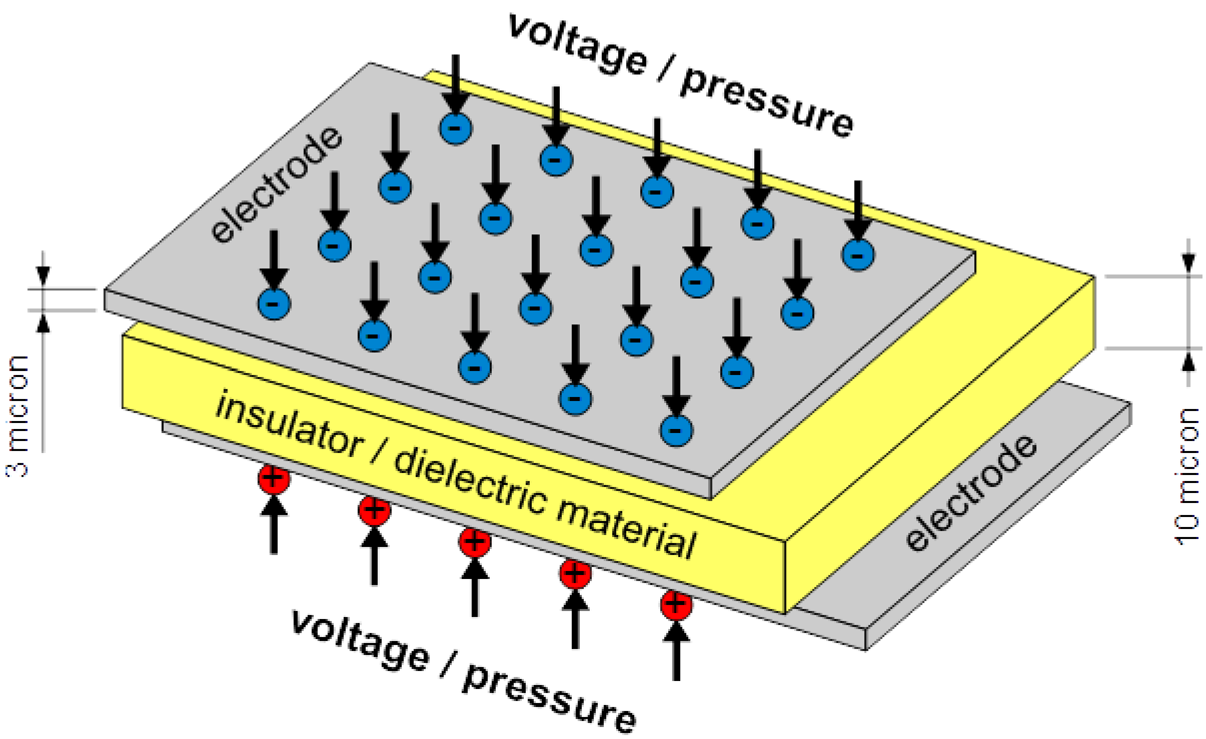
Understanding EEStor Parameters

This primer is intended to help readers understand the technical data published by EEStor. There are three key parameters and two formulas that are important to the understanding of our solid-state capacitors' high energy storage performance.

Capacitor Basics

A capacitor is a simple electrical component that stores energy without any chemical reaction. A capacitor is basically made of two plates of metal (electrodes) with a thin layer of electric insulator (dielectric) between them. A useful analogy is to compare storing energy in a capacitor with storing air in a compressed air tank. That analogy will be used below to explain the behavior of capacitors.

When a capacitor is charged, voltage is used to pump electrons from one plate to the opposing plate. The additional electrons accumulated on one electrode (negative charges) repel each other along the surface of the insulator, with more and more force as they are pushed closer together. The missing electrons on the other electrode (positive charges) repel each other in the same manner. At the same time, the positive and negative charges, compressed by voltage on both electrodes, are also attracted to each other across the thin insulator layer.



Pumping electric charges with voltage really *results in a mechanical pressure on the insulator layer.*
Applying too much voltage will cause it to break down (electrically, not from the mechanical pressure itself).

Three Key Parameters of a Capacitor

There are three key parameters measured to evaluate the performance of a capacitor:

1. **Electric Field** (*E*) is the number of volts (V) pushed across a layer of electric insulator divided by the *thickness* of the layer. Applying too large a field will cause the insulator layer to breakdown. Using the compressed air analogy, Electric Field is the equivalent of pressure applied within the tank, divided by the thickness of the tank wall. The thickness of the material is important, because it's desirable to use the least amount of insulator material to support a given pressure or voltage.

   Measuring *E*: *E* is measured in volts per micron of thickness of the insulator layer. There are 1000 microns (µm) in a millimetre (mm). If 6,000 V can be applied on a 200 micron (0.2 mm) thick layer without breaking the insulator down, then the dielectric is said to support a field of 30 volts per micron: 6000 V / 200 µm = 30 V/µm.

2. **Relative Permittivity** (*K*) is a unit-less ratio that indicates the density of electrons (charges) that can be compressed by a given electric field along the surfaces of an insulator layer. Using the air tank analogy again, *K* is like the number of molecules of gas that can fit, at a given pressure, within a unit volume of an air tank. Why is unit volume important? If one reservoir is twice as large as another, one can fit twice as much air (or electrons) into it, but it takes more material to do so. When we compare materials, it's important to take the "size of the reservoir" out of the equation - so it's really a density that's being measured.

   Measuring *K*: To measure *K***,** the capacitance (*C*) needs to be measured first. Capacitance is a measurement of the number of electrons pumped from one electrode of a capacitor to the other using the pressure of a given voltage. From there, the thickness and area of the insulator layer is used to calculate the electron density at a given field. That density is then *compared* (hence the use of the word "relative" in "relative permittivity") to that of a capacitor using vacuum as its dielectric. Vacuum (the absence of any matter) is the insulator known to result in the lowest possible density of electrons at a given field. It is therefore used as a reference and is given a *K* of 1 by convention. Therefore, having a *K* of 10,000 really means that 10,000 times more electrons have been compressed at the insulator-layer-surface of the electrodes than would be possible using vacuum as the dielectric, using the same field.

3. **Insulation Resistance** (*IR*) is a measure of how much the insulator layer resists the leakage of electrons from one plate of the capacitor to the other over time. Negative charges on one plate of the capacitor are attracted by the positive charges on the other. Since no insulator is perfect, the charges will leak through the thin material layer that separates them. The greater the IR the slower the leakage. The dimensions of a layer have comparable but opposite effects on capacitance and resistance: doubling the area doubles the leakage (half the resistance) and doubling the thickness cuts leakage in half (double the resistance). So, to compare material, the notion of *resistivity* has been defined as the resistance but with the layer area and thickness taken out of the equation. Therefore, resistivity is to resistance what permittivity is to capacitance

   Measuring *IR*: The resistance to capacitor leakage is typically measured in giga-ohms (GΩ). It is the result of the voltage being applied on the electrodes (in volts) divided by the tiny leakage current flowing through the insulator (in nano-amperes). High *IR* means low leakage.

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Calculating Energy Density

The energy density (*ED*) of a capacitor is the amount of energy it can store per unit of volume. A capacitor with higher *ED* requires *less material* to store the same energy, which *reduces* its cost.

We've seen above that the Electric Field is a measure of how much pressure is applied on the electrons in the reservoir, and that the κ indicates the density at which electrons can be held under such pressure as they repel each other. The combination of both the κ and the *square* of the field *E* results in the energy density (*ED*) of the *dielectric*. ED is measured in watt-hours per litre (Wh/l).

The formula: $ED = \kappa \times E^2 / 813175$ (with *ED* in Wh/l, and the *E* in V/µm)

The 813175 value is derived from a universal constant called the absolute permittivity of vacuum (ε_0). It's one of the fundamental values in physics, and is used to define the speed of light and a few other core properties of the universe. It basically measures the force by which two electrons repel each other in vacuum at a given distance. It is also at the core of capacitor science.

Here's an example of an energy density calculation: a dielectric layer able to hold a κ of 10,000 at a field (*E*) of 9 V/µm has an energy density of:

$$ED = 10{,}000 \times 9^2 / 813175 = \sim 1 \text{ Wh/l}$$

In EEStor's Phase 8 tests report, an energy density of 1.4 Wh/l was reached in the CMBT-Glass hybrid dielectric sample 344-2B with a κ of 154 at a field *E* of 85.9 V/µm:

$$ED = 154 \times 85.9^2 / 813175 = 1.4 \text{ Wh/l}$$

Calculating the Self-Discharge Time Constant

The self-discharge time constant (*TC*) is the time (in seconds) for a capacitor to leak ~86.5% of its stored energy through its insulator layer. That loss is akin to the half-life of radioactive materials.

We've seen above that capacitance *C* measures the number of electrons that fit in a reservoir at a given voltage and that insulation resistance *IR* measures how much the insulator layer resists leakage of electrons from one plate of the capacitor to the other over time. The self-discharge time constant *TC* results from the combination of both that *C* and *IR*.

> **The formula**: $TC = IR \times C$
> with *IR* in giga-ohms (GΩ), *C* in nano-farads (nF) and *TC* in seconds

It means, as is confirmed by common sense, that a reservoir holding twice as many electrons takes twice as long to empty at a given leakage rate; as does a reservoir holding a given number of electrons that resists leakage twice as much. It's also worth noting that since the area and thickness of a layer affect capacitance and resistance in the exact opposite way, they cancel each other out and multiplying both gives the same time *constant* regardless of the dimensions of the reservoir. Finally note that, the effect of dimensions being already cancelled out, replacing IR and C by their density-oriented dimension-less version, resistivity and permittivity, would give the same TC result.

To apply this formula, let's use some Phase 8 test report example again. In Phase 8 the CMBT-Glass hybrid dielectric sample 344-2B exhibited a measured capacitance *C* of 0.29 nF and a calculated insulation resistance *IR* of 1528 GΩ, at a calculated field of 85.9 V/µm. Its time constant *TC* was therefore calculated as:

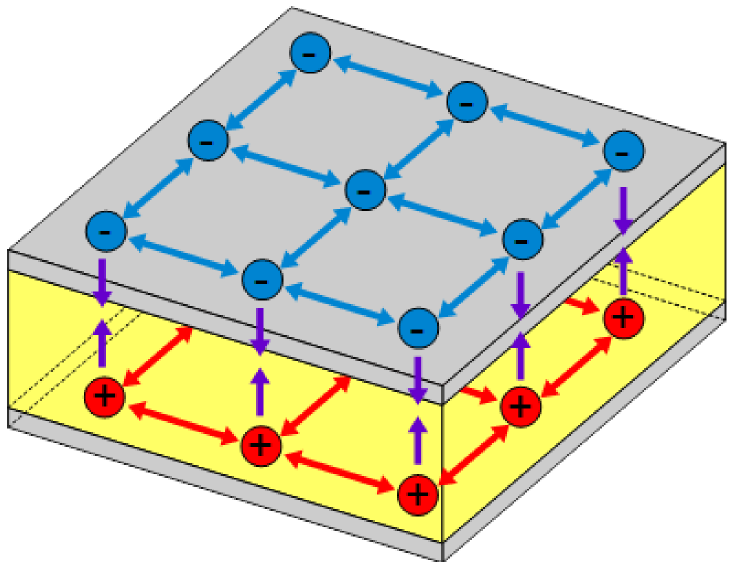
$$TC = 1528 \text{ G}\Omega \times 0.29 \text{ nF} = 443 \text{ second.}$$

Finally, note that another indication of loss is given by the Dissipation Factor (*DF*). It measures the portion of energy instantaneously lost when the capacitor energy reservoir is filled and then emptied.

Improving Capacitor Performance

The three key parameters described above (*K, E* and *IR*) are the targets of most of EEStor's research program efforts. They form the equivalent of a three-legged stool. Ideally, the three legs would be grown proportionally to create a well-balanced, strong, high-reaching stool. If one or two legs grow at the expense of the others, the resulting unbalanced stool might prove less useful.

Interestingly, the pursuit of balanced performance gains has proven difficult for the entire capacitor industry. Take, for instance, trying to grow *K* **and** *E* at the same time. Typically, *K* shrinks as *E* grows. Indeed, when electrons are pumped with more voltage pressure from one electrode to the other (higher *E*), the charges push against one another at the surface of their respective electrode with more force, which slows the increase of their density (lower *K*).



Compressed at higher voltage, electrons (and missing electrons) have more energy and repel each other with more force on their respective electrode, making it harder to increasing their density at the surface of the insulator.

A similar phenomenon happens with leakage, which logically tends to increase (thus, lower resistance to leakage *IR*) as higher voltage is pushed on the insulator layer (higher *E*). Therefore, growing all three parameters at once is anything but a trivial quest.

Summary

Understanding EEStor's technical data requires mastering these three key parameters:

- **The field *E***, which is the pressure of voltage applied to hold the mutually repelling electrons inside the reservoir, divided by thickness of electric insulator (measured in volts per micron);
- **The relative permittivity *K***, which is the density of electrons that can be held inside the reservoir under such pressure, *compared* to that density if vacuum was the dielectric, (a density is used to compare dielectric materials regardless of the size of the reservoir, when the size of the reservoir is considered, the *K* becomes the measured capacitance *C*);
- **The insulation resistance *IR***, which is how much the insulator layer resists the leakage of electrons from one plate of the capacitor to the other, through time (measured in giga-ohms);

With these in mind, the energy density *ED* of the *dielectric* (in watt-hour per liter), and the time constant *TC* of its self-discharge (how many seconds before the reservoir leaks 86.5% of its stored energy) can easily be calculated, using the formulas:

- $ED = \kappa \times E^2 / 813175$ (with *ED* in Wh/l, and the field *E* in V/µm)
- $TC = IR \times C$ (with *TC* in seconds, resistance *IR* in GΩ, and capacitance *C* in nF)

The *ED* of a *full capacitor* includes the extra volume of its electrodes and is thus proportionally lower. With this knowledge in hand, any technical data disclosed by EEStor can be correctly interpreted.

Glossary

Capacitor – an electrical component that stores energy without any chemical reaction involved
Capacitance (*C*) – the number of charges that can be pumped from a capacitor electrode to another using a given voltage
Charges – additional or missing electrons pumped by voltage into or out of each of two electrodes
Dielectric – an electrical insulator used to build a thin layer setting apart two parallel electrodes
Dissipation Factor (*DF*) – portion of the energy instantaneously lost each time a capacitor energy reservoir is filled and emptied
Electrode – a typically very thin plate of metal holding either positive or negative charges at the surface of an insulator layer
Electric field (*E*) – the number of *volts* used to push electric charges on electrodes, against the two surfaces of an insulator layer of a *given thickness*
Energy Density (*ED*) – amount of energy that can be stored in a reservoir of a given volume
Insulation Resistance (*IR*) – how much an insulator layer resists the leakage of electrons across its thickness over time, from the surface of an electrode to the other
Relative permittivity (*κ*) – the density of charges compressed in a capacitor by a given electric field
Resistivity – the Insulation Resistance but with the dimensions of the layer taken out of the equation
Self-discharge Time Constant (*TC*) – the time it takes for a capacitor to leak 86.5% of its stored energy through its insulator layer.
Vacuum – a space entirely devoid of matter, it has a *κ* of 1 by convention