PS-6-19
Extended Abstracts of the 2015 International Conference on Solid State Devices and Materials, Sapporo, 2015, pp204-205

Low Interface Trap Density $HfO_2/Al_2O_3/InAs$ MOS Capacitors Prepared by Nitrogen Plasma Treatment

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Abstract

Nitrogen plasma treatment has been successfully used to fabricate high quality InAs MOS capacitors. Mid-gap interface trap density (D_{it}) of the $HfO_2/Al_2O_3/InAs$ MOS capacitors is about 7.49×10^{11} $eV^{-1}cm^{-2}$. Frequency dispersion as small as 1.95% in the accumulation region is achieved. X-ray photoelectron spectroscopy shows the presence of Al-N bonds at the $Al_2O_3/InAs$ interface, which result in a well passivated surface for the subsequent gate stack processes.

1. Introduction

InAs is one of the III-V compound semiconductors that exhibits very high electron mobility (~ 40,000 $cm^2V^{-1}s^{-1}$), which offers high on-current at low voltage for future logic metal-oxide-semiconductor (MOS) transistors. However, the lack of high quality high-k/InAs interface has been a major obstacle to realizing its full potential. There often exist significant amount of interface trap states, which cause Fermi-level-pinning. Rough surface could introduce severe carrier scattering and degrade both the on-current and off-current of highly-scaled III-V MOS field-effect transistors (MOSFETs). To overcome these difficulties, both chemical and plasma treatments on InAs surface have been explored. [1-3] In this study, we demonstrate that nitrogen plasma treatment is feasible approach to prepare low interface state density (D_{it}) MOS devices as evidenced by atomic force microscope (AFM), capacitance-voltage (C-V) and conductance-voltage (G-V) measurements as well as X-ray photoelectron spectroscopy (XPS).

2. Experiments

Native oxide of the InAs samples were removed by HCl solution before the plasma treatment process. The nitrogen plasma cleaning treatment was carried out with a gas flow of 50 sccm, RF power of 100W, and process time of 1min. For comparison, one sample was subject to hydrogen plasma using the same process condition as well. After the plasma treatment, HfO_2/Al_2O_3 (2 nm/3 nm) high-k gate stack was deposited on the samples at 250 °C by atomic layer deposition (ALD). After the ALD process, the gate metal, Ni, was evaporated on the top of HfO_2 through a shadow mask. Ni was also the backside ohmic contact metal. A post metal annealing (PMA) process was performed at 300 °C in a forming gas ambient (nitrogen: 95%, hydrogen: 5%) for 7.5 minutes to improve high-k oxide quality and reduce the interface trap density.

3. Result and discussion

Figure.1 shows the surface morphology of the $HfO_2/Al_2O_3/InAs$ samples subject to nitrogen and hydrogen plasma treatments. The surface root-mean-square roughness (RMS) is 7.39 nm for the sample subject to hydrogen plasma treatment. The rough surface was attributed to the chemical reaction during the hydrogen plasma process as shown below:

$$3H^{+}_{(g)} + InAs_{(s)} \rightarrow In^{+}_{(s)} + AsH_{3(g)} \quad (1)$$

Aggressive hydrogen ambient and high process temperature could facilitate indium clustering on the surface, leading to a rough surface morphology. [4] As for the sample prepared by nitrogen plasma treatment, its surface roughness is about 1.308 nm only. As shown in Fig. 2, the current-voltage characteristics of the MOS capacitors on hydrogen plasma treated sample is leaky while the one on nitrogen plasma treated sample shows well isolated behavior.

Shown in Fig. 3 are the C-V characteristics of the MOS capacitors prepared on the samples with and without the nitrogen plasma treatment. The measurements were performed at various frequencies (from 5 K Hz to 500 K Hz) and temperatures (150 K, 200 K, 250 K, and 300 K). In Fig. 3(a), the effective capacitance modulation is about 55% extending from the accumulation region to the depletion region. Comparing the frequency dispersion in the accumulation region in Fig. 3(a) and Fig. 3(b), an improvement from 6.45% to 1.95% is observed for the MOS capacitor prepared nitrogen plasma treatment, implying the quality of gate oxide is slightly improved. In-depth analysis shows that the D_{it} estimated by the conductance method is also reduced to 8.83×10^{11} $eV^{-1}cm^{-2}$ for the nitrogen plasma treated capacitor, compared to 3.92×10^{12} $eV^{-1}cm^{-2}$ for the one without nitrogen plasma treatment. The D_{it} distribution within the bandgap is shown in Fig. 3(f). A low D_{it} of 7.49×10^{11} $eV^{-1}cm^{-2}$ near midgap is achieved.

Figure 4 shows the XPS analysis on the Al_2O_3 and InAs interface of the MOS capacitors with nitrogen treatment. From the fitting of In 3d spectra in Fig. 4(a), the In_2O_3 line at 444.7 eV is hardly observed. No signal from the $As_2O_3/As3^+$ and $As_2O_5/As5^+$ binding at 45.8 eV and 44.1 eV in Fig. 4(b) indicates the $Al_2O_3/InAs$ interface is AsO_x free. The binding energy peak of Al-N bond is observed at 74.7 eV of the Al 2p spectra and 397.5 eV of the N 1s spectra in

Fig. 4(c) and (d).[5] The appearance of Al-N binding is attributed to the reaction of trimethyl-aluminum (TMA) and surface nitrogen during the initial stage of ALD process. This Al-N passivation could play a decisive role in mitigating interface trap states.

4. Conclusions

HfO_2/Al_2O_3/InAs MOS capacitors with low D_{it} have been demonstrated using nitrogen plasma treatment. The D_{it} near the conduction band can be reduced from 3.92×10^{12} $eV^{-1}cm^{-2}$ to 8.83×10^{11} $eV^{-1}cm^{-2}$ by the nitrogen plasma treatment based on the capacitance-voltage and conductance-voltage measurements. X-ray photoelectron spectroscopy investigations show the plasma treatment results in an AsO-free oxide-semiconductor interface with the presence of Al-N bonds, indicating the effectiveness of nitrogen plasma treatment for high quality InAs MOS devices.

Acknowledgements

This work was partly supported by National Science Council program NSC:101-2221-E-008 -045 -MY3, R.O.C.. The authors thank Dr. Mao-Lin Huang for his suggestions on this work.

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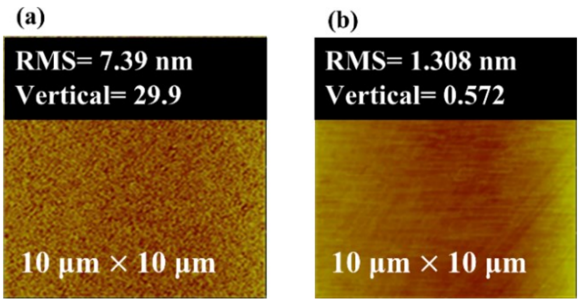

Fig. 1 AFM images of InAs surface treated by (a) hydrogen and (b) nitrogen plasma with RF power of 100W, gas flow of 50 sccm, and process time of 1 min.

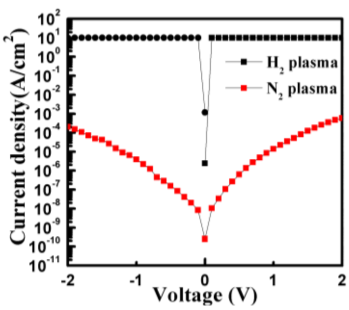

Fig. 2 Current-voltage characteristics of InAs MOS capacitors prepared by hydrogen and nitrogen plasma treatment process.

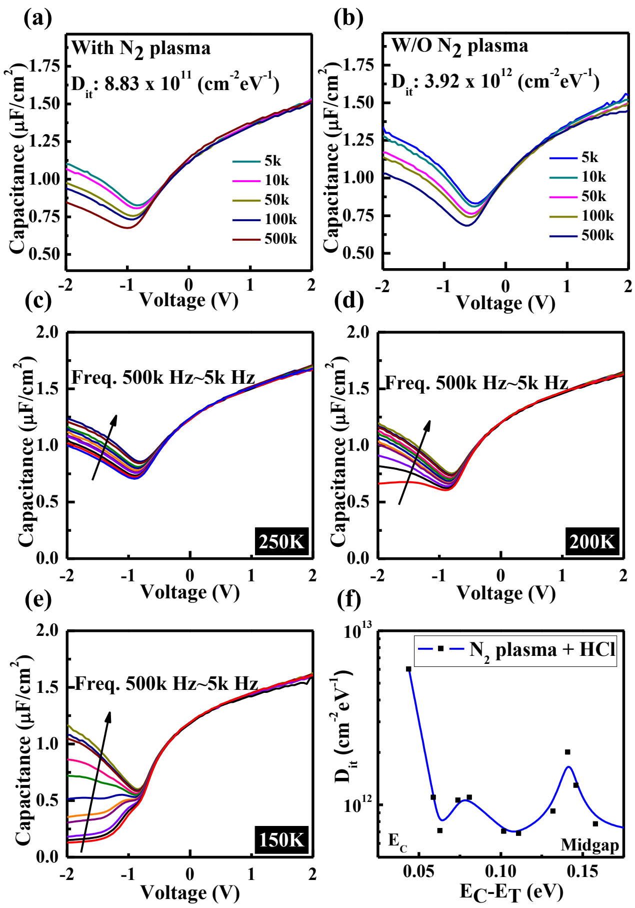

Fig. 3 Capacitance-voltage characteristics and D_{it} of n-type InAs MOS capacitors (a) with and (b) without nitrogen plasma treatment. Capacitance-voltage curves at (c) 250 K, (d) 200 K, and (e) 150 K at frequencies from 5 KHz to 500 KHz. (f) D_{it} distribution within the bandgap of HfO_2/Al_2O_3/n-InAs MOS capacitor with N_2 plasma treatment as determined by the conductance method.

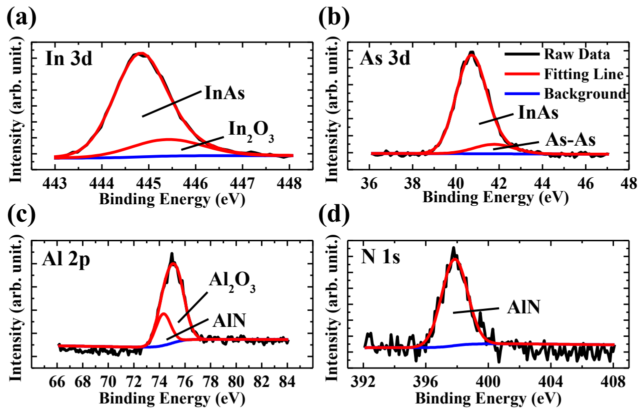

Fig. 4 XPS core-level spectra of (a) In3d, (b) As3d, (c) Al2p, and (d) N1s for the Al_2O_3/InAs interface of HfO2/Al_2O_3/InAs MOS capacitor prepared by nitrogen plasma treatment.