

High Voltage Capacitors for Next-Generation Power Modules in Electric Vehicles

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Abstract – This paper describes an innovative approach to develop high density and ultra-thin solid aluminum capacitors for high voltage automotive applications. Form factors of less than 100 μm thickness are achieved with densities of 16.85, 1.91, 1.13, and 0.705 $\mu\text{F}/\text{cm}^2$, for capacitors anodized to 10, 100, 150, and 200 V respectively. The capacitors exhibit good frequency stability up to 100 kHz and demonstrate the first aluminum capacitors to come in such a thin format. These capacitors can be used in new era automotive electronics where high density and high voltage stability is critical.

I. Introduction

The trend towards system miniaturization with lower cost and higher efficiency is driving new methods of power module integration. This is especially true for new era automotive electronics, where high-performance systems include motor controllers, recuperation, electricity import/export, boost converters, climate control, sensing and communications, and other electronic subsystems [1]. The increased number of components add weight to the vehicle and add to the system complexity, necessitating smaller size formats. At the same time, moving to larger systems means moving the electronics closer to vehicle motors due to geometric restraints, resulting in higher temperatures and voltages of operation. Passive components such as capacitors improve power module operation by reducing noise from other high impedance components within the system. However, surface-mounted capacitors suffer from large interconnection lengths resulting in parasitic inductance that limit their efficiency and

frequency stability [2]. Therefore, research continues to focus on integration of passives closer to the integrated circuits (ICs) and other active components.

DC-DC convertors from Murata and Texas Instruments (TI) have already employed embedded component packaging to yield highly miniaturized low power modules [3, 4], while processing units from Apple featuring deep trench silicon capacitors have also yielded highly competitive packaging densities [5]. For high-voltage modules, such embedding approaches have not been successful so far because of the challenges associated with miniaturization of passive components such as capacitors, inductors and transformers, which take up the majority of the volume in power modules. Trench capacitors are limited due to their low voltage ratings and high cost. High capacitance density with high voltage stability, low leakage current, high frequency and temperature stability in a small form factors are critical for power supply in automotive and industrial applications. The capacitors must also exhibit low ESR to minimize ripple voltage and heat generation inside the component.

Ceramic capacitors exhibit excellent frequency stability and remain the workhorse capacitors for low-power consumer applications, but for high voltage applications their use is limited. Due to the high processing temperatures and large thicknesses, ceramic capacitors are almost always mounted as discrete components leading to longer interconnection lengths. Thinner capacitors can be achieved by using barium titanate-based X7R ceramics, but their ferroelectricity results in major capacitance losses at higher bias levels as much as 10-50% at 300V. They also show a dramatic capacitance

drop with increasing temperature, on the order of 50% at 200°C and 15% between -55°C and 150°C [6]. Additionally, X7R capacitors are much more susceptible to crack and failure from vibration or flexural stresses, with a rupture modulus half that of COGs [7]. COG capacitors such as those based on calcium zirconate titanate (CZT) dielectrics exhibit low thermal coefficient of capacitance (TCC) of 30ppm/°C up to about 250°C and a negligible voltage coefficient of capacitance (VCC) due to their paraelectricity. However, COG capacitors suffer from low capacitance density [8]. Kemet's X8R capacitors also show great stability, but suffer from low capacitance values. TDK's CeraLink LP series can operate up to 700VDC bias while handling high switching frequencies all with ultra-low ESR and a compact design. The ferroelectric lead lanthanum zirconate titanate (PLZT) dielectric in ceralink caps is superior to existing technologies at high temperatures up to 150°C, but has lead toxicity and voltage stability issues.

Polymer film capacitors like those based on polypropylene (PP) and polyethylene terephthalate (PET) are capable of ultra-high voltage applications due to their nonpolar and paraelectric self-healing dielectrics. However, the capacitors are based on low-permittivity polymer films with relatively low electrode surface areas, compromising their capacitance density [9,10]. Thus, combining voltage stability and specific capacitance is an issue for ceramic as well as polymer film dielectrics.

Electrolytic capacitors based on valve metals are more suitable for high-power applications because of their high volumetric density and tolerance to defects, unlike ceramic capacitors, while the oxide dielectrics can stand higher voltages than traditional ferroelectrics. The effective volumetric density, however, is compromised because of the large packaging volume with metal cases. This paper describes an innovative approach to integrate planar capacitor technologies with thin form factors while also addressing issues such as low volumetric densities, higher losses, or poor voltage stability posed by current approaches.

II. State of Capacitor Technology

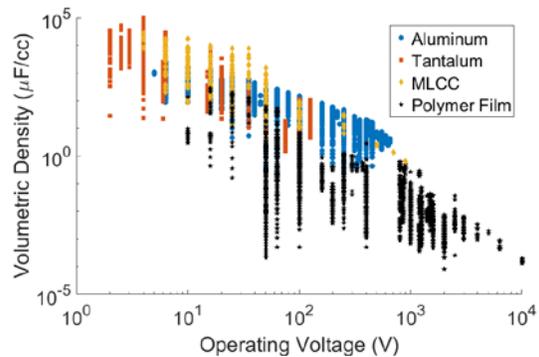


Figure 1. Comparison of capacitor technologies by DC operating voltage and volumetric density

There exists a trade-off between higher capacitance values and rated operating voltage due to the thicker dielectrics needed to prevent breakdown during high voltage operation. The relationship between capacitance and dielectric thickness can be described using equation (1):

$$C = \epsilon_0 \epsilon_r \frac{A}{t} \quad (1)$$

where C is capacitance, ϵ_0 and ϵ_r are the electric constant and dielectric constant, respectively, A is the mutual surface area of the electrodes, and t is the dielectric thickness. Figure 1 compares the operation voltage to the volumetric density for various state-of-the-art capacitor technologies available. While MLCCs dominate the 1-100 V regime, tantalum capacitors find use at lower voltages due to their higher volumetric densities. Despite this, the lower ESR and greater frequency stability of MLCCs make them the capacitor of choice for most low-medium voltage electronic applications. Polymer film capacitors find use in ultra-high voltage applications but have limited capacitance. Aluminum capacitors, however, find use in the 50-500 V regime as they can achieve significant capacitance density compared to their ceramic and polymer film counterparts and operate up to 150°C. The combination of density and high voltage stability make aluminum capacitors useful for power electronic applications.

While capacitors continue to improve as new materials and processing techniques are developed, there is still exists a large gap between current technology and theoretical capability. Using equation (1), equation (2) can be derived to

give the theoretical maximum volumetric density for various dielectric capacitors:

$$C_p = \epsilon_0 \epsilon_r \frac{R_A}{t} \quad (2)$$

where C_p is the volumetric capacitance density, t is the minimum film thickness of the dielectric, and R_A is the aspect ratio of the mutual electrode surface area to the capacitor volume. It is evident that much of the capacitor density is dictated by dielectric material selection, including the permittivity and dielectric strength. For a given operating voltage, a higher dielectric strength allows for thinner dielectric and thus higher volumetric density. Much of the capacitor density, however, is controlled by the amount of electrode surface area that can be packed into a given volume. Therefore, packaging efficiency is critical for high density capacitors. Table 1 compares the relative permittivity, dielectric strength, and highest achieved aspect ratios for different types of dielectric materials. The aspect ratio in electrolytic capacitors will depend heavily on the particle size (tantalum) or foil thickness and channel length (aluminum). The ratio in ceramic and polymer film capacitors will depend on the thickness of the plastic or ceramic film. Higher voltage capacitors will require lower aspect ratios to accommodate the thicker dielectric, so a range is provided.

Table 1. Electrical parameters and aspect ratios for common capacitor types (room temperature)

Dielectric Material	Relative Permittivity	Dielectric Strength (V/ μ m)	Aspect Ratio $\times 10^6$ (m^2/m^3)
Ta₂O₅	25 [11]	400 [12]	1-15
PLZT	1300 [13]	260 [13]	.1-1
CZT	40 [14]	200 [14]	.1-1
Al₂O₃	8 [15]	650 [16]	0.5-5
PP	2.2 [9]	540 [17]	.01-1
PET	3.2 [10]	700 [18]	.01-1

Figure 2 compares the theoretical limits of volumetric density for 100 V_{DC} capacitors to the best densities that have been achieved. The calculations assume a film thickness such that the theoretical breakdown voltage is twice the rated voltage. The aspect ratios for tantalum and

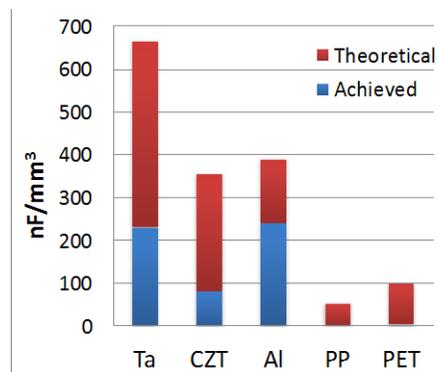


Figure 2. Technology gap between theoretically achievable volumetric density (red) and the best densities that have been achieved (blue) for different types of 100 VDC capacitors

aluminum capacitors was 1.5×10^6 , while 1×10^6 was used for all others. Tantalum capacitors have both the highest realized density and capability, but their dielectric strength drops off significantly at higher voltages and the leakage is generally high, limiting their use in high voltage applications. Likewise, CZT-based capacitors also find limited use at higher voltages due to their voltage stability issues. Aluminum capacitors, however, have a combination of high volumetric density and stability at high voltages, making them in many ways an ideal choice when smaller form factors are required. Despite this, a large gap exists between the theoretical density and the realized density. Part of this is due inefficient large metal casing surrounding the wound aluminum foil. Typically, much of the volume in aluminum capacitors is wasted on the rubber, aluminum casing, and insulating sleeve needed to hermetically seal the capacitor. In this paper, an innovative approach is proposed to integrate aluminum capacitors with improved density closer to what is theoretically possible with an ultra thin form factor. This is achieved through the removal of bulky casing and replacement with active electrode area

III. Experimental Procedures

To determine the maximum capacitance achievable for high voltage applications, aluminum capacitors were anodized at 10 V, 100 V, 150 V, and 200 V. Chemically etched aluminum foils were obtained from Kendeil and cut into six 0.5×3 cm² strips. The foils were first

gently cleaned of contaminants using acetone followed by isopropyl alcohol, and dried under a nitrogen air jet. The anodization was carried out at room temperature in a 0.15 M solution of ammonium pentaborate $(\text{NH}_4)\text{B}_5\text{O}_8$ for growth of barrier type alumina. Anodization in strong acids like sulfuric acid is known to grow porous alumina films [19] which is undesirable for dielectrics. The foils were partially dipped and anodized using a galvanostatic approach where the current was maintained at 2.5 mA, or 4 mA/cm² of foil area, which equates to less than 2 $\mu\text{A}/\text{mm}^2$ of aluminum surface area. The current was held as the potential increased until the final formation voltage was reached, at which point the current was allowed to drop below 400 μA or less before removing the potential.

A weakly acidic electrolytic solution of 0.5 M K_2SO_4 was then used to obtain wet measurements of the foils capacitances after anodization. The weak acid was used to prevent dissolution of the oxide during measurement. A high surface area stainless steel cathode was used to make good electrical contact with the electrolytic solution. The measurements were produced using the Hewlett Packard 4263B LCR meter at 120 Hz and under a 0 V bias 100 mV peak amplitude.

Next a polymer cathode was applied to the foils. Both Clevios low-viscosity (LV) and high-viscosity (HV) PEDOT:PSS conducting polymer suspensions from Heraeus were obtained. The foils were dipped eight times in a solution with a 1:1 ratio of water to LV polymer, followed by six more times in 100% LV polymer and one time in HV polymer. After each one-minute dip, the foils were dried at 120° C for five minutes. The foils were then dipped in carbon black and cured for 120 minutes at 100° C to provide a layer of mechanical integrity and diffusion barrier. Finally, the foils were dipped in silver paste and cured again for 120 minutes at 100° C to provide a terminal for good electrical contact.

Again the capacitances of the foils were measured. Measurements were made at 120 Hz and from 1 kHz to 1 MHz.

IV. Results and Discussion

SEM images of the etched Al foils were taken before and after anodization, as shown in Figure 3. The images reveal a microstructure consisting of a 3D network of channels with varying diameters and lengths, with the density of channels traveling along the thickness of the foil being much greater than of those traveling perpendicularly. The large channels are ~2-3 μm in diameter and are up to 25-35 μm deep as shown in Figure 3b. The spacing between parallel channels appears to vary from 400 nm in some place to 1 μm in others, resulting in a ~20 \times increase in surface area. Assuming a dielectric growth rate of 1.3 nm/V for barrier type aluminum oxide film [20], anodization beyond 150 V could likely result in complete oxidation of the more narrow aluminum walls and loss of capacitance. It was observed that the 100 V anodization resulted in approximately 160 nm thick aluminum oxide (Figure 3d), with growth rate of 1.6 nm/V. While similar to previous results [20], the high growth rate is likely the result of small current density and long dwell times during anodization.

The current and voltage were carefully monitored during anodization of the aluminum foils. First the steadily increasing voltage (during the ramp-phase) was monitored until the final voltage was reached (Figure 4a), then the current was monitored as the foils were allowed to dwell at the formation voltage (Figure 4b). The linearly

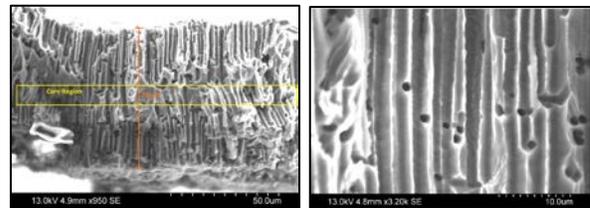


Figure 3a. 75 μm thick aluminum foil with 10 μm core

Figure 3b. Electrochemically etched channels in aluminum

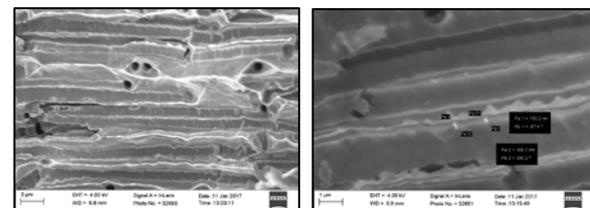


Figure 3c. Aluminum channels after 100 V anodization

Figure 3d. Al_2O_3 dielectric with 160 nm thickness

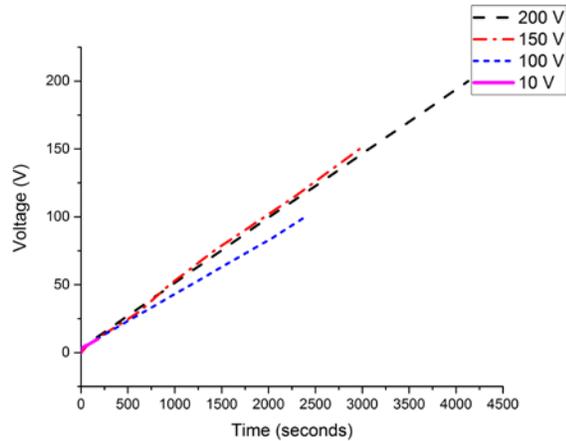


Figure 4a. Voltage versus time during anodization of aluminum foils in 0.15 M (NH₄)₂SO₄

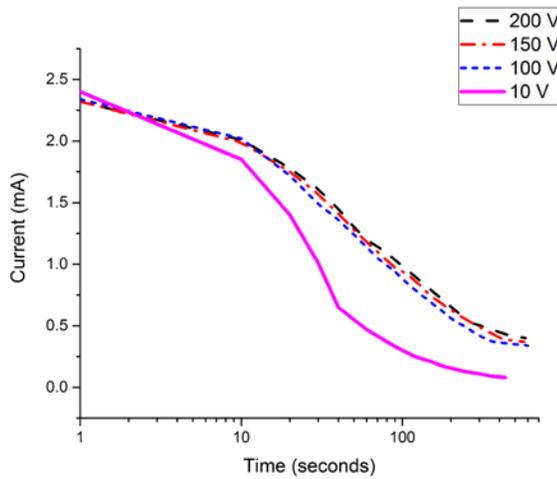


Figure 4b. Current versus time during anodization dwell of aluminum foils

increasing voltage indicates a conformal oxide layer with a low level of impurities. The voltage increased at a rate of ~0.05 V/s, but was slightly slower for the 100 V anodization which may be attributed to small differences in foil surface area.

Wet capacitance measurements were used to determine the effective surface area of anodized foils. The results are included in Figure 5, and show an inverse relationship to the anodization voltage ($R^2=0.988$). Assuming the dielectric thickness is directly related to the anodization voltage, this agrees with Equation (1). While the density at 100 V is comparable to commercially available aluminum capacitors, the density at 150 V is very high. It is evident that this electrode architecture has been optimized for the 100-150 V regime, as previously predicted. Higher

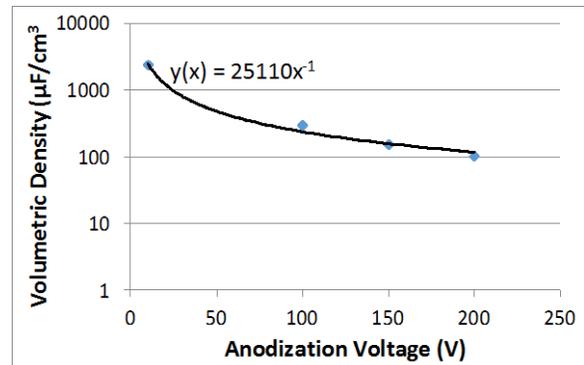


Figure 5. Volumetric density at 120 Hz using a 0.5 M K₂SO₄ wet electrolyte

anodization voltages will begin to fully oxidize the aluminum between channels.

The capacitance was also measured after applying a conducting polymer cathode and current collecting layers. The capacitance was measured at 120 Hz for comparison to the wet measurements, and then from 1 kHz to 1 MHz to observe the high frequency dependence of the capacitance. Figure 6 shows the capacitor during different steps in the fabrication process, and Table 2 compares the capacitance measured at 120 Hz when using a solid versus liquid electrolyte. The similarity between the two measurements indicates high polymer infiltration into the aluminum channel structure.

Figure 7 shows the aluminum-polymer capacitor's response to frequency from 1 kHz to 1 MHz. The capacitors formed at high voltages show high capacitance density of ~1uF/cm² until 0.5 MHz and 0.4-0.5 uF/mm² until 1 MHz. The high frequency stability measured in thin-

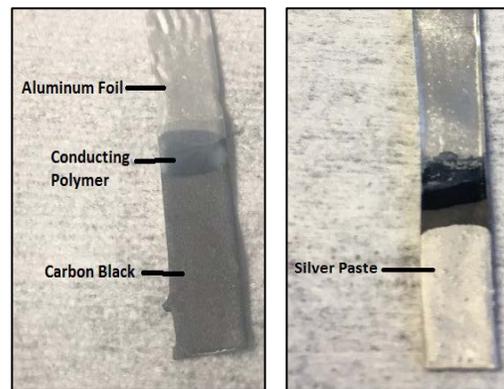


Figure 6. Aluminum capacitor response to frequency from 1 kHz to 1 MHz for samples anodized to 10 V, 100 V, and 200 V

Table 2. Comparison of capacitance densities of 75 μm thick Al capacitors at 120 Hz for solid vs. liquid electrolytes

Anodizing Voltage	0.5 M K_2SO_4 Electrolyte ($\mu\text{F}/\text{cm}^2$)	PEDOT: PSS Electrolyte ($\mu\text{F}/\text{cm}^2$)	% Polymer Infiltrated
10 V	17.4	16.85	96.8
100 V	2.20	1.91	87.0
150 V	1.14	1.13	98.7
200 V	0.758	0.705	93.1

Al capacitors can be very beneficial for decoupling in power converters. The initial drop in capacitance with frequency is attributed to high RC product for capacitors with thin dielectrics, such as the ~ 16 nm of Al_2O_3 in the sample formed at 10 V. The combination of long and narrow conduction paths (aluminum channels) and a relatively higher resistivity cathode results in higher resistivity in the capacitors during charge and discharge. This can be modeled electrically as an RC ladder network and leads to less frequency stability [21]. While the conduction paths are similar among all the samples measured, the high capacitance of the 10 V sample leads to a high RC constant and greater drop in capacitance with increasing frequency.

As previous results have shown, high densities were achieved with thin layers of aluminum foil. Therefore, a novel integration approach is proposed to remove the need for metal casing and retain the density of the foils while maintaining an ultra-thin form factor. The integration scheme is depicted in Figure 8, and

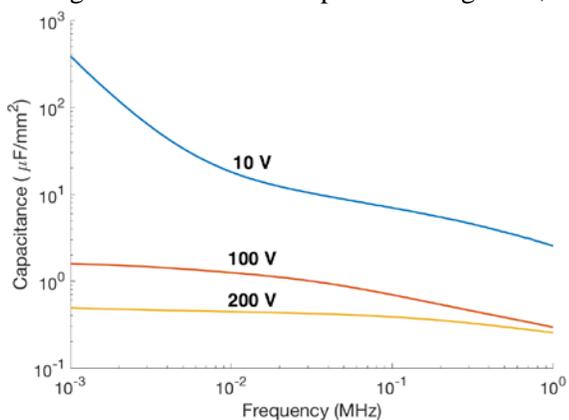


Figure 5. Aluminum capacitor response to frequency from 1 kHz to 1 MHz for samples anodized to 10 V, 100 V, and 200 V

utilizes through vias and a planarizing polymer to laminate the capacitors onto any substrate. Many aluminum capacitors come in cylindrical shapes resulting in inefficient packaging on small devices, but even those that come in a planar configuration do not achieve form factors of much less than 1 mm in thickness. By utilizing thin aluminum sheets filled with conducting polymer cathode, high density solid aluminum capacitors can be fabricated with thicknesses of less than 100 μm . A thin polymer coating such as parylene C can finally be deposited to provide a hermetic seal and provide a volumetrically efficient replacement for large metal cases.

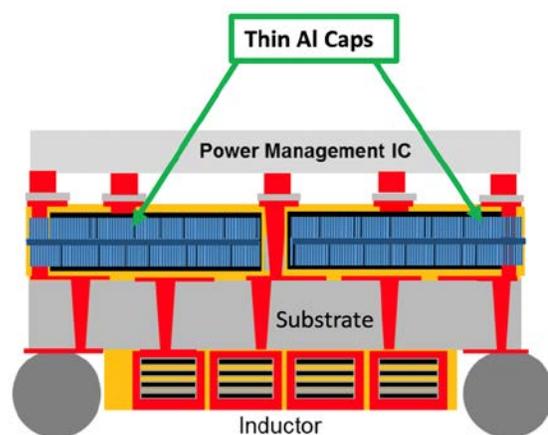


Figure 4. Power module integration scheme for thin solid aluminum capacitors based on sheets of etched aluminum foil

Taking into account 25 μm total of carbon black, silver paste, and planarizing polymer, densities of 1685 $\mu\text{F}/\text{cm}^3$, 191 $\mu\text{F}/\text{cm}^3$, 113 $\mu\text{F}/\text{cm}^3$, and 70.5 $\mu\text{F}/\text{cm}^3$ were achieved for the capacitors anodized to 10 V, 100 V, 150, and 200 V respectively, all with a thickness of 100 μm .

V. Conclusion

High density aluminum capacitors with ultra-thin form factors were fabricated by anodizing thin electrochemically etched foils and filling with conducting polymer. Capacitance densities of 16.85, 1.91, 1.13, and 0.705 $\mu\text{F}/\text{cm}^2$ were achieved for solid polymer aluminum capacitors anodized to 10, 100, 150, and 200 V with an ultra-thin form factor of less than 100 μm . By integrating the foils as laminated sheets with ultra-short copper interconnects, ultra-dense and

highly efficient packaging can be achieved. These capacitors could be used to accommodate the growing need for denser and more stable high voltage electronics in future automotive applications.

VI. Acknowledgments

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VII. References

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