High CV BME C0G

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ABSTRACT

C0G multilayer ceramic capacitors (MLCC) are a ‘workhorse’ of the capacitor industry. C0G MLCCs are selected for high temperature stability, low dissipation factor (DF) applications where capacitance aging cannot be tolerated. In recent years, C0G MLCCs have been favored increasingly over film capacitors as higher volumetric efficiency state-of-the-art C0G MLCCs are becoming available. This paper discusses C0G MLCC recently introduced at KEMET. These BME C0G MLCCs utilize base metal electrode (BME) technology, combined with lead-free dielectric and termination systems. The resulting C0G MLCC systems exhibit relatively high volumetric efficiency combined with a high level of capacitance stability with respect to temperature. Additionally, these systems exhibit exceptionally robust highly accelerated life test (HALT) performance. Small device footprints (as low as 0402) are also available with these dielectric systems. These high capacitance per unit volume (CV) BME C0G MLCC products are suitable as film replacements for numerous applications, enabling the designer to select a capacitor that is environmentally green, as well as robust with respect to surface mount processes that require lead-free solder.

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 0±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 voltage, no aging of the dielectric constant, no “piezo effect” or microphonics, as well as a low dielectric loss with voltage or frequency.

Traditional C0G dielectric materials for precious metal electrodes (PME, such as Pd or Ag/Pd) are based on the barium neodymium titanate (BNT). However, with constant price pressures of the MLCC industry, precious metal based MLCCs are at a disadvantage. Because of this, the MLCC manufacturers have mostly converted the PME to base metal electrodes (BME, mainly Ni) in the industry in order to remain cost competitive. The BME C0G dielectrics are mainly $CaZrO_3$-based materials. Compared with PME C0G dielectric, these BME C0G dielectric systems have the additional benefit that they can offer much higher insulation resistance and better reliability (HALT and Life test bases), and higher *Q* even at a much thinner dielectric layers [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, the BME C0G MLCCs have reached a level where they can compete with and exceed the film capacitors from the standpoint of capacitance per unit volume. Thus, due to their high volumetric efficiency, better thermal performance and high performance/price ratio, the BME C0G

MLCCs are starting to replace the 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.

In this paper, high CV BME C0G MLCCs recently developed at KEMET Electronics are introduced and compared to the PME C0G MLCCs and plastic film capacitors based on various testing results.

SAMPLE SELECTION

KEMET BME C0G MLCCs 1206-103-50V (Catalog number: C1206C103J5GAC), 1206-104-25V (Catalog number: C1206C104J3GAC), and 1210-224-25V (Catalog number: C1210C224J3GAC) were selected for this evaluation. The 10nF (labeled as BME1206-103) and 100nF (labeled as BME1206-104) samples were compared with a commercially available PME C0G 1206-103-25V MLCC sample, labeled as PME1206-103. The 1210-220nF sample (labeled as BME C0G224) was compared with two commercially available surface mount film capacitors with the same capacitance, labeled as film CAP A and film CAP B. Unfortunately, no 1210-220nF PME C0G were available for the comparison as they are not commercially available.

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 usually measured at twice rated voltage as was necessary for accurate measurements since they typically exhibit extremely high IR. For BME C0G224 and the two film capacitor samples, room temperature IR were measured at 50V and 25°C, and hot temperature IR were measured at 25V and 125°C for direct comparison.

Capacitance and DF frequency responses were measured on an HP 4275A multi-frequency LCR meter at 1 Vrms and room temperature over the frequency range of 10 kHz to 1 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.

The MLCCs were characterized by the highly accelerated life test (HALT), in which the acceleration is accomplished by temperature and voltage stresses. The HALT test was performed at 175°C and 400 Volts for 46 hours. The normal maximum working temperature of C0G dielectric is 125°C, but these BME C0G MLCCs are generally very robust, such that a combination of high temperature and high voltage is needed to achieve device failure within a reasonable time. A sample size of 40 pieces was used for each sample. HALT time to failure (TTF) was recorded when IR at test temperature dropped below 3.78 MΩ.

RESULTS AND DISCUSSION

(1) PME C0G MLCC vs. BME C0G MLCC

The major electrical properties of these samples are listed in Table I. As both PME C0G and BME C0G are non-ferroelectric materials, their VCC and aging rate of capacitance were all zero. The calculated dielectric constant for PME C0G was about 63, while for the BME C0G was about 30. Due to the low dielectric constant of BME C0G materials, the dielectric thickness of BME1206-103 (6.97 μm) was thinner than PME1206-103 (11.62 μm) in order to meet the same capacitance. Despite the reduced dielectric thickness of the BME C0G MLCC devices, the room temperature IR measured at 100 Volts was still higher than for PME1206-103 measured at 25 Volts. For the IR at

125°C, the BME1206-103 was almost two times higher than PME1206-103 even when the measurement voltage was doubled.

Furthermore, with the latest thin layer BME technology in the same 1206 case size and at the same 25V rating, the BME C0G offers much higher capacitance than PME C0G as the dielectric thickness can be reduced substantially compared to PME C0G. The BME1206-104 sample shown in Table I, has a dielectric thickness of 2.82 µm, and exhibits not only 10 times higher capacitance than the PME1206-103 sample, but also much smaller dissipation factor (DF). The capacitance per unit volume (CV) of the BME1206-104 is 6 fold greater than that for the PME1206-103 sample.

Table I. Properties of PME C0G and BME C0G MLCCs

Sample	**PME1206-103**	**BME1206-103**	**BME1206-104**
Dielectric Material	BNT Based	$CaZrO_3$ based	$CaZrO_3$ based
Internal Electrode	Ag/Pd	Ni	Ni
Rated Voltage (Volts)	25	50	25
Capacitance (nF)	10.63	9.78	101.23
DF (%, @1kHz)	0.017	0.015	0.004
Q Factor (@1MHz)	1012	823	1900
Calculated Dielectric Constant	62.9	32.3	29.6
25°C IR Test Voltage	25 V	100 V	50 V
25°C IR (GOhms)	4961.3	6682.7	2079.0
125°C IR Test Voltage	25 V	50 V	25 V
125°C IR (GOhms)	74.1	134.7	4.9
TCC within -55~125°C (ppm/°C)	<±30	<±30	<±30
Breakdown Voltage (Volts)	1315.5	1044.5	652.0
Dielectric Thickness (µm)	11.62	6.97	2.82
ΔC at Rated Voltage (%)	0.00	0.00	0.00
Aging Rate (%)	0.00	0.00	0.00
CV (nF/cc)	4.9	4.4	31.9
Relative Price	medium	low	medium

All above samples have no problem in passing the required QA life test, which is at 125°C and twice rated voltage for 1000 hours. In order to make these parts fail, the HALT test was conducted at an extreme severe environment, which was at 175°C and 400V. The HALT reliability of the two 1206-103 samples (PME and BME) is shown in Fig. 1. It is obvious to see from the figure that the BME1206-103 sample exhibits markedly longer TTF values compared to the PME1206-103. The median time-to-failure (MTTF) at HALT for PME1206-103 was 62.6 minutes, while for BME1206-103 was 869.6 minutes, more than an order of magnitude improvement in MTTF. Due to its high IR and good reliability, the BME1206-103 can be qualified as 50V rated.

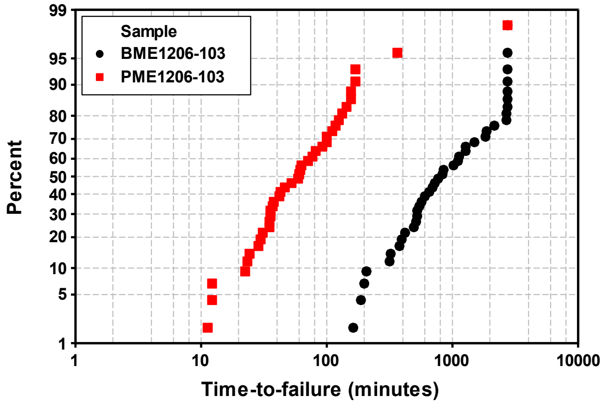


Fig. 1. HALT for PME and BME C0G MLCCs. (Please note that this HALT was run at 175°C and 400V.)

Impedance and ESR measured over the frequency range of 1MHz to 1GHz for PME1206-103 and BME1206-103 are plotted in Fig. 2. Basically, the behavior of each is similar with respect to ESR and impedance over the frequency range measured. Below the resonance frequency, ESR for both is less than 30 mΩ. In high frequency applications, a figure of merit, known as "*Q* factor", is used to characterize the dielectric loss. The higher the *Q* factor value, the lower is the dielectric loss as $Q = DF^{-1}$. The *Q* factor at 1MHz for PME1206-103 and the BME1206-103 were comparable at 1,012 and 823, respectively. The *Q* factor for the BME1206-104 MLCC was 1,900 even with a much thinner dielectric thickness (2.8 μm), due to the greater number of electrodes.

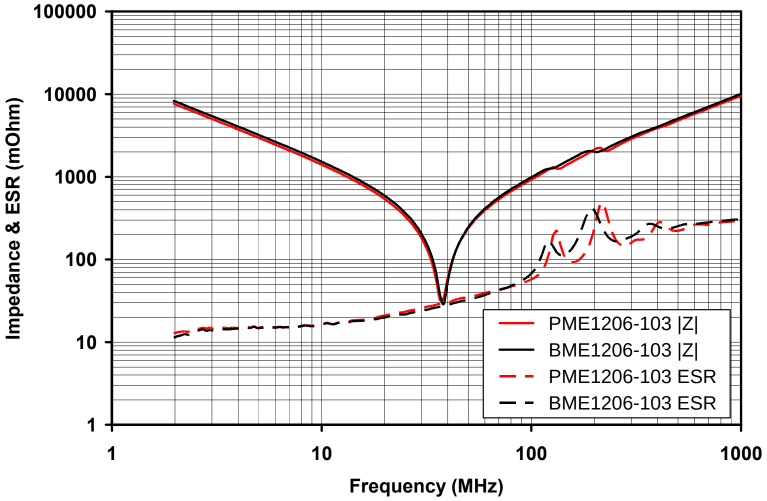


Fig. 2. Impedance and ESR of PME1206-103 and BME1206-103.

(2) BME C0G MLCC vs. Film Capacitors

As both of C0G dielectric and the 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. A detailed discussion on these two types of capacitors is given in the following section. The relative foot print dimensions of the BME

C0G224 MLCC vs. two film capacitors used in this study are shown in Fig. 3. The properties for BME C0G224 and two film capacitor samples are summarized in Table II.

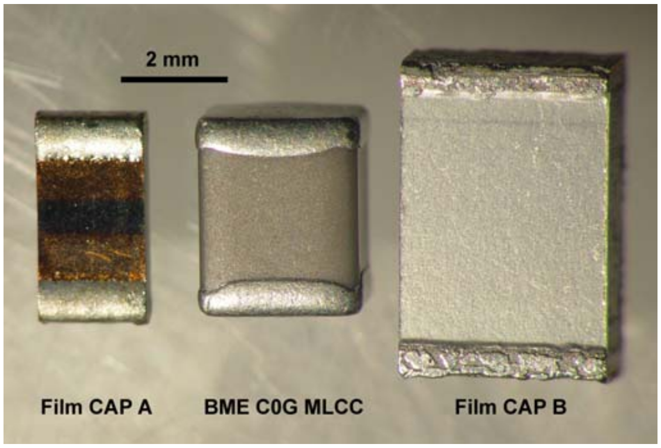


Fig. 3. BME C0G MLCC and film Capacitors with 220 nF capacitance.

Table II. Properties of BME C0G224 and Film Capacitors

Sample	**BME C0G224**	**Film CAP A**	**Film CAP B**
Dielectric Material	$CaZrO_3$ based	PET	PEN
EIA Case Size	1210	1206	1812
Rated Voltage (Volts)	25	25	50
$T_{operation,\ Min}$ (°C)	-55	-40	-55
$T_{operation,\ Max}$ (°C)	125	105	125
Capacitance (nF)	224.2	215.2	223.4
DF (%, @1kHz)	0.0066	0.5965	0.3720
Q Factor (@1MHz)	257	13	57
25°C IR (GOhms @ 50V)	901.1	35.7	69.7
125° IR (GOhms @ 25V)	1.55	0.03	3.39
TCC @ $T_{operation,\ Min}$ (ppm/°C)	-11.5	874.4	245.9
TCC @ $T_{operation,\ Max}$ (ppm/°C)	3.6	811.1	336.7
Breakdown Voltage (Volts)	626.0	115.0	222.5
Dielectric Thickness (µm)	2.91	<0.5	0.85
ΔC at 25 Volts DC Bias (%)	0.00	0.06	-0.39
CV (nF/cc)	34.9	132.4	18.8
Max Soldering Temp (°C)	>260	250	250
Relative Price	medium	High	High

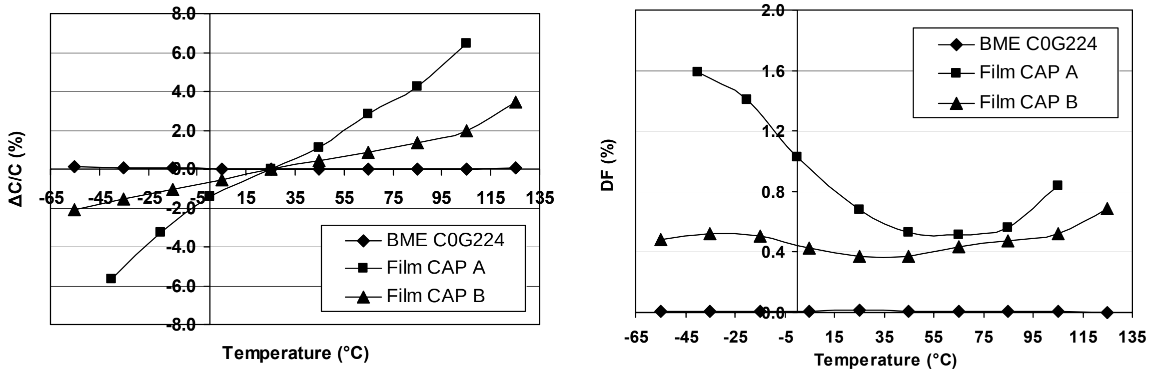
The dielectric materials for film capacitors are typically based on one or more of either Polyethylene terephthalate (PET), Polyethylene naphthalate (PEN), Polyphenylene sulphide (PPS), Polytetrafluoroethylene (PTFE), or Polypropylene (PP). PPS and PTFE film capacitors usually have better performance than the PET and PEN based capacitors. However, PTFE capacitors are very expensive and rarely seen in SMD form. On serious drawback of

PPS capacitor is the dramatic increasing of DF at temperature above 100°C. The PP film capacitor has limited heat resistance (up to 105°C), and is rarely found in surface mount packages.

These plastic materials have a dielectric constant typically ranged from 2.2 to 3.3 [2,3]. The dielectric constant of about 30 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 less than in BME C0G MLCC due to the intrinsic low dielectric constants. Thus, one tradeoff with thin dielectric layer film capacitors is the breakdown voltage (e.g., 115.0 Volts for the PET capacitors and 222.5 Volts for the PEN capacitors) were much lower than that of BME C0G224 (626.0 Volts), as shown in Table II. 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 typically not a concern for normal applications as the breakdown voltage is 3 to 5 times higher than for film capacitors, and is about 25 times the rated voltage. The second tradeoff for film capacitors is relatively low IR. The room temperature IR of BME C0G224 is about 25 times higher than film CAP A and about 13 times higher than film CAP B.

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 II. The polarization mechanism for $CaZrO_3$ based BME C0G dielectric involves typical ionic polarization, while PET 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 PET and PEN 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 ($\Delta C/C$) with the reference to 25°C within each sample's working temperature range are plotted in Fig. 4 (a). For BME C0G224, the maximum $\Delta C/C$ 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 $\Delta C/C$ of 6.49% over the temperature range of -40°C to 105°C, while the film CAP B sample had a maximum $\Delta C/C$ of 3.37% over the temperature range of -55°C to 125°C.

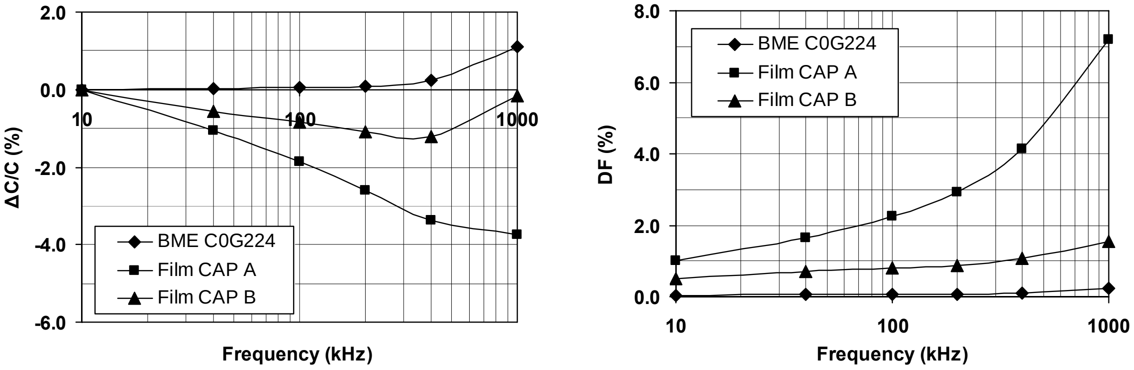
The dissipation factor (DF) values of the BME C0G224, film CAP A, and film CAP B at 1 kHz are 0.0066%, 0.5965%, and 0.3720%, respectively. The DF variation within each sample's working temperature range is plotted in Fig. 4 (b). Again, the BME C0G224 sample exhibits extremely flat DF with temperature compared to two film capacitors which exhibit much higher DF throughout the whole temperature range.



(a) (b)

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

The frequency responses of capacitance and DF over the frequency range of 10kHz to 1MHz are shown in Fig. 5 (a) and (b). The BME C0G224 sample had more stable capacitance and DF compared to the two film capacitor samples, 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 PET and 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.



(a) (b)

Fig. 5. Capacitance drift and DF vs. frequency.

The measured impedance and ESR for three capacitor samples is illustrated in Fig. 6. 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. 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 three samples are 256, 13, and 57, respectively. The Q factor at various frequencies is shown in Fig. 7. The BME C0G224 sample showed the highest Q value in the frequency range of 1MHz to 10MHZ. The dielectric loss per unit capacitance can be expressed as: $W_{CAP}=V^2\omega \tan\delta$, where V is the rms voltage across the capacitor. At the same rms voltage, W_{CAP} is proportional to ω and $\tan\delta$ or DF (e. g. the reciprocal of the Q factor). At low frequencies, the power loss is small. However, at high frequencies, the loss can be significant if Q factor is relatively low.

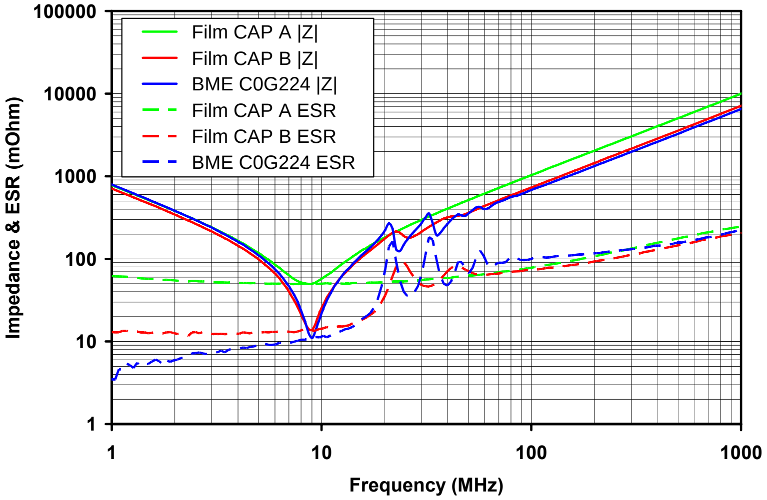


Fig. 6. Impedance and ESR of BME C0G224 and film Capacitors.

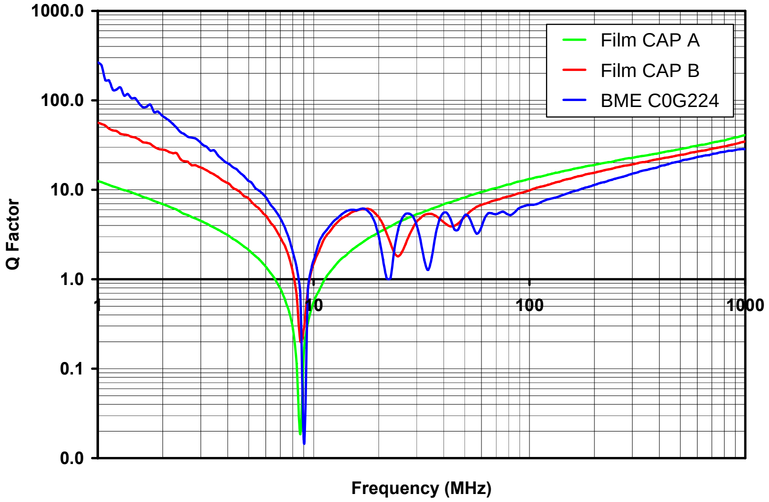


Fig. 7. *Q* factor of BME C0G224 and film Capacitors.

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. Thus, 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.

SUMMARIES AND CONCLUSIONS

1. Despite the relatively low dielectric constant compared with the PME C0G, BME C0G MLCC still can achieve much higher capacitance in the same case size due to the breakthroughs of the BME technology. Additionally, BME C0G MLCCs exhibit much higher IR and better HALT performance than the PME C0G MLCCs even with a thinner dielectric layer. The BME C0G MLCCs also have the advantage of relatively low materials cost.

2. Compared with the film capacitors, BME C0G MLCCs have extremely low TCC, low DF, low ESR, high insulation resistance, and high breakdown voltage. Unlike the film capacitors, BME C0G MLCCs also meet the lead-free soldering requirement for peak soldering temperature.

3. KEMET lead-free BME C0G MLCCs provide a robust, low cost and green solution for various electronic applications. The offerings include case sizes from the 0402 to 1210 and above, and voltage ratings from 25V to 100V and above.

4. A summary of KEMET BME C0G MLCCs features:
    - High volumetric efficiency compared to film capacitors and other C0G MLCC
    - High insulation resistance and excellent HALT reliability performance
    - 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
    - Low ESR and high *Q* factor
    - Meet the lead-free soldering requirement

REFERENCES

[1] P. Pinceloup, et al., p293-296, 12th US-Japan Seminar on Dielectric and Piezoelectric Ceramics, Nov. 6-9, 2005, Annapolis, Maryland, USA.
[2] A. Perez, et al., p249-257, CARTS USA 2006, Orlando, FL, USA.
[3] K. Saarinen, et al., p187-191, CARTS USA 2004, San Antonio, TX, USA.