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150°C Capacitors for DC-Link Applications

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Abstract

Newly introduced high-heat ultra-thin dielectric film has been used to build high temperature commercial quality capacitors suitable for DC-Link applications. The capacitors have been tested at high temperatures reaching 150°C. Operating at 900 volts, the capacitors passed 2000 hours of life testing at 150°C, and passed 3600 hours at 1000 volts and 130°C. Insulation resistance (IR), dielectric losses (tan δ) and Equivalent Series Resistance (ESR) were stable over the test duration. A positive capacitance change (ΔC) was noted early in the test and remained acceptable at the end of the test.
Reaching 900V and 1000V performance was enabled by appropriate segmented metallization of the dielectric film and process optimization for building capacitor elements. Achieving 150°C performance was possible due to stable inherent dielectric characteristics (BDS, D_k and D_f) of the high heat film.
Operating at high temperature and high voltage is advantageous for efficiency improvement in AC-DC inverter modules, in particular those based on SiC technology. Additionally, the demand for active cooling can be reduced or eliminated giving rise to compact module design and bringing the capacitors closer to the SiC switch for lower induction losses. Compact designs may offer opportunity for weight reduction in electric vehicles.

1 Introduction

1.1 High Heat Performance, an Unmet Need

Societal demand for solutions to climate change is increasing. A key element for such solutions is switching the bulk of the internal combustion engine fleet to electric vehicles (EVs). For this big shift, perception of performance by consumers needs to change, particularly in range, acceleration and fast charging. EV companies want to move from conventional semiconductor technology, based on silicon, to wide band-gap (WBG) technology based on silicon carbide (SiC) and gallium nitride (GaN), to provide higher efficiency AC-DC inverter modules to deliver the desired performance improvements. These improvements are best realized when the WBG module operates under high voltages, frequencies and at higher temperatures. Components used in the module need to withstand the same operating conditions.

Film capacitors are a key passive component in the AC-DC inverter module. Incumbent capacitor technology relies typically on BOPP film (biaxially oriented polypropylene). BOPP is limited in its temperature handling ability to about 105°C along with implementation of active cooling of the electronic components. Active cooling systems consume valuable energy, add weight and require physical separation between components, which could lead to increase in induction losses. Other materials such as PET (polyethylene terephthalate) and PEN (polyethylene naphthalate) can survive higher temperatures. However, their use is limited to about 125°C due to excessive internal losses in the film at higher temperatures. Materials such as COC-PP blends (cyclic olefin copolymer - polypropylene) were recently introduced. However, these are still limited to about 125°C maximum operating temperature. Cooling systems or reducing the energy throughput is still necessary for capacitors made with PET, PEN and COC-PP films.

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Adoption of Silicon Carbide (SiC) technology in AC-DC inverter modules in electric vehicles has signified the need for passive components, such as capacitors, that can operate at higher temperatures reaching 150°C. Operating at higher temperatures beyond the limits of incumbent BOPP film has been an ongoing industry and academic challenge [1,2,3].

1.2 High Heat Material Solution

SABIC has been developing new materials for use in ultra-thin film dielectric applications with operating temperatures upwards of 150°C [4]. The current work addresses this need and offers a solution of an ultra-thin high heat dielectric film for capacitors operating at high temperatures and high voltages. A high-heat engineering thermoplastic material was developed by SABIC to balance the often conflicting electrical and thermal requirements of the application and the challenge of processing into very thin film and optimizing performance in demanding downstream processes (e.g., metallization, slitting, capacitor winding, and heat treatment).

SABIC's ELCRES™ HTV150A film was engineered to provide a new generation of ultra-thin dielectric films and offer a different solution to meet the need for high temperature capacitor films [5]. The base resin in HTV150A film is an amorphous engineering thermoplastic resin with high glass transition temperature (T_g) of 205°C and relatively stable loss factor (D_f) at temperatures up to 150°C, avoiding the issues seen in some crystalline resins where the loss factor can change significantly at higher temperatures, or at temperatures near the glass transition temperature of the material. The polymer's aromatic carbon/aliphatic carbon ratio and net polarizability are balanced to deliver a higher dielectric constant than conventional BOPP while maintaining adequate self-clearing for many high voltage applications [6].

Reliability life-testing of HTV150A film has been previously demonstrated at conservative voltage of 100V/µm at 150°C for 2000 hours [5]. This corresponds to 500V for 5µm-based capacitors and 300V for 3µm-based capacitors. The main objective of the current work is to demonstrate stable capacitor performance at a higher operating voltage up to 1000V, or 200V/µm for 5µm-based capacitors. Preliminary performance results for 3µm-based capacitors operating at 600V, or 200V/µm are also discussed.

1.3 Optimized Capacitor Design

Nichicon implemented high heat HTV150A films into capacitor designs to demonstrate performance at high temperatures and high voltages to offer candidate components to AC-DC module manufacturers.

Based on the dielectric, thermal and mechanical characteristics of the film, appropriate processing parameters were tuned to fit the thermo-mechanical characteristics of the HTV150A film. The film was metallized prior to capacitor building in standard metallization schemes. Segmentation (patterning) of the metallization was employed to maximize the operating voltage. Segmented metallization offers a mechanism to eliminate (electrically isolate) regions (i.e., segments) of the metallized surface where an electrical breakdown can occur. Similar to blowing a fuse, the affected segment is disconnected from the rest of the metallized surface whenever an imperfection within the segment causes local current increase. An optimum segmentation design must have appropriate responsivity to local current spikes, but not be overly sensitive to avoid excessive premature isolation of segments and large reductions in capacitance.

2 Dielectric Film Characteristics

In the current work, HTV150A dielectric film made with an advanced high-heat engineering thermoplastic material is selected for building high heat temperature capacitors. The film has desirable permittivity and dissipation losses [5]. Fig.1 shows D_k at room temperature and at 150°C as a function of frequency with (a) at room temperature and (b) at 150°C, respectively. HTV150A has a D_k of 2.9 that is very stable over the temperature range. By comparison, PEN has similar D_k performance whereas BOPP is 30% lower.

At 150°C, HTV150A and PEN retain their D_k performance. BOPP has no D_k value since the material will degrade at 150°C.

Fig. 1 (c and d) shows dissipation losses, represented by D_f, at room temperature and 150°C, respectively. Dissipation losses are lower for HTV150A film vs PEN at room temperature. At 150°C HTV150A film maintains stable performance, whereas losses in PEN increase. The increased losses limit use of PEN films beyond 125°C. BOPP has low losses at low temperatures but cannot survive higher temperature levels.

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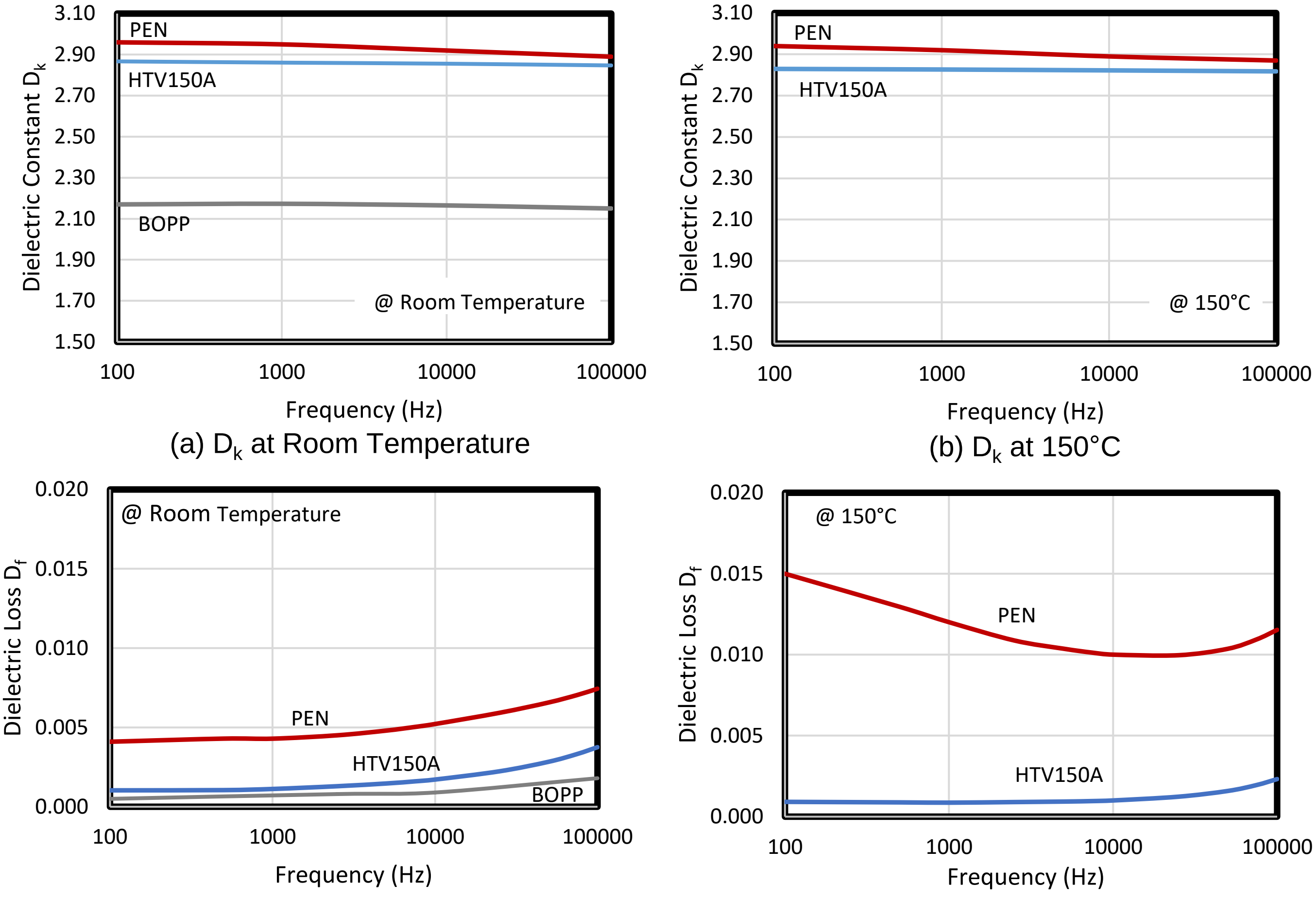

(a) D_k at Room Temperature (b) D_k at 150°C

(c) D_f at Room Temperature (d) D_f at 150°C

Fig. 1 Dielectric constant (D_k) and dielectric loss (D_f) for HTV150A film

Breakdown voltage (BDV) is measured according to ASTM D149 on unmetallized film. Fig. 2 shows HTV150A film having a highest BDV of about 850 V/µm at room temperature and 720 V/µm at 150°C. PEN and BOPP have lower values; noting that no value exists for BOPP at 150°C and the test for PEN is performed up to 125°C since losses limit use of PEN at higher temperatures.

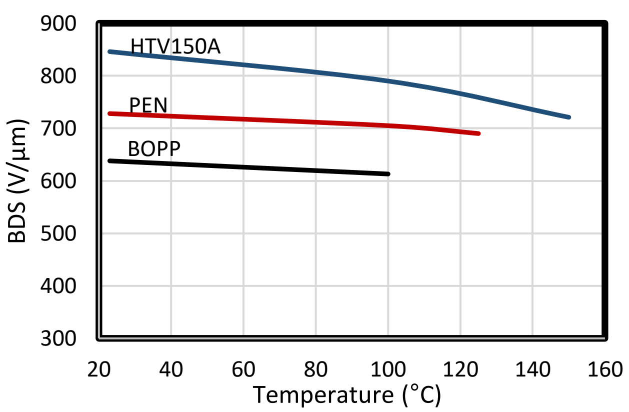

Fig. 2 Breakdown strength (V/µm)

3 Capacitor Building and Testing

Metallized 5µm and 3µm films were used to build test elements. Metallized film has 20Ω/sq active electrode, 5Ω/sq heavy edge and constant width margin. Round elements were made from the film using standard capacitor winding equipment following process parameters suited for HTV150A film characteristics. The round elements were flattened to an oval shape, followed by heat conditioning to stabilize the geometry and tighten the elements. Thermal end-spray and soldered terminals were applied to provide electrical connectivity. High temperature epoxy potting was applied to all elements to create finished capacitors for testing. Reference characteristics for each capacitor were recorded, including initial capacitance, internal losses (tan δ), insulation resistance (IR) and equivalent series resistance (ESR).

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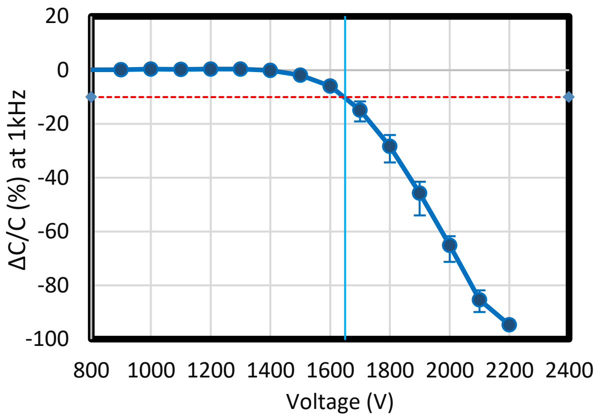
4 Capacitor Performance

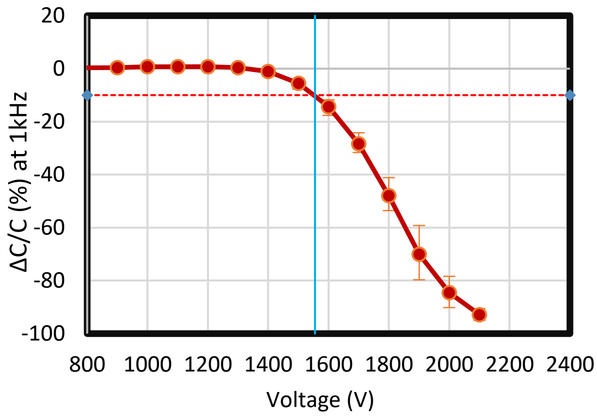
To determine appropriate operating voltage, voltage stress tests were performed at temperatures of interest. Reliability life-testing is then performed at the operating voltage and temperature.

4.1 Voltage Stress Testing

A group of six similar 5µm-based capacitors was used to determine the operating voltage for each of 130°C and 150°C continuous temperature levels. Voltage was applied at 100V increments over 60 second steps during which change in capacitance was monitored. Maximum voltage for the capacitors is determined from the response charts as the voltage corresponding to 10% capacitance drop. Fig.3 (a and b) shows the voltage stress test results, averaged for the six capacitors, at 130°C and 150°C, respectively. The maximum voltage is 1650V at 130°C and 1550V at 150°C. Based on the stress test results operating voltages of 900V and 1000V were selected for the 5µm-based capacitors for 150°C and 130°C temperatures, respectively. Similarly, for the 3µm-based capacitors 600V operating voltage was determined for 150°C.



(a) At 130°C



(b) At 150°C

Fig. 3 Voltage Stress test on Capacitors made with HTV150A film

4.2 Reliability Testing (Life-Testing)

Reliability testing was performed on two groups of finished capacitors (5µm) subjected to constant voltage of 900V at 150°C and 1000V at 130°C. Typically the test is run for 2000 hours. In the current work the test was extended to 3600 hours for 130°C. Preliminary testing on a group of 3µm-based capacitors was done at 150°C and 600V for 1500 hours.

Throughout the test, change in capacitance (ΔC), insulation resistance (IR), dielectric losses (represented by tan δ) and equivalent series resistance (ESR) were monitored over the test duration.

For 130°C and 1000V, capacitance value over time is visualized in Fig. 4(a) for the 5µm-based capacitors. Performance is represented by the average value for the group of 10 capacitors; standard deviation is also shown. After the first 50 hours there is a slight increase (~5%) in capacitance. This is likely due to additional tightening of the wound element when subjected to initial heat; a known condition that can be mitigated by adjusting the winding and heat conditioning steps during capacitor building.

The change in capacitance over time, ΔC/C%, is relatively stable and remains positive (gain) as shown in Fig. 4(b). The change is within 10% threshold of the initial value. Excluding the initial capacitance increase, capacitance change during the remainder of the test (i.e., 3550 hours) is actually less than 5%.

Loss factor, tan δ, is shown in Fig. 4(c). Expectation is that tan δ remains less than twice the initial value over the duration of the test. Tan δ had very little change, from an average value of 0.07% at the beginning of the test to 0.09% after 3600 hours. Insulation resistance (IR) and equivalent series resistance (ESR) are shown in Fig. 4 (d and e). IR and ESR remained stable over the 3600 hours of testing.

Similarly, at 150°C and 900V over 2000 hours of life-testing, capacitance level had an initial increase of 8~10% and remained positive (gain) throughout the test (see Fig. 5 (a and b)). This initial increase is slightly higher than at 130°C,

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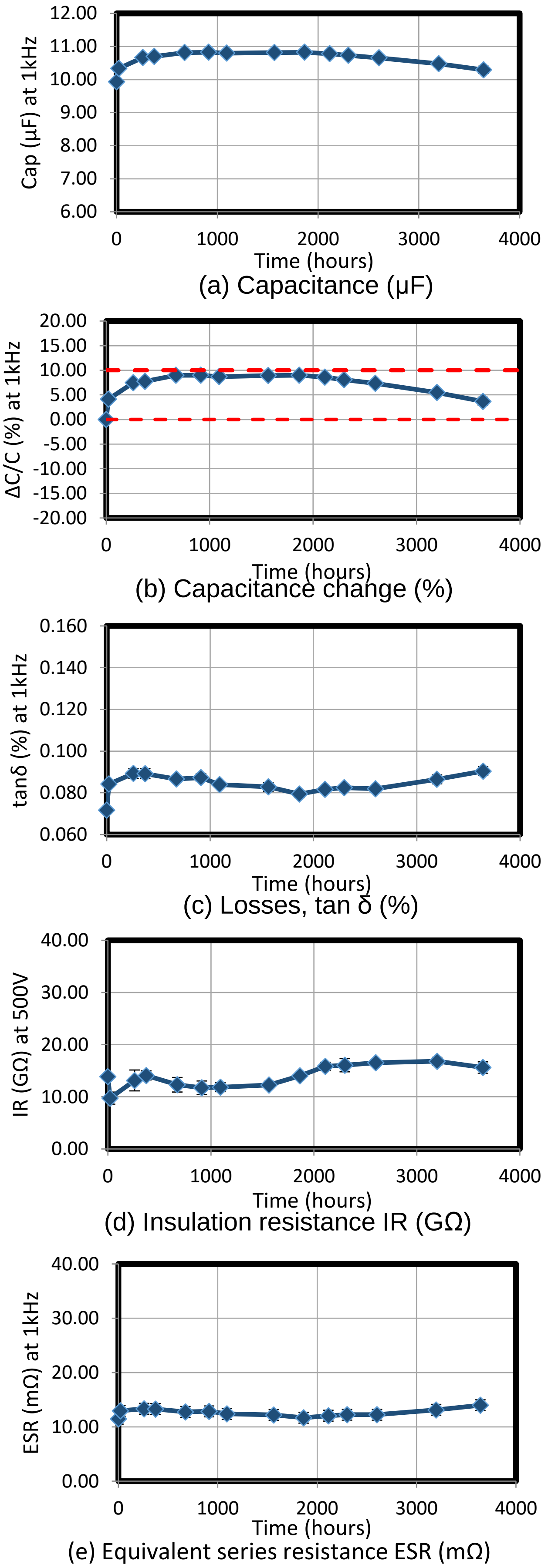


(a) Capacitance (µF)

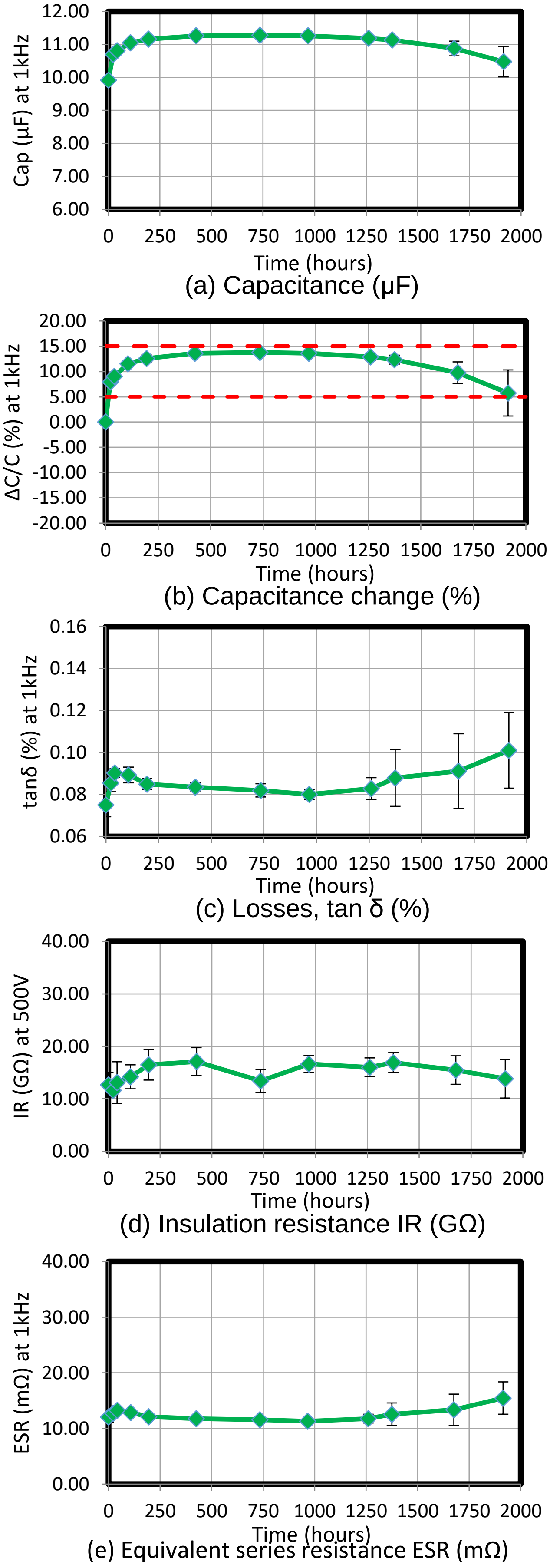
(b) Capacitance change (%)

(c) Losses, tan δ (%)

(d) Insulation resistance IR (GΩ)

(e) Equivalent series resistance ESR (mΩ)

Fig. 4 Reliabilty life-testing at 130°C and 1000V for 5µm-based capacitors



(a) Capacitance (µF)

(b) Capacitance change (%)

(c) Losses, tan δ (%)

(d) Insulation resistance IR (GΩ)

(e) Equivalent series resistance ESR (mΩ)

Fig. 5 Reliabilty life-testing at 150°C and 900V for 5µm-based capacitors

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likely due to more tightening of the wound element at a higher temperature. Excluding this initial increase, capacitance over the test duration was within 5% (gain).

Loss factor, tan δ, insulation resistance (IR) and equivalent series resistance (ESR), shown in Fig. 5 (c, d and e), remained stable within acceptable limits over the 2000-hour test duration.

For the 3µm-based capacitors the trends and stability over time are similar to 5µm-based capacitors. Fig. 6 (a) shows capacitance value over time at 150°C and 600V. Capacitance change (%) is shown in Fig. 6 (b). An initial gain in capacitance of ~15% is noted within the first 50 hours and remained stable thereafter. This initial increase is likely due to tightening of the wound element when heat is applied and can be mitigated through further tuning of the winding tension as well as heat conditioning after winding. Longer testing (>1500 hours) will be repeated on the modified capacitors. Excluding this initial increase, capacitance over the test duration was within 5% (gain). Loss factor, tan δ and equivalent series resistance (ESR), shown in Fig. 5 (c and d), remained stable within acceptable limits over the 1500-hour test duration.

Passing reliability testing offers new opportunities for the module designer to consider efficient module architectures whereby active cooling may be reduced or eliminated, components may be brought closer together for reduced induction losses and better thermal management or combining components together into integrated drives for efficiency improvements and possibilities for weight reduction.

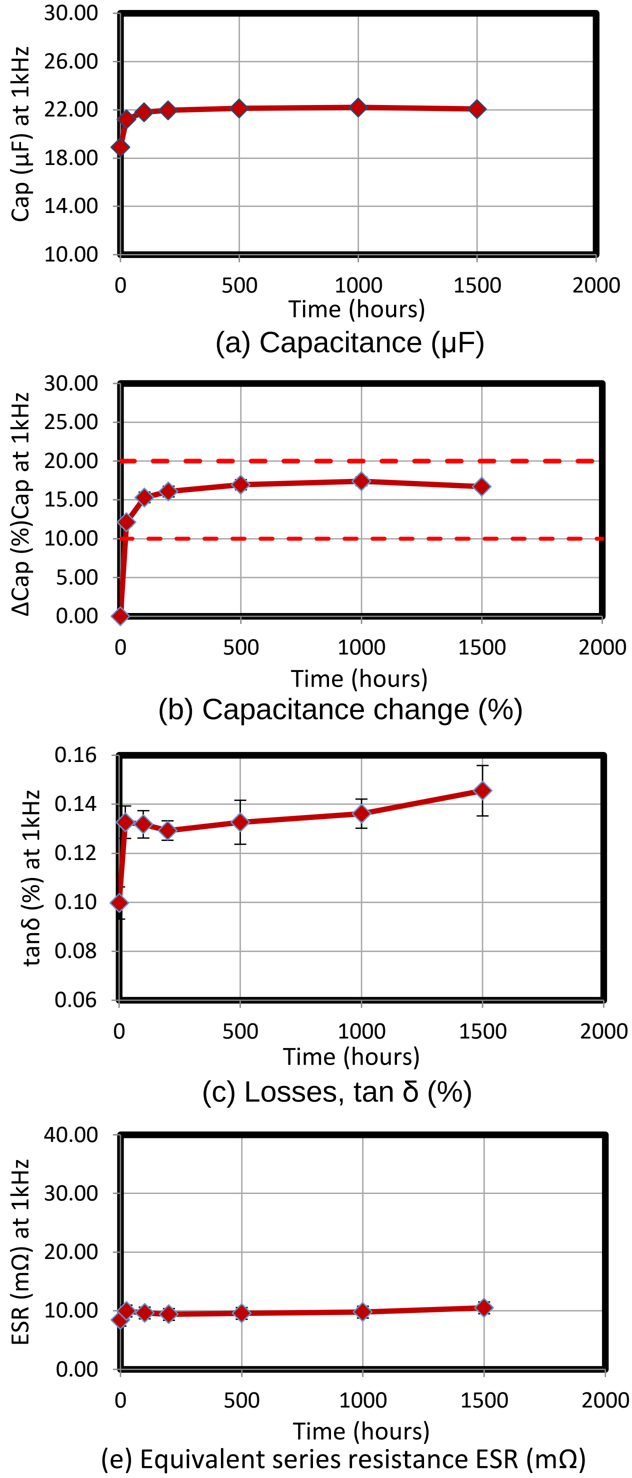

Fig. 6 Reliability life-testing at 150°C and 600V for 3µm-based capacitors

5 Conclusions

High-heat ELCRES™ HTV150A dielectric films have been used to build high temperature capacitors. Under 1000V applied voltage, the 5µm-based capacitors passed accelerated reliability life testing at 130°C for 3600 hours and passed 2000 hours at 150°C under 900V. Early results for 3µm-based capacitors showed similar stable trend over 1500 hours of lie-testing under 600V at 150°C.

Excluding an initial increase in capacitance, likely caused by tightening of the film winding upon application of heat, the capacitance change ΔC remained within 5% throughout the test duration. Dissipation losses, tan δ, remained lower than twice the starting value; insulation resistance IR and equivalent series resistance ESR remained stable.

Capacitors made with HTV150A film are well positioned to help realizing full benefits of SiC and GaN MOSFETs when used in AC-DC inverters for EV applications.

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