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Fabrication of SMD Type PTC Thermistor with Multilayer Structure

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요 약

본 연구에서는 내부전극 접합기술을 이용하여 적층구조의 PTC 서미스터를 제작하였다. 적층구조 PTC 서미스터는 저저항, 소형, 대전류 등의 특징을 갖는다. PTC 특성을 조사하기 위하여 첨가제효과, 전압-전류특성, 온도특성, 복합임피던스 특성 등을 측정하였다. 적층구조 PTC서미스터는 저항의 온도특성과 전압-전류특성에서 높은 비선형성을 나타내었다. 적층수가 증가함에 따라 상온저항이 감소되는 특성이 결정립의 효과에 기인됨을 알았다. 전류의 스윗칭 변화는 적층구조가 갖는 열용량의 크기에 비례하였으며, 적층수가 증가할수록 스윗칭 시간이 증가하였다.

Abstract

PTC thermistors with multilayer structure were fabricated by internal electrode bonding technique in order to realize low resistance. MLPTC (Multilayer Positive Temperature Coefficient) possess various features, such as small size, low resistivity and large current. We describe the effect of additives on the PTC characteristics, voltage - current characteristics, temperature dependence of resistance and complex impedance spectra as a function of frequency range 100 Hz to 13MHz to determine grain boundary resistance.

It was found that MLPTC thermistor has both highly nonlinear effects of temperature dependent resistance and voltage dependent current behaviors, which act as passive element with self-repair mechanisms. Decrease of room temperature resistance with increasing the number of layers was demonstrated to be a grain boundary effect. Switching characteristics of current were caused by heat capacity of PTC thermistor with multilayer structure. Switching times are lengthened by increasing the number of layers.

Ⅰ. Intoduction

Semiconducting barium titanate ($BaTiO_3$) exhibits positive temperature coefficient(PTC) of resistivity in the temperature range above the curie point. This effect involves a substantial nonlinear change of resistivity with temperature, at which phase transition takes place from tetragonal to cubic phase. It has long been established that the PTCR phenome-non is a grain boundary resistive effect.[1]-[3] The room-temperature resistivity of PTC ceramics is much higher than that of the single crystal. Further decrease of resistivity must be enhanced to contribute the application of electronic element. It is very difficult to achieved the low resistivity at room temperature by substituting additives such as Ca, Pb and Mn in $BaTiO_3$ ceramics. On the other hand, in the application of electronic elements, one important effect is the resistance rather than the resistivity of the PTC element. Multilayer structure will be realize the low resistance compared with that of disk type

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PTC ceramics since the multilayer structure shortens the distance between two electrode and widens the electrodes area. however, it is difficult to fabricate a multilayer structure for the PTC ceramics by conventional cofiring multilayer process because of internal electrode for the good ohmic contact. J. Arakawa et al[4] fabricated ceramic actuator where the internal electrodes of the actuators had a role in bonding laminated ceramic plates..

In this study, we fabricated multilayer PTC ceramics by an internal electrode bonding method, that was demonstrated the advantage of low resistance in multilayer PTC ceramics. The present investigation is conducted that nonlinear characteristics on resistance dependent temperature on the multilayer PTC thermistor, and how the multilayer structure affects the electrical property such as a resistance change, electric field dependence and current transient response.

2. Experimental Procedure

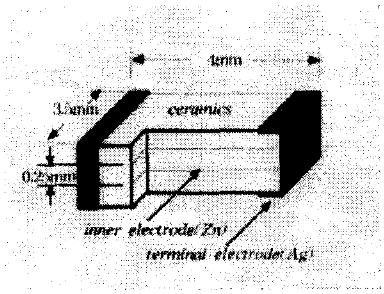

FIg. 1 Schematic configuration of multilayer PTC thermistor

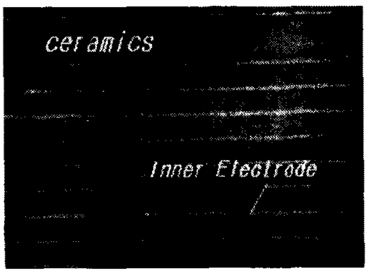

Fig. 2 Cross section of multilayer PTC thermistor

The composition of PTC ceramics powder used in this study is

$(0.8Ba+0.15Sr+0.05Ca)TiO_3$ + $0.01TiO_2$ + $0.01SiO_2$ + $0.001MnO_2$ + $0.0015Nb_2O_5$ (mol%)

All of mixture were ball milled in deionized water for 12 hours with zirconia balls. After being dried, powder was calcined at 1050 ℃ for 2 hours. The powder was ground again by ball milling for 2 hours and granulated by a 100 mesh sieve. The granulated powder was mixed with binder and solvent by ball milling for 20 hours, and tape cast into 300 μm thick green sheet by a doctor blade method. Tape casting speed was 0.75 cm/sec. The green sheet was cut into plates 10 mm×12 mm square. The binder was burned out at 350℃ for 12 hours. The green sheets were sintered at 1350℃ for 2 hours in air. After sintering, the zinc paste for the internal electrode was printed onto the surface of the plates and the silver paste was printed for external electrode. The plate was fabricated with the multilayer structure. The plates were fired at 580 ℃ for 10 minutes to bond themselves together with the formation of internal electrode.

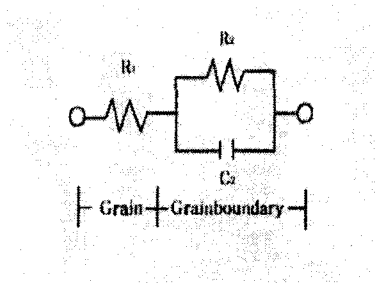

Fig. 3 Equivalent circuit of PTC thermistor

Figure 1 shows the schematic configuration of multilayer PTC thermistor used in this study. The internal electrodes are 4.5×5mm square. Termination electrode was printed on to the both surface with the silver paste. Figure 2 shows the cross section of the multilayer PTC thermistor showing layer structure.

Temperature dependence of resistivity was measured at temperature range from 25 ℃ to 280 ℃ with a rate of 4 ℃/min. Current-voltage characteristics were measured by using D.C voltage supply in a current range up to 30 mA. Complex impedance was observed with a impedance analyzer at frequency range from 5 Hz to 13 MHz.

3. Results and Discussion

3-1 Complex Impedance Analysis

Complex impedance analysis is usually used to determine the grain and grain boundary resistance of $BaTiO_3$ based ceramics. The resistance of grain can be decided from the highest frequency real axis intercept of the Cole-Cole plot and the grain boundary resistance from the low frequency intercept. PTC thermistor on ac voltage is not a purely ohmic resistor. It also acts as a capacitive resistor because of the grain boundary junctions. As shown in Figure 3, the equivalent circuit of the PTC ceramics can be expressed as a grain resistance in series a parallel RC network[5]

Figure 4 shows complex impedance plots according to the number of layer. Grain resistance (R_1) was unchanged by the number of layer, remaining constant ~3Ω. But the grain boundary resistance (R_2) was decreased with increasing the

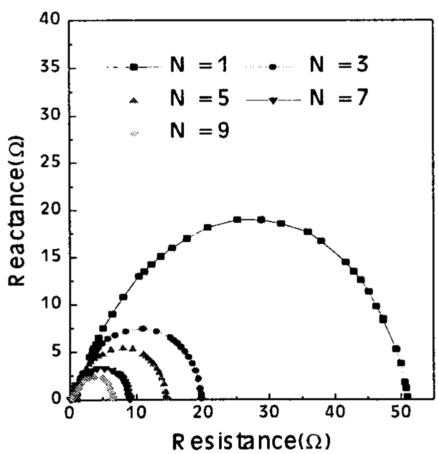

Fig. 4 Complex impedance plots with different number of layers

the number of layers. It was found that multilayer structure play an role decrease the grain boundary resistance and PTC effect differed widely according to grain boundary resistance.

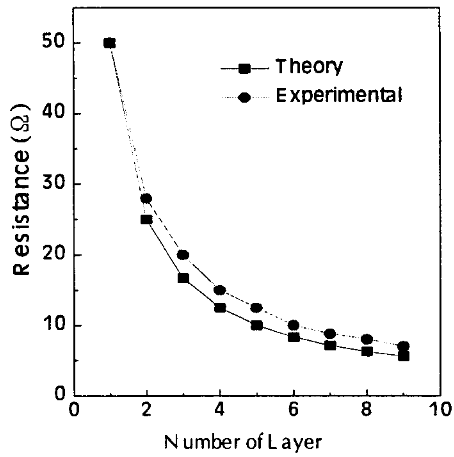

Fig. 5 Effect of layers on theoretical and experiment values of room temperature resistance

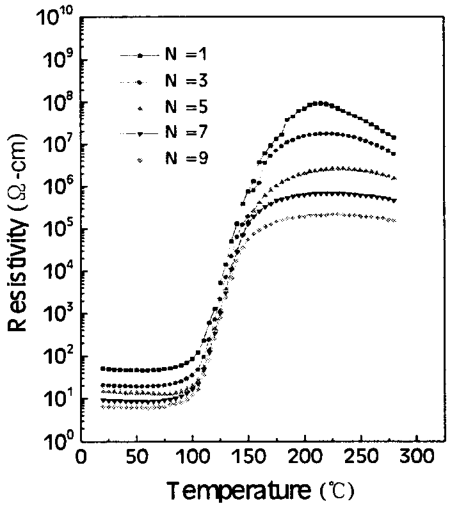

Fig. 6 Temperature dependence of the electrical resistivity

From the ohm's law, the total resistance of multilayer PTC thermistor (Rt) is

$$Rt = (1/N) \times Rs \quad (1)$$

where Rs is resistance of single layer, and N is number of layers.

On the multilayer PTC thermistor, the thickness is the same as that of a single layer, but area is N times larger.

Figure5 shows a comparison of theoretical and experimental results of the room temperature resistance. The experimental values are slightly higher than the corresponding theoretical ones with the same number of layers. It was suggested due to the thickness of electrode, the two ends not covered by electrode, and some other causes leading to disagreement between two opposite electrode.

3-2 Temperature dependance of Resistivity

Figure 6 shows the electrical resistivity as a function of temperature in the PTC thermistor with the multilayer structures. The room temperature resistivity and peak resistivity were greatly decreased according to number of layers increased. The plots are flatter until the transition temperature, but they increase abruptly at about 110℃. With the increase of layers, transition point was shifted to the higher temperature region and temperature coefficients in the transition point were not changed. This results are shown that multilayer structure propose much lower room temperature resistivity and higher transition temperature.

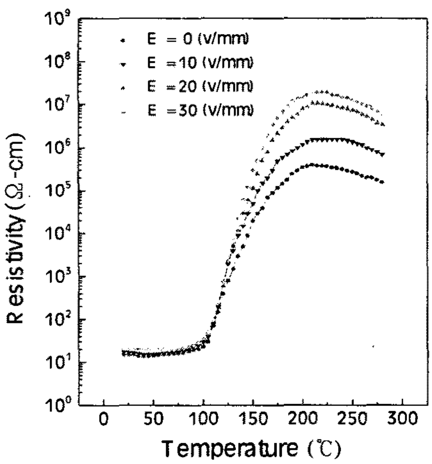

Fig. 7 Effect of electric field on temperature dependence of resistivity

3-3 Electric field dependance of Resistivity

The resistance of the PTC thermistor is composed of the grain resistance and grain boundary transition resistance. Particularly in the high temperature state, the potential barriers are determining high resistance. When higher voltage applied to the PTC thermistor, the high field strengths dominating produce a break up of the potential barriers at the grain boundaries and thus a lower resistance. The most of the applied voltage is absorbed by the grain resistance. Thus the field strength at the grain boundaries decreases.

Figure 7 shows electric field dependance of resistivity of multilayer PTC thermistor with three layers as an example. Resistivity at room temperature hardly changed with applied electric field. In the high resistivity region, the resistivity largely decreased with increasing electric field. This results can be explained by the Heywang theory,[6] which discussed the electric field dependance of the potential barrier in the grain boundary. Grain boundary plays an important role the PTC behavior

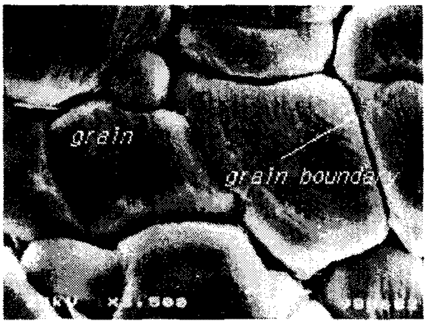

Fig. 8 Microstructure of PTC thermistor

It is considered hat applied electric field concentrates in the grain boundary in a high resistance region. In the under the curie point, electric field which concentrated in the grain boundary does not influenced the temperature dependance. In order to clearly finding grain boundary effect, The microstructure of PTC thermistor showing grain and grain boundary shown in Figure 8. Grain size was around 20μm and grain boundary layers were formed clearly. Potential barriers are formed at the grain boundary. They prevent free electrons from diffusing into adjacent areas. Thus a high resistance results. Above the curie temperature, dielectric constant and polarization decline so far that there is a strong growth of the potential barriers and hence of resistance. Beyond the range of the PTC, free carriers is increased by thermal activation. The resistance then decreases and exhibits a negative temperature characteristic (NTC) typical of semiconductors. As a results, grain boundaries are responsible for the PTC thermistor effect.

3-4 Current - Voltage Characteristics

The electrical properties in self heated mode are better described by the I/V characteristic than by the R/T curve. It illustrates the relationship between voltage and current in a thermally steady state in still air at 25℃, unless another temperature is specified.

Figure 9 shows current-voltage characteristics of multilayer PTC thermistors according to the number of layers. It was shown a nonlinear relationship between current and voltage. After Initial current flows, in the above the trip current (maximum current), current density abruptly decreased with

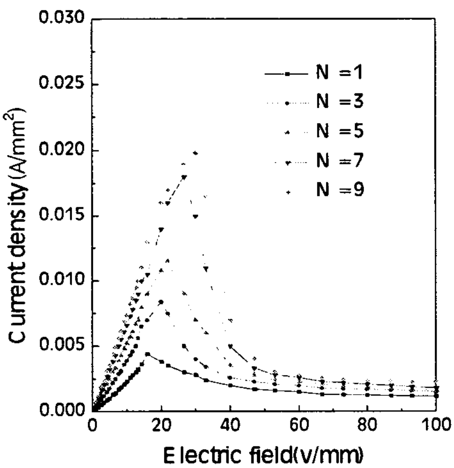

Fig. 9 Electric field dependence of current density with different number of layers

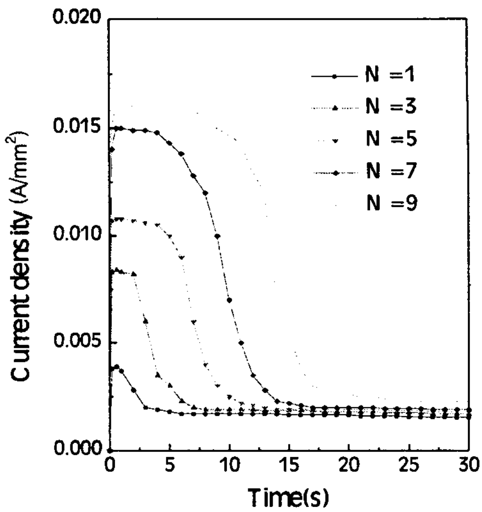

Fig. 10 Time dependence of current density with different number of layers

increasing applied voltages. With the increase of number of layers, maximum current increased because of resistivity decreases showing in Figure 6. This is cause to the lower resistivity with the increase of number of layers. The maximum current (so call breakdown voltage) is principal point which use to analysis the load behavior and to design the rated voltage. When current flows in the thermistor, heat generated and the temperature increases. However above curie temperature, resistance suddenly increases, which causes the current to decrease and the temperature to cease rising. Finally thermistor reaches an equilibrium state.

3-5 Current Decay Characteristics

Figure 10 shows current-time characteristics according to the number of layers while a constant electric field E = 20 mv/mm is applied. The current decreasing with increasing time. Increasing the number of layers changes the curves to result in a long time to achieve the steady state. The results were probably caused by a difference in heat quantity released out of samples, and this difference is base on the surface areas of samples. While electric field is applied, initially the resistance is low, so that the large current, termed "inrush current", will flow. Simultaneously, however the thermistor generates heat, so the temperature rises rapidly, and then, the current decreases as shown in Figure 9. This current decreasing characteristic depends on the heat capacity of the PTC thermistor,[7] the efficiency the heat radiation, and the appled voltage. If the heat capacity or heat radiation is large, it takes a lot of time to reach the equilibrium state, which means that time required for decreasing current is long. While a constant electric field is applied to the PTC ceramics, stored energy Q, can be written as

$$Q = H\ (T - Ta) \qquad (2)$$

where T is the temperature of PTC ceramics, Ta is the temperature of air surrounding the PTC ceramics and H is heat capacity of the sample, being equal to the product of volume and specific heat.

From the Equation 2, the dynamic heating behavior of the PTC thermistor is determined by the heat capacity of the constitute material and volume of the sample. The specific heat of BaTiO3, main material of this experiment, depends little on temperature in the range from room temperature to 300 ℃. Therefore, stored energy is proportional to the volume of the PTC ceramics. Conversely, a large applied voltage makes it short such as that shown in Figure 11. Switching times were greatly decreased according to electric field increased. If current higher than specified current is applied to the PTC thermistor, heat is generated inside the PTC thermistor, increasing the resistance and decreasing current with time. Since the heat capacity is proportional to the number of layers, increase the number of layers leads to the increase of time to achieve steady state. Although fast switching rates to the reduction of current can not be realized with multilayer structures such as that shown in Figure 1, they can consequently be achieve the larger current application.

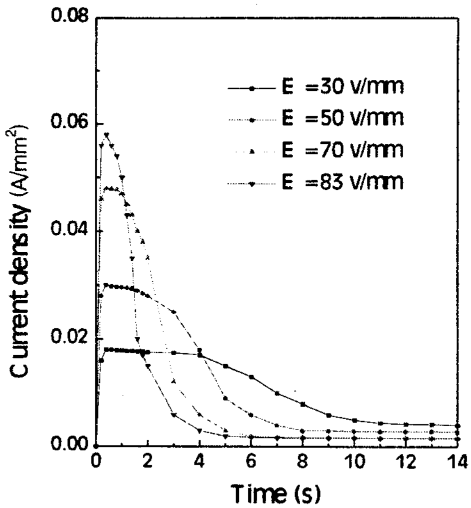

Fig.11 Time dependence of current density under different applied electric field

The switching function of the PTC thermistor consist in limiting current flowing through the load at high operating voltage after thermistor has heated up. The switching time ts can be approximated as follows[8] :

$$ts = \frac{K \cdot V\ (TRef - T_A)}{P} \qquad (3)$$

where TRef is Reference temperature of PTC thermistor, T_A is ambient temperature, K is material specific constant, V is PTC thermistor volume and P is switch-on power of PTC thermistor.

This shows' that switching time can be influences by the size of the PTC thermistor. Switching times are lengthened by increasing the number of layers, reference temperature and specific constant. Therefore, PTC thermistors with multilayer structure are able to control the switching time in a wide range.

4. Conclusion

SMD type multilayer PTC thermistors were fabricated and examined, and the following results were obtained.

1) Electrode bonding technology is a good method to manufacture low resistance and large current PTC thermistors.
2) Multilayer PTC thermistors possess non linear effect of temperature dependent resistance and voltage dependent current behavior.
3) Room temperature resistances of the multilayer structure are slightly higher than the corresponding theoretical ones.
4) Decrease of room temperature resistance with increasing the number of layers was demonstrated to be a grain boundary effect.
5) Switching characteristics of current were caused by heat capacity of PTC thermistor with multilayer structure. Switching times are lengthened by increasing the number of layers.

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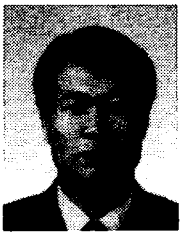

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