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Electrical properties of reactive-ion-sputtered Al_2O_3 on 4H-SiC

Madhup Shukla [a,*], Gourab Dutta [a], Ramanjaneyulu Mannam [b], Nandita DasGupta [a]

[a] Microelectronics and MEMS Laboratory, Electrical Engineering Department, Indian Institute of Technology Madras, Chennai 600036, India
[b] Department of Physics and Nano Functional Materials Technology Centre, Indian Institute of Technology Madras, Chennai 600036, India

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ABSTRACT

Al_2O_3 was deposited on n-type 4H-SiC by reactive-ion-sputtering (RIS) at room temperature using aluminum target and oxygen as a reactant gas. Post deposition oxygen annealing was carried out at a temperature of 1100 °C. Metal-oxide-semiconductor (MOS) test structures were fabricated on 4H-SiC using RIS-Al_2O_3 as gate dielectric. The C-V characteristics reveal a significant reduction in flat band voltage for oxygen annealed RIS-Al_2O_3 samples (V_{fb} = 1.95 V) compared to as-deposited Al_2O_3 samples (V_{fb} > 10 V), suggesting a reduction in negative oxide charge after oxygen annealing. Oxygen annealed RIS-Al_2O_3 samples also showed significant improvement in I-V characteristics compared to as-deposited RIS-Al_2O_3 samples. A systematic analysis was carried out to investigate the leakage current mechanisms present in oxygen annealed RIS-Al_2O_3 on 4H-SiC at higher gate electric field and at different operating temperature. For measurement temperature (T) < 303 K, Fowler–Nordheim (FN) tunneling was found to be the dominant leakage mechanism and for higher temperature ($T \geq 303$ K), a combination of FN tunneling and Poole-Frenkel (PF) emission was confirmed. The improvement in I-V characteristics of oxygen annealed RIS-Al_2O_3/4H-SiC MOS devices is attributed to large effective barrier height (Φ_B = 2.53 eV) at Al_2O_3/SiC interface, due to the formation of an interfacial SiO_2 layer during oxygen annealing, as confirmed from X-ray Photoelectron Spectroscopy results. Further improvement in C-V characteristics for oxygen annealed RIS-Al_2O_3/4H-SiC MOS devices was observed after forming gas annealing at 400 °C.

1. Introduction

Silicon Carbide (SiC) has unique physical and electrical properties like wider band gap (~3 eV), higher thermal conductivity (~4.9 W/cm), higher breakdown electric field (~3 MV/cm) and high electron saturation drift velocity (~2.0×10^7 cm/s) [1], making it an excellent candidate for high temperature and high frequency applications. Along with this, SiC is the only compound semiconductor on which thermally stable silicon dioxide (SiO_2) can be grown [2]. This has led to the development of SiC based metal-oxide-semiconductor (MOS) technology, particularly in the field of power electronics. However, the commercialization of SiC MOS devices with SiO_2 as gate dielectric remains a challenge because of low channel mobility due to high SiO_2/SiC interface states near the conduction band edge of SiC [3]. Furthermore, as the dielectric constant of SiO_2 is low compared to that of 4H-SiC (k_{SiC} = 10), the electric field in SiO_2 is 2.5 times higher than that in SiC resulting in a premature dielectric breakdown [4]. This leads to serious reliability issues for SiO_2-SiC MOS devices as well as, underutilization of high breakdown electric field of SiC, which is an asset of SiC for high power applications. These limitations of SiO_2 have prompted researchers to investigate the use of high-k dielectrics on SiC. Among several high-k dielectrics, Al_2O_3 has generated a lot of interest due to its excellent properties such as high dielectric constant (k_{Al2O3} ~ 10), large band gap (~6.2 eV), chemical inertness, excellent conduction band and valence band offset with 4H-SiC [5].

In the past, several techniques such as, atomic-layer-deposition (ALD, using either ozone [5] or H_2O [6] as an oxidant), nitric acid oxidation [7] and RF-sputtering (using Al_2O_3 target at a deposition temperature of 220 °C) [8], have been tried to deposit Al_2O_3 on 4H-SiC. High temperature annealing of Al_2O_3 on 4H-SiC at different temperatures (800 °C to 1100 °C) [5,9,10,11] and in various gas ambient (N_2/O_2/Ar) [5,10,11] has demonstrated reduction in capacitance-voltage (C-V) hysteresis and flat band voltage (V_{fb}) by trap passivation.

In this work, for the first time we report on the electrical characteristics of Al_2O_3 deposited by reactive-ion-sputtering (RIS) on 4H-SiC at room temperature, using Aluminum (Al) as target. Our earlier work has shown RIS deposited Al_2O_3 as a promising gate dielectric for Gallium Nitride (GaN) based metal–insulator–semiconductor (MIS) devices [12]. RIS deposition technique provides several advantages such as low-cost, uniform deposition at lower temperatures and no formation of any by-products and contaminants. Annealing in different gas ambient was carried out in order to improve bulk and interface properties of RIS-Al_2O_3 on 4H-SiC. Significant improvement in gate leakage current was observed after oxygen annealing. Analysis of gate leakage current in oxygen annealed RIS-Al_2O_3 on 4H-SiC revealed the presence of Fowler–Nordheim (FN) tunneling for below room temperature operation and a combination of FN tunneling and Poole-Frenkel (PF) emission for above room temperature operation. RIS-Al_2O_3 with subsequent

* Corresponding author.
E-mail address: madhup.iit@gmail.com (M. Shukla).

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oxygen annealing showed better/comparable gate leakage performance as compared to Al_2O_3 deposited by other methods or in stacked configuration (Al_2O_3/SiO_2 stack) on 4H-SiC. Further improvement in C-V characteristics of oxygen annealed RIS-Al_2O_3 was observed by annealing it in forming gas (5% H_2 and 95% N_2) ambient. X-Ray photoelectron spectroscopy (XPS) studies were carried out to analyze any change in compositional ratio at bulk/interfacial oxide due to annealing.

2. Experimental details

300 μm thick, n-type (Nitrogen doped) 4H-SiC with a doping concentration of about 1×10^{19} cm^{-3}, has been used in this work as bulk substrate to fabricate MOS capacitor structures. Three sets of devices were fabricated, designated as S_0 (MOS capacitors with as-deposited RIS-Al_2O_3 as gate dielectric), S_1 (MOS capacitors with oxygen annealed RIS-Al_2O_3 as gate dielectric) and S_2 (MOS capacitors with oxygen + forming gas annealed RIS-Al_2O_3 as gate dielectric). The samples were cleaned by organic solvents and piranha solution to remove organic impurities. Then standard Radio Corporation of America (RCA) [13] cleaning was performed on the samples. The cleaned 4H-SiC samples were immediately loaded in the RF sputtering chamber. Al_2O_3 was deposited at room temperature, using 99.999% pure Al as target. The RF sputtering chamber was initially evacuated to a base pressure of 5×10^{-7} mbar. Then, Ar and O_2 gasses were introduced into the chamber at a flow rate of 30 sccm and 5 sccm respectively. A process pressure of 1.2×10^{-2} mbar was maintained during sputter deposition. RF input power was kept at 100 W. The sputtered Al reacted with O_2 in the plasma to form Al_2O_3 and get deposited on 4H-SiC surface. This Al_2O_3 is designated as RIS-Al_2O_3. The rate of deposition of RIS-Al_2O_3 on 4H-SiC was ~1.5 nm/min. After the deposition, samples S_1 and S_2 underwent annealing in O_2 ambient at a temperature of 1100 °C for around 2 h. Sample S_2 underwent an additional annealing in forming gas at 400 °C for another 2 h. Subsequently, Al was deposited over Al_2O_3, for all the three samples (S_0, S_1 and S_2), by thermal evaporation in vacuum and then patterned by photolithographic technique to form an array of circular metal gate contacts of 40 μm diameter. Finally, back aluminum metallization was carried out after back oxide etching by buffered hydro fluoric acid (BHF). Multi-frequency C-V and current–voltage-temperature (I-V-T) measurements in dark were performed using Agilent's B1500A semiconductor device analyzer and Cascade Microtech Summit 12000AP thermal chuck probe station. The I-V measurements were carried out at different measurement temperatures (T) from 223 K to 393 K to obtain the gate current density (J_G) vs. gate electric field (E_G) plot given by Eqs. (1) and (2).

$$J_G = I_G/A \tag{1}$$

and

$$E_G = (V_G - \Phi_{ms})/EOT. \tag{2}$$

Here A, Φ_{ms} and EOT are gate area, metal–semiconductor work function difference and equivalent oxide thickness respectively. In order to study the film composition of oxygen annealed RIS-Al_2O_3 on 4H-SiC, XPS measurements were carried out using SPECS with PHIBOS 100 energy analyzer (SPECS GmbH, Germany). Mg Kα radiations were used to excite electrons.

3. Results and discussion

The physical thickness of as-deposited RIS-Al_2O_3 and oxygen annealed RIS-Al_2O_3 as measured by a spectroscopic ellipsometer (J.A. Woollam EC 400) were around 18 nm and 22 nm respectively. The dielectric constant of as-deposited RIS-Al_2O_3 was calculated to be around 5.5 which is comparable to the previous reported result on sputtered-Al_2O_3 [14] for similar oxide thickness. From the value of the accumulation capacitance and physical thickness (~22 nm) of the gate oxide, the dielectric constant and EOT of oxygen annealed RIS-Al_2O_3 of sample S_1 was calculated to be around 5.1 and 17 nm respectively. The higher physical thickness and lower value of dielectric constant of oxygen annealed RIS-Al_2O_3 in comparison with as-deposited RIS-Al_2O_3 is attributed to the growth of interfacial SiO_2 layer during oxygen annealing as discussed later. The I-V and C-V measurements were first carried out at room temperature for both samples S_0 and S_1. As can be seen from Fig. 1, J_G for as-deposited RIS-Al_2O_3 of sample S_0 is 4.67×10^{-7} A/cm^2 at a low gate electric field of 3 MV/cm which is reasonably good, however the breakdown field strength is low. Post deposition annealing in oxygen ambient (sample S_1) further improves the I-V characteristics in terms of leakage current and dielectric breakdown field strength (9 MV/cm) as shown in Fig. 1.

Inset of Fig. 1 shows the C-V characteristics of sample S_1 with a flat band voltage (V_{fb}) of 1.95 V. However, the C-V curve of S_0 (not shown) could not reach accumulation capacitance because of its large positive flat band voltage ($V_{fb} > 10$ V). In order to reach accumulation for S_0, a much large positive gate voltage had to be applied, leading to oxide breakdown. This large value of positive V_{fb} is due to the presence of large negative fixed oxide charge density (Q_f) in as-deposited RIS-Al_2O_3. In earlier reports [15,16], the negative Q_f in Al_2O_3 has been attributed to intrinsic and stable oxide defects such as oxygen interstitials [17,18]. Oxygen annealing on RIS-Al_2O_3 improves the C-V characteristics (by reducing negative Q_f in RIS-Al_2O_3) as well as improves its gate leakage current. Investigation of conduction mechanisms, affecting the gate leakage current in oxygen annealed RIS-Al_2O_3 on 4H-SiC was carried out in order to understand the quality of Al_2O_3/SiC interface and oxide trap energy levels.

3.1. Study of leakage current conduction mechanism in oxygen annealed RIS-Al_2O_3 on 4H-SiC

In order to study the gate leakage current through oxygen annealed RIS-Al_2O_3 at moderate-to-high electric fields, various leakage current mechanisms were explored. J_G vs. E_G characteristics of sample S_1 at different T (223 K ≤ T ≤ 393 K) are shown in Fig. 2(a). Presence of FN tunneling has been previously reported in Al_2O_3 on 4H-SiC [6]. Temperature independent FN tunneling occurs in thicker oxides and at higher E_G [19] and is given by Eq. (3) [20].

$$J_G = AE_G^2 \exp\left[\frac{-B}{E_G}\right] \tag{3}$$

where, $B = \left(8\pi\sqrt{2m_n^*(q\phi_B)^3}\right)/3qh$.

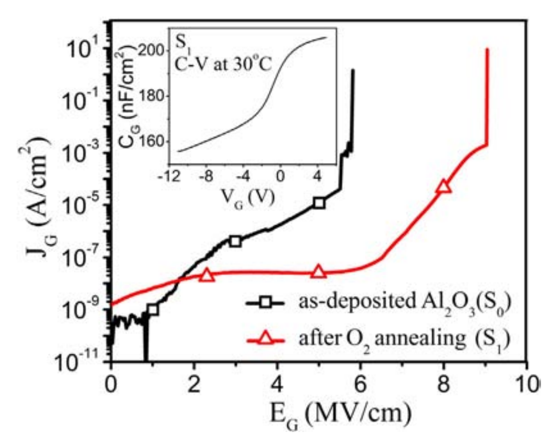

Fig. 1. Room temperature J_G vs. E_G characteristics of sample S_0 and S_1. Inset: C-V characteristics of sample S_1.