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Base Metal Electrodes Reduce Size And Weight Of MLCCs In Satellites

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Decades ago, it would have been difficult to predict private companies competing in a space race. Likewise, it would have been difficult to predict whole classes of small satellites emerging or the incredible performance enhancements within larger satellites. The rate of change in the satellite world is accelerating and along with that comes the changes needed for power supplies onboard. This article provides a high-level view of the emergence of base metal electrode (BME) multilayer ceramic capacitors (MLCCs) for satellite applications.

After providing some background on MLCCs and the development of their electrode materials, this article describes the advances in component materials, construction and fabrication techniques, and the track record in automotive and other sectors that have proven the reliability of BME MLCCs. Then the size advantages which motivate the use of these capacitors in space are discussed. The rest of this article reviews the reliability studies that AVX has performed to qualify BME MLCCs for space, and the status of space approvals for these capacitors, particularly Mil Prf 32535. Finally, it discusses details of BME capacitor design for space.

BMEs Versus PMEs

MLCCs have been the predominant capacitor technology used in ground-based large-scale electronics for almost three decades now; and, ever since the advent of high-volume surface-mount technology (SMT) in the 1990s, these parts have continually been downsized and had their capacitance ranges expanded to satisfy ever-increasing demand.

Ceramic capacitor technology itself has also changed over the course of the last 30 years, especially with regard to the move from precious metal electrodes (PMEs) to base metal electrodes (BMEs). This evolution was initially driven by the instability of palladium silver pricing in the late 1990s, but has continued since in an effort to satisfy demanding cost versus performance objectives.

In fact, around 99% of all ceramic capacitors currently in use feature BME materials, design, and construction. Ceramic capacitors are used in almost every electronics application spanning the commercial, industrial, automotive, aerospace, and space markets. However, until recently, BME capacitors have seen only limited use in space applications. Space specification systems have historically mandated that PME technology be used for ceramic capacitors in flight applications, but materials, fabrication, and testing developments have finally enabled the use of BME capacitors on a widespread basis in space applications.

Advances In BME Technology

There have been many advancements in the ceramic materials set used for BME capacitor products. These include the use of smaller particle size barium titanate (BT) ceramics and the addition of rare earths to the base ceramic. Both of these changes have enhanced the reliability performance of the very high capacitance values now in production.

There have also been significant improvements in the fabrication equipment capabilities required to successfully cast, print, stack, and fire extremely thin ceramic layers. For example, the production of high-capacitance BME components with an electrode count in the region of 400 to 500 electrodes (versus the 100 to 200 electrodes in early BME components) is now commonplace. This advancement is the result of both highly accurate registration systems capable of aligning each electrode inside the capacitor and automatic vision inspection at the stacking stage, which precisely measures the position of each electrode with reference to the previous layer.

Developed in the 1990s, the firing process for BME capacitors uses a large tunnel furnace with finely tuned temperature and gas control systems that manipulate the inert, predominantly nitrogen (N_2) atmosphere in order to create highly reliable ceramic capacitors.

Additionally, the long-term reliability of BME capacitors imparted by materials, fabrication, and testing developments has been effectively proven over the past 15 years. This is due in large part to their employment in the automotive industry, which requires that several stringent AEC-Q200 specifications—including life testing to a minimum of 1,000 hours—be met before products can be released into production and supply.

BME MLCC Advantage In Space Designs

BME capacitors enable a significant reduction in physical size (often on the order of four to eight times) when compared to PME capacitors with equivalent capacitance and voltage ratings. This size reduction—combined with the proven reliability achieved through the advancements discussed above—has prompted design engineers to gradually replace most PME capacitor systems with BME systems in applications across all markets. These now include space, for which the reduction of size and weight is nearly as critical as high reliability performance. As illustrated in Fig. 1, the difference in size is often so appreciable that designers can move from a leaded/assembled PME capacitor to a surface-mount BME capacitor.

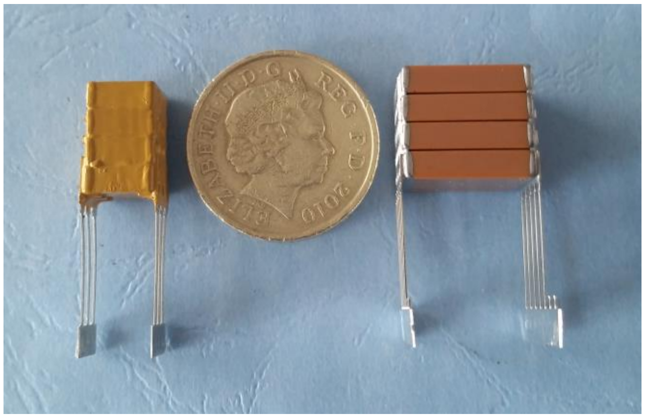

Fig. 1. A four-stack BME capacitor for space applications (left) and a four-stack PME capacitor with equivalent capacitance and voltage rating (right).

Initial High-Reliability BME Work

In 2008, the European Space Agency (ESA) and AVX, a manufacturer of passive components and interconnect solutions, initiated a program to evaluate BME capacitors for space applications. This program initially set out to define a range of surface-mount device (SMD) ceramic capacitors for evaluation in a reliability test program with a significant focus on overstressing the components with high temperatures and voltages in order to establish the performance of the product range at elevated conditions.

The initial test product range featured components ranging in case size from 0603 (EIA values) to 1812. Smaller 0402 BME products were available in 2008, but were not selected for evaluation due to both their low design-in rate at that time and the fact that power supplies, which tend to use larger capacitors, were one of the primary space applications for these BME capacitors. There have been extended long-term reliability tests carried out on the maximum capacitances values for the ESCC initial ranges extending out to 10,000 hours of reliability test time with no failures as indicated in Table 1.

That initial study resulted in AVX's X7R BME MLCCs achieving the European Space Agency's (ESA's) Qualified Parts List (QPL) status in 2015 under the criteria of the European Space Components Coordination's (ESCC's) 3009/041 specification. The AVX parts featured Sn/Pb-plated Flexiterm terminations, which provided enhanced resistance to mechanical stress by allowing for more board flexure than standard terminations, especially in large case sizes.

The initial case sizes and ranges qualified were 0603 to 1812 cases rated at 16 V to 100 V and 2.2 nF to 8.2 µF. Since that time, the ESA-qualified product offering has expanded to 0402 to 2220 cases with capacitance values and voltage ratings extending from 2.2 nF to 22 µF and 16 V to 100 V.

Table 1. Long-term standard life testing of BME MLCCs.

	Life Testing 2 x Rated Voltage @ 125 Deg C . Sample Size 125 pcs									
AVX Part number	1,000 Hrs	2,000 Hrs	3,000 Hrs	4,000 Hrs	5,000 Hrs	6,000 Hrs	7,000 Hrs	8,000 Hrs	9,000 Hrs	10,000 Hrs
18123C825K	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
06033C184K	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
12105C105K	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
12065C105K	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
08051C104K	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS
18121C225K	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS

The various stringent evaluation programs for BME capacitors deliberately overstressed the parts with both voltage and temperature to generate long-term data for life performance evaluation. These tests have shown that the long-term reliability performance of these devices under highly accelerated conditions is excellent, and complies with all of the necessary performance expectations for space applications. Table 2 gives two examples of this ESA evaluation data on a maximum capacitance value with significant overvoltage of 4x the rated voltage at 125°C (3.75x rated voltage for the 0805 part) and a test time of 2,000 hrs. Twenty five samples were tested with no failures recorded.

Table 2. Accelerated life test results for a 50-V, 1.0-µF BME MLCC in a 1210 case and a 100-V, 0.1-µF BME MLCC in an 0805 case. Accelerated test conditions include 200 V, 125°C and 2000 hours.

	Defect level		
	1000 hrs	1500 hrs	2000 hrs
1.0 µF in 1210	0/25	0/25	0/25
0.1 µF in 0805	0/25	0/25	0/25

The BME product designs used were conservative compared to the range of BME capacitors currently available for the automotive and commercial markets. In particular, these designs for space incorporated larger dielectric layer thickness between opposing polarity electrodes and greater margins/cover layers surrounding the electrode stack for added protection. (More on these design choices in the next section.) However, these parts utilized a heritage BME materials set with approximately 10 years of field data, and can therefore be trusted.

Additionally, the BME products tested were all the maximum values within their corresponding size, voltage, and capacitance categories, so the lower values were expected to at least meet, and likely exceed, the long-term accelerated life data. The actual accelerated life performance for the few BME parts tested to both 2,000 and 10,000 hours exhibited MTTF values of ≥26,000,000 hours, which is nearly 3,000 years.

Specifically, the 2000 hours of failure-free operation of the 50-V, 1.0-µF BME MLCC in the 1210 case at 4x the rated voltage and 125°C was equivalent to

- 16,000 at 2x the rated voltage and 125°C, or
- 26,000 component hours at half the rated voltage at 85°C.

Similarly, the 2000 hours of failure-free operation of the 100-V, 0.1-µF BME MLCC in the 0805 case at 3.75x the rated voltage and 125°C was equivalent to

- 13,000 hours at 2x the rated voltage and 125°C, or
- 22,000 component hours at half the rated voltage at 85°C.

These results show that hi-rel BME capacitors are capable of excellent performance in long-term accelerated life tests.

In addition to achieving the ESA's QPL status, AVX also pursued the Mil Prf 32535 specification (approved 2018) and NASA S311-P838 specification (approved 2016). The current state of Mil 32535 approvals for AVX BME MLCCs is shown in Table 3.

Table 3. Current state of approvals for AVX BME MLCCs.

MIL PRF 32535 X7R APPROVED RANGE

Mil		M3253502			M3253503			M3253504			M3253505			M3253506			M3253507			M3253508		
Case Sizes		0402			0603			0805			1206			1210			1812			2220		
Code	Value	16/25V	50V	100V	16/25V	50V	100V	16/25V	50V	100V	16/25V	50V	100V	16/25V	50V	100V	16/25V	50V	100V	16/25V	50V	100V
222	2.2 (nF)																					
272	2.7																					
332	3.3																					
392	3.9																					
472	4.7																					
562	5.6																					
682	6.8																					
822	8.2																					
103	10																					
123	12																					
153	15																					
183	18																					
223	22																					
273	27																					
333	33																					
393	39																					
473	47																					
563	56																					
683	68																					
823	82																					
104	100																					
124	120																					
154	150																					
184	180																					
224	220																					
274	270																					
334	330																					
394	390																					
474	470																					
564	560																					
684	680																					
824	820																					
105	1 (µF)																					
125	1.2																					
155	1.5																					
185	1.8																					
225	2.2																					
275	2.7																					
335	3.3																					
395	3.9																					
475	4.7																					
565	5.6																					
685	6.8																					
825	8.2																					
106	10																					
126	12																					
156	15																					
186	18																					
226	22																					

Design Is Key To High Reliability

The capacitor design model used for high-reliability BME "space " capacitors employed a very conservative approach in which the individual dielectric layers, capacitor cover layers, and margin areas were selected to give the part a lot of additional protection from overvoltage stress and any external environment influences. Fig. 2 illustrates the typical construction of a high-reliability MLC capacitor for space applications.

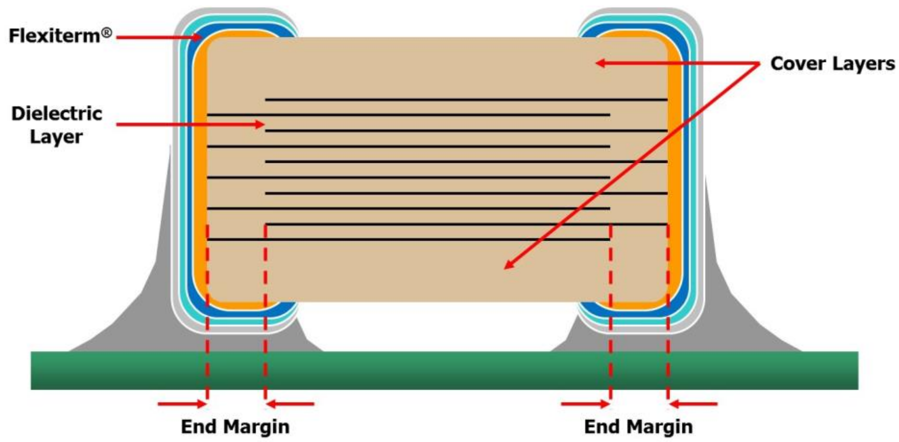

Fig. 2. The typical construction of a high-reliability BME MLC capacitor for space applications.

MLCC product design has four key component areas: dielectric layer thickness, side/end margin dimensions, capacitor cover layer thickness, and capacitance value.

Ceramic Layer Dielectric Thickness

Commercial BME capacitor products are presently using fired dielectric thicknesses of anywhere from ≤2 µm for low-voltage (4-V) X5R devices to 80 µm for the higher-voltage (2-kV) X7R devices. So, a 25-V to 100-V X7R product would have a dielectric thickness in the range of 5 µm to 18 µm, depending on the actual voltage rating. This may differ from supplier to supplier, but these are typical design parameters.

All of the space products designed for the ESA evaluation used an extremely conservative approach that featured an additional dielectric layer thickness beyond even the present automotive designs. For example, a 50-V automotive-grade capacitor would have used a dielectric layer of around 4.5 to 5 µm, but its equivalent space part was designed with a minimum ceramic layer thickness of 11 µm (green/unfired dielectric), approximately 2x greater giving enhanced product protection with respect to voltage stress and reliability performance.

Capacitor End And Side Margins

Capacitor margins are used to protect the inner electrode structure from the outside environment, and the end terminations from opposing polarity voltages. These are usually made as small as possible for manufacturing in order to maximize the area of the electrode plate (EPA) and, hence, the capacitance value. The minimum side and end green margins for a commercial part are around 75 µm, and around 100 µm for an automotive part. For the space designs, these margins were set at 170 µm for 25-V rated products to ensure an extra design safety.

Dielectric Cover Layers Top And Bottom

The cover layers that are set on the top and bottom of the internal electrode stack are normally a minimum of approximately 75 µm for a commercial part and 100 µm for an automotive part. The space designs featured a minimum cover layer thickness of 112 µm for the 25-V parts, 160-µm for the 50-V parts, and 160-µm for the 100-V parts.

Summary

Around 99% of all ceramic capacitors currently in use—spanning the commercial, industrial, automotive, and aerospace markets—feature BME materials, design, and construction. However, until recently, due to space system specifications, BME capacitors have been restricted in space applications. Fortunately, materials, fabrication, and testing developments over the past 15 years have finally enabled the use of BME capacitors in space applications. In space, these capacitors are particularly beneficial due to the high costs of space payload and the fact that BME capacitors enable a significant reduction in physical size.

About The Authors

Employed by AVX Ltd since April 1983 and based in the Coleraine manufacturing facility in Northern Ireland, John Marshall serves as technical liaison on the Space PME Product Materials, Product Engineering and Development where he provides technical support for the AVX Space and Aerospace BME ceramic capacitor development programs through Materials, Process Engineering, Screening Techniques and Reliability programs. John is also a customer technical liaison and assists with design-in for projects utilizing BME capacitor products within the U.S.A and Asia regions with particular emphasis on the space and aerospace ceramic capacitor market and the automotive ceramic capacitor customer base.

Additionally, John has held various responsibilities in the Process Engineering, Production and Quality areas and several years as Manufacturing and Operations manager. He has spent two periods of secondment in the Asia region, first in 2002 to 2004 providing technical support to the Ceramic Manufacturing operations in Malaysia and China and developing the AVX customer base with particular emphasis on the power supply, telecommunications and automotive industries. During the second period from 2009 to 2010, John was responsible for Distribution, Logistics, Planning and MIS for all AVX Asia regional groups. He holds a BSc degree from Queens University, a PgDip from the University of Ulster, and an MSc from the University of Ulster as well as a CEng. M.I.E.T.

Currently an AVX Fellow, Ron Demcko manages the TSG team at AVX headquarters in Fountain Inn, SC. This role centers on projects ranging from simulation models for passive components to product support/new product identification and applied development. Prior to that Ron was the EMC lab manager for AVX in Raleigh N.C. This lab concentrated on subassembly testing and passive component fixes for harsh electrical and environmental applications. Before the EMC lab work, he held an application engineering position at AVX. Product work included integrated passive components, EMI filters and transient voltage suppression devices.

Previously Ron worked as a product engineer and later as a product engineering manager at Corning Glass Works' electronics division. In this role he supported production, sale and development of pulse-resistant capacitors, high-temperature capacitors and radiation-resistant capacitors. He developed high-frequency test methods and co-developed high-temperature test systems. Ron received a BSEE from Clarkson College of Technology.

For more information on capacitors, see How2Power's Design Guide, locate the Component category and click on "Capacitors". For information on power design for space applications, see How2Power.com's Space Power section.