Structural Origin of Dimensional Effect on Dielectric Breakdown Strength of ZnO Varistors

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Zinc oxide (ZnO) varistors are widely used for transient protection in electronic circuits and electrical systems, since they have a super-nonlinear voltage-current characteristic and high withstanding capability against surge overvoltage.^{(1),(2)} Although it is generally considered that grain boundaries play important roles in the varistor characteristics, the details are unknown.⁽³⁾⁻⁽⁵⁾ In the present paper, the effect of the grain shape is discussed based on the experimental results on the thickness dependence of the breakdown strength. Four types of samples were used. Sample H has a relatively high breakdown field and is a commercial product in a disk shape with a diameter of 7.4 mm and a thickness of 1.98 mm. Sample M has a medium breakdown field and is a commercial product in a disk shape with a diameter of 7.4 mm and a thickness of 0.71 mm. Samples L1 and L2 have a relatively low breakdown field and are made for the present experiments and in a disk shape with a diameter of 14.0 mm and a thickness of 1.71 mm.

In order to change the sample thickness, the sample was carefully thinned from both sides by grinding. Silver was sintered on both surfaces and used as electrodes. When the DC current flowing through the sample became 1 mA, the voltage across it was measured and taken as a breakdown voltage. After the sample has been polished, preferentially etched in HF solution, cleaned and finally dried, the sample structure was observed with an optical microscope. Since the grain shape is elliptic, the longer and the shorter diameters of each grain were measured.

Fig. 1 Thickness dependence of the breakdown field for four types of ZnO varistors.

The relation between the breakdown field E_B and the thickness d of various samples is shown in Fig. 1. It can be seen that there exists a transition point for all the samples, which is characterized by the critical thickness d_c and the

transition breakdown field E_c . Before the transition point where d is smaller than d_c , breakdown field E_B increases sharply with an increase in d , while it increases slowly after the transition point. That is to say, if E_B is expressed as

$$E_B \propto \exp(bd),$$

the exponent b before the transition (referred to as b_1) is larger than the one after the transition (referred to as b_2). Table 1 shows the values of b_1 , b_2 , d_c and E_c for the four types of varistors.

Table 1 The exponents b_1 and b_2 , the critical thickness d_c and the transition breakdown field E_c of four types of ZnO varistors.

Sample	b_1	b_2	d_c (mm)	E_c (V/mm)
H	9.4	0.21	0.19	185
M	18.6	0.31	0.28	110
L1	6.0	0.36	0.98	33
L2	2.4	0.43	1.34	18

From Table 1, it is clearly seen that b_2 decreases as E_c increases. While b_1 increases as E_c increases except for sample H, d_c clearly decreases as E_c increases. Such an effect of d on E_B is called dimensional effect. As mentioned above, the sample thickness was changed by grinding in the present experiments. However, one of the authors (G. J.) has reported

Fig. 2 Optical micrographs of four types of ZnO varistors.

the same tendencies for samples with different as-grown thickness⁽⁶⁾. Therefore, it is considered that the dimensional effect is an intrinsic characteristic of ZnO varistors, and that the values b_1 , b_2 , d_c and E_b are the factors representing the dimensional effect.

Optical micrographs of the samples are shown in Fig. 2. Sample H has a well-developed microstructure with nearly hexagonal grains of a similar size, and the number of pores is small. In the case of sample M, most grains are of a slightly elongated hexagonal shape and their sizes are scattered to some extent. Compared with samples H and M, the grains in samples L1 and L2 are elliptic in shape with a highly nonuniform size distribution. It contains a large number of pores.

From the optical micrographs, the longer and the shorter diameters of more than 150 grains were measured for every sample, and their average and standard deviation, and the aspect ratio between the two diameters was calculated. Figure 3 shows the relation between the critical thickness d_c and the dispersive ratio between the standard deviation and the average of the longer diameters. It is clearly shown that d_c depends linearly on the dispersive ratio along the longer diameter. A similar investigation indicates that d_c also depends linearly on the dispersive ratio along the shorter diameter. It is simply concluded that the critical thickness d_c is determined by the dispersive ratio of the ZnO grain size.

Fig. 3 Relation between the critical thickness d_c and the dispersive ratio along the longer diameter of grains.

Fig. 4 Relation between b_2 and the average aspect ratio.

Figure 4 shows the relation between the exponent b_2 and the aspect ratio. It is shown that b_2 increases linearly with an

increase of the average aspect ratio. This indicates that the thickness dependence of the breakdown field E_b is enhanced as the grain shape becomes more elongated.

To conclude, the two statistical parameters, the aspect ratio and the dispersive ratio for the grain shape, are proved to be useful parameters to characterize the dimensional effect and to estimate the dielectric strength of ZnO varistors. Since the dimensional effect is seen not only in the breakdown field, but also in the nonlinear coefficient and the withstanding capability per unit volume, the present finding is very important.

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