

Structural, Magnetic and Electrical Properties of Barium Titanate and Magnesium Ferrite Composites

(Struktur, Sifat Magnet dan Elektrik Komposit Barium Titanat dan Ferit Magnesium)

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ABSTRACT

Structural, magnetic and electrical characteristics of multiferroics $(1-x)\text{BaTiO}_3-x\text{MgFe}_2\text{O}_4$ composites with weight fractions of $x = 0.3, 0.5$ and 0.7 are reported. MgFe_2O_4 powders were prepared using sol-gel auto combustion technique. It was combined with commercial BaTiO_3 to form composites by using wet milling solid state reaction technique. Formation of tetragonal perovskite for the ferroelectric BaTiO_3 and cubic spinel for the ferrimagnetic MgFe_2O_4 phases, were identified from the XRD pattern. The average grain size for each composite was about $0.5 \mu\text{m}$. The M-H loop showed soft ferrimagnetic properties due to the presence of MgFe_2O_4 in the composites. The increment of the MgFe_2O_4 weight fraction increased the saturation magnetization and slightly changed the coercive field. The complex impedance plot can be represented by a parallel R and C circuit. Composite sample with $x = 0.5$ has the highest resistance with lowest capacitance and dielectric constant value at room temperature. The dielectric constant showed a very strong dispersion at low frequencies, due to the Maxwell-Wagner mechanism and a slight dispersion at higher frequencies. Based on the results obtained, all of the composite samples exhibited high dielectric constant and tangent loss at the low frequency range.

Keyword: Ceramic; dielectric; ferrimagnet; ferroelectric

ABSTRAK

Struktur, sifat magnet dan elektrik komposit multiferroik $(1-x)\text{BaTiO}_3-x\text{MgFe}_2\text{O}_4$ dengan pecahan berat, $x = 0.3, 0.5$ dan 0.7 dilaporkan. Serbuk MgFe_2O_4 telah disediakan menggunakan teknik sol-gel pembakaran auto. Ia digabungkan bersama BaTiO_3 komersil untuk membentuk komposit dengan menggunakan teknik tindak balas keadaan pepejal pengisaran basah. Pembentukan fasa perovskit tetragon bagi feroelektrik BaTiO_3 dan fasa kubus spinel bagi ferimagnet MgFe_2O_4 , dikenal pasti daripada corak XRD. Purata saiz butiran setiap komposit ialah $0.5 \mu\text{m}$. Lengkung M-H menunjukkan sifat-sifat ferimagnet lembut disebabkan oleh kehadiran MgFe_2O_4 di dalam komposit. Kenaikan pecahan berat MgFe_2O_4 meningkatkan pemagnetan tepu dan mengubah sedikit medan paksa. Plot impedans kompleks boleh diwakili oleh litar selari R dan C. Sampel komposit $x = 0.5$ mempunyai rintangan tertinggi serta nilai kapasitans dan pemalar dielektrik terendah pada suhu bilik. Pemalar dielektrik menunjukkan penyerakan yang tinggi pada frekuensi rendah disebabkan mekanisme Maxwell-Wagner dan sedikit penyerakan pada frekuensi lebih tinggi. Berdasarkan hasil yang diperolehi, kesemua sampel komposit memaparkan pemalar dielektrik dan kehilangan tanga yang tinggi pada julat frekuensi rendah.

Kata kunci: Dielektrik; ferimagnet; feroelektrik; seramik

INTRODUCTION

A wide range of multiferroics materials have been studied due to their special properties and technological applications (Spaldin et al. 2010). This type of material has more than one ferroics ordering such as ferroelectricity and ferromagnetic ordering where the electrical polarization can be switched with magnetization switching and vice versa (Roy et al. 2012). Ferroelasticity and ferrotoroidics are two other ferroics ordering that may exist in the multiferroics materials. Multiferroics materials may exist as single phase or as composites form (Zolkepli & Zainuddin 2015). Single phase multiferroics are materials that have simultaneous interaction between two or more primary ferroics order. However, due to lack of single phase materials, multiferroics in composite form are being considered

(Fina et al. 2010). Significant interest in the multiferroics composite research due to their multifunctionality leads to the combination between ferroelectric and piezoelectric material with the magnetic material. $\text{BaTiO}_3\text{-CoFe}_2\text{O}_4$, $\text{NiFe}_2\text{O}_4\text{-BaTiO}_3$ and $\text{BaTiO}_3\text{-Ni}_{0.7}\text{Zn}_{0.3}\text{Fe}_2\text{O}_4$ are examples of some multiferroics composites with combination of ferrimagnetic and ferroelectric materials (Leonel et al. 2011; Liu et al. 2013; Zhang et al. 2013). The ferrimagnet-ferroelectric characteristic can be used in multifunctional devices such as sensors, actuators and magnetoelectric transducers.

Spinel ferrite, such as MgFe_2O_4 and CoFe_2O_4 , consists of two crystallographic sites which are the tetragonal and octahedral sites. The oxygen atoms forms an arrangement of cubic closed-packed (Sutka & Mezinskis 2012). Spinel

ferrite has been used for magnetic switches, magnetic resonance imaging, drug delivery, magnetic ferrofluids, high-density data storage, microwave absorber and magnetic bulk cores (Yadav et al. 2016). Besides that, spinel ferrite was used in medicine because it is not damaging the tissues and magnetic properties remains unchanged after medical used (Siong et al. 2013). Ferrite was also hybridized with carbon nanotube to improve its magnetic properties and its dielectric properties (Yu et al. 2012). Meanwhile, BaTiO_3 was widely studied due to its wide application and various properties of ferroelectric, piezoelectric and dielectric. It becomes an option to be used in applications such as multilayer capacitors, thermistors and electrooptic devices. BaTiO_3 also has high dielectric constant and low tangent loss. Curie temperature of BaTiO_3 is about 120°C where at this temperature, it undergoes a phase transition from tetragonal to cubic and loss its ferroelectric properties. Research on the coupling between fine grained BaTiO_3 - MgFe_2O_4 composite prepared using Pechini-like method has been conducted by Köferstein et al. (2015).

Based on previous research, different compositions of perovskite BaTiO_3 and spinel ferrite powders altered the electrical and magnetic properties of the composite (Liu et al. 2013; Ravindar Tadi et al. 2010). In this study, MgFe_2O_4 powders were synthesized via the sol-gel autocombustion method and then combined with commercial BaTiO_3 powders at 3 different weight fractions through a simple wet milling solid state reaction process to obtain BaTiO_3 - MgFe_2O_4 composite materials with potential multiferroics properties. We will discuss on how variation of weight fractions of the composites could affect the structure, magnetic and electrical properties of the materials.

MATERIALS AND METHODS

$(1-x)\text{BaTiO}_3$ - $x\text{MgFe}_2\text{O}_4$ composite samples with different weight fraction of $x = 0.3, 0.5$ and 0.7 were prepared using the wet ball milling process. BaTiO_3 powders were obtained commercially (Sigma Aldrich $< 2 \mu\text{m}$, 99.9%), whereas MgFe_2O_4 powders had been synthesized using the sol-gel auto combustion technique. Starting materials that have been used for the MgFe_2O_4 preparation were iron (III) nitrate nonahydrate $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (Sigma Aldrich, 98%), magnesium nitrate hexahydrate $\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (Sigma Aldrich, 99%) and citric acid monohydrate $\text{C}_6\text{H}_8\text{O}_7 \cdot \text{H}_2\text{O}$ (Merck KGaA, 99.95%). The molar ratio of citric acid monohydrate to metal nitrate was fixed at 1:2. Each starting materials were mixed, dissolved and stirred in deionized water until they are completely dissolved. Next, ammonia solution was dropped until the pH value of the solution approached 7. The solution was stirred and heated at 95°C until the solution slowly evaporated to form brown gel. The dehydration process was continued until the gel turned into a fluffy mass and burnt in an autocombustion manner. After that, the MgFe_2O_4 precursor was grinded to get fine MgFe_2O_4 powders.

Both BaTiO_3 and MgFe_2O_4 powders were then weighted according to the predetermined percentage and milled in ethanol using agate balls at 250 rpm for 5 h. The slurry was then dried at 100°C for an hour and subsequently grinded. The dried powders then uniaxially pressed by applying pressure of 147 MPa to form a 13 mm diameter pellet, which was finally sintered in air at 1100°C for 3 h.

Structural and phases determination of the composites powders were performed at room temperature using an X-ray diffractometer, model D8 Advance Bruker AXS Germany with $\text{CuK}\alpha$ ($\lambda = 0.15406 \text{ nm}$) up to 2θ of 90° with a scanning speed $0.025^\circ/\text{step}$ and under 40 kV and 40 mA condition. The morphology and microstructure of the composites fractured pellets were observed by using the field-emission scanning microscope (FESEM, Supra 55VP). Magnetic hysteresis loop was investigated using Vibrating Sample Magnetometer (VSM, LakeShore/7404). Circular platinum electrodes were sprayed on both sintered pellet surfaces and electrically analyzed by Solartron 1260 Impedance/gain-phase analyzer.

RESULTS AND DISCUSSION

X-ray diffraction patterns of the $(1-x)\text{BaTiO}_3$ - $x\text{MgFe}_2\text{O}_4$ composites with different weight fractions of $x = 0.3, 0.5$ and 0.7 are shown in Figure 1. The peaks of XRD pattern were indexed and matched with the JCPDS 01-070-9164 and JCPDS00-017-0464 for tetragonal perovskite BaTiO_3 and cubic spinel MgFe_2O_4 phases, respectively. The relative peak intensity of MgFe_2O_4 phase increases when its weight fraction increases, while the BaTiO_3 peaks decrease as expected. The results also showed no formation of new phases, which indicates the chemical reaction between BaTiO_3 and MgFe_2O_4 did not happen during milling and sintering process. This was further confirmed using *TOPAS*, which is a new generation profile and structure analysis

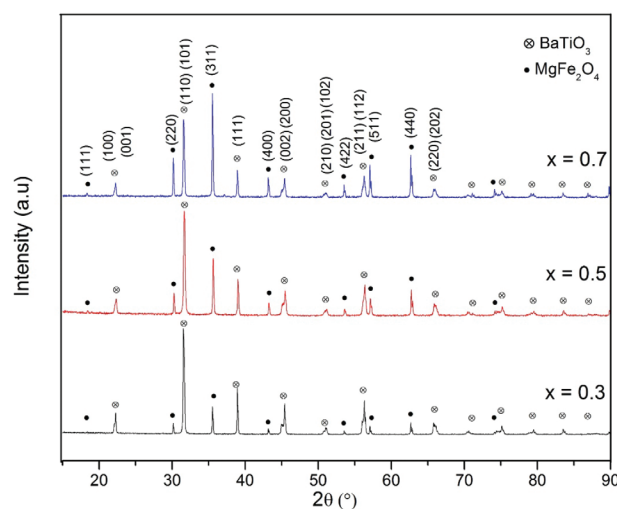


FIGURE 1. XRD patterns of $(1-x)\text{BaTiO}_3$ - $x\text{MgFe}_2\text{O}_4$ composites with different weight fractions

XRD software that can be used to determine the percentage of two phases more precisely, which is shown in Table 1. From the table, there is only a slight differences between the theoretical and the experimental values of both phases confirming the absence of any impurities. A peak splitting at $2\theta = 45^\circ$ suggest that there is a ferroelectric tetragonal phase with piezoelectric properties of Tadi et al. (2012). The average crystallite size and lattice parameters of BaTiO_3 and MgFe_2O_4 in the composite samples for each weight fraction were also calculated using *TOPAS* software and tabulated in Table 2. Composite sample with $x = 0.5$ shows the smallest BaTiO_3 and MgFe_2O_4 crystallite size. Combination with MgFe_2O_4 lowered the tetragonality ratio, c/a of BaTiO_3 , which has a theoretical value of 1.011. (Leonel et al. 2011).

TABLE 1. BaTiO_3 and MgFe_2O_4 percentage measured using TOPAS

Weight fraction, x	Phase percentage (%)	
	BaTiO_3	MgFe_2O_4
0.3	69.97	30.03
0.5	49.45	50.55
0.7	29.83	70.17

Figure 2 illustrates the SEM micrographs of the cross section from the fractured surface of $(1-x)\text{BaTiO}_3-x\text{MgFe}_2\text{O}_4$ composites pellets. It can be observed that grains with irregular shape and various sizes ranging from 0.1 to 1.2 μm are evenly distributed across the samples with pores between the grains and formation of grains agglomeration. Sample with $x = 0.5$ seems to have less pores compared to the other two composite sample. The average grain size was calculated using *ImageJ* software and was found that the average size of the grains are almost the same for all composite samples as shown in the Table 2. Although the weight fraction was changed, the grain size are not highly affected due to the same sintering temperature used for all samples.

Powdered sample was sandwiched between two circular tapes to form a very thin disk. It was put parallel to the applied external magnetic field and was analysed at room temperature. The $M - H$ hysteresis loops for all samples were shown in Figure 3. The shape of the loops clearly shows a soft ferrimagnetic nature with low coercive field value. The magnetic behaviour is due to the presence of an ordered magnetic structure in the mixed spinel-perovskite system from the presence of MgFe_2O_4 (Köferstein et al. 2015). The magnetization and coercive field of the samples were shown in Table 3. It is found that with the addition of MgFe_2O_4 content, the values of

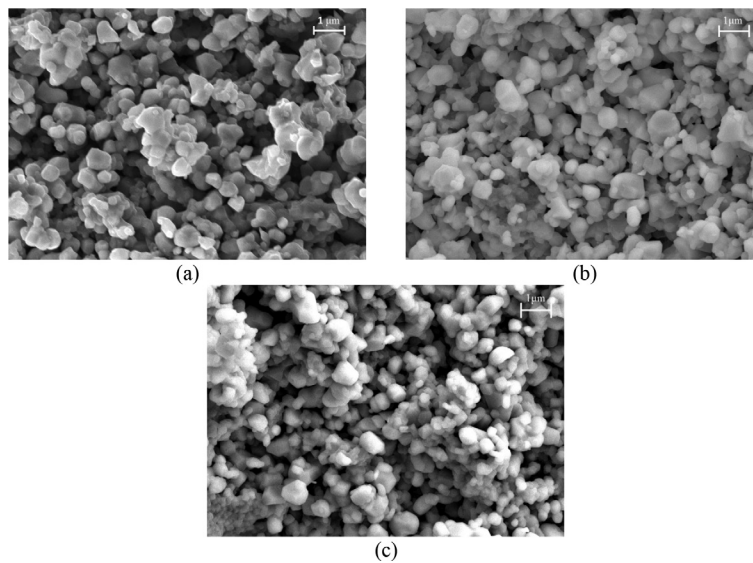


FIGURE 2. SEM images of $(1-x)\text{BaTiO}_3-x\text{MgFe}_2\text{O}_4$ composites for (a) $x = 0.3$, (b) $x = 0.5$ and (c) $x = 0.7$

TABLE 2. Crystallite size, lattice parameters, tetragonality ratio of BaTiO_3 and average grain size for each composite sample

Weight fraction, x	Crystallite size (nm)		Lattice parameter (\AA)			Tetragonality ratio of BaTiO_3 (c/a)	Average grain size (μm)
	BaTiO_3	MgFe_2O_4	BaTiO_3		MgFe_2O_4		
			$a = b$	c			
0.3	74	165	3.9957	4.0293	8.3820	1.0084	0.55 0.20
0.5	50	89	3.9990	4.0291	8.3858	1.0075	0.55 0.22
0.7	60	117	3.9982	4.0259	8.3837	1.0069	0.51 0.17

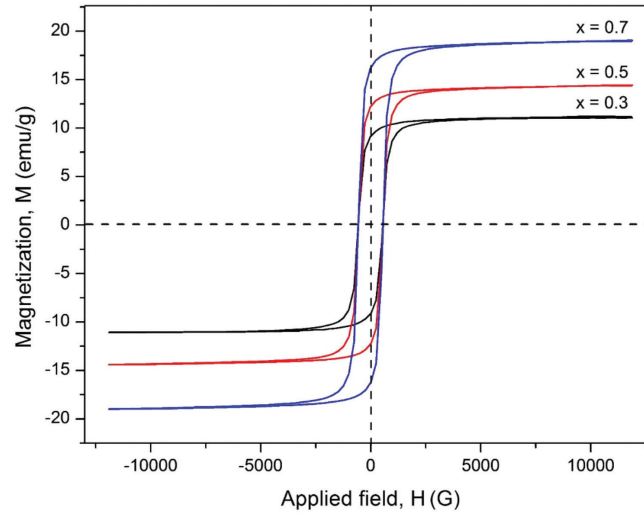


FIGURE 3. Magnetization, M versus magnetic field, H hysteresis loops for $(1-x)$ BaTiO_3 - $x\text{MgFe}_2\text{O}_4$ composite with different weight fractions

TABLE 3. Magnetic parameters of each weight fractions of $(1-x)\text{BaTiO}_3$ - $x\text{MgFe}_2\text{O}_4$

Weight fraction, x	Coercive field, H_c (Oe)	Saturation magnetization, M_s (emu/g)	Remanent magnetization, M_r (emu/g)
0.3	54	11.1	9.2
0.5	55	14.3	12.5
0.7	56	19.1	16.2

saturation magnetization, M_s also increased. Magnetization of the samples was contributed by the ferrite grains in the composite which acts as a source of magnetic moments. By increasing the ferrite amount, it lead to a higher value of net magnetization due to the increasing of magnetic contacts between the ferrite grains (Hrib & Caltun 2011). BaTiO_3 , as the ferroelectric material, integrated with MgFe_2O_4 phase and affects the magnetic properties of the composites (Kanamadi et al. 2009). Remanent magnetization, M_r also increased with higher ferrite content. Due to the higher M_s , the magnetization left behind in the sample after an external magnetic field was removed is also high and the material remains magnetized (Callister 2007). Although MgFe_2O_4 content increased the magnetization of the samples, the coercive field, H_c for the samples did not altered much because of the small variation of the grain size of the samples. The properties of magnetic coercive field was recognized through its microstructure such as density, magnetic phase percolation or ferrite doped with other ions. Coercive field was hard to control by using the variation of compositions (Mitoseriu & Buscaglia 2006).

The complex impedance spectroscopy is usually used to identify the AC electrical response contributed by the grain, grain boundary and the electrode with consideration of their different relaxation time. The Nyquist plot for all samples are shown in Figure 4 with a frequency range from 1 Hz to 10 MHz. Compressed single semicircle arc with the centre under the real impedance, Z' axis was obtained for all samples by using ZView software. The electrical process due to grain and grain boundary cannot be distinguished

clearly from the complex impedance loop. Therefore the equivalent circuit of the sample can be represented by a parallel bulk resistance, R and capacitance, C as shown in inlet of Figure 4. The bulk resistance value can be estimated from the intercept of the semicircular arc extension at Z' axis. The universal capacitor with a complex capacitance:

$$C^* = A(j\omega)^{n-1} = A\omega^n \left(\cos \frac{n\pi}{2} + j \sin \frac{n\pi}{2} \right),$$

is used to represent the ordinary capacitor due to the non-perfect semicircle where A is a constant, exponent n is the frequency dependence which is between 0 and 1 and $\omega = 2\pi f_p = RC = 1$ with f_p is frequency at the peak of the impedance loop (Jonscher 1983). The complex impedance, Z^* data were fitted using:

$$Z^* = \frac{1}{Y^*}$$

$$Y^* = \frac{1}{R} \left[1 + \left(\frac{f}{f_p} \right)^n \cos \frac{n\pi}{2} \right] + \frac{j}{R} \left[1 + \left(\frac{f}{f_p} \right)^n \sin \frac{n\pi}{2} \right] \text{ with } 0 \leq n \leq 1.$$

Table 4 shows the parameters obtained from the fitting analysis. Composite sample with $x = 0.5$ has the lowest value of capacitance, C and highest R compared to the others. Density, interface between ferrite and ferroelectric phase and oxygen vacancies are among the factors that influenced the variation in the resistance values (Pahuja et al. 2013). The peak frequency and n increased with higher MgFe_2O_4 weight fraction.

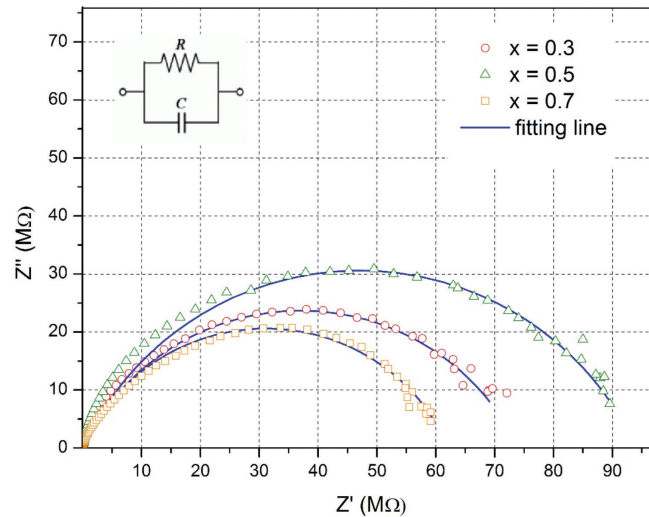


FIGURE 4. Complex impedance plots for all samples fitting lines and the equivalent R - C circuit

TABLE 4. Capacitance, resistance, peak frequency and n for each composite

Weight fractions, x	Capacitance, C (nF)	Resistance, R (MΩ)	n	Peak frequency, f_p (Hz)
0.3	0.114	73.0	0.735	15.8
0.5	0.081	93.0	0.740	21.0
0.7	0.136	62.0	0.743	22.5

Figure 5(a) shows the variation of dielectric constant with applied frequency measured at room temperature. A strongly dispersive region can be observed at low frequencies with a smaller dispersion at higher frequencies. The strong low frequency dispersion can be described by the Maxwell-Wagner relaxation mechanism (Pahuja et al. 2013). It may be a result of the interfacial or space charge polarization process between the BaTiO_3 and MgFe_2O_4 grains and between the material interface with the electrode. Factors that often contribute to the space charge polarization in materials is inhomogeneities in the dielectric structure such as impurities, porosity and grain structure (Mo et al. 2013). In dielectric-magnetic composite ceramics, there is a threshold of critical concentration and when this threshold state is achieved, the dielectric value increased significantly due to increasing of orientation polarization between ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions in spinel ferrite (Zhang et al. 2013). At higher frequencies the dielectric constant is very low because charge carriers cannot follow the rapid change of the electric field direction (Pahuja et al. 2013).

As explained, dielectric constant depends on the applied frequency because there is a relaxation time for the charge transport. Composite sample with $x = 0.07$ has the highest dielectric constant at lower frequency, followed by $x = 0.03$ and 0.05 . According to Liu et al. (2013), due to inhomogeneity between the two phases in the composite which is between BaTiO_3 and MgFe_2O_4 , there is a difference of the dielectric values at lower frequency (Liu et al. 2013). The ferroelectric phase was spread among

the spinel ferrite region in the composite. Based on Figure 5(b), high tangent loss were obtained for each composite and it decreased with increasing frequency. According to Köferstein et al. (2015), loss tangent increased with more MgFe_2O_4 weight fraction in the composite due to the nature of MgFe_2O_4 that has an electrically leakage properties (Köferstein et al. 2015). The leakage path to charge carrier was caused by the ferrite grains hence a conduction losses was increased. Therefore, there are a change in dielectric values and tangent loss when the MgFe_2O_4 content was increased.

CONCLUSION

MgFe_2O_4 powders were synthesized by the sol-gel autocombustion technique and successfully integrated with the commercial BaTiO_3 powders to form $(1-x)\text{BaTiO}_3$ - $x\text{MgFe}_2\text{O}_4$ multiferroics composite with different weight fractions, $x = 0.3, 0.5$ and 0.7 by using wet milling solid state reaction method. The XRD patterns of the composites confirmed the formation of cubic spinel for MgFe_2O_4 phase and tetragonal perovskite for BaTiO_3 phases. The grain size of the composite samples does not change much with increment of weight fraction of MgFe_2O_4 . The variation of ferrite content influenced the magnetic and the electrical properties of the composite. For magnetic characterization, all samples show the soft magnetic signal due to MgFe_2O_4 presence and the composite with more MgFe_2O_4 content has higher saturation and remanent magnetization which vary from 11.1 to 19.1 emu/g and 9.2

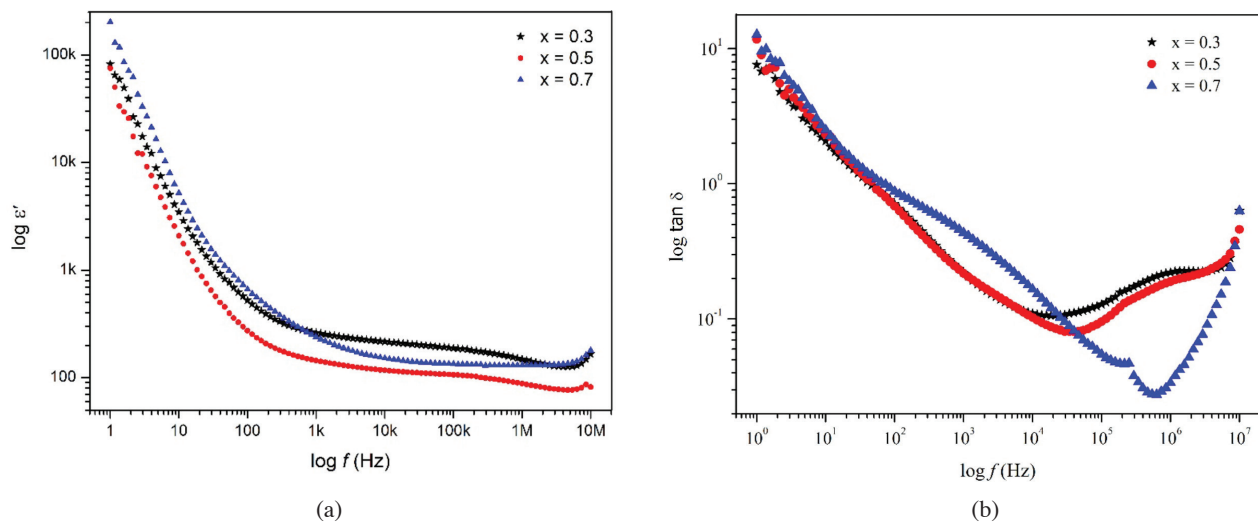


FIGURE 5. (a) Dielectric constant and (b) loss tangent of $(1-x)\text{BaTiO}_3-x\text{MgFe}_2\text{O}_4$ multiferroics composite at different frequency

to 16.2 emu/g, respectively. However, the coercive field remains nearly the same. For the electrical properties, the semicircle arc impedance plot were fitted with a parallel R and C^* circuit and shows there are irregular trend in the resistance values of the composites due to variation of ferrite content. The sample of $x = 0.5$ also has the lowest dielectric constant for the whole frequency range.

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