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論　　文

An equivalent circuit for ZnO varistors deduced from electrical characteristics of a single grain

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An equivalent circuit for the ZnO varistor was proposed on the basis of electrical investigation on a microstructure of sample varistors. Only one internal electrode pair into varistors was chosen for experiments. Electrical and dielectric characteristics were measured. The breakdown voltage (V_b) was found to be around 14 V for the sample sintered at 1320°C. We considered every grain between the internal electrodes and deduced an equivalent circuit. The circuit's parameters were determined by PSpice circuit simulator. The resistance of a grain boundary holds the characteristics of a voltage-dependence resistance that impels the non-linearity in a varistor. Again, with the simulated circuit, the electric characteristics and the dielectric characteristics were calculated. The electrical characteristics were very similar to the experimental studies; however a minor variation was found in dielectric characteristics. We have also obtained the V-I relationship with the simulation results for a grain boundary, which shows that non-linearity appears around input voltage 1.5 V in the grain boundary. This calculated V-I relationship is in good agreement with the published results of other researchers.

1. Introduction

ZnO varistors are novel ceramics to protect electrical appliances from electrical surge. Several papers are reported since Matsuoka [1, 2] had clarified the non-ohmic electrical behaviour of ZnO varistors. The popular concept to explain the non-linearity is the formation of a Double Schottky Barrier in the grain boundary [3].

Many researchers had explained ZnO varistors with a simple circuit including two resistors and a capacitor [4-9]. Although the circuit had shown a good reproduction of measured data, it did not reflect the microstructure of ceramic devices. Furthermore it is well known that the microstructure takes on a very important role for ceramic devices caused by a Double Schottky Barrier in the grain boundaries.

Several reports had been published to describe these multijunctions and interestingly various types of junctions were found within the same varistor [10-15]. Therefore a varistor can be considered as a total of small varistors accomplished in grain boundaries. In order to decide the equivalent circuit, it is required that the sufficient parameter must be taken as shown in a paper of Tao et al. [16] having studied on different types of junctions within a varistor. They also made some simulations with several types of grain boundaries in series and parallel connections. But they did not take into consideration of all junctions existing between the electrodes of a varistor. Recently, with a rapid progress of computer processing systems, it is possible to calculate a large scale circuit with many parameters by using a circuit simulation program. The circuit simulations are useful to understand the characteristics of ZnO varistors.

Sun et al. [17] reported three types of Schottky Barrier in the grain boundary region of varistors and they made simulations with 100 grain boundaries and

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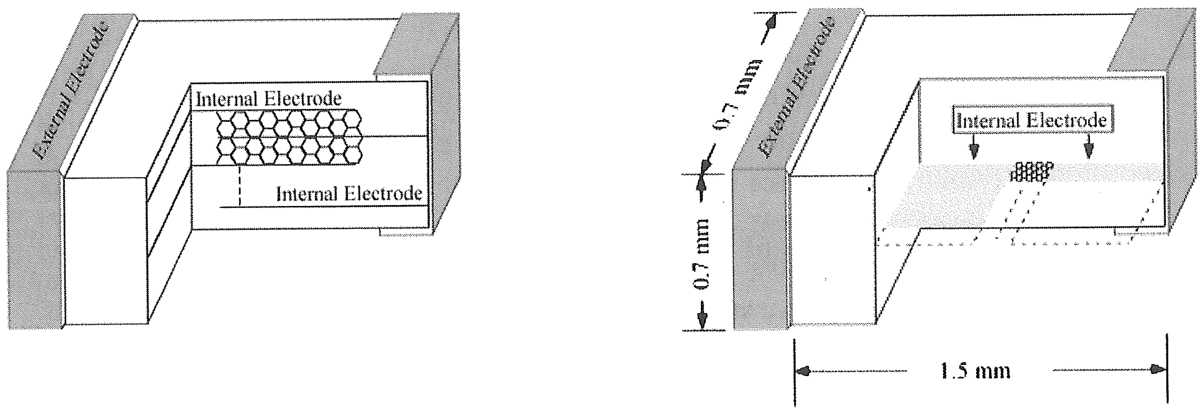


(a) An ordinary varistor

(b) The sample

Fig.1 Schematic diagrams which show the comparison between an ordinary varistor and the sample used in this experiment.

30 grain boundaries respectively with the PSpice program. They used two Schottky diodes in series to represent a grain boundary. Again, Bartkowiak et al. [18-20] used two dimensional voronoi networks to describe microstructure of ZnO varistors and they took 986 cells for computer simulations. Most of these calculations were carried out on the basis of ordinary chip varistors. Some experiments were made for a single ZnO crystal with needle electrodes to measure directly the V-I relationship of a single ZnO grain. But, it is difficult to understand the electrical characteristics of a single grain from too many grains of a chip varistor. Again, direct measurements cause damages to the grains by the process of setting micro electrodes in it. However a varistor with only one internal electrode pair may be more useful to understand electrical behaviour of a single grain as it deals with less and unharmed ZnO grains compared to chip varistors and single grain measurements.

The purpose of this study is to decide the average electrical characteristics of the grain particle, which constitutes varistor by the comparison with the measured value. From the results, we can decide an equivalent circuit model of a varistor.

In the present study, we investigated a special varistor with a paired electrode placed in an identical plane. First, the crystal configuration between electrodes was observed in this sample and the composition of the equivalent circuit model was decided. Next, dielectric characteristics and voltage-current relationship were measured in this sample and characteristics of the elements which constituted the equivalent circuit model were decided.

In addition, the varistor voltage of one grain boundary was determined from the present equivalent circuit, and the value was compared with those reported in the previous works.

2. Schematics and microstructure of the sample

The schematic diagrams of the ordinary and the present special varistor are shown in Fig.1, respectively. Ordinary chip varistors contain about 20-100 internal electrodes whereas the sample prepared for the present study holds only one internal electrode pair made of Pd. The samples used in the present study were prepared by ordinary

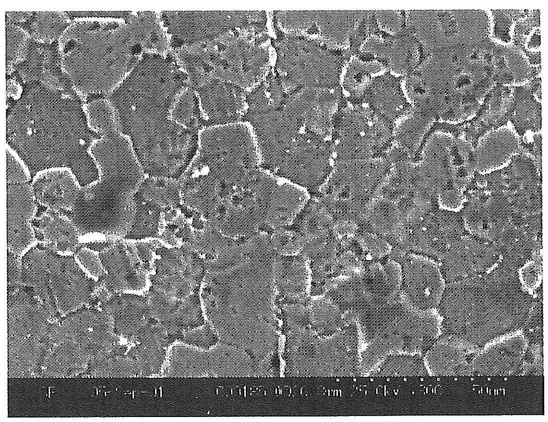


Fig.2 SEM image of the sample.

method sintered at 1320°C in air for 4 hours. These varistors are about 5mg in mass and the size is 1.5 × 0.7 × 0.7 [units are in mm] as shown in Fig.1 (b). The internal electrode of the sample is 710μm in length and 390 μm in width. The distance between the electrodes is 80μm.

The microstructure of the ZnO varistors carries a very important role on the non-linear characteristics of the varistors [14]. The size, shape and the distributions of the grains were measured by SEM (S-3000H SEM, Hitachi Co, Japan.). The samples were sanded from the front side, polished and then observed by SEM after having etched with 1% HCl solution. Figure 2 provides a SEM image of the internal surface of the sample. ZnO crystals are Wurtzite in shape [21], though practically it was very rare in the samples' microstructure. It can be seen that the shape of the grains as well as the grain boundary are not equal in size for all cases. As the size of a grain for this varistor was about 9 ~12μm in average; it can be considered that about 7 grains exist between the internal electrodes. The average thickness of a grain boundary is about 1μm. These figures are very similar to the previous works [2, 22, 23]. However we have assumed the grain size to be equal to make the equivalent circuit model.

3. Electrical characteristics

3.1 V-I relationship

A Ga-In alloy contact electrode was used to measure the electrical characteristics of the sample. Non-linear characteristics were measured by R8340 ULTRA HIGH Resistance Meter (Advantest Co.). Non-linearity for a varistor is empirically expressed by the following equation,

$$I = kV^{\alpha} \qquad \text{...........(1)}$$

Where

I = Electric current flowing through the sample [A],

V = Input voltage [V],

α = Non linearity coefficient and

k = constant number.

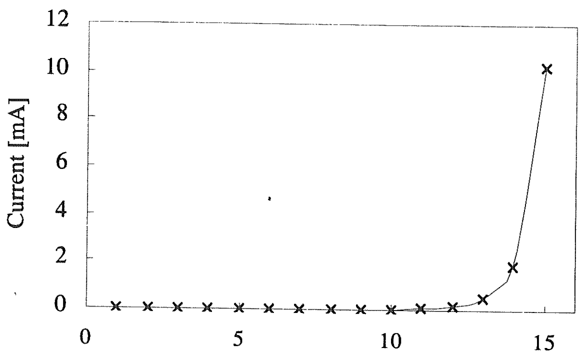
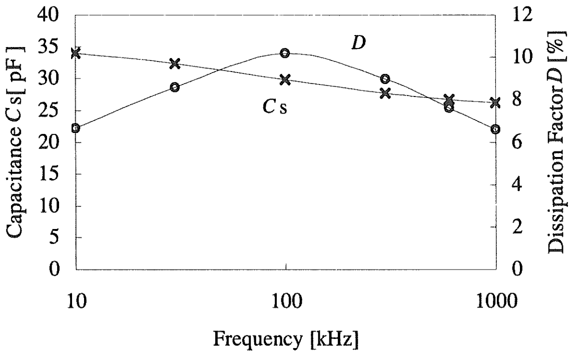


Fig.3 V-I relationship of the sample.

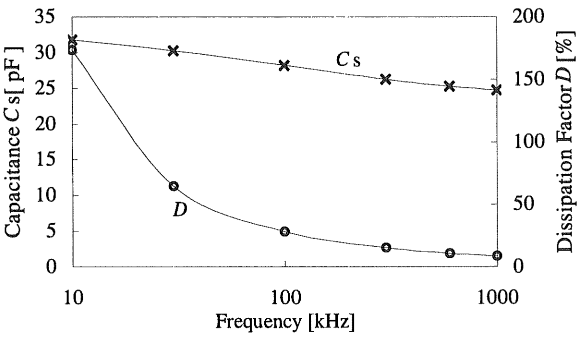
Generally, the applied voltage in which 1mA current flows is known as breakdown voltage (V_b) or varistor voltage. Figure3 shows the results of the measured V-I relationship of the sample. The varistor voltage for the sample is 13.5V and the non-linearity coefficient α is calculated as 23.4. However this value is smaller than that of the commercial varistors as α varies from 20 to 100 for them [24]. It is because this varistor was specially made for the experiment, and there are only a small number of the grain boundaries contributed in the electrical characteristics compared with the commercial one.

3.2 Dielectric characteristics

Varistors like other ceramic matters show dielectric characteristics. To investigate the dielectric characteristics of the sample, we used a 4192A LF Impedance Analyzer (HP Co, Japan.). The dielectric characteristics of a varistor depend on applied DC voltage and the frequency of AC applied voltage. Therefore DC bias was applied to the sample from 0V to varistor voltage controlling over the frequency with the range of 10 -1000 kHz. Figure 4 shows the measured dielectric characteristics of the samples for DC bias 0V and 10V. Total capacitance (Cs) decreases with DC bias and frequency, which can be understood by the behaviour of the junctions [14]. Another important parameter is the dissipation factor (D) for ceramic devices. Unlike capacitance (Cs), dissipation factor (D) increased with DC bias.



(a) for DC bias 0 V and AC voltage=1V



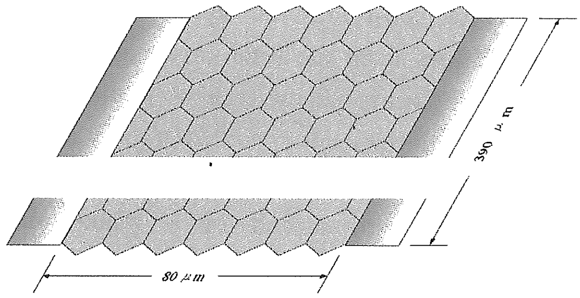
(b) for DC bias 10 V and AC voltage=1V

Fig.4 Measured dielectric characteristics of the sample where frequency are shown in logarithmic value.

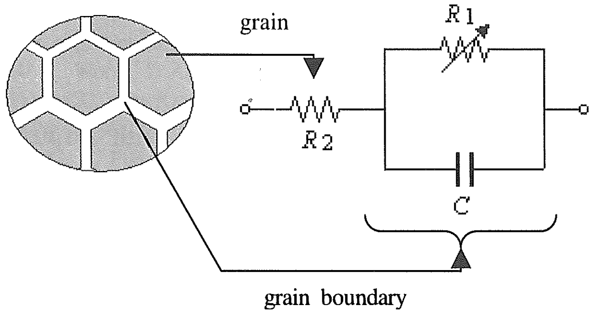
4. Equivalent Circuit

We developed a simple equivalent circuit model on the basis of electrical microstructure of the sample. In spite of the irregularity in microstructure of the sample varistor; we assumed a regular model as shown in Fig. 5(a). It is an idealized model where orthohexagonal ZnO grains are located in a systematic way between the internal electrodes. In order to make an equivalent circuit for the sample varistor, we have taken into account all the grains of the model structure of Fig. 5(a). There are 45 grains along the internal electrode with 7 rows. Thus a total of 315 grains were considered to make the equivalent circuit in this work.

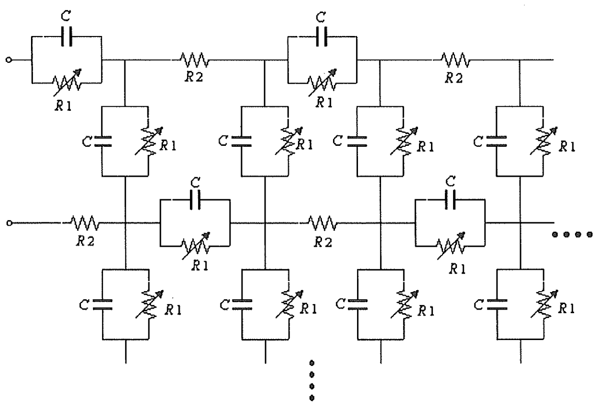
ZnO grains behave electrically as a low valued resistance, whereas a grain boundary is represented by a parallel circuit of a capacitance and a high resistance [4-7]. R_1 represents the resistance of a grain boundary shown in Fig. 5 (b) and it varies with the input voltage. C is the capacitance of a grain boundary and R_2 represents the resistance of a ZnO grain. It is noted that C shown here is a



(a) Modeling of the microstructure of the sample varistor.



(b) Model circuit representing a grain and a grain boundary. C and $R1$ are the resistance and capacitance of a grain boundary, respectively. R 2 is the resistance of a ZnO grain.



(c) Model circuit for the sample varistor used in the simulation program.

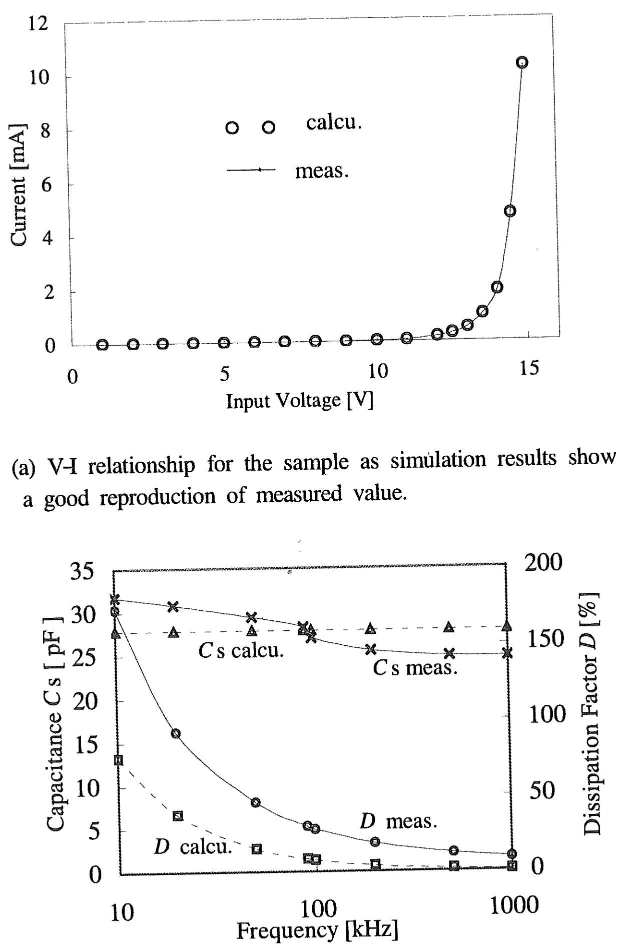
Fig.5 Proposed equivalent circuit for the sample.

capacitor which constitutes the equivalent circuit, and it is different from the total capacitance (Cs) calculated in dielectric characteristics. Figure 5(b) shows the equivalent model circuit for a grain and a grain boundary.

As the grains are placed in a grain-grain boundary-grain model; the equivalent circuit for the sample becomes a repeating of the Fig. 5(b). Figure 5(c) provides a portion of the equivalent circuit used in this experiment. The rest of the circuit is the repetition of it.

5. Results and Discussion

A circuit analysis was performed with PSpice Circuit Simulator. The equivalent circuit parameters were determined by Cuts & Try method to fit the electric characteristics of the sample. Table1 shows the parameters of the circuit. The resistance of a grain boundary varies with the applied voltage. Therefore a grain boundary's resistance can be replaced by a voltage-dependant-resistance with the values of the Table 1. With these parameters, the sample's V-I relationship, Cs and D were calculated by the PSpice circuit simulator for each input voltage. Figure 6 shows a typical result of the analysis. The non-linearity of the sample is confirmed again by the simulation as shown in Fig. 6(a). Figure 6(b) shows the comparison of calculated dielectric characteristics with experimentally measured result. A little difference was found between the measured value and the calculated one. As we assumed the value of C is



(a) V-I relationship for the sample as simulation results show a good reproduction of measured value.

(b) Comparison of simulation results with measured value for dielectric characteristics at DC bias 10 V and AC voltage =1 V of the sample.

Fig.6 Simulation results for the sample varistor using the proposed equivalent circuit model.

constant for all input voltage, the calculated total capacitance Cs becomes unchanged in the Fig. 6(b). Therefore the C-V relationship should be reconsidered. Moreover, it is important to consider the irregularity of shape and size of the grains to propose of an equivalent circuit. However calculated V-I relationship has completely reproduced the measured one. In order to compare the varistor voltage of one grain boundary with that reported in the previous works, we have calculated the current flowing through the grain boundary for each applied voltage per grain boundary. Figure 7 provides the V-I relationship of the grain boundary. This is a semi logarithmic graph, which shows that non-linearity appears around input voltage 1.5 V in

Table1 Circuit parameters for the sample.

Applied Voltage [V]	C [pF]	R_2 [Ω]	R_1 [kΩ]
1	2.6	0.1	1.10E+08
5			5.78E+06
9			3.25E+04
10			8.12E+03
11			2.16E+03
12			7.20E+02
13			2.81E+02

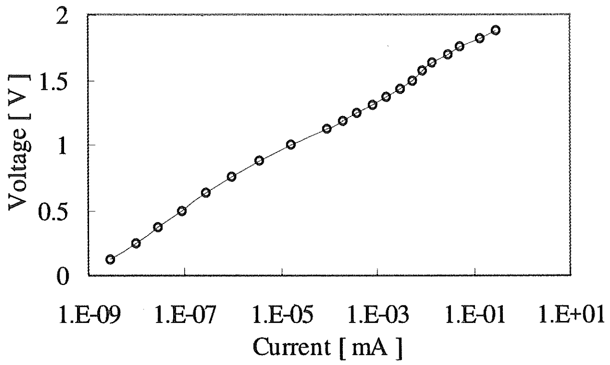


Fig.7 V-I relationship of a grain boundary of the sample varistor calculated from the simulation results.

the grain boundary. These values are very similar to those of the other workers [15, 25, 26]. From all these results, it seemed that the present equivalent circuit model proposed in the present study was confirmed.

6. Conclusion

In order to understand the electrical characteristics of ZnO varistors, an equivalent circuit model was proposed based on the internal structure of the sample varistor. In the present model, the inside of a grain is replaced with a resistance and the grain boundary is replaced with a connection of capacitor and voltage-dependence resistance. Thus, characteristics of a grain can be considered in the present model. The values of the resistance and the capacitor which constitutes the equivalent circuit were determined so that the calculated electrical characteristics may agree with the measured value. The varistor voltage (V_b) of a grain boundary was determined from the present equivalent circuit, and the value is in a good agreement with that reported in the previous works.

In this study, from all these results, it seemed to succeed in making the equivalent circuit of the varistor. In the actual varistor, individual grain size is different. However if the average value can be decided, the effect of the dispersion of the crystal size on the electrical characteristics of a varistor could be simulated accurately. Therefore it is suggested that the present equivalent circuit model is very much useful for the analysis of the noise absorption mechanism.

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