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Dielectric properties of composition spread SiO_2–Al_2O_3 mixed phase thin films deposited at room temperature by off-axis RF magnetron sputtering

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Abstract

The dielectric properties of composition spread SiO_2–Al_2O_3 thin films deposited by off-axis radio-frequency magnetron sputtering at room temperature were explored to obtain optimized compositions, which have low dielectric constants and losses. The specific points (compositions) showing superior dielectric properties of low dielectric constants (8.13 and 9.12) and losses (tanδ ∼0.02) at 1 MHz were found in area of the distance of 25.0 mm ($Al_2Si_3O_8$) and 42 mm ($Al_{2.4}Si_3O_8$) apart from SiO_2 target side in 75 mm × 25 mm sized Pt/Ti/SiO_2/Si(1 0 0) substrates, respectively. The specific thin films were amorphous phase and the compositions were $Al_2Si_3O_8$ (k ∼8.13) and $Al_{2.4}Si_3O_8$ (k ∼9.12).

Keywords: C. Dielectric properties; Low dielectric loss; Continuous composition spread; Off-axis RF magnetron sputtering

1. Introduction

Low-k dielectric thin films as interlayer dielectrics (ILDs), exhibiting lower dielectric constant and loss, are necessary to improve time-delay of resistor–capacitor (RC) and power consumption because of increasing demand on high integrating density in system-level and wafer-level packaging [1]. The RC delay, i.e. the delay of signal propagation in integrated circuit (IC) devices, is decided by the resistance of metal-wiring layer and parasitic electrostatic-capacity in the insulating interlayer. To be concrete, signal propaganda delay is proportional to the square root of dielectric constant of large scale integration (LSI) circuit packaging substrates.

To improve speed within the circuit lines, copper, which has approximately 30% lower electrical resistance than aluminum, has replaced aluminum in many high performance IC devices. However, copper has the lowest resistivity of metals that can easily be incorporated into IC devices, making reduction of ILD dielectric constant critical for realizing further decreases in interconnect delay times. Accordingly, several approaches have been identified for producing low-k ILD materials. Fluorinated silicate glass (FSG) (k ∼3.7) [2], porous carbon-doped silicon dioxide (SiOC) (k ∼2.1) [3], hydrogen silesquioxane (HSQ) (k ∼2.9) [4], organosilicate glass (OSG) (k ∼3.0) [5] and porous silica (k ∼1.1) [6] dielectrics were recently studied to reduce the dielectric constant and loss compared to conventional SiO_2 (k ∼4.0).

The process by combinatorial techniques is much beneficial to saving time and cost compared to conventional bulk process. Among the combinatorial techniques, CCS by off-axis sputtering is remarkably useful in the formation of thin film containing wide range of composition by single [7–10].

In this study, CCS SiO_2–Al_2O_3 thin films were investigated with focusing on dielectric values and film composition by radio-frequency (RF) magnetron sputtering forming a part of research of mixed composition in low-k thin films.

2. Experimental

The SiO_2–Al_2O_3 thin films were deposited on a Pt/Ti/SiO_2/Si(1 0 0) substrate (75 mm × 25 mm) by using off-axis RF

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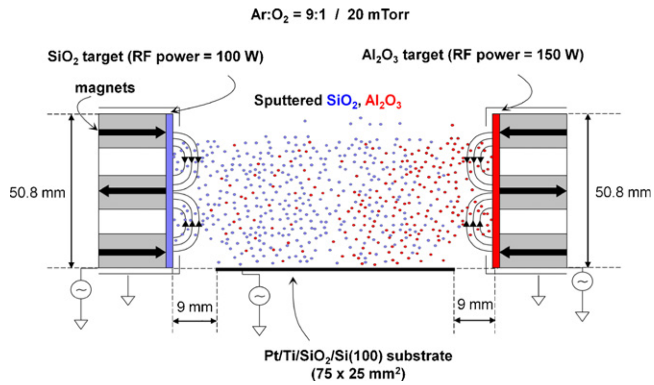

Fig. 1. Schematic presentation of cosputtering configuration for deposition of continuous composition spreads. Ar and O_2 gas are introduced at 27 and 3 sccm, respectively, to obtain a working pressure of 20 mTorr. RF power at SiO_2 and Al_2O_3 targets, which diameter is 50.8 mm, are 100 and 150 W, respectively.

magnetron sputtering system as shown in Fig. 1 with SiO_2 and Al_2O_3 targets (dia. 50.8 mm). The base pressure was $<2.0 \times 10^{-6}$ Torr and the working pressure by mixed Ar + O_2 gas (Ar:O_2 = 9:1) was 20 mTorr. The flow rates of Ar and O_2 gases are 27 and 3 sccm, respectively. The RF power of 100 and 150 W was conducted on SiO_2 and Al_2O_3 targets, respectively. The aluminum top-electrodes (200 μm × 200 μm), *x–y* 300 μm apart from each other, were deposited by electron beam evaporator using Al source (99.999%, Kurt J. Lesker) after a photo-lithography process.

The thickness profiles of thin films were examined by scanning electron microscopy (XL-30 FEG, FEI). The dielectric values of thin films were measured at 1 MHz by Precision Impedance Analyzer (4294A, Agilent) using Auto Probe Station (19S, TNP). The composition and area density of thin films were characterized by Rutherford backscattering spectroscopy (RBS) (6SDH2, NEC). An X-ray diffractometer (RINT 2000, Rigaku) using Cu Kα radiation was used for phase identification.

3. Results and discussion

Fig. 2 shows the thickness profiles of SiO_2, Al_2O_3 and co-sputtered SiO_2–Al_2O_3 thin films deposited at RF power of 100 and 150 W for SiO_2 and Al_2O_3 targets, respectively. The deposition rates and thickness of SiO_2–Al_2O_3 thin films were measured by cross-sectional SEM analysis. The deposition rate of each component from the corresponding target decreased as the distances from the target increased. It means that each content of SiO_2 and Al_2O_3 in the thin films decreases as the distance from each source (target) increases.

Fig. 3 shows the dielectric maps and the variations of dielectric constant and loss tangent along core horizontal-lines in the dielectric maps of CCS SiO_2–Al_2O_3 thin films prepared by off-axis RF magnetron sputtering, exhibiting dielectric constant and loss at each compositional point. The low dielectric constant (<6) and loss tangent (<0.04) were found at the distances of 0–16 mm and 25–34 mm apart from SiO_2 side in 75 mm × 25 mm sized Pt/Ti/SiO_2/Si(1 0 0) substrates, respectively. The dielectric constants are gradually increased with respect to the increase of distance from SiO_2 to Al_2O_3 target. It is due to the fact that the Al_2O_3 is high-*k* material better than SiO_2 material. Especially, the lowest dielectric loss (tanδ) around 0.024 was exhibited at both of the points of SA2 (3.5 mm below the core line and 25 mm apart from SiO_2 side) and SA11 (3 mm above the core line and 42.5 mm apart from SiO_2 side) as marked with

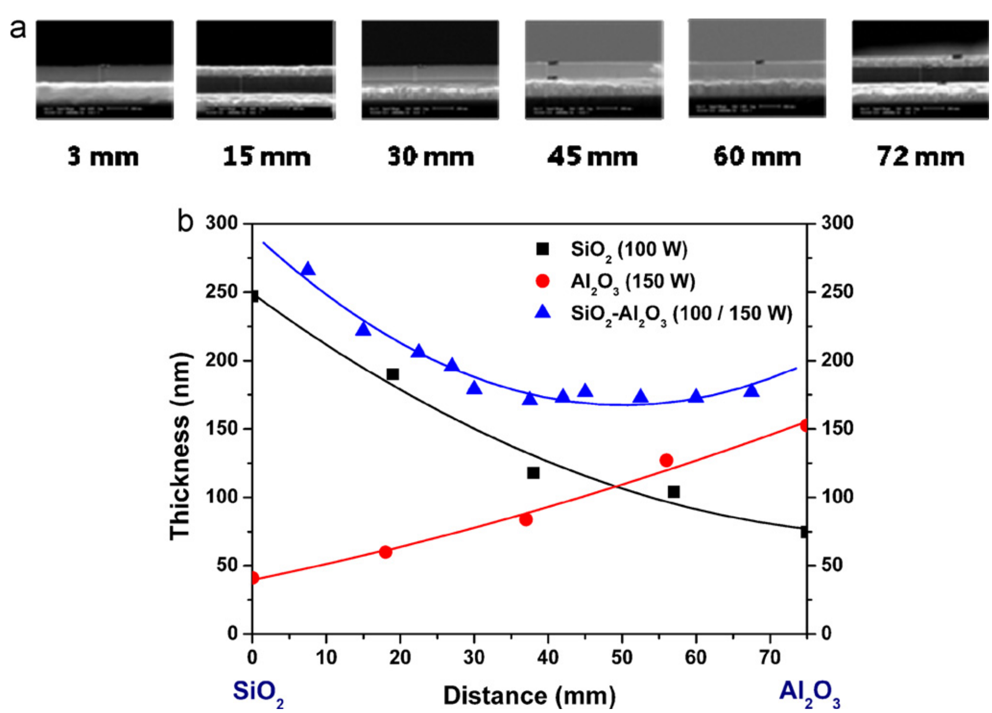

Fig. 2. (a) Cross-sectional SEM images and (b) Thickness profiles of SiO_2, Al_2O_3 and SiO_2–Al_2O_3 thin films deposited at RF power of 100 and 150 W for SiO_2 and Al_2O_3 targets, respectively, along the distance from SiO_2 side.

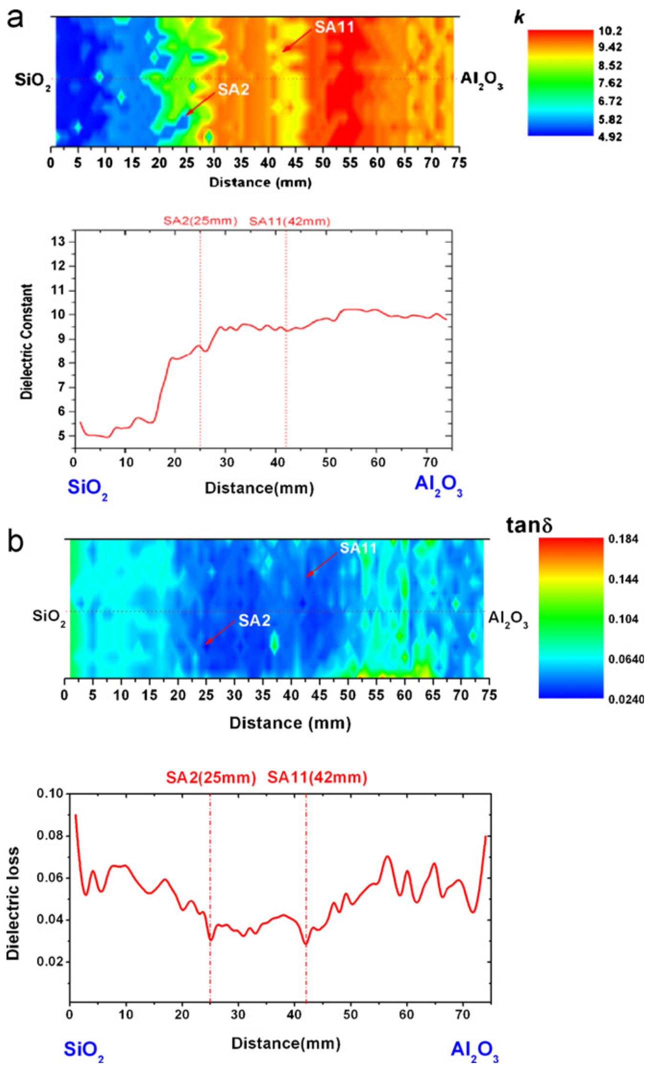

Fig. 3. Dielectric maps and dielectric profiles (along core horizontal-lines in the dielectric maps) of the SiO_2–Al_2O_3 binary thin films: (a) dielectric constant (k) and (b) dielectric loss (tanδ).

arrows in Fig. 3b. It was found that the each component of SiO_2 and Al_2O_3 decreases as the distance from each source or target increases. Accordingly, the ratio of Si and Al components is different as the distance is varied, which is identified by different compositions at the different distances from the colligation of thickness profiles and composition data in Figs. 2 and 4, respectively.

Fig. 4 shows the as-received RBS spectrum and simulated spectrum by Rutherford universal manipulation program (RUMP) code. The RBS was carried out using 2 MeV $^4He^{2+}$ particles with scattering angle of 170°. The atomic% of each element of Si, Al and O at SA2 and SA11 points, calculated from the data in Fig. 4, was shown in Table 1. The ratio of Si/Al component at SA2 is higher as 1.50 than the ratio of 1.25 at SA11, corresponding to the fact that SA2 is closer to the SiO_2 side than SA11. It is also coincident with the lower dielectric constant of SiO_2 (k ~4.0) compared to that of Al_2O_3 (k ~9.8). The corresponding compositions of SA2 and SA11 are $Al_2Si_3O_8$ and $Al_{2.4}Si_3O_8$, respectively.

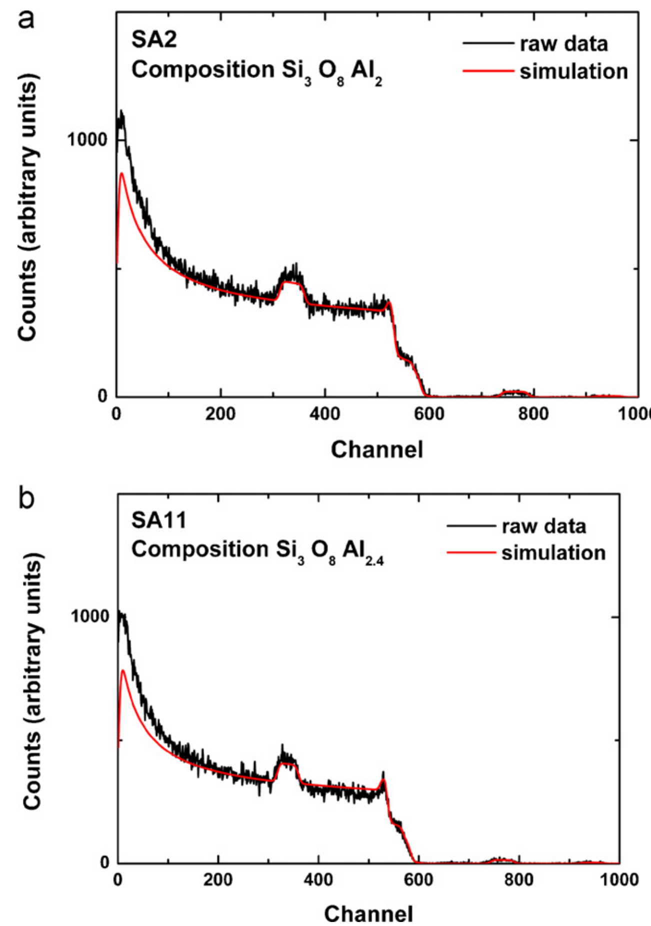

Fig. 4. The as-received RBS spectrum and simulation spectrum by RUMP for SiO_2–Al_2O_3 binary thin films: (a) SA2 and (b) SA11. The film composition and mass thickness were calculated from the simulation.

The bulk densities of thin films at SA2 and SA11 were obtained by calculating the ratio of mass thickness from RBS analysis and film thickness from cross-sectional SEM images (Fig. 2). As a result, the bulk densities of SA2 and SA11 films are 6.51×10^{22} atoms/cm^3 and 6.46×10^{22} atoms/cm^3, respectively. It is assumed that the larger content of SiO_2 and the lower content of Al_2O_3 results in the lower dielectric

Table 1
Compositional, physical, and dielectric properties of the SiO_2–Al_2O_3 thin films at specific points.

Point	Film composition (at%)			Bulk density (atoms/cm^3)	Dielectric constant (k)	Dielectric loss (tanδ)
	Si	Al	O			
SA2	23.1	15.4	61.5	6.51×10^{22}	8.13	0.024
SA11	22.4	17.9	59.7	6.46×10^{22}	9.12	0.024

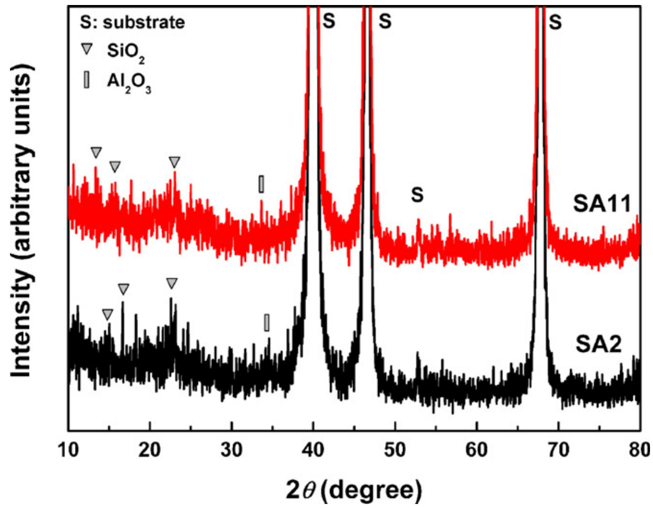

Fig. 5. XRD patterns of the SiO_2–Al_2O_3 binary thin films at specific points (SA2 and SA11).

constant because the bulk density of SA2 is similar with that of SA11 as shown in Table 1.

The thin films at SA2 and SA11 points, prepared at room temperature by off-axis RF magnetron sputtering, showed amorphous-like phases by X-ray diffractometry (XRD) as shown in Fig. 5. There was no distinct crystalline peak of SiO_2–Al_2O_3 binary system which is assumed to be necessary to be deposited at high temperatures or post-annealed to crystallize. It is well known that Al_2O_3 films synthesized directly on Si have been reported to remain amorphous up to 1000 °C, and The diffraction peak of SiO_2 films appear after annealing at near 1000 °C [11].

4. Conclusions

Much time and cost are consumed in the conventional bulk process to identify an optimized composition, contributing low dielectric constant and loss, compared to CCS method. Moreover, the CCS method is beneficial to find unknown compositions with unknown dielectric values. The SiO_2–Al_2O_3 CCS thin films deposited at room temperature by RF magnetron sputtering showed a low-*k* characteristics containing the dielectric constant of 8–9 and dielectric loss of 0.024 at 1 MHz with composition of Si: Al: O = 21–24: 15–19: 59–63 atomic%. Much improved dielectric properties are expected hereafter when the process conditions of the CCS thin films, e.g. substrate temperature, are optimized.

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