High Temperature Performance of Oxide Film Capacitors

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Abstract

Film capacitors that perform well at temperatures exceeding 150ºC and have energy densities in excess of 1 J/cm^3 are an enabling technology for many applications in automotive, geophysical exploration, aerospace, and the military. To address this need Faradox Energy Storage, Inc. has produced and is testing high temperature film capacitors fabricated using amorphous oxides (OxFilm^{TM}) as the dielectric material. The capacitors are made by depositing thin films of an oxide dielectric on both sides of a double metalized polyimide substrate to form dielectric-coated electrodes. Currently Faradox is producing 2" long, 1/4" diameter 2 uF, 100 VDC capacitors using silicon dioxide as the dielectric material.

In this paper we present test data demonstrating that OxFilm capacitors have relatively stable properties over a wide temperature range. Measurements include capacitor testing at different 3rd Party test facilities and internal testing using a variety of test conditions including:

- *Life testing at 200 and 250ºC for over 1000 hours with measurements of capacitance, leakage, dF and ESR.*
- *Capacitance versus voltage, temperature and frequency*
- *Impedance, ESR, and dF versus frequency and temperature and voltage*

Data will also be presented that show these capacitors can be cycled between 0ºC and 200ºC without degrading their performance. Work is ongoing to obtain additional test data with more statistically significant numbers of capacitors.

Key words. Film capacitor, high temperature operation, silicon dioxide

Introduction

In order to produce electronic systems that operate reliably at elevated temperatures all components including integrated circuits, transistors and capacitors must function efficiently in this environment. Even though a capacitor is generally thought of as an inexpensive passive component, its ubiquity in electrical energy storage, filtering, and power conversion, and the tendency of certain capacitor technologies to fail catastrophically, emphasize the need for more stable and reliable capacitors for harsh environments. The key to producing highly reliable and temperature stable capacitors is through improvements in the capacitor dielectric to allow the production of self-clearing film capacitors that operate at high temperatures. Ideally these capacitors would have the temperature handling capability of ceramic capacitors coupled with the self healing capability of film capacitors.

This paper builds on previous work [1,2]. We will present detailed test results from capacitors fabricated using flexible amorphous silicon dioxide as an alternative dielectric to polymer films in the fabrication of non-polar, self clearing film capacitors. Amorphous silicon dioxide has a higher dielectric constant, improved breakdown strength, and is able to tolerate higher temperatures than its polymer counterparts. This allows capacitors fabricated using silicon dioxide as the dielectric to achieve high energy densities with consistent operational

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properties, and self-clearing over a large temperature range. This improves capacitor performance and lifetime in harsh environments. In addition, the temperature stability of the amorphous silicon dioxide dielectrics will make these capacitors compatible with the next generation of high temperature / high power electronic devices made using SOI, GaN and SiC.

Experimental

To fabricate silicon dioxide on metalized film (OxFilm) capacitors, a thin polyimide web with a metal coating on both sides is used as the starting electrode. Next, a submicron layer of SiO_2 is deposited on both sides of the electrode using a custom built web coater. The thin, metal coated polyimide film serves as a flexible electrode that maintains the clearing properties of traditional film capacitors. To fabricate the capacitor, two such coated electrodes are placed together, slightly offset, and wound into a cylinder. A metal end spray is used to make electrical contact to the ends of the film.

Using the above fabrication method, the capacitance of the device is determined by the thickness and dielectric constant of the deposited SiO_2. The metalized polyimide electrode serves as a support structure for the oxide dielectric and should be as thin as possible to maximize energy density. Figure 1 shows the web coating system used to produce the SiO_2 coated electrodes and Figure 2 shows finished OxFilm capacitors after winding, end spray, wire attach and potting.

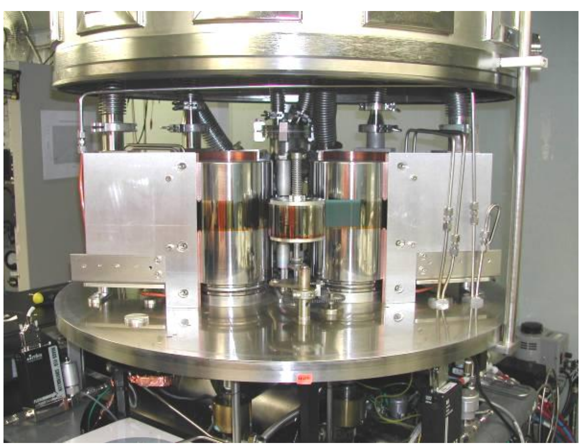

Figure 1. Picture of the custom built web coating system used to deposit the dielectric on the metalized film.

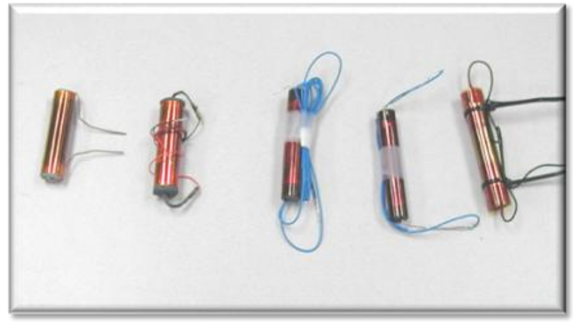

Figure 2. Packaged OxFilm capacitors made from winding the SiO_2 coated metalized polyimide electrodes into a cylindrical shape, end spray solder lead attach then wrap-and-fill end-pot.

Capacitor Testing and Discussion

OxFilm test capacitors were made using ~0.35μm of reactively sputtered SiO_2 deposited on each side of a 13 micron thick metalized polyimide film. Two of these films were then placed on top of each other and wound ~60 times around a 1/4" mandrel using a hand winder to produce ~2.0 μF film capacitors that are shown in Figure 2. These capacitors were then subjected to testing and compared to tantalum and ceramic capacitors.

Heating and Cooling

After fabrication, the thermal performance of the SiO_2 film capacitors was characterized. For comparison, we also tested high temperature tantalum electrolytic capacitors and high temperature (200°C) ceramic capacitors. Figure 3 shows a comparison of various capacitor technologies as the capacitors are heated and cooled.

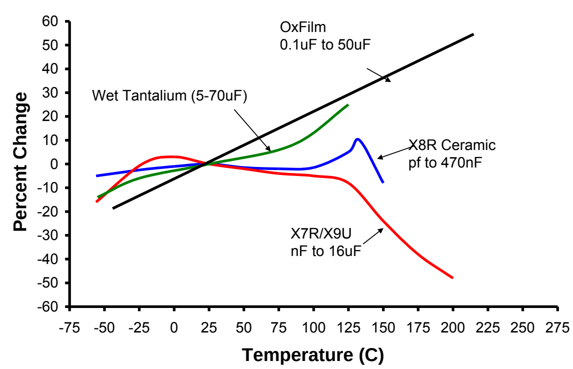

Figure 3. Typical capacitance change as a function of temperature for various capacitor technologies

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Initially, we tested a 0.1uF ceramic C0G capacitor, a 49uF Tantalum capacitor, and a 2.5uF Faradox SiO_2 film capacitor. For thermal testing all three capacitors were placed in an oven. At room temperature 75VDC was applied to the capacitors, then they were heated to 200°C. The capacitors were operated under these conditions for 1000 hours. Figure 4 shows the leakage current as a function of temperature. The maximum temperature used was 200C due to limitations of the tantalum and ceramic capacitors. The OxFilm capacitors show very little increase in leakage as the temperature increases.

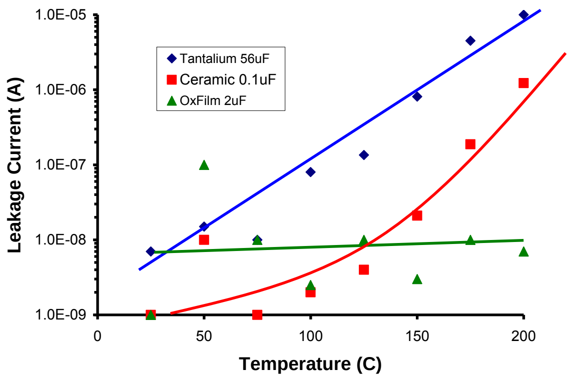

Figure 4. Leakage of various capacitors as a function of temperature

Figure 5 shows the leakage current as a function of time when heated to 200°C and left under a 75 VDC stress for 1000 hours.

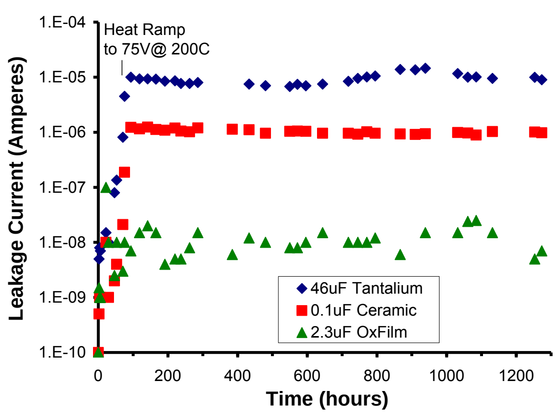

Figure 5. Leakage current of different capacitor technologies as a function of time at 200°C.

Figures 6 shows life test of five capacitors at 250˚C under a 50 VDC continuous bias. This data was taken at Sandia National Laboratory. As noted earlier, the OxFilm capacitors increase in capacitance as a function of temperature. Over time the capacitance gradually decreases for a final state. The capacitance returns to its original value when cooled Figure 6 shows the time dependent capacitance of five OxFilm capacitors at 250°C that were tested at Sandia.

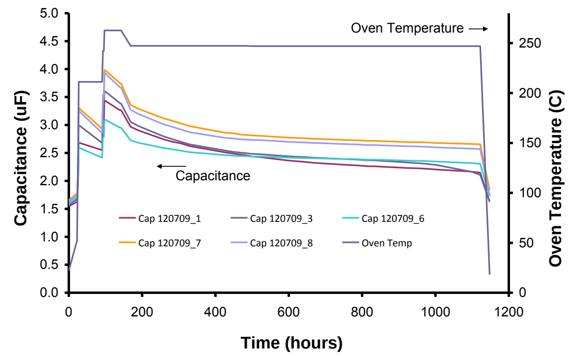

Figure 6. Capacitance at 250°C over 1000 hours.

Figure 7 shows the leakage of a typical capacitor as a function of time at 250°C with 50 VDC applied. Again this data was taken at Sandia.

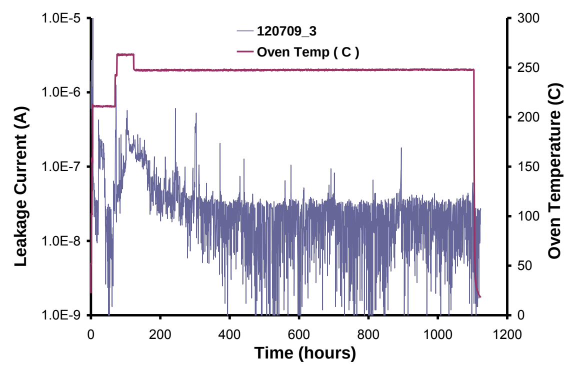

Figure 7. Leakage current as a function of time

Measurements at different frequencies

In addition to capacitance and leakage measurements, measurements were made of the equivalent series resistance (ESR) and capacitance at both room temperature and 250°C at a variety of frequencies. At room temperature we initially compared the performance of the OxFilm capacitor to a standard polyester film capacitor of similar value. Figure 8 shows the capacitance as a function of frequency for both a typical polyester capacitor and an OxFilm capacitor between 100Hz and 100kHz.

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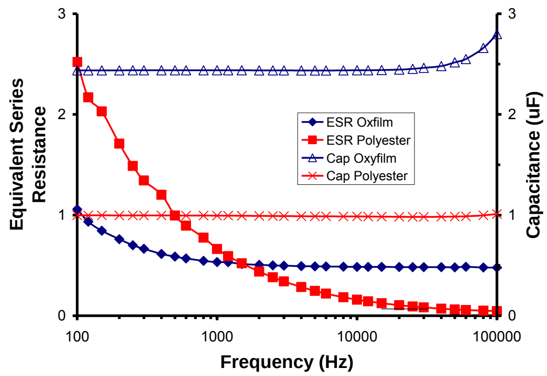

Figure 8. Capacitance and ESR as a function of frequency for OxFilm and a standard polyester film capacitor.

In figure 8 the high frequency measurement of the OxFilm capacitor shows a relatively high ESR value compared to the polyester capacitor. This can be explained by understanding the contributions to the ESR measurements. In the future the ESR will be lowered by optimizing the design of the OxFilm capacitor.

There are three types of losses that comprise the ESR of a film capacitor. They are, metal losses (R_m), leakage or insulation losses at DC and low frequencies (R_{in}), and dielectric losses (R_{da})[3]. Mathematically these losses can be expressed by the following equation with the first term the metallization loss, the second term the insulation resistance loss and the third term the dielectric loss:

$$ESR = R_m + \frac{1}{R_{in}(2\pi fC)^2} + \frac{DF}{2\pi fC}$$

with DF being the dielectric dissipation factor.

Metallization losses are constant with frequency (f), while leakage losses fall off as $1/f^2$ and dielectric losses fall off by 1/f. At high frequencies, leakage and dielectric losses become negligible leaving only metal losses. An examination of ESR as a function of frequency for the SiO_2 film capacitor shows that metal losses begin dominating the ESR at frequencies as low as 1 KHz.

For a given capacitance value, OxFilm capacitors use significantly less film than standard film capacitors due to the increased breakdown strength and higher dielectric constant of SiO_2. For metalized film capacitors the ESR from the metallization (R_m) may be expressed as:

$$R_m = \frac{2}{3}\rho\frac{W}{L}$$

Where ρ is the resistivity of the film in ohms/square, W is the width of the film, L is the length of the film and the constant 2/3 results from the uneven axial current distribution in the metallization.

The winding length (L) for a film capacitor of capacitance C made from a film with a dielectric constant ε, film thickness d and active film width W may be expressed as:

$$L = \frac{dC}{2\varepsilon W}$$

Substituting for L in the prior expression yields:

$$R_m = \frac{4\rho\varepsilon W^2}{3dC}$$

As one can see from the above equation, both a larger dielectric constant (ε) and a smaller electrode spacing (d) will increase the ESR. OxFilm sample capacitors have a relatively large dielectric constant (4.5) and small electrode spacing (0.8 um). In addition, the metallization (ρ) of Oxfilm samples is approximately 15 to 30 ohms per square, and the width (W) is 50 mm.

The ESR for OxFilm capacitors can be lowered through a number of changes that will be made in future designs. These include, reduction in metallization resistance, thicker dielectric layers, and narrower films with narrower films yielding the most significant reduction in metal loss and ESR because the width term is squared.

Figures 9, 10 and 11 show the ESR and impedance of the OxFilm capacitor at room temperature and 250C, a comparable (1uF) X7R ceramic capacitor at these temperatures, and a Tantalum capacitor at room temperature and its temperature limit of 200C. [Note: all measurements were made using 1 Meter wire attached to the samples. No effort was made to compensate for this wire.]

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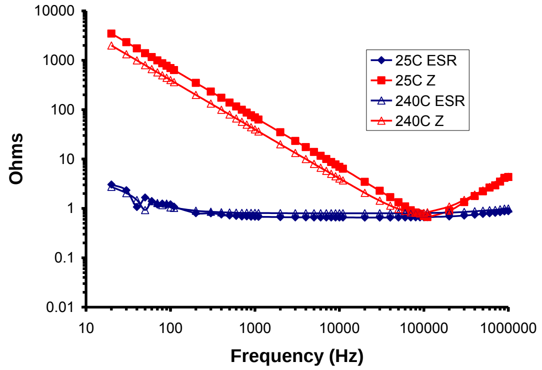

Figure 9. ESR and impedance of a 2.4 uF OxFilm capacitor at room temperature and 250°C.

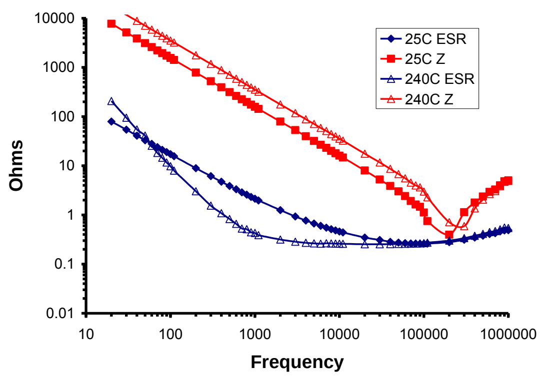

Figure 10. ESR and impedance of a 1uF ceramic XR7 capacitor at room temperature and 250°C

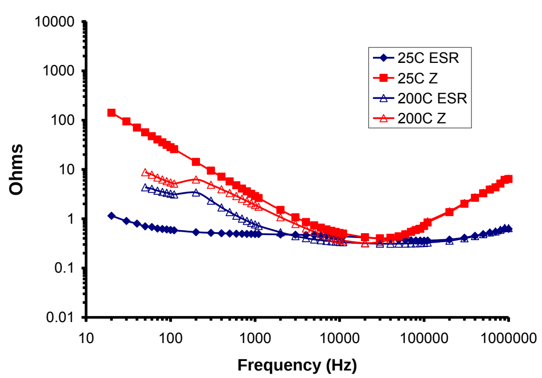

Figure 11. ESR and Impedance of a 56uF tantalum capacitor as a function of frequency at 25 and 200°C

Measurements of the OxFilm capacitor ESR and impedance measurements are extremely stable between these temperature extremes while the ceramic and tantalum measurements exhibit significant variation demonstrating the inherent stability of OxFilm capacitors.

We next examined the leakage current of the OxFilm capacitor as a function of voltage when the capacitor is stressed thermally and with high voltage. Figure 12 shows the leakage current as a function of voltage as the capacitor is heated to various temperatures. This data was taken by an external laboratory[4]. The leakage remains below 1uA at low voltages / temperatures. The leakage remained well below 1 uA at voltages up to 100VDC. Only when voltages over the rated value were applied at high temperatures were currents in excess of 1uA measured.

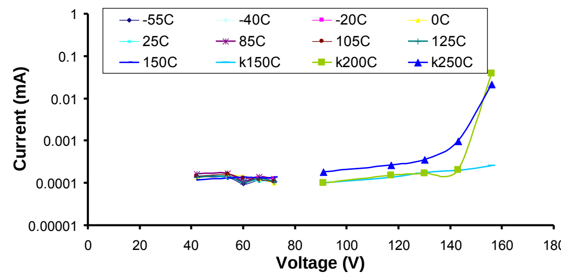

Figure 12. leakage current vs voltage at a number of temperatures.

In one final test we cycled OxFilm capacitors rapidly between 200°C and 0°C. Ten cycles were performed with no degradation in performance.

Conclusions

Silicon dioxide shows promise as a dielectric material for fabrication of temperature stable film capacitors that can operate at temperatures >150˚C. Testing is ongoing to demonstrate the performance advantages of this capacitor technology over competitive technologies in a high temperature environment.

Acknowledgements

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