BME C0G MLCCs: The High Capacitance Class-I Solution

Xilin Xu, Abhijit Gurav, Michael Randall, Jim Magee, Mark Laps and Aziz Tajuddin

KEMET Electronics Corporation, 201 Fairview Street Extension, Fountain Inn, SC 29644
Phone: +01-864-409-5653, FAX: +01-864-409-5665, e-mail: aziztajuddin@kemet.com

ABSTRACT

Lead-free soldering is required for surface-mount devices to meet RoHS compliance. Ceramic capacitors are robust at the 260°C lead-free soldering profiles recommended by JEDEC, however these profiles need to be modified with respect to time and peak temperatures while using plastic film capacitors. Based on the characteristics of capacitance, temperature capacitance coefficient (TCC) and insulation resistance (IR), the film capacitors perform reasonably well between the C0G and X7R dielectric multilayer ceramic capacitors (MLCCs). They have better capacitance stability and lower dielectric losses compared to the X7R MLCCs, and tend to offer higher capacitance than typical C0G MLCCs. Recently, with the breakthrough of the base-metal electrode (BME) technology, the BME C0G MLCCs are showing significant increase in volumetric efficiency while maintaining high reliability. The BME C0G dielectric is typically based on $CaZrO_3$ which has a perovskite structure. These C0G MLCCs can match the film capacitors both on capacitance as well as performance. This paper will introduce the high capacitance per unit volume (CV) BME C0G MLCC developed at KEMET. The typical electrical properties of this BME C0G MLCC will be compared with film capacitors made from different plastic materials. Overall, the BME C0G MLCCs exhibit extremely flat TCC, low dielectric dissipation factor (DF), low equivalent series resistance (ESR), high *Q* factor, high IR, and high breakdown voltage.

INTRODUCTION

In applications where capacitance needs to be precisely controlled over a wide temperature range, such as digital tuning and timing, C0G dielectric is the optimum choice. The C0G designation, also known as NP0 ("negative-positive-zero"), is the most common Class-I dielectric for chip capacitors. The Electronic Industry Association (EIA) specification for C0G dielectric is that the capacitance variation per °C from the room temperature (25°C) should be within ±30 ppm/°C (or capacitance variation $\Delta C/C \leq 0.3\%$) over the temperature range of -55°C to 125°C. These C0G dielectrics are usually non-ferroelectric materials, and exhibit linear response to voltage and temperature. Compared with Class-II dielectrics, typically X7R/X5R materials, C0G dielectrics have the advantages of high stability of capacitance over temperature and/or voltage, no aging of the dielectric constant, no "piezo effect" or microphonics, as well as a low dielectric loss.

Traditional C0G dielectric materials for precious metal electrodes (PME, such as Pd or Ag/Pd) are based on the barium neodymium titanate (BNT). The dielectric materials of BME C0G MLCCs are mainly based on $CaZrO_3$. Compared with PME C0G MLCCs, these BME C0G MLCCs have the additional benefits that they can offer high volumetric efficiency, high insulation resistance and better reliability (HALT and Life test bases) at a relatively lower cost [1].

With the recent breakthroughs in coating and handling thin dielectric layers (as thin as ~1 μm) and the capability of stacking hundreds of dielectric layers in BME technology, BME C0G MLCCs have reached a level where they can match the film capacitors in capacitance. Thus, due to their high volumetric efficiency, robust thermal performance and high performance/price ratio, BME C0G MLCCs are starting to replace film capacitors in many applications. One such example is coupling and decoupling capacitors in audio devices, where low distortion and absence of microphonics are critical for high-fidelity sound quality. Another application is high performance bypass capacitors in power source circuits for Plasma Display Panel (PDP) and Liquid Crystal Display (LCD), because sound noise can not be tolerated for these devices while in operation.

SAMPLE SELECTION

KEMET surface mount BME C0G 1210-224-25V MLCCs (Catalog number: C1210C224J3GAC), labeled as BME C0G224, were used for this evaluation. KEMET is the first company to release the 0.22 μF C0G MLCC in 1210 case size in the industry. This sample was compared with three commercially available surface mount film capacitors with the same capacitance. The typical plastic dielectric materials for film capacitors are based on acrylic resin, Polyethylene terephthalate (PET), Polyethylene naphthalate (PEN), Polyphenylene sulphide (PPS). Polytetrafluoroethylene (PTFE) film capacitors usually have better performance than the other type of film capacitors. However, PTFE capacitors are very expensive and rarely seen in surface mount (SMT) form. Polycarbonate, polystyrene (PS), and polypropylene (PP) capacitors are also rarely found in surface mount packages mainly due to their limited heat resistance. Thus, three film capacitor samples (labeled as Film CAP A, Film CAP B and Film CAP C) made from acrylic resin, Polyethylene naphthalate (PEN), and Polyphenylene sulphide (PPS) respectively, were selected in this study.

EXPERIMENTAL

The capacitance was measured on a HP-4284A Precision LCR meter at 1 kHz and 1 Vrms. Insulation resistance (IR), temperature coefficient of capacitance (TCC), and voltage coefficient of capacitance (VCC) were measured in a Saunders & Associates 4220A temperature test chamber. For BME C0G MLCCs, the room temperature IR was measured at twice rated voltage as was necessary for accurate measurements since they typically exhibit extremely high IR. The hot temperature IR was measured at 25V and 125°C.

Capacitance and DF frequency responses were measured on an HP 4294A multi-frequency LCR meter at 1 Vrms and room temperature over the frequency range of 1 kHz to 10 MHz. The impedance and equivalent series resistance (ESR) were measured on an Agilent E4991A RF Impedance/Material Analyzer at room temperature over the frequency ranged of 1 MHz to 1 GHz.

In order to evaluate the heat resistance capability in lead-free soldering, BME C0G224 MLCCs were compared with the PPS based sample Film CAP C. Only Film CAP C was chosen from the three film capacitor samples, because PPS has much better heat resistance than most other plastic film materials. First, the insulation resistance of 10 chips each from the BME C0G224 and Film CAP C was measured. Then these chips were mounted to a testing circuit board in an IR-reflow oven using a Pb-free soldering profile, as shown in Fig. 1. This Pb-free soldering profile meets the requirement from the film capacitor manufacturers, which has a maximum peak temperature below 250°C and has less than 30 seconds at temperatures above 230°C. The Pb-free solder alloy used has a composition of Sn96.5/Ag3.0/Cu0.5. After the soldering, the insulation resistance for each chip was re-measured and compared to the readings before the soldering.

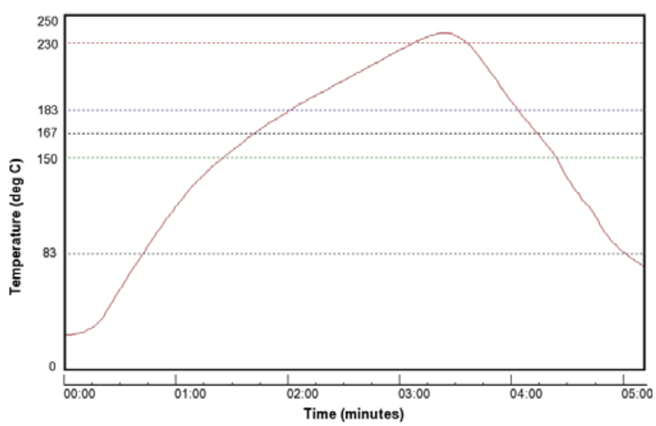


Fig. 1. Pb-free soldering profile used in this work.

RESULTS AND DISCUSSION

(1) Overview

As both the C0G dielectric and plastic films are non-ferroelectric materials, they both have the advantages of no aging and low dielectric loss compared to Class-II and Class-III dielectrics. However, ceramic C0G MLCCs and plastic film capacitors still perform differently with respect to several important properties. The relative foot print dimensions of the BME C0G224 MLCC vs. three film capacitors used in this study are shown in Fig. 2. The properties for BME C0G224 and three film capacitor samples are summarized in Table I.

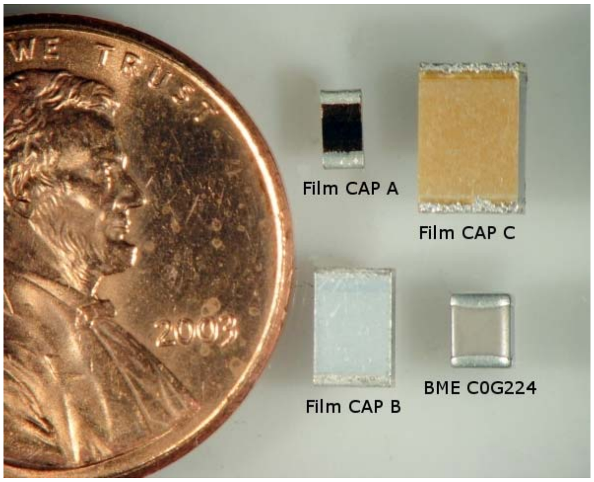


Fig. 2. BME C0G MLCC and three film capacitors with the same capacitance of 220 nF.

Table I. Properties of BME C0G224 and Film Capacitors

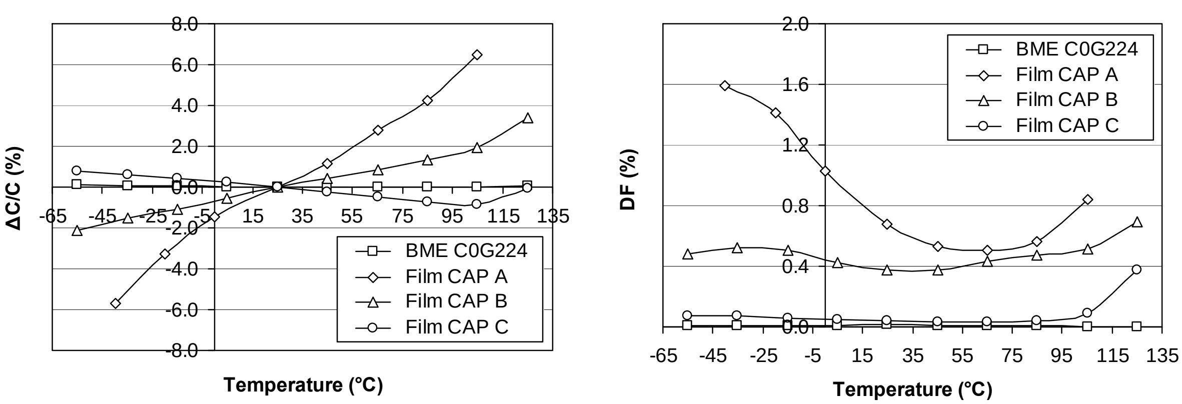
Sample	BME C0G224	Film CAP A	Film CAP B	Film CAP C
Dielectric Material	$CaZrO_3$ based	Acrylic Resin	PEN	PPS
EIA Case Size	1210	1206	1812	2416
Rated Voltage (Volts)	25	25	50	50
Capacitance (nF)	224.2	215.2	223.4	221.6
Dielectric Constant	30.7	3.3	3.0	3.0
DF (%, @1kHz)	0.0066	0.5965	0.3720	0.0321
Q Factor (@1MHz)	257	13	57	30
25°C IR (GOhms @ 50V)	901.1	35.7	69.7	667.9
125°C IR (GOhms @ 25V)	1.55	0.03	3.39	4.61
$T_{operation, Min}$ (°C)	-55	-40	-55	-55
$T_{operation, Max}$ (°C)	125	105	125	125
TCC @ $T_{operation, Min}$ (ppm/°C)	-11.5	874.4	245.9	-97.1
TCC @ $T_{operation, Max}$ (ppm/°C)	3.6	811.1	336.7	-4.8
Breakdown Voltage (Volts)	626.0	115.0	222.5	326.0
Dielectric Thickness (μm)	2.91	<0.5	0.85	1.34
CV (μF/cc)	13.7	52.1	7.4	3.0
Max. Soldering Temp (°C)	>260	250	250	260

The plastic materials for film capacitors have a dielectric constant typically ranged from 2.2 to 3.3 [2]. The dielectric constant of about 31 for the BME C0G dielectric is nearly ten times higher than that for the plastic films. To meet the same capacitance target in a similar size package, the dielectric thickness of film capacitors must be much thinner than in BME C0G MLCC due to the intrinsic low dielectric constants. As a result, the dielectric layer thickness for the BME C0G224 and three film capacitor samples are 2.91μm, <0.5μm, 0.85μm, and 1.34μm, respectively. Thus, one big tradeoff with thin dielectric layer film capacitors is their breakdown voltages were much lower than that of BME C0G224 (626.0 Volts), as shown in Table I. Film capacitors exhibit a feature of 'self-healing' after the dielectric breakdown, which helps prevent short type failures if the current and voltage available are sufficient to create the self healing effect (typically not the case in lower voltage circuits). Alternatively, the breakdown voltage for BME C0G224 is not a concern for normal applications as the breakdown voltage is 2 to 5 times higher than for film capacitors, and is about 25 times the rated voltage.

(2) Temperature Response

BME C0G MLCCs offer superior temperature stability of capacitance as well. The TCC over the working temperature range for each sample is shown in Table I. The polarization mechanism for $CaZrO_3$ based BME C0G dielectric involves typical ionic polarization, while acrylic resin and PEN are polar organic polymers, which have permanent dipole side groups attached to the polymer chains. Thus, the polarization mechanisms of these polymers include both electronic polarization and orientational dipolar polarization. At room temperature, the contribution to capacitance from the dipole is small due to the restricted rotation of dipoles. The capacitance of acrylic resin and PEN based film capacitors increases with temperature, because increased polymer molecular motion enables the dipolar polarization mechanism increasingly with increasing temperature and there is more volume between polymer chains for dipoles to rotate. The capacitance drifts (ΔC/C) with the reference to 25°C within each sample's working temperature range are plotted in Fig. 3 (a). For BME C0G224, the maximum ΔC/C over the temperature range of -55°C to 125°C range was less than 0.12%. In contrast, the Film CAP A sample had a maximum ΔC/C of 6.49% over the temperature range of -40°C to 105°C, while the Film CAP B sample had a maximum ΔC/C of 3.37% over the temperature range of -55°C to 125°C. However, the PPS plastic is a non polar polymer, and no dipoles can be aligned with the applied electrical field. Thus, sample Film CAP C showed the best capacitance temperature stability among three film capacitors. Its maximum ΔC/C over the temperature range of -55°C to 125°C was about 1%.

The dissipation factor (DF) value of the BME C0G224 is only 0.0066%, which is much lower than all film capacitor samples. The DF for Film CAP A, Film CAP B, and Film CAP C at 1 kHz are 0.5965%, 0.3720%, and 0.0321%, respectively. The DF variation within each sample's working temperature range is plotted in Fig. 3 (b). Again, the BME C0G224 sample exhibits extremely flat DF with temperature compared to Film CAP A and Film CAP B which exhibit much higher DF throughout the whole temperature range. The Film CAP C, which is PPS based, shows close performance to BME C0G224 sample. However, one serious drawback of the PPS capacitor is the dramatic increasing of DF at temperature above 100°C.



(a) (b)

Fig. 3. Capacitance drift and DF vs. temperature.

(3) Frequency Response

The frequency responses of capacitance and DF over the frequency range of 1 kHz to 10 MHz are shown in Fig. 4 (a) and (b). The BME C0G224 sample had more stable capacitance and DF compared to Film CAP A and Film CAP B, over the frequency range investigated. Like the temperature responses above, Film CAP A again had the greatest capacitance and DF variation with frequency among the three capacitor samples. This again, can be explained by the polarization mechanism. In acrylic resin or PEN dielectrics, when the dipole rotation can not catch up with the increasing frequency, the capacitance decreases because the contribution from the orientational polarization is diminishing. This effect is responsible for the steady increase in dissipation factor with increasing frequency as well. In contrast, the PPS based Film CAP C sample exhibits close capacitance and DF dependence with frequency to BME C0G224 sample.

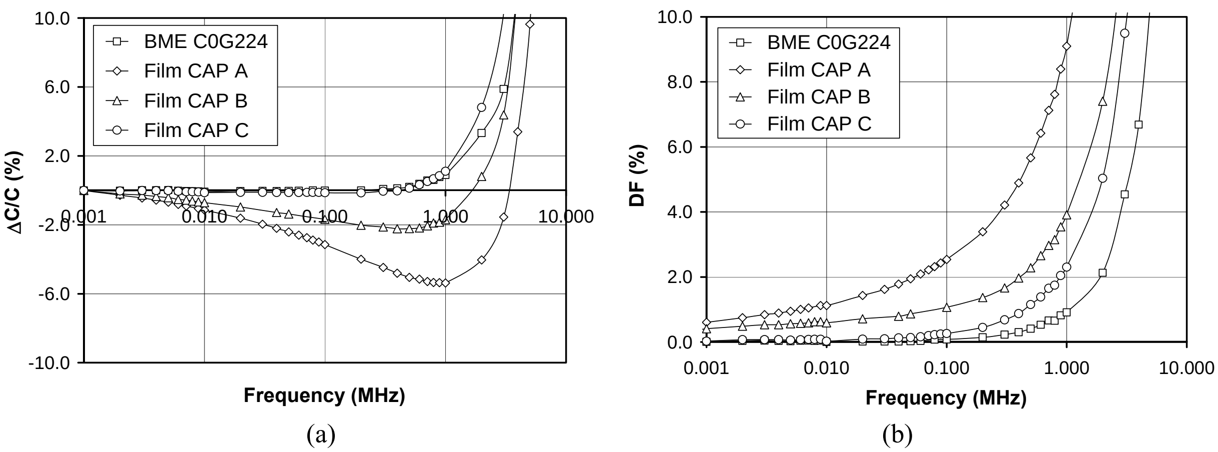


Fig. 4. Capacitance drift and DF vs. frequency.

The measured impedance and ESR for three capacitor samples is illustrated in Fig. 5. While the BME C0G224 has the lowest ESR, the BME C0G224 and film CAP B basically exhibit the same impedance behavior over the range of measurement frequency. Both the BME C0G MLCC and Film CAP B exhibit markedly lower ESR and impedance than Film CAP A and Film CAP C. Below the resonance frequency, the ESR for BME C0G224 is less than 10 mΩ, while sample Film CAP A has an ESR about 50 mΩ. At 1MHz, the *Q* factors for these samples are 256, 13, 57 and 30, respectively. The *Q* factor at various frequencies is shown in Fig. 6. The BME C0G224 sample showed the highest *Q* value in the frequency range of 1MHz to 10MHZ.

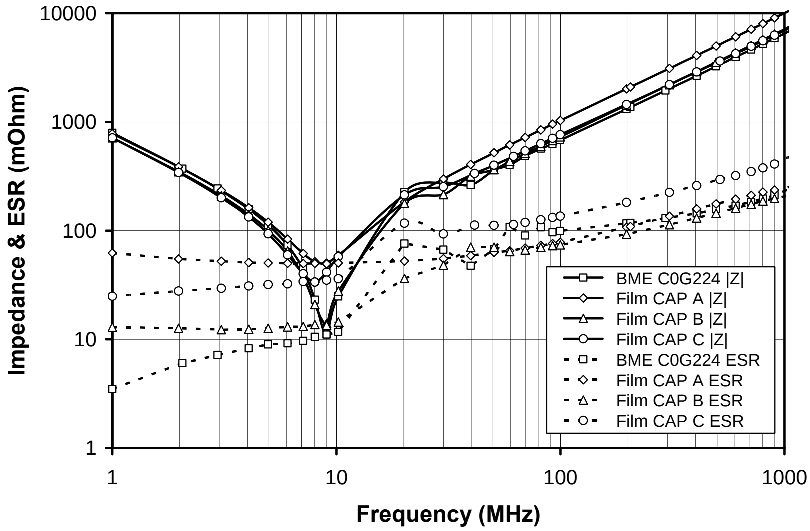


Fig. 5. Impedance and ESR of BME C0G224 and film capacitors.

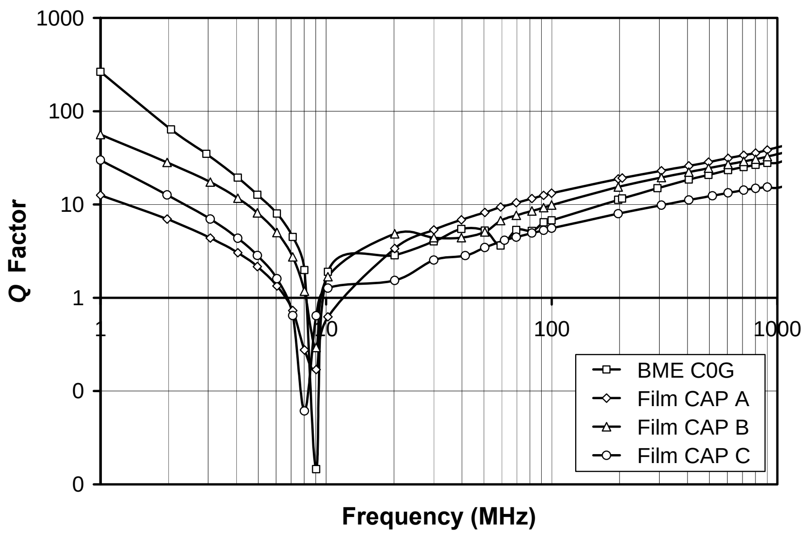


Fig. 6. *Q* factor of BME C0G224 and film capacitors.

(4) Lead-Free Soldering Capability

Another advantage of the ceramic BME C0G MLCCs over film capacitors is the better thermal performance. To meet the Restriction on Hazardous Substances (RoHS) compliance, the SMT capacitors need to be suitable for mounting to the circuit board with a lead-free solder. This requires an increase in the reflow temperature profile, from a typical 225°C peak to about 260°C peak. As most of the film capacitors can only withstand a maximum soldering temperature of ~250°C due to the relatively low melting temperature of the polymers used, the lead-free soldering for film capacitors can be more difficult than MLCCs because ceramic materials have much higher melting temperatures. Film capacitors usually will have excessive leakage after the lead-free IR reflow. On the other hand, BME C0G MLCCs are not limited by this factor and can be mounted using recommended reflow profiles for RoHS compliant solders. The insulation resistance before and after the Pb-free soldering for BME C0G224 and Film CAP C was compared, and shown in Fig. 7. The IR at 125°C dropped about 40% after the Pb-free soldering for sample Film CAP C, while BME C0G224 was still the same as before soldering. The maximum temperature of the Pb-free soldering profile in this test is only about 240°C. Thus, it is expected to see more leakage for film capacitors at higher maximum soldering temperatures or if multiple IR-reflow passes is required in soldering.

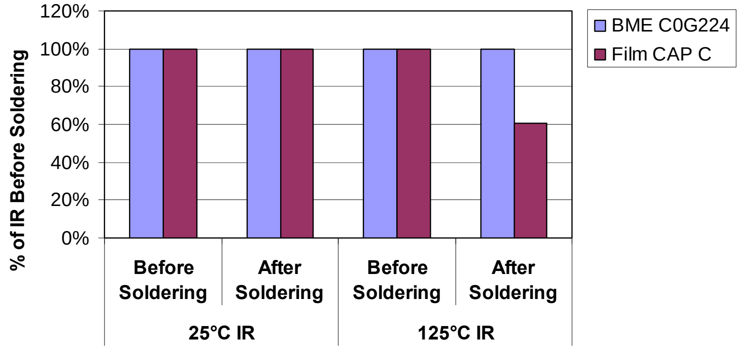


Fig. 7. Insulation resistance before and after the Pb-free soldering.

SUMMARIES

1. Compared with film capacitors, BME C0G MLCCs have extremely low TCC, low DF, low ESR, high insulation resistance, and high breakdown voltage. Unlike film capacitors, BME C0G MLCCs also meet the lead-free soldering requirement for peak soldering temperature. PPS based film capacitors show close performance to BME C0G MLCCs, except for the poor volumetric efficiency.

2. KEMET lead-free BME C0G dielectric, combined with the lead-free termination system, provide a high performance green solution for design engineers for applications where capacitance stability is critical. The offerings include case sizes from the 0402 to 1210 and above, and voltage ratings from 25V to 100V and above. A summary of these features includes:

- High volumetric efficiency compared to film capacitors and other C0G MLCCs
- Extremely flat capacitance and DF over the operating temperature range
- No aging of capacitance and zero voltage coefficient of capacitance
- High breakdown voltage compared to film capacitors
- No 'piezo effect' or microphonics, means excellent performance in audio circuit
- High insulation resistance
- Low ESR and high *Q* factor
- Meet the lead-free soldering requirement

ACKNOWLEDGEMENT

The authors would like to thank the support from Kevin Lynn and George Haddox from the testing lab in KEMET Electronics Corporation.

REFERENCES

[1] X. Xu, et al., p179-188, CARTS USA 2007, Alburquerque, NM, USA.
[2] A. Perez, et al., p249-257, CARTS USA 2006, Orlando, FL, USA.