

Ultra-High Energy Density Capacitors Through Improved Glass Technology

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The dielectric performance of stronger glass will make it the material of choice for next-generation high-energy capacitors. The new technology will drive miniaturization and cost reduction in power electronic and pulse power applications. Specifically, products like hybrid electric vehicles and implantable medical devices will utilize the new glass capacitors. The increased availability of these items will be of great benefit to the environment, economy, and human health.

A material's dielectric breakdown strength is closely related to its mechanical strength. This is not surprising since failure in both cases occurs at the weakest point in the area of the material being tested. Invariably, this weakest point is the location of a flaw in the form of a microcrack, pore, or a compositional inhomogeneity. The flaw serves as a stress concentrator under a mechanical load, or an electric field concentrator in the presence of an externally applied electrical potential. Since there is a statistical distribution of flaws in a given glass sample, both electrical and mechanical failure probabilities follow Weibull statistics.

The similarities in the Weibull plots for mechanical and dielectric strength have been established by several investigators.^{1,2} Figure 1 shows the Weibull data for failure of a

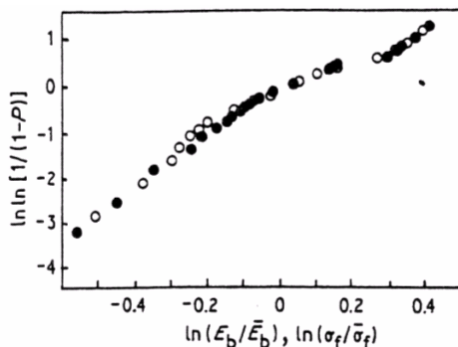


Figure 1. Weibull plots for dielectric and mechanical failure in barium titanate thin films.¹

barium titanate thick film.¹ The two sets of data are virtually indistinguishable, suggesting that the physical origins of the dielectric and mechanical failures are identical. Thus, it is reasonable to expect that the dielectric strength of a material will increase as its mechanical strength is improved. The 50-fold improvement in strength that will be realized in the new glass is expected to be accompanied by roughly an order of magnitude enhancement to its dielectric strength.

The importance of a high dielectric breakdown strength is that it allows for a larger volumetric energy density in a capacitor. Quantitatively, the stored energy density is given by

$$\dot{U} = \frac{1}{2} \epsilon_0 \epsilon_r E^2 \quad (1)$$

where ϵ_0 is the permittivity of free space, ϵ_r is the relative dielectric constant, and E is the electric field applied to the capacitor. It is evident from the equation that the two ways to improve a capacitor's energy density is to increase either the dielectric constant or the field that the dielectric material can withstand. However, energy density only improves linearly with increasing dielectric constant, whereas it grows quadratically with electric field. Thus,

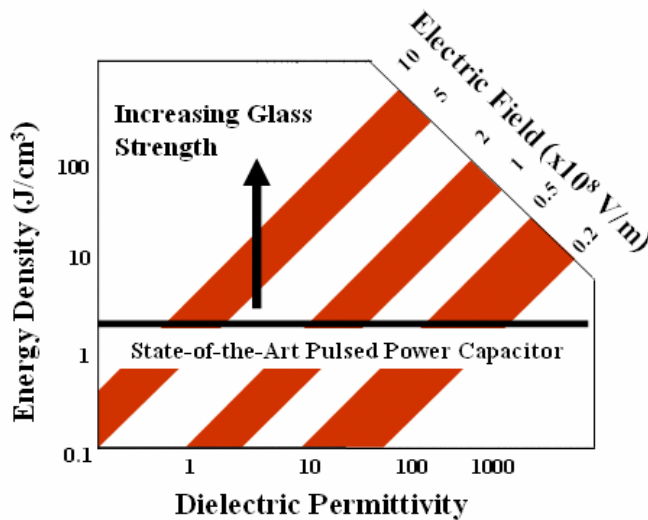


Figure 2. Energy density in state of the art capacitors.³

that will be realized in capacitors fabricated with the new glass will be between 15 and 100 J/cm³. This will position the glass firmly at the front of the market for two emerging capacitor applications.

The new glass capacitors will replace bulky electrolytic and polymer-based capacitor technologies in power electronic applications. The most important practical use of the new capacitors will be in hybrid electric vehicles (HEVs). In HEVs like the popular Toyota Prius (Figure 3), a power electronic circuit is required to convert the DC input from the battery or fuel cell into an AC output to apply to the electric motor. The new glass capacitors will provide for the miniaturization and extended lifetime of the power converter in HEVs. The associated cost reduction will accelerate the already robust market for these vehicles, which

there is a much larger incentive for improving the breakdown strength of a dielectric material so it can operate at high fields. This is shown graphically in Figure 2.³ The arrow indicates the direction that the new thrust in glass research will take the capacitor industry. The new glass is expected to have a relatively low dielectric constant between 3 and 6, but will be capable of reliably operating at fields of roughly 1–2×10⁹ V/m. At those values, the energy density

has grown nearly ten-fold in the past five years.⁴ The advance in capacitor technology will also be a significant step toward fulfilling the DOE Freedom Car Initiative, which challenges the American industry and scientific community to develop automobiles powered only by hydrogen fuel cells.⁵ The corresponding increase in the use of fuel cell technology in transportation will help reduce the economy's oil dependence and curtail greenhouse gas emissions.



Figure 3. A hybrid electric vehicle.

Capacitors are critical components in the power electronic circuit, as seen in Figure 4.⁶ DC bus capacitors (C_E) are responsible for energy storage, discharge and voltage smoothing. They require a large capacitance (100-2000 μF) and energy density. Snubber capacitors (C_C) are used to reduce power dissipation in a solid-state inverter, and have a capacitance of 10-1000 nF. Filter capacitors (C_R and C_F) remove unwanted frequencies and harmonics from the output AC signal, so their capacitances depend on the output frequency.

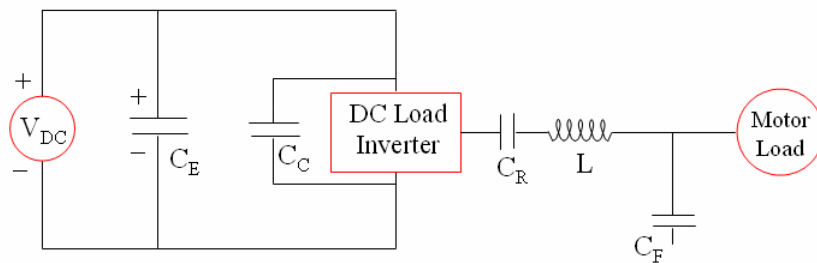


Figure 4. Schematic diagram of a power electronic circuit for use in a hybrid electric vehicle.⁶

Power converter miniaturization and cost reduction will be achieved by the use of the new glass in DC bus and snubber capacitors. Currently, these components are made from electrolytic and polymer technologies, which are volumetrically inefficient. Figure 5 shows that DC bus and snubber capacitors currently occupy over half of the total volume of a power

electronic circuit. Depending on the dielectric constant, the new glass will reduce the required volume by a factor of 2-3. Furthermore, under elevated operating temperatures, the glass capacitors are expected to have a longer lifetime than electrolytic capacitors, which are prone to evaporation of the electrolyte solution. Finally, the high dielectric strength of the glass will allow the capacitors to be rated for much higher voltages than allowed by current

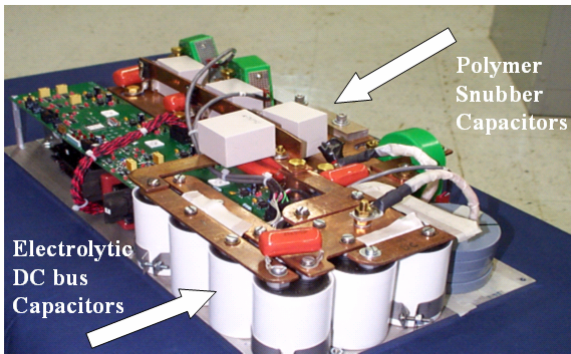


Figure 5. Power converter developed at Oak Ridge National Laboratories.

technology. This will provide more alternatives for fuel cell and battery voltage selection.

The new glass capacitor technology will also be of great benefit to pulse power applications. This generally includes any device that requires a large electrical power delivery in a short amount of time.

Capacitors can have discharge times on the order of microseconds, and are ideal for powering devices including defibrillators, resistance welders, pulsed lasers, and flash lamps. However, in order to store a sufficient amount of energy, the capacitors in these devices are large. The high energy density provided by the new glass will allow miniaturization of pulse power devices.

The most important application for smaller capacitors is implantable medical devices. Current medical technology allows for a number of monitoring and regulating devices to be implanted into the body, as shown in Figure 6. The purpose of these electronics include controlled drug or hormone delivery, bone growth stimulation, heart pace control, and hearing aids. Since space within the human body is limited, highly compact batteries or capacitors are needed to power these devices. Those that require pulse power, such as a defibrillator, need a capacitor that can deliver about 7-10 J of energy. Capacitors available today, shown in Figure 7, only provide an energy density of up to 5 J/cm³. As a consequence, their large size limits the use of implant technology.



Figure 6. Implantable medical devices currently available.⁷

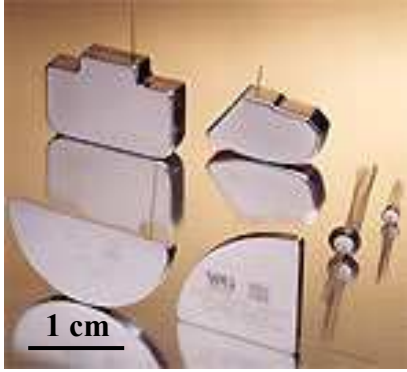


Figure 7. Medical capacitors for implantable devices.⁷

The new glass technology will increase the energy density in these capacitors at least three-fold. Glass capacitors of less than 0.5 cm^3 in volume will replace the state of the art tantalum capacitors (front right in Figure 7), which have a volume of roughly 2 cm^3 . The smaller overall size of implantable defibrillators will provide for more widespread use in patients with heart trouble. The American Heart Association (AHA) has estimated that 335,000 deaths last year were caused by coronary heart disease, which leads to sudden cardiac arrest.⁸ The AHA also estimates a survival rate between 48 and 74 percent when defibrillation is promptly administered to a cardiac arrest victim. Thus, the contribution to human health that the new glass capacitor technology will make cannot be overstated.

In conclusion, the research initiative to make stronger glass will lead to higher dielectric breakdown strength as well. The new glass will be the basis for ultra-high energy density capacitors used in power electronic and pulse power devices. Hybrid electric vehicles will use the glass capacitors in their power converter circuit, providing a cost reduction that will help drive the market for hybrids. Also, implantable medical devices will be more readily available because of the size reduction that the glass capacitors impart. Thus, the incidental improvement of the dielectric properties of the new glass will bring great economic, environmental, and medical benefits.

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