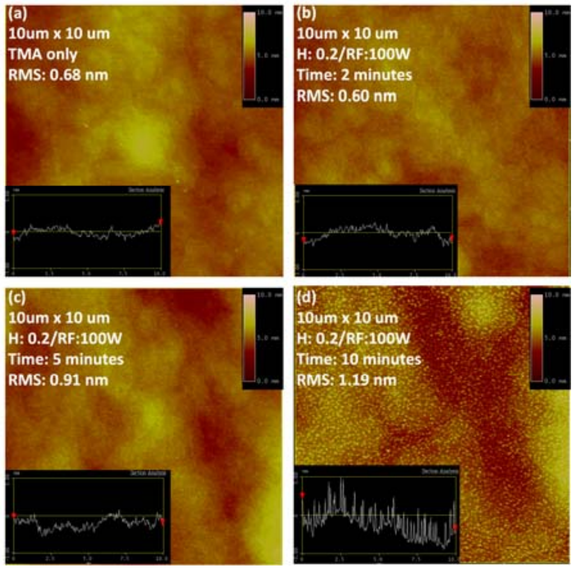

Fig.1 Atomic force microscopy of Al_2O_3/InAs surfaces treated by (a) TMA only, and hydrogen plasma for (b) 2 minutes, (c) 5 minutes, and (d) 10 minutes.

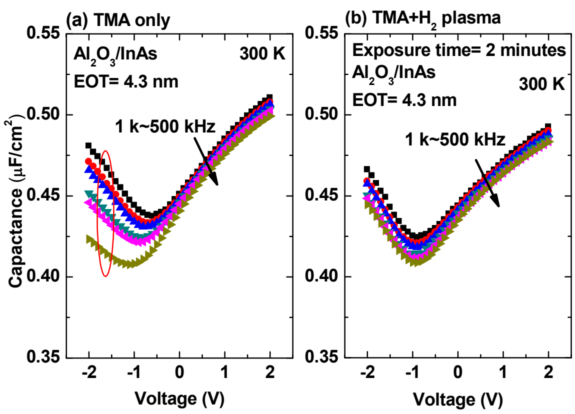

Fig.2 Room temperature multi-frequency C-V characteristics of Al_2O_3/InAs MOSCAPs with (a) TMA treatment only and (b) hydrogen plasma treatment prior to high-κ deposition

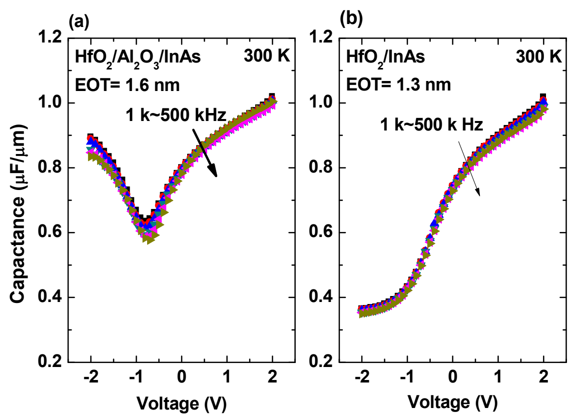

Fig.3 Room temperature multi-frequency C-V characteristics of (a) HfO_2/Al_2O_3/InAs and (b) HfO_2/InAs MOSCAPs with hydrogen plasma treatment prior to high-κ deposition