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Surface scaling evolution and dielectric properties of sputter-deposited low loss Mg_2SiO_4 thin films

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ABSTRACT

The evolution of surface roughness and dielectric properties of sputter-deposited Mg_2SiO_4 thin films have been studied. Analysis of height–height correlation function and power spectrum densities of the atomic force microscope images revealed that the growth surface experiences a difference in short-range and global roughening, indicating an anomalous scaling (super-rough) behavior. The growth exponent $\beta = 0.9$ suggests that the growth instability due to the shadowing far outweighs the effects of a high substrate temperature (700 °C). The dielectric loss tangent showed a pronounced dependence on deposition time, while dielectric constant remained unchanged at the bulk value; the changes in the grain structure via the evolution of surface scaling are suggested as a contributing factor.

1. Introduction

In recent years, nonconventional dielectric thin films have received significant attention for their potential in upcoming high frequency applications such as high speed LAN, intelligent transport systems, point-to-point telecommunication, etc. [1,2]. The key requirements for such applications include high frequency selectivity and stability, low power dissipation, and reduced delay time of electronic signal transmission, which has demanded engineering of thin films with exceptionally low dielectric loss (tan δ) as well as low dielectric constant (ε). Among the few candidates, α-Mg_2SiO_4 (forsterite) offers unique advantages from its low electrical conductivity, competitive dielectric properties and high tunability, as evidenced from the recent report of a *Qf* value as high as 270,000 GHz for the bulk forsterite [3–5]. In thin films, however, the dielectric properties can be substantially different from that of the bulk counterpart, arising due to various aspects of microstructure, interface between the electrode and thin film, residual stress, etc. [6–8]. Typically, thickness of the dielectric thin films has been identified to significantly affect all of the above features, and thus the values of both ε and tan δ [8,9].

On the other hand, the increase in film thickness leads to an evolution of surface roughness during growth of the films [10]. The surface roughening process is quite predominant in the initial stages of film growth (extending up to several hundred nanometers of thickness, which is of practical interest) and affects various, for example, electrical, optical, and tribological properties of the films. The kinetic roughening of the surface growth front follows from the competition between various roughening and smoothening mechanisms depending upon the process parameters [10]. Therefore, from a study of the surface roughness evolution versus deposition time (thickness), one can gain insight into growth mechanisms appropriate to the deposition process, and their influence on various properties of the films. Thus, such a study has tremendous technological implications and forms the basis of this work. The present study aims at understanding the evolution of the surface roughness and the dielectric properties of the Mg_2SiO_4 thin films grown by RF magnetron sputtering. We show that the surface width scaled differently at short-range and long range scales (anomalous scaling behavior). Concurrently and more importantly, the dielectric loss showed a pronounced dependence on the deposition time, while the dielectric constant remained surprisingly constant.

2. Experimental

The Mg_2SiO_4 thin films were grown on Pt(111)/Ti/SiO_2/Si(100) substrates at 700 °C by rf magnetron sputtering from a two-inch α-Mg_2SiO_4 ceramic target of purity 99.99% (LTS Chemical Inc.). The substrates were tilted by an angle of ~45° with respect to the target normal and the distance between the centers of substrate and the target was ~6 cm. The substrates were rotated at 7 RPM about their axes during sputtering. Prior to loading into the deposition chamber, the substrates were ultrasonic-cleaned sequentially with acetone, isopropyl alcohol, and ethyl alcohol anhydrous each for 10 min. The sputtering chamber was evacuated to a base pressure of 5×10^{-6} Torr using a turbomolecular pump backed by a rotary pump and a constant working pressure of 10 mTorr was maintained by allowing an argon–oxygen gas mixture (Ar/O_2: 30/10) through mass-flow controllers. Films of different growth times (15–150 min) were deposited at a rf power of 200 W.

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Under the given sputtering condition, the thickness of the films increased linearly with deposition time at a rate of ~2 nm/min. The deciding factor to choose the above combination of working pressure, composition of the gas mixture and the substrate temperature was to produce single phase α-Mg_2SiO_4 thin films.

The film surface was characterized by atomic force microscopy (AFM) using a Digital Instruments, Nanoscope IIId system. The images were acquired in air at room temperature in tapping mode of operation using Al-backcoated Si cantilevers. The tip radius was less than 10 nm with a resonant frequency of 330 kHz and, typically, a force constant of 42 Nm^{-1}. Images were obtained at 512×512 pixels. Thickness of the films was determined by field emission scanning electron microscopy (Hitachi S-4700) from the fracture cross-section area of the films. Dielectric properties were measured at room temperature by an impedance analyzer (Agilent 4294A) after the fabrication of a metal–insulator–metal sandwich structure utilizing a Pt top electrode deposited by DC sputtering.

3. Results and discussion

Fig. 1 shows the representative surface morphologies of the films for different deposition times. These AFM images indicate that all the films consist of well-defined crystallites with the high level of densification regardless of the deposition time. The growth trend is easily identified from the corresponding line profiles (Fig. 2). As the deposition time increases, an increase in grain height as well as in grain size is observed as the deposition time increases, resulting in a reduction of grain boundary density.

We have studied the evolution of surface roughness with deposition time under the frame work of dynamic scaling theory (DST), the rationale being quantitative determination of technologically important factors such as surface width $w(r,t)$ and scaling exponents. In a system size (or measurement window) of L, $w(r,t)$ corresponds to the local surface width for $r \leq L$, and for $r = L$, it is same as the rms roughness σ_{rms}. The quantitative details were derived from the height–height

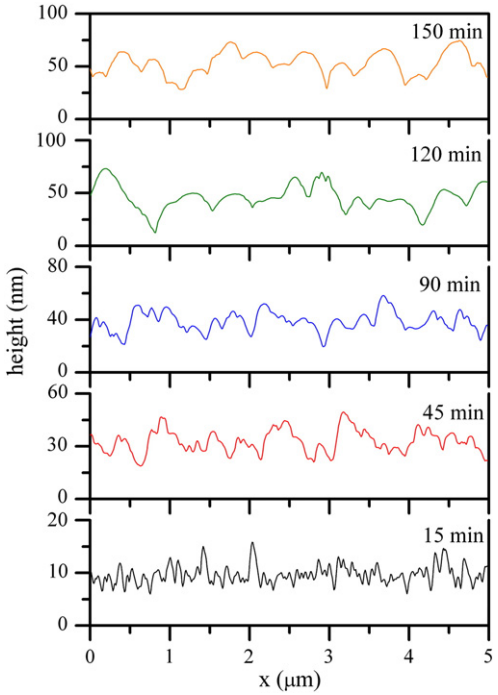

Fig. 2. Typical surface profiles (obtained from AFM scans of sample surface) as a function of deposition time.

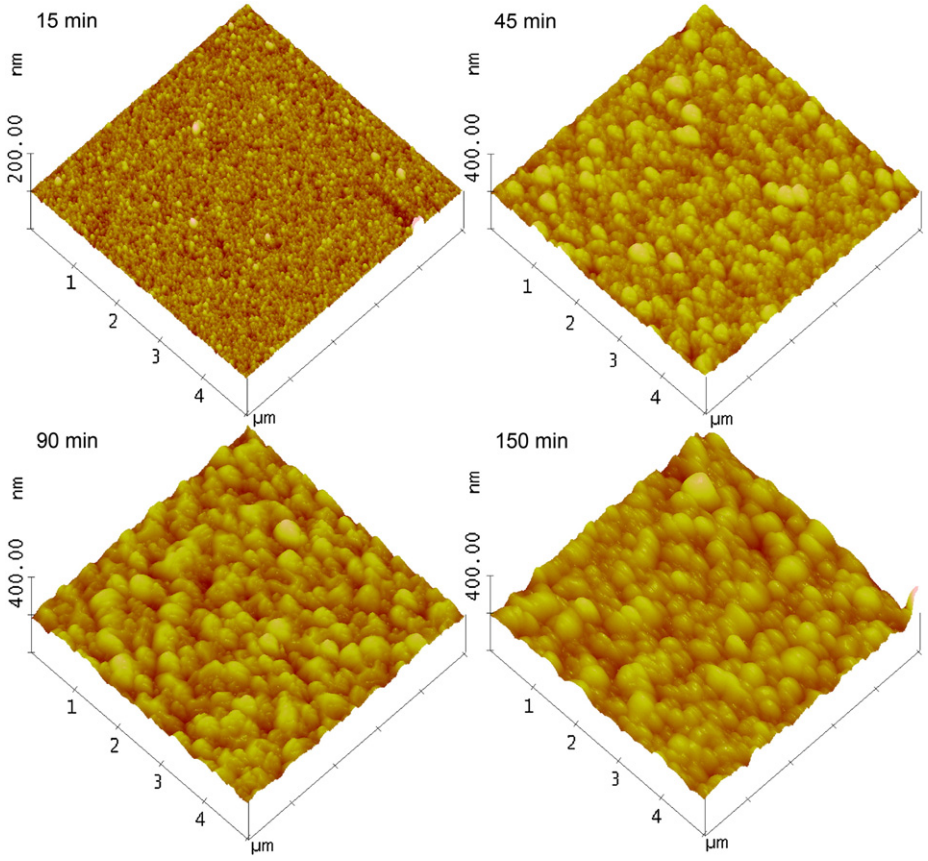

Fig. 1. Representative AFM images (5 μm×5 μm) of surface morphology as a function of deposition time.