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Frequency and Temperature Dependence of the Dielectric Properties of a PCB Substrate for Advanced Packaging Applications

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The frequency- and temperature-dependent dielectric properties for printed circuit board (PCB) applications are investigated in the frequency range from 1 kHz to 1 MHz and the temperature range from 300 K to 600 K. The applicable range of frequency for the capacitance-voltage (C-V) technique is discussed. An analytical model based on the experimental results and the theoretical analysis is proposed to give rise to a comprehensive understanding of the correlations between the operation temperature and the dielectric properties, where the temperature-dependent dipole property is investigated.

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I. INTRODUCTION

The demands of high-quality dielectric materials, such as printed circuit board (PCB), used for system-on-package (SOP) [1, 2] are rapidly increasing for mobile device applications. PCB is a compound of several materials, where resin provides optimized mechanical properties, electrical performance and chemical stability, being advantageous in mass-production for its low cost and glass fiber is widely used in reinforcement for its high tensile strength and low extensibility. The temperature and the frequency dependences of PCB's properties are important parameters for SOP design and system reliability and the investigation of the PCB material's stability under various disturbances provides an effective approach to enhance advanced package technologies.

Several methods based on the frequency domain have been proposed for the investigation of dielectric properties. In the transmission line method, the transmission and the reflection coefficients are measured by using high-frequency resonant circuits, so the main advantage is the narrow frequency range applied while the disadvantage is the necessity for resonance [3]. In the cavity resonator method, the sample is metalized on all sides to form a resonator cavity with the resonance frequency of a small hole [4] or a ring resonator [5,6]. Recently, the free-wave method was also proposed [7]. However, these proposed methods are applicable only to the microwave-frequency (GHz) band, being unable to characterize the dielectric properties of thin film materials such as PCBs. In contrast, the C-V technique based on a parallel-plate capacitor [8, 9] provides greatly extended applicability and accuracy, as sample metallization can be waived in the measurements and frequency bands are more flexible.

In other works, measurements were applied for high-temperature operation and the results suggested that the changes of the dielectric properties were triggered by a temperature-enhanced molecular mobility [10]. In this work, we extended the range of temperatures investigated. We found that some variations of dielectric properties are permanent and irreversible, even at low-temperature conditions where the mobility-enhanced theory is no longer applicable. In addition, we studied dielectric parameters, such as the dielectric constant and the loss factor, for PCB substrates by using a parallel-plate capacitor in the C-V measurements. The limited frequency range for the parallel-plate capacitor test is also discussed. A possible mechanism is proposed to investigate the experimental results for the dielectric properties by analyzing the dipolar rotating conditions in a range of temperatures.

II. EXPERIMENT

In this work, a glass-fiber PCB substrate is used which structure and images are shown in Figure 1. The capac-

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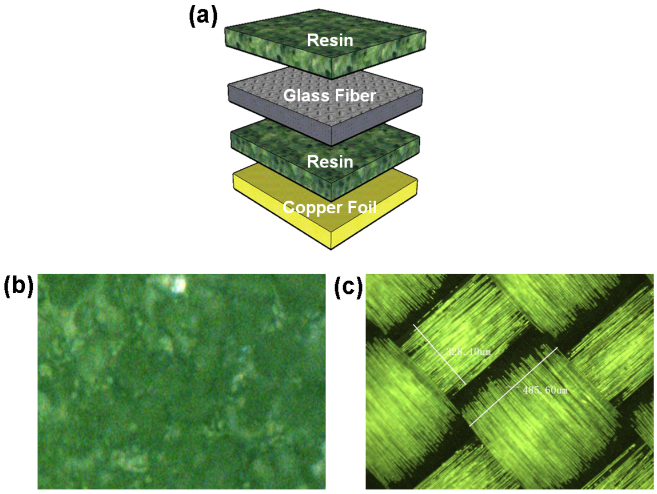

Fig. 1. (a) Separated structure of the single-sided PCB substrate, including resin, glass fiber and copper foil. (b) Resin surface at a magnification of 50. (c) Glass fiber at a magnification of 10.

Table 1. Setup for the experiment.

	Start	Stop	Step
Temperature	300 K	600 K	50 K
Frequency	1 kHz	1 MHz	*
Bias	–40 V	40 V	2 V

* The frequency step is set as 1 kHz, 10 kHz and 100 kHz in the ranges of 1 kHz to 10 kHz, 10 kHz to 100 kHz and 100 kHz to 1 MHz, respectively.

itor is formed by depositing metal electrodes on both surfaces of the sample, where Ag is used for its high conductivity and excellent high thermal stability. The dielectric constant can be calculated as $\varepsilon_r = Cd/\varepsilon_0 \pi r^2$, where C and d are the capacitance and the thickness of the PCB substrate, respectively. r is the radius of the deposited electrode cap. A LCR meter is employed and the loss factor can be obtained simultaneously with the capacitance. Here, it is necessary to point out that the thickness d is a variable in this experiment and that it will change with the temperature in theory. However, the practical result indicates that this variation is below 1.4 % even after heating at 675 K. In this case, the influence from the variation of the thickness can be neglected and d is regarded as a constant.

Table 1 lists the setup for the experiment in which the frequency dependence mainly focuses on the range of medium-frequency (MF) band and the sweep bias is set from –40 V to 40 V. For the temperature dependence, the test points are not set at a high temperature in the heating process, but set at room temperature after the heating process is completed, in order to make a comparison with other works.

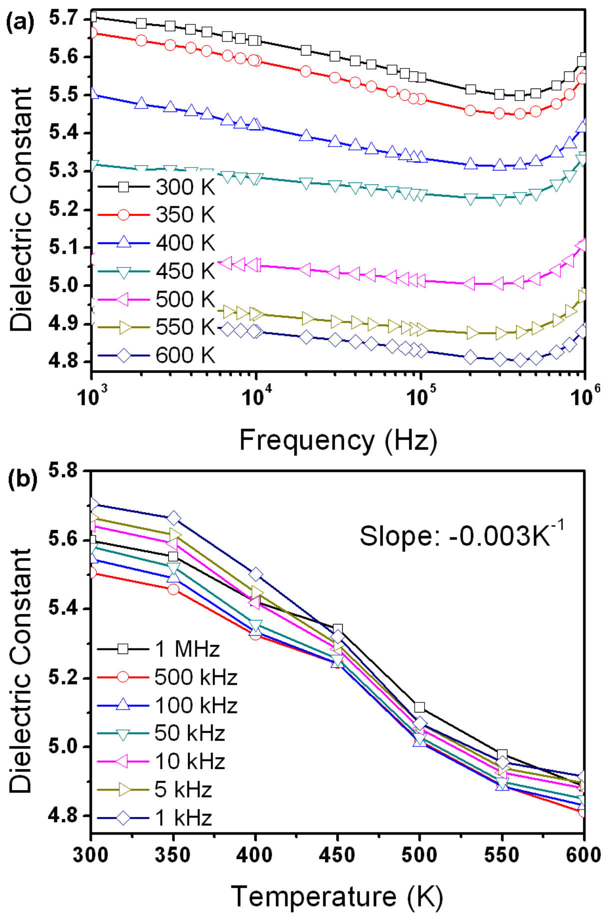

Fig. 2. (a) Frequency dependence of the dielectric constant at different temperatures. (b) Temperature dependence of the dielectric constant at different frequencies and the temperature coefficient of the dielectric constant extracted from the average linear slope.

III. RESULTS AND DISCUSSION

1. Dielectric Constant and Loss Factor

The dielectric constant is an essential parameter to design passive devices for integrated circuits and advanced package technologies. Figure 2(a) shows a dielectric constant reduction of 5 % with increasing frequency from 1 kHz to 1 MHz after heating at different temperatures. A decrease in the dielectric constant with increasing frequency is expected in most dielectric materials due to the dielectric relaxation, as the speed of dipole rotation at high frequency is insufficient to match the shift in the applied AC bias. We also found that the decrease in the dielectric constant with increasing temperature was uniform at both low and high frequencies. The temperature-dependent dielectric constant is shown in Figure 2(b), where linear decreases are observed in the dielectric constant for various frequencies and a negative temperature coefficient, about –0.003 K^{-1}, can be obtained from the

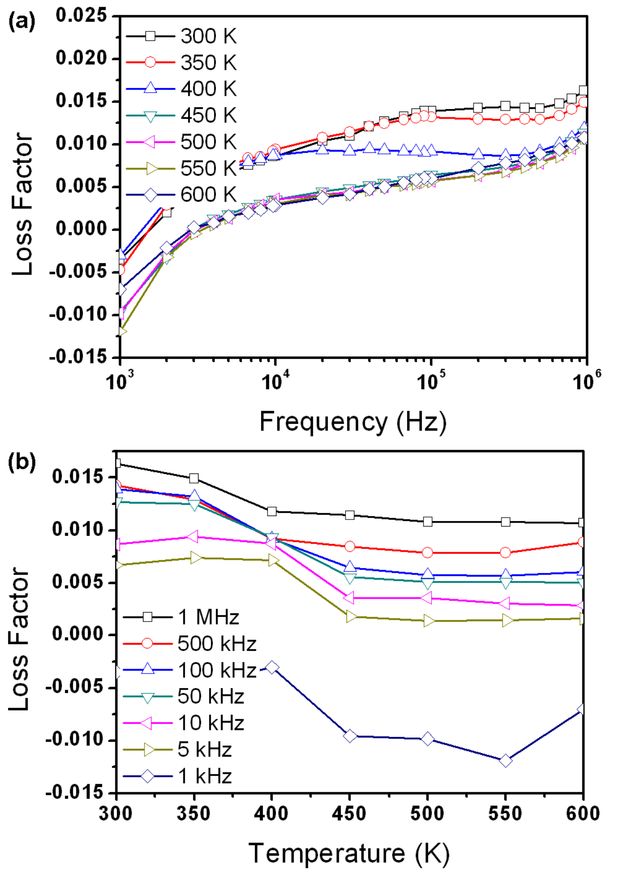

Fig. 3. (a) Frequency dependence of the loss factor after heating at different temperatures. (b) Temperature dependence of the loss factor at different frequencies.

Table 2. Relative bias dependence of the dielectric constant.

	300 K	400 K	500 K	600 K
1 MHz	0.09 %	0.05 %	0.09 %	0.10 %
500 kHz	0.14 %	0.18 %	0.18 %	0.17 %
100 kHz	0.31 %	0.14 %	0.15 %	0.34 %
50 kHz	0.14 %	0.07 %	0.11 %	0.07 %
10 kHz	0.07 %	0.13 %	0.19 %	0.12 %
5 kHz	0.20 %	0.27 %	0.10 %	0.25 %
1 kHz	1.02 %	1.02 %	2.00 %	0.94 %
500 Hz	2.79 %	2.71 %	3.68 %	3.50 %
100 Hz	64.48 %	62.37 %	55.18 %	80.78 %
50 Hz	111.68 %	98.97 %	76.53 %	75.15 %

Table 3. Bias dependence of the loss factor.

	300 K	400 K	500 K	600 K
1 MHz	0.0008	0.0008	0.0006	0.0008
500 kHz	0.0016	0.0018	0.0027	0.0013
100 kHz	0.0025	0.0019	0.0033	0.0039
50 kHz	0.0017	0.0007	0.0008	0.0009
10 kHz	0.0010	0.0015	0.0011	0.0017
5 kHz	0.0019	0.0020	0.0021	0.0022
1 kHz	0.0075	0.0106	0.0178	0.0103
500 Hz	0.0238	0.0212	0.0404	0.0283
100 Hz	0.7144	0.6883	0.6080	0.8697
50 Hz	1.0102	0.8619	0.7600	1.4012

slope.

The loss factor, or dissipation factor, is an important indicator of a capacitor's quality because it represents the energy loss in a dielectric material. The loss factor is found to depend strongly on the frequency and the increase from negative to positive region is found to be about 0.02 in the frequency range from 1 kHz to 1 MHz, as shown in Figure 3(a). As a comparison, the temperature effect on the loss factor is not very obvious because the reductions are only about 0.005 at different frequencies when the temperature is increased from 300 K to 600 K, as shown in Figure 3(b).

2. Frequency Dependence

The influence of the frequency on the dielectric constant, which is represented as the reduction shown in Figure 3 and the frequency range, which is covered in the measurements, are similar with the theoretical results for the polarization mechanisms [10]. However, the frequency range for the C-V measurement in the parallel-plate capacitor technique is still noted to be limited. For example, we understand that the error in the dielectric constant from the C-V measurements can be described as $((k_{max} - k_{min})/k_{ave} \times 100\ \%)$ and that the offset would be lower than about 1 % for frequencies higher than 1 kHz. If the frequency exceeds the above range, this offset increases dramatically. The details are listed in Table 2. The offset of the loss factor, $(D_{max} - D_{min})$, shows similar frequency dependences, which are listed in Table 3. Therefore, a test for applicable frequency range should be performed before the C-V measurements to ensure the accuracy and the reliability of the data.

3. Temperature Dependence

Figure 4 shows the differences between the conventional and the new methods for the temperature dependence research. In conventional tests, the dielectric constant and the loss factor are measured at high temperature and they show an increasing trend due to the enhanced molecular mobility and dipolar rotation [10]. In this work, we used the new method and tested the dielectric constant and the loss factor at room temperature when the heating process was finished. We found that

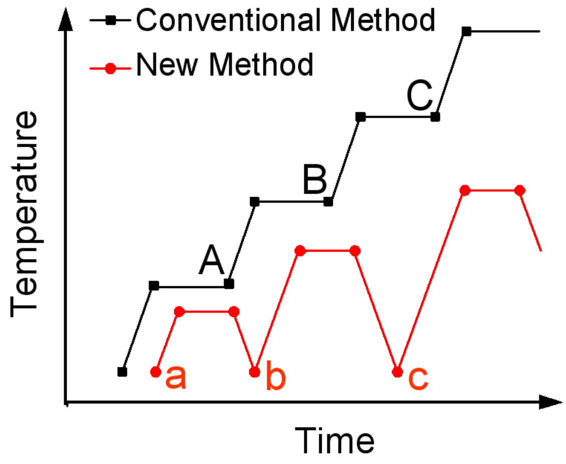

Fig. 4. Comparison of the conventional and the new methods to investigate the temperature dependence. Dielectric properties are measured at points A, B and C in the conventional method and at points a, b and c in the new method.

the measured values of the dielectric constant and the loss factor showed a decreasing trend. It is difficult to understand this phenomenon by using the same theory. Therefore, a possible mechanism is proposed based on the differences between the two test methods and the results. At room temperature, the rotation of the dipoles is restricted to follow the AC field closely. When the temperature rises, dipolar rotations and molecular motions become easier and the response to field variation is reinforced. Therefore, both the dielectric constant and the loss factor increase with temperature. When the temperature is reduced, dipolar rotation and molecular mobility will be restricted again. Note that it may not be a simple reverse process relative to the heating process. Due to some damage of rebuilding in the microstructure at high temperature, some dipoles and molecules will not go back to the previous conditions before heating but will arrive at a new equilibrium, where the restraint becomes greater. Moreover, we found that the higher temperature experienced during heating, the larger the number of microstructures that are rebuilt and the more restricted they become after heating. Therefore, if the sample goes under heating and cooling alternatively, the dipole rotation and the molecular mobility will be enhanced and restricted repeatedly. The dielectric constant will show an increase when measured at high temperature, as conventional tests reported, or show a reduction when measured at low temperature, as our experiment shows.

IV. CONCLUSION

In this work, the correlations between the dielectric properties of PCB substrate and frequency / temperature are revealed in the C-V measurements. The limitations of the frequency when using a parallel-plate capacitor are discussed. Comparing the experimental results with the conventional theory, we propose a comprehensive mechanism in which the heating process is irreversible and new microstructure and equilibrium will be rebuilt after heating with greater restraints on the dipole rotation.

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