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Indium tailors the leakage current and voltage gradient of multiple dopant-based ZnO varistors

Pengfei Meng[a], Shanglin Lyu[b], Jun Hu[a,*], Jinliang He[a]

[a] State Key Laboratory of Control and Simulation of Power System and Generation Equipment, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China
[b] Xi'an Thermal Power Research Institute Co., Ltd., Xi'an, Shaanxi 710054, China

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ABSTRACT

In the present study, the effect of indium doping on the micro-characteristics and electrical properties of ZnO varistors co-doped with Al_2O_3 and Y_2O_3 were determined. Scanning electron microscopy, current-voltage testing in a range from small to large current, capacitance-voltage testing, and X-ray diffraction pattern testing were conducted. The results show that both the residual voltage ratio and the leakage current of sintered ZnO varistors decrease and then increase as the indium dopant increases at a given aluminum and yttrium content. The nonlinear coefficient shows an inverse relationship. In addition, the voltage gradient of the samples increases as the indium dopant increases. The sintered ZnO varistor samples with 0.02 mol% indium, 0.2 mol% aluminum, and 0.9 mol% yttrium show the optimal performance, exhibiting a 1-mA residual voltage of 448 V/mm, a leakage current of 0.69 $\mu A/cm^2$, a nonlinear coefficient of 76, and a residual voltage ratio of 1.58. This study has great significance for improving the protective effects of surge protection devices assembled with ZnO varistors and the stability of power systems.

1. Introduction

ZnO varistors are a kind of polycrystalline ceramic obtained by sintering ZnO powder with other minor oxide additives, such as Bi_2O_3, Sb_2O_3, Co_2O_3, MnO_2, Cr_2O_3, and SiO_2[1,2], and are widely applied in electrical systems as surge protection devices [3]. The insulation and protective level in high-voltage power systems depend heavily on the residual voltage ratio of metal oxide arresters (MOA), the core elements of which comprise ZnO varistors [4]. Thus, decreasing the residual voltage ratio of ZnO varistors is effective for reducing the insulation requirements and the costs of power systems. The voltage gradient is another important parameter for ZnO varistors. In previous studies, reducing the sintering temperature and sintering time improved the voltage gradient, but it also caused poor nonlinearity for ZnO varistors [2]. In addition, the leakage current is an important electrical parameter of ZnO varistors and directly influences the service life of MOAs [5].

Previous studies suggest that the introduction of rear-earth oxides to a Bi-based ZnO varistor can significantly improve the voltage gradient [6,7]. Nevertheless, it also makes the leakage current increase [6]. Furthermore, dopants like aluminum ions have been doped into ZnO varistors to enhance the conductivity of ZnO grains [8,9], which leads to lower residual voltage. However, the leakage currents of Al-doped varistor samples increase greatly, and the voltage gradient, as well as the nonlinear coefficients, decrease to some extent [9]. Therefore, it is necessary to restrain the leakage current while also improving the voltage gradient of ZnO varistors with low residual voltage ratios.

It has been reported that In_2O_3 dopants can improve the voltage gradient and inhibit the leakage currents of ZnO varistors [10]. Nevertheless, there is little research on the properties of multiple dopant-based ZnO varistors using indium. In this work, based on our previous study [11], various concentrations of indium additives were used at given Al and rear-earth element Y dopant concentrations to study the effect of indium doping on the electrical properties of ZnO varistors.

2. Experimental procedure

The ZnO varistor samples were manufactured in the following proportions: (94.35-x) mol% ZnO, 1.0 mol% Bi_2O_3, 0.75 mol% MnO_2, 1.0 mol% Co_2O_3, 0.5 mol% Cr_2O_3, 1 mol% Sb_2O_3, 1.2 mol%SiO_2, 0.2 mol% $Al(NO)_3{\cdot}9H_2O$, 0.9 mol% $Y(NO)_3{\cdot}9H_2O$, and x mol% $In(NO)_3{\cdot}9H_2O$ (x=0.0, 0.01, 0.015, 0.02, and 0.025 mol%). The

* Corresponding author.
E-mail address: hjun@tsinghua.edu.cn (J. Hu).

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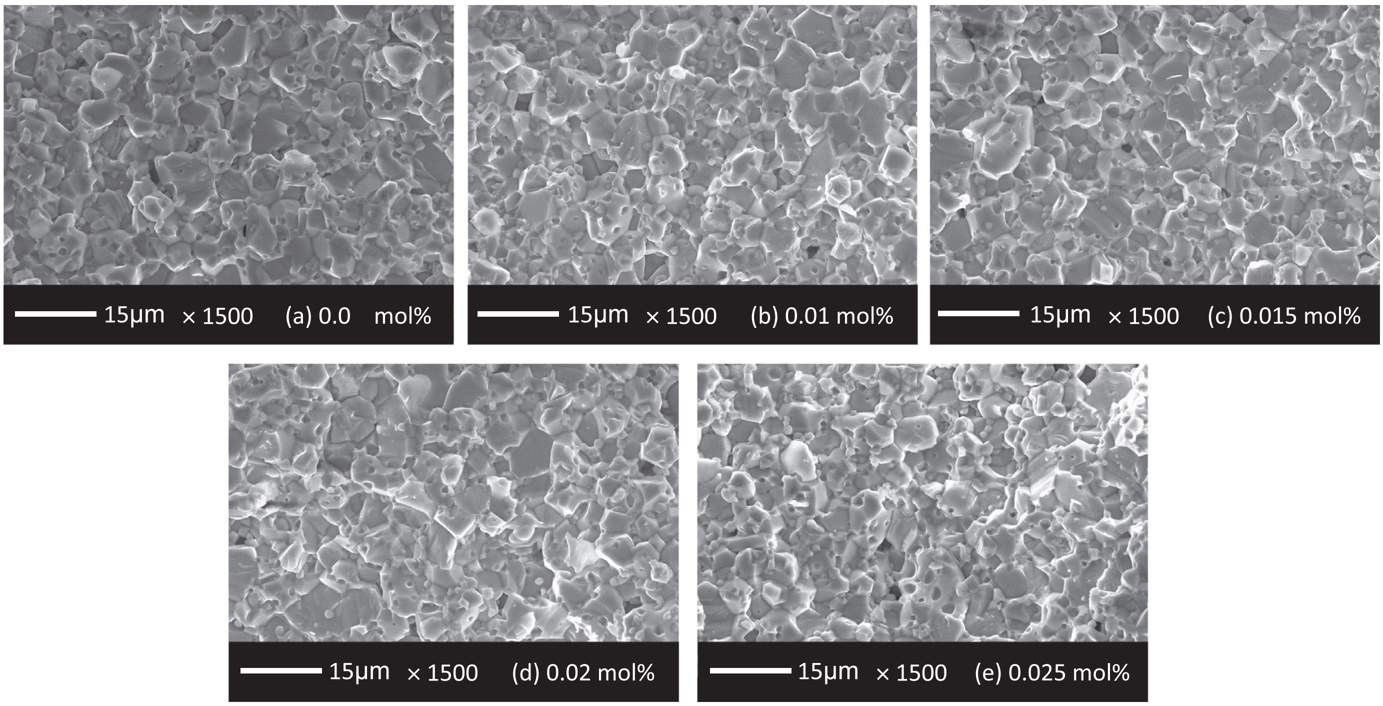

Fig. 1. SEM images of the ZnO varistor samples prepared with various indium content.

Table 1
Microstructure and electrical parameters of varistor samples with various indium content.

In content (mol%)	E_{1mA} (V/mm)	J_L (μA/cm^2)	α	d (μm)	N_d (10^{23}m^{-3})	N_i (10^{16}m^{-2})	ϕ_b (eV)	K
0.0	390.28	2.47	53.79	7.6	2.2	1.9	1.56	1.67
0.01	405.36	1.64	68.33	7.2	2.5	2.1	1.74	1.64
0.015	435.55	1.20	72.12	6.9	2.7	2.3	1.92	1.60
0.02	448.03	0.69	76.26	6.7	3.2	2.7	2.21	1.58
0.025	453.21	0.93	75.31	6.6	3.0	2.5	2.03	1.61

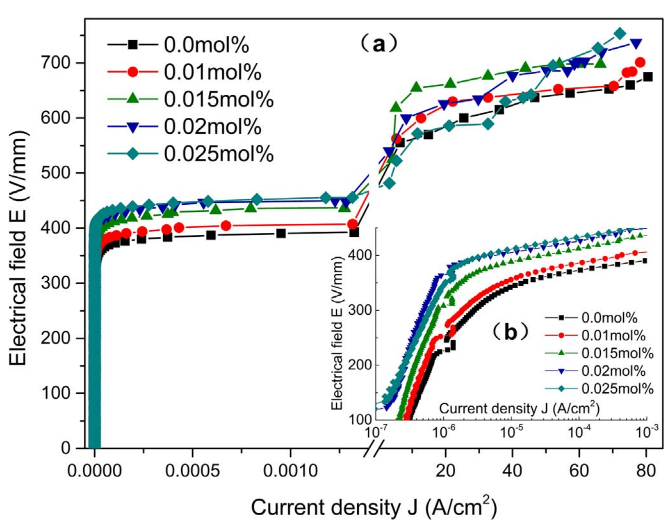

Fig. 2. (a) *E-J* characteristics from prebreakdown region to upturn region and (b) *E-J* characteristics from 0 to 1.0×10^{-3} A/cm^2 of the ZnO varistors samples with various indium content.

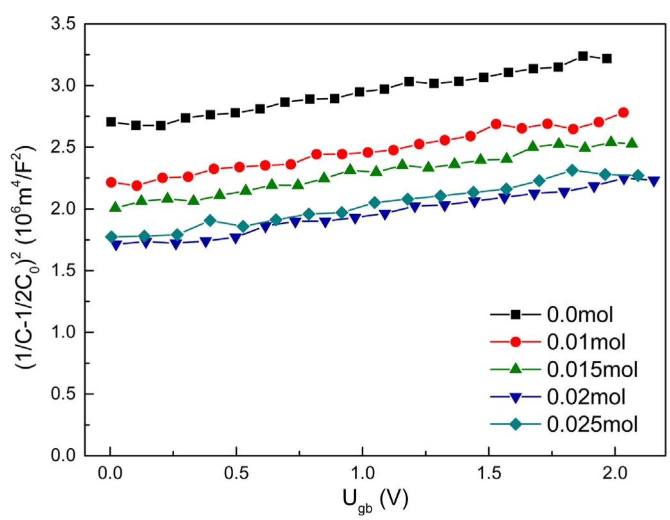

Fig. 3. *C-V* characteristics of the ZnO varistors samples with various indium content.

analytical-grade raw materials were mixed in proper ratios with deionized water in a planetary ball mill for 10 h. Then, the mixture was dried at 90 °C for 12 h. Then, the mixture was pressed at 400 kg/cm^2 into discs 30 mm in diameter and 2.0 mm in thickness. Then, the obtained discs were sintered at 1200 °C for 2 h using a heating rate of 5 °C/min and a cooling rate of 2 °C/min in a furnace (Nabertherm LH60/14, Germany) under an air atmosphere. Finally, the surfaces of the ZnO varistor samples were polished and coated with silver paste to serve as electrodes by heating at 200 °C for 2 h.

The microstructures were examined by a scanning electron microscope (SEM, Hitachi 8010 instrument, Japan). The electric field-current density (*E-J*) of the ZnO varistor samples in the pre-breakdown region was determined using a source meter (Keithley 2410, USA). In the upturn region of *E-J*, an impulse current with a waveform of 8/20