AIP | Applied Physics Letters

Electrical performance of Al 2 O 3 gate dielectric films deposited by atomic layer deposition on 4 H - Si C

Carey M. Tanner, Ya-Chuan Perng, Christopher Frewin, Stephen E. Saddow, and Jane P. Chang

Citation: Applied Physics Letters **91**, 203510 (2007); doi: 10.1063/1.2805742
View online: http://dx.doi.org/10.1063/1.2805742
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/91/20?ver=pdfcov
Published by the AIP Publishing

Electrical performance of Al_2O_3 gate dielectric films deposited by atomic layer deposition on 4*H*-SiC

Carey M. Tanner and Ya-Chuan Perng
Department of Chemical and Biomolecular Engineering, UCLA, Los Angeles, California 90095, USA

Christopher Frewin and Stephen E. Saddow
Department of Electrical Engineering, University of South Florida, Tampa, Florida 33620, USA

Jane P. Chang[a)]
Department of Chemical and Biomolecular Engineering, UCLA, Los Angeles, California 90095, USA

(Received 1 July 2007; accepted 16 October 2007; published online 13 November 2007)

Stoichiometric and pure Al_2O_3 gate dielectric films were grown on *n*-type 4*H*-SiC by a thermal atomic layer deposition process. The electrical properties of both amorphous and epitaxial Al_2O_3 films were studied by capacitance-voltage and current-voltage measurements of metal-oxide-semiconductor capacitors. A dielectric constant of 9 and a flatband voltage shift of +1.3 V were determined. A leakage current density of 10^{-3} A/cm^2 at 8 MV/cm was obtained for the amorphous Al_2O_3 films, lower than that of any high-κ gate oxide on 4*H*-SiC reported to date. A Fowler-Nordheim tunneling mechanism was used to determine an Al_2O_3/4*H*-SiC barrier height of 1.58 eV. Higher leakage current was obtained for the epitaxial γ-Al_2O_3 films, likely due to grain boundary conduction. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2805742]

The integration of high dielectric constant (high-κ) gate oxides in SiC power metal-oxide-semiconductor field-effect transistors (MOSFETs) has gained more attention in recent literature.[1] The vast majority of research has focused on a SiO_2 gate dielectric since SiC can be thermally oxidized to yield SiO_2, a property that makes it unique among wide bandgap semiconductors. The performance of these SiO_2/SiC MOSFETs has been improved by various nitridation methods, but their commercialization remains limited by a low channel mobility due to a high interface state density near the conduction band.[2] In addition, since the electric field across an interface scales inversely with the dielectric constant of the material, the low dielectric constant of SiO_2 (κ =3.9) relative to that of 4*H*-SiC (κ=10) results in an electric field in SiO_2 that is 2.5 times higher than that in SiC. This inequity requires device operation at an electric field far below the SiC breakdown field in order to avoid premature SiO_2 breakdown.[3] Thus, the high breakdown field of SiC (3.0 MV/cm) is severely underutilized, minimizing one of the material's major advantages for high-power applications. Additionally, since the blocking voltage of the power MOSFET scales with the square of the electric field, the device's blocking voltage capability is dramatically reduced for a given on-resistance. The limitations imposed by SiO_2 prompt the search for a high-κ gate oxide to enable MOSFET operation near the SiC breakdown field while maintaining a significantly lower field in the oxide. Numerous high-κ gate dielectric materials and stacks have been investigated on SiC, including Al_2O_3,[4] oxidized Ta_2Si,[5] SiO_2/TiO_2,[6] Gd_2O_3,[7] SiO_2/HfO_2,[8] and AlN.[9] Several intrinsic properties of Al_2O_3 make it a viable candidate as a gate dielectric material in SiC-based devices. First, the higher dielectric constant of Al_2O_3 (κ=10) compared to SiO_2 allows device operation at a higher electric field, taking advantage of the high breakdown field of SiC.[3] Second, the large bandgap of Al_2O_3 thin films (E_g=7.0 eV) relative to other high-κ oxides, such as HfO_2 and La_2O_3, potentially enables adequate barrier heights at the interface with 4*H*-SiC (E_g=3.26 eV).[4]

n-type 4*H*-SiC (0001) substrates (8° off-axis) were obtained from Cree and cleaned to remove particles and native oxide. Hydrogen etching was used to prepare the samples for subsequent SiC epitaxial growth.[10] Epitaxial growth was performed in a horizontal hot-wall chemical vapor deposition system[11] to produce an 8–10 μm specular, single crystalline layer of 4*H*-SiC. Al_2O_3 thin films of 200–300 Å thickness were deposited by thermal atomic layer deposition (ALD) at 200 °C using trimethylaluminum and water vapor. Alternating precursor pulses of 15 s were introduced at 2×10^{-4} Torr and separated by 60 s evacuation steps. Film thickness was determined by spectroscopic ellipsometry over a range of 280–760 nm. *In situ* x-ray photoelectron spectroscopy (XPS) was performed with a monochromatic Al $K\alpha$ (1486.6 eV) x-ray source. *In situ* reflection high-energy electron diffraction (RHEED) was performed with a 15 keV electron gun. To determine the impact of film structure on the electrical performance, some of the films were crystallized by post-deposition rapid thermal annealing in a N_2 ambient at 1100 °C for 4 min with a 30 s ramp up from room temperature. MOS capacitors were fabricated with evaporated Al gate electrodes and patterned using standard photolithographic methods. An evaporated Ti/Pt gate electrode was also tested and similar results were obtained. Capacitance-voltage (*C-V*) measurements were performed using an HP 4284A precision *LCR* meter at 1 MHz with a voltage sweep rate of 98 mV/s. Current-voltage (*I-V*) measurements were performed using an HP 4145A semiconductor parameter analyzer with a voltage sweep rate of 64 mV/ms. At least 20 devices were measured with consistent behavior, and representative data sets were selected for this manuscript.

The Al_2O_3 films were found to be stoichiometric with negligible carbon incorporation based on *in situ* XPS analy-

[a)]Author to whom correspondence should be addressed. Electronic mail: jpchang@seas.ucla.edu

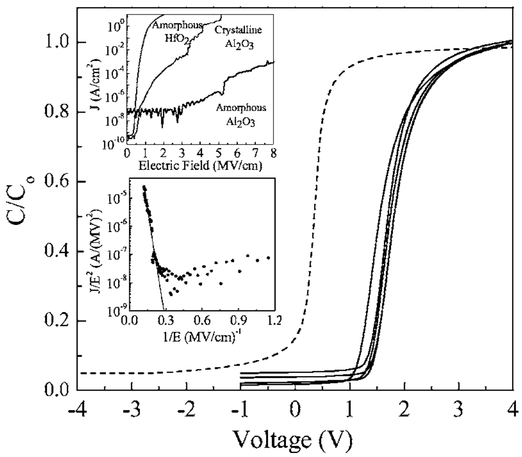

FIG. 1. The area-normalized capacitance-voltage curves (solid lines) of $4H$-SiC MOS capacitors (40×200, 100×200, and $200\times200\ \mu\text{m}^2$) and an ideal curve (dashed line) with an amorphous as-deposited 260 Å Al_2O_3 gate dielectric layer. The upper inset shows the leakage current density as a function of electric field across the gate dielectric in capacitors with amorphous Al_2O_3, crystalline γ-Al_2O_3, and amorphous HfO_2 thin films. The lower inset shows the Fowler-Nordheim tunneling fit for the amorphous $Al_2O_3/4H$-SiC MOS capacitor. Note that a different test equipment with a lower sensitivity at low current values was used to measure the amorphous Al_2O_3 sample.

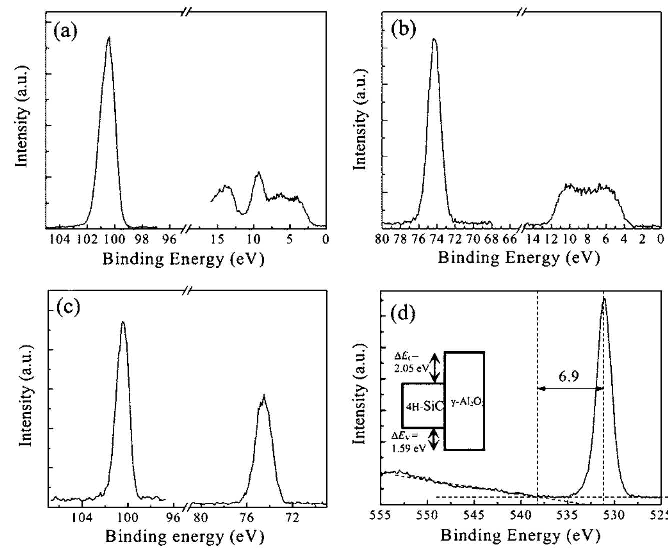

FIG. 2. X-ray photoemission spectra of (a) $4H$-SiC, (b) a 200 Å Al_2O_3 film, and (c) a 25 Å Al_2O_3 film. (d) The O $1s$ peak and inelastic scattering loss for a 200 Å Al_2O_3 film.

sis. The Al_2O_3 film growth rate was determined to be 0.88 ± 0.03 Å/cycle by spectroscopic ellipsometry, and was confirmed by high-resolution transmission electron microscopy (HRTEM). The as-deposited films were amorphous and smooth as determined by *in situ* RHEED and atomic force microscopy. As detailed in our earlier report, amorphous Al_2O_3 films are transformed into epitaxial γ-Al_2O_3 films by rapid thermal annealing.[12] The films are chemically stable up to 1100 °C, as no significant interfacial layer formation was observed by XPS or HRTEM.

C-V measurements indicated a dielectric constant of 9 for the Al_2O_3 films based on the film thickness measured by ellipsometry. This value is reasonable for Al_2O_3 thin films and consistent with previous reports.[13,14] As shown in Fig. 1, a reasonably constant flatband voltage shift of +1.3 V relative to the ideal flatband voltage was observed for various devices, suggesting a negative fixed charge density of $(2-3)\times10^{12}\ \text{cm}^{-2}$. The source of the fixed charge is attributed to trapped hydroxyl groups in the film due to the deposition process.[15] This flatband shift is relatively small compared to other reports of Al_2O_3 films grown by various methods,[16,17] suggesting that the thermal ALD method is better suited for gate dielectric deposition.

I-V measurements of $Al/Al_2O_3/4H$-SiC MOS capacitors are shown as an inset in Fig. 1, where the electric field represents the gate voltage divided by the physical film thickness. Although hard breakdown was observed for the amorphous Al_2O_3 films at an electric field (E) of 5.2 MV/cm, a relatively low leakage current density (J) of 10^{-3} A/cm^2 was observed at 8 MV/cm. However, the epitaxial γ-Al_2O_3 films exhibited a leakage current density of 10^{-3} A/cm^2 at a lower electric field of $E=2.5$ MV/cm. The higher leakage current is attributed to charge conduction along the grain boundaries in the oxide, which were identified as twinned crystallites during the structural analysis of the film by synchrotron x-ray diffraction.[12] However, the leakage current is far lower than that measured for amorphous HfO_2 gate dielectric films on $4H$-SiC. The high leakage current of the HfO_2 films is likely due to the low conduction band offset at the $HfO_2/4H$-SiC interface.[18] HfO_2 is a promising gate oxide material on Si due to its high dielectric constant ($\kappa=20$); however, its small bandgap ($E_g=5.7$ eV) appears to be prohibitive for $4H$-SiC MOS device integration.

The *J-E* response of an Al/amorphous-Al_2O_3/n-$4H$-SiC capacitor, shown as an inset in Fig. 1, was analyzed using Poole-Frenkel emission, Schottky emission and Fowler-Nordheim (FN) tunneling mechanisms. The FN tunneling mechanism[19] was found to yield the most reliable fitting and has been previously used to characterize SiC-based MOS capacitors.[17,19] The model is described by $J=AE^2\exp(-B/E)$, where $A=(q^3/8\pi h)(m_{\text{SiC}}/m_{\text{ox}})(1/\phi_b)$, $B=8\pi(2m_{\text{ox}})^{1/2}\phi_b^{3/2}/3hq$, q is the electron charge, m_{SiC} and m_{ox} are the effective electron masses in SiC and Al_2O_3, and ϕ_b is the $Al_2O_3/4H$-SiC barrier height. The value of m_{ox} was assumed to be $0.2m$,[20] where m is the free electron mass. An $Al_2O_3/4H$-SiC barrier height of 1.58 eV was obtained from this analysis based on the fitting between 4.4 and 8.3 MV/cm.

We also used XPS to determine the band offsets at the Al_2O_3/SiC interface. Based on the method described by Puthenkovilakam and Chang[21] and Van de Walle and Martin,[22] XPS spectra were obtained for bulk $4H$-SiC, a 200 Å Al_2O_3 film, and a 25 Å Al_2O_3 film grown on $4H$-SiC, as shown in Fig. 2. To determine the band alignment, first, the valence band maximum of bulk $4H$-SiC, $E_V^{\text{SiC}}=1.92$ eV, is referenced to the Si $2p_{3/2}$ core-level binding energy, $E_{\text{CL}}^{\text{SiC}}=100.40$ eV. Similarly, the valence band maximum of Al_2O_3, $E_V^{Al_2O_3}=3.33$ eV, is referenced to the Al $2p_{3/2}$ core-level binding energy, $E_{\text{CL}}^{Al_2O_3}=74.30$ eV. The valence bands are then aligned based on the core-level to core-level energy difference, $\Delta E_{\text{CL}}=25.92$ eV, determined from a thin $Al_2O_3/4H$-SiC sample in which both layers are sampled simultaneously. The valence band offset is $\Delta E_V=(E_V^{\text{SiC}}-E_{\text{CL}}^{\text{SiC}})-(E_V^{\text{oxide}}-E_{\text{CL}}^{\text{oxide}})+\Delta E_{\text{CL}}=1.59$ eV. The Al_2O_3 bandgap was determined from the onset of the inelastic scattering loss signal on the higher binding energy side of the O $1s$ peak for a 200 Å Al_2O_3 film, as shown in Fig. 2(d). The separation

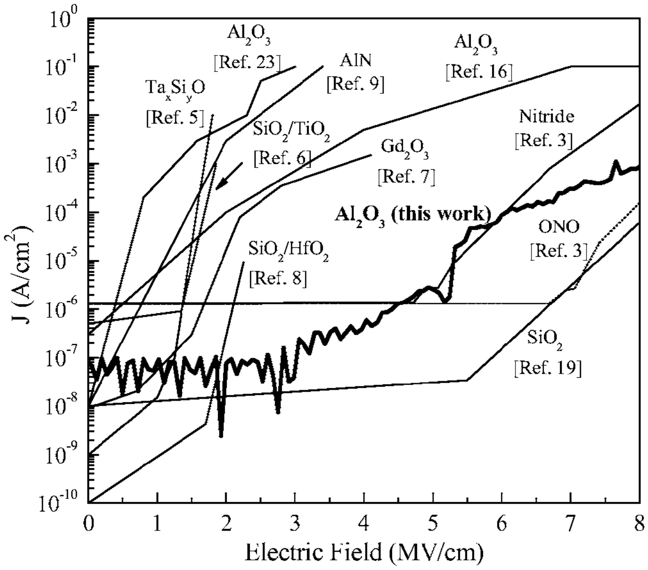

FIG. 3. Comparison of the leakage current density vs electric field response of various gate oxide/4*H*-SiC devices reported in the literature. The data from the literature were adapted as accurately as possible using a linear approximation.

between the peak and the scattering onset is 6.9 eV, in good agreement with previous studies.[4] The conduction band offset is therefore $\Delta E_C = E_g^{Al_2O_3} - E_g^{SiC} - \Delta E_V = 2.05$ eV. These band offset values are consistent with the rather symmetric band alignment previously reported for Al_2O_3-4*H*-SiC,[4] and reasonably close to the barrier height extracted from our *I-V* analysis.

The leakage current density of the amorphous Al_2O_3 films compares favorably with those of other Al_2O_3 films reported in the literature, as shown in Fig. 3. Specifically, we compare our films with those deposited by wet oxidation of evaporated Al as well as UV-assisted ALD, which reported leakage current densities of 10^{-3} A/cm^2 at 1.3 and 3.2 MV/cm, respectively.[16,23] These data suggest the unique properties and high quality of the thermal ALD process for gate dielectric deposition. The amorphous Al_2O_3 films in this work also have superior leakage current density characteristics compared with other high-κ materials and stacks investigated on 4*H*-SiC as reported in the literature, including oxidized Ta_2Si,[5] SiO_2/TiO_2,[6] Gd_2O_3,[7] SiO_2/HfO_2,[8] AlN,[9] Si_3N_4,[3] and $SiO_2/Si_3N_4/SiO_2$.[3] Finally, the *J-E* behavior of the amorphous Al_2O_3 films in this work is also reasonably close to that reported for the state-of-the-art thermal SiO_2 gate dielectrics on 4*H*-SiC.[19] This level of performance suggests that ALD Al_2O_3 films are very promising for integration as a gate dielectric in SiC power MOSFET devices.

In conclusion, Al_2O_3 gate dielectrics with superior electrical performance were demonstrated in 4*H*-SiC MOS capacitors. A dielectric constant of 9 and state-of-the-art leakage current densities were obtained for amorphous Al_2O_3 films. Higher leakage current was obtained for the epitaxial γ-Al_2O_3 films, suggesting the need for further optimization of the crystalline quality of these films.

The authors acknowledge the financial support of a Young Investigator Award from the Office of Naval Research.

[1] V. V. Afanas'ev, F. Ciobanu, S. Dimitrijev, G. Pensl, and A. Stesmans, J. Phys.: Condens. Matter **16**, S1839 (2004).
[2] M. K. Das, Mater. Sci. Forum **457-460**, 1275 (2004).
[3] L. A. Lipkin and J. W. Palmour, IEEE Trans. Electron Devices **46**, 525 (1999).
[4] K. Y. Gao, T. Seyller, L. Ley, F. Ciobanu, G. Pensl, A. Tadich, J. D. Riley, and R. G. C. Leckey, Appl. Phys. Lett. **83**, 1830 (2003).
[5] A. Perez-Tomas, P. Godignon, J. Montserrat, J. Millan, N. Mestres, P. Vennegues, and J. Stoemenos, J. Electrochem. Soc. **152**, G259 (2005).
[6] R. Mahapatra, A. K. Chakraborty, N. Poolamai, A. Horsfall, S. Chattopadhyay, N. G. Wright, K. S. Coleman, P. G. Coleman, and C. P. Burrows, J. Vac. Sci. Technol. B **25**, 217 (2007).
[7] A. Fissel, M. Czernohorsky, and H. J. Osten, J. Vac. Sci. Technol. B **24**, 2115 (2006).
[8] V. V. Afanas'ev, A. Stesmans, F. Chen, S. A. Campbell, and R. Smith, Appl. Phys. Lett. **82**, 922 (2003).
[9] M. Wolborski, D. Rosen, A. Hallen, and M. Bakowski, Thin Solid Films **515**, 456 (2006).
[10] S. Soubatch, S. E. Saddow, S. P. Rao, W. Y. Lee, M. Konuma, and U. Starke, Mem. Soc. Astron. Ital. **483-485**, 761 (2005).
[11] R. L. Myers, Y. Shishkin, O. Kordina, and S. E. Saddow, J. Cryst. Growth **285**, 486 (2005).
[12] C. M. Tanner, M. Sawkar-Mathur, M. F. Toney, J. Lu, H.-O. Blom, and J. P. Chang, Appl. Phys. Lett. **90**, 061916 (2007).
[13] M. D. Groner, J. W. Elam, F. H. Fabreguette, and S. M. George, Thin Solid Films **413**, 186 (2002).
[14] H. R. Lazar, V. Misra, R. S. Johnson, and G. Lucovsky, Appl. Phys. Lett. **79**, 973 (2001).
[15] J. E. Crowell, J. Vac. Sci. Technol. A **21**, S88 (2003).
[16] K. Y. Cheong, J. H. Moon, D. Eom, H. J. Kim, W. Bahng, and N.-K. Kim, Electrochem. Solid-State Lett. **10**, H69 (2007).
[17] A. Paskaleva, R. R. Ciechonski, M. Syvajarvi, E. Atanassova, and R. Yakimova, J. Appl. Phys. **97**, 124507 (2005).
[18] C. M. Tanner, J. Choi, and J. P. Chang, J. Appl. Phys. **101**, 034108 (2007).
[19] A. Agarwal, S. Seshadri, and L. B. Rowland, IEEE Electron Device Lett. **18**, 592 (1997).
[20] S. Meng, C. Basceri, B. W. Busch, G. Derderian, and G. Sandhu, Appl. Phys. Lett. **83**, 4429 (2003).
[21] R. Puthenkovilakam and J. P. Chang, J. Appl. Phys. **96**, 2701 (2004).
[22] C. G. Van de Walle and R. M. Martin, Phys. Rev. B **35**, 8154 (1987).
[23] S.-W. Huang and J.-G. Hwu, IEEE Trans. Electron Devices **51**, 1877 (2004).