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Interface sulfur passivation using H_2S annealing for atomic-layer-deposited Al_2O_3 films on an ultrathin-body $In_{0.53}Ga_{0.47}As$-on-insulator

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ABSTRACT

Atomic-layer-deposited Al_2O_3 films were grown on ultrathin-body $In_{0.53}Ga_{0.47}As$ substrates for III-V compound-semiconductor-based devices. Interface sulfur (S) passivation was performed with wet processing using ammonium sulfide ($(NH_4)_2S$) solution, and dry processing using post-deposition annealing (PDA) under a H_2S atmosphere. The PDA under the H_2S atmosphere resulted in a lower S concentration at the interface and a thicker interfacial layer than the case with $(NH_4)_2S$ wet-treatment. The electrical properties of the device, including the interface property estimated through frequency dispersion in capacitance, were better for $(NH_4)_2S$ wet-treatment than the PDA under a H_2S atmosphere. They might be improved, however, by optimizing the process conditions of PDA. The PDA under a H_2S atmosphere following $(NH_4)_2S$ wet-treatment resulted in an increased S concentration at the interface, which improved the electrical properties of the devices.

1. Introduction

Passivating the interface between the gate insulator (GI) and the III-V compound substrates using sulfur (S) has been known to be effective for improving the interfacial properties in metal-insulator-semiconductor (MIS) devices based on III-V compound semiconductor substrates. The S at the interface between the GI and III-Vs plays an important role: that of passivating the surface-dangling bonds so as to reduce the electrical defects at the interface, and suppressing undesirable interfacial-layer (IL) growth [1–7]. One of the commonly adopted methods of incorporating S onto the interface is wet-treating the III-V substrates in a $(NH_4)_2S$ solution [8–10]. S passivation using $(NH_4)_2S$ solution, however, is not appropriate for industrial mass production because S bonding on the substrate surface is unstable in the atmosphere, and the S is likely to be sensitively released from the surface depending on the process variables, such as the temperature, air exposure time, and pressure. Therefore, various methods for S incorporation into the interface need to be studied [11,12]. Among them, the post-deposition annealing (PDA) of the GI films grown either under a H_2S atmosphere or with S powder in the annealing chamber [13,14] can be a feasible candidate for replacing wet processing using a $(NH_4)_2S$ solution with simple dry processing. S could be accumulated at the interface after PDA due to the stress at the interface between the dielectric film and the substrate, which is similar to the case of the nitrogen accumulated at the interface between the SiO_2 GI and the Si substrate after PDA under NH_3, N_2O, etc. [15–18].

In this work, the feasibility of replacing wet processing for the interface S passivation in III-V compound-semiconductor-based devices with dry processing using PDA under a H_2S atmosphere was examined. Al_2O_3 films were grown using the atomic-layer-deposition (ALD) technique on ultrathin-body $In_{0.53}Ga_{0.47}As/Al_2O_3/SiO_2/Si$ substrates. The interface properties of

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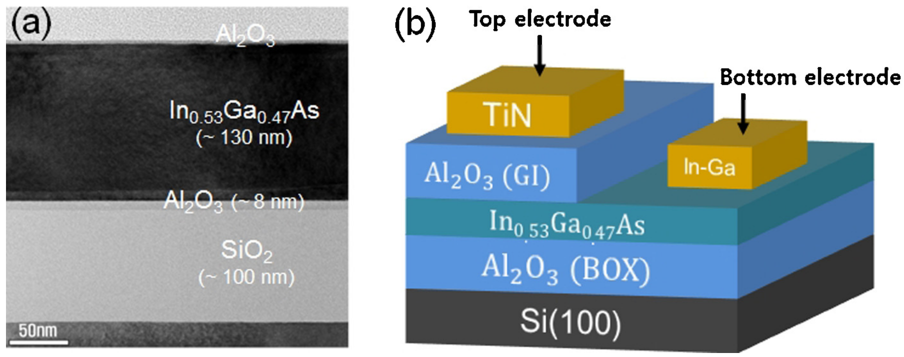

Fig. 1. (a) TEM image of the prepared ultrathin-body $In_{0.53}Ga_{0.47}As$ on $Al_2O_3/SiO_2/Si$ substrates with Al_2O_3 gate oxide. (b) Schematic structure of the MIS capacitor with a TiN top electrode.

the various samples were systematically observed from the viewpoints of (i) the S distribution at the interface and (ii) the IL growth behavior. The chemical composition and bonding status at the interface were traced through secondary ion mass spectroscopy (SIMS) and X-ray photoelectron spectroscopy (XPS), respectively. MIS capacitors were fabricated, and their electrical properties were examined. Furthermore, the properties of the devices with PDA under a N_2 atmosphere were compared with those with PDA under a H_2S atmosphere.

2. Experimental

Ultrathin-body $In_{0.53}Ga_{0.47}As$ layers (~130 nm) on Al_2O_3 (~8 nm)/SiO_2(~100 nm)/Si substrates were prepared using a wafer bonding technique [19,20], whose cross-section transmission electron microscopy (TEM) image is shown in Fig. 1(a). The surfaces of the substrates were cleaned for 30 s using a diluted HF solution with deionized water (10%) and were selectively wet-treated with $(NH_4)_2S$ solution (22 vol%) for 10 min at room temperature (to achieve chemical S passivation). ALD Al_2O_3 films were grown on the as-prepared wafer-bonded ultrathin-body $In_{0.53}Ga_{0.47}As/Al_2O_3/SiO_2/Si$ substrate in a 4-inch traveling-wave-type ALD reactor (CN-1 Co., Atomic Classic) using $Al(CH_3)_3$ and H_2O as the metal precursor and oxygen source, respectively, at a substrate temperature of 280 °C. Pure N_2 (99.999%) was used as carrier gas. The feeding times of $Al(CH_3)_3$ and H_2O were 1.5 s. The purging times after $Al(CH_3)_3$ and H_2O pulses were 15 and 30 s, respectively.

PDA of the grown films was performed using a rapid thermal annealing process at 500 °C for 30 s, under a pure N_2 or $5\%H_2S/95\%N_2$ atmosphere with the working pressure of ~100 torr. The schematic diagram of the fabricated MIS devices is shown in Fig. 1(b). A sputtered TiN gate electrode was deposited through a shadow mask, which was followed by forming gas (95% N_2/5% H_2) annealing at 300 °C for 30 min. In-Ga eutectic alloy was used for back Ohmic contact after the etch-out of the Al_2O_3 GI film using the HF solution. The capacitance-voltage (C–V) and hysteresis characteristics were examined using an Agilent E4980A precision LCR meter. The equivalent oxide thickness (EOT) of the films was calculated from the accumulation capacitances measured at 1 MHz, considering the quantum mechanical effects. The interface chemical binding status of the film was examined via XPS, using Mg *Kα* as the X-ray source (VG Multilab ESCA 2000) with the analysis angle of 45°. The depth profiles of the elements in the films were traced via dynamic SIMS (ION-TOF IV GmbH) equipped with 25 kV Bi ion gun operated with the target current of 1 pA. The film was sputtered by Cs ion gun with the energy of 500 eV (target current of 30 nA). The microstructures of the films and interfaces were observed through high-resolution transmission electron microscopy (HRTEM) equipped with a field emission gun (FEI Co., Ltd.).

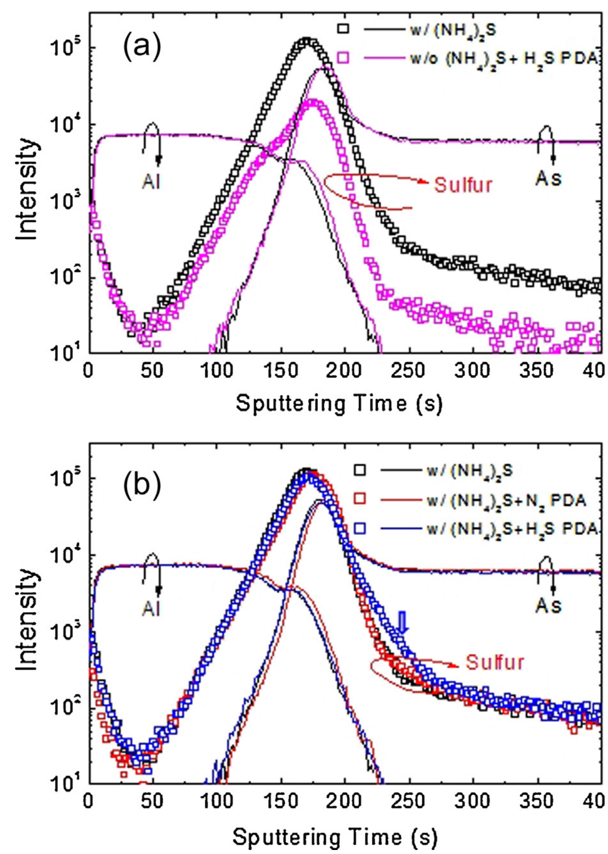

Fig. 2. SIMS depth profiles for S, Al, and As in the ALD Al_2O_3 films (~3 nm) on the ultrathin-body $In_{0.53}Ga_{0.47}As$ substrate (a) with interface S passivation using $(NH_4)_2S$ solution, and PDA under a H_2S atmosphere without $(NH_4)_2S$ wet treatment, and (b) with $(NH_4)_2S$ wet treatment after the PDAs under N_2 and H_2S atmospheres.

3. Results and discussion

First, the S distribution at the interface in the various cases was traced using the SIMS depth profile. Fig. 2(a) shows the SIMS depth profiles for S, Al, and As in the ALD Al_2O_3 films (~3 nm) on an ultrathin-body $In_{0.53}Ga_{0.47}As$ substrate with interface S passivation using $(NH_4)_2S$ solution, and PDA under a H_2S atmosphere with no $(NH_4)_2S$ wet treatment. The Al and As signals were included to identify the position of the interface, which seem to be practically identical for both samples in Fig. 2(a). S was accumulated at the interface by the $(NH_4)_2S$ wet treatment as well as PDA under a H_2S