

Crystallization kinetics of $\text{Bi}_{0.25}\text{Y}_{2.75}\text{Fe}_5\text{O}_{12}$ prepared from coprecipitation process under non-isothermal conditions

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Abstract

The non-isothermal crystallization kinetics of $\text{Bi}_{0.25}\text{Y}_{2.75}\text{Fe}_5\text{O}_{12}$ powder prepared by the coprecipitation process has been investigated. The activation energy of crystallization was calculated by differential scanning calorimetry (DSC) at different heating rates. From non-isothermal DSC data presented values in the range of 712–772 kJ/mol and 2.90–3.46 for the activation energy of crystallization and the Avrami exponent, respectively at specific temperature ranging from 750.0 to 757.5 °C. This value for the Avrami exponent indicates that the controlling mechanism of crystallization is three-dimensional interfacial growth.

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1. Introduction

Yttrium iron garnet (YIG) was extensively studied owing to its interesting physical properties. For example, this material possesses the highest quality factor in microwave regime, and the smallest linewidth in magnetic resonance among magnetic materials [1,2]. YIG materials are important components of electronic products, such as circulators, oscillators, and phase shifters. However, YIG is hardly used in multilayer microwave components because of its high sintering temperature (>1350 °C) for YIG. Since the sintering temperature of YIG is generally higher than the melting point of highly conductive metals such as Ag–Pd alloy (1145 °C) [3]. Previous investigations have shown that Bi-substituted and 2Ca–V-substituted YIG powders can be prepared at much lower temperatures (<1100 °C) than that of pure YIG due to their lower melting temperature of substitution, and the sintering temperature of these materials is much lower than that of YIG polycrystalline ceramics [4–6].

Magnetic fine particles are very attractive for magnetic ceramic research. This is because they have a single magnetic domain and their mutual interaction can be studied without

magnetic domain effects. Polycrystalline YIG and substituted YIG have attracted much attention for microwave device and magneto-optical applications [7]. The conventional method of producing these materials is by the solid-state reaction with oxide/carbonate and then calcined at a high temperature (≥ 1200 °C). The solid-state reaction has some inherent disadvantages as follows: (1) chemical inhomogeneity, (2) coarser particle size, and (3) introduction of impurities during ball milling. In order to improve the performance and quality of Bi-YIG magnetic ceramics, coprecipitation is an alternative method to overcome the deficiencies in the conventional solid-state reaction.

There have been many investigations on the microwave and magneto-optical properties, and they have focused on correlations between the microstructure, composition, and magnetic properties of Bi-YIG. However, there seem to be almost no report on the crystallization characterization of these materials. Therefore, in this study, we used coprecipitation process to produce as-prepared $\text{Bi}_{0.25}\text{Y}_{2.75}\text{Fe}_5\text{O}_{12}$ powder and studied its non-isothermal crystallization kinetics.

2. Experimental procedures

Fig. 1 plots the preparation process of Bi-YIG particles by coprecipitation. The preparation details are described as follows. According to the stoichiometric composition of

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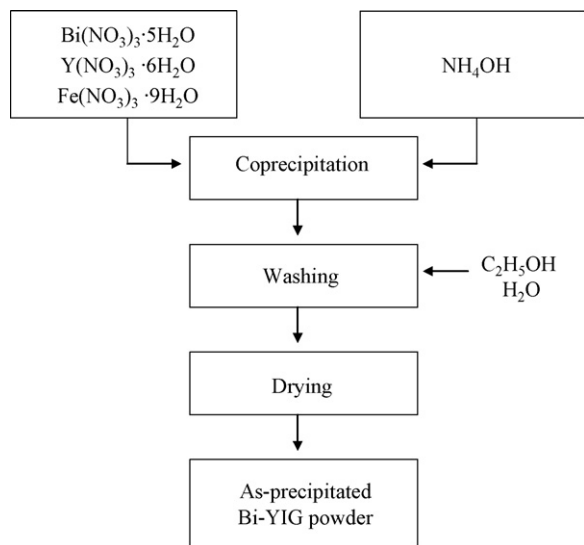


Fig. 1. Flowchart for the preparation of as-precipitated $\text{Bi}_{0.25}\text{Y}_{2.75}\text{Fe}_5\text{O}_{12}$ powder by coprecipitation.

$\text{Bi}_{0.25}\text{Y}_{2.75}\text{Fe}_5\text{O}_{12}$, specified amounts of bismuth nitrate pentahydrate [$\text{Bi}(\text{NO}_3)_3 \cdot 5\text{H}_2\text{O}$], yttrium nitrate hexahydrate [$\text{Y}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$], and iron nitrate nonahydrate [$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$] were dissolved in a certain quantity of water. The 28% ammonia solution (NH_4OH) was added rapidly into the stirred solution at room temperature. In the pH range of more than 8.7, the ratio of the cations in the powders was the same as that in the nitrate solution. In this study, the pH of the solution was controlled to be above 12. The obtained slurry was washed with alcohol to remove the alkaline ions and obtain a weak agglomeration of Bi-YIG powders. This slurry was filtered and dried at 90°C for 24 h.

A computer-interfaced X-ray powder diffractometer (XRD) with Cu $\text{K}\alpha$ radiation ($\lambda = 1.5418 \text{ \AA}$) (Model Rigaku D/Max-II, Tokyo, Japan) was used to identify the crystalline phase during crystallization process. BET surface area measurements were made by nitrogen adsorption employing a Micromeritics ASAP 2000 instrument and calculated using the five point Brunauer-Emmett-teller (BET) theory. Mean particle size (D_{BET}) was calculated from the BET data according to the following equation assuming that the particles are closed sphere with smooth surface and uniform size: $D_{\text{BET}} = 6 \times 10^3 / (\rho_{\text{th}} S_{\text{BET}})$, where D_{BET} (nm) is the average particle size, S_{BET} is the measured specific surface area expressed in m^2/g and ρ_{th} is the theoretical density of the compound (g/cm^3) [8]. Differential scanning calorimetry (DSC; Model TG-DTA/DSC Setaram, Caluire, France) was used to carry out the crystallization characterization of as-precipitated Bi-YIG powders. A heating rate of $10\text{--}25^\circ\text{C}/\text{min}$ was used in DSC up to 900°C in air. Thermal analysis was carried out under flowing air at $100 \text{ ml}/\text{min}$. A constant sample weight of $12.0 \pm 0.2 \text{ mg}$ was used for all measurements.

3. Results and discussions

Crystallization characterization of the Bi-YIG powder was estimated by non-isothermal DSC analysis. Fig. 2 shows the

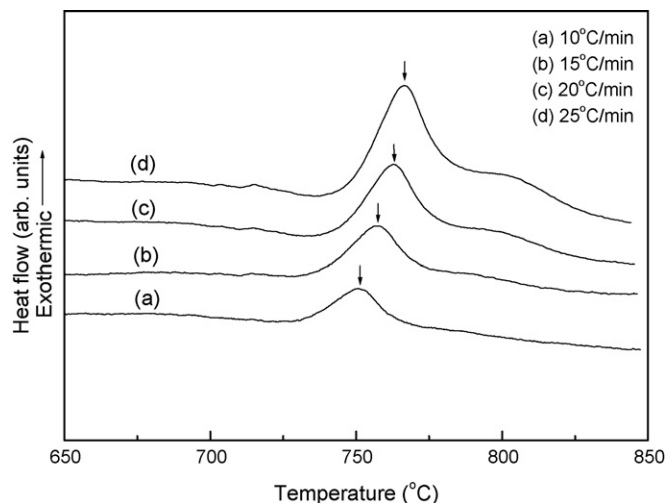


Fig. 2. Differential scanning calorimetry curves of as-precipitated $\text{Bi}_{0.25}\text{Y}_{2.75}\text{Fe}_5\text{O}_{12}$ powder at different heating rates of 10, 15, 20, and $25^\circ\text{C}/\text{min}$, respectively.

DSC curves of a sample with different heating rates ranging from 10 to $25^\circ\text{C}/\text{min}$. With increasing heating rate, the exothermic peak shifts to a higher temperature. Phase development of as-precipitated Bi-YIG specimen during heat treatment was measured by XRD. The XRD results for specimen annealed from 650 to 725°C for 2 h are shown in Fig. 3. The Bi-YIG specimen was primarily amorphous due to the broad low-intensity peak that appeared at 32° diffraction angle. When the annealing temperature reached 675°C , the specimen showed (420) and (422) low-intensity peaks. With increasing annealed temperature, the number of broad hump associated with the amorphous phase decreased, and the intensity of XRD peaks increased as the amorphous phase got transformed into the crystalline phase, i.e. the garnet phase. The volume fraction of the crystallized phase increases with increasing annealed temperature. These results are consistent with the DSC results. The specific surface area and mean particle size of Bi-YIG powders calcined at different temperatures is listed in Table 1. The result indicates that

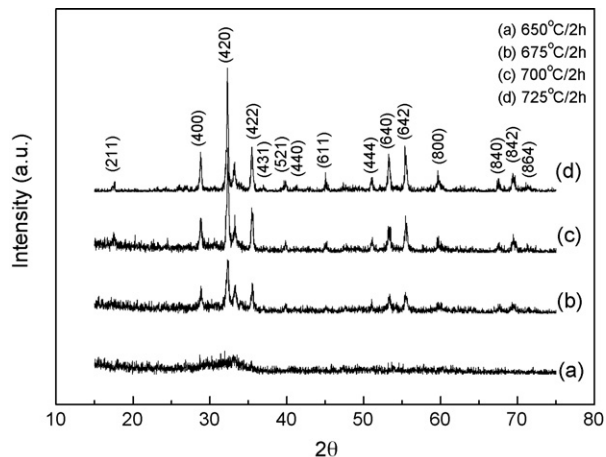


Fig. 3. X-ray diffraction results of as-precipitated $\text{Bi}_{0.25}\text{Y}_{2.75}\text{Fe}_5\text{O}_{12}$ powder annealed at various temperatures.

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