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Non-linear behavior of multilayer ceramic capacitors with a new equivalent circuit under AC-fields

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The electrical properties were investigated to understand better the non-linear behavior of multilayer ceramic capacitors (MLCCs). The electrical properties of the capacitors with a new equivalent circuit were simulated by a Sawyer-Tower circuit system under a high AC-field using B^2 spice software, the simulated results were then compared with the experimental results. The experimental Q-V curves showed the non-linearity of ferroelectricity in the applied AC-fields. The predicted Q-V curves using B^2 spice software under various AC-fields also showed the non-linearity of ferroelectricity in high AC-fields. As a result, the nonlinear dielectricity of the MLCCs was successfully simulated by the new circuit model.

Key words: Multilayer ceramic capacitor, Non-linearity, Sawyer-Tower circuit, B^2 spice software.

Introduction

High performance portable electronic appliances such as potable computers, mobile phones, personal digital assistants (PDA) are being continuously scaled down to smaller and smaller sizes. As a result, the demand for minimizing technology of passive components containing resistors, inductors, and capacitors with low power consumption and high performance has significantly increased. The advantages of miniaturization and low power consumption of passive ceramic components are now understood in industry.

As the leading passive ceramic components for computers and telecommunications, multilayer ceramic capacitor (MLCC)s are widely used for DC-blocking, RF choking, by-passing, coupling, and the degeneration of signals in electronic devices. The electronic performance of MLCCs should be maintained, even though the size is much smaller. The high performance of the MLCCs can be attained through understanding of electrical applications and functions in electronic devices. Even though several references have been suggested, the electrical properties of MLCCs under high AC-fields [1-3], the non-linearity of these capacitors is not well understood.

In this study, we investigated the electrical properties of 4.7 μF and 1 μF MLCCs with X7R temperature property to understand better the non-linearity behavior. For each electrical charge, the electrical properties of the capacitors with a new equivalent circuit were simulated by the Sawyer-Tower circuit system under a high AC-field using B^2 spice software, the simulated results were then compared with the experimental results.

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Experimental Procedure

Measurement of Q-V curves under various ac-fields

Figure 1 shows a schematic diagram of the tool used for the measurement of Q-V curves as a function of various AC-fields. A response analyzer (NF Corp., NF-5050) was utilized to detect the sinusoidal signal generated from a signal generator. The current displacement was measured with a current probe (Yokohama Electric Corp., 700937). The frequency response analyzer detected the voltage signal converted from the current displacement. The current was integrated to calculate the electric charge (Q) and capacitance (C).

Simulations of Q-V curves for MLCCs

The electric charge of MLCCs was measured using a frequency response-analyzer. Except for the current displacement of negative voltage parts, the current displacement of positive voltage parts was reversed in order to maintain the balance of the current displacement. The current displacement measured as a function of AC-fields is [1]:

$$Q=CV, \quad (1)$$

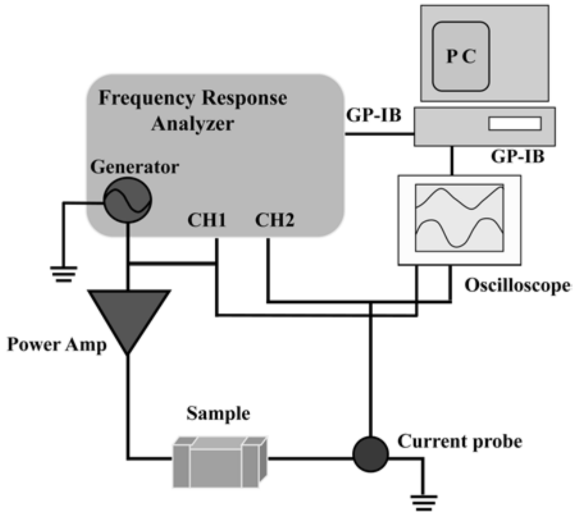

Fig. 1. Schematic diagram of the tool used for the measurement of Q-V curves.

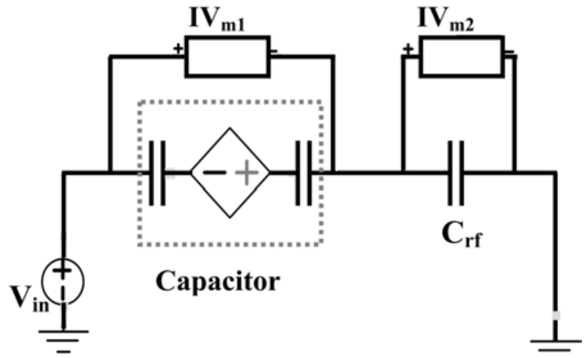

Fig. 2. Schematic diagram of the Sawyer-Tower circuit with a new equivalent circuit for MLCCs.

where Q is the electric charge, and C and V are the capacitance and the applied voltage, respectively. Eq. (1) can only show a linearity of Q-V curves. The non-linearity of Q-V curves is represented using poly-nominal functions such as:

$$Q=\alpha_1 V+\alpha_2 V^2+\alpha_3 V^3+\alpha_4 V^4, \quad (2)$$

where α_1, α_2, α_3, are α_4 are the capacitance of each order, respectively.

Figure 2 shows the Sawyer-Tower circuit in which the non-linear dependent voltage source part was derived for a capacitor by converting Eq. (2) to Eq. (3) [2]. The equation for the controlled voltage source for capacitors in the Sawyer-Tower circuit is:

$$V=\beta(V_1-V_2)-(V_1-V_2), \quad (3)$$

where V_1 is the input voltage and V_2 is the output voltage in the MLCCs.

β is defined as:

$$\beta=Ce/Cm, \quad (4)$$

where Ce and Cm are the capacitance of each order for the MLCCs, respectively. The B^2 spice software (Beige Bag Software, A/D 2000) was used to simulate Q-V curves as a function of the AC-field.

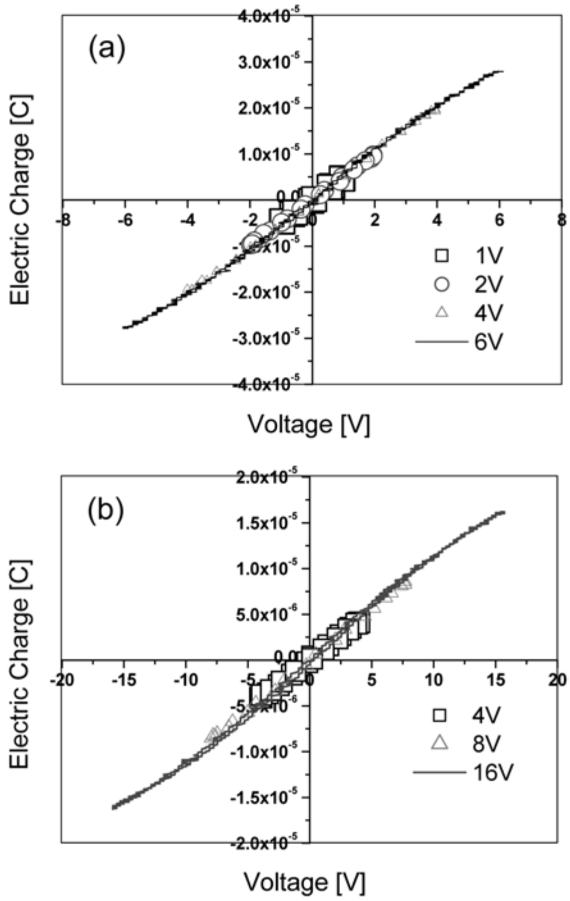

Fig. 3. Q-V curves under different AC-fields: (a) 4.7 μF and (b) 1.0 μF MLCCs.

Results and Discussion

Measurement of electric charge (Q)

Figure 3 shows the Q-V curves of the MLCCs with capacitances of 4.7 μF and 1 μF. The electric charge (Q) was measured as a function of the applied voltage for various AC-fields at room temperature. The slope of the Q-V curves is in agreement with the capacitance of the MLCC chips. Figure 3 shows that the capacitance of the MLCC chips increased with increases in the AC-field. It seems that the gradual rise in domain switching gives rise to the non-linearity of the capacitors [3]. It has been reported that domain switching is affected by the grain size of $BaTiO_3$ [4-6]. Therefore, the increase in capacitance is attributed to an improvement in the ferroelectricity of $BaTiO_3$ which counteracts the size suppression effect that occurs with increasing AC-fields, which in turn could explain the non-linear dependence of the electric charge (Q) to the applied voltage (V) in the MLCCs.

Fitting and simulation of Q-V curves for various ac-fields

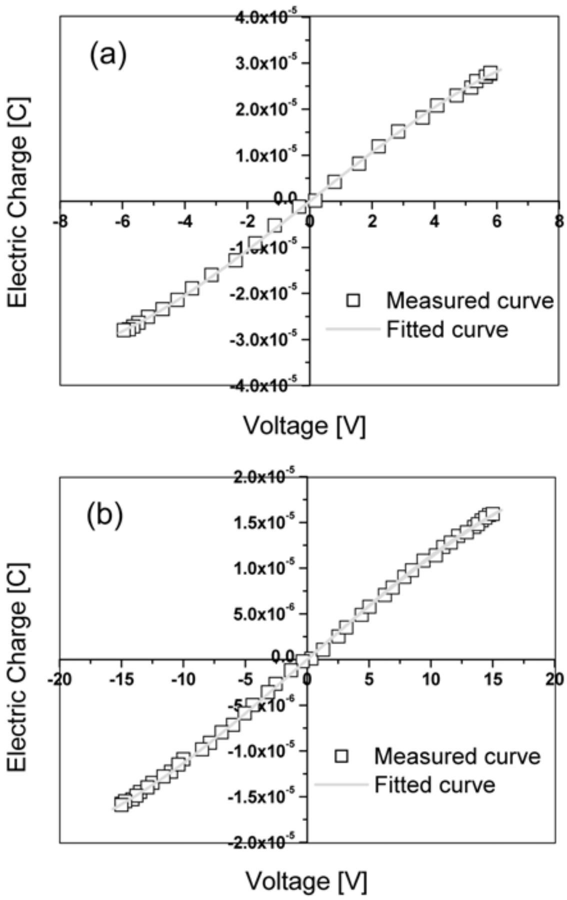

Fig. 4. The fitted Q-V curves with a poly-nominal function: (a) 4.7 μF and (b) 1.0 μF MLCCs.

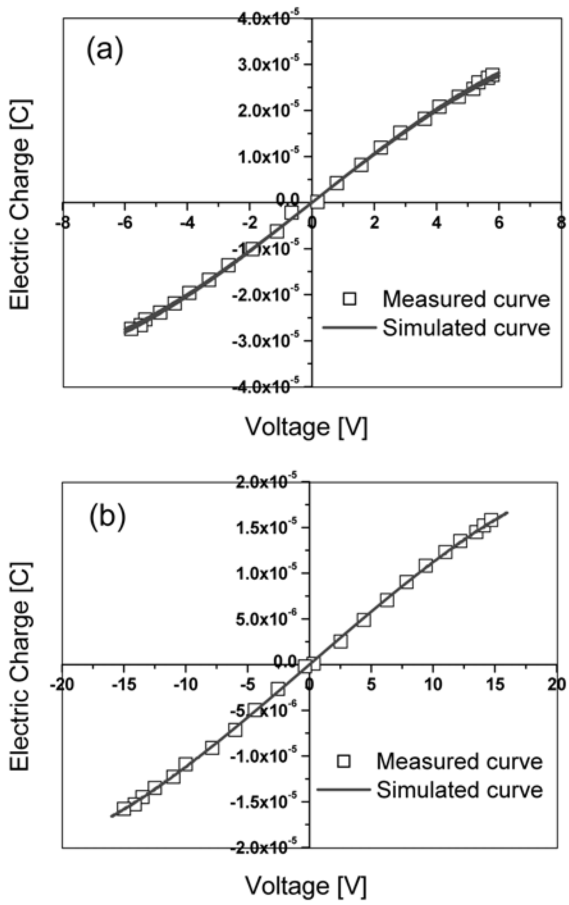

Fig. 5. Simulated and measured Q-V curves of MLCCs under different AC- fields: (a) 4.7 μF under 6 V AC-field; (b) 1.0 μF under 16 V ac-field.

Figure 4 shows the Q-V curves fitted with a poly-nominal function (Eq. 2). It is apparent that electric charge (Q) is non-linearly proportional to the applied voltage. The Q-V curves can be expressed by Eq. (5) and (6) for 4.7 μF and 1.0 μF MLCCs respectively:

$$Q=-3\times10^{-18}\,V^4-2\times10^{-8}\,V^3+2\times10^{-17}\,V^2+5\times10^{-6}\,V \tag{5}$$

$$Q=-3\times10^{-18}\,V^4-5\times10^{-10}\,V^3+5\times10^{-16}\,V^2+1\times10^{-6}\,V \tag{6}$$

Eq. (5) and (6) may be converted to Eq. (3) to input a non-linear dependent voltage source with the new equivalent circuit in the Sawyer-Tower circuit which was shown in Fig. 2. The converted formula was inserted into the non-linear dependent voltage source parts and simulated using B^2 spice software under each AC-field, as shown in Fig. 5.

Figure 5 shows the simulated Q-V curves and the measured Q-V curves for various AC-fields. The simulation Q-V curves are in agreement with the measured Q-V curves, both of which show the non-linearity of Q-V curves. It was noted that the non-linearity was related to harmonics [7, 8]. Harmonics are defined as a multiple ingredient of the fundamental frequency and have cyclic frequency dependence. It is characteristic that harmonics are reduced to vanish with an increase in frequency due to the increasing loss. Harmonics can be expressed as following trigonometric function:

$$V=a+bV+cV^2+dV^3+eV^4+\cdots \tag{7}$$

V is an input voltage of the AC-field and is defined as:

$$V=A\cos(\omega t)\ \text{at}\ \omega=2\pi f. \tag{8}$$

The combination of Eq. (7) and (8) provides the following equation:

$$V=a+bA\cos(\omega t)+cA^2\cos^2(\omega t)+dA^3\cos^3(\omega t)+eA^4\cos^4(\omega t) \tag{9}$$

The applied voltage (V) is the DC term without frequency at constant (zero order), which approached zero in the experiments. The fundamental frequency is observed at the 1st order. For the 2nd order, the following equations were derived:

$$cA^2\cos^2(\omega t)=cA^2\left(\frac{1+\cos2\omega t}{2}\right)=\frac{cA^2}{2}+\frac{cA^2}{2}\cos2\omega t \tag{10}$$

where $cA^2/2$ is the all of the amplitude. Eq. (10) consists of a DC term and the 2nd harmonic, which is at

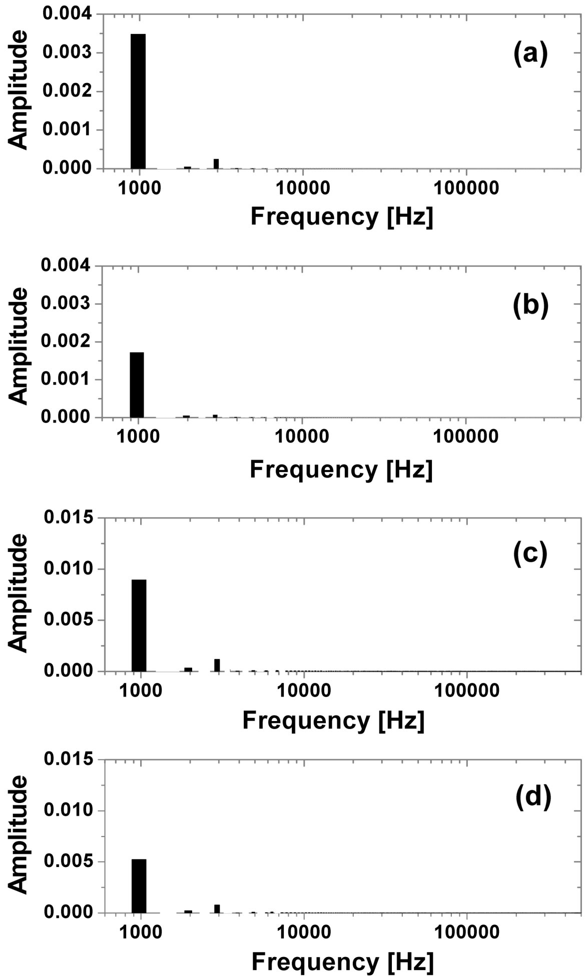

Fig. 6. The amplitude-frequency relationship applied at 1 kHz for each AC-field: (a) and (b) are simulated results for 4.7 μF and 1.0 μF under 6 V and 16 V AC-fields, respectively. (c) and (d) are experimental results for 4.7 μF and 1.0 μF under 6 V and 16 V AC-fields, respectively.

the second location of the fundamental frequency. For the third order, the following equation was observed:

$$\mathrm{dA}^3\cos^3(\omega t) = dA^3\left(\frac{\cos 3\omega t + 3\cos\omega t}{4}\right)$$
$$= \cos\omega t + \frac{dA^3}{4}\cos 3\omega t \qquad (11)$$

Eq. (11) consists of the fundamental frequency ingredient and the 3rd harmonic, which is at the third location of the fundamental frequency. The amplitudes are $3dA^3/4$ and $dA^3/4$, respectively. The following equation was given for the fourth order:

$$\mathrm{eA}^4\cos^4(\omega t) = \mathrm{eA}^4\left(\frac{1+\cos 2\omega t}{2}\right)^2 = \frac{3}{8}eA^4$$
$$+\frac{1}{2}eA^4\cos 2\omega t + \frac{eA^4}{8}\cos 4\omega t \qquad (12)$$

Eq. (12) is composed of a DC term ingredient, a 2nd harmonic ingredient and a 4th harmonic ingredient, which is at the fourth location of the fundamental frequency. The amplitudes are $3/8eA^4$, $1/2eA^4$ and $eA^4/8$, respectively. Therefore, we can compare the measured data with simulated data using Fourier series functions. Figure 6 shows the amplitude-frequency relations at 1 kHz for each AC-field. The amplitude of the 3rd harmonic was larger than that of the 2nd harmonic in the amplitude-frequency relationship for all MLCC chips. It was matched with the Q-V relation for MLCCs with 4.7 μF and 1.0 μF. The third order consisted of the fundamental frequency ingredient and the 3rd harmonic. This suggests that the 3rd harmonic was strongly affected by the amplitude of the fundamental frequency ingredient.

Even though the simulated results were in agreement with the measured ones, there was a slight difference in the harmonic frequencies resulting from experimental noise. These were from the five or seven times the frequency of the fundamental frequency; however, they were ignored in the simulation because the amplitude was very small.

Conclusions

The non-linearity of MLCCs with a new equivalent circuit was studied under various AC-fields. An experimental technique to measure the capacitance for the MLCCs was developed. The new equivalent circuit of the capacitors was developed in a Sawyer-Tower circuit at high AC-fields. The non-linearity of the Q-V curves for the 4.7 μF and 1.0 μF MLCCs, appeared from high order harmonics under high AC-fields. The simulated results for the 4.7 μF and 1.0 μF MLCCs with the new equivalent circuit were consistent with the experimental results. The amplitude-frequency relationships simulated for the MLCCs were also consistent with the experimental results.

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