

A study of the electrical fatigue behavior of lead zirconate titanate for micro-actuator application in hard disk drives

Z. Luo, S. Kamposiri, T. Sonklin, W. Jongpinit, B. Marungsri, S. Pojprapai*

Abstract— This research work reports the effect of electric field amplitude on fatigue behavior of lead zirconate titanate ceramics (PZT) for micro-actuator hard disk drive application. The soft PZT samples were subjected to bipolar electrical cyclic loads to study the fatigue behavior. The amplitudes of electric fields of 1.00, 1.25, and 1.50 kV/mm at 10 Hz of frequency were applied. Polarization-electric field (PE) loops representing fatigue degradation were demonstrated. The fatigue behavior was indicated by the alternation of the size and shape of PE loops and remanent polarization (Pr). It was found that the remanent polarization decreased significantly with the number of loading cycles. Fatigue degradation was more pronounced in greater applied field. A mathematical model for fatigue degradation was proposed in this work.

Keywords— P-E hysteresis loop, Sawyer-Tower circuit, fatigue, polarization, micro-actuator

I. INTRODUCTION

Ferroelectrics materials have a variety of unique physical properties in dielectric coefficient, electric-optical coefficients, piezoelectric coefficients, elastic coefficient, etc. [1-5]. The most common ferroelectric material, lead zirconate titanate (PZT), is widely used in electronic applications [5], which one of them is as a fine-tune micro-actuator (see Figure 1) used in a highly precise servo control system for the read/write (R/W) positioning of a high track per inch (TPI) hard disk drives (HDDs). In this application the PZT is undertaken cycles of electrical loads, could lead to the material fatigue due to the constant change of the polarity. This can significantly degrade the ferroelectric properties [6] and lifetime of the PZT, thus lead to the degraded performance and potential failure of the read/write process in a hard disk drive.

The fatigue of PZT is usually caused by the polarization fatigue attributed to the decrease in the ability of domain switching. Previous studies have investigated the factors that influence the fatigue of PZT, including mechanical

deterioration [7-8], interface damage and delamination [9, 10], temperature [11-14], cycle frequency [15-17], amplitude of the applied field [18-19], polarity of loading [4, 20], etc. Considering the operational conditions and modes of PZT materials in micro-actuator of hard disk, in this work we specifically investigated the effect of electric field amplitude on the fatigue of PZT by resembling several field conditions in actuator application.

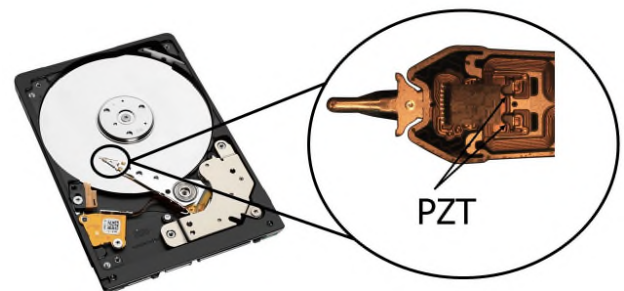


Fig. 1 PZT micro-actuator in HDD.

II. EXPERIMENT PROCEDURE

This research used Lead Zirconate Titanate (PZT) that manufactured by Thales Underwater Systems (Australia) Company. They are disk-shape samples with a diameter of 6 mm and 1 mm of thickness. After the polishing process with 1200 and 1400 grit SiC grinding papers, the samples were coated by gold electrode on both sides. The Sawyer-Tower circuit as shown in Figure 2 was used to measure the ferroelectric hysteresis loops of the samples. When fatigue occurs, changes in the size of the hysteresis loop, the remanent polarization (the polarization when electric field is zero) and the coercive field (the electric field when the polarization is zero) will be observed.

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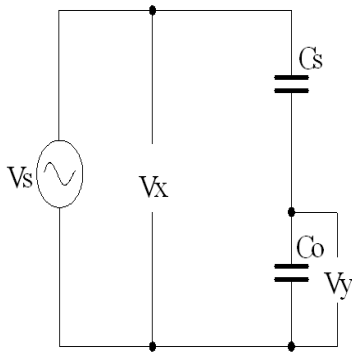


Fig. 2 (a) Sawyer-Tower circuit diagram ($C_0 = 1\mu\text{F}$, $C_s = \text{sample}$; $C_0 \gg C_s$)

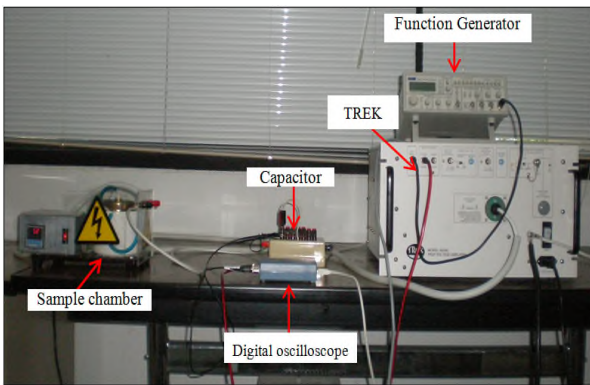
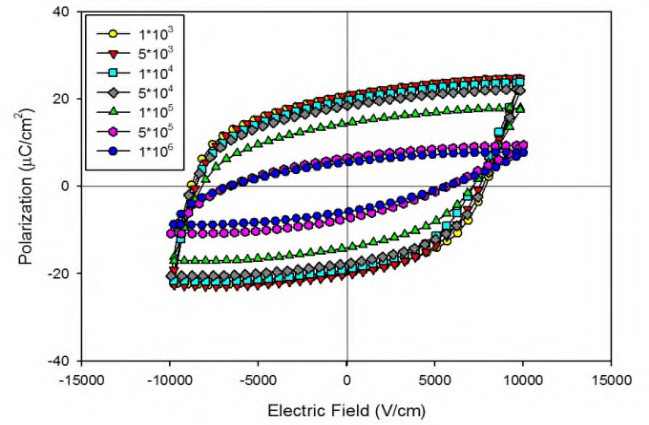


Fig. 2 (b) The set-up of the Sawyer-Tower testing rig

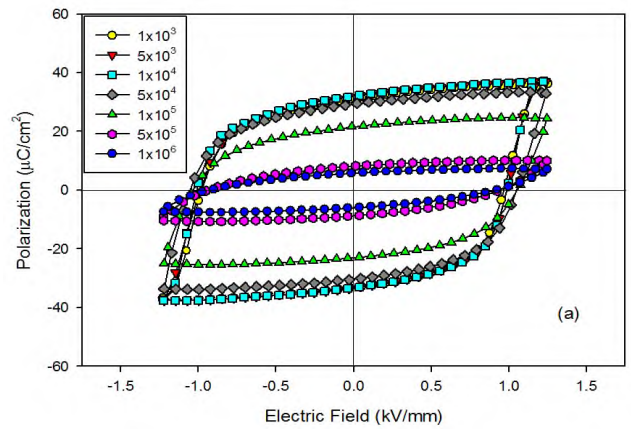
At the testing rig, The PZT samples were subjected to electrical cyclic load at different amplitudes (1.00, 1.25, and 1.50 kV/mm), at room temperature and frequency of 10Hz. The cyclic electric field was applied up to a million of cycles. Measurements of the hysteresis loops were taken at 1×10^3 , 5×10^3 , 1×10^4 , 5×10^4 , 1×10^5 , 5×10^5 and 1×10^6 cycles, respectively. The remanent polarization (P_r) was extracted from the measured hysteresis loops to provide the information on the ferroelectric/piezoelectric properties of the PZT at difference electric field amplitudes and fatigue cycles.

III. RESULTS AND DISCUSSIONS

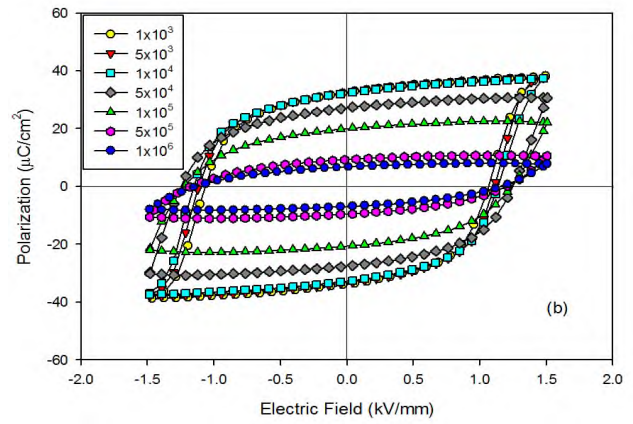
The hysteresis loops measured at different fields and cycles are shown in Figure 3.



(a) 1kV/mm.



(b) 1.25kV/mm.



(c) 1.50kV/mm.

Fig. 3 The hysteresis loops measured at different fields (a) 1kV/mm (b) 1.25kV/mm (c) 1.50kV/mm.

As shown in Figure 3, the fatigue behavior of the PZT samples were significantly influenced by the amplitude of the fields. It was found that at the electric field of 1.5 kV/mm, up to 1×10^4 cycles little change was observed in the measured loops. Obvious changes were observed at 5×10^4 cycles. Significant changes were at 1×10^5 and 5×10^5 cycles. From 5×10^5 to 1×10^6 cycles, the changes in the hysteresis loops were slowed down again.

Figure 4 shows the remanent polarization (P_r) derived from the measured hysteresis loops at different cycles. Little change was observed in P_r up to 1×10^4 cycles. The P_r started to decrease slowly between 1×10^4 and 5×10^4 cycles. The rate of decrease accelerated between 1×10^5 and 5×10^5 cycles, then slowed down again from 5×10^5 cycles. At the 1×10^6 cycles, the P_r at 1.5 kV/mm was decreased 81.76% compared to the value at the 1st measurement of 1×10^3 cycles. Similarly, the P_r at 1 and 1.25 kV/mm were decreased to 69.85% and 78.91% respectively. This indicates that higher applied electric field results in a faster degradation of polarization.

Figure 5 shows the coercive field (E_c) derived from the measured hysteresis loops. It was observed that at the applied electric field of 1.25 and 1.50 kV/mm, the E_c increased slowly up to 1×10^4 cycles. Their increases were accelerated from 1×10^4 cycles up to the peak values at around 1×10^5 cycles, then decreased again up to the last measurement point at 1×10^6 cycles. The increase of the E_c at 1.50 kV/mm was more significant than that at 1.25 kV/mm. At 1 kV/mm, however, little increase was observed up to 5×10^4 cycles, and the E_c decreased from this point up to 1×10^6 cycles.

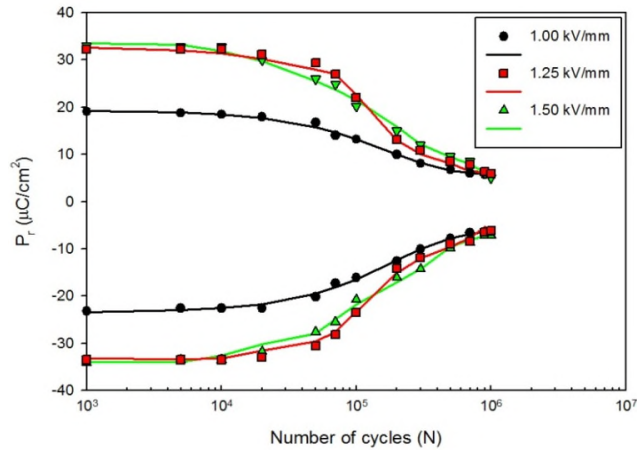


Fig. 4 Remanent polarization derived from the measured hysteresis loops at different electric fields and cycles.

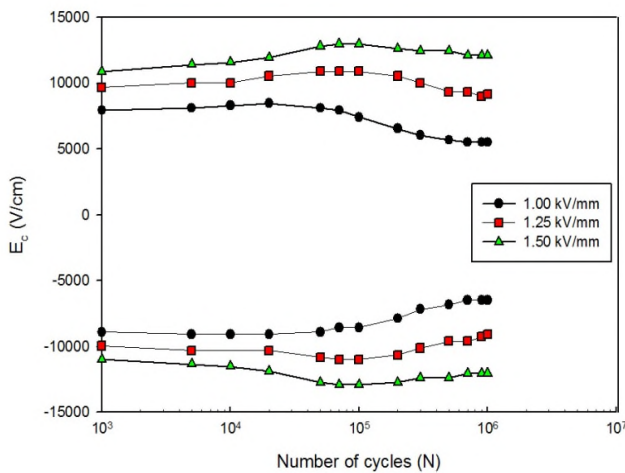


Fig. 5 Coercive field derived from the measured hysteresis loops at different electric fields and cycles.

The observed behavior of P_r and E_c can be explained by the domain pinning mechanism. When the number of cycles increases, some of the domains in the PZT becomes unmovable since they are pinned by charged defects or oxygen vacancy, in a mechanism called domain pinning [7, 21-22]. The mechanism was explained by the reduction of free energy when two or more defects join and share a common domain wall, leading to the stability of domains [23]. The defects can be oxygen vacancies generated during electric cycles which hinder the 180° and 90° domain walls [19, 24]. The defect cluster were observed at domain walls by atomic force microscope (AFM) [24] and piezo-response force microscope (PFM) [25]. If the defects further accumulate and pass a threshold of size, many domains are totally clamped and further affect the orientation of adjacent domains. This leads to the decrease in P_r , which is an indication of the switchability of the domains in the PZT [26-27]. The coercive field, E_c , on the hand, indicates the energy required to completely switch the domains back to their 'neutral' orientation. An increase of E_c indicates the difficulty in switching the remanent domains due to fatigue of the PZT [20, 28].

The effect of amplitude of the applied electric field on fatigue can be explained by the viscosity concept. By assuming that movement of domains and defects occurs in a viscous medium. The displacement of domain walls and defects is dependent on the electric field. At higher electric field, the charged defects have sufficient energy to move to the domain walls due to the stronger field potential. Therefore, the P_r decreases at a faster rate. On the other hand, at lower electric field, the charged defects move slower and some charged defects are not responding to such electric field (e.g., at 1 kV/mm); these defects can only move over a short distance compared to those at higher electric field. Therefore, there are fewer charged defects which are accumulated at the domain boundaries, leading to weaker domain pinning effect. Consequently, the pinned domains at 1 kV/mm sample after fatigue are less than that at 1.25 and 1.50 kV/mm, thus less fatigue degradation.

The fatigue mechanism can be further explained by the domain switching model in Figure 6. The number of reversible-switching and irreversible-switching domains are indicated in the model. Up to 1×10^4 cycles, the defects began to build up at the domain wall but still need time to accumulate, thus only a few domains were pinned, demonstrated by the slow decrease of P_r . As the cycle number increased, the effect of the pinned defects became significant and large number of domains were pinned, demonstrated by the decrease of P_r and increase of E_c . From 5×10^5 cycles, when the majority of domains were pinned, the decrease in P_r was slowed down because less switchable domains remained and few were switched when the electric field was applied in the previous cycle. The reduced number of switched domains also led to the decrease of E_c since fewer domains require less energy to switch.

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REFERENCES

- [1] Wang, H, Yang, X, Wang, Z, He, C, Long, X, Investigation of switching behavior of acceptor-dope ferroelectric ceramics, *Acta Materialia*, 170, 100 – 108 (2019)
- [2] Kamposiri, S, Pojprapai, S, Yimnirunand, R, Marungsri, B, Effect of Electric Field Amplitude on Electrical Fatigue Behavior of Lead Zirconate Titanate Ceramic. *International Science Index, Electrical and Computer Engineering*, 6(12), 1456 – 1460 (2012)
- [3] Zhang, Y, Glaum, J., Ehmke, M. C., Bowman, K. J., Blendell, J. E., Hoffman, M. J., Unipolar Fatigue Behavior of BCTZ Lead-Free Piezoelectric Ceramics, *J. Am. Ceram. Soc.*, 99 (40) 1287–1293 (2016)
- [4] Promsawat, M., Deluca, M, Kamposiri, S, Pojprapai, S, Marungsri, B, Electrical fatigue behavior of lead zirconate titanate ceramic under elevated temperatures, *J. Euro. Ceram. Soc.*, 37(5), 2047 – 2055 (2017)
- [5] Pojprapai, S, Russell, J, Daniels, JE, Hoffman, M., Frequency effects on fatigue crack growth and growth-tip domain switching behavior in a lead zirconate titanate ceramic, *Acta Mater.*, 54 (11), p. 3075 – 3083 (2007)
- [6] Zhukov, S., Glaum, J., Kungl, H., Sapper, E., Dittmer, R., Genenko, Y. A, von Seggern, H., Fatigue effect on polarization switching dynamics in polycrystalline bulk ferroelectrics, *J. Appl. Phys.* 120,064103-1 – 064103-14 (2016)
- [7] Nuffer, J., Lupascu, D.C., Glazounov, A., Kleebe, H-J., Rödel, J., Microstructural modifications of ferroelectric lead zirconate titanate ceramics due to bipolar electric fatigue, *J. Euro. Ceram. Soc.*, 22, 2133 – 2142 (2002)
- [8] Pojprapai, S., Luo, Z., Clausen, B., Vogel, S.C., Brown, D.W., Russel, J., Hoffman, M., Dynamic Process of Domain Switching in Lead Zirconate Titanate under Cyclic Mechanical Loading by in situ Neutron Diffraction, *Acta. Mater.*, 58, 1897 – 1908 (2009)
- [9] Jiang, Q., Cao, W., Cross, L.E., Electric Fatigue in Lead Zirconate Titanate Ceramics, *J. Am. Ceram. Soc.* 77[1], 211 – 215 (1994)
- [10] Luo, Z., Pojprapai, S., Glaum, J., & Hoffman, M., Electrical Fatigue-Induced Cracking in Lead Zirconate Titanate Piezoelectric Ceramic and Its Influence Quantitatively Analyzed by Refatigue Method, *J. Am. Ceram. Soc.* 95(8), 2593-2600. (2012)
- [11] Jiang, Q., Subbarao, E.C., Cross, L.E., Effect of Composition and Temperature on Electric Fatigue of La-doped Lead Zirconate Titanate Ceramics, *J. Appl. Phys.*, 75[11], 7433 – 7443 (1994)
- [12] Wang, D., Fotinich, Y., Carman, G.P., Influence of Temperature on the Electromechanical and Fatigue Behavior of Piezoelectric Ceramics, *J. Appl. Phys.*, 83[10], 5342 – 5350 (1998)
- [13] Pojprapai, S., & Glaum, J. (2012). The effect of temperature on bipolar electrical fatigue behavior of lead zirconate titanate ceramics. *Funct. Mater. Lett.*, 5(03), 1250027.
- [14] Promsawat, M., Marungsri, B., Promsawat, N., Janphuang, P., Luo, Z., & Pojprapai, S. (2017). Effects of temperature on aging degradation of soft and hard lead zirconate titanate ceramics. *Ceramics International*, 43(13), 9709-9714.
- [15] Majumder, S.B., Mohapatra, Y.N., Agrawal, D.C., Fatigue Resistance in Lead Zirconate Titanate Thin Ferroelectric Films: Effect of Cerium Doping and Frequency Dependence, *Appl. Phys. Lett.*, 70[1], 138 – 140 (1997)
- [16] Colla, E.L. Taylor, D.V. Tagantsev, A.K., Setter, N., Discrimination between Bulk and Interface Scenarios for the Suppression of the Switchable Polarization (Fatigue) in Pb(Zr, Ti)O₃ Thin Films Capacitors with Pt Electrodes, *Appl. Phys. Lett.*, 72[19], 2478 -2480 (1998)
- [17] Pojprapai S, Luo Z., Yimnirun R., Frequency effect on electrical fatigue behaviour of lead zirconate titanate, *Electronics Letters*, 2012, 48 (17), p. 1062-1064.
- [18] Mihara, T., Watanabe, H., Paz De Araujo, C.A., Polarization Fatigue Characteristics of Sol-Gel Ferroelectric Pb(Zr_{0.4}Ti_{0.6})O₃ Thin-Film Capacitors, *Jpn. J. Appl. Phys.*, 33, 3996 -4002 (1994)

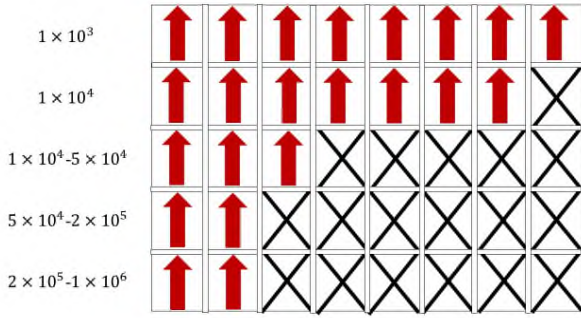


Fig. 6 Model indicates the domains with reversible switching (↑) and irreversible switching (X)

Based on the result in Figure 4, the reduction of the P_r can be expressed in the form of logarithmic equation as:

$$P_N = P_o - A \ln (N+B) \quad (4)$$

where

A, B is constant value

P_o is the initial polarization.

N is the electric field's cycle.

The parameters A and B obtained from curve fitting at the electric field values of 1, 1.25 and 1.50 kV/mm are displayed in Table 1.

TABLE I
REDUCTION OF THE REMANENT POLARIZATION PARAMETER AT THE DIFFERENT ELECTRIC FIELD

Electric Field (kV/mm)	P_o		A		B	
	+ field	- field	+ field	- field	+ field	- field
1.00	59.707	-79.219	3.969	-5.347	23635.36	30863.46
1.25	126.4	-134.648	8.832	-9.408	34260.47	37930.91
1.50	110.08	-110.136	7.571	-7.567	20381.16	18516.50

IV. CONCLUSION

The effect of electric field amplitude on the fatigue behavior of PZT ceramics was investigated. The fatigue behavior was represented by the change of the ferroelectric hysteresis loop, remanent polarization and coercive field as a function of loading cycles. It is found that the fatigue degradation increases as the field amplitude increases. This implies that the PZT micro-actuator operating at higher electric field may result in greater fatigue degradation compared to that at lower electric field amplitude. The fatigue behavior could be attributed to the domain pinning effect and can be quantified using a logarithmic fatigue model. The results from this study can be used as a guideline for the life time testing and estimation for PZT micro-actors in hard disk drives.

- [18] Nuffer, J., Lupascu, D.C., Rödel, J., Damage Evolution in Ferroelectric PZT induced by Bipolar Electric Cycling, *Acta Mater.*, 48, 3783 – 3794 (2000)
- [19] Balke, N., Lupascu, D.C., Granzow, T., Rödel, J., Fatigue of Lead Zirconate Titanate Ceramics. I: Unipolar and DC loading, *J. Am. Ceram. Soc.*, 90[4], 1081 – 1087 (2007)
- [20] Park CH, Chadi DJ., Microscopic study of oxygen - vacancy defect in ferroelectric perovskites, *Physical Review*, 57(22), p. 13961-13964 (1997)
- [21] Zhang, Y., Lupascu, D.C., Aulbach, E., Baturin, I., Bell, A., Rödel, J., Heterogeneity of fatigue in bulk lead zirconate titanate, *Acta mater.*, 53, 2203 – 2213 (2005)
- [22] Brennan, C., Model of Ferroelectric Fatigue Due to Defect/Domain Interactions, *Ferroelectrics*, 150[1], 199 – 208 (1993)
- [23] Lupascu, D.C., and Rabe, U., Cyclic Cluster Growth in Ferroelectric Perovskites, *Phys. Rev. Lett.*, 89[18], 187601, 4pp (2002)
- [24] Shvartsman, V.V., Kholkin, A.L., Verdier, C., Lupascu, D.C., Fatigue-induced Evolution of Domain Structure in Ferroelectric Lead Zirconate Titanate Ceramics investigated by Piezoresponse Force Microscopy, *J. Appl. Phys.*, 98, 094109, 7pp (2005)
- [25] Duiker, H.M., Beale, P.D., Scott, J.F., Paz de Araujo, C.A., Melnick, B.M., Fatigue and switching in ferroelectric memories: Theory and experiment, *J. Appl. Phys.*, 68, 5783- 5791 (1990)
- [26] Mihara, T., Watanabe, H., Paz De Araujo, C.A., Polarization Fatigue Characteristics of Sol-Gel Ferroelectric Pb(Zr_{0.4}Ti_{0.6})O₃ Thin-Film Capacitors, *Jpn. J. Appl. Phys.*, 33, 3996 -4002 (1994)
- [27] Pan, M.-J., Park, S.-E., Park, C.W., Markowski, K.A., Yoshikawa, S., Randall, C.A., Superoxidation and Electrochemical Reactions during Switching in Pb(Zr, Ti)O₃ Ceramics, *J. Am. Ceram. Soc.*, 79[11], 2971 – 2974 (1996)

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