Breakdown Limited Capacitors

Richard Wallace Kenyon & Frank Barnes
Department of Electrical, Computer, and Energy Engineering,
University of Colorado Boulder.

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The use of capacitors for energy storage is often limited by their energy storage capacity and the energy density. Capacitors have an advantage over batteries in that they can be both rapidly charged, and discharged. We show that for parallel plate capacitors the energy density per unit volume, W, is limited by:

$$W = \frac{\epsilon_0 \epsilon_r E_M^2}{2\left(1 + \frac{t_p}{d}\right)} \tag{1}$$

where ϵ_0 is the dielectric constant of free space, ϵ_r is the dielectric constant, E_M is the electric field at breakdown, d is the thickness of the dielectric and t_p is the thickness of the conducting plates. We examine the possibility of making a capacitor out of thin alternating layers of diamond dielectric and graphene plates, and show that theoretical energy densities of $85^{MJ}/_{m^3}$ or $24^{kWh}/_{m^3}$ can be achieved by with the reported breakdown field strength $E_M = 2^V/_{nm}$, $d = 10nm$, $\epsilon_r = 5$, and $t_p = 0.34nm$. Because the energy density is proportional to the square of the dielectric breakdown field, maximizing this characteristic of the dielectric yields a much greater energy density than similar efforts to maximize the relative dielectric constant; diamond has the largest breakdown field we could locate. Graphene used as the conducting plates harnesses the advantage of it having a conductivity greater than copper. Furthermore, graphene can be grown in very smooth, atomically thin layers which means it can be employed as a conducting plate that occupies a very small portion of the overall capacitor volume. The energy densities of various materials and energy storage devices are now presented for comparison.

Material/Device	**Energy Density** $(^{MJ}/_{m^3})$	**Energy Density** $(^{MJ}/_{kg})$
Diamond Dielectric, $\epsilon_r = 5$	85	0.025
Barium Strontium Titanate, $\epsilon_r \approx 2,500$	3	≈ 0.001
Hexagonal Boron Nitride, $\epsilon_r = 4$	11	0.005
Supercapacitor	50	0.01 - 0.036
Lithium Ion battery	900-2,630	0.36 - 0.875
Alkaline Battery	1,300	0.5
Hydrogen (700 bar)	5,600	142
Wood	13,000	16
Gasoline	34,200	46.4

Table 1: Comparison of the energy densities (W) of various materials and devices in both energy per unit volume and energy per unit mass.

In general the breakdown strength of an insulator increases with the band gap between the valence and conduction bands in the insulator. Especially with thin films, the breakdown strength is also dependent on the work function between the insulator and the conducting layer, as well as the inelastic mean free path for a free electron moving through the dielectric. With a comparatively large IMFP at low energies, which facilitates the passage of electrons through the dielectric without causing avalanche breakdown, a theory is presented for thin film diamond layers that yields a greater breakdown field strength than the standard value accepted for the material. The proportionality of the energy density to the square of the breakdown field allows a significant energy density increase with only slight gains in the breakdown field.