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FABRICATION OF $BaTiO_3$ THICK-FILM LEAD-FREE PIEZOELECTRIC CERAMIC BY USING SCREEN PRINTING METHOD

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ABSTRACT

This paper describes the fabrication process of thick-film lead free piezoelectric ceramics, consisting of barium titanate ($BaTiO_3$), borosilicate, terpineol, on alumina (Al_2O_3) substrate. The $BaTiO_3$thick-films piezoelectric are prepared by screen printing. Suitable ratio for the paste composition is crucial to ensure printability and functionality of lead-free piezoelectric ceramic. Ag/Pd is deposited as the lower and upper electrodes to form a unimorph piezoelectric device. The thick-film which contained 50wt. % $BaTiO_3$, 10wt.% borosilicate, and 20wt.% terpineol demonstrated the optimal piezoelectric properties with the maximum piezoelectric charge coefficient of 17 pC/N. The thick-film was also inspected under SEM to investigate the quality of the films.

Keywords: thick-film technology, lead-free piezoceramic, piezoelectric charge coefficient d_{33}.

INTRODUCTION

The piezoelectric materials can be categorized into two classification, one of them is Pb-based piezoelectric and the other is non Pb-based piezoelectric. Potential piezoelectric material option exist in either natural crystal (e.g. quartz) or polycrystalline ceramic (e.g. PZT) or polymer form (e.g. PVDF). Lead-based piezoelectric ceramic such as lead zicronatetitanate (PZT) have been widely used as piezoelectric sensor and piezoelectric actuator because of their excellent piezoelectric properties (Chen *et al*., 2013).However, due to the environmental and health related hazards concern, legal restriction are being taken to reduce or eliminate the use of lead in electronic products (Alkoy & Dursun, 2012). The lead-based piezoelectric ceramics containing PbO more than 60 wt% can cause serious environment pollution and human health problems because of its high toxicity (Cui *et al*., 2012). Nowadays, advanced materials have been widely studied for consumer, healthcare and military applications, where it enable the design of garments incorporating distributed non-obtrusive sensors (Pons *et al*., 2007). Therefore, extensive studies and investigation have been conducted on Pb-free piezoelectric ceramic materials for environment friendly and the replacement in electronic products (Cheng *et al*., 2014) (Byeon and Yoo, 2014).

Barium Titanate ($BaTiO_3$) is perovskite family with an inorganic compounds and the empirical formula, ABO_3. It is a good candidate for non Pb-based material among the lead-free substances (such as Potassium Niobate (Byeon and Yoo, 2014), and Polyvinylidene Fluoride (Arlt and Wegener, 2010)) for a variety of applications that avoid toxicity of lead-based materials. $BaTiO_3$ has been studied widely for its structural transition (Cheng *et al*., 2014) and applications (Ali *et al*., 2013). Therefore, development of alternative method that can produce a smart material integrated for electronic functions play an important role in lead-free piezoelectric devices. $BaTiO_3$is considered as one of the most promising candidate materials for the replacement of Pb-based piezoelectric materials because of its exhibit piezoelectric properties (Jiang *et al*., 2014). Recent reports of $BaTiO_3$ materials remains a major scientific challenge in requirements to develop high piezoelectric sensitivity and composition of lead-free piezoelectric ceramics (Ali *et al*., 2013). It was reported by (Bai *et al*., 2012), the lead-free piezoelectric ceramics shows high piezoelectric properties but it limited on bulk ceramic devices.

Ceramic thick-film technology refers to the technology involved deposition of cement based pastes screen printed onto a flat base material (substrate) through the use of a fine woven mesh with desired geometryand then fired at temperatures in the region of 800 – 1000 °C (Kok *et al*., 2009)(Wu *et al*., 2011) (Wei *et al*., 2012). Screen printing technique is the oldest yet simple forms of graphic art reproduction. Fabrication piezoelectric materials usually consist of at least two physical and chemically different materials as states by (Stojanovic *et al*., 2007) (Fu *et al*., 2014) (Vijatović *et al*., 2010) (Zhang and Hao, 2014) (Park and Park, 2011), there are active material, binder and solvents.

Many studies have been reported on the preparation piezoelectric thick films by screen printing, tape casting, composite sol-gel, aerosol spray deposition, electrophoretic deposition, sputter coating, polymeric precursor and reactive-template grain growth (RTGG) method (Bai *et al*., 2012) (Wu *et al*., 2011) (Zhang *et al*., 2010) (Hu *et al*., 2014). Recently, researchers used a thick film technology in fabricating the $BaTiO_3$lead-free piezoelectric ceramic by a screen printing method. However, the thickness range is the primary reason for their piezoelectric properties notable lack of availability (Stojanovic *et al*., 2002).

The majority of this research is the fabrication of thick-film lead-free piezoelectric ceramic by using screen-printing technique. This process is useful to fulfill the demands for miniaturization, multilayer assembles and circuit complexity. Thus, this paper reports screen printing unimorph design on alumina substrate with a lead free material piezoelectric layers with the difficulties on the preparation of $BaTiO_3$thick-films. The aim of this work is to characterize electrical properties $BaTiO_3$ based thick-films piezoelectric ceramics via thick-film technology. The microstructure quality and the electrical properties of the thick-film were analyzed.

Material and preparation of $BaTiO_3$ piezoelectric films

The lead-free piezoelectric ceramic powders with ratio of 5:2:1 were prepared by thick-films technology. The powders of all chemicals, $BaTiO_3$ (<3µm, 99%), $BaTiO_3$ (<2µm, 99.9%), $BaTiO_3$ (<100nm, 99.9%), borosilicate glass (7056) and terpineols (99%) were obtained from Sigma-Aldrich. The raw powders were accurately weighed with different amounts according to ratio as shown in Table-1.The first step in fabrication the lead-free thick-film piezoelectric ceramic is the formulation of the powder into pastes. Thus, the mixtures for the lead free piezoelectric pastes are made from the combination of functional powder material, solvent and permanent binder.

Table-1. Material weight ratio 5:2:1 of the lead free piezoelectric ceramic powder.

Material	Function	Weight,%
$BaTiO_3$ (<3µm, 99%)	Active material	30
$BaTiO_3$ (<2µm, 99.9%)	Active material	15
$BaTiO_3$ (100nm, 99.9%)	Active material	5
Borosilicate glass (7056)	Binder	10
Terpineol (alpha)	Solvent	20

The primary powders were fully mixed through dry-milling process with mortar and pestle. Then, the primary powders were ball-milled with the addition of borosilicate glass powder for 30 min. The mixtures of the raw powder materials were homogenized together through a triple roller millin wet-milling process with alpha-terpineols solvent for 1 hour, where it formed a printable paste. The viscosity of the prepared screen printable pastes were measured by viscometer and adjusted in the range 20 to 60 Pa.

Screen printing method of $BaTiO_3$ thick film

Screen-printing is a printing technique that uses a woven mesh to support an inks or pastes medium blocking stencil, as shown in Figure-1. The equipment for fabrication via thick-films technology required inks, which are the piezoelectric pastes, squeegee, image unimorph design, photoemulsion (woven mesh) and screen, mesh frame. The screen printing process was carried out using a fine woven mesh that was mounted on a metal frame. The screen printable pastes were transported over the screen by a squeegee. A squeegee was moved across the screen stencil, forcing the pastes past the threads of the woven mesh.

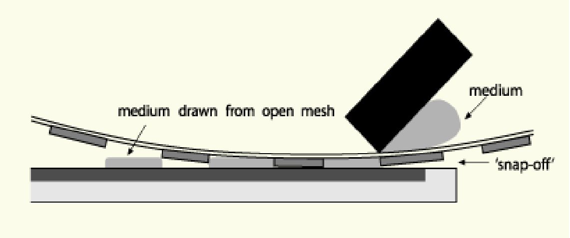


Figure-1. Screen printing method of thick-film lead-free piezoelectric ceramics.

Initially, the bottom electrode was deposited with silver/palladium (Ag/Pd) slurry directly on 96% alumina (Al_2O_3) substrate (40 mm x 10m x 0.5 mm) substrate in the predefined geometric pattern. After printing, the films were dried off with 60°C exposure of infrared light for 15 min. Then, the $BaTiO_3$ piezoelectric layers were screen-printed with a 280 mesh screen mask to the underlying bottom electrode. The $BaTiO_3$films were left at room temperature one minute in order to level out and dry. The thick film was dried offwith 60°C exposure of infrared light for 1 hour. This process was repeated twice with the second layer of $BaTiO_3$thick film. Before deposition of top electrode, a heat treatment for firing condition was carried out in the thick films according to the temperature profile in Figure-2.

Table-2. Summary of printed layer drying process parameters.

Layer	Drying conditions	Duration
Bottom electrode	Infrared, 60°C	15 min
Active layer	Infrared, 60°C	1 hours
Top electrode	Infrared, 60°C	15 min

The top electrode layer was screen printed similarly with the bottom electrode through desired pattern on the layer of $BaTiO_3$thick film. The $BaTiO_3$thick film was sandwiched in between bottom electrode and top electrode. The drying process was performed in air at 60°C using a homemade box with infrared light distance 20 cm from$BaTiO_3$thick film. The printed layer was dried for certain duration according to the material that deposited on the Al_2O_3 substrate as stated in Table-2. The final heat treatment of firing condition was carried out for whole $BaTiO_3$thick-film piezoelectric ceramic cantileverin air. The variable temperature ranging from 850°C to 1050°C.

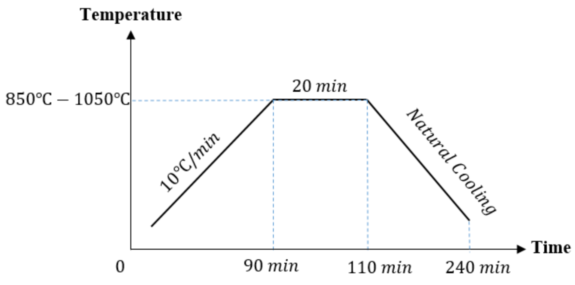


Figure-2. Temperature profile of the $BaTiO_3$thick-film piezoelectric ceramics enabled by firing condition.

The thick-film usually consists of several layers of material in order to obtain the desired thickness. The number of printed layers of film was shown in Table-3. The bottom and top electrode of thick film consisted of one screen-printed layer which was approximately 10-15μm. The specimen dimension for the$BaTiO_3$thick-film piezoelectric ceramics measurements were in shown in Table-4 with0.5 mm of and 0.2 mm thickness for the alumina substrate and sandwich layer of barium titanate ($BaTiO_3$) ceramics, respectively. The films dimensions depend on the geometric design on the woven mesh of the screen.

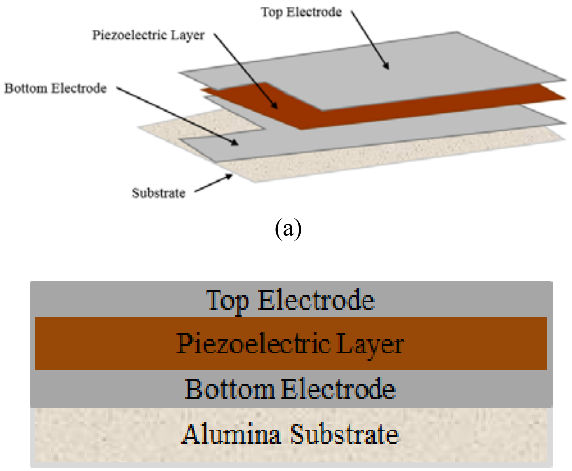
Table-3. Material layers of the lead free piezoelectric ceramic membrane structures.

Layer	Role	Prints
Al_2O_3	Substrate	-
Ag/Pd	Bottom electrode	1
$BaTiO_3$	Active layer	2
Ag/Pd	Top electrode	1

Electrical poling was performed by heated on the hot plates with applied external electric fields. The $BaTiO_3$thick-film piezoelectric ceramics were polarized in direct contact. For short-term 15 minutes poling duration, the $BaTiO_3$thick-film piezoelectric ceramics were poled with ranging temperature 60°C to 160°C and the applied electric fields at 20 kV/cm . The static piezoelectric charge coefficients (d_{33}) were characterized by a direct method based on ZJ-6B Quasi-static d_{33} meter using the Berlincourt Method. Scanning electron microscopy (SEM) investigations were performed in order to record the microstructure of the $BaTiO_3$thick-films piezoelectric ceramic and to analyse the particle size of the $BaTiO_3$ pastes deposited on the bottom electrode. In addition, the film-thickness was determined using ZEISS EVO 50 XVP.

Structure of $BaTiO_3$ thick-film piezoelectric ceramicscantilever

The thick film piezoelectric ceramic printed on alumina substrate is intended to be operated in the form of cantilever structure. The structure can provide a more comfortable approach for mounting the device on the body of vibrational machinery for harvesting kinetic energy. The sandwiched cantilever structure is shown in Figure-3 (a) and (b), consisting of four layers which are substrate, Ag/Pd electrode for bottom layer, piezoelectric layers, and Ag/Pd electrode for top layer.



(a)

(b)

Figure-3. (a) Breakout diagram and (b) cross sectional view of the sandwiched $BaTiO_3$thick-film piezoelectric ceramic.

Fabrication of $BaTiO_3$ thick-films

$BaTiO_3$films were deposited on the underlying Ag/Pd bottom electrode. In this experiment, the screen printed electrode was specifically used Ag/Pd paste because to produce strong adhensions for $BaTiO_3$ films and high stresses from drying shrinkage and thermal expansion while firing. As a result of printed films, the Ag/Pd conductor also serves as glue for the $BaTiO_3$thick film piezoelectric ceramic cantilever. The $BaTiO_3$ thick film piezoelectric was successfully fabricated by using screen printing techniques as shown in Figure-4.

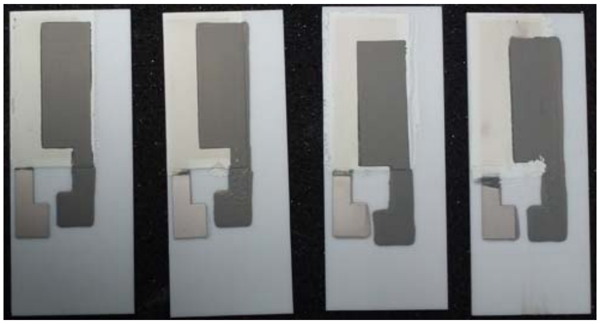


Figure-4. The $BaTiO_3$thick film piezoelectric sandwiched between the top electrode and bottom electrode on alumina substrate.

Electrical properties

The fabricated $BaTiO_3$thick-film piezoelectric cantilever was characterized both visually and electrically.

The electrical characterization is done by measuring the direct piezoelectric effect. The direct measurement method of $BaTiO_3$ thick-film piezoelectric ceramic cantilever were characterize with d_{33} meter using Berlincourt method as shown in Figure-5.

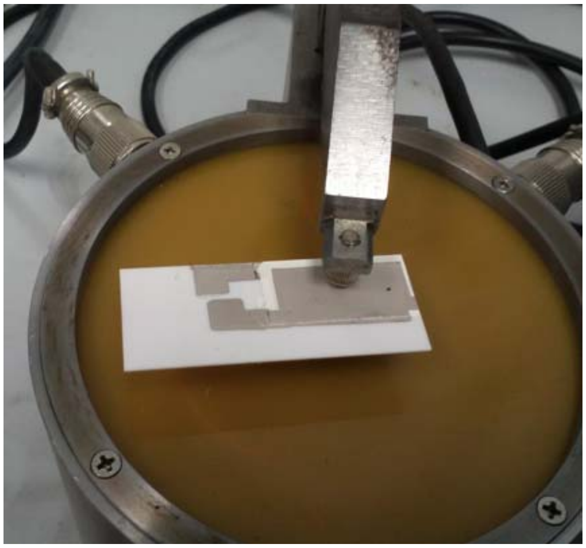


Figure-5. Direct measurement method of the $BaTiO_3$thick-film piezoelectric ceramics.

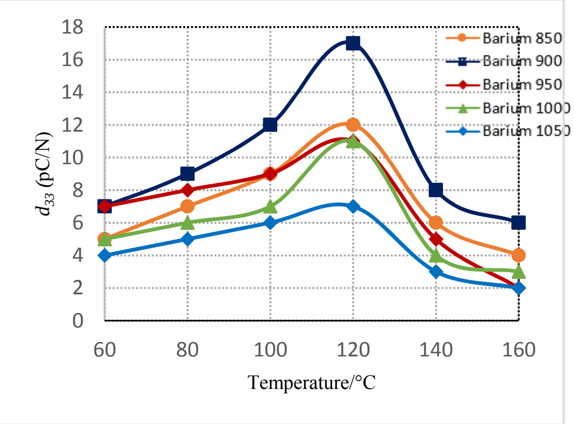


Figure-6. Polarization measurement of $BaTiO_3$ thick-film piezoelectric ceramic with different sample firing condition.

The compulsory process in the fabrication of$BaTiO_3$ thick-film piezoelectric ceramics is polarization. There are two important variables in this process, which are the applied electric fields and the Curing temperature. The electrical properties of the $BaTiO_3$thick filmpiezoelectric ceramics samples were investigated on the piezoelectric charge coefficient and polarization behavior. The $BaTiO_3$thick-film piezoelectric ceramics were polarized in direct contact with applied external electric fields at 20 kV/cm for 15 minutes poling duration. Too high external electric field could lead the piezoelectric in occurring short circuit. The applied external electric fields depend on the thickness of the piezoelectric layers between top and bottom electrode. A thick the thickness of the piezoelectric film cantilever need high applied electric field compare to thin films. The response of $BaTiO_3$thick-film piezoelectric ceramics were poled with different firing condition ranging temperature 60°C to 160°C were presented in Figure-7.

The measurement results of the highest charge coefficient piezoelectric properties (d_{33}) value was 17pC/N at 120°C. On the other hand, all the $BaTiO_3$thick films were reached at high value of d_{33} piezoelectric properties at 120°C as shown. It was reported that the piezoelectric ceramic was exhibit high value of ofd_{33} piezoelectric properties as it reaches or near to its Curie temperature (Ali *et al*. 2013) (Stojanovic *et al.* 2007). However, $BaTiO_3$exhibit a relatively low Curie Temperature (Tc), which resulting from the tetragonal to paraelectric cubic phase transition at 120°C (Ali *et al.* 2013). From the polarization measurement, the highest peak response was $BaTiO_3$with 900°C firing temperature, followed by second peak was $BaTiO_3$with 850°C, the third and fourth share the same peak were $BaTiO_3$with 950°C and 1000°C, respectively and lastly was $BaTiO_3$with 1050°C firing temperature. In summary, the optimum firing condition for $BaTiO_3$thick films is 900°C and the poling temperature is 120°C.

The result of the high piezoelectric properties characterization performed as function of temperature between 850°C to 1050°C were presented in Figure-10. Measurements were made with the different firing condition of $BaTiO_3$thick filmpiezoelectric sample. The result shows it increasing to the highest value charge coefficient piezoelectric properties (d_{33}) was recorded at 900°C. The d_{33} values gradually decreasing at 950°C and further decreasing at 1050°C. There are many factors during preparation of thick-films piezoelectric ceramics could effect on the characterization of piezoelectric properties (Stojanovic *et al*. 2007). The observation can be made through$BaTiO_3$thick film piezoelectric sample start to peel off at 1050°C but it still have a small d_{33} value piezoelectric was measured and there is no obvious crack. In order to explore more on firing condition, we try to increase the firing temperature to 1100°C for $BaTiO_3$thick filmpiezoelectric sample. Unfortunately, the samples were totally defects and the Ag/Pd electrode peel off from the substrate. In the meantime, there is no d_{33} value was observed in the measured data. This evidence was expected due to the effect of different thermal treatment for the $BaTiO_3$thick filmpiezoelectric ceramics samples. It have been reported by (Kok *et al.* n.d.) That the electrode was peeling off from the ceramic layer as stated.

In order to investigate the aging response in Figure-9, the $BaTiO_3$films co-fired at 900°C were measured for three constitutive days. The measurements were taken for one hour with continuously applied dynamic force of 1N at 1 kHz. At the beginning of measurement it shows that the value of d_{33} which is due to the residual charges on the film and it reduces exponentially as the force is applied continuously and settle down at around 6 pC/N. From the graph it also shows the aging response of the piezoelectric thick-film material which decay over time.

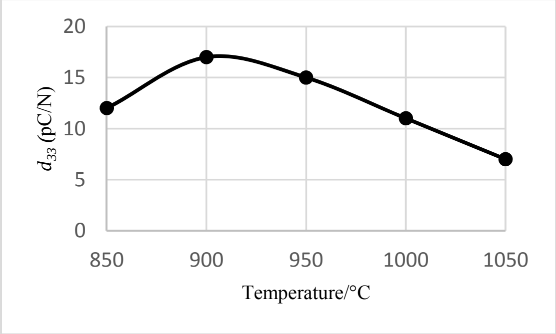


Figure-7. The measurement of charge coefficient properties (d_{33}) of $BaTiO_3$thick-film with firing conditions.

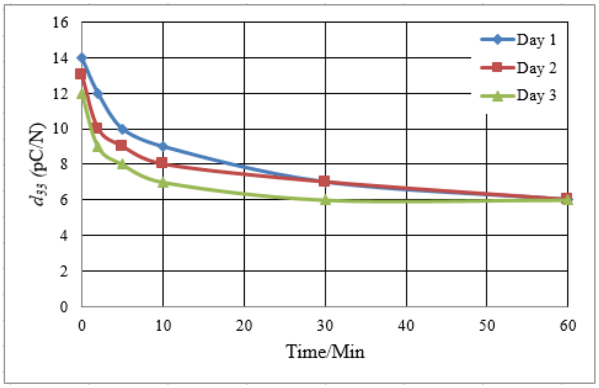


Figure-8. The aging response of $BaTiO_3$thick-film piezoelectric ceramic with continuously one hour applied dynamic force for three days.

SEM Analysis

The cross-section of two layers screen-printed $BaTiO_3$films is presented in Figure-10. The thickness of the two layers of $BaTiO_3$films was approximately 140 µm. The adhension of the bottom and the top electrode layer over-printed were good and it could not be peeled off with tape. There is no interdiffusion were observed between Ag/Pd electrode and the$BaTiO_3$thick films. The dense of the $BaTiO_3$thick films and homogenous microstructure were observed.

The $BaTiO_3$ thick film piezoelectric prepared by screen printing method show after screen-printed good crystallinity and no evident presence of secondary phases in Figure-13. As it is seen from the results obtained by SEM analysis, the particle size is possible to observe. The highly textured microstructure of $BaTiO_3$ is visible pattern structure in high magnification shown in Figure-11. The grain size of the thick films seems to be uniform.

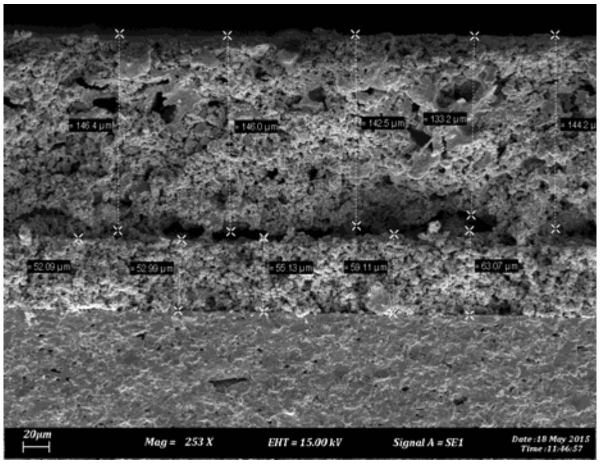


Figure-9. The cross section of the $BaTiO_3$thick film piezoelectric sandwiched between the top electrode and bottom electrode on alumina substrate.

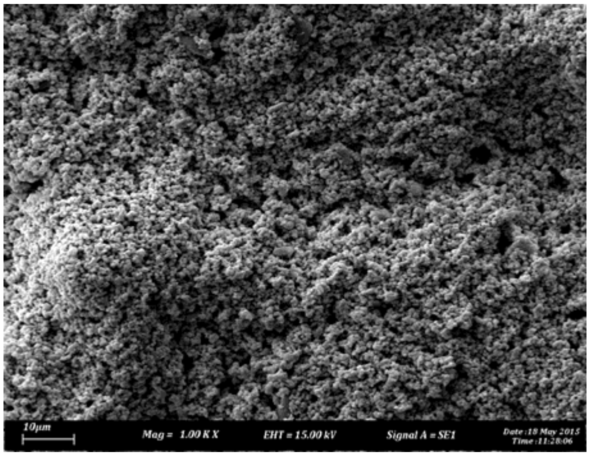


Figure-10. The microstructure of $BaTiO_3$layers of the thick-film piezoelectric ceramic on the alumina substrate.

According to (Wolf and Trolier-McKinstry, 2004), temperature dependence on thickness and grain size of piezoelectric materials. Therefore, the Curie temperature of bulk piezoelectric materials and films material may not be identical. From the observation and experimentation, this $BaTiO_3$thick filmpiezoelectric ceramics samples cannot be fired exceed than 1100°C because need to lower in order to obtain full densification of the films. The $BaTiO_3$content of material decrease of density by observation made in SEM analysis which is containing little pores is presented in Figure-12. This behavior may be due to an oxygen vacancy because the samples were firing at high temperature (850°C-1050°C) and in an oxygen environment. The grain size of $BaTiO_3$thick-films are less than 1 µm, approximately 800-600 nm and are influenced by the milling process and annealing time that make the compounds good. This evidence were prove and realized by (Ha and Choi, 2014) that particle size control give effect in improvement of piezoelectric properties. Hence, the phenomenon of this cause can be explained by relationship of printing force in order to obtain a dense structure.

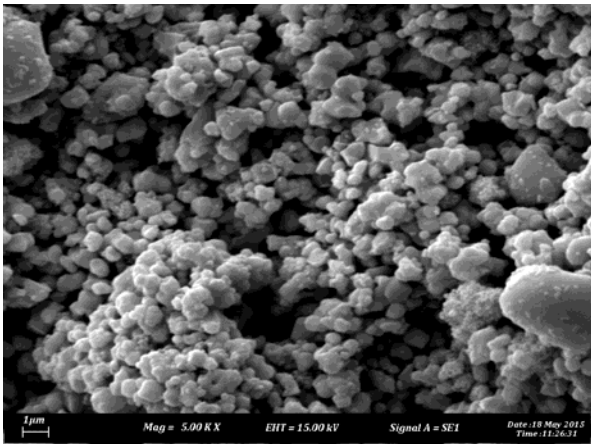


Figure-11. The high magnification of $BaTiO_3$thick-film piezoelectric ceramics.

Another factor that can be made from the observation of SEM image was the homogeneity of the $BaTiO_3$ ceramic. The fact that the powders strong agglomeration is because of the thick-films were prepared from the mixture of barium titanate powders, binder and borosilicate glass and after that deposited on Al_2O_3 substrates. The ratio was the main part of making piezoelectric ceramics. In addition, the combination between the different particles sizes of the $BaTiO_3$powders as shown in Table-1. Therefore, the small hole of particle can be filled by the small particle size (100 nm) make the homogeneous $BaTiO_3$films. It is difficult to reach an optimal paste composition within reasonable time. Thus by combining with other process will help the increasing piezoelectric properties in the materials.

CONCLUSIONS

Screen printing is one of the simple techniques in fabricating thick-film piezoelectric ceramics. It also suitable be used for printing multilayers films, besides that it is relatively low-cost without involving any complicated process. From the experiment, the results demonstrated that the screen-printed lead-free $BaTiO_3$thick-films are potential to be used for non-invasive applications of the sensor devices. The composition of $BaTiO_3$, borosilicate and temporary binder in the ratio of 5:2:1 has produced an optimum piezoelectric charge coefficient of 17 pC/N when co-fired at 900°C and poling temperature at 120°C.

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REFERENCES

Ali, A.I., Ahn, C.W. and Kim, Y.S. 2013. Enhancement of piezoelectric and ferroelectric properties of BaTiO3 ceramics by aluminum doping. Ceramics International. 39(6), pp. 6623-6629.

Alkoy, S. and Dursun, S. 2012. Textured lead-free KSr2Nb5O15piezoelectric ceramics, fibers and piezocomposites - Processing and properties. Proceedings of ISAF-ECAPD-PFM 2012, 6, pp. 1-4.

Arlt, K. and Wegener, M. 2010. Piezoelectric PZT / PVDF-copolymer 0-3 composites: aspects on film preparation and electrical poling. IEEE Transactions on Dielectrics and Electrical Insulation, 17(4), pp. 1178-1184.

Bai, W. *et al*. 2012. Dielectric, ferroelectric, and piezoelectric properties of textured BZT–BCT lead-free thick film by screen printing. Materials Letters, 83, pp. 20-22.

Byeon, S. and Yoo, J. 2014. Dielectric, piezoelectric properties and temperature stability in modified (Na,K,Li)(Nb,Ta)O3 ceramics for piezoelectric energy harvesting device. Journal of Electroceramics, pp. 17-21.

Chen, L. *et al*. 2013. Poling induced dielectric anomalies in a PZT ceramic. Ceramics International, 39(8), pp. 8941-8944.

Cheng, X. *et al*. 2014. Dielectric, ferroelectric, and piezoelectric properties in potassium sodium niobate ceramics with rhombohedral-orthorhombic and orthorhombic-tetragonal phase boundaries. Ceramics International, 40(4), pp. 5771-5779.

Cui, Y. *et al*. 2012. Lead-free (Ba0.85Ca0.15) (Ti0.9Zr0.1) O3-CeO2 ceramics with high piezoelectric coefficient obtained by low-temperature sintering. Ceramics International, 38(6), pp. 4761-4764.

Fu, F. *et al*. 2014. Electric properties of BaTiO3 lead-free textured piezoelectric thick film by screen printing method. Journal of Electroceramics, 33(3-4), pp. 208-213.

Ha, J. and Choi, J. 2014. Improved piezoelectric properties of lead-free (1- x) (Na0.5K0.5) NbO3- x (Ba0.95Sr0.05) TiO3 ceramic by particle size control. Ceramics International, 40(8), pp. 12023-12028.

Hu, D. *et al*. 2014. Fabrication of [100]-oriented bismuth sodium titanate ceramics with small grain size and high density for piezoelectric materials. Journal of the European Ceramic Society, 34(5), pp.1169–1180.

Jiang, Y. *et al*. 2014. Lead-Free Piezoelectric Materials and Composites for High Frequency Medical Ultrasound Transducer Applications. 2014 IEEE International Ultrasonics Symposium Proceedings, pp. 903-906.

Kok, S.L., White, N.M. and Harris, N.R., Free-Standing Pb(Zr,Ti)O3Thick-Films Prepared By a One-Step Air Co-Firing Technique.

Kok, S.L., White, N.M. and Harris, N.R. 2009. Free-standing thick-film piezoelectric multimorph cantilevers for energy harvesting. 2009 IEEE International Ultrasonics Symposium. pp. 1977-1980.

Park, J.H. and Park, H.-H. 2011. In situ method of densification for powder-based piezoelectric thick films for microelectromechanical system applications. Micro and Nano Letters, 6, p.749.

Pons, J.L. *et al*. 2007. Biomedical instrumentation based on piezoelectric ceramics. Journal of the European Ceramic Society, 27(13-15), pp. 4191-4194.

Stojanovic, B.D. *et al.* 2002. Barium titanate screen-printed thick films. Ceramics International, 28(3), pp. 293-298.

Stojanovic, B.D. *et al*. 2007. Screen printed PLZT thick films prepared from nanopowders. Journal of the European Ceramic Society, 27(13-15), pp. 4359-4362.

Vijatović, M.M. *et al*. 2010. Barium titanate thick films prepared by screen printing technique. Processing and Application of Ceramics, 4(2), pp. 53-58.

Wei, Y. *et al*. 2012. Screen Printed Capacitive Free-standing Cantilever Beams used as a Motion Detector for Wearable Sensors. Procedia Engineering, 47(0), pp. 165-169.

Wolf, R. a. and Trolier-McKinstry, S. 2004. Temperature dependence of the piezoelectric response in lead zirconate titanate films. Journal of Applied Physics, 95(3), pp. 1397-1406.

Wu, M. *et al*. 2011. Enhanced electrical properties of textured NBBT ceramics derived from the screen printing technique. IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 58(10), pp. 2036-41.

Zhang, H. *et al*. 2010. Low temperature preparation and electrical properties of sodium–potassium bismuth titanate lead-free piezoelectric thick films by screen printing. Journal of the European Ceramic Society, 30(15), pp. 3157-3165.

Zhang, L. and Hao, X. 2014. Dielectric properties and energy-storage performances of (1-x) (Na0.5Bi0.5)TiO3-xSrTiO3 thick films prepared by screen printing technique. Journal of Alloys and Compounds, 586, pp. 674-678.