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MgO insulating films prepared by sol–gel route for SiC substrate

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Abstract

Silicon carbide (SiC) is a wide bandgap semiconductor suitable for high-voltage, high-power, and high-temperature devices from dc to microwave frequencies. However, the commercialization of advanced SiC power devices remains limited due to performance limitation of the SiO_2 dielectric among other issues. Indeed, SiO_2 has a dielectric constant 2.5 times lower than that of SiC, which means that at critical field for breakdown in SiC, the electric field in the adjoining SiO_2 becomes too high for reliable operation. This removes the main advantage of using SiC power devices if the ten times higher breakdown field for SiC in comparison to Si cannot be exploited. Therefore, alternative dielectrics having a dielectric constant higher than or of the same order as that of SiC ($\varepsilon_r \approx 10$) should be used to reduce the electrical field in the insulator. Among alternative dielectrics to silicon dioxide (SiO_2), magnesium oxide (MgO) seems to be a good candidate regarding its bulk properties: large bandgap, high thermal conductivity and stability, and a suitable dielectric constant ($\varepsilon_r \approx 10$). In order to evaluate such promising candidate, the sol–gel process appears to be a convenient route to elaborate this kind of coatings. By selecting appropriate precursor solution and optimizing the curing conditions of the films, MgO films could be obtained under various crystallization states: non-oriented and preferred ⟨1 1 1⟩ orientation. MIM structures have been used to investigate the insulating potentialities of the sol–gel MgO films. The dielectric strength of the films was found to be microstructure dependent, and reached 5–8 MV/cm at room temperature. Leakage currents were measured from 25 °C up to 250 °C.

Keywords: Films; Sol–gel processing; Electrical properties; SiC; MgO; Insulator

1. Introduction

Silicon carbide (SiC) is a wide bandgap semiconductor suitable for high-voltage, high-power, and high-temperature devices from dc to microwave frequencies.[1–3] One of the most important techniques in the development of SiC-based devices is the formation of a suitable insulator or passivation layer. The properties of silicon dioxide (SiO_2, standard dielectric used in microelectronics) are not sufficient because its dielectric constant is 2.5 times lower than that of SiC ($\varepsilon_r \approx 10$), which means that at critical field for breakdown in SiC, the electric field in the adjoining SiO_2 becomes too high for reliable operation.[4] This removes the main advantage of the high breakdown field of SiC (10× that of Si): the maximum voltage of SiC power devices is limited by the field in the dielectric, not by the breakdown of the semiconductor. Therefore, alternative dielectrics with a higher dielectric constant (typically $\varepsilon_r \geq 10$) should be used to reduce the electrical field in the insulator.[5] Among alternative dielectrics to silicon dioxide (SiO_2), magnesium oxide (MgO) seems to be a good candidate regarding its bulk properties: large bandgap (7.8 eV), high thermal conductivity and stability, and a suitable dielectric constant ($\varepsilon_r \approx 10$). In order to evaluate such promising candidate, the sol–gel process appears to be a convenient route to elaborate oxide coatings. Sol–gel films have a high purity and the thickness is easily controlled. Deposition is performed at room temperature and atmospheric pressure, with a low cost compared to conventional vacuum deposition. Furthermore, spin-coating

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process can be easily integrated to industrial microelectronic production lines.

We report herein on the structural and electrical properties of sol–gel MgO thin films deposited onto Pt/Si(1 1 1), so as to select optimal coating preparation before exploring the electrical properties on SiC substrate.

2. Experiment

2.1. Sample preparation

MgO precursor solutions have been prepared using magnesium methoxide and anhydrous magnesium chloride dissolved in methanol. Spin-coating was performed to deposit MgO films onto Pt/Si⟨1 1 1⟩ substrate at room temperature. Substrate rotation speed was 1500 rpm and 100 nm-thick nanocrystalline MgO layers were obtained after as-deposited film heat treatment in a conventional furnace at 700 °C for 1 h under ambient air. For electrical characterization, top electrodes (gold, circular dots, Ø = 200 μm) were deposited using RF magnetron sputtering.

2.2. Characterization

Crystalline structure of the films was investigated using θ–2θ angular X-ray diffraction ($\lambda K_{\alpha 1} = 1.78897$ Å). Refractive index and thickness of the films was estimated from ellipsometry. Porosity of the films was evaluated from refractive index using effective medium approximation (Bruggeman model) and correlated with density measurement from X-ray reflectometry. The films surface were observed using field effect scanning electron microscopy.

$I(V)$ characteristics were performed using a Keithley 236 source-measurement unit and a prober station equipped with a temperature controller. For breakdown measurements, 40 capacitors were tested on each sample. The breakdown field was measured by applying a voltage stepped in 2 V increments every 0.1 s, and measuring the current until the compliance (25 mA/cm^2) was reached.[5]

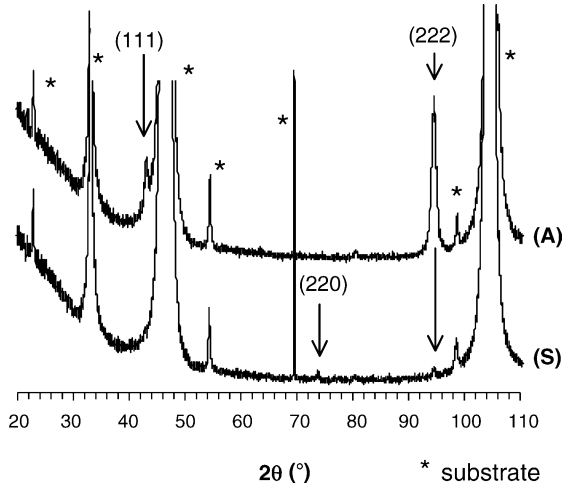

Fig. 1. XRD patterns of sol–gel MgO films deposited on Pt/Si(1 1 1) substrate.

3. Results and discussion

Two sol–gel routes have been investigated for the synthesis of MgO films: an alkoxide (A) and a salt (S) route. All synthesized MgO sol–gel films are nanocrystallized. As shown in Fig. 1, (S) film seems poorly crystallized and the crystallites are randomly oriented. For (A) film, the crystallites exhibit a sharp preferred ⟨1 1 1⟩ orientation. It has been verified that the crystallization was independent on the substrate nature and orientation (Pt/Si⟨1 1 1⟩, Si⟨1 0 0⟩ and Si⟨1 1 1⟩) for both type of films. Thus, sol–gel coating structural properties can be controlled by selecting appropriate precursors in coating solutions. Ellipsometry and X-ray reflectometry measurements give a higher porosity for (S) film (36 ± 2%) compared to (A) film (31 ± 2%). Considering such porosity levels, films would be expected not to provide efficient electrical insulation. But we highlight that porosity

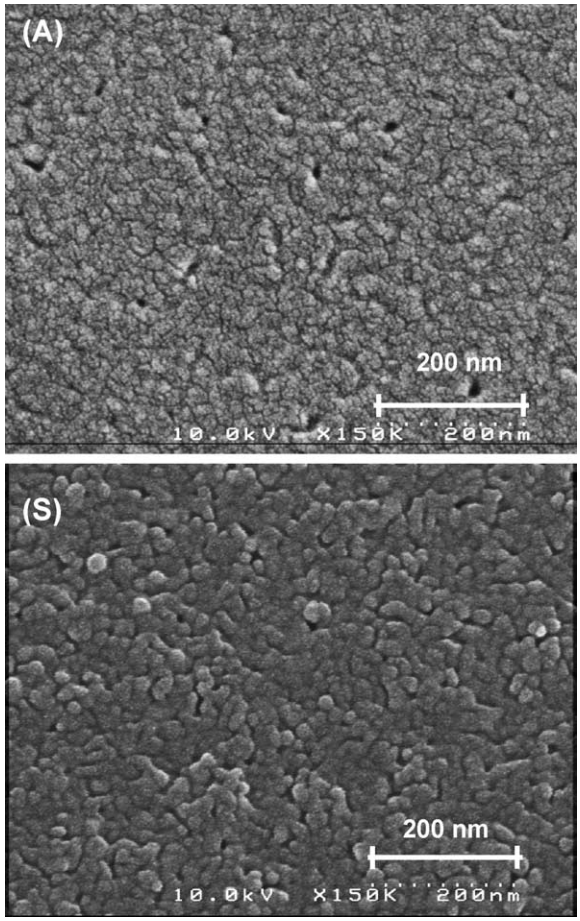

Fig. 2. Field Effect SEM micrographs of sol–gel MgO film surfaces.

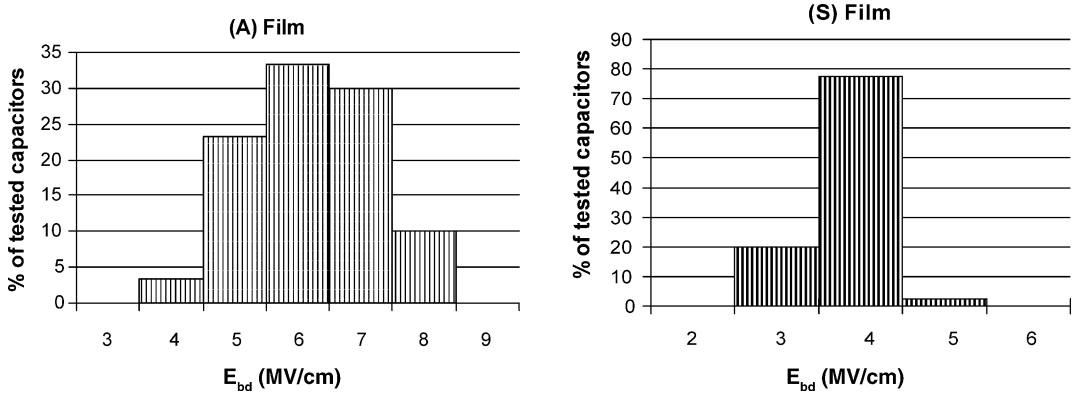

Fig. 3. Frequency of breakdown vs. breakdown electric field (E_{bd}) of (A) and (S) sol–gel MgO thin films.

levels were derived from the comparison between the measured parameters (optical index by ellipsometry and volumic mass density by X-ray reflectometry) and the MgO bulk material values (see Ref. [6] for MgO optical index and Ref. [7] for MgO volumic mass density). Furthermore sol–gel MgO films being polycrystalline, the grain boundary network can contribute to a further reduction of the apparent film density. Therefore, extracted porosity levels cannot be either exclusively, or directly attributed to the physical presence of holes inside the films. SEM films surface micrographs (Fig. 2) show nano-sized pores and grains, and qualitatively confirm the difference of porosity between the two types of film samples.

From breakdown field histograms in Fig. 3, the mean breakdown field (E_{bd}) is found around 4 MV/cm and 6 MV/cm, respectively, for (S) film and (A) film, with a narrow standard deviation (respectively $\sigma \approx 0.4$ and $\sigma \approx 1$). These values are higher than those reported for sputtered MgO films ($E_{bd} < 3$ MV/cm),[8,9] and less than thermal-evaporated MgO films values ($E_{bd} \approx 10$ MV/cm).[10]

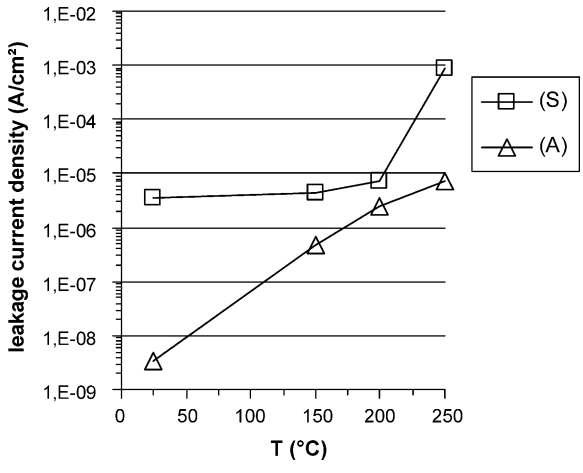

Fig. 4. Leakage current densities at 2 MV/cm vs. sample temperature.

Fig. 4 shows the leakage current densities measured at 2 MV/cm as a function of sample temperature for both types of films. It is clear that lower leakage current densities ($\leq 10^{-5}$ A/cm^2 even at 250 °C) were measured on (A) film, which corresponds to the sharp preferred ⟨1 1 1⟩-oriented film. TEM and X-ray texturation analyses are currently under progress in order to link microstructure and electrical properties.

4. Conclusion

The potentialities of sol–gel prepared MgO thin films used as an insulator for SiC substrates have been investigated. Sol–gel process appears to be a convenient route for preparation of homogeneous MgO coatings. Film structural properties can be controlled by varying precursor nature and optimizing densification conditions. The electrical properties of sol–gel MgO films have been investigated in MIM configurations. The best performances for insulation (dielectric strength and leakage currents) have been reached on sharp preferred ⟨1 1 1⟩-oriented films. In further work, we will characterize electrical properties of sol–gel MgO films deposited onto SiC substrate.

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