200°C operating temprerature film capacitor

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Abstract

The increased availability and reliability of SiC devices has addressed the need for space efficient high power, high temperature power electronics modules for a More Electric Aircraft architecture. As SiC technology matures, the availability of high temperature passives has become a limiting component in an efficient design, often requiring designers to implement complex liquid cooling systems. The use of reliable, high temperature capacitors can potentially eliminate the need for liquid cooling, mitigating the complexity and cost of the total power electronics module. This paper will introduce a new high temperature film capacitor technology based on a unique Gore engineered fluoropolymer film. These films exhibit high breakdown strength, exceptional mechanical strength and a low dissipation factor, resulting in a high temperature, small, wound film capacitor.

Introduction

The More Electric Aircraft (MEA) is part of the industry trend of replacing non-propulsive mechanical, pneumatic, and hydraulic systems with advanced electric system alternatives. A more electric architecture can offer improved energy efficiency, more advanced power control, reduced operating costs, and reduced environmental emissions. One challenge for the MEA architecture is the desire for the power electronics section to reliably operate in harsh environments, including high ambient temperatures. A power electronics module that can operate at higher temperatures can eliminate the need for liquid cooling, reducing the complexity, volume, weight, and cost of the total power electronics system. A typical power electronics inverter used to drive a motor includes DC-link capacitors and semiconductor switches. For higher temperature operation the traditional silicon IGBT switches are being replaced by Silicon Carbide (SiC) or Gallium Nitride (GaN) wide bandgap semiconductor technology. Wide bandgap semiconductors not only offer higher operating temperatures than silicon, but also higher power handling capabilities. To gain the full benefits of SiC or GaN power electronics modules, higher operating temperature passive components are needed, in particular reliable high temperature DC-link capacitors. Metalized film technology is often the preferred capacitor technology because of its ability to self-clear. Self-clearing is the process of the thin metal electrode vaporizing during an electric field breakdown event;
small area of the electrode is lost but the capacitor still functions. This phenomenon is commonly termed “graceful failure” and is a desired attribute, particularly for critical applications. Self-clearing enables the film capacitors to withstand high voltage spikes without destroying the capacitor, allowing the power electronics to continue to function normally. To date, the limiting factor in the development of high temperature metallized film capacitors is the dielectric film. Capacitor-grade dielectric films The search for higher temperature dielectric films for use in metallized film capacitors has been going on for many years[1]. The challenge is not only adequate electrical properties, such as dielectric loss and breakdown strength, but mechanical properties as well. The film must be thin (preferably < 6 µm) with the mechanical strength to withstand the capacitor manufacturing processes, including winding and metallization. Additionally, the metallized film must self-clear and have a low dielectric loss. The resulting capacitor should have stable capacitance over the entire operating temperature and voltage range. Polypropylene is an excellent dielectric material for producing metallized film capacitors. Biaxially- oriented polypropylene (BOPP) has a very low dissipation factor (< 0.1%), a high electric field breakdown strength (> 600 V/µm), and a low temperature coefficient of capacitance. It also has the ability to self-clear; many polymers do not self-clear as they form carbon tracks when the vaporized material re-condenses after a breakdown event. Polypropylene also has good mechanical strength such that it does not stretch or neck-down when wound into capacitors during manufacturing. Polypropylene is typically limited in temperature to 105 °C[2]. The industry desires a polymer film with the properties of polypropylene but at higher operating temperatures. Commonly cited higher operating temperature dielectric films include: FPE (fluorenyl polyester), PPS (polyphenylene sulphide), PI (polymide), PET (polyethylene terephthalate), and PEN (polyethylene naphthalate). While all are capable of being manufactured into metallized film capacitors, they often suffer from a weakness that limits their suitability for the MEA architecture. Some exhibited weaknesses include: poor ability to clear, unstable capacitance at high temperatures, and limited mechanical strength. Gore has developed a polytetrafluoroethylene (PTFE) based fluoropolymer film with many of the desired properties of BOPP, with the capability to operate at temperatures greater than 250 °C[3]. For many years PTFE has been used as a dielectric material for high temperature capacitors due to its outstanding electrical properties. Similar to polypropylene, PTFE molecule chains lack polar groups that orient under electrical field stresses. The absence of these polar groups gives PTFE an intrinsically low dissipation factor and high volume resistivity. However, traditional sources of PTFE films have not had very high dielectric strength. The low dielectric strength typically required the use of a foil-film capacitor structure utilizing thicker PTFE films to meet the application voltage. A foil-film construction does not self-clear making it less desirable. When thinner PTFE films are considered, the available PTFE films often do not exhibit the desired mechanical strength to withstand the capacitor winding operation. Figure 1 shows the breakdown strength of Gore’s PTFE film vs. commercially available cast and skived PTFE films. The two-parameter Weibull cumulative distribution function is well accepted as the proper approach to studying breakdown voltage of insulators. The scale factor, , is the voltage at which 63% of the films have broken down, and the shape parameter, , is the Weibull modulus indicating the width of the distribution. The highest performing materials have a high (farther to the right) and a high (more vertical). Fig. 1: Breakdown strength of various PTFE films at 25 C The high breakdown strength of the Gore PTFE film is comparable to capacitor grade biaxially oriented polypropylene film at room temperature. However, for a viable product the film must exhibit high breakdown strength over a wide temperature range. Figure 2 shows the breakdown strength over temperature of the Gore PTFE film. Although the dielectric strength degrades as temperature increases, it still exceeds 400 V/µm at 250 C. This is more than adequate for a viable high temperature film capacitor for typical MEA application. Figure 2: Breakdown strength of Gore PTFE film over temperature. The Gore PTFE film was also tested to ensure its applicability for use as a metallized film capacitor. Metal clearing tests were performed and no changes in insulation resistance were measured. The film’s dissipation factor was measured and found to be extremely low (< 0.1%) and stable up to the 300 °C test temperature. The dielectric material also exhibited stable capacitance over frequency[3]. The mechanical strength of the film was also characterized to ensure suitability in the capacitor manufacturing process. While the films did exhibit lower tensile strength compared to BOPP films, the values are compatible with the manufacturing process requirements. 200 °C Film Capacitor Development A 6µm Gore PTFE film was metallized with aluminium, wound into capacitor sections, and end- sprayed with Zn using traditional capacitor manufacturing processes. The Gore PTFE film was found to be compatible with both standard metallization and winding equipment. End termination and capacitor packaging was also feasible utilizing standard capacitor processing methods. Figure 3 shows a picture of example embodiments of the fabricated capacitors. Figure 3. Examples of Gore manufactured metallized film capacitors. Sample capacitors were tested under a variety of conditions. Figure 4 shows the change in capacitance and equivalent series resistance (ESR) of a typical Gore packaged capacitor from room temperature to 200 °C. The capacitance only dropped 2.4% and the ESR increased 3 m ; both very good results for this wide temperature range. Figure 4: Temperature change in capacitance and ESR of Gore 50 µF capacitor In addition to the capacitor electrical characterization, capacitors were subjected to stresses to better characterize their fitness for use in a future MEA application. Ripple current tests were performed to characterize the capacitors internal temperature rise based upon a set input voltage and RMS current. A subset of capacitors were mechanically stressed to characterize their performance in given vibration conditions, thermal shock, and mechanical shock conditions. All tests showed comparable performance to commercial polypropylene capacitors. Finally a preliminary reliability study was implemented to build confidence the new capacitors were feasible for the required aircraft life expectations. Representative parts were tested at various temperatures and voltage stresses to accelerate potential failures. A lifetime model was then developed to predict the capacitor life at a given temperature and voltage rating. Figure 5 shows one result of this reliability testing on early prototype capacitors. After an initial stabilization period which causes a small increase in capacitance, the capacitors showed less than 1% drop in capacitance over 2000 hours at a 600 Vdc and 200 °C stress level. Post-test analysis was performed on many capacitors to show areas for future improvement. The results of the early stress testing are providing insight for on-going improvement throughout the capacitor manufacturing
process. Figure 5: Change in capacitance of Gore 50 µF capacitor at 200°C and 600 Volts. Conclusions Gore has developed a 6µm thick PTFE film that meets both the mechanical and electrical requirements for commercial high temperature metalized film capacitors. First generation capacitors built using this film have shown the technology is applicable to meeting the needs of the More Electric Aircraft industry. Continued development will improve performance and reliability of the technology while also optimizing package designs that meet the MEA requirements. References 1 Venkat, N. et al, “High Temperature Polymer Film Dielectrics for Aerospace Power Conditioning Capacitor Applications”, Materials Science and Engineering B, 2010, vol 168, pp. 16-21. 2 Bond, J., “Power Film Capacitors for DC Bus Applications”, 2013 Applied Power Electronics Conference, March 2013. 3 Donhowe, M. 250 “Operating Temperature Dielectric Film Capacitors”, IMAPS High Temperature Electronics Network (HiTEN 2011), July 2011.

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