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Remote plasma atomic layer deposited Al_2O_3 4H SiC MOS capacitor with remote H_2 plasma passivation and post metallization annealing

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ABSTRACT

Hydrogen (H_2) plasma treatment at the interface between 4H-SiC substrate and Al_2O_3 dielectric prepared by the atomic layer deposition (ALD) was performed and its effects on capacitance–voltage characteristics as well as the interface state density (D_{it}) was evaluated with metal oxide semiconductor devices. The atomic force microscopy result indicates that the remote H_2 plasma treatment reduces surface roughness. Compared with the non-passivated devices, lower leakage current, lower hysteresis and higher breakdown voltage are attained with remotely hydrogen plasma-treated devices. Without post metallization annealing (PMA), D_{it} value more than $10^{14}\,eV^{-1}\,cm^{-2}$ is attained with hydrogen plasma passivated devices, indicating plasma-induced damage on the surface. However, using PMA, D_{it} of the H_2 plasma treated device is significantly reduced to as low as $1.00 \times 10^{12}\,eV^{-1}\,cm^{-2}$ at $E_c - E_t = 0.4$ eV and is about five times lower than that of sample without H_2 plasma passivation ($D_{it} = 4.84 \times 10^{12}\,eV^{-1}\,cm^{-2}$).

1. Introduction

Silicon carbide (SiC) is an attractive wide band gap (WBG) material for the high power, high frequency and high temperature devices due to a large band gap energy (~2.3 eV for 3C-SiC, ~3.2 eV for 4H-SiC, ~3.0 eV for 6H-SiC), higher dielectric breakdown field strength compared to Si, high thermal conductivity and saturated electron drift velocity due to their excellent material properties [1,2]. Main advantage using SiC over other WBG materials is that SiO_2 as a gate dielectric can be thermally grown on SiC substrates. However, it has been reported that SiO_2/SiC interface has at least one or two orders of magnitude higher interface state density (D_{it}) than that of the SiO_2/Silicon (Si) interface due to carbon residual clusters, incomplete oxidation and intrinsic oxygen deficiencies during the process [3–6]. Several results from SiO_2/4H-SiC system have been reported with D_{it} values from 10^{13} to about $10^{11}\,cm^{-2}\,eV^{-1}$ for the energy range between midgap and ~0.1 eV below the conduction band edge of SiC [7–11]. Interface quality is significantly affected by the various oxidation or post nitridation process. Also, alternative phosphorus passivation substantially reduces D_{it} down to $2–4 \times 10^{11}\,cm^{-2}\,eV^{-1}$ [12]. The mobility of metal–oxide–semiconductor (MOS) devices is limited by these higher interface state densities because defects act as electron trap sites.

Various approaches have been suggested in order to suppress D_{it}. These ones include thermal treatments as well as plasma passivation using various gases (N_2O, NO, N_2, H_2, F_2) at the SiO_2/SiC interface during oxidation or pre-/post-oxidation annealing steps [13–16]. However, poor interface quality could be still possible due to carbon precipitates, lattice mismatch and plasma damage during high temperature oxidation step or plasma treatment. Therefore, alternative process for the oxide formation where deposition temperature is as low as 200–400 °C has been proposed since it does not give rise to a disruption of the gate oxide/SiC interface and the formation of carbon clusters could be avoidable.

Besides overcoming an inherent drawback of SiO_2 such as low dielectric constant leading to lower breakdown voltage and drain current, ALD high-*k* dielectrics such as HfO_2, Al_2O_3, MgO, Gd_2O_3 and their laminated structures have been investigated as alternative gate dielectrics for further D_{it} reduction [17–20]. Al_2O_3 is a promising gate dielectric due to reasonably high *k* (~10), excellent lattice matched with SiC, good thermal stability and large conduction band offset in SiC-Al_2O_3 system. However, despite several attempts to investigate ALD Al_2O_3/SiC system with interface passivation [21–24], remote plasma atomic layer deposition (RPALD) Al_2O_3/SiC system with remote H_2 plasma passivation has not been studied yet, which could potentially reduce plasma-induced damage on the SiC substrate because plasma is separately generated at

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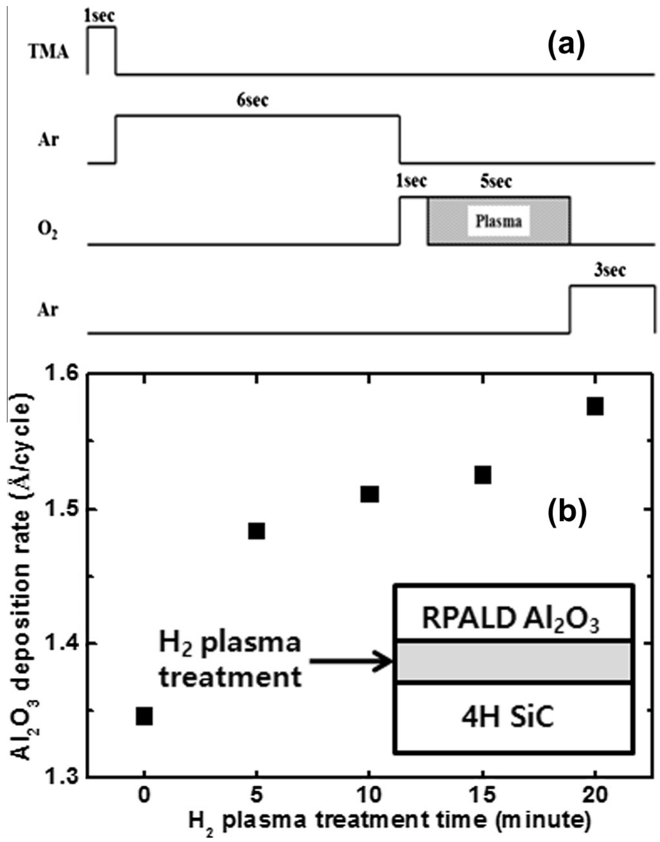

Fig. 1. Process sequence of RPALD Al_2O_3 on the H_2 plasma-treated device (a) and deposition rate (b).

the different location and hence it is not directly exposed to the substrate.

In this paper, we characterized the MOS device with RPALD Al_2O_3 on the H_2 plasma-treated SiC substrate. Structural and chemical properties of RPALD Al_2O_3 on H_2 plasma-treated SiC were analyzed by atomic force microscopy (AFM), field emission scanning electron microscopy (FE-SEM), and X-ray photoelectron spectroscopy (XPS). Also, the effects of varying H_2 plasma exposure time and post annealing were investigated with MOS devices.

2. Experiment

The MOS device was prepared by n-type 4H-SiC substrate with 10 μm thick epi layer doped with about 5×10^{15} cm^{-3} of nitrogen. After SiC substrate was pre-cleaned with diluted hydrofluoric acid solution (HF (47%): DI = 10:1) for 1 min, followed by deionized wafer rising and N_2 gas drying, SiC substrate (denote "H_2") was exposed to H_2 plasma under 0.5 torr gas pressure, 200 sccm gas flow rate and 250 W RF power in inductively-coupled plasma type. Plasma exposure time was 5, 15 and 20 min. The substrate was heated up to 300 °C during the plasma treatment. Compared to other direct plasma type, in our remote plasma system, reduced plasma-induced damage on the SiC substrate is expected because the substrate is neutral with respect to the plasma and is located outside of the generated plasma region. For the comparison, the other control SiC sample (denote "HF-Last") did not receive plasma exposure. Subsequently, the samples were loaded into RPALD chamber for Al_2O_3 deposition by admitting tri-methyl-aluminum ($Al(CH_3)_3$, TMA) source, O_2 as an oxidant, plasma exposure and Ar purging gas sequentially to the substrate held at 350 °C with 100 W RF for 130 cycles as shown in Fig. 1. It is found that Al_2O_3 film on the H_2 plasma-treated SiC is thicker than that of HF-treated SiC substrate and thicker film is attained with longer plasma exposure times. Al_2O_3 thickness was measured by an ellipsometer

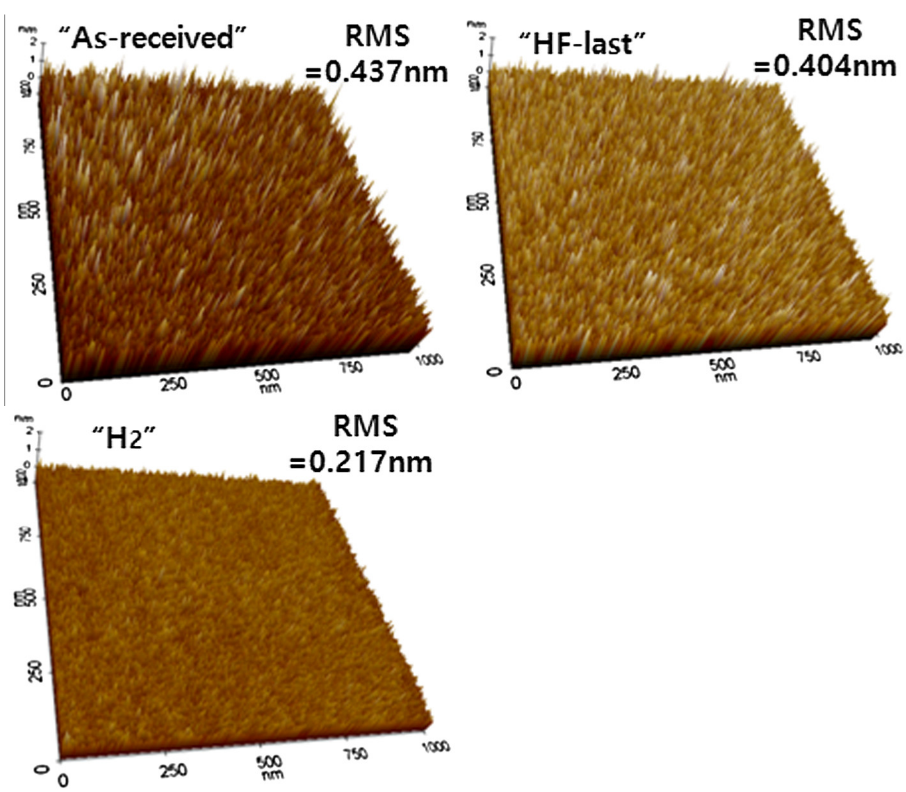

Fig. 2. Surface morphologies of as-received, HF Last, and H_2 plasma treated SiC substrate.