CRYSTALLOGRAPHIC STRUCTURE AND MAGNETIC PROPERTIES OF PSEUDOBROOKITE Fe$_{2-x}$Ni$_x$TiO$_5$ SYSTEM (x = 0, 0.1, 0.2, 0.3, 0.5 and 1)

Yosef Sarwanto and Wisnu Ari Adi

Center for Science and Technology of Advanced Materials - BATAN
Kawasan Puspiptek, Serpong 15314, Tangerang Selatan, Indonesia

Received: 25 July 2017         Revised: 20 September 2017         Accepted:25 September 2017

ABSTRACT

CRYSTALLOGRAPHIC STRUCTURE AND MAGNETIC PROPERTIES OF PSEUDOBROOKITE Fe$_{2-x}$Ni$_x$TiO$_5$ SYSTEM (x = 0, 0.1, 0.2, 0.3, 0.5 AND 1). Crystallographic structure and magnetic properties of pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ system (x = 0, 0.1, 0.2, 0.3, 0.5 and 1) have been performed through solid state reaction. Pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ system was synthesized by mixing of Fe$_x$O$_5$, NiO, and TiO$_2$ with stoichiometry composition using wet mill. The mixture was milled for 5 hours and sintered in the electric chamber furnace at 1000°C in the air at atmosphere pressure for 5 hours. The refinement against of X-ray diffraction data shows that the sampless with composition of (x = 0) and (x = 0.1) have a single phase with Fe$_5$TiO$_3$ structure. However the samples with composition of (x > 0.1) consist of multiple phases, namely Fe$_{2-x}$Ni$_x$TiO$_5$, Fe$_x$TiO$_2$, FeNiO$_4$ and NiO. Particle morphologies of the composition x = 0 and x = 0.1 are homogenous and uniform on the sample surface with a polygonal particle shape and particle size varies. At room temperature, the sample with x=0 is paramagnetic and that with x=0.1 is ferromagnetic. Magnetic phase transformation of this study is the caused by the present of Ni substituted Fe in the system. Thus substitution Ni into Fe on the system pseudobrookite Fe$_5$TiO$_3$ only capable of 0.1 at.% without changing the crystal structure of the material. It means that there is an interaction between the magnetic spin Fe$^{3+}$ on the 3d$^3$ configurations and Ni$^{2+}$ on the 3d$^8$ configurations through the mechanism of double exchange. Double exchange mechanism is a magnetic type of exchange that appears between the ions Fe$^{3+}$ and Ni$^{2+}$ adjacent in different oxidation states.

Keywords: Pseudobrookite, Fe$_{2-x}$Ni$_x$TiO$_5$, Substitution, Crystal structure, Magnetic

ABSTRAK

STRUKTUR KRISTAL DAN SIFAT MEGNET DARI BAHAN PSEUDOBROOKITE SISTEM Fe$_{2-x}$Ni$_x$TiO$_5$ (x = 0, 0.1, 0.2, 0.3, 0.5, DAN 1). Analisis struktur kristal dan sifat magnetik dari bahan pseudobrookite sistem Fe$_{2-x}$Ni$_x$TiO$_5$ (x = 0, 0.1, 0.2, 0.3, 0.5, dan 1) hasil reaksi padatan telah dilakukan. Bahan pseudobrookite sistem Fe$_{2-x}$Ni$_x$TiO$_5$ disintesis dengan mencampurkan bahan baku Fe$_x$O$_5$, NiO, dan TiO$_2$ dengan komposisi stoikimetri menggunakan metode milling basah. Campuran dimilling selama 5 jam dan disinter dalam tungku listrik pada 1000 °C di udara pada tekanan atmosfer selama 5 jam. Hasil refinement pola difraksi sinar-X menunjukkan bahwa sampel dengan komposisi (x = 0) dan (x = 0.1) memiliki fase tunggal dengan struktur Fe$_5$TiO$_3$. Namun sampel dengan komposisi (x > 0.1) terdiri dari multi-fase, yaitu Fe$_{2-x}$Ni$_x$TiO$_5$, Fe$_x$TiO$_2$, FeNiO$_4$, dan NiO. Morfologi partikel komposisi x = 0 dan x = 0.1 memiliki homogenitas yang cukup baik dan seragam dalam seluruh permukaan sampel dengan bentuk partikel poligonal dan ukuran partikel bervariasi. Sifat magnetik dari komposisi x = 0 adalah paramagnetik pada suhu kamar. Sementara komposisi x = 0.1 berubah menjadi feromagnetik pada suhu kamar. Transformasi fasa magnetik ini disebabkan oleh kehadiran Ni yang telah berhasil memsubstitusi sebagian atom Fe. Namun subststitusi Ni ke dalam Fe pada sistem pseudobrookite Fe$_5$TiO$_3$ hanya mampu sebesar 0.1 % tanpa mengubah struktur kristal dari bahan ini. Ini berarti bahwa ada interaksi antara spin magnetik Fe$^{3+}$ pada konfigurasi 3d$^3$ dan Ni$^{2+}$ pada konfigurasi 3d$^8$ melalui mekanisme pertukaran ganda. mekanisme pertukaran ganda adalah jenis magnetik pertukaran yang muncul antara ion Fe$^{3+}$ dan Ni$^{2+}$ berdekatan di bilangan oksidasi yang berbeda.

Kata kunci: Pseudobrookite, Fe$_{2-x}$Ni$_x$TiO$_5$, Substisusi, Struktur kristal, Magnetik
INTRODUCTION

Absorber material of electromagnetic wave is now becoming one of the interesting topics to be studied and understood. The electromagnetic wave absorber materials began to attract attention since the emergence of the phenomenon of electromagnetic wave interference (EMI) on several electronic components that work at high frequencies along with the development of telecommunications technology. This EMI can degrade the performance of the electronic components. Characteristics intrinsic and extrinsic of electromagnetic wave absorber material make a very unique phenomenon to be studied. Because the main requirement is needed as a material absorbing electromagnetic waves is the presence of intrinsic characteristics (properties of magnetic loss and dielectric loss) on the material in addition to the extrinsic characteristics (factors of the geometry of the particles).

At first the absorber materials developed until now are a carbon-based material that has a high dielectric loss [1]. However recently too is found many studies of electromagnetic wave absorber materials began to lead to the use of magnetic materials, especially ferromagnetic [2-4]. Ferromagnetic material is believed to have a high permeability which is expected through the structure engineering may have high magnetic loss. But it is very interesting to study if these materials are paramagnetic at room temperature. It means that the paramagnetic material is necessary a structure engineering in order to transform into a ferromagnetic phase [5]. This study has been done structure engineering on the paramagnetic material of pseudobrookite Fe$_3$TiO$_5$-based. Main reason for choosing this system is the magnetic material of pseudobrookite Fe$_3$TiO$_5$ has a stable structure up to high temperatures. Pseudobrookite Fe$_3$TiO$_5$ may also be obtained from the phase transformation of ilmenite (FeTiO$_3$) [6], while ilmenite itself can be obtained from iron sand where their reserves were very large in Indonesia. Therefore, this material becomes excellent products at low prices as well as raw materials are easily obtained.

Pseudobrookite Fe$_3$TiO$_5$ previously can be used for multiple applications such as microelectronics materials, gas sensors, non-linear optics, magnetic applications, filter optics [7], photocatalyst [8], photo electrode, anode batteries [9], pigments, and a membrane at high temperatures for fuel cell applications [10]. Thus the application of Pseudobrookite Fe$_3$TiO$_5$ material is very wide and makes this material is one of the multifunctional materials so the further understanding of this material is very interesting to study. Several methods have been developed to synthesize this compound is by using a hydrothermal method [11], ball-milled [9], sol-gel processes [8], solid state [12], and chemical vapor deposition [13]. However, one of the simplest methods is to use a solid state reaction method through mechanical milling.

Pseudobrookite Fe$_3$TiO$_5$ is a semiconductor material and has the crystal structure of orthorhombic with space group Cmcm. Pseudobrookite Fe$_3$TiO$_5$ has magnetic spin glass transition. Magnetic properties of pseudobrookite Fe$_3$TiO$_5$ material is paramagnetic phase at room temperature [14]. This research will be conducted preliminary studies for structural engineering on the pseudobrookite Fe$_{2.5}$Ni$_x$TiO$_5$ materials by solid state reaction using a wet milling process. The addition of nickel (Ni) atoms is expected able to replace most of the position of the iron (Fe) atoms so that the interaction between the magnetic spin Fe$^{3+}$ ions with Ni$^{2+}$ occur it and can affect the magnetic properties of this material. Thus the aim of this study is to synthesize and characterize pseudobrookite Fe$_{2.5}$Ni$_x$TiO$_5$ material with variations in composition ($x = 0, 0.1, 0.2, 0.3, 0.5$ and $1$). The discussion will be focused on the analysis of the crystal structure (phase and parameter structures), morphology of particles and magnetic properties of the pseudobrookite Fe$_{2.5}$Ni$_x$TiO$_5$ due to the addition of Ni atoms in the system.

EXPERIMENTAL METHOD

Pseudobrookite Fe$_{2.5}$Ni$_x$TiO$_5$ was synthesized by solid state reaction method with variations in composition ($x = 0, 0.1, 0.2, 0.3, 0.5$, and $1$). The raw materials are used α-Fe$_2$O$_3$, TiO$_2$ (anatase) and NiO, by following Equation (1).

\[
(2-x)Fe_2O_3(S) + 2xNiO + 2TiO_2(S) \rightarrow 2Fe_{2-x}Ni_xTiO_5(S) + \frac{1}{2}(4-x)O_{2(g)}
\]

The three materials were weighed according to the calculation of stoichiometric composition, then mixed and placed in a media that is made of stainless steel. Once it is added ethanol and balls are also made of stainless steel with a mass ratio between the balls and the material are 1: 2. The mixture is then milled for 5 hours using high energy milling equipment of Spex8000. The mixture of milling result is then dried and compacted with a pressure of 5000 psi. Furthermore, samples were sintered at 1000 °C for 5 hours in a furnace.

Crystalline phase identification was measured by X-Ray Diffractometer (XRD), Shimadzu type XD610. Measurement of the diffraction pattern using X-ray tube with a wavelength of $\lambda = 1.5406$ Å, mode: continuous scan, step size: 0.02°, and time per step: 0.5 seconds, and qualitative-quantitative phases analysis formed in the sample was used by GSAS software (General Structure Analysis System). While the particle morphologies were observed by using Scanning Electron Microscope (SEM) of JEOL type JED 2300. The magnetic properties were measured by using a Vibrating Sample Magnetometer (VSM) of Oxford type VSM1.2H instrument.
RESULTS AND DISCUSSION

Figure 1 shows the results of measurements of X-ray diffraction pattern of the sample pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ with variations in composition (x = 0, 0.1, 0.2, 0.3, 0.5, and 1).

Based on the results of phase identification appears that the reaction has been successfully formed a single phase Fe$_{2-x}$Ni$_x$TiO$_5$ is on the composition of x = 0 and x = 0.1, while for the composition of 0.1 < x < 0.5, the sample can not react perfectly so the sample consists of three phases, namely phases of Fe$_{2-x}$Ni$_x$TiO$_5$, FeTiO$_3$, and Fe$_2$NiO$_4$. More reaction unperfectly occurs on the composition x = 1, which results in four phases, namely phases of Fe$_{2-x}$Ni$_x$TiO$_5$, FeTiO$_3$, Fe$_2$NiO$_4$ and NiO. Results of phase identification is very interesting to understand because for x = 0.1 shows that atoms of nickel has succeeded in substituting partially of the atoms Fe in the structure Fe$_{2-x}$Ni$_x$TiO$_5$, and for x > 0.1 is thought to occur reaction inbalance when the amount of Fe content is reduced meanwhile the Ni content increased. In Figure 3 appears too that with increasing Ni content (x > 0.1) in the sample, cause the phases of FeTiO$_3$, Fe$_2$NiO$_4$ and NiO increasing. Thus required further analysis to determine the changes of the crystal structure parameters, the amount of mass fraction formed, and cationic distribution on the results of substitution Ni into the Fe atom.

In Figure 2 shows the results of refinement X-ray diffraction data of the sample pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ with variations in composition (x = 0, 0.1, 0.2, 0.3, 0.5, and 1).

Figure 2(a) and 2(b) are the result of refinement of the XRD patterns for x = 0 and 0.1 that have been formed Bragg diffraction peaks with a single phase following the Fe$_2$TiO$_5$ structure. Figure 2((c) to (e)) are the result of refinement of the XRD patterns for x = 0.2, 0.3, and 0.5 have been formed bragg diffraction peaks with a multi-phase, which follows the structure Fe$_2$TiO$_5$, FeTiO$_3$, and Fe$_2$NiO$_4$. While Figure 2(f) is the result of refinement of the XRD patterns for x = 1 which has been formed bragg diffraction peaks with a multi-phase, which
Refinement complete summary of the results of X-ray diffraction pattern of the sample pseudobrookite Fe<sub>2</sub>Ni TiO<sub>5</sub> with variations in composition (x = 0, 0.1, 0.2, 0.3, 0.5, and 1) for all of samples are shown in Table 1.

Figure 2 and Table 1 show that the refinement results of X-ray diffraction pattern has a very good fitting quality based on the criteria of fit (R<sub>wp</sub>) and goodness of fit (χ<sup>2</sup>) in accordance with the agreement [15]. R<sub>wp</sub> is the weight ratio of the difference between the XRD pattern of observation and calculation (ideal value of R<sub>wp</sub> < 10%). While χ<sup>2</sup> (chi-squared) is the ratio of the XRD pattern of observation results comparable with expectations (ideal value of 1 < χ<sup>2</sup> < 1.3).

In Table 2 shows that based on the refinement pattern of X-ray diffraction samples pseudobrookite Fe<sub>2-x</sub>Ni<sub>x</sub>TiO<sub>5</sub> with variations in composition (x = 0, 0.1, 0.2, 0.3, 0.5, and 1), the sample has a single phase is in the composition x = 0 (Fe<sub>2</sub>TiO<sub>5</sub>) and x = 0.1 (Fe<sub>1.9</sub>Ni<sub>0.1</sub>TiO<sub>5</sub>). This refinement results are also supported by observations of the surface morphology of particles for both single phase using SEM as shown in Figure 3.

In Figure 3 shows that the particle morphologies of the composition x = 0 has a good particle homogeneity and uniform across the sample surface with a polygonal particle shape and particle size varies from 2 μm to 10 μm. The similar with the particle morphologies of the composition x = 0.1 has a good homogeneity and uniform too with polygonal particle shape and particle size varies, but relatively more small compared with the composition x = 0 from 1 μm to 5 μm. In general a single phase characteristics of polycrystalline samples by observation of SEM image is homogeneity and uniformity particle shape in across the sample surface.

The interesting thing to studied are that both have a single phase with the same structure, but their composition are different. On the composition x = 0.1, there is a 0.1 % Ni atoms have succeeded substituting...
Crystallographic Structure and Magnetic Properties of Pseudobrookite $\text{Fe}_{2-x}\text{Ni}_x\text{TiO}_5$ System ($x = 0, 0.1, 0.2, 0.3, 0.5,$ and $1$) (Yosef Sarwanto)

Table 2. Cationic distribution on the $\text{Fe}_{2-x}\text{Ni}_x\text{TiO}_5$ ($x = 0.1$) was calculated from XRD data.

| Atom     | Site | Point symmetry | $\text{Fe}_{2-x}\text{Ni}_x\text{TiO}_5$ ($x = 0.1$) | Fe | Ni |
|----------|------|----------------|--------------------------------------------------|----|----|
| Fe       | 8f1  | m              | $0.94$                                           | 0.06 |
|          |      |                | ($94$ at.%)                                      | ($6$ at.%) |

Composition by GSAS result $\text{Fe}_{1.88}\text{Ni}_{0.12}\text{TiO}_5$.

Figure 3. (a). The particle morphology of the pseudobrookite $\text{Fe}_{2-x}\text{Ni}_x\text{TiO}_5$ ($x = 0$) ; (b). The particle morphology of the pseudobrookite $\text{Fe}_{2-x}\text{Ni}_x\text{TiO}_5$ ($x = 0.1$).

Figure 4. The volume of unit cells as a function of composition (a). $\text{Fe}_2\text{TiO}_5$ (b). $\text{FeTiO}_3$ and $\text{Fe}_2\text{NiO}_4$.

Because Ni has a valence of $2^+$, is thought to affect on the oxygen content. Since XRD can not refine the oxygen content, it is necessary a structure analysis using neutron diffraction facilities, but in this study has not been conducted. Data supporting the other is from the analysis of changes in the volume of the unit cell as shown in Figure 4.

In Figure 4(a) it appears that the composition $x = 0.1$ occurs shrinkage of unit cell volume. This is due to the atomic radius Ni ($r = 1.62$ Å) is shorter than the atomic radius of Fe ($r = 1.72$ Å), thus resulting in lattice parameter is also reduced for the third axis. Then for the composition $x = 0.2$ and $x = 0.3$, the unit cell volume increased again and gradually declined allegedly caused the lattice distortion by the presence of another phase is formed. The addition of Ni excess ($x > 0.1$) results in an imbalance of the reaction so that Ni prefers to bind Fe to form Ferronickel, since the composition of these compounds is relatively stable compared with $\text{Fe}_{2-x}\text{Ni}_x\text{TiO}_5$. While another Fe will bind to Ti forming $\text{Fe}_2\text{TiO}_5$ and $\text{FeTiO}_3$. It can be described as in Figure 4 (b) that on the composition of $x > 0.1$, no change in the unit cell volume on the phases of $\text{FeTiO}_3$ and $\text{Fe}_2\text{NiO}_4$. It means that Ni has reacted with Fe to form $\text{Fe}_2\text{NiO}_4$.

Besides, the presence of Ni can affect the magnetic properties of these systems. In Figure 5 is shown the results of measurement of magnetic properties by using VSM.

From the hysteresis curve shows that samples with composition $x = 0$ ($\text{Fe}_2\text{TiO}_5$) has paramagnetic behavior and marked with the magnetization response on the external magnetic field is a linear. While the composition $x = 0.1$, the magnetic properties of materials...
Increasing the value of magnetic saturation on the mass fractions as shown in Figure 6. The refinement pattern of X-ray diffraction samples pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ shows that the samples has a single phase is in the composition $x = 0$ (Fe$_2$TiO$_5$) and $x = 0.1$ (Fe$_{1.9}$Ni$_{0.1}$TiO$_5$). The particle morphologies of the composition $x = 0$ and $x = 0.1$ are homogenous and uniform in across the sample surface with a polygonal particle shape and the particle size varies. Thus substitution Ni into Fe on the pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ only capable of 0.1 at.% without changing the crystal structure of the material and can alter the magnetic properties of the paramagnetic behavior becomes ferromagnetic at room temperature.

CONCLUSION

Synthesis of pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ with variations in composition ($x = 0, 0.1, 0.2, 0.3, 0.5$, and $1$) have been successfully carried out. The refinement pattern of X-ray diffraction samples pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ shows that the samples has a single phase is in the composition $x = 0$ (Fe$_2$TiO$_5$) and $x = 0.1$ (Fe$_{1.9}$Ni$_{0.1}$TiO$_5$). The particle morphologies of the composition $x = 0$ and $x = 0.1$ are homogenous and uniform in across the sample surface with a polygonal particle shape and the particle size varies. Thus substitution Ni into Fe on the pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ only capable of 0.1 at.% without changing the crystal structure of the material and can alter the magnetic properties of the paramagnetic behavior becomes ferromagnetic at room temperature.

ACKNOWLEDGEMENT

This work is supported by the program of DIPA 2016, Center for Science and Technology of Advanced Materials. The authors are thankful to Mujamilah, M.Sc., Drs. Bambang S., Imam W., S.ST., and Dr. A. Taufig for their kind help to characterize using VSM, XRD and SEM, respectively.

REFERENCES

[1]. Xiaohuan Wang. “Investigation of Electromagnetic Shielding Effectiveness of Nanostructural Carbon Black/ABS Composite.” Journal of Electromagnetic Analysis and Applications, vol. 3, pp. 160-164, 2011.

[2]. Shuyuan Zhang, Quanxi Cao. “Electromagnetic and Microwave Absorption Performance of Some Transition Metal Doped La$_{0.3}$Sr$_{0.7}$Mn$_{1-x}$TM$_x$O$_{3±1}$ (TM = Fe, Co or Ni).” Materials Science and Engineering B, vol. 177, pp. 678-684, 2012.

[3]. T. Nurul. Rochman and Wisnu Ari Adi. “Preliminary Study of The Developm Ent of Absorber Electromagnetic Wave Materials by Modifying Iron Sand.” International Journal of Academic Research Part A. vol. 5, no. 4. pp. 91-96, 2011.

[4]. Wisnu Ari Adi and Azwar Manaf. “Structural and Absorption Characteristics of Mn-Ti Substituted Ba-Sr Hexaferrite Synthesized by Mechanical Alloying Route.” Journal of Basic and Applied Research Part A. vol. 5, no. 4, pp. 91-96, 2011.

[5]. Priyo Sardjono and Wisnu Ari Adi. “Thermal Analysis and Magnetic Properties of Lanthanum Barium Manganite Perovskite.” Journal of Advanced Materials Research, vol. 896, pp. 381-384, 2014.
Crystallographic Structure and Magnetic Properties of Pseudobrookite Fe$_{2-x}$Ni$_x$TiO$_5$ System (x = 0, 0.1, 0.2, 0.3, 0.5, and 1)
(Yosef Sarwanto)

[6]. Wei XIAO, Xiong-gang LU, Xing-li ZOU, Xue-mei WEI, Wei-zhong DING. “Phase Transitions, Micro-Morphology and its Oxidation Mechanism in Oxidation of Ilmenite (FeTiO$_3$) Powder.” Trans. Nonferrous Met. Soc. China, vol. 23, pp. 2439-2445, 2013.

[7]. Lei JIN and Chungen ZHOU. “Electronic Structures and Optic Properties of Fe$_2$TiO$_5$ using LSDA+U Approach.” Progress in Natural Science: Materials International, vol. 23, no. 4, pp. 413-419, 2013.

[8]. E. Khosravi, M.K. Razi, and M. Enhessari. “Photocatalytic and Magnetic Behavior of Fe$_2$TiO$_5$ -5A Zeolite Nanocomposites.” Int. J. Bio-Inorg. Hybd. Nanomat., vol. 1, no. 2, pp. 115-122, 2012.

[9]. Kyung-Mi MIN, Kyung-Soo Park, Ah-Hyeon Lim, Jae-Chan Kim and Dong-Wan Kim. “Synthesis of Pseudobrookite-type Fe$_2$TiO$_5$ Nanoparticles and their Li-ion Electroactivity.” Ceramics International, vol. 38, pp. 6009-6013, 2012.

[10]. K. Houshyari, M. Javanbakht, L. Naji, and M. Enhessari. “Physical and Electrochemical Study of Nafion/Fe$_2$TiO$_5$ Nanocomposite Membranes for High Temperature PEM Fuel Cells.” Proceedings of the 4th International Conference on Nanostructures (ICNS4) 12-14 March, 2012.

[11]. Prince Saurabh Bassi, Sing Yang Chiam, Gurudayal, James Barber, and Lydia Helena Wong. “Hydrothermal Grown Nanoporous Iron Based Titanate, Fe$_2$TiO$_5$ for Light Driven Water Splitting.” Appl. Mater. Interfaces, vol. 6, no. 24, pp. 22490-22495, 2014.

[12]. N.I. Aljuraide, M.A.A. Mousa, M. Hessien, M. Qhatani, and A. Ashour. “Structural Properties of Ferric Pseudobrookite Fe$_2$TiO$_5$ Powder Prepared by A New Method.” Int. J. Nanoparticles, vol. 4, no. 1, 2011.

[13]. M. A. Ehsan, A.A. Tahic, M. Hamid, M. Mazhar, K.G.U. Wijayantha, M. Zeller. “Deposition of Iron Titanate/Titania Ceramic Composite Thin Films From A Single Molecular Precursor.” Inorganica Chimica Acta, vol. 376, pp. 189-194, 2011.

[14]. M. Enhessaria, M.K. Razib, L. Etemad, A. Parvizc, and M. Sakkhaeib. “Structural, Optical and Magnetic Properties of the Fe$_2$TiO$_5$ Nanopowders.” Journal of Experimental Nanoscience, vol. 9, no. 2, pp. 167-176, 2014.

[15]. B.H. Toby. “EXPGUI A Graphical User Interface for GSAS.” J. Appl. Crystallogr. No. 34, pp. 210-221, 2001.

[16]. Yosef Sarwanto and Wisnu Ari Adi, Modification of pseudobrookite Fe$_{2-x}$Mn$_x$TiO$_5$ with Solid State Reaction Method using a Mechanical Milling, published in ICAMST, Malang. 2016.