CAPACITOR INSULATION

As the consumer and industrial requirements for compact, high power density, electrical power systems grow substantially over the next decade, development of high-power/energy density capacitor technology is a major enabling technology component element. For microsecond to fractional-second electrical energy storage, discharge, filtering and power conditioning, capacitor technology is unequaled in flexibility and adaptability to meet a broad range of requirements in the future (1–21). This review presents the current status of modern capacitor technology, materials of fabrication, manufacturing technologies, and areas of application. In addition, the largest market sector types of capacitors have future requirements that will be driven by the ever increasing electrification of nearly all aspects of the modern world. Discussions in this article concentrate on commercially available capacitor technologies in broad marketplace use. Those who have an interest in advanced research underway in emerging areas of this technology will find this well addressed in the numerous technical research journals broadly available within international technical societies.

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

Table 1. Trends in Capacitor Applications and Operating Conditions[a]

Power kW (average)	Voltage kV (peak)	Run Time[b] s	Application
<1	<50	>1000	• Electronic countermeasures • LADAR • Communications • Computers • Uninterruptible power supplies (UPS)
1–10	<100	>10	• LADAR • RADAR • Workstation computers • Telecommunications • Power quality • UPS
10–1000	<500	>100	• High-power microwaves • RADAR • Power quality • Distributed power systems
>1000	>100	Single-pulse to continuous	• Directed energy weapons • Antimine • Power stabilization/quality • Power factor control • Industrial processing

[a] Most systems are projected to be divided by voltage/average power/run-time considerations as shown in the table.

[b] Run time refers to one operational cycle. For some applications, such as power factor control, systems run continuously for the entire life of the system.

Today, high-energy pulsed power conditioning has been achieved for pulse durations from 0.05 μs to over 1000 μs at voltages from megavolt levels for microseconds to subkilovolt levels up to millisecond durations (3–5,9,10,12,19–21). Voltage levels have been determined by the nature of the load. Developing innovative new capacitor and related insulation systems operating at near ultimate voltage withstands (>2× to 5× today's operational levels), will enable the achievement of lightweight systems needed in the future (4–21). Repetition rates will move up to multimegahertz, necessitating integrated development of capacitor technology with that of low-loss ($\ll$1%) switching topologies and voltage multiplication transformers (1–20). Most future systems are projected to be divided by voltage/average power/run-time considerations, as shown in Table 1 (3–7,9,10,19–21).

Description of the Technology

A capacitor generally consists of conducting plates or foils separated by thin layers of an insulating medium. The plates on the opposite sides are charged by a voltage source. The resultant electrical energy of this charged system is stored in the polarized insulating medium and the physically separated surface charges on the electrodes. Capacitors permit storing electrical energy over a long charging time and then release it as required over very short (submicroseconds to multimilliseconds) periods under controlled conditions (4,18). Such energy discharge operation, as with filtering duty, requires device technology of very high efficiency per unit volume/mass to minimize thermal management constraints on the system designer, as summarized in Table 1 (4,7,14,15). Particular attention must be given to the life and reliability necessitated by the system requirements. The main classes of capacitor applications are illustrated in Table 2 (7,8,11,14,15,18–21).

Scalability of Capacitor Technology

To date capacitors for ac ripple filtering in dc systems, passive energy storage, and power transfer are unequaled in their geometric flexibility, permitting rapid design optimization for man-portable, vehicular, and large mobile or fixed ground installations for voltages from subkilovolts to megavolts, allowing rapid turnaround time and modular field maintenance (7–19). For future users of advanced power sources, the compact systems being driven by ever-increasing electrification of modern systems would be enabled with capacitor energy and power densities two to ten times those available today (1–15,19). This is potentially feasible and should be conjoined with the possibility of developing advanced capacitor technologies that may well yield capacitors whose performance degrades gracefully, hence, no longer a single point of failure within a power conditioning system (7,8,13–15). Indeed, even during normal life and under adverse environments, such a technology would always result in graceful and predictable reduction in performance, so that total system operation could be retained at levels of declining cycle-life performance (7,14).

Table 3 projects next-decade or so future performance of capacitors, building upon the state-of-the-art capacitor technology, and also shows selected examples of several classes of advanced capacitors that R&D might turn into future practical, highly compact systems (1–21). These advanced systems all have the potential for elevating the energy (kJ/kg) and power (kW/kg) densities by a factor of two to ten times. Costs for these advanced units in production volumes are projected to be comparable to current technology (7,13,14,19). Projected energy densities for advanced storage capacitors are illustrated in Fig. 1. Projected power densities for high frequency ac+dc filter capacitors are shown in Fig. 2.

The observed evolutionary advance rate for capacitor technology is about a factor of 2× per decade in any performance factor well away from *nature's limits* (e.g., such as power density) (2,3,7,19). If evolution were allowed to drive capacitor technology, meeting these requirements would take 80 to 90 years. Therefore, R&D underway now will move toward these requirement-driven performance levels within the next decade (7,8). On the other hand, the current advance rate in supported R&D for high-energy, pulse-discharge capacitor technology for high energy capacitor systems is projected at eighteen times per decade. When applied to the other types of capacitors needed in the next generation power systems, this will meet far-term requirements by the end of this de-

Table 2. Main Classes of Capacitor Applications[a]

- Low- and high-frequency filtering in ac + dc systems
- ac resonant-charging power supplies
- Switched-mode power supplies
- Energy discharge
- High-frequency bypass

[a] See Ref. (18–21).

Table 3. Performance of State-of-the-Art and Advanced Capacitor Systems[a]

Capacitor System	kJ/kg Now/Future	kW/kg (average power) Now/Future	Rep-Rate Hz	Main Issues
Polymer film	0.4/20	5/20 k	>1000 k	• New polymer films • Impregnants • Foils and conductors • >200°C • ⩾1 kJ/unit • Voltage reversal • Pulse duration • Repetition rate • Surface mount—solder reflow stability
Ceramic	0.01/5	10/10 k	>1000 k	• Ceramic formulations • Electrodes • >300°C • 1 kJ/unit • Voltage scaling • Fusing
Electrolytic	0.2/2	2/10 k	>10 k	• Electrolytes • Separators • >200°C • 1 kJ/unit • Gassing • Hermetic sealing • Voltage reversal • Pulse repetition rate
Mica	0.005/0.05	5/50 k	>100 M	• Electrodes • >400°C • 1 kJ/unit • Voltage scaling/reversal • Materials • Impregnants

[a] Projects near term and future performance of state-of-the-art capacitor technology and shows selected examples of several classes of advanced capacitors that R&D could turn into future practical, highly compact systems.

cade, provided the necessary R&D is set and maintained (3,6,7,11,13,15,19–21). For comparison, Table 4 shows a summary of the performance parameter ranges of current electrolyte and polymer film capacitors.

Competitive Advantages of Higher Power Density Capacitor Technology

A major factor in designing the next generation of advanced power conditioning systems and switched-mode power supplies is selecting available high-power density components (7,14,15,18,19–21). Observations over recent years have shown that a technically highly demanding area is the application of capacitors for switched-mode power supplies and switching regulators, mainly in the areas of dc input and output filtering, as well as resonant elements internal to the power conditioning system (2,8,11,14). Only with adequate data on compact (at least two to ten times higher power density) capacitors, performing at the higher frequencies of inter-

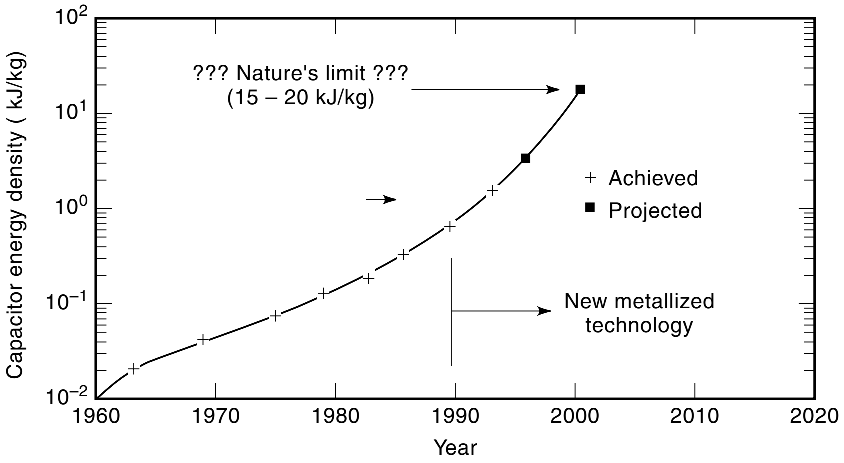

Figure 1. The time line of increasing energy density in energy discharge capacitors, starting from the early 1960s.

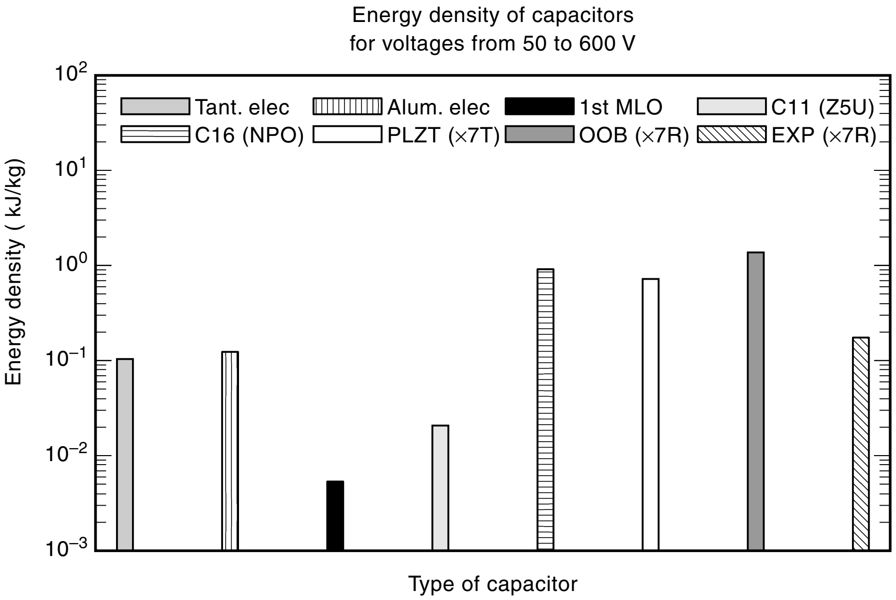

Figure 2. Projected power densities for high-frequency ac + dc filter capacitors.

est (≫1 MHz) can cost-effective designs of such power systems be practical for both the international marketplace and domestic use (7,14,15). Ceramics presently appear to be one intrinsically high-temperature, and hence long-lived, technology available with a very large potential for advancement, particularly with the recent advent of new materials and the multilayer ceramic capacitor's (MLC) demonstrated production capacitance and voltage scalability (≫ 100 μF, > 500 WVdc (11). Costs are also coming down from $1 per microfarad a few years ago, to less that $0.25 per microfarad today (11).

The development of new solid and liquid materials, in conjunction with advanced methods of manufacturing technology, is feasible with tools emerging from present successful technology programs (6–9,18,19). What will be required further is a tightly integrated material/component set of development programs tailored to areas of need for the main classes of capacitor technology (7,18–21). The advancement of capacitor technology to date has been successful because of the preeminent role that capacitor developers in industry have directly taken in integrating materials development into the practical realization of advanced capacitors (7,18,19,21). The power source developers of the future may well find that working together in this materials technology arena will enable a systems-responsive technology development program in each of the major capacitor technology areas. This would result in demonstration subscale hardware that will operate at the power and energy densities needed, being no smaller than tenth-scale in unit capacitance (4–9).

An example of the projected increase in energy density of electrostatic and electrochemical capacitors for use in switched-mode power supplies is illustrated in the trend plot of Figure 2 (2,8,13–15). Achieving the power densities, at, say, an operational frequency of 10 kHz, of between 10 MVAR

Table 4. Summary of Capacitor Characteristics[a]

Ceramic	Electrolytic	Film
Commercially available sizes:		
10 pF–100 μF	0.1–2,000,000 μF	100 pF–5,000 μF
Operating voltage:		
(Vdc) 25–500	6–600	25–300,000
(Vac) 25–500	110–330[b]	25–5,000
Dissipation factor (%):		
1 kHz: 0.15–2.5	2–10	0.05–1.5
100 kHz: <1	—	<0.1–10
Gravimetric energy density:		
0.005–0.50 (kJ/kg)	0.05–0.7	0.1–2.5
General relative cost:		
1×	3×	1×–10× (size dependent)

[a] Presently available capacitor performance parameter ranges available in the commercial marketplace.
[b] Short-term ac duty.

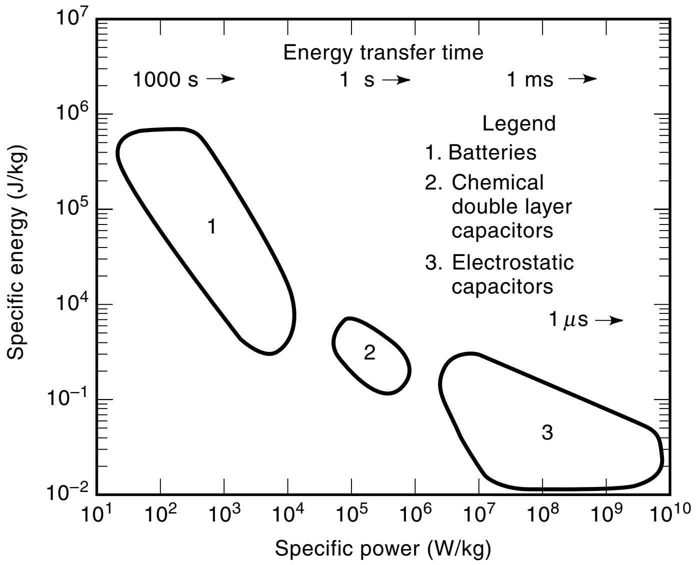

Figure 3. Capabilities of batteries, electrochemical capacitors, and electrostatic capacitors as functions of energy and power densities. Each power source optimizes over specific parametric regions of energy transfer time, ranging from microseconds through thousands of seconds. Appropriate efficiency energy transfer time technologies can be readily identified (1,23,28).

and 20 MVAR per cubic meter would mean a reduced capacitor volume fraction in such systems from the 30% to 50% of today to negligible proportions (<5%) in the near future (3,6–8). The inductance and internal series loss resistances at the higher frequencies of operation will also be reduced proportionately to achieve higher frequency operation at higher efficiencies (4–9,19–21). Clearly, the new chemical double layer technology whose performance is illustrated in Fig. 3 will evolve to fill the important technology performance position between the capabilities of modern batteries and conventional capacitors. Rapid progress in this area is expected, and new product lines are under development.

In the following status update section on film (Ian Clelland and R. Price), tantalum (John Prymak), ceramic (John Prymak), electrolytic (Martin Hudis), mica (John Bowers), and related technologies, progress over the last few years and projections of the future will be addressed by experts in the field.

ULTRALOW ESR MULTILAYER POLYMER CAPACITORS PROVIDE STABILITY AND RELIABILITY IN POWER CONVERSION APPLICATIONS

Background

Modern high-frequency switching converters designed around MOSFET technology have attained new, higher levels of reliability due to quality improvements made in switching diodes and the employment of zero-transition switching. This is less true for inverters using hard-switched integrated gate bipolar transistors (IGBT) diode sets, but the power switch quality trend is still positive. An increase in switching frequency has allowed significant size reduction of the magnetic and reactive filter components, but this has also shifted the circuit's critical stress point. More attention must now be paid to the filter components and in particular to the filter capacitors that must operate at very high ripple and load currents relative to their small size. Like any electrical/electronic component, all capacitor technologies have potential wear-out and failure mechanisms which depend on voltage, frequency, temperature, and time. When dramatically increasing any one of these parameters (such as the frequency), much more care must be taken in choosing the proper component for the application. Because of their proven reliability and endurance, plastic film capacitors have historically been specified for critical applications. Evolved from plastic film technology, a novel *multilayer polymer* (MLP) technology utilizing metallized polymer film laminated into high density stacks is now contributing to power system reliability because of its stability under operating stresses and its inherently low impedance per unit volume.

Trends and Solutions

PWM and Resonant Voltage Converters. Operating between 200 kHz and 1 MHz, these devices are radio-frequency noise generators due to the switching frequency and pulse generated harmonics. The input and resonant power train sections need low-loss capacitors to achieve low impedance at high frequency. The output filter sections require large capacitance values for load current holdup and low voltage ripple current handling. Ceramic or film capacitors are used in the input whereas tantalum electrolytic capacitors are generally used for the output. All capacitors must be surface mount compatible.

Inverter and ac Motor Drives. Now operating above 20 kHz, inverters and ac motor drives require low-loss, pulse-decoupling (snubbing) and high-current dc link/bypass capacitors. Film capacitors are used for the IGBT decoupling and bypass whereas banks of aluminum electrolytic capacitors are used on the dc link bus. Surface mounting is not presently much of an issue, but component selection is becoming more critical as the switching frequency increases.

EMI Filters. Used in prerectified front ends, EMI filters require across-the-line and line-to-ground ac-rated film capacitors. Because of the high voltages and pulse conditions, polymer film capacitors are preferred over ceramic types. Conventional plastic film capacitors tend to be physically large and unsuitable for surface mounting, so an evolution is taking place at the component level. To achieve significant size reduction and produce a low profile input module, MLP capacitors are proposed for the EMI filter section.

Polymer Dielectric Approach

The MLP capacitor, best described as a construction hybrid between MLC and stacked, plastic film capacitors is fully surface mount compatible. The parts were developed for high-frequency, ripple-current handling and high-pulse applications demanding over 10 years of operating life. The chip and block shaped parts are not subject to the aging, cracking, and shorting sometimes experienced in other capacitor systems. The system substitutes the catastrophic single point of failure (shorting and heating) with a more gentle failure mode.

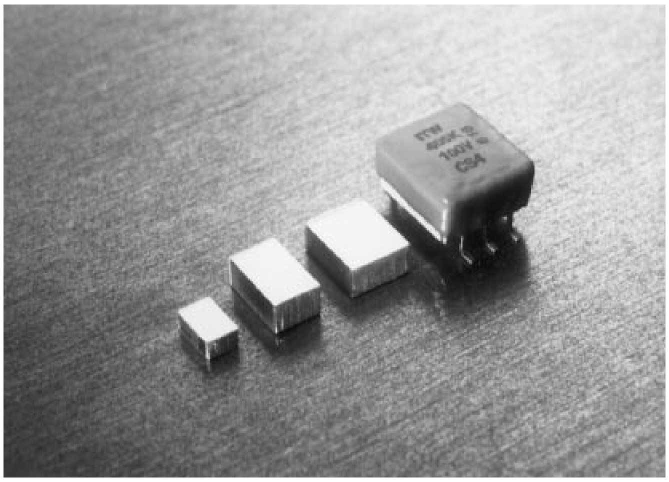

Figure 4. Examples of the newest surface mount MLP capacitors designed for low-profile board mounting.

The present offering of nonpolar, highly stable MLP capacitors covers the range from 0.047 μF through 20 μF with voltages from 25 Vdc to 500 Vdc. Today, this technology is leading in *CV* density and is growing most rapidly in input voltage filtering from 48 V to 400 V and output filtering at 24 V to 48 V. Many of the products are available in surface mount styles as lead-framed construction or as true *chip* capacitors. A key element in the success of this system is the gentle failure mode, which manifests itself as a gradual loss of capacitance. Because the units can self-clear, short-circuiting as the single point of failure is virtually eliminated. The body of the units is *plastic* eliminating the well-known problem of cracking caused by temperature coefficient of expansion (TCE).

The photo in Fig. 4 shows examples of the newest surface mount multilayer polymer capacitors designed for low-profile board mounting. Lead frame pin-outs are offered at 0.100 in. (0.254 cm) pitch. Figure 5 shows a cross section of the capacitor section that highlights similarities to conventional metallized film and MLC constructions. The dielectric systems in current use are polyethylene terephthalate (PET), polyethylene napthalate (PEN) and polyphenylene sulfide (PPS). The dielectric selected is based on the specific environmental and electrical properties required. PET and PEN are voltage-stable materials that compete favorably with X7R ceramic capacitor types. PPS is a very low loss and temperature-stable dielectric which offers size reduction compared to zero temperature coefficient ceramic chips.

PET thin-film dielectric has been available at 1.5 μm thickness for over 10 years. This material is now commercially available from multiple sources down to 1.2 μm and 0.9 μm thickness (with 0.6 μm in development) that is allowing another expansion of MLP capacitor capacitance-voltage products. PET was selected because of its good electrical characteristics, excellent reliability, and ready availability. PEN dielectric is now available down to 1.5 μm and 1.35 μm thickness. PEN film, a virtual clone of PET, has increased thermal resistance for surface mount applications and very good high-temperature electrical stability. Capacitor grade PPS film was introduced several years ago to address the needs of surface mount technology and thermal resistance. PPS is an extremely low loss dielectric, similar to polypropylene and zero temperature coefficient ceramics, which is contributing to reducing the size of resonant power converters.

High-Frequency Power Conversion Applications

High-frequency dc to dc converters require a wideband input filter and sufficient output capacitance to drive the load during the off-duty cycle. Because of wide use in telecommunication systems, 48 V dc bus (plus an ac component) filtering is approached with a 100 V rated electrostatic capacitor. Off-line, computer, and aviation bus voltages range from 300 V to 370 V and require a 400 V input capacitor. The capacitor must act as a low-pass filter to the input ripple voltage, which can be low frequency, and sees the reflected RFI due to the downstream switching noise. The capacitor typically selected is a MLP capstick capacitor (or alternately a ceramic type) with multiple leads for high current handling. Because of the frequency extremes and high voltage, the stability of PET is desirable for good ripple attenuation and noise suppression. The ESR of these filter capacitors is below 10 mΩ above 100

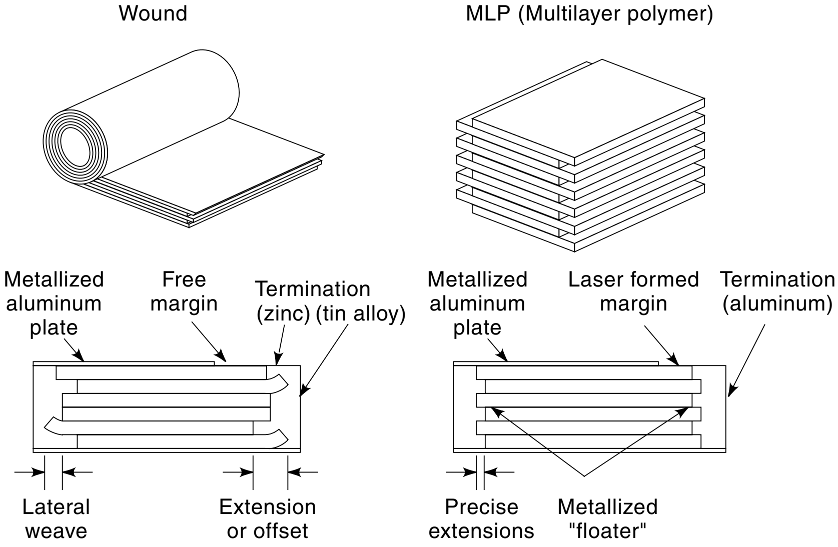

Figure 5. Cross section of the MLP capacitor body that highlights similarities to conventional metallized film and multilayer ceramic capacitor constructions.

kHz (see Fig. 6) allowing them to sink high ripple current. For output filtering these capacitor types are preferred over tantalum capacitors, especially at higher bus voltages, such as 48 V output.

Resonant and quasiresonant dc to dc converters achieve the highest power densities with good efficiency. For low voltage output, the circulating current in the resonant tank can be very high. For this application a 0.10 μF to 0.22 μF capacitor constructed with PPS is ideal. Polypropylene Film and COG ceramics work in this application but they are large and can be expensive. The capacitor can see in excess of 10 A rms at the switching frequency which makes the low dielectric loss of PPS highly desirable. These 5.0 mm lead-spacing PPS capacitors in leading and surface mount packages are rated from 25 Vdc to 400 Vdc for various output voltages.

Inverter Bus Applications

Space and efficiency constraints have forced 20 kHz and higher IGBT switching. The snubber and bypass capacitors are physically large and inductive at present. New MLP high-voltage chip capacitors are proposed for greatly reducing the size and height profile of the inverter package. The automotive industry is driving this effort because of the electric vehicle and various charging system requirements. The illustration in Figure 7 shows the proposed size reduction using the newer multilayer polymer technology.

Summary

Power conversion applications still require large capacitors to carry high load currents, and these are generally electrolytic in nature (aluminum or tantalum types). Because of the poor frequency response of electrolytic types above 100 kHz, electrostatic capacitors are filling more of the filter capacitor slots. Ceramic capacitors are ideal at low voltage, but the MLP type has better electrical characteristics and is much more stable under increasing voltage. At a given voltage level, this becomes critical as attested by the industry shift from MLC to MLP Types for 48 V inputs and outputs.

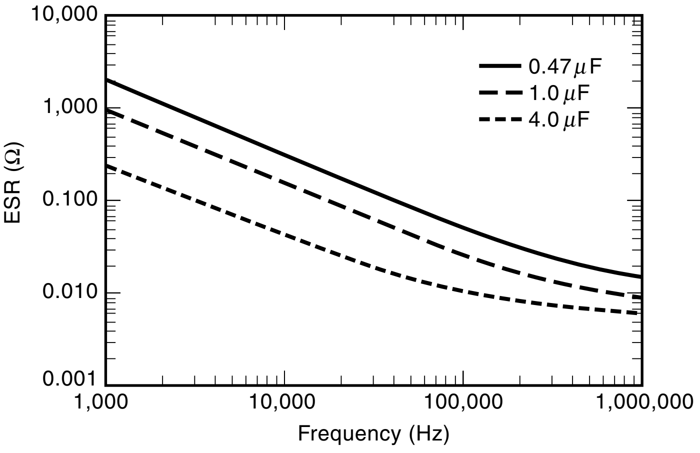

Figure 6. The ESR of 400 V class MLP capacitors used for power supply output filters for good ripple attenuation and noise suppression up into the multimegahertz frequency regime. The ESRs are generally less than 10 mΩ above 100 kHz, supporting sinking high rms ripple currents ⩾ 15 A_{rms}.

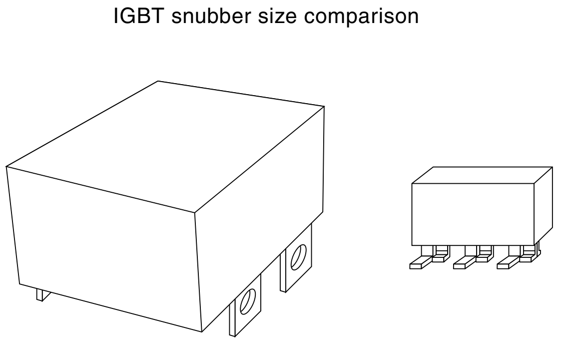

Figure 7. Standard capacitor and MLP size comparisons for high-voltage snubber and bypass applications.

TECHNOLOGICAL EVOLUTION IN METALLIZED POLYMERIC FILM CAPACITORS OVER THE PAST 10 YEARS

Introduction

This section analyzes the highlights of design, construction, and application of metallized polypropylene capacitors. Polypropylene (PP) capacitors are indispensable in high-voltage power applications, where the ultralow loss characteristics of PP film is not approached by other dielectric systems.

Metallized film technology has evolved into dry and liquid ac line-frequency capacitors, low- and high-voltage dc capacitors, high-peak-current capacitors, and high-frequency capacitors. Liquid metallized film capacitors are available in many different constructions. *Liquid filled* refers to a wound section encapsulated in a liquid dielectric fluid. The dielectric fluid does not penetrate between the metallized film layers. Liquid impregnated refers to a wound section containing either a metallized kraft paper used as the electrode or paper used as part of the insulation pad. In a liquid impregnated construction, the dielectric fluid actually impregnates the kraft paper and penetrates the insulation layers. Another variation of the impregnated construction comes from the use of hazy dielectric film. Hazy film contains an embossed surface (typically 6% to 12% space factor) allowing the dielectric fluid to penetrate between the film layers. Dry film capacitors are available using either metallized film or film foil, but this paper is confined to liquid-filled and dry metallized technologies (i.e., no foil construction). Ac line-frequency, high-frequency and high-peak-current capacitors all use polypropylene (PP) film because they require a low dissipation factor typically less than 0.1%. Dc-rated capacitors tend to use polyester (PET) because they require very thin gauges and a large modulus of elasticity for machine winding. In addition, the dc applications do not require a very small dissipation factor like ac capacitors and can generally use 1% limit.

Design evolution occurred slowly from 1960 to 1985, resulting today in an image as a mature industry, that is, very little change took place after 1985. During that 25-year period other polymer films have been used, such as polystyrene and polycarbonate, but polypropylene and polyester remain the dominant films for metallized polymeric film capacitors. The image of a mature industry is in fact not correct. Metallized PP film capacitors have continued to evolve beyond the 1985

Figure 8. Example of (top) the metal case liquid-filled and (bottom) plastic case dry-potted motor run capacitor.

status with many changes occurring over the last decade. Following are specific examples of these developments:

1. Liquid-filled, self-protected motor run capacitors progressing from metal case to plastic case
2. Self-protected motor run capacitors with a pressure interrupter progressing from a liquid-filled metal case to a dry-potted plastic case including the introduction of segmented metallized electrodes
3. Pitch-potted fluorescent ballast capacitors (≤660 Vac) going from a liquid-impregnated metal case to dry-coated construction using wax blends for the coating
4. High-voltage rate-of-rise snubbers progressing from a liquid-impregnated metal case to a dry-potted plastic case, including, in some cases, the transition from foil construction to metallized electrode construction
5. High-frequency ac capacitors progressing from foil liquid-impregnated construction to metallized dry construction
6. Very high peak power energy-discharge capacitors progressing from foil/paper construction to metallized kraft/film construction.

Discussion of Examples

Self-Protected Motor Run Capacitors. Line-frequency motor run capacitors require both long service life and fault protection. Over the years, this required a liquid-filled metal case capacitor incorporating a pressure interrupter. By 1985, this technology began to be replaced above the 200 Vac level with a plastic case, liquid-filled capacitor incorporating a pressure interrupter molded into the cover, and below the 440 Vac level with dry-potted, segmented metallized film construction. An example of the plastic case, liquid-filled capacitor is shown in Fig. 8 (top), and an example of the dry-potted, segmented metallized capacitor is shown in Fig. 8 (bottom).

The plastic case, liquid-filled capacitor utilizes an ultrasonic weld for the cover-case seam that is both leak tight and can withstand the high internal gas pressure which develops during a fault interruption of the pressure interrupter. Examples of segmented metallized electrode patterns are shown in Fig. 9. In general the continuous metallized pattern is divided up into segments connected to the end spray (schooping) through fusible links. The fusible links isolate the individual faulted segments giving rise to a soft failure mode, that is, capacitors fail open not short. In the dry-potted, segmented metallized film construction, the segmented pattern provides the equivalent function to the pressure interrupter. The common and attractive attributes for both new constructions are the plastic case and completely automatic assembly. The plas-

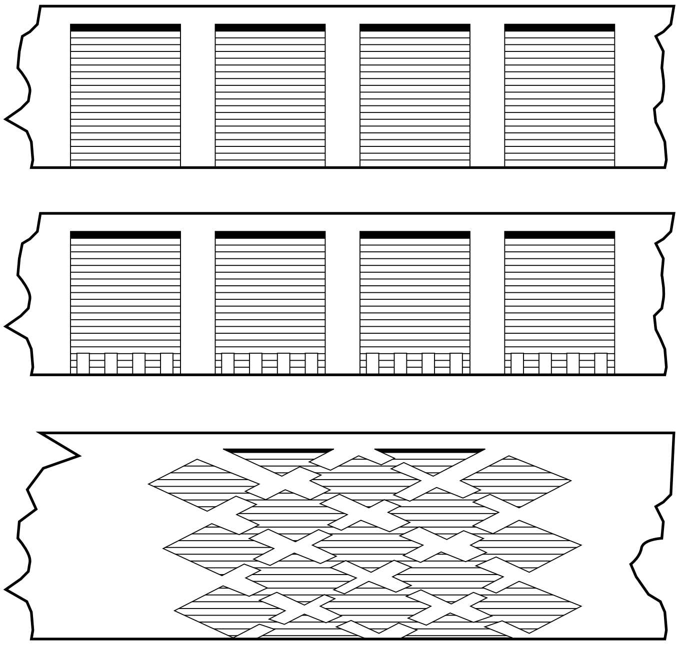

Figure 9. Examples of segmented, metallized electrode patterns.

tic case, unlike the metal case, does not rust, does not dent, and does not require grounding. Completely automatic assembly leads to a lower workmanship defect level which results in a higher mean time between failures (MTBF).

High-Current Snubbers. High-peak-current and high dV/dt film capacitors have also been available for many years, but have been constructed as liquid-impregnated foil polypropylene film capacitors using metal case and stud terminations. For high-peak-power applications, these capacitors require low inductance (ESL), low series resistance (ESR), high dV/dt aging capability and high-peak-current capability. In the past few years, the liquid metal case technology has slowly been replaced (in applications where $dV/dt \leq 2{,}000$ V/μs) by dry-potted technology by metallized film and by a capacitor with either a direct tab termination to the IGBT or a tab termination for printed circuit board mounting. The dry, direct-mount snubber has four main advantages over the liquid construction, lower ESL, lower ESR, smaller size, and lower total system inductance due to the direct mounting. The dV/dt aging and peak withstand capability of the dry design is not equivalent to the liquid-impregnated foil polypropylene metal can design, but over the past few years the dry design has improved to the point where it can be applied in many power electronic circuits.

High-Pulse Power Energy Discharge

Large energy discharge capacitors are commonly used for laser fusion, magnetic forming, electromagnetic guns, defibrillators, large strobe lights, to name a few examples. These capacitors can be as large as 125 kJ. Stored energy density for energy discharge (EDC) has increased from less than 0.3 J/cm^3 to over 1.5 J/cm^3 during the past 10-year period. This technology has been accomplished by moving from foil with kraft paper construction to metallized kraft paper with polymer film construction. Energy density is only one of the capacitor's performance parameters which has improved during this 10 year period. Voltage-reversal-withstand capability, peak-current capability, and cycle aging under various conditions have all improved dramatically with the movement from foil with kraft paper to metallized kraft paper with polymer film construction.

Discussion of the Technology

Technologies. Six technologies play a major role in metallized film capacitor performance. Some of these have changed over the past 10 years, and others have not. These technologies are the following:

1. Unmetallized polymer film dielectric strength
2. High temperature polymers for dielectric films
3. Dielectric fluids and capacitor processing
4. Lead attachment processing
5. Polymeric packaging and encapsulation
6. Metallurgy and metallization patterns.

Of these six technologies, unmetallized PP and PET polymer film dielectric strengths have had very little impact on the metallized film capacitor changes which have taken place over the past 10 years. The other five technologies have all had a measurable impact. The changes in a couple of the really significant technologies are briefly discussed in the following:

Dielectric Fluids. For higher voltage ac applications (≥370 Vac), liquid encapsulation is required to achieve long-term performance. In a metallized PP film capacitor, the dielectric fluid is used to encapsulate the section, reduce gas voids to increase the corona inception voltage, and limit the oxygen and water vapor which can penetrate the section and scavenge the activated gas molecules generated in and around the section. For voltages above 660 Vac, the capacitor must be liquid-impregnated and requires a metallized kraft or foil construction. With the banning of polychlorinated biphenyls (PCBs) in 1977, there has been considerable fluid development activity with focus on hydrocarbon and ester-based compounds. By the early 1980s, DOP (dioctylpthalate) was established as one of the best available fluids for long-term metallized polypropylene performance.

Impregnation fluids have contributed to a much higher reliability (i.e., smaller capacitance change over an accelerated 2000 h life test) and further increase in reactive energy density. As a final impact, these new dielectric fluids have today increased the operating voltage up to 660 Vac. In most cases, the increase in the reactive energy density and the operating voltage can be traced to advancements in both the dielectric fluids and the metallization.

Polymeric Packaging and Encapsulation. Injection molding technology has been developed that can produce a capacitor case and cover with a built-in pressure interrupter. These cases and covers are leak-tight and can withstand high fault pressure. These new chemistries provide superior humidity resistance, improved dielectric strength and can be applied with a much faster process which translates into lower cost.

Metallization Technology. Metallization technology has had a big impact on the performance improvements achieved over the past 10 years. A continuous metallized pattern has evolved from straight body to heavy edge. The body resistance has evolved from typically 1.5 W/cm^2 to values in the 7.5 W/cm^2 range with values in some cases going as high as 25 W/cm^2 for ac applications. The clearing energy is directly related to the thickness of the metallization layer which in turn affects the electric stress which can be applied. The metallurgy has changed from aluminum to zinc to a new generation of alloy. Zinc has a lower clearing energy than aluminum but does not have the same corrosion resistance to humidity. The newest generation of alloys has both a low clearing energy and high corrosion resistance to humidity.

Another area involving a large change has been the introduction of segmented patterns which provide the basis for dry, self-protected capacitors. Examples of segmented patterns are shown in Fig. 9. The big commercial development has been the metallization of segmented patterns with high-speed manufacturing processes. Dielectric film coatings, used either as a substrate for the metallization layer or a protected coating on top of the metallization layer, have also been used during the past 10 years. Although this is not a metallizing technology, coated dielectric film can interact with the metallized layer during the humidity corrosion process and/or during the clearing process resulting in improved performance.

Conclusions

The combination of metallized alloys, high surface resistance (thinner metallized layers), dielectric film coatings, and segmented patterns has contributed in large part to the changes in film capacitors which have taken place during the past 10 years. These technologies are in their early life cycle, As they continue to evolve over the next 10 years, so, too, will metallized film capacitors.

CHARACTERIZATION OF RECONSTITUTED MICA PAPER CAPACITORS USED IN HIGH-VOLTAGE AND HIGH-TEMPERATURE POWER ELECTRONICS APPLICATIONS

Introduction

High-voltage, high-temperature power electronics systems designed for commercial, aerospace, and military applications require highly reliable components. These types of power electronics circuits and systems include, or can include, the use of reconstituted mica paper capacitors. Reconstituted mica paper capacitors are particularly suited for operation where high ambient temperatures exist (18) and are an excellent choice for these types of systems.

Applications

Reconstituted mica paper capacitors are typically used for energy storage, filtering, coupling, etc., in high-voltage, high-temperature applications where radiation resistance, corona resistance, high volumetric efficiency, physical durability, and capacitance stability (with respect to temperature, voltage frequency, or mechanical stresses) are required. These types of applications include, but are not limited to the following:

- Airborne or surface radar systems
- ECM power supplies
- High-voltage transmitters for missile applications
- High-voltage TWT power supplies
- Ignition systems
- Power transmission systems
- Laser devices
- Gas and oil exploration equipment.

Small, high-voltage electronic modules can be designed and manufactured to include these types of capacitors in conjunction with other high-voltage components (i.e., resistors, diodes, spark gaps, strip lines, inductors).

Design and Construction

The dielectric material used in designing and constructing these types of capacitors is reconstituted mica paper impregnated with a liquid polymer resin (i.e., polyester, epoxy, or silicone). The National Electrical Manufacturers Association defines mica paper as flexible, continuous, and uniform layers of mica reconstituted into a paperlike, electrical insulating material composed entirely of small, thin, overlapping flakes or platelets with sufficient strength to be self-supporting and to be capable of being wound into roll form for commercial use (22). Capacitor-grade mica paper does not contain binders, adhesives, foreign matter, or coloring agents and is substantially free of any substance which will adversely affect its performance.

Capacitor-grade, reconstituted mica paper is manufactured from natural muscovite mica ($K_2Al_4Al_2[Si_6O_{20}](OH,F)_4$). An energy dispersive X-ray spectrum (EDX) for muscovite mica reveals a very complex composition that varies significantly with the natural source location on the globe (23). The van der Waal's forces between the crystal surfaces of the mica platelets in close proximity hold the layers together. Reconstituted mica paper ranges in thickness from 12.7 μm (0.0005 in.) to 50.8 μm (0.002 in. Depending on the type of packaging, capacitance, voltage rating, terminations, etc., various dimensions can be achieved.

Electrical, Environmental, and Physical Characteristics

Reconstituted mica paper capacitors are well known for their outstanding electrical, environmental, and physical characteristics (4,24). Most notably, these parts exhibit long life, a very low capacitance drift over the entire temperature range, withstand high voltages, are naturally resistant to the effects of partial discharges, and exhibit low radiation-induced conductivity caused by the absorption of ionizing radiation, such as x-rays, gamma rays, and neutrons. In addition, they exhibit a fractional voltage or charge loss as a function of the absorbed dose.

Percent capacitance change, dissipation factor (in percent), and insulation resistance (in megaohms times microfarads) from −55°C to 125°C for typical reconstituted mica paper capacitors are shown in Fig. 10.

Reliability

High reliability is the greatest strength of reconstituted mica paper capacitors. A complete understanding of the customer's requirements, proper design, the selection of highly reliable

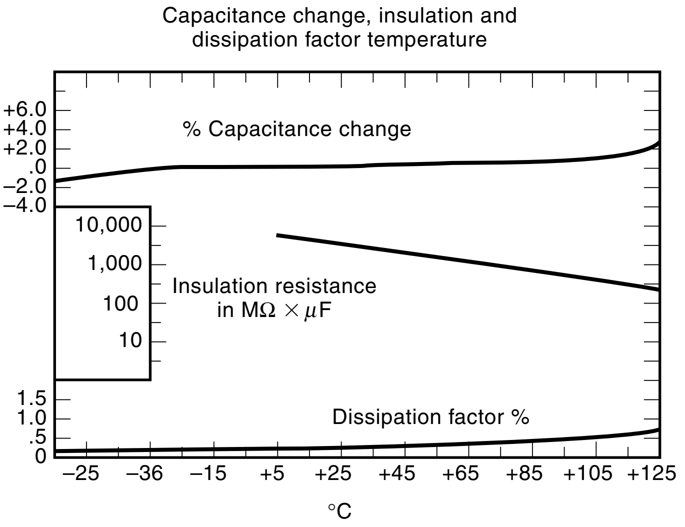

Figure 10. Typical reconstituted mica capacitor change in capacitance, dissipation factor (i.e., ac + pulse power losses), and dc insulation resistance (in MΩ × μF) from −55° to 125°C.

materials, and tight control of the manufacturing and testing processes all lead to the reputation of these types of capacitors.

Studies are currently being conducted to determine the voltage and temperature acceleration factors for the dc life of reconstituted mica paper capacitors. A voltage acceleration factor of 7 to 10 is typically used for reconstituted capacitors.

Standard electrical tests (i.e., capacitance, dissipation factor, and dielectric withstand) are completed for every capacitor. Other electrical tests normally conducted on a sampling basis include insulation resistance, ac and dc partial discharge, burn-in, pulse discharge, and inductance.

Environmental tests are frequently conducted in accordance with customer and/or military specifications. For example, these tests include temperature shock, barometric pressure, humidity resistance, extreme temperature, and so on. Typical physical tests include shock, vibration, solderability, resistance to soldering heat, resistance to solvents, and terminal strength.

Conclusions

The applications, design and construction, electrical, environmental, and physical characteristics, and reliability of this type of capacitor have been described. High-reliability reconstituted mica paper capacitors provide outstanding characteristics when properly designed, manufactured, tested, and applied to high-voltage and high-temperature power electronics systems.

CERAMIC CAPACITORS

Introduction

Ceramic capacitors have been in use since the 1940s. Developments of ferroelectric ceramics in the late 1940s and 1950s led to the greatest growth spurt for this type of capacitor. The $BaTiO_3$ ceramics are used almost extensively in these capacitors through to the present, with recent challenges by the latest developments in $Pb(Zr, Ti)O_3$ and other Pb-based ceramics.

The main construction employed today is the multilayer chip capacitor. These chips are still being offered with radial and axial leads attached, but this is a dying business and the surface mountable chips dominate the market. As this construction involves multiple layers (Fig. 11), the formula for capacitance C based on the physical parameters of the ceramic capacitor is as follows:

$$C = \kappa\epsilon_0(A/t)\%(n-1)$$

where ϵ_0 is the permittivity of free space; κ is the relative permittivity multiplier (hereafter referred to as the dielectric constant); A is the area; and t is the thickness.

State of the Art and Characteristics

The two methods of assembly for this capacitor vary in how the ceramic layers are built up. The *tape* or *dry* method involves casting the ceramic slurry and plastic binders into a dry tape. The tape thickness is controlled by process and material parameters. This method usually involved handling unsupported ceramic *sheets*, but now processing is on a polymeric film, and the film carries the ceramic deposit through the process. After the metal plate patterns are screened on the ceramic layer, the ceramic layer is lifted off the polymer carrier and placed into a stacking die for compression and additional processing.

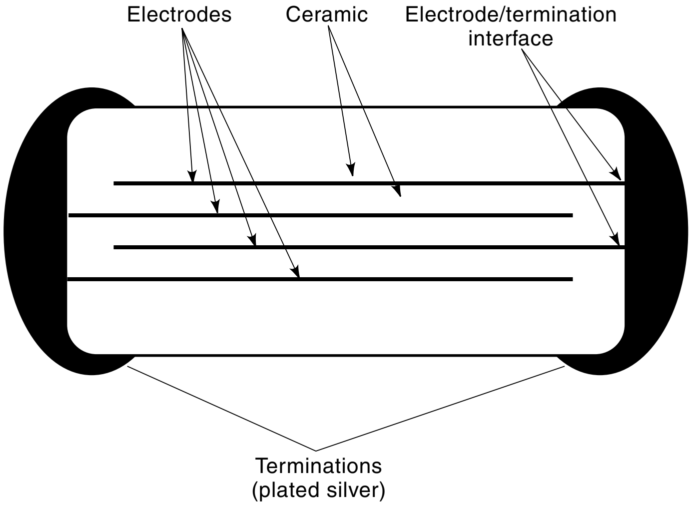

Figure 11. A typical ceramic capacitor construction in cross section for a completed part. Material issues for performance enhancement are described in (1).

The *wet* method requires that the ceramic slurry be deposited by squeegee on a base plate, usually glass. Then the deposited layer is dried after each layer is deposited. The metal electrode pattern is also applied wet, and after each application of the patterns, they must also be dried. This method came before the film carrier was introduced to the *tape* process and led the push to thinner dielectric thickness.

The most recent developments for ceramic capacitors have improved volumetric efficiency thereby increasing the capacitance range available with these devices. Looking back at the formula for capacitance, the factors that can be manipulated to increase capacitance involve the k or dielectric constant, the area, and the thickness. The area is somewhat restricted if these devices are to remain monolithic surface mount packages. Ceramic capacitors are susceptible to thermal and mechanical damage induced in the surface mount process and subsequent stress transfer from the boards themselves. These ceramic materials are brittle and have poor thermal transfer capabilities. As such, they develop thermal gradients large enough to crack them if they are heated too rapidly or if their mass is significant, as in very large chips. Chip sizes up to 3.8 mm × 2.5 mm can readily be processed by wave soldering. Chip sizes up to 5.6 mm × 6.4 mm can be processed by infrared reflow solder techniques. These chips are mounted to boards that are flexible and also have coefficients of thermal expansion dissimilar to that of the ceramic. This difference in thermal expansion defines the maximum chip size to be mounted directly to the board. Flexural movement of the board can also apply enough stress to the chip to cause cracks, and the larger the chip, the greater the susceptibility to either of these damages. Chips larger than these require a lead-frame attachment that relieves the flexural and thermal expansion stresses.

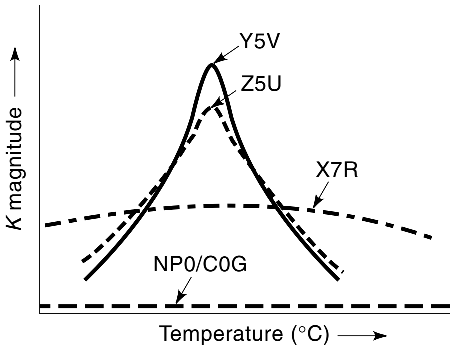

Figure 12. Ceramic capacitor variation in actual capacitance as a result in the change in the relative dielectric constant K as a function of temperature for several standard classes of capacitors.

The dielectric constant (k) can be manipulated to increase capacitance but at a cost of temperature (Fig. 12) and bias stability (Fig. 13) of the capacitance. The higher dielectric constant ceramics usually have higher temperature and voltage sensitivity in capacitance.

Both the area and the dielectric constant manipulation offer a direct relationship with capacitance. Doubling either, doubles the capacitance, but the thickness offers a geometric gain. If the thickness of the dielectric is reduced by half, the capacitance per layer of the capacitor doubles. Because the package size is fixed, twice the number of layers of the half thickness dielectric can be built into the package. Therefore halving the dielectric thickness increases capacitance by a factor of four. This is where the largest gains have been made to date. The thinnest ceramic dielectric previously produced had a 50 WVdc (12 μm thickness) rating which has been reduced to 25, 16, 10, and in rare cases, 6 WVdc (down to 2 μm to 3 μm thickness).

Ceramic Capacitors for Small-Signal Applications. The growth of ceramic capacitors has been mainly in small signal applications and only recently in power applications. Their small size, performance, cost and availability have led them to dominate small-signal processing from filtering to decoupling. It has really been the decoupling of IC circuitry that has allowed the ceramic market to develop along with the growth of the semiconductor industry. This application is well suited for a device that excels in high frequency and transient performance, is low cost, and is available in a surface mount package.

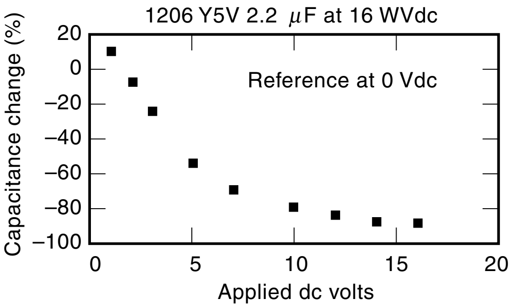

Figure 13. Ceramic capacitor voltage coefficient for high dielectric constant formulations.

Ceramic Capacitors in Power Applications. The growth of ceramic capacitors in switched-mode power supply (SMPS) applications is directly tied to the increased frequency designs in these systems. As the frequency increases, the magnitude of the capacitance required decreases along with the decreasing inductance of the choke. These decreases are the primary reasons for the increased frequencies as smaller element requirements translate into smaller component sizes. The real goal is the smaller sized components for smaller package sizes of the SMPS itself. Also, the capacitances used in many power supply designs are overkill brought about by the need for lower ESRs (the ESR of a family of capacitors is usually inversely proportional to the capacitance value. The higher the capacitance, the lower the ESR).

When ceramic capacitors are compared to electrolytic types with common values, the high-frequency performance of the ceramic type is two to three orders of magnitude lower in ESR. This lower ESR allows a window where the impedance is also dramatically lower (Fig. 14). The ceramic capacitor responds nearly like a true RLC circuit with little capacitance change with frequency. The phase shift for common values across these types occurs near the same frequency for the different types, but because the electrolytics have dramatically decreasing capacitance, wish increasing frequency, the ESLs are also significantly higher. In application, because of their lower ESR and insignificant capacitance roll-off in high frequency, typical swapping of ceramic for electrolytic types results in ratios of capacitance from 8 : 1 to as high as 20 : 1. Electrolytics need to be some 8 to 20 times greater in capacitance to achieve full-load ripple reduction similar to that of the ceramic capacitor filters.

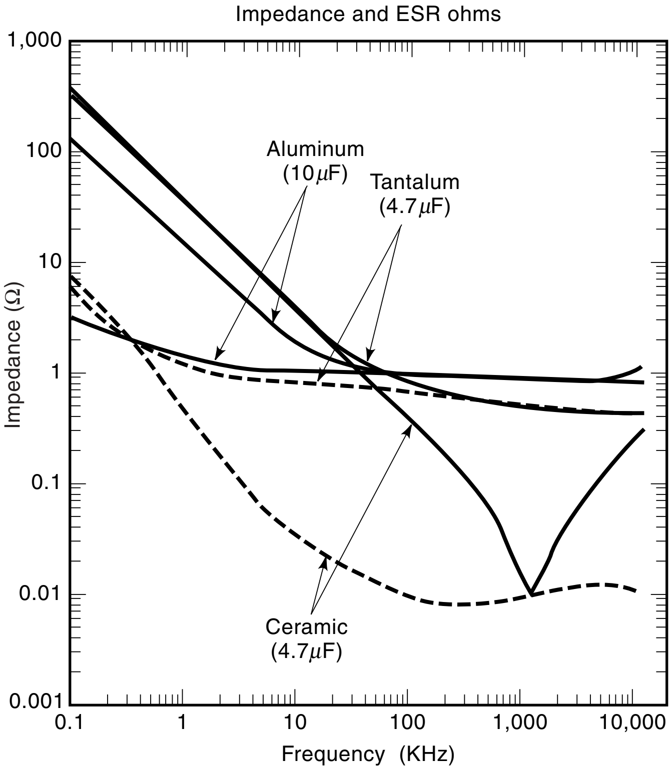

Figure 14. Frequency response comparison among aluminum, ceramic, and tantalum capacitors.

The ceramic capacitor is more beneficial in the higher frequencies, where the ESR decreases, because it continues almost to mirror the decay in capacitive reactance. On the other hand, lower frequencies can activate a piezoelectric response that may be detrimental to the ceramic chip and especially to the multiple chip packages. At low frequencies < 500 Hz, the ESRs of ceramic capacitors of value comparable to electrolytic types are actually higher. Ceramic capacitors performed poorly in these early linear supply circuits and were shunned by design engineers for this application. In moving into the high-frequency realm, ceramic capacitors have become the preferred device because of their low power losses and inductances, leading to much smaller volume capacitors than electrolytics for comparable ripple reduction.

The MLC's ability to fit form to function allows designing these capacitors to optimized performance with very low aspect ratios (length divided by width). Aspect ratios down to 0.2 result in much lower ESR and ESL, and the extremely short and wide thermal transfer path allows a much lower temperature rise for equal amounts of power dissipation. Typical ESLs might be as low as 500 pH. Using a feedthrough design (a four terminal MLC), ESLs as low as 100 pH are achievable.

For the SMPS design from 100 kHz through 1 MHz, the ESR has made the MLC a preferred choice for performance. Its low ESL will make it equally superior in the range of SMPS designs above 1 MHz.

Cost of Ceramics. For the small surface-mountable commercial chips with capacitances up to a few microfarads, the major cost factor is the metal, though these chips are already extremely inexpensive. The direction of the industry is to eliminate the precious metals palladium, platinum, and even silver in the electrode and convert to systems favoring nickel or copper. The low-fire ceramics already use ratios of silver to palladium that have greatly lowered electrode costs.

For the larger chips in these applications, the major cost is the labor involved in handling, processing, and adding the leadframe. The equipment used in the manufacture of ceramic capacitors has always been optimized to produce smaller chip sizes, resulting in a performance sacrifice when manufacturing the larger sized units needed today. The chips themselves are built up in a mother pad configuration, stacking one layer at a time. For the smaller chip sizes, this mother pad may yield thousands of small chips, but only tens of the larger. This inefficiency is then multiplied if that pad is divided by five when a chip assembly requires five chips stacked in a leadframe. In addition, the test and handling equipment are not applicable to the manufacture of larger chip sizes. Their size and mass results in self-created physical damage when machine transported or fed in bulk. The smaller chips are light enough that their mass is far too small to cause damage to each other in bulk. The result for large chips is excessive hand labor and inefficient handling.

Mounting Considerations. Larger capacitances are now being made available in smaller surface mount chips. These chips may have to be spread out on the board to achieve even higher capacitance goals, but their performance is undeniably shared with the larger ceramics. Hand-in-hand with greater emphasis on distributed power supplies, their availability, performance, cost, and process capability make them a preferred choice for future expansion into this market. Placement of multiple, true surface mount chips is still cheaper than the more expensive leadframe devices. Improvements in volumetric efficiency through thinner dielectrics will greatly enhance this solution.

SOLID TANTALUM CAPACITORS

Introduction

The solid tantalum capacitor was originally developed by Bell Telephone Laboratories. It evolved from the *wet* tantalum capacitor that used a porous anode block with the liquid electrolyte solution replaced by a semiconductor solid. Problems of sealing common to all electrolyte capacitors were eliminated with this approach. Conventional hermetic sealing was now possible with the elimination of the liquid electrolyte solution.

The construction of the tantalum capacitor utilizes a very porous anode built with tantalum powder. The powder is pressed in a pellet form with a tantalum wire inserted (Fig. 15). Then the pellet is sintered to allow contact growth among all individual particles (Fig. 16). The result is a porous block that electrically connects all tantalum particles to each other and to the tantalum wire.

The dielectric is formed on the exposed surfaces of the tantalum by electrochemical treatment which produces a Ta_2O_5 (tantalum pentoxide) film (Fig. 17). This film is insulating and has a dielectric constant of approximately 22. Though this constant is relatively small, the dielectric thicknesses are also extremely thin, and the surface area of the porous block is extremely high. The thickness is controlled by the process allowing different ratings for different bias applications. The volumetric efficiency of this capacitor exceeds that of aluminum electrolytics.

The *counterelectrode* or cathode plate is formed by the electrolyte in the wet tantalums. This solution readily penetrates the porous anode and forms itself to the exposed Ta_2O_5 surfaces. In the dry tantalum capacitor, the counterelectrode ma-

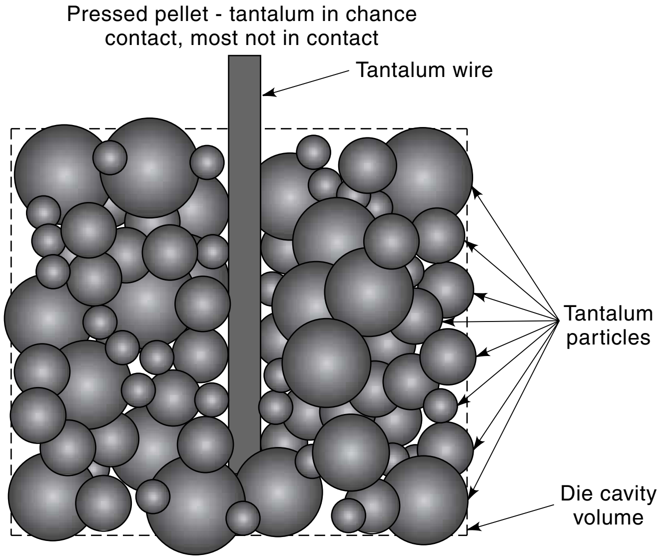

Figure 15. Tantalum capacitor pellet construction at the pressing stage during fabrication.

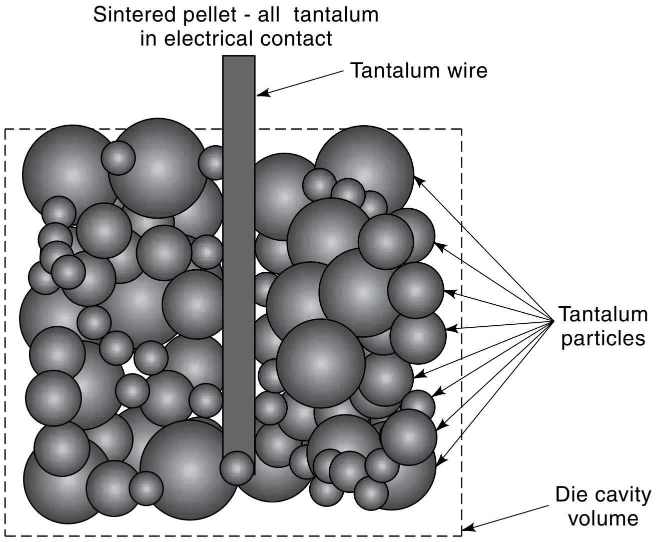

Figure 16. Sintered tantalum capacitor pellet after high temperature processing.

terial is MnO_2, and it is formed in successive dip and dry processes. As a solution, it penetrates the anode as a wet electrolyte and upon drying leaves a film of MnO_2 behind, which adheres to the exposed surfaces of the Ta_2O_5. This cathode plate is connected in the package to an external contact with a coating of carbon and silver as the final coat (Fig. 18).

State of the Art and Characteristics

The tantalum capacitor has the highest volumetric efficiency of any of the popular types of capacitors. The direction of development in the industry has been to push that envelope further still with higher density tantalum powders, smaller package sizes, and higher capacitance and voltage ratings. Figure 19 illustrates the steps producing the modern tantalum capacitor.

With time, evolution of the processes has led to denser applications of the counterelectrode material. Even so, the effective series resistance (ESR) of this electrode material dominates the performance of this capacitor throughout the frequency spectrum. As a porous anode, the connections to the inner depths of the secondary electrode are through the same pores of the anode block. These paths are resistive and result in the appearance of an *RC* ladder effect with increasing frequency. The deepest penetration is through these channels or pores, and the resistance of this is cumulative.

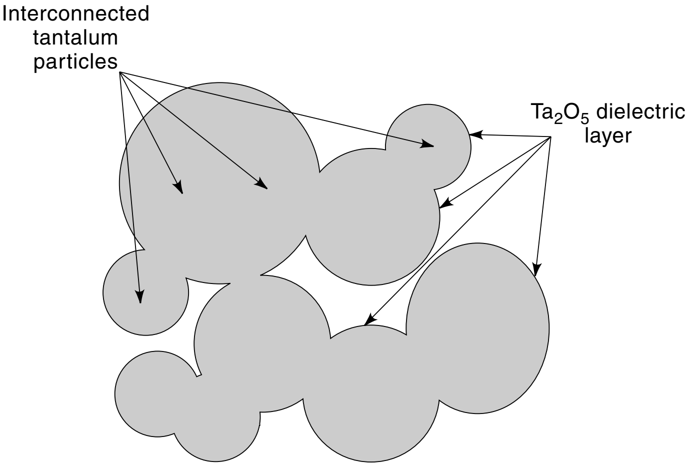

Figure 17. Dielectric oxide formulation on exposed surfaces of a tantalum capacitor.

With the higher frequencies, the resistance to the inner cells of capacitance makes the *RC* time constant of these elements greater than the period of the signal. This results in capacitance loss as they are effectively isolated from responding to the signal. Physically, the higher frequencies allow less penetration into the depths of the anode and depend more on the surface area of the anode block (Fig. 20). Electrically, the effect is a multiple *RC* ladder effect where the summary resistance to the inner capacitive cells and its capacitance cause the signal to have no effect on this element, electrically cutting them out of the circuit response.

Tantalum Capacitors for Small-Signal Applications. The greatest growth in dry tantalum capacitors is in the surface mount version. These are plastic packaged devices that allow wave and reflow solder operations with no concerns for a *wet* electrolyte solution.

Their surface mount capability and large capacitance have supplanted many aluminum electrolytic applications. Their temperature range eclipses that of the aluminum electrolytics. Their frequency response in many cases is a decade improvement over aluminum electrolytics.

Applications include filtering, timing, power holdup, and decoupling. Early assessments of this type in power applications found them susceptible to high current surges. This may have been attributable to inconsistent laydowns of the MnO_2, poor penetration of the dip solution, inconsistent processing, any number or combination of these leading to a localized highly resistive path penetrating into the anode. There have been major steps made in the processing of the counterelectrode to increase its density. Along with quality improvements and consistency came the need for improvement when utilizing finer powders. The smaller powders increase the surface area, but they decrease the pore or channel size available to the MnO_2 electrode. Because the improvements in process and material capabilities were always tied to improvements in volumetric efficiency, they may have been obscured in the push to reduce size. The extension of capacitor range and size reduction has always dictated the direction of tantalum chip improvements.

Tantalum Capacitors For Power Applications. The power application of tantalum capacitors could not be effectively measured with the commercial product because the primary goal was always volumetric efficiency, with ESR always a secondary or sacrificial object. Power application required that the ESR be the primary goal and capacitance the dependent variable.

Working against the volumetric goals of the commercial chip with older powders that were larger and processes meant to obtain optimum penetration of thinner channels, the low ESR tantalum chip evolved. These devices were born out of customers' demands for this specific product. Their application was for filtering, both input and output, of SMPS circuitry, never a standard application of tantalum capacitors.

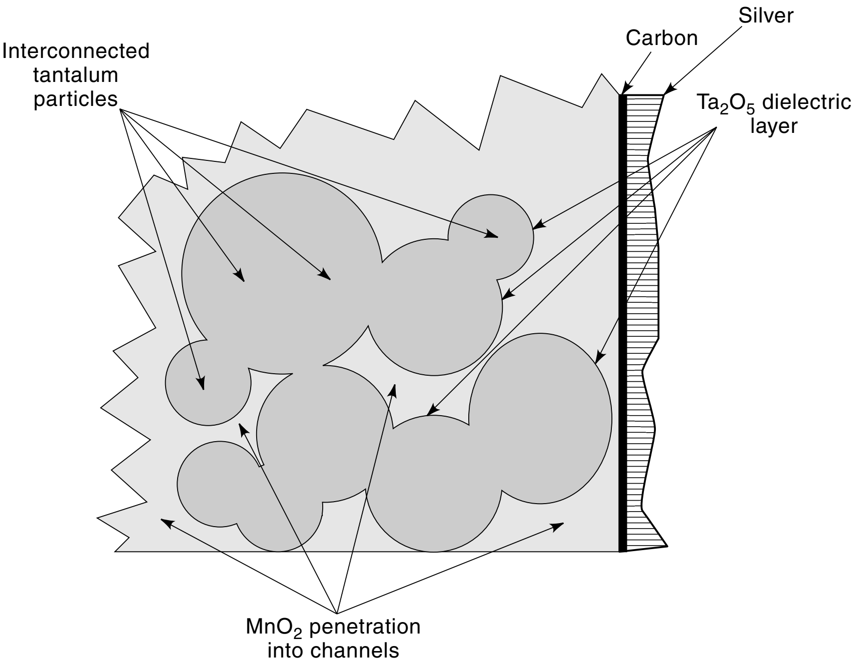

Figure 18. Cathode plate connected in the tantalum capacitor package to an external contact via a coating of carbon and then silver as a final coat.

Their performance in this application may be decades worse than ceramics but they are readily surface mountable and they cost much less. They can easily withstand the surges and the constant ripple currents.

Again, manufacturing moves in a direction opposite to the traditional tantalum chip development philosophy. By using larger powders, the surface area is reduced, but the channel or pore size is increased. Using the same procedures used to fill the smaller pores, with some repetition because of larger amounts of material to be deposited, the larger pores are filled extremely densely. The result is a dramatic improvement in ESR. A comparison of the two devices for common capacitances is shown in Fig. 21.

These devices are available in the largest sizes of the commercial products, specifically the *D* case and the *X* case. It did not make any sense to build smaller case sizes with smaller capacitances, because capacitance is a secondary consideration in this application. ESR is the primary concern.

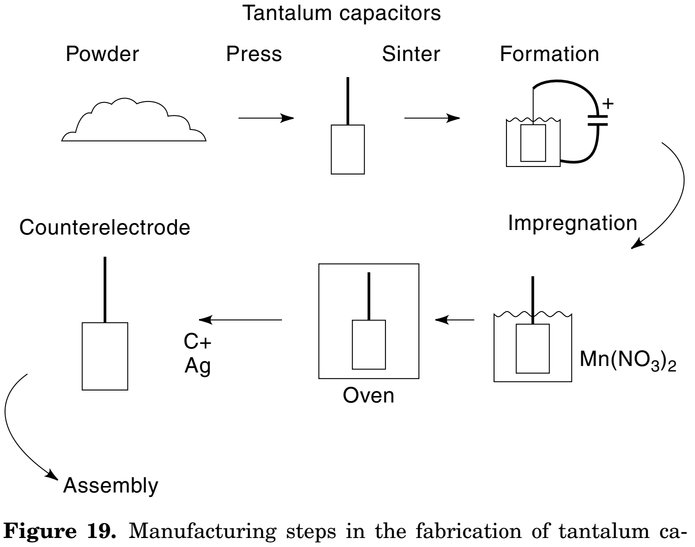

Figure 19. Manufacturing steps in the fabrication of tantalum capacitors.

These devices are all life tested and surge tested. They have been put on extended surge testing from 0 Vdc to rated Vdc and back through millions of pulses with no failures. Extended ac current testing has shown that the heat buildup within the part is proportional to the ESR, and because the ESR is so much lower, there is little additional heat developed internally.

Though dramatically improved, the ESR still contributes to an *RC* ladder effect. This limits the useful range of these capacitors to 500 kHz and below. The capacitance roll-off above this frequency leaves the ceramic as the only viable approach now.

Tantalum capacitors require additional process steps and additional testing. There is a fairly small premium required to cover the additional costs. The resulting chips are packaged on reels with true surface mount capability. Surge and ripple capabilities not common with other commercial products allow power filtering and power decoupling applications with little cost incentives.

The chips are packaged in reels and can be fed like any of the larger cased commercial surface mount products. Profiles for infrared reflow and wave solder procedures are the same as those for other commercial products.

Future Directions

Lower ESR and higher capacitance are the goals in developing low ESR tantalum SMD capacitors. The graph in Fig. 22 shows the results of the work accomplished in making the tantalum capacitor more applicable in power or energy applications.

As shown in Fig. 22, the ESR limits for a 330 μF, 6 WVdc rated X-Case (7342) chip vary dramatically as the product type varies. T491 is the standard commercial chip with an

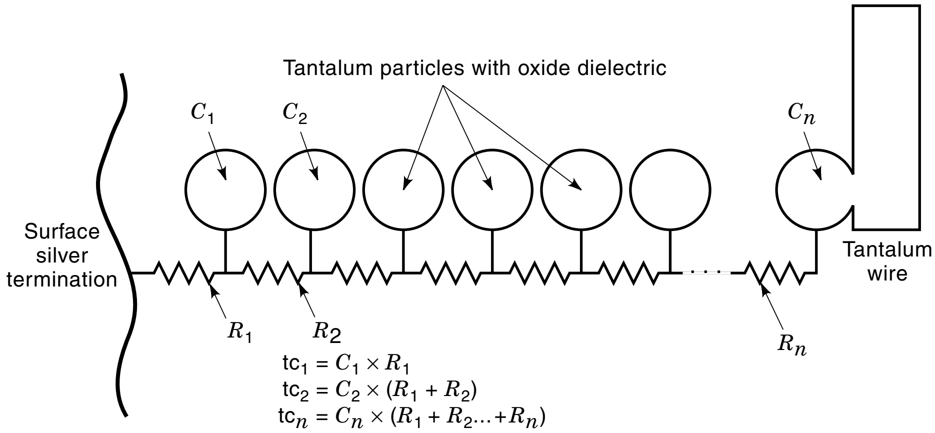

Figure 20. Apparent *RC* ladder network equivalent circuit of the tantalum capacitor.

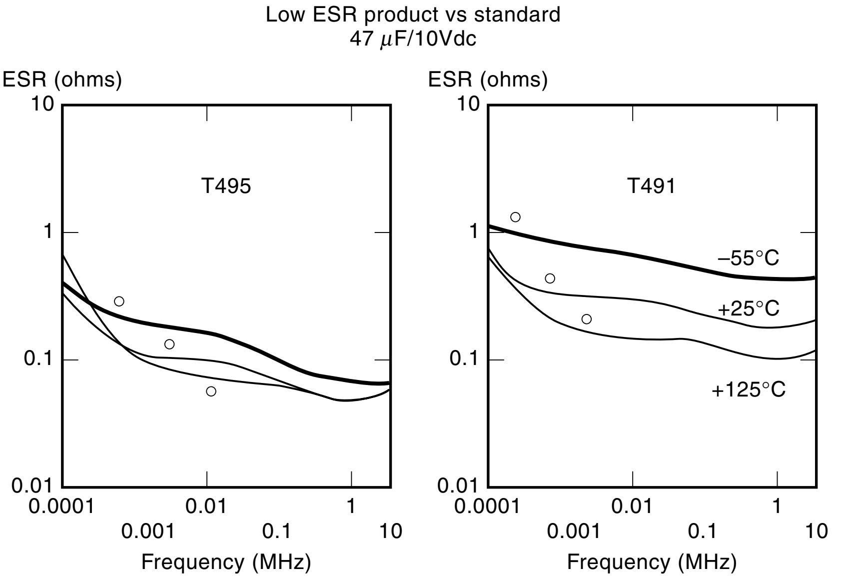

Figure 21. Equivalent series resistance for low ESR and standard tantalum capacitors as a function of frequency.

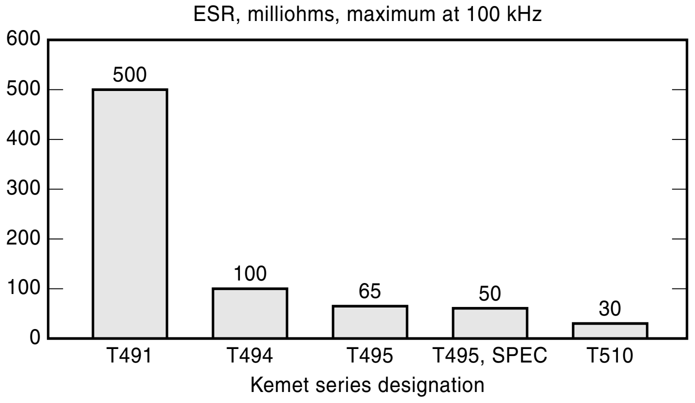

Figure 22. Equivalent series resistance decrease in the evolution of tantalum capacitor technology (KEMET™ data)

EIA defined ESR limit of 500 mΩ. The T494 is the same chip but with greater restrictions on ESR, and its limit drops to 150 mΩ. The T494 incurs increased losses due to the tighter testing requirements plus additional testing not applied across the board to the T491. The T495 represents a true departure from the standard product in test and limits (ESR maximum of 100 mΩ) and also in materials. Heat treatment experiments have allowed us to move the limits of the T495 lower still, to a specified limit of 65 mΩ. The MAT chip is a design that employs a different geometry of design for the anode structure, offering more surface area and requiring lower depth penetration into the volume of the anode. This allows the maximum limit now to drop to 30 mΩ.

The next offering will be the MAT chip with a conductive polymer replacing the manganese dioxide as the cathode plate. MnO_2 has been used exclusively in the solid tantalum capacitor because it offers a *self-healing* effect with these devices. At a fault site in the Ta_2O_5, the current is localized and high through the MnO_2, allowing a conversion of the MnO_2 to a higher resistive state such as Mn_2O_3. This conversion seals or isolates the fault site in the capacitor. In actual manufacturing, there are many fault sites in the dielectric that cause a conversion like this to take place and *heal* the capacitors but it requires using the semiconductor MnO_2 as the cathode plate. It also requires restricting the current. If the fault site is exposed to an unlimited current source, the conversion to a higher resistive state may not take place, resulting in a catastrophic failure.

It has been shown that new polymer materials vaporize at these fault sites, creating a loss of connection of the fault sites in the dielectric in the same manner as the MnO_2. The conductive polymer offers two advantages over the MnO_2: it has lower resistivity, and it does not offer a readily available source of oxygen on which tantalum feeds when the device fails catastrophically.

ALUMINUM ELECTROLYTIC CAPACITORS

Market Direction

The aluminum electrolytic capacitor is a product which has developed over many years and is still evolving at a rapid rate today. The worldwide aluminum electrolytic capacitor industry is over $3 billion in sales and is driven by the following large commercial and military applications:

- Motor drives
- Power supplies
    - Uninterruptible
    - Switch-mode
- Audio
- Appliance and small pump motors
- Strobe and flash lamps
- Medical defibrillators
- Electronic control circuits.

In general the evolution continues in size reduction and rating extensions (cost reduction and continuously improving quality are required today to be a major, worldwide supplier). Examples as specific rating extensions follow:

- Larger ripple current
- Longer life expectancy
- Larger energy density
- Lower ESR (equivalent series resistance)
- Higher resonant frequency
- Small temperature coefficient.

Aluminum electrolytic capacitors are used in large volumes in one of five circuit applications: (1) dc bus (rectifier circuits); (2) filtering; (3) control circuits; (4) power factor correction; and (5) pulse discharge. All of these circuit applications benefit from one or more of the rating extensions cited above. Small specialty markets for aluminum electrolytic capacitors drive rating extensions in the following different directions:

- Higher ambient temperature ratings ($\gg$ 125° to 200°C)
- Higher dc voltage ratings ($\gg$ 600 to 700 Vdc)
- Larger surge voltage withstand
- More flame resistance.

New Products, Technology, and Specific Performance

Specific Energy Density. Larger specific energy density can be traced to increased foil gains (etched surface area per projected surface area measured as microfarads per square centimeter at a specific voltage). The improvement in the high-voltage anode foil gain over the past 10 years can be seen in Fig. 23 (25).

Foil gain curves are a function of voltage and show the same general improvement for low voltage typically in the 25 V to 75 V range as well as medium and high voltage. As can be seen, in the 550 V to 600 V range (typical formation voltage for a 400 Vdc to 450 Vdc rated capacitor), the gains have increased by over a factor of two in ten years. Etching gains continue to come from improved control and uniformity in the tunnel length, geometry, and spacing. The theoretical limit on gain is still a long way from current performance, and there is no reason to believe that performance improvements will not continue to evolve over the next few years. Five percent gains per year have been taking place for the past five years and should continue into the future.

Expected Life Performance. Longer capacitor life can be traced to development over many technical areas. The more important items are the following:

- More stable aluminum oxide
- Smaller dc leakage currents
- Improved self-healing (electrolyte chemistry)
- Improved H_2 gas absorption (electrolyte chemistry)
- Lower halogen contamination levels
- Decreased electrolyte leakage (deck to case sealing)
- Smaller thermal resistance within the capacitor
- Reduced dielectric stress (V/μm).

These developmental areas can be grouped in electrolyte chemistry, formation chemistry, capacitor construction, and

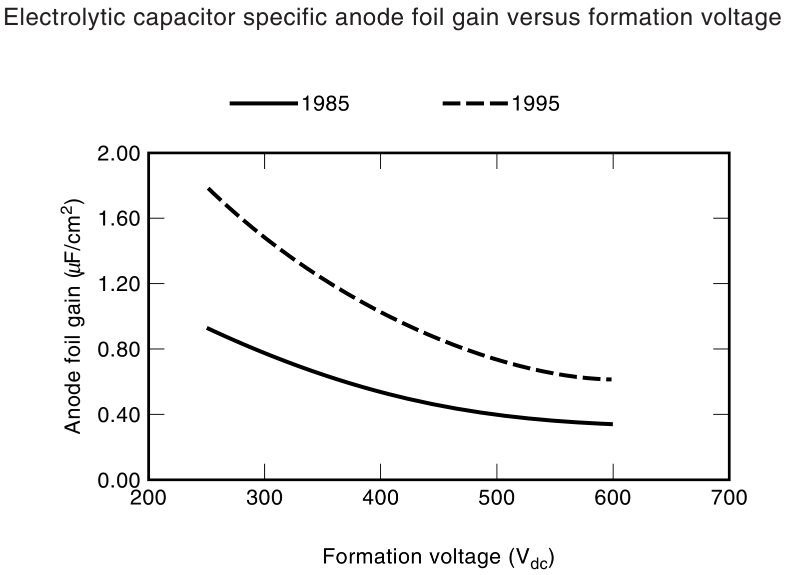

Figure 23. High-voltage foil gain versus formation voltage from 1985 to 1995.

capacitor design. The impact of these parameters on the rated life and the expected life performance can be seen through the catalog of changes over the past 10 years (26–28). Rated life has evolved from 1000 h and 2000 h to 3500 h and recently to 5000 h (at name plate ratings) with expected life going from 2000 h to values in the 12,000 h to 28,000 h range (the life expectancy is a function of the case diameter which in part accounts for the large spread in the expected life range) (29).

Larger specific ripple current ratings are being generated by reducing the ESR within the capacitor and reducing the thermal resistance from the section to the case and from the case to the mounting plate. The impact of this development can be seen by the normalized data in Fig. 24.

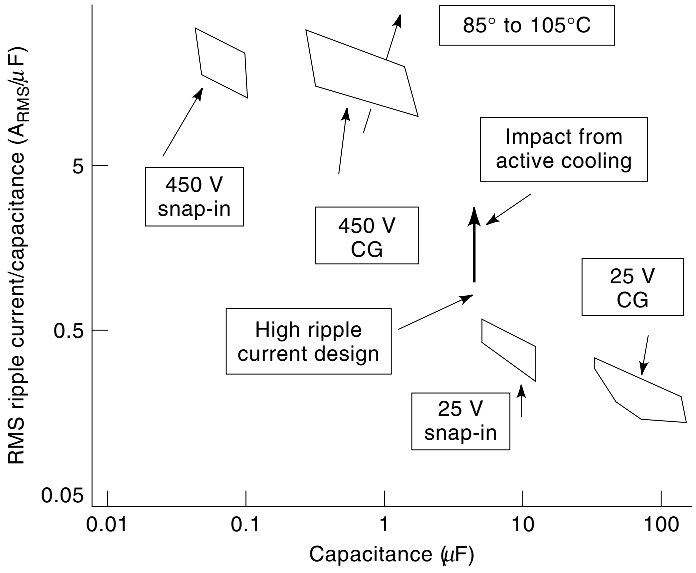

Figure 24. Specific ripple current measured as A_{rms} (at 120 Hz) per microfarad as a function of the capacitance of the capacitor in microfarads.

The data in Fig. 24 summarize ripple current (120 Hz) performance at name plate conditions offered today by many manufacturers (26–28). As a figure of merit, the ripple current has been normalized to the size of the capacitor (surface area is the key scaling parameter for ripple current, but volume is a more convenient normalizing parameter) for many capacitor ratings over a large selection of snap-in and computer grade (screw terminal) products. Specifically this table covers diameters from 22 mm to 77 mm, heights from 30 mm to 220 mm and temperature ratings at 85° and 105°C. As can be seen, the data in the graph demonstrates a dependence on rated temperature, rated voltage, and the construction of the capacitor. Pitchless extended foil designs with thick case bottoms are common construction today for computer-grade capacitors, whereas snap-in capacitors may use none or some of these techniques for improved heat transfer. Tracing the ripple current performance over a 10-year period would also show a dramatic change in the ripple current ratings. The data in Fig. 24 also show a high ripple current design (designated with an X) compared to the normal ripple current design and the impact on the ripple current rating by going from static cooling to active cooling. Increasing the ripple current ratings is a continual drive within the industry. Large electrolytic capacitors with over 50 A ripple current ratings are no longer difficult to obtain even when coupled with long life expectancy.

Product Availability and Further Development

There are two major areas for new products. One is based on solid instead of liquid electrolytes specifically for higher voltage (30), and the second is hybrid design which uses different materials and/or geometries for the cathode and the anode (31). Both are under active development and have been discussed in the literature. The solid electrolyte has the potential for a much smaller capacitance and ESR temperature coefficient compared to the temperature coefficient for a liquid electrolyte. Typical thermal coefficient for ratings at 50/60 Hz with liquid electrolytes are in the 700 ppm range whereas they can be well below 100 ppm for solids. More importantly, the electrolyte resistivity can be two orders of magnitude smaller for a solid electrolyte compared to a liquid electrolyte. Today solid electrolytes are available with ratings up to about 25 V, but the voltage should increase with time. The hybrid construction is a relatively new concept and holds the potential for increasing the specific energy density of the aluminum capacitor by a factor of 2 to 4. With this increase will also come an increase in thermal resistance and impedance, both of which will limit the capacitor to slower frequency applications more typical of a battery than a capacitor, and to applications with reduced ripple current. These applications are already appearing which continue to cloud the dividing line between a capacitor and a battery. In addition to rating extension, these new technologies are providing the foundation for aluminum electrolytic capacitors with much longer life expectancy and larger surface mount devices (SMD) ratings.

A second trend within the industry is product proliferation. Increased specific energy joules per cubic centimeter increased ripple current (amperes per microfarad), and increased life expectancy usually are achieved individually but not collectively. The aluminum electrolytic capacitor is continuing to divide into multiple products, one for high ripple current, one for high energy density, one for very long life, and one for high ambient temperature.

Reference to commercial products is solely for purpose of illustration of specific device operational characteristics and is no way an endorsement of one product over another.

BIBLIOGRAPHY

1. W. J. Sarjeant, *R&D subcommittee report on capacitors* —1995, Power Sources Manufacturers Association Tech. Rep. Power Sources Manufacturers Association, Cedar Knolls, NJ, 1995.
2. *Proc. IEEE Power Electronics Conf.,* Long Beach Convention Center, Long Beach, CA, February 13–16, 1990, pp. 112–117.
3. W. J. Sarjeant, *Briefing to the defensive technologies study team on space power technology,* Institute for Defense Analysis Report, Washington, DC, 1989.
4. W. J. Sarjeant and R. E. Dollinger, *High Power Electronics,* New York: TAB Professional and Reference Books, 1989.
5. I. Vitkovitsky, *High Power Switching,* New York: Van Nostrand Reinhold, 1988.
6. D. Furgal, *Power conditioning for multimegawatt space power systems* —SDI-SLKT/AF space power architecture studies independent evaluation group, Sandia National Laboratories Report, Albuquerque, NM, 1989.
7. W. J. Sarjeant, ed., *Advanced Power Sources For Space Missions.* NAS-NRC (EEB) Committee on Advanced Spaced Based High Power Technologies, #ADVPOW, Washington, DC: National Academy Press, 1989.
8. *Mobile Electric Power Technologies For The Army Of The Future—Engines, Power Sources And Electrical Aspects.* NAS-NRC (EEB) Committee on Mobile Electric Power Plant Technologies Energy Engineering Board, Commission on Engineering and Technical Systems, Washington, DC: National Academy Press, 1988.
9. T. R. Burkes and W. J. Sarjeant, Discussion paper on SDI power and power conditioning components, study paper for the NAS-NRC (EEB) Committee on Advanced Space Based High Power Technologies, 1987 (unpublished—available from the authors).
10. T. R. Burkes, A critical analysis and assessment of high power switches, Naval Surface Weapons Center Report NP30/78, Dahlgren, VA, 1978.
11. *Olean Advanced Products, Technical Catalogue #10875OAP,* Olean, NY, 1996.
12. J. Ennis, High energy capacitor development, *Symp. High Power Electron. Inst. State Univ. New York at Buffalo,* Buffalo, NY, November, 1986. Available from Maxwell Energy Products, San Diego, CA.
13. G. R. Love, Energy storage in ceramic dielectrics, Sprague Technical Paper TP87-4, *Ameri. Ceramic Soc. Spring Meet.,* Pittsburgh, PA, April, 1987.
14. J. D. Moynihan, Editor-in-Chief, *Selection and Application of Capacitors,* 2nd ed., Components Technology Institute, 1987. Available from CTI, Huntsville, AL.
15. *Capacitors for switching regulator filters,* Electrocube Technical Bulletin no. 13, 1987.
16. J. J. Svec, Capacitors from 0.01 ounce to 50 pounds, *Ceramic Industry,* pp. 32–34, August, 1979.
17. J. Hansen, Development of an 1100°F Capacitor, NASA, Washington, DC, Tech. Rep. NASA-CR-1213, 1968 and Tech. Rep., NASA-CR-1799, 1971.
18. W. J. Sarjeant, Capacitor fundamentals, *Proc. 1989 IEEE Electr. Insulation Conf.,* Chicago, IL, 1989, pp. 1–51.
19. The Department of Defense Critical Technologies Plan for the Committee on Armed Services, United States Congress, March 15, 1994.
20. J. R. Laghari and W. J. Sarjeant, Energy storage pulsed power capacitor technology, *Proc. IEEE Power Sources Symp.,* Cherry Hill, NJ, June 25–28, 1990, pp. 380–386.
21. J. Ennis, K. Haskell, and J. Sevigny, Development of energy storage/pulse discharge capacitors, *Proc. IEEE Power Sources Symp.,* Cherry Hill, NJ, 1990, p. 127–129.
22. *Untreated mica paper used for electrical insulation,* National Electrical Manufacturers Association Report No. NEMA FI 2-1992, Washington, DC, 1992.
23. J. E. Welton, *SEM Petrology Atlas,* Tulsa, Oklahoma: The American Association of Petroleum Geologists, 1984.
24. C. J. Kaiser, *The Capacitor Handbook,* Olathe, KS: CJ Publishing, 1990.
25. *Becromal catalog,* etched and formed anode foils, 1997.
26. *United ChemiCon,* capacitor catalogs, 1997.
27. *Nichicon,* capacitor catalogs, 1997.
28. Aerovox catalogs (*AeroM* and *BHC*), New Bedford, MA, 1997.
29. M. Gasperi, Life prediction model for aluminum electrolytic capacitors, *Proc. IEEE IAS Conf.,* San Diego, CA, October 1996.
30. P. Lunsmann and D. R. MacFariance, High energy density capacitor for implantable defibrillators, *Proc. 16th Capacitor Resistor Technol. Symp.,* New Orleans, LA, 1996, p. 277–280. Available from CTI, Huntsville, AL.
31. Kensi et al., *Solid electrolytic capacitor and method for making same,* U.S. Patent 5,198,967, 1993.

I. CLELLAND
Paktron Division of Illinois Tool Works, Inc.
W. J. SARJEANT
State University of New York at Buffalo
J. BOWERS
Custom Electronics Inc.
M. HUDIS
Aerovox Group
R. A. PRICE
Paktron Division of Illinois Tool Works, Inc.
J. PRYMAK
KEMET Electronics Corporation

CAPACITORS, THIN FILMS. See Thin film capacitors.