Varistor Properties and Aging Behavior of ZnO-V$_2$O$_5$-MnO$_2$-Co$_3$O$_4$-La$_2$O$_3$ Ceramics Modified with Various Additives (Cr, Nb, Dy, Bi)

Choon-Woo Nahm$^\ddagger$, Sun-Kwon Lee, Jae-Seok Heo, and Don-Gyu Lee
Semiconductor Ceramics Laboratory, Department of Electrical Engineering, Dongeui University, Busan 614-714, Korea
Jong-Hyuk Park and Han-Goo Cho
Korea Electrotechnology Research Institute, Changwon 641-120, Korea

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The effects of additives (Cr, Nb, Dy, and Bi) on microstructure, electrical properties, dielectric characteristics, and aging behavior of ZnO-V$_2$O$_5$-MnO$_2$-Co$_3$O$_4$-La$_2$O$_3$ (ZVMCL) ceramics were systematically investigated. The phase formed in common for all ZVMCL ceramics modified with various additives consisted of ZnO grain as a main phase, and Zn$_3$(VO$_4$)$_2$ and ZnV$_2$O$_4$ as the secondary phases. The sintered density and average grain size were in the range of 5.4-5.54 g/cm$^3$ and 3.7-5.1 μm, respectively. The ZVMCL ceramics modified with Cr exhibited the highest breakdown field (6,386 V/cm) and the ZVMCL ceramics modified with Nb exhibited the lowest breakdown field (3,517 V/cm). All additives enhanced the nonlinear coefficient ($\alpha$), by a small or large margin, in particular, additives such as Bi and Nb noticeably increased the nonlinear coefficient, with $\alpha=25.3$ and $\alpha=23$, respectively. However, on the whole, all additives did not improve the stability against a DC stress, compared with ZVMCL ceramics.

Keywords: Additives, Nonlinear properties, Aging behavior, ZnO-V$_2$O$_5$-based varistor ceramics

1. INTRODUCTION

ZnO is a versatile material that possesses a wide range of applications as active component in gas sensors, optical devices, grain boundary effect devices, etc. ZnO varistors are typical semiconducting electro-ceramic devices, which exhibit a nonlinear V-I relation due to the grain boundary effect formed by sintering ZnO powder with minor additives [1]. The sintering process gives rise to a microstructure, which consists of semiconducting n-type ZnO grains surrounded by very thin insulating intergranular layers. Each ZnO grain acts as if it has a semiconductor junction at the grain boundary [2,3]. Since nonlinear electrical behavior occurs like back-to-back zener diode at each boundary, the impurity doped ZnO varistors can be considered as a multi-junction device composed of many series and parallel connection of grain boundaries [2,3]. The grain size distribution plays a major role in electrical behavior. Electrically, ZnO varistors exhibit highly nonlinear voltage-current (V-I) properties expressed by the relation $I = CV^\alpha$, where I is the current, V is the voltage, C is a constant, $\alpha$ is the nonlinear coefficient, which characterizes the nonlinear properties of the varistors [4,5]. ZnO ceramics cannot exhibit a varistor behavior without adding heavy elements with large ionic radii such as Bi, Pr, Ba, etc. Commercial ZnO-Bi$_2$O$_3$-based ceramics and ZnO-Pr$_2$O$_3$-based ceramics cannot be co-fired with a silver inner-electrode (m.p. 961°C) in multilayered chip varistors because of the relatively high sintering temperature above 1,000°C [6,7]. Therefore, new varistor ceramics are required in order to use a silver inner-electrode. Among the various ceramics, one candidate is the ZnO-V$_2$O$_5$ ceramics [8,9]. This system can be sintered at a rela-
tively low temperature in the vicinity of about 900°C. This is very important for multilayer chip varistor applications, because it can be co-sintered with a silver inner-electrode without using expensive palladium or platinum metals [8,9]. A study on ZnO-V$_2$O$_5$-based ceramics is in early stage in terms of ceramic composition and sintering process [10-18]. To develop useful ZnO-V$_2$O$_5$-based ceramics, as usual it is very important to investigate the effects of various additives on varistor properties. In this paper, the effects of additives (Cr, Nb, Dy, and Bi) on varistor properties and aging behavior of ZnO-V$_2$O$_5$-MnO$_2$-Co$_3$O$_4$-La$_2$O$_3$ (ZVMCL) ceramics were systematically examined and new results were attained.

2. EXPERIMENTAL PROCEDURE

2.1 Sample preparation

Reagent-grade raw materials were prepared in the proportion of ZVMCL [96.9 mol% ZnO + 0.5 mol% V$_2$O$_5$ + 2.0 mol% MnO$_2$ + 0.5 mol% Co$_3$O$_4$ + 0.1 mol% La$_2$O$_3$ + 0.1 mol% Nb$_2$O$_5$ + 0.1 mol% Dy$_2$O$_3$ + 0.1 mol% Bi$_2$O$_3$, independent additives added to ZVMCL composition]. The detailed composition of the samples is shown in Table 1. Raw materials were mixed by ball milling with zirconia balls and acetone in a polypropylene bottle for 24 h. The mixture was dried at 120°C for 12 h. The dried mixture was mixed by a magnetic stir bar into a container with acetone and 0.8 wt% polyvinyl butyral (PVB) binder of powder weight. After drying at 120°C for 24 h, the mixture was granulated by sieving through a 100-mesh screen to produce starting powder. The powder was uniaxially pressed into disk-shaped pellets of 10 mm in diameter and 1.3 mm in thickness at a pressure of 100 MPa. The pellets were sintered at 900°C in air for 3 h and further cooled to room temperature. The final pellets were about 8 mm in diameter and 1.0 mm in thickness. Conductive silver paste was coated on both faces of the pellets and the electrodes were formed by heating at 550°C for 10 min. The electrodes were 5 mm in diameter. Finally, after soldering the lead wire to both electrodes, the samples were packaged by dipping them into a thermoplastic resin powder.

2.2 Microstructure examination

Both surfaces of the samples were lapped and ground with SiC paper and polished with 0.3 μm-Al$_2$O$_3$ powder to a mirror-like surface. The polished samples were chemically etched into 1 HClO$_4$:1000 H$_2$O for 25 s at 25°C. The surface of the samples was metallized with a thin coating of Au to reduce charging effects and to improve the resolution of the image. The polished samples were chemically etched into 1 HClO$_4$:1000 H$_2$O for 25 s at 25°C. The surface of the samples was metallized with a thin coating of Au to reduce charging effects and to improve the resolution of the image. The polished samples were chemically etched into 1 HClO$_4$:1000 H$_2$O for 25 s at 25°C. The surface of the samples was metallized with a thin coating of Au to reduce charging effects and to improve the resolution of the image. The polished samples were chemically etched into 1 HClO$_4$:1000 H$_2$O for 25 s at 25°C. The surface of the samples was metallized with a thin coating of Au to reduce charging effects and to improve the resolution of the image. The polished samples were chemically etched into 1 HClO$_4$:1000 H$_2$O for 25 s at 25°C. The surface of the samples was metallized with a thin coating of Au to reduce charging effects and to improve the resolution of the image. The polished samples were chemically etched into 1 HClO$_4$:1000 H$_2$O for 25 s at 25°C. The surface of the samples was metallized with a thin coating of Au to reduce charging effects and to improve the resolution of the image. The polished samples were chemically etched into 1 HClO$_4$:1000 H$_2$O for 25 s at 25°C. The surface of the samples was metallized with a thin coating of Au to reduce charging effects and to improve the resolution of the image. The polished samples were chemically etched into 1 HClO$_4$:1000 H$_2$O for 25 s at 25°C. The surface of the samples was metallized with a thin coating of Au to reduce charging effects and to improve the resolution of the image.

2.3 Electrical measurement

The electric field-current density (E-J) characteristics were performed for stress state of 0.85 E$_{B рем}$/85°C/24 h. Simultaneously, the leakage current was monitored at intervals of 1 min during stressing using a high voltage source unit (Keithley 237). The degradation rate coefficient (K$_t$) was calculated by the expression I$_t$ = I$_0$ + K$_t$ t$^{1/2}$ [20], where I$_t$ is the leakage current at stress time (t) and I$_0$ is I$_t$ at t = 0. After applying the stress, the E-J characteristics were measured at room temperature.

3. RESULTS AND DISCUSSION

Figure 1 shows the SEM micrographs of surface of the samples for different additives. The grain structure is relatively homogeneously distributed throughout the entire samples, compared with ternary ZnO-V$_2$O$_5$-MnO$_2$ ceramics [13]. The average grain size (d) decreased in the order of ZVMCL-Bi (5.1 μm) > ZVMCL-Nb (4.9 μm) > ZVMCL-Dy (4.6 μm) > ZVMCL-Cr (4.3 μm). It was found that the additives such as Bi, Nb, and Dy improved the grain growth, whereas the Cr inhibited it. The additive such as Nb seems to prompt the movement of the grain boundaries because of the increase of interface energy at the grain boundaries. On the contrary, the additive such as Cr seem to hinder the movement of the grain boundaries because of the decrease of interface energy at the grain boundaries. The sintered density ($\rho_3$) was measured at 1.0 mA/cm$^2$ and the leakage current density (I$_L$) was measured at 0.8 E$_{B рем}$. In addition, the nonlinear coefficient (α) is defined by the empirical law, $I = C E^\alpha$, where $I$ is the current density, $E$ is the applied electric field, and C is a constant. The α was calculated by the following expression, α = 1/(logE$_1$-logE$_2$), where E$_1$ and E$_2$ are the electric fields corresponding to 1.0 mA/cm$^2$ and 10 mA/cm$^2$, respectively.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Composition (in mol%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZVMCL</td>
<td>96.9 ZnO + 0.5 V$_2$O$_5$ + 2.0 MnO$_2$ + 0.5 Co$_3$O$_4$ + 0.1 La$_2$O$_3$ + 0.1 Cr$_2$O$_3$ + 0.1 Bi$_2$O$_3$</td>
</tr>
<tr>
<td>ZVMCL-Nb</td>
<td>96.8 ZnO + 0.5 V$_2$O$_5$ + 2.0 MnO$_2$ + 0.5 Co$_3$O$_4$ + 0.1 La$_2$O$_3$ + 0.1 Cr$_2$O$_3$ + 0.1 Bi$_2$O$_3$</td>
</tr>
<tr>
<td>ZVMCL-Dy</td>
<td>96.8 ZnO + 0.5 V$_2$O$_5$ + 2.0 MnO$_2$ + 0.5 Co$_3$O$_4$ + 0.1 La$_2$O$_3$ + 0.1 Dy$_2$O$_3$ + 0.1 Bi$_2$O$_3$</td>
</tr>
<tr>
<td>ZVMCL-Bi</td>
<td>96.8 ZnO + 0.5 V$_2$O$_5$ + 2.0 MnO$_2$ + 0.5 Co$_3$O$_4$ + 0.1 La$_2$O$_3$ + 0.1 Bi$_2$O$_3$ + 0.1 Cr$_2$O$_3$</td>
</tr>
</tbody>
</table>

Figure 3 shows the electric field-current density (E-J) char-
Fig. 1. SEM micrographs of the samples for different additives: (a) ZVMCL, (b) ZVMCL-Cr, (c) ZVMCL-Nb, (d) ZVMCL-Dy, and (e) ZVMCL-Bi.

Table 2. Microstructure, E-J, and dielectric characteristic parameters of the samples for different additives.

<table>
<thead>
<tr>
<th>Samples</th>
<th>d (μm)</th>
<th>ρ (g/cm³)</th>
<th>E_app (V/cm)</th>
<th>υ_gb (V/gb)</th>
<th>α</th>
<th>Jl (μA/cm²)</th>
<th>ε_app' (V/gb)</th>
<th>tanδ (1 kHz)</th>
<th>tanδ (1 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZVMCL</td>
<td>4.1</td>
<td>5.51</td>
<td>4,117</td>
<td>1.9</td>
<td>8.3</td>
<td>436.1</td>
<td>592.1</td>
<td>0.440</td>
<td></td>
</tr>
<tr>
<td>ZVMCL-Cr</td>
<td>3.7</td>
<td>5.34</td>
<td>4,306</td>
<td>2.4</td>
<td>9.0</td>
<td>376.8</td>
<td>373.4</td>
<td>0.281</td>
<td></td>
</tr>
<tr>
<td>ZVMCL-Nb</td>
<td>4.9</td>
<td>5.50</td>
<td>3,517</td>
<td>1.7</td>
<td>23.0</td>
<td>247.5</td>
<td>701.5</td>
<td>0.331</td>
<td></td>
</tr>
<tr>
<td>ZVMCL-Dy</td>
<td>4.6</td>
<td>5.50</td>
<td>5,040</td>
<td>2.3</td>
<td>15.0</td>
<td>364.1</td>
<td>591.2</td>
<td>0.455</td>
<td></td>
</tr>
<tr>
<td>ZVMCL-Bi</td>
<td>5.1</td>
<td>5.40</td>
<td>4,207</td>
<td>2.1</td>
<td>25.5</td>
<td>172.9</td>
<td>464.7</td>
<td>0.246</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. XRD patterns of the samples for different additives: (a) ZVMCL, (b) ZVMCL-Cr, (c) ZVMCL-Nb, (d) ZVMCL-Dy, and (e) ZVMCL-Bi.

Fig. 3. Electric characteristics of samples for different additives.

The varistor properties are characterized by nonlinearity in the E-J characteristics. The conduction characteristics consisted of a linear region before breakdown and a nonlinear region after breakdown. The sharper knee of the curves between the two regions leads to the better nonlinear properties. It can be forecasted that the ZVMCL-Nb and ZVMCL-Bi should exhibit the good nonlinear properties in the light of the sharp knee. Therefore, it is clear that the additives such as Nb and Bi seem to significantly enhance the varistor properties. The breakdown field ($E_{1 mA}$) decreased in the order of ZVMCL-Cr (6,386 V/cm) > ZVMCL-Dy (5,040 V/cm) > ZVMCL-Bi (4,207 V/cm) > ZVMCL (4,117 V/cm) > ZVMCL-Nb (3,517 V/cm). The $E_{1 mA}$ can be explained by both the average ZnO grain size and the breakdown voltage per grain boundaries ($\eta_{gb}$), as expressed by the following expression [4]: $E_{1 mA} = C \cdot \eta_{gb}/d$, where $d$ is the grain size and $\eta_{gb}$ stands for the breakdown voltage per grain boundaries. In general, the decrease of the grain size leads to increasing $E_{1 mA}$. However, the $E_{1 mA}$ decreases in the case of decrease of $\eta_{gb}$ though the $d$ decreases. The all additives enhanced the nonlinear properties, in particular, the additives such as Nb and Bi significantly enhanced the nonlinear coefficient ($\alpha$) beyond 20. The $\alpha$ decreased in the order of ZVMCL-Bi (25.5) > ZVMCL-Nb (23.0) > ZVMCL-Dy (15.0) > ZVMCL-Cr (9.0) > ZVMCL (8.3). It can be seen that each additive has a significant effect on the nonlinear properties. This is attributed to the barrier height caused by the electronic states at active grain boundary. The leakage current ($I_L$) shows an opposite relation to the nonlinear coefficient ($\alpha$). On the whole, the $I_L$ value is much higher than the expected value in the light of $\alpha$ value. Presumably, a high leakage current of these samples seems to be due to the recombination of electron and hole rather than thermionic emission over barrier at the grain boundary.

Figure 4 shows the apparent dielectric constant ($\varepsilon_{app}'$) and dissipation factor (tanδ) of the samples for different additives. With increasing frequency for all samples, the $\varepsilon_{app}'$ decreased with a relatively sharp dispersive drop less than 1 kHz. The $\varepsilon_{app}'$ at 1 kHz decreased in the order of ZVMCL-Nb (701.5) > ZVMCL-Bi (846.7) > ZVMCL (592.1) > ZVMCL-Dy (591.2) > ZVMCL-Cr (373.4) and this tendency was maintained for the frequency above 1 kHz. This is directly related to $d/t$ ratio, as can be seen in the following equation, $\varepsilon_{app}' = \varepsilon_t (d/t)$, where $\varepsilon_t$ is the dielectric constant of ZnO (8.5), $d$ is the average grain size, and $t$ is the depletion layer width of the both sides at the grain boundaries. On the other hand, the tanδ decreased until the vicinity of 20 kHz with increasing frequency, which exhibits very weak second dispersion peak in the vicinity of 300 kHz, and thereafter again decreased. The tanδ at 1 kHz decreased in the order of ZVMCL-Dy (0.455) > ZVMCL (0.440) > ZVMCL-Nb (0.331) > ZVMCL-Cr (0.281) > ZVMCL-Bi (0.246). On the whole, the high tanδ coincides with a high leakage current. The tanδ might be attribute to the joule loss by the leakage current than frictional loss by dipole rotation. The detailed
dielectric characteristic parameters at 1 kHz are summarized in Table 2.

Figure 5 shows the variation of leakage current during DC accelerated aging stress of the samples for different additives. It can be seen that the additives have a significant effect on aging behavior. All the samples except for the ZVMCL and ZVMCL-Nb exhibited the thermal runaway within a short time (approximately 1 min) under specified DC accelerated aging stress of 0.85 $E_{1mA}$/85 °C/24 h. The additives such as Cr, Dy, and Bi deteriorated the stability against an accelerated aging stress. In particular, the additive such as Bi improved nonlinear electrical properties, whereas it resulted in a severe problem in stability. On the contrary, the ZVMCL-Nb was found to exhibit a good stability with no thermal runaway, contrary to expectation. Therefore, it is difficult to jump to a conclusion that the Nb is additives improving the stability against an accelerated aging stress. In particular, ZVMCL-Bi exhibited very large variation of E-J curves in the entire range of electric field after applying the stress. In particular, ZVMCL-Bi exhibited the omhicity. On the contrary, the ZVMCL-Nb and ZVMCL-Dy exhibited a small variation in E-J curves after applying the stress, in particular, in the ZVMCL-Nb case. The detailed variation of E-J characteristic parameters after applying the stress is summarized in Table 3. ZVMCL, ZVMCL-Nb, and ZVMCL-Dy exhibited comparatively low variation within -30% in the %ΔE1mA. Of the samples, ZVMCL-Dy exhibited the smallest variation despite the thermal runaway. It is assumed that this sample may be the result from quick recovery capability against a stress. Moreover, the %Δα of this sample is compared with ZVMCL and ZVMCL-Nb with no the thermal runaway. The ZVMCL and ZVMCL-Nb resulted in a large variation despite no thermal runaway, contrary to expectation. Therefore, it is difficult to jump to a conclusion that the Nb is additives improving the stability against a DC stress for at least ZVMCL ceramics. On the other hand, it can be seen that the ZVMCL-Bi changed almost ohmic properties, as revealed in the %ΔE1mA and %Δα.

Figure 6 shows the behavior of dielectric constant ($\varepsilon_{\text{pp}}$) after applying the stress for the respective samples. The $\varepsilon_{\text{pp}}$ of ZVMCL doped with impurities exhibited a large variation less than 100 kHz. The ZVMCL and ZVMCL-Cr, which revealed a thermal runaway, exhibited a high variation for $\varepsilon_{\text{pp}}$. However, the ZVMCL-

![Fig. 4. Dielectric characteristics of samples for different additives.](image)

![Fig. 5. Leakage current during accelerated aging stress of samples for different additives: (a) ZVMCL, (b) ZVMCL-Cr, (c) ZVMCL-Nb, (d) ZVMCL-Dy, and (e) ZVMCL-Bi.](image)

![Fig. 6. E-J characteristics after applying the stress of samples for different additives: (a) ZVMCL, (b) ZVMCL-Cr, (c) ZVMCL-Nb, (d) ZVMCL-Dy, and (e) ZVMCL-Bi.](image)

<table>
<thead>
<tr>
<th>Samples</th>
<th>Stress state</th>
<th>$E_{1mA}$ (V/cm)</th>
<th>$\alpha$</th>
<th>$I_L$ (mA/cm$^2$)</th>
<th>$\varepsilon_{\text{pp}}$ (1 kHz)</th>
<th>tanδ (1 kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZVMCL</td>
<td>Initial</td>
<td>4,117</td>
<td>8.3</td>
<td>0.44</td>
<td>592.1</td>
<td>0.440</td>
</tr>
<tr>
<td></td>
<td>Stressed</td>
<td>2,998</td>
<td>4.3</td>
<td>0.60</td>
<td>635.0</td>
<td>0.649</td>
</tr>
<tr>
<td>ZVMCL-Cr</td>
<td>Initial</td>
<td>6,386</td>
<td>9.0</td>
<td>0.18</td>
<td>373.4</td>
<td>0.281</td>
</tr>
<tr>
<td></td>
<td>Stressed</td>
<td>3,119</td>
<td>9.0</td>
<td>0.73</td>
<td>757.0</td>
<td>0.996</td>
</tr>
<tr>
<td>ZVMCL-Nb</td>
<td>Initial</td>
<td>3,517</td>
<td>23</td>
<td>0.25</td>
<td>781.5</td>
<td>0.331</td>
</tr>
<tr>
<td></td>
<td>Stressed</td>
<td>2,430</td>
<td>5.3</td>
<td>0.60</td>
<td>946.4</td>
<td>0.599</td>
</tr>
<tr>
<td>ZVMCL-Dy</td>
<td>Initial</td>
<td>5,040</td>
<td>15</td>
<td>0.36</td>
<td>591.2</td>
<td>0.455</td>
</tr>
<tr>
<td></td>
<td>Stressed</td>
<td>3,780</td>
<td>5.5</td>
<td>0.64</td>
<td>817.7</td>
<td>0.760</td>
</tr>
<tr>
<td>ZVMCL-Bi</td>
<td>Initial</td>
<td>4,207</td>
<td>25.5</td>
<td>0.17</td>
<td>648.7</td>
<td>0.246</td>
</tr>
<tr>
<td></td>
<td>Stressed</td>
<td>310</td>
<td>1.2</td>
<td>0.78</td>
<td>1,266.4</td>
<td>4.134</td>
</tr>
</tbody>
</table>
Nb and ZVMCL-Dy exhibited a comparatively low variation. This $\varepsilon_{APP}'$ behavior is very similar to E-J characteristic behavior. It is assumed that the reason why the $\varepsilon_{APP}'$ increases with DC stress is related to the migration of zinc interstitial (Zn) within depletion layer. The Zn is diffused toward grain boundaries under external stress and reacts with the negatively charged Zn vacancy: $V_{zn}^-$ and $V_{zn}'$. Then, this leads to the decrease of the density of interface states and that causes the width of depletion layer to decrease. As a result, the decrease of width of depletion layer with DC stress will increase the $\varepsilon_{APP}'$. The detailed variation of $\varepsilon_{APP}'$ before and after applying the stress is summarized in Table 3.

Figure 8 shows the behavior of dissipation factor ($\tan\delta$) after applying the stress for the respective samples. It can be seen that the tan$\delta$ also exhibited a similar behavior to the $\varepsilon_{APP}'$ after applying the stress. Other samples except for sample ZVMCL after applying the stress exhibited a very large variation more than 50%, in particular for ZVMCL-Cr and ZVMCL-Bi. Also, sample ZVMCL exhibited the high stability for tan$\delta$. The detailed variation of tan$\delta$ before and after applying the stress is summarized in Table 3. On the whole, the various additives in the ZVMCL ceramics deteriorated the stability in the dielectric characteristics, like the E-J characteristics.

In discussing stability, in general, macroscopically, the sintered density and the leakage current have a significant effect on the stability against a stress. That is, the higher the sintered density and the lower the leakage current, the higher the stability. The low sintered density decreases the number of parallel conduction path and eventually leads to the concentration of current. The high leakage current gradually increases the carrier generation due to Joule heat and it leads to repetition cycle between Joule heating and leakage current. In this viewpoint, although the ZVMCL has a high leakage current, the ZVMCL did not exhibit any thermal run-away. On the contrary, although the ZVMCL-Bi has the lowest leakage current, it exhibited the thermal run-away. Therefore, it is difficult to assert that macroscopic factors such as sintered density and leakage current affect the stability. Microscopically, this is related to the rather migration of zinc interstitial (Zn) within depletion layer[21]. In this viewpoint, it is guessed that the reason why the sample ZVMCL-Nb exhibits good stability is because the Nb spatially restricts the migration of ions within the depletion layer.

4. CONCLUSIONS

The electrical, dielectric properties, and aging behavior of ZnO-V$_2$O$_5$-MnO$_2$-Co$_3$O$_4$-La$_2$O$_3$ (ZVMCL) ceramics were comprehensively investigated in accordance with different additives (Cr, Nb, Dy, and Bi). The phases formed for all the samples consisted of Zn$_3$(VO$_4$)$_2$ and ZnV$_2$O$_4$ in common as the secondary phases in addition to ZnO grain as a main phase. The sintered density and average grain size were found to have a fluctuation in a reference for ZVMCL ceramics. All additives enhanced the varistor properties based on the nonlinear coefficient ($\alpha$) and leakage current density. The ZVMCL ceramics modified with Bi and Nb exhibit a relatively high nonlinear coefficient, with $\alpha$=25.5 and 23, respectively. However, on the whole, all additives did not improve the stability against a DC stress, compared with ZVMCL ceramics. Conclusively, it was found that various additives have a significant effect on varistor properties of ZVMCL ceramics. Obviously, Nb and Bi will be significantly applied to as additives for ZnO-V$_2$O$_5$-based ceramics.

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REFERENCE


