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Microstructure and dielectric properties of amorphous $BaSm_2Ti_4O_{12}$ thin films for MIM capacitor

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Abstract

$BaSm_2Ti_4O_{12}$ (BST) film grown at room temperature was amorphous, while the film grown at 300 °C was also amorphous but contained a small amount of crystalline $Sm_2Ti_2O_7$ (ST). The crystalline BST phase was formed when the film was grown at 700 °C and subjected to rapid thermal annealing (RTA) at 900 °C. On the other hand, the ST phase was formed in the film grown at 300 °C and subjected to RTA at 900 °C. A high capacitance density of 2.12 fF/μm^2 and a low leakage current density of 1.15 fA/pF V were obtained from the 150 nm-thick BST film grown at 300 °C. Its capacitance density could conceivably be further increased by decreasing the thickness of the film. It had linear and quadratic coefficients of capacitance of −785 ppm/V and 5.8 ppm/V^2 at 100 kHz, respectively. Its temperature coefficient of capacitance was also low, being approximately 255 ppm/°C at 100 kHz.

Keywords: Films; Electrical properties; $BaSm_2Ti_4O_{12}$; Capacitors

1. Introduction

Metal–insulator–metal (MIM) capacitors have been widely investigated for their use in passive device for radio-frequency (RF) and the analog/mixed-signal integrated circuits for wireless communication. To minimize the chip size and cost of integrated circuits (IC), it is natural that MIM capacitors should be down-scaled.[1] Therefore, high k dielectric materials have attracted much attention because they can afford a high capacitance density for the same capacitor size. According to the International Technology Roadmap for Semiconductor (ITRS), a high capacitance density will be required for analog capacitors (10 fF/μm^2) and RF bypass capacitors (30 fF/μm^2) by the years 2016 and 2010, respectively.[1] In previous studies, the conventional silicon oxide and silicon nitride, which have low k values of 3–7 were replaced by dielectric materials with a high k value of around 20–30, such as HfO_2 and Ta_2O_5.[2–7] A MIM capacitor made using a film with an Al_2O_3 and HfO_2 laminate structure was also investigated to obtain better electrical performance than that of the films grown using pure dielectric materials such as HfO_2 and Al_2O_3.[8,9] However, they could not satisfy all the requirements for MIM capacitors simultaneously, which are a high capacitance density, voltage linearity of the capacitance, temperature stability, and a low leakage current.[1,10] Recently, it was reported that a 17 nm-thick TiTaO film had a very high capacitance density of 23 fF/μm, which would satisfy the requirement for RF MIM capacitors, however its leakage current density was relatively high.[11] A high capacitance density of 17.6 fF/μm^2 was also obtained from a capacitor consisting of a 8 nm-thick Nb_2O_5 film with HfO_2 (3 nm)/Al_2O_3 (1 nm) barriers.[12] However, the problem of its comparatively low leakage current density remains to be overcome.

Microwave dielectric materials are well known for their high k value, high quality factor (Q-factor) and good temperature stability and, thus, they can be used as MIM capacitors.[13] Especially, $BaSm_2Ti_4O_{12}$ (BST) ceramics show good microwave dielectric properties with values of $Q = 2289$ at 3.6 GHz and $k = 78.91$, along with good temperature stability of the resonance frequency.[14] Crystalline BST thin film was also shown to be potentially applicable to MIM capacitors.[15] However, the process temperature used to grow crystalline BST films is higher than that used for the VLSI back-end process (≤400 °C).

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Consequently, it is necessary to lower the process temperature used for fabrication of the device within the thermal budget of back-end process. In this study, amorphous BST films were grown at room temperature and 300 °C and their dielectric properties were investigated in order to assess their potential for use in MIM capacitors.

2. Experimental procedure

Amorphous $BaSm_2Ti_4O_{12}$ films were grown on Pt/Ti/SiO_2/Si(1 0 0) substrate by RF-magnetron sputtering using a 3 in.-diameter BST target, which was synthesized by the conventional solid state method. Deposition was carried out between room temperature and 700 °C in an oxygen and argon (O_2:Ar = 1:4) atmosphere at a total pressure of 8 mTorr, sputtering power of 120 W and deposition time of 3 h. The structure of the film was studied using X-ray diffraction (XRD; Rigaku D/max-RC, Japan). To measure the dielectric properties at low frequencies (100 kHz to 1 MHz), Pt was deposited on the BST thin films as the top electrode of MIM capacitors using conventional dc sputtering. The top electrode was patterned using a shadow mask to form a disk with diameter of 360 μm. The capacitance and dissipation factor were measured by precision LCR meter (Agilent 4285A, USA). Leakage current was measured using Source meter (Keithley2400, USA).

3. Results and discussion

Fig. 1 shows the XRD patterns of the BST films grown at various temperatures. An amorphous phase was formed in the film grown at room temperature. Moreover, for the films grown at high temperatures, no peaks were observed for the crystalline phase. Therefore, it is considered that these films also have an amorphous phase. However, it is also possible that the crystalline phase was formed in these films but its amount is too small to be detected in the XRD patterns.

Fig. 2 also shows the XRD patterns of the films grown at various temperatures and subjected to RTA at 900 °C for 3 min. For

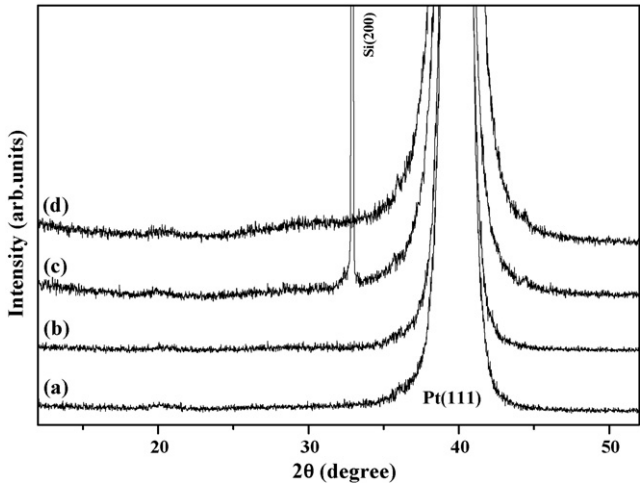

Fig. 1. X-ray diffraction patterns of the films grown at: (a) room temperature; (b) 300 °C; (c) 600 °C; (d) 700 °C.

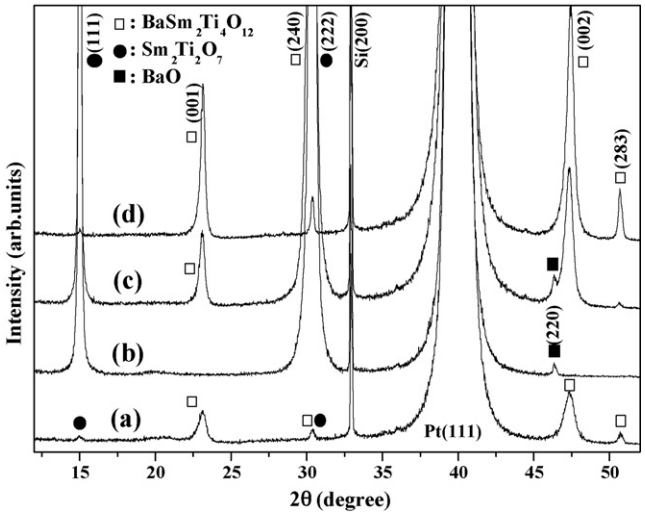

Fig. 2. X-ray diffraction patterns of the films grown at: (a) room temperature; (b) 300 °C; (c) 600 °C; (d) 700 °C and subjected to rapid thermal annealing at 900 °C.

the film deposited at room temperature and annealed at 900 °C, a crystalline BST phase was found and a small amount of ST phase was also observed, as shown in Fig. 2(a). However, only peaks for the ST phase were found in the film grown at 300 °C and annealed at 900 °C. The intensity of the [1 1 1] peak is very large, indicating that the ST film has its preferred orientation along the [1 1 1] direction. A small peak for BaO phase was also observed in this film [see Fig. 2(b)]. When the growth temperature exceeded 300 °C, BST phase started to be form and both ST and BST phases coexisted in these films, as shown in Fig. 2(c). Furthermore, for the film grown at 700 °C and annealed at 900 °C, only crystalline BST film was formed, as shown in Fig. 2(d). According to previous works, ST ceramic is formed when the sintering temperature of the specimen with the nominal composition of BST is lower than 1150 °C.[16] On the other hand, when the sintering temperature of the specimen exceeds 1150 °C, BST ceramic is formed.[17] Therefore, ST phase is considered to be a low temperature phase of BST ceramics, which is formed when the sintering temperature is not high enough to sinter the BST phase. These results can be used to explain the phase changes, which occurred in the BST films with respect to the growth temperature.

When it was deposited at room temperature, the BST film was amorphous and crystalline BST phase was formed from the amorphous phase during the annealing process at 900 °C, resulting in the formation of the BST crystalline film shown in Fig. 2(a). On the other hand, when the film was grown at 300 °C, although they were not detected in XRD patterns, small ST crystals could be formed instead of BST crystals because the growth temperature was too low for BST crystal to be formed. When this film was annealed at 900 °C, these small ST crystals, which were formed during the deposition at 300 °C, grew and developed to produce the ST crystalline film shown in Fig. 2(b). As the growth temperature was increased, small BST crystals started to form and both small ST and BST crystals coexisted in the film. These small crystals grew during the