Crystals of synthetic atoms: High energy density, a record power density, and small leak currents

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Commercial Partners: Lockheed-Martin, AMSENG

Theoretical Limits for the Energy Density and the Power Density

- The energy density in the bonds limits **the overall energy density** (tensile strength, ionic bonds, covalent bonds, metallic bonds, nuclear bonds, …)

Flywheel

Li-ion battery

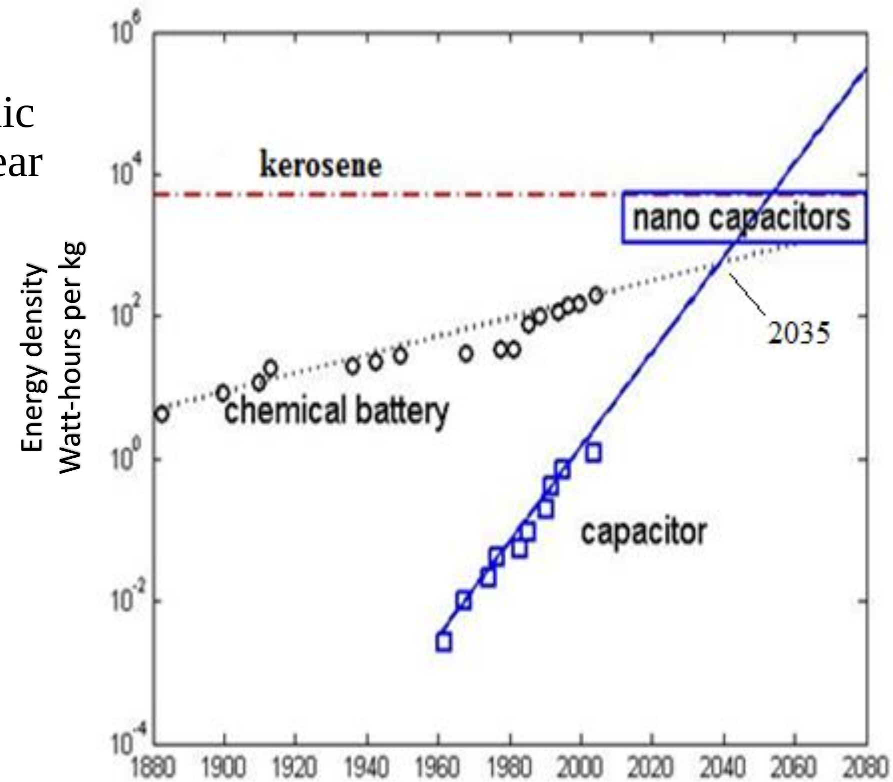


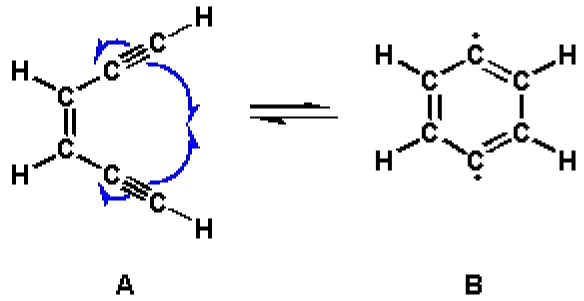
Fig. 1 Trend lines for the energy density *C. Magee, Complexity* 18, 10–25 (2012).

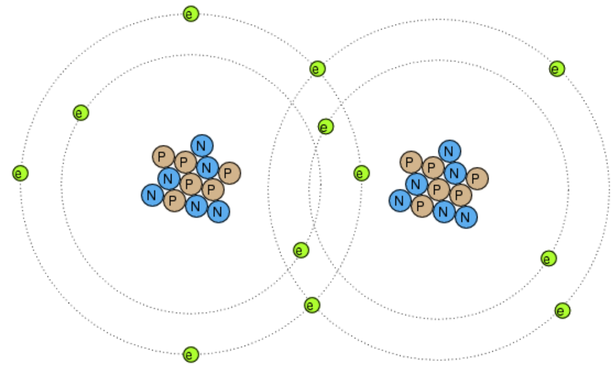
- **The power density** is mostly limited by the limiting speed of the energetic particle (diffusion of molecules, particles or phonons moving at the speed of sound, photons or electrons moving at speed of light-almost).

Chemical batteries can transition from diffusion-limited to speed-of-sound-limited in thermal run-away.

Chemical Energy Storage vs. Energy Storage in Solid State Devices

All chemical energy storage is electrical energy storage. Why is the energy density in solid state devices small?



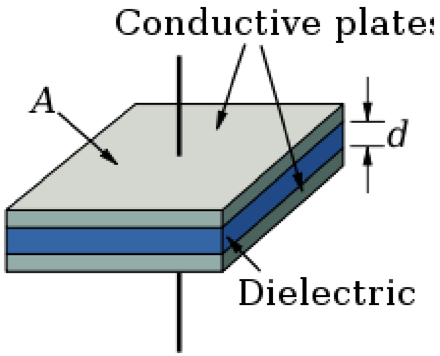


- Dielectric strength of dielectric capacitors with 600 nm silicon dioxide layer have a dielectric strength of 400V. This corresponds to a dielectric strength of 600MV/m.

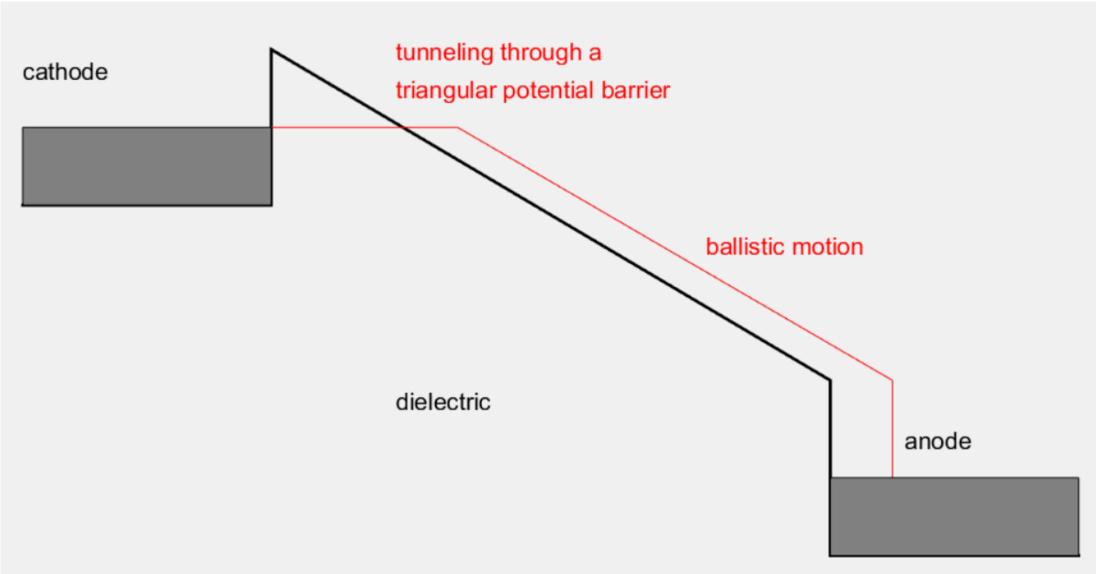
- Capacitors with a 1mm layer have a dielectric strength of only 6MV/m.

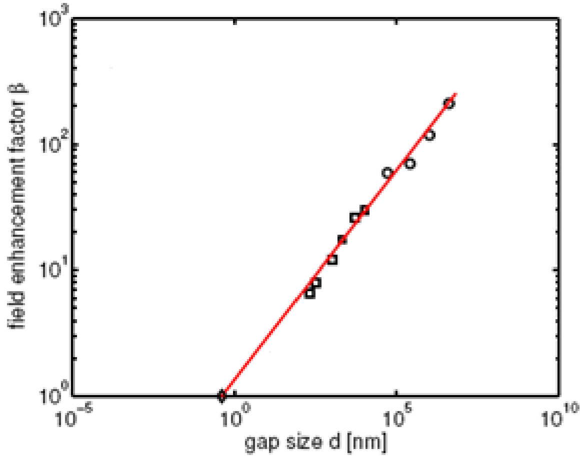
Miniaturization seems to help:

Preliminary experimental studies of vacuum gaps suggest that the energy density can exceed 1GJ/m^3.



Miniaturization Increases the Energy Density





Field emission current:

$$I = \frac{A_r a}{\phi}(\beta E(0))^2 \exp\left[\frac{-v(f) b \phi^{\frac{3}{2}}}{\beta E(0)}\right]$$

β = field enhancement factor

β = 1 if d < 10 nm, otherwise:

$\beta = (d / 10\text{nm})^{-1/3}$

Why is it a power law?

d ..... vacuum gap size

d_0 = 10 nm

Φ ....work function

A_r ... capacitor area

Breakdown occurs when the electrodes melt,

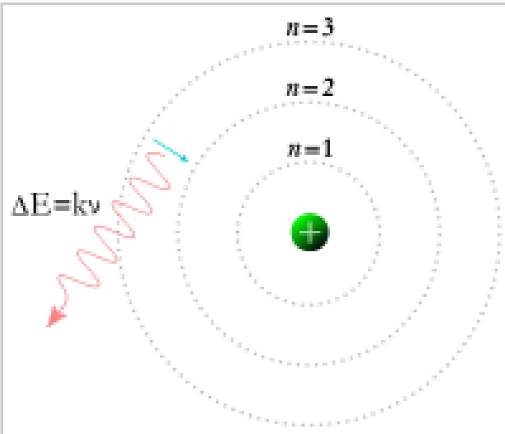
i.e. field emission current I = 10^5 A/cm^2

Miniaturization decreases the field enhancement factor

⇒ Decreases the field emission current

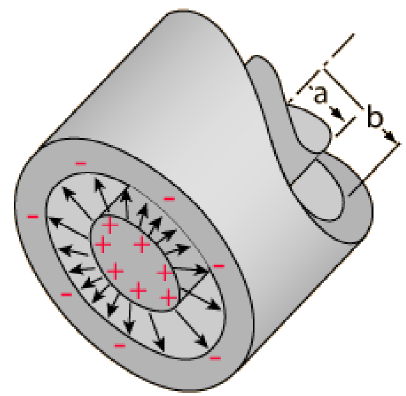
⇒ Increases the dielectric strength ... **but the energy density is less than in chemical systems**

Main Idea: Quantization Suppresses Charge Recombination



A Bohr model of the hydrogen atom, showing an electron jumping between fixed orbits and emitting a photon of energy with a specific frequency.

No charge recombination despite of very large fields (TV/m).



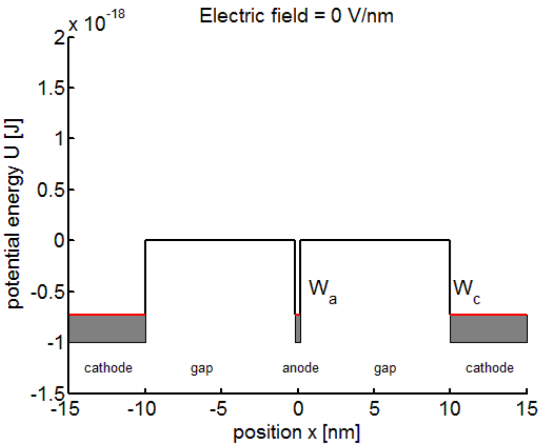
2-dim synthetic atom: Cylindrical nanocapacitor, where
a = 1nm and b = 10nm

Synthetic Atom: A nano capacitor where the cathode envelops the anode

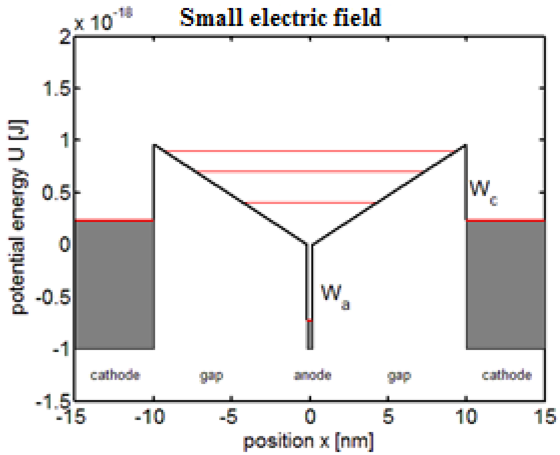
Main Idea: Quantized space charge in synthetic atoms =>

Leak currents are suppressed because electrons in the gap are governed by Fermi statistics and block field emission (Coulomb-blockade).

No current



Field Emission / STM style tunneling



Field Emission, Coulomb blockade, Quantum cap.

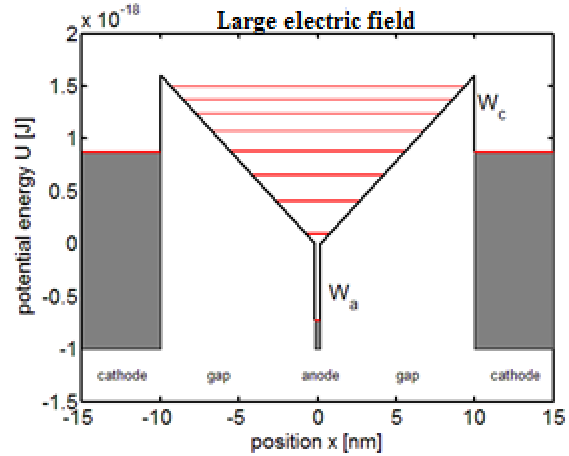
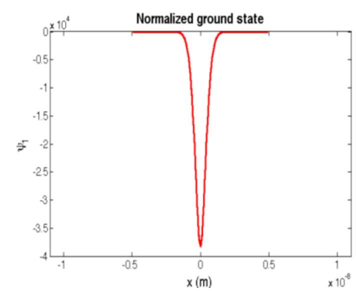
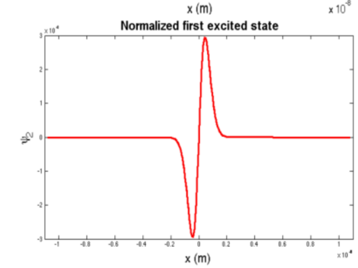


Diagram of potential energy function. W_c is the work function of the 2 cathodes. W_a is the work function of the anode. The occupied levels of the conduction bands are shown in gray. The Fermi energy and occupied energy levels in the gap are shown in red. Thin red lines are un-occupied energy levels in the gap.





We consider problem of a confined particle in this linear potential, $U = F\,q|\,x|$ which is described by the following Schrodinger equation:

$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}\right)+U(x,y,z)\psi=E\psi$$

Main Idea: Coulomb Blockade in 3-Electrode Capacitors

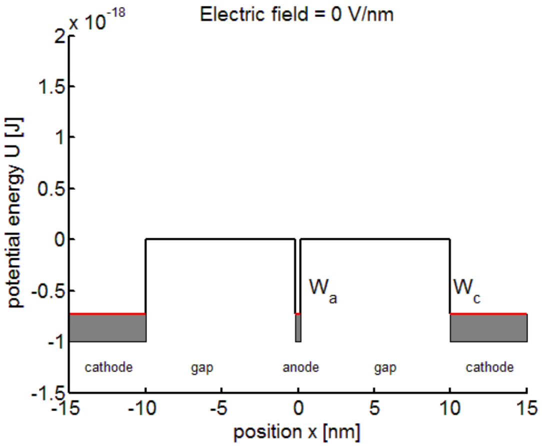
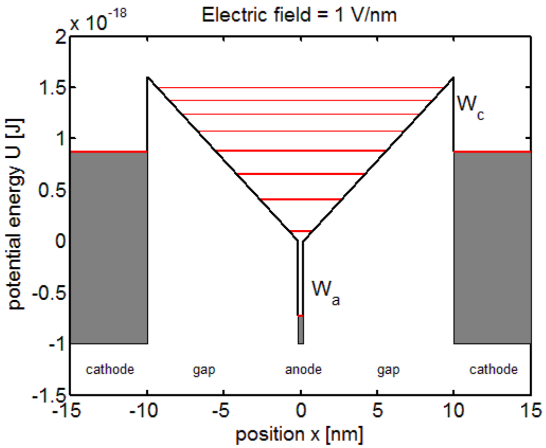


Diagram of potential energy function. The work function of the 2 tungsten cathodes is about $W_c = 4.55eV \approx 7.29\times10^{-19}J$. The work function of a graphene anode is about $W_a=4.56eV \approx 7.31\times10^{-19}\ J$. The occupied levels of the conduction bands are shown in gray. The Fermi energy and occupied energy levels in the gap are shown in red. Thin red lines are unoccupied energy levels in the gap.



Quantization at room temperature: For typical system parameters the energy difference between ground and first excited state ($E_2 - E_1$) is about 20 times larger than $E_t=k_bT$ at room temperature.
Coulomb blockade: We computed the corresponding wave functions both analytically and numerically and find that the spontaneous emission rate of the first excited state is about $T= 470ns$. Therefore space charge blocks field emission.
Quantum capacitance: Quantized space charge increases the capacity beyond the geometric capacity.

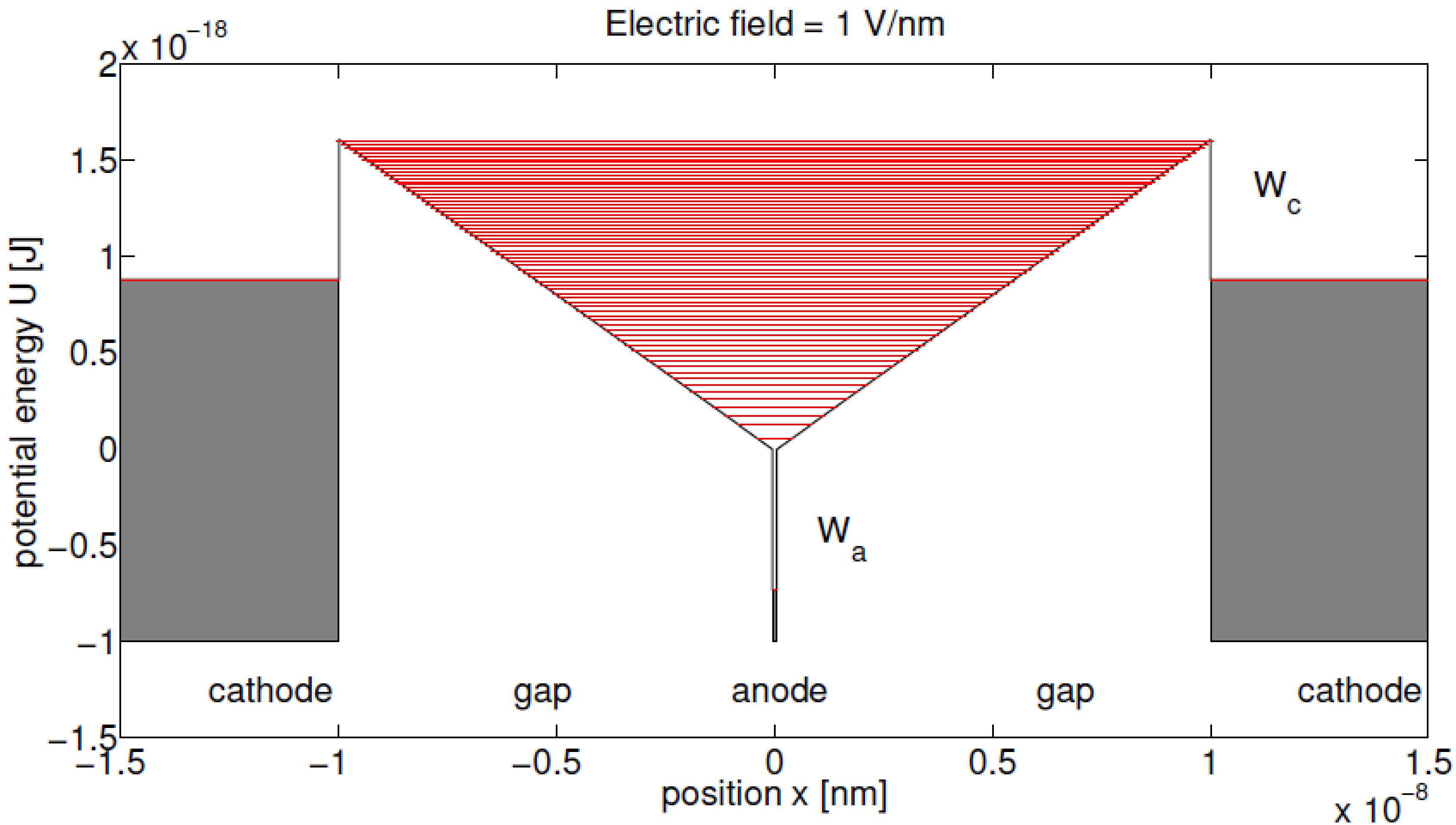
Energy levels: $E_n = C\, E^{2/3} (n - ½)^{2/3}$

where E = electric field, C = constant, n=1,2,3,…

Coulomb blockade: Leakage current much smaller than tunnel current

$$J_{\mathrm{leak}} = 53 \cdot 4.088 \times 10^{-5} \left(\frac{\mathrm{A}}{\mathrm{cm}^2}\right) = 2.167 \times 10^{-3} \frac{\mathrm{A}}{\mathrm{cm}^2} \ll J_{\mathrm{tun}} = 8.497 \times 10^{4} \frac{\mathrm{A}}{\mathrm{cm}^2}$$

Modeling quantized space charge in synthetic atoms =>
Leak currents are suppressed because electrons in the gap are governed by Fermi statistics and block field emission (Coulomb-blockade).



The quantized energy levels are added into the potential energy function in a double layer capacitor with **gap size 10 nm**. The work function of the **2 tungsten cathodes** is about $W_c = 4.55eV \approx 7.29\times10^{-19} J$. The work function of a **graphene anode** is about $W_a = 4.56eV \approx 7.31\times10^{-19} J$. There are 69 bound states. **28 bound states** are below the Fermi energy of the cathode. The largest energy spacing is between the ground and the first excited state, which is $\mathbf{E_2 - E_1 \approx 7.12 \times 10^{-20}}$ **J**; the smallest energy spacing is between the highest two energy levels, which is $E_{69} - E_{68} \approx 1.56 \times 10^{-20}$ J. Thermal activation is rare at room temperature, because $\mathbf{k_b T \approx 4.0\times 10^{-21}}$**J** is about a factor of 10 smaller.

Synthetic Atoms: Coulomb Blockade in Quantum Resonators

Attorney Docket: 2895/190

Energy Storage in Quantum Resonators

[0001] The present application is a continuation-in-part of US Serial No. 14/186,118, issued as US Patent No. __________, which is a continuation-in-part of US Serial No. 12/908,107, issued as US Patent No. 8,699,206, and also claims the benefit of US Provisional Application No. 61/774,133 filed March 7, 2013. The present application, additionally, claims the benefit of US Provisional Application No. 62/083,775, filed November 24, 2014.

[0002] This invention was made with government support under Grant DMS 03-25939 ITR, awarded by the National Science Foundation under Contract No. 1-485927-244014-191100, awarded by the U.S. Air Force, under Grant N00014-14-1-0381 awarded by the Office of Naval Research, and under Grant No. FA9453-14-1-0247, awarded by the Air Force Research Laboratory. The Government has certain rights in the invention.

Technical Field

[0003] The present invention relates to devices and methods for high-density storage ergy in materials configured as nano-capacitors subject to specified material and trical properties.

Title: Energy Storagein Quantum Resonators
Inventor: Hübler
Application No.: Not Yet Assigned
Att'y Docket No. 2895/190
Sunstein Kann Murphy & Timbers LLP
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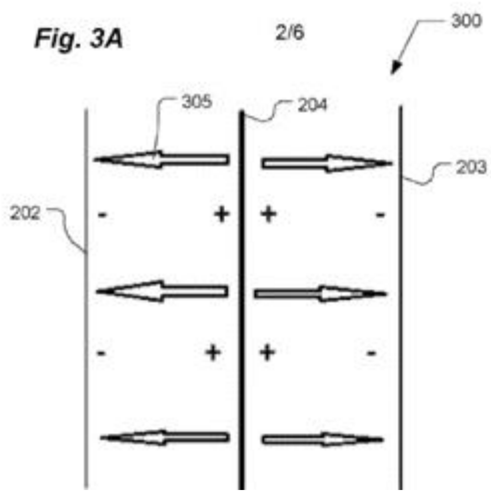
Fig. 3A 2/6



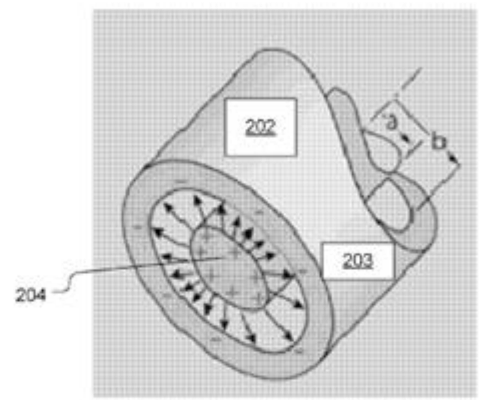


Fig. 3B

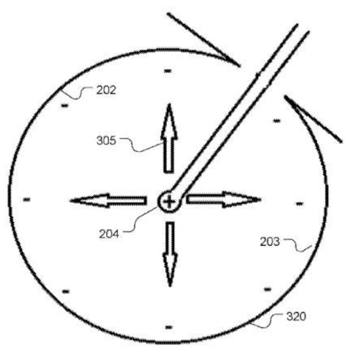
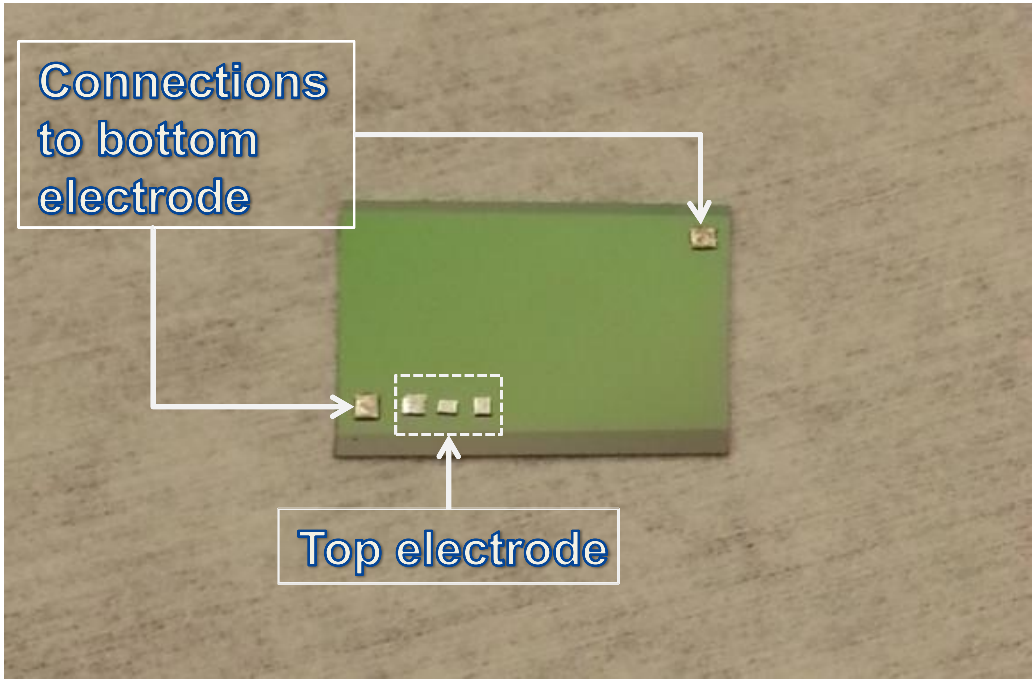
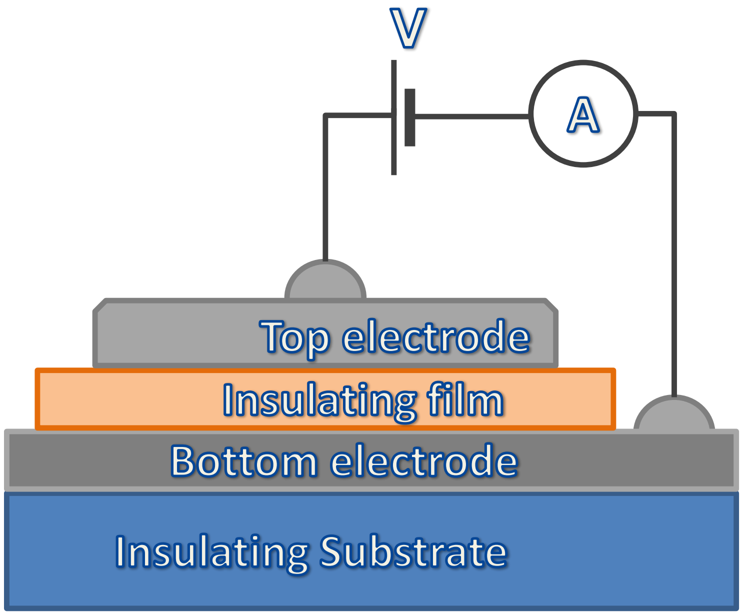
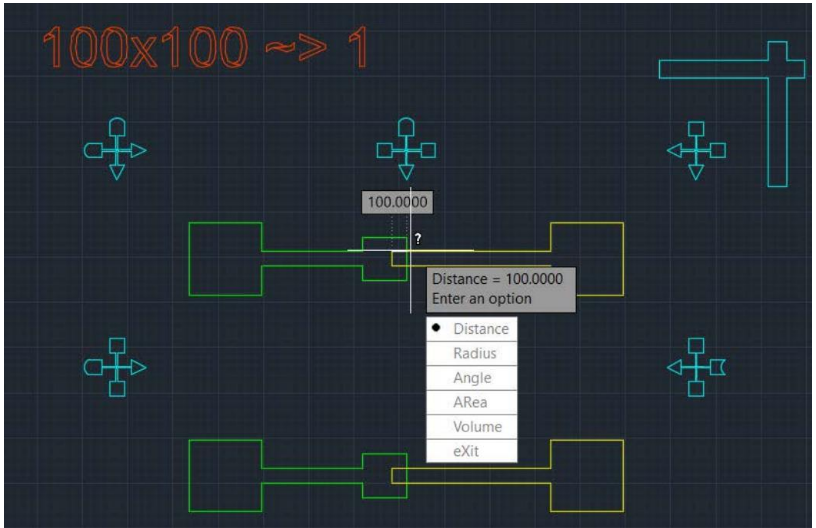


Fig. 3C

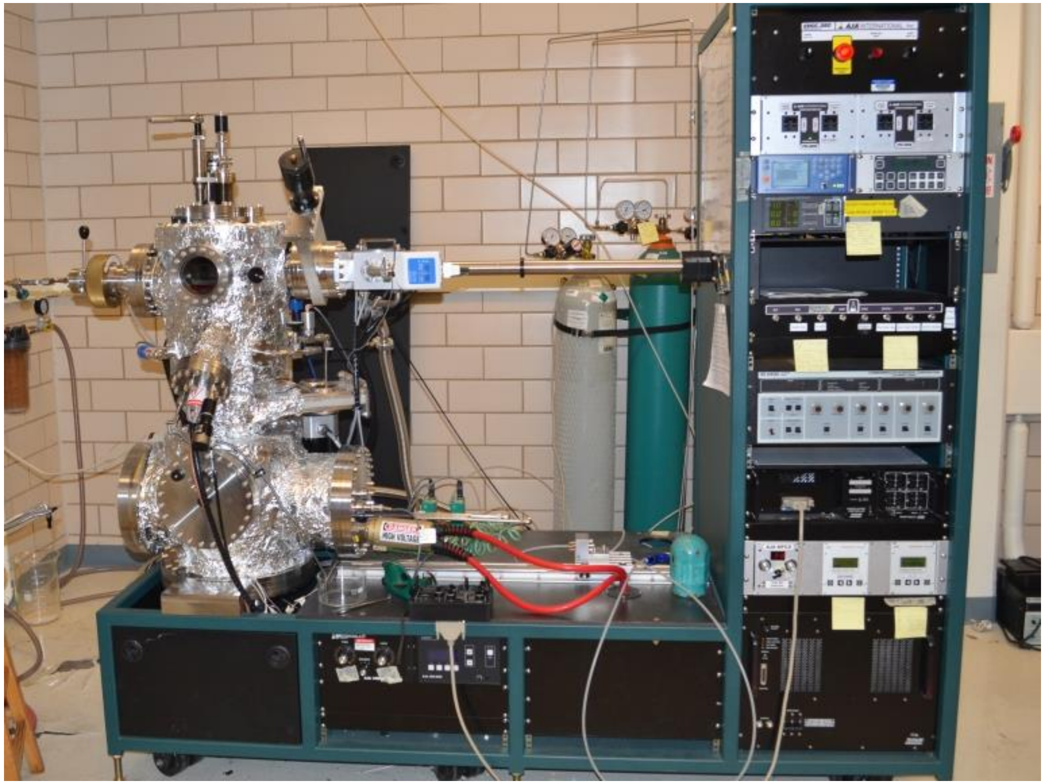
Nanocapacitor Fabrication

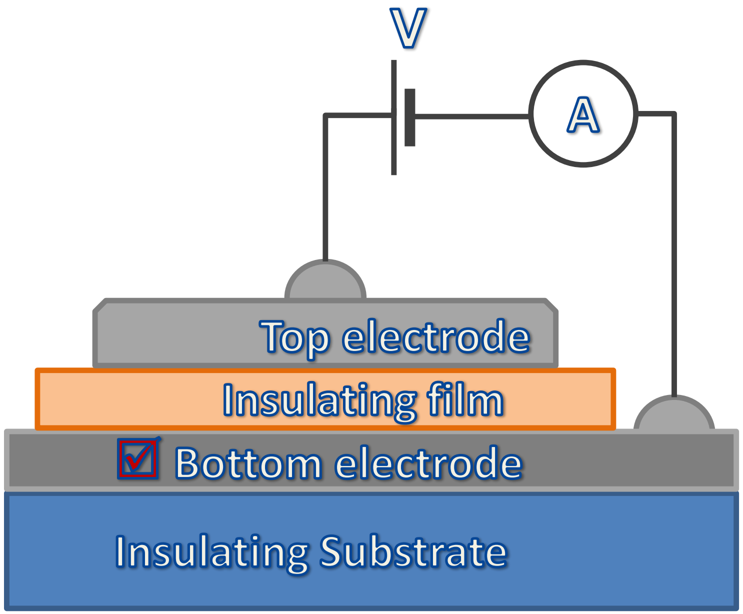






Fabrication Setup – Magnetron Sputtering System or E-beam Evaporation System



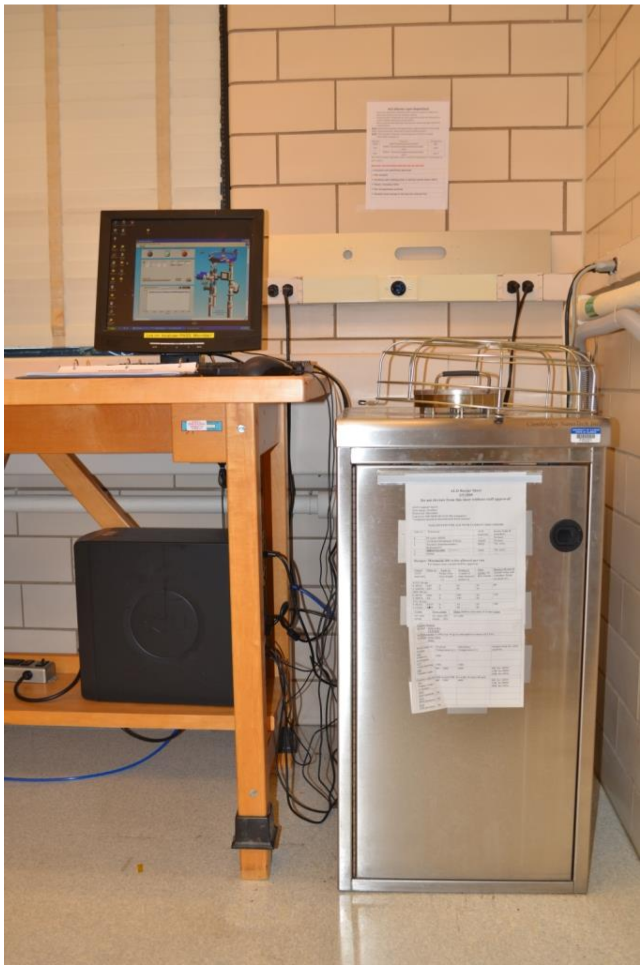


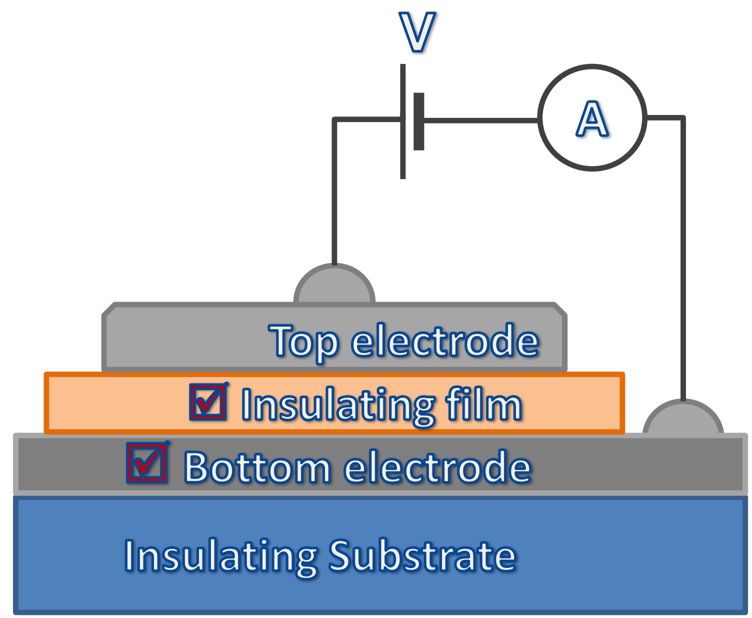
Two-step surface cleaning of the insulating substrate:

1. Sonification in acetone for 3 minutes
2. Sonification in isopropyl alcohol (IPA) for another 3 minutes.

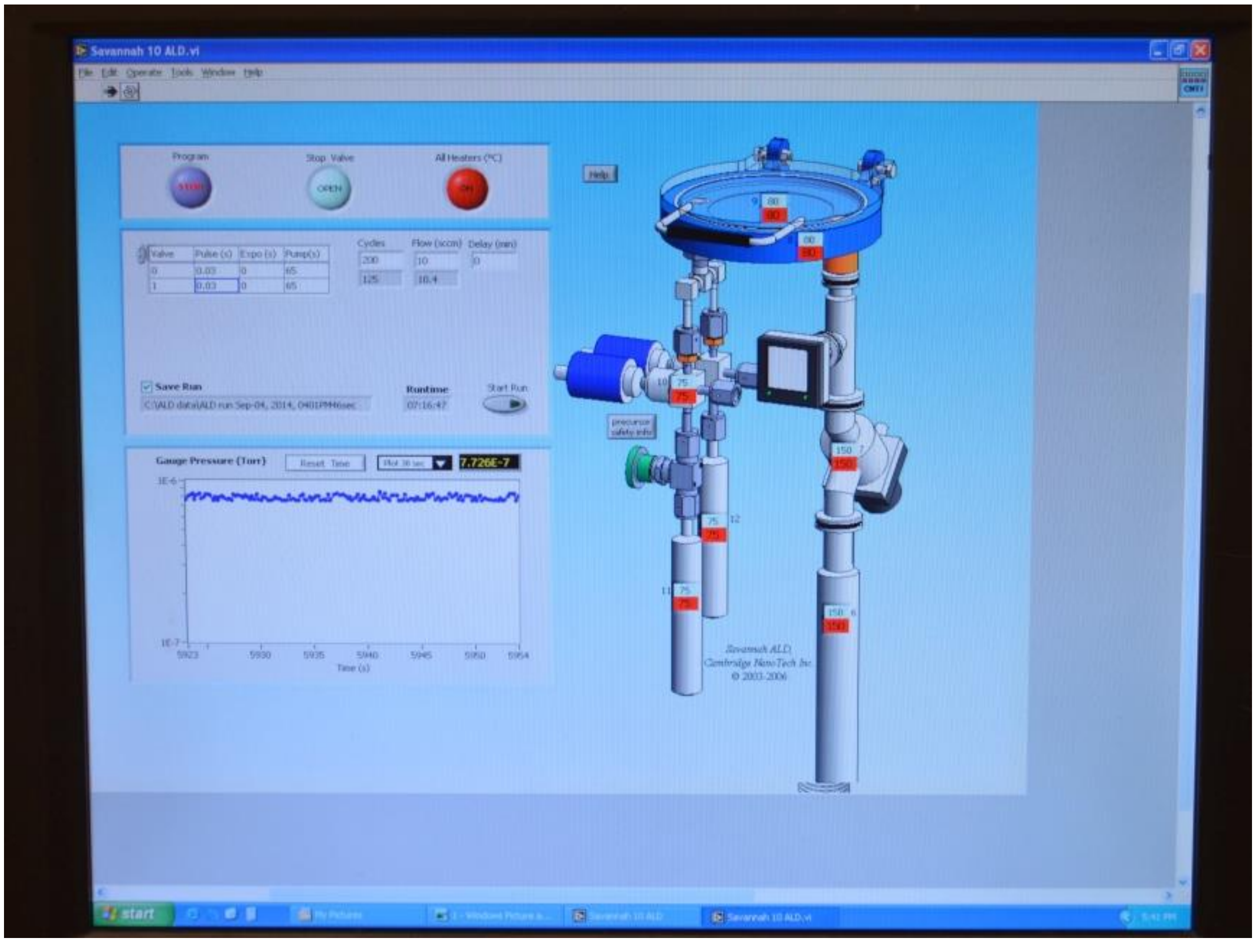
Then we blow-dry the surface with pure nitrogen.

Fabrication Setup – Atomic Layer Deposition System





Fabrication Setup – Atomic Layer Deposition System



Film options:

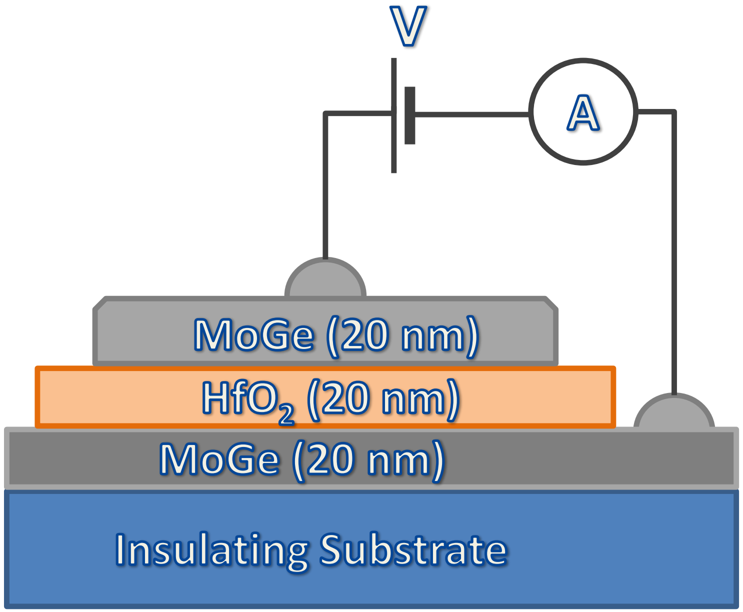
Al_2O_3

TiO_2

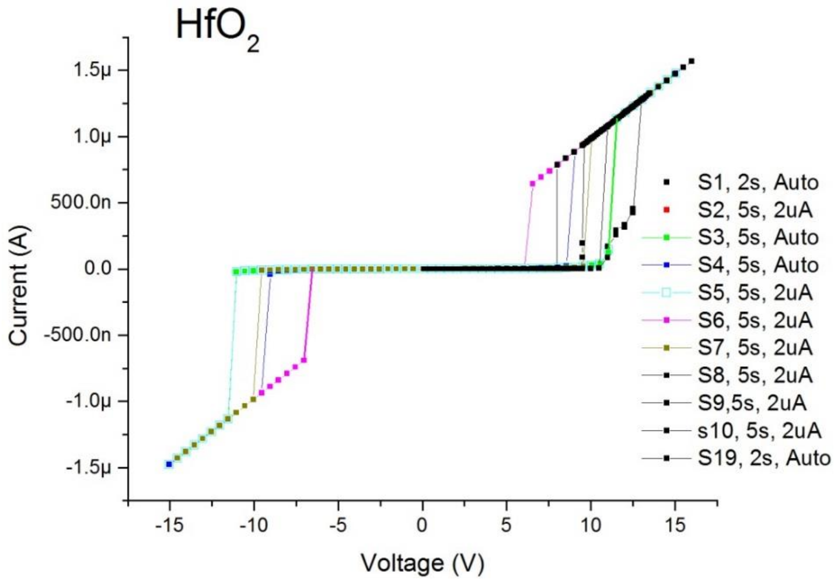
HfO_2

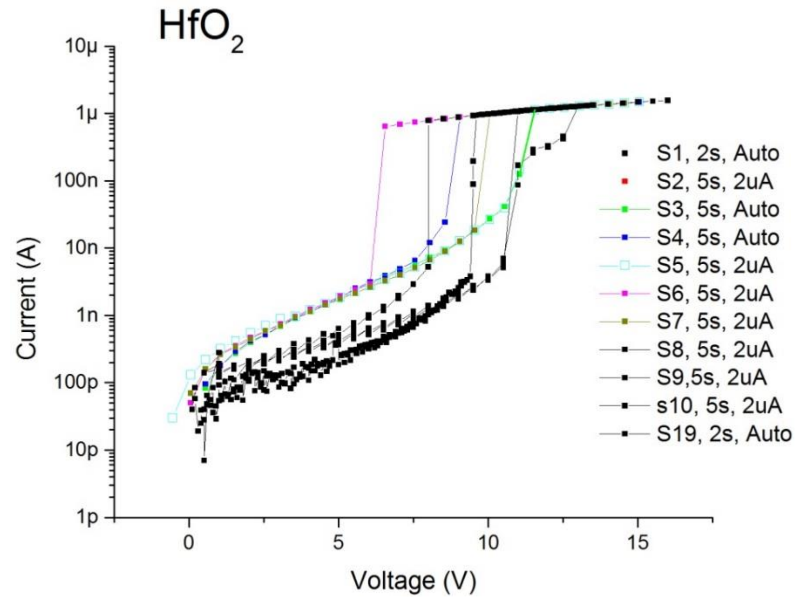
HfO_2 Nanocapacitors

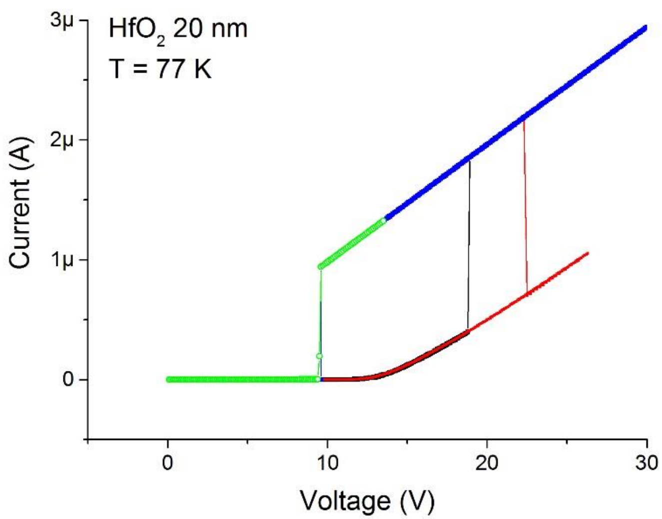
Wire contacts: Silver paint / conducting epoxy / indium dots

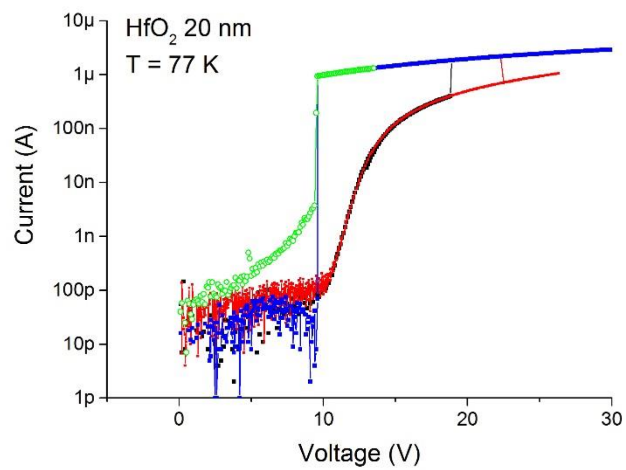


IV-Curves at Room Temperature and 77 K



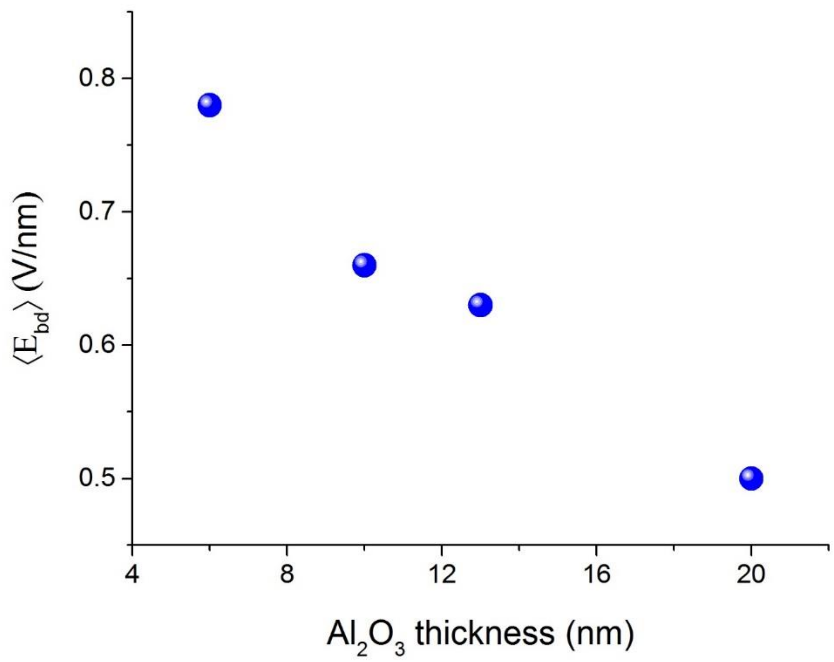


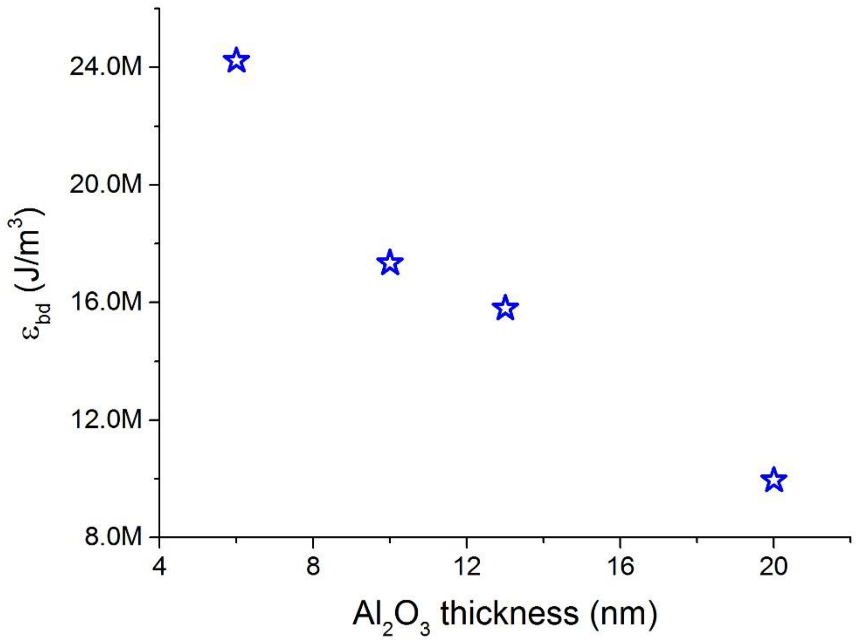




20nm MoGe / 20nm HfO_2 / 20nm MoGe

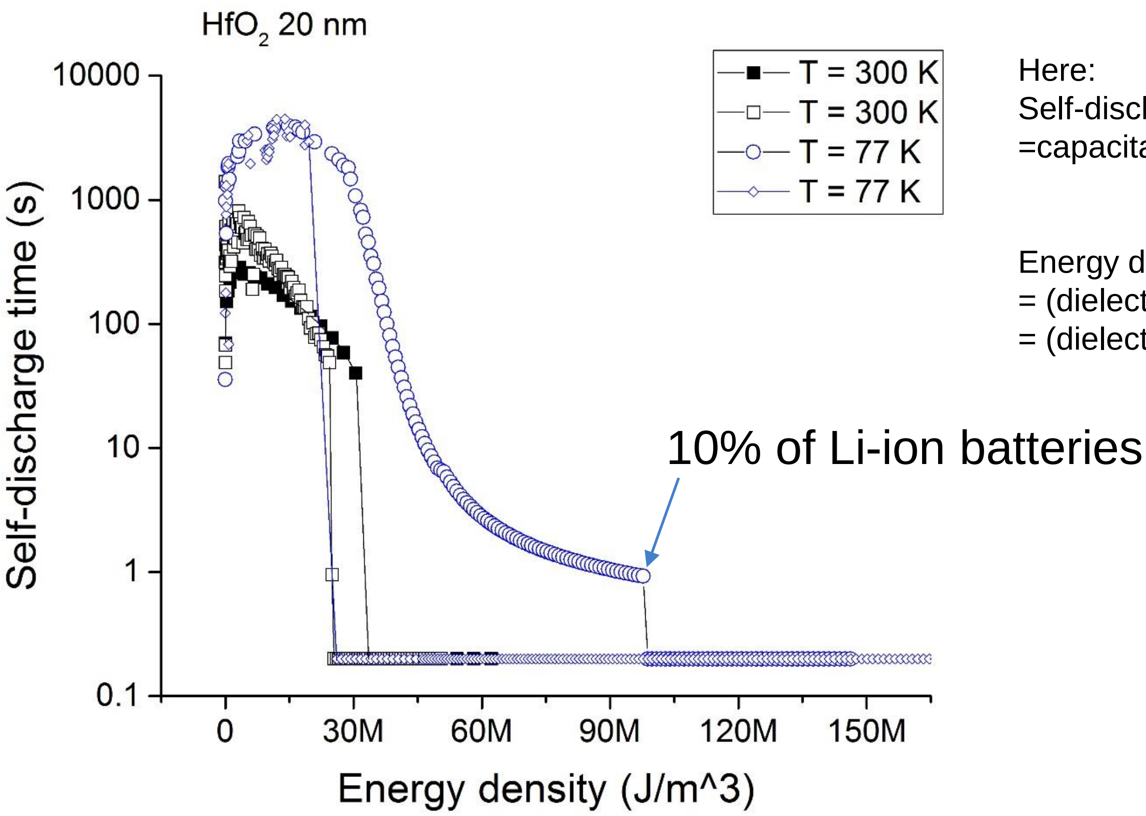
Dielectric Strength and Maximum Energy Density versus Oxide Thickness at RT





20 nm MoGe / Al_2O_3 / 20 nm MoGe

Instantaneous Self-discharge Time Based of Instantaneous Leak Current Versus Energy Density

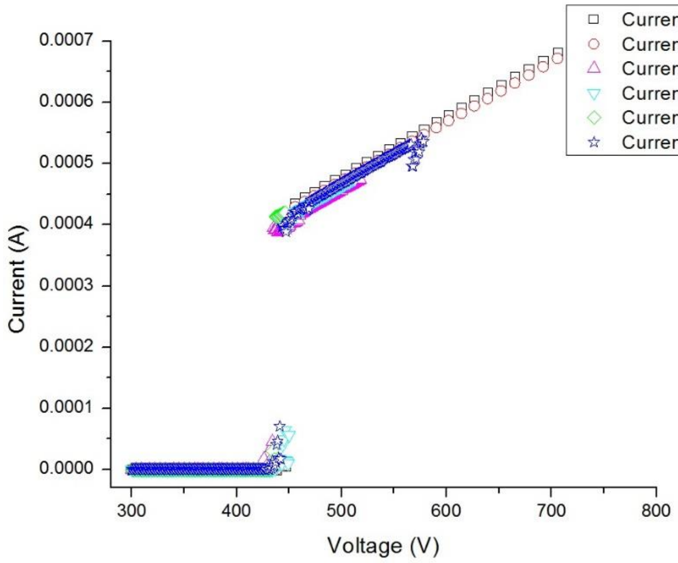


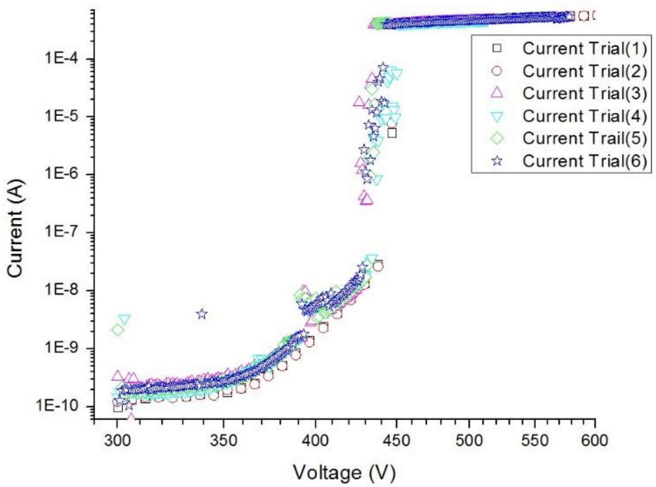
Here:
Self-discharge time =
=capacitance * voltage / (leak current)

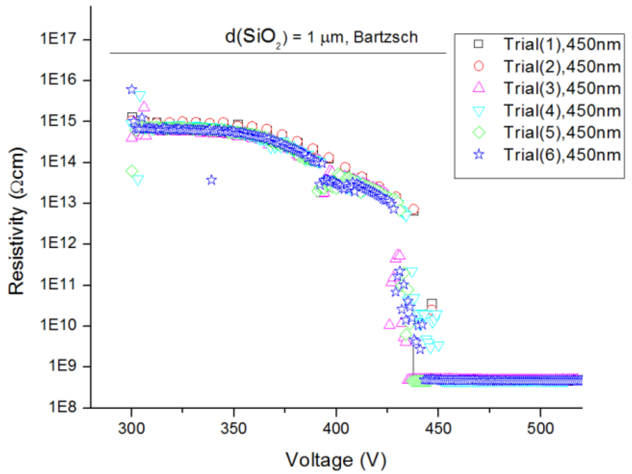
Energy density =
= (dielectric constants) * (electric field)^2 / 2=
= (dielectric constants) * voltage^2 / (gap size)^2 / 2

20nm MoGe / 20nm HfO_2 / 20nm MoGe

IV-curves a 450nm SiO_2 Capacitor: High Voltages



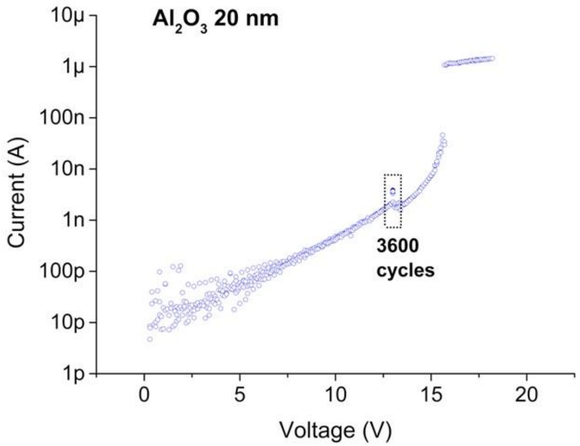


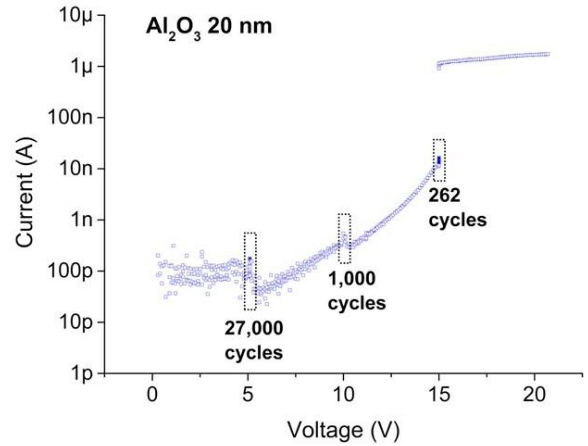


doped Si /450nm SiO_2/ 5nm Cr/ 50nm Au

The silicon wafer was fabricated from Silicon Quest International with n-type (phosphorous) dopant substrate, <1-0-0> orientation, resistivity of 1-10ohms, and approximately 15mm in thickness.

Nanocaps operate with undiminished efficiency after thousands of charging/discharging cycles in a large temperature range





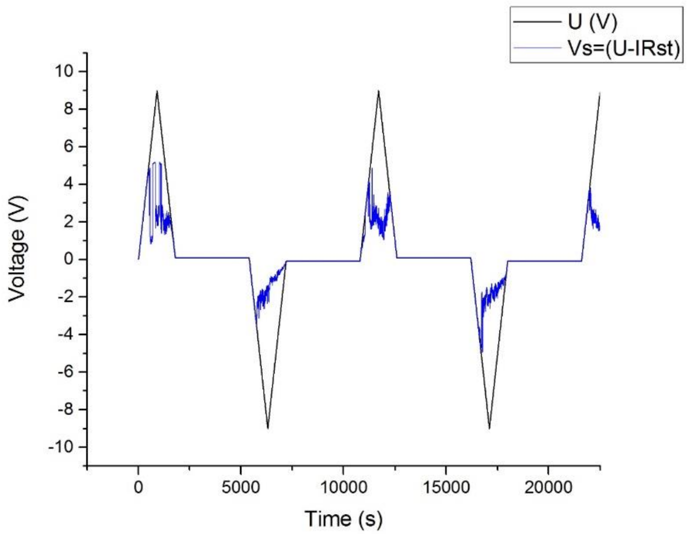
I-V curves for many charge/discharge cycles with a 10MOhm resistor in series (left). The plot on the right shows a set of similar experiment, except that the last 262 cycles reached 99% of the anticipated break down voltage. The plot indicates that there is no change in the leak current even after many charge/discharge cycles.

A capacitor in a 60Hz power grid experiences 2.6 million charge/discharge cycles per day.

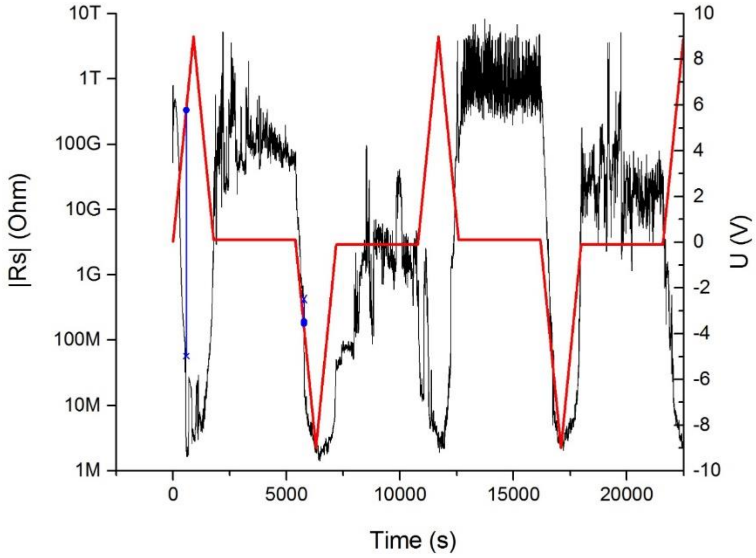
Capacitors in advanced electronics have 10^{15} of charge/discharge cycles per day.

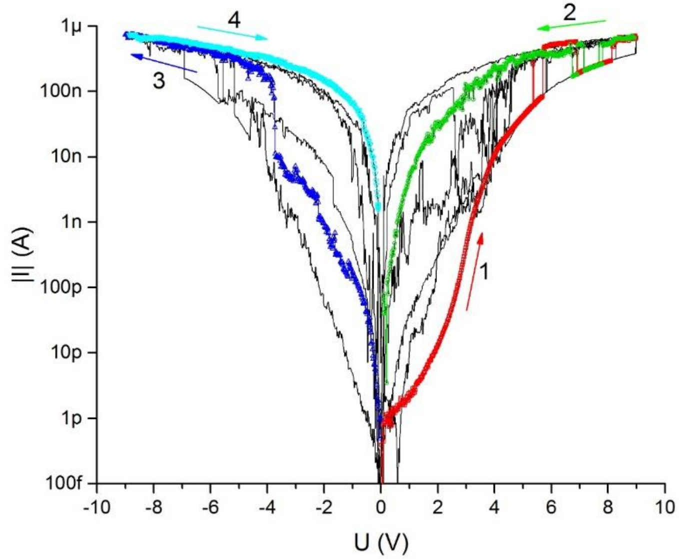
What happens when a capacitor fails? (1-day blackout in Southern California, laptop dead)

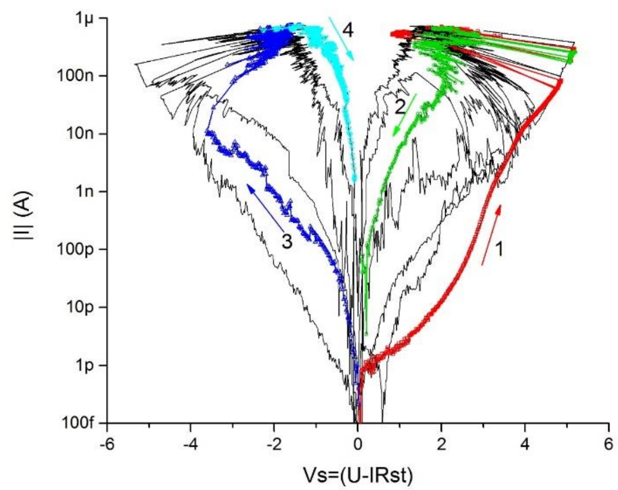
Self-repairing high voltage capacitors with a large charge density



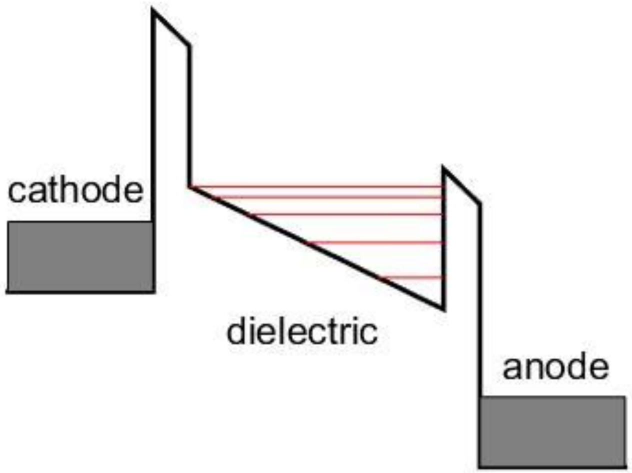
5nm Al_2O_3 nanocapacitor







Quantum Theory: Coulomb Blockade in 2-Electrode Capacitors with space charges



Field emission current J:

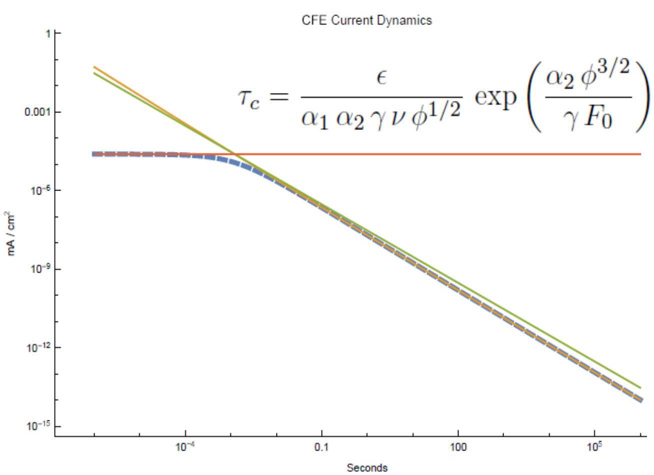
$$J = -\frac{\alpha_1 \nu}{\phi} (\gamma F)^2 \exp\left(\frac{\alpha_2 \phi^{3/2}}{\gamma F}\right)$$

Discharging the capacitor: F = electric field

$$F'(t) = -\frac{\alpha_1 \nu}{\epsilon \phi} (\gamma F(t))^2 \exp\left(\frac{\alpha_2 \phi^{3/2}}{\gamma F(t)}\right)$$

Solution of the differential equation:

$$F(t) = \left(\frac{\alpha_2 \phi^{3/2}}{\gamma}\right) \log\left[\exp\left(\frac{\alpha_2 \phi^{3/2}}{\gamma F_0}\right) + \frac{\alpha_1 \alpha_2 \gamma \nu \phi^{1/2}}{\epsilon} t\right]^{-1}$$



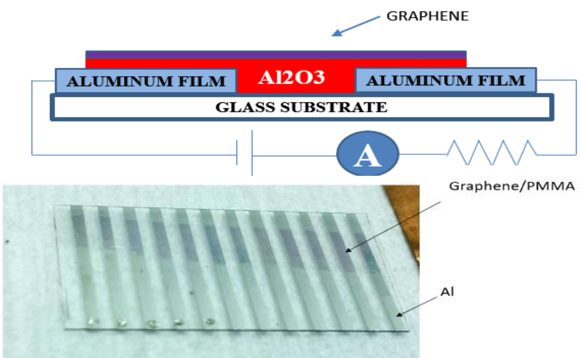
$$J(t) \approx -\frac{\alpha_1 \gamma^2 F_0^2 \nu}{\phi} \exp\left(\frac{\alpha_2 \phi^{3/2}}{\gamma F_0}\right)$$

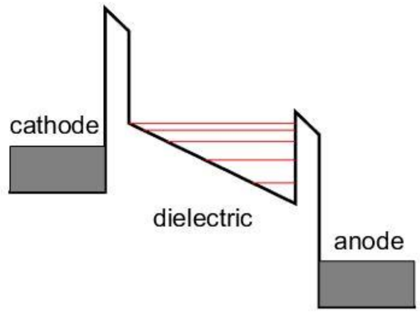
Initially constant current

$$J \approx -\frac{\alpha_2 \epsilon \phi^{3/2}}{\gamma t} \log\left[\frac{\alpha_1 \alpha_2 \gamma \nu \phi^{1/2}}{\epsilon} t\right]^{-2}$$

Later the current drops as 1/t

Quantum Theory: Coulomb Blockade in 2-Electrode Capacitors with space charges.





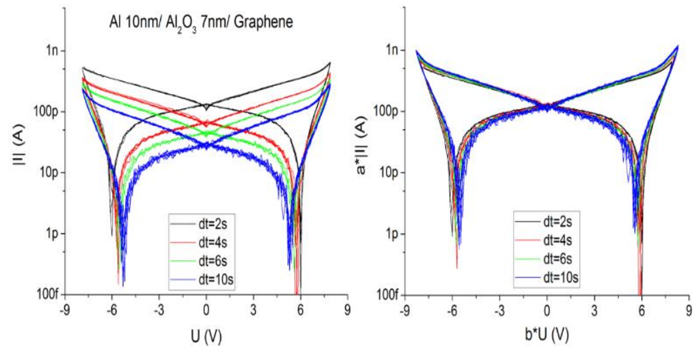


Figure1. Hysteresis in the I-V curve indicates that there is space charge

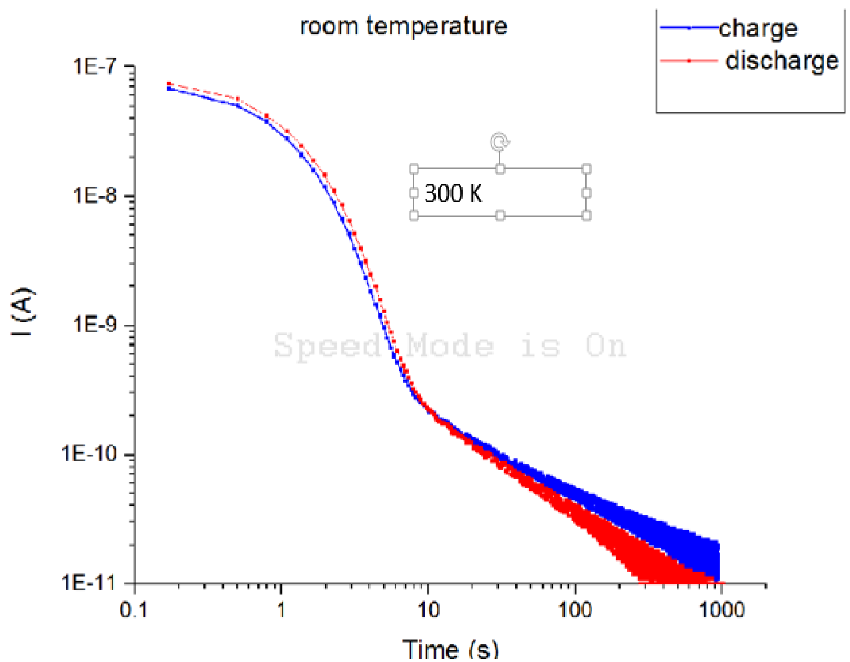


Figure 2. *The current measured in the circuit shown in Fig.12. The blue curve is measured when the voltage is applied (charging). The red curve is measured when the voltage is set to zero (V=0), which is the discharge process. The red curve (discharge) clearly shows two regimes.*

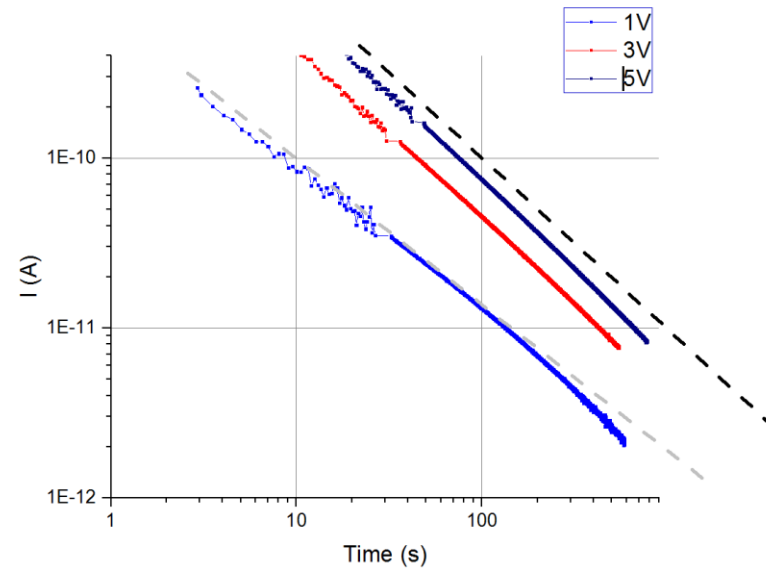


Figure 3. *The graphene nanocapacitor discharge process, current versus time, shown for three different voltages. In all three cases the dependence is similar to I(t)~1/t. The exact power of this power law decay can be either slightly smaller or slightly larger than the generic value of -1.*

2-dimensional synthetic atom with space charges in the vacuum gap

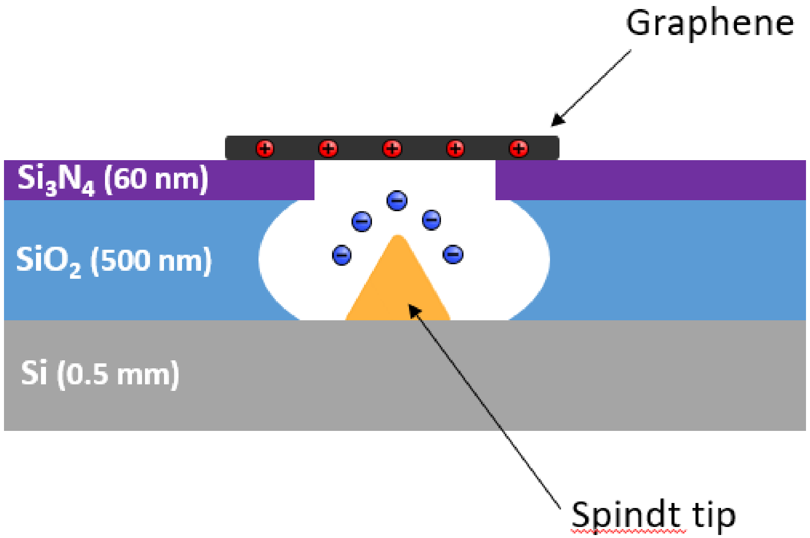


Figure 1. *Schemtics of a two-dimensional synthetic atom (Wire width ~130 nm Spindt tip height ~200 nm Distance from the tip to the graphene ~100 nm).*

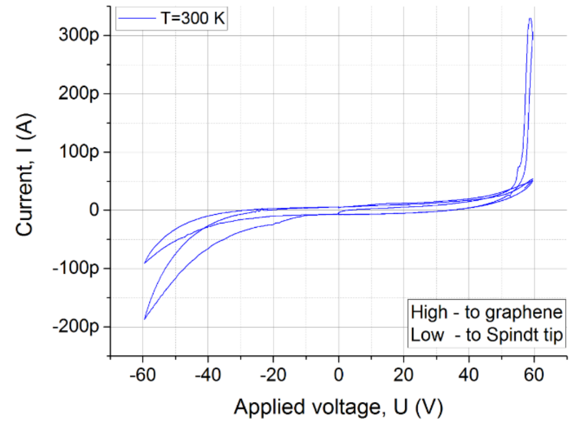
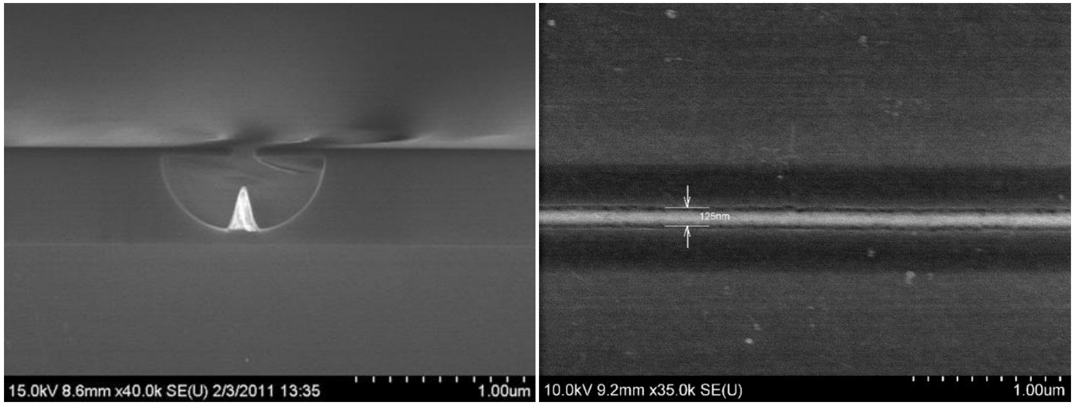


Figure 2. The hysteresis in the I-V curve indicates the there is space charge in the vacuum gap.



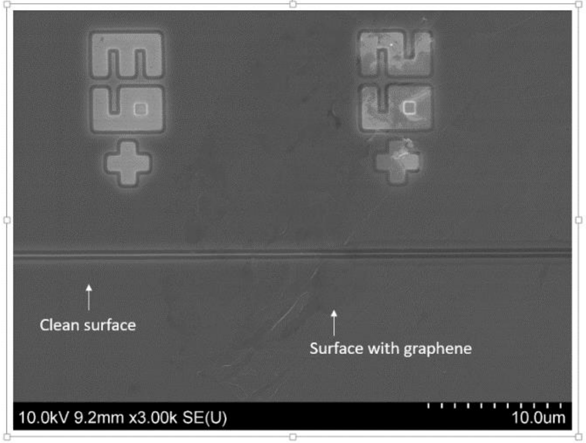


Figure 3. *SEM images of a Spindt ridge in a trench, on the left is the image of a cross-section, in the middle is the top view, on the right is the top view with graphene.*

Coulomb Blockade in stacks of 1-dimensional synthetic atoms with space charges

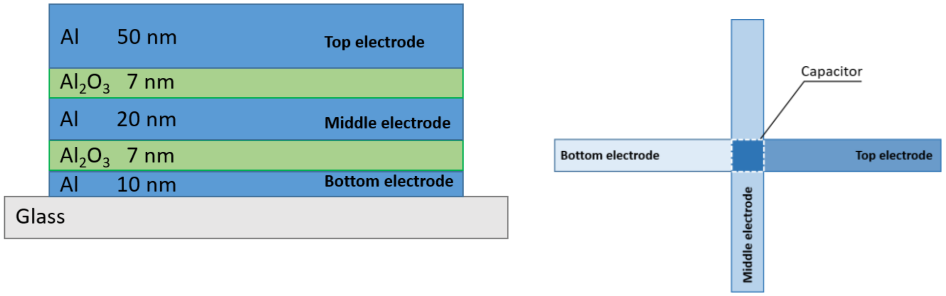


Figure 1: *Sketch of a 3-layer nano-capacitor system. The side view is on the left. The top view is on the right.*

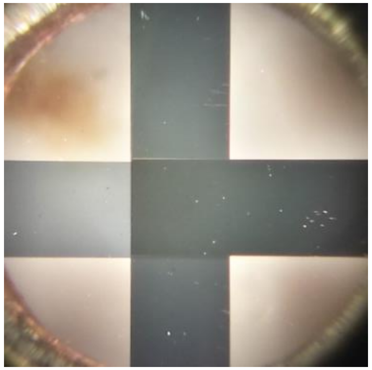


Figure 2: *Photos of the 3-layer nano-capacitor system described in Fig. 1. Al deposition is done by with e-beam evaporation. Al_2O_3 deposition is done in ALD system Metal shadow mask is used to make the pattern*

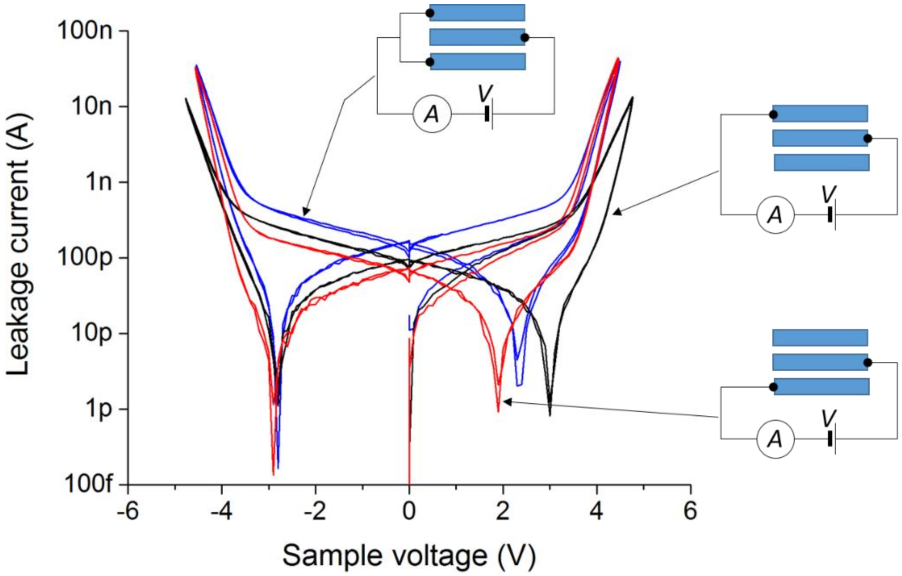


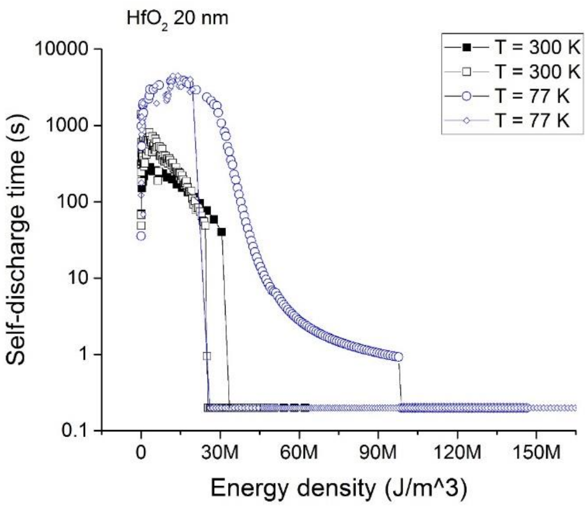
Figure 3: *I-V curves of the 3-layer nano-capacitor system.The I-V curve for the double-layer capacitor is asymmetric and has hysteresis. This supports the theory of synthetic atoms.*

Summary

(1) **Miniaturization** reduces the tunnel currents by several orders of magnitude. Dielectric nanocapacitors have a large dielectric strength and small leakage currents.

(2) In nanocapacitors the electric field at the cathode is (indirectly) limited by the work function of the cathode surface material (280 MJ/m^3 for platinum) and the tensile strength of the anode (150 GJ/m^3 - 360 GJ/m^3 for MWNVTs). Synthetic atoms with **quantized space charges** are not limited by the work function of the cathode and have an increased capacity. In synthetic atoms, leakage currents are suppressed by 7 orders of magnitude (i) because the population of the electrons in the gap is governed by the **Fermi statistics** and (ii) because of **Coulomb blockade.**

(3) **Electrons are 1000 times less massive** than atoms. The Fermi velocity is close to **the speed of light**. A voltage of 5V accelerates electrons to a speed close to the speed of light. The energy release time of all other energy sources is limited by the **speed of sound** or **diffusion**.



Self-discharge times are much longer than this plot suggests, because most of the ‘leak current’ is stored as space charge.

All-electronic charge storage devices with large energy density and small leakage currents

Alfred Hubler, UIUC

Objective / Goal

- Design and fabricate nanocapacitor charge storage systems **which exceed the energy density and reliability of Li-ion batteries, have a record power density,** and have an almost 100% efficiency in a large temperature range for more than 10 years.

Summary of Effort

- **Measure the dielectric strength and the residual leak current** of silicon oxide layers and other dielectrics, including vacuum gaps.
- Describe each system with classical theory and a fully quantum-mechanical theory including **band structure effects**. Model the power law scaling of the **field enhancement factor**.
- A better model for the dielectric strength and leakage currents in nanocapacitors and two types of charge storage systems: (i) a **stack** of dielectric nanocapacitors and (ii) a stack of vacuum nanocapacitors.
- Study **degradation**, failure modes, and **safety issues**.

Major Participants

- Hubler, Bezryadin – UIUC

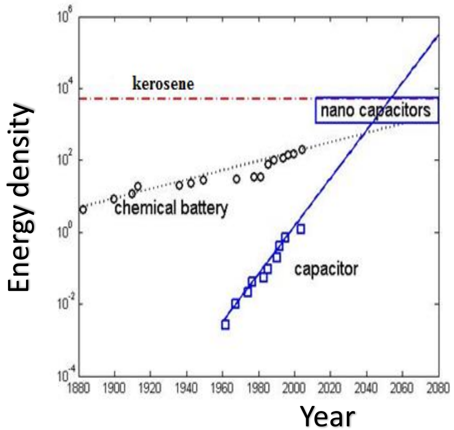


Fig. 1 Trend lines for the energy density *C.Magee, Complexity* 18, 10–25 (2012).

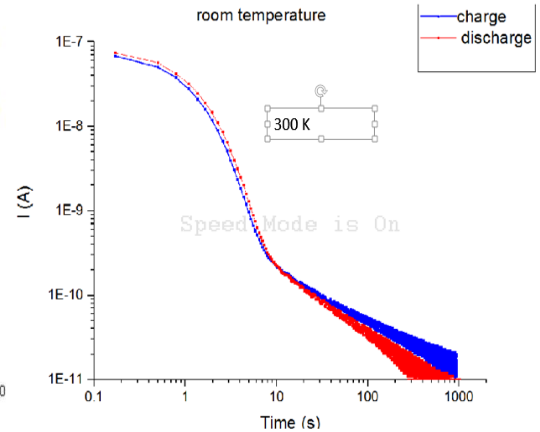


Fig. 2 Discharging a synthetic atom: *Surface charge and space charge have different time scales.*

Recent Accomplishments

- **Verified** that there are surface charges and **space charges.**
- **Verified** that the dielectric strength for typical oxide layers in nanometer range is **around 1V / nm.**
- Showed experimentally that the energy density in vacuum gaps can exceed the energy density of Li-ion batteries.
- Showed theoretically that **Coulomb blockade** can reduce the leakage current by more than 4 orders of magnitude.

Key Milestones / Projected Transition

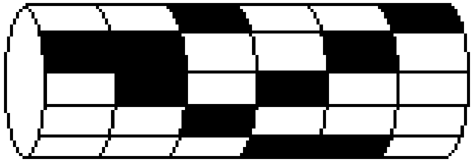
- Several publications in the Nature journal Scientific Reports and Physical Rev. E, several patents

Application 1: Rechargeable battery made of synthetic atoms

Rechargeable batteries made of synthetic atoms:

- Can reach an energy density comparable to Li-ion batteries (currently linear dim a factor of 3 larger), the limiting energy density is 3 orders of magnitude larger than the energy density of Li-ion batteries;
- Operate with undiminished efficiency after millions of charging/discharging cycles;
- Operate with undiminished efficiency in a large temperature range, compared to chemical batteries;
- Have a record power density among all sources of energy;
- Have a large range of operating voltages (currently 10 MV / cm dielectric);
- Can be integrated on the chip in advanced electronics;
- Can be on a nano-scale and on a utility-scale.
- Can self-repair.

Related applications: High-voltage **insulation**, **charge storage** devices with a large charge density and small leak currents



Application 2: Digital Wires

Analog wires are used to move energy (power lines, power grid) and information (data transmission lines, Internet) in electrical networks.

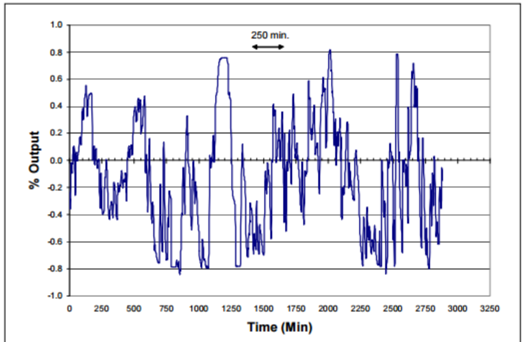


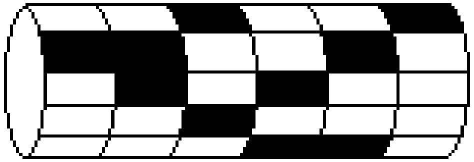
Figure 2: PJM Ancillary Services Power Requirements – Prepared by C. Koontz, WPS.

However, most dynamical systems with more than 7 degrees of freedom are chaotic => the dynamics of large networks of analog wires is unstable => congestions & cascading failures

A survey in 2004 estimated the cost of power-interruption due to cascading, **non-weather related failure in the US to be $80 billion per year**. The number of major **blackouts nearly doubled from 2001-2005 to 2006-2010**, increasing the cost estimate to $80-$188 billion annually.

From a global security standpoint, foreign power systems are generally more fragile and prone to failure during disaster conditions.

Costs are amplified significantly in DOD facilities and forward operating bases, where a negative impact to readiness can have an adverse outcome for the mission and personnel safety. Though cascading failure from sudden load requirements does not generally occur in smaller scale distribution systems such as forward operating bases, the nature of analog power allows for induced cascading failures from third-party grid tied threats. **Power transferred along analog power lines is largely unmonitored and uncontrolled**, meaning sudden surges will affect all connected systems. Digitized power can prevent this by managing the transfer of power at each step of the power packet's propagation.



Application 2: Digital Wires

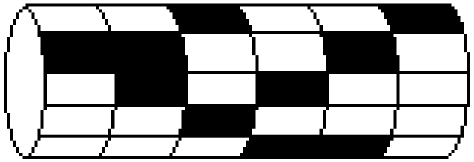
Digital wires: Wires that propagate only patterns of rectangular pulses. Digital wires are capacitor networks. Each capacitor has an energetic *on* state with a fixed voltage and a zero-energy *off* state.

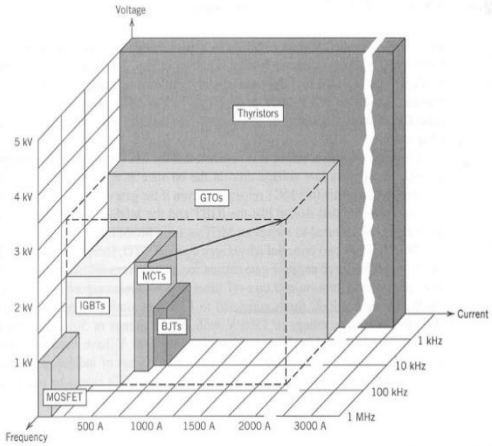
Specific advantages of digital wires:

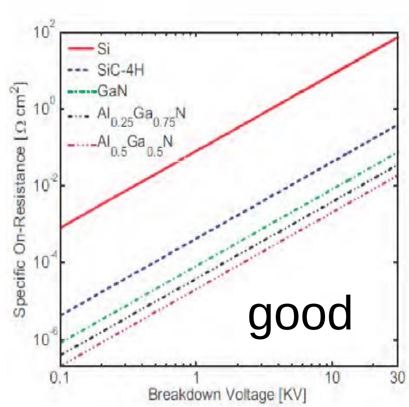
- Fixed pulse shape (increased reliability & speed);
- Robust against electric noise and EMP attacks (increased reliability & speed);
- No cross talk (increased reliability & speed);
- No reflected waves (increased reliability & speed);
- Adjustable pulse speed (increased adjustability);
- Encryption (advanced data security);
- Fully independent addressability of power to/from specific locations, for distributed power generation (added flexibility and reduced cost);
- Multiple AC and/or DC operational regimes on a single multi-parallel cable;
- Ability to store/buffer additional power within the distribution network itself with nanocapacitors;
- Digital wire can be general purpose computers with nanocapacitors.

Neurons are digital wires. Digital wires move information in parallel.

Application 2: Digital Wires. They need nano-caps and fast solid state relays







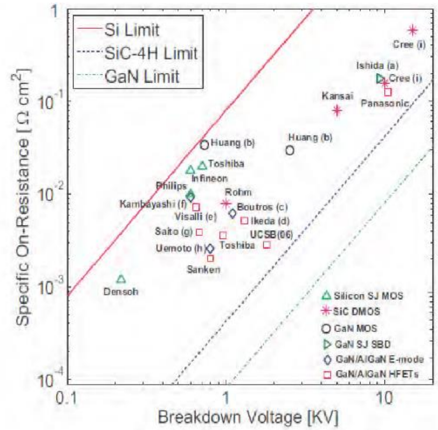
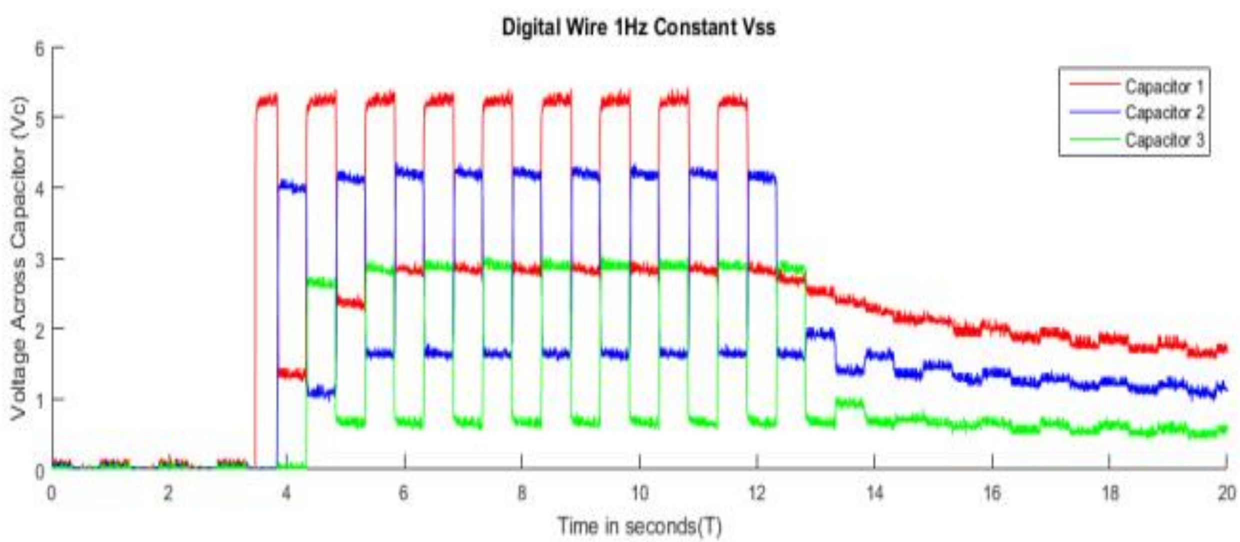
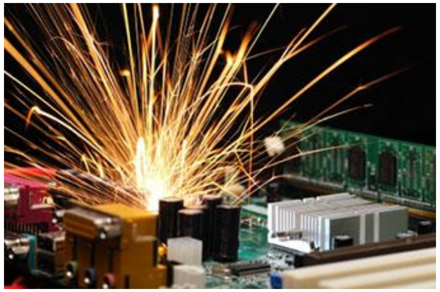


Figure Theoretical limits of assorted switch types compared to current state-of-the-art (GaN) [16]. Higher breakdown voltages and lower on-resistances are essential for better switches (i.e. towards the bottom right of both plots). Theoretical material limits are shown as diagonal lines, and on the right specific switches are represented by data points. It can be seen that the limit given by Si alone has been surpassed by various multi-element semiconductors, though researchers are still far from achieving the limit associated with gallium nitride (GaN).





Application 3: Explosive work with synchronized energy release of synthetic atoms

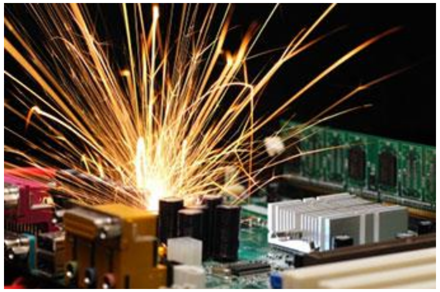
Top few of a doped-silicon/SiO_2/gold capacitor. The photo shows damage done by the EMP (Scale 5:1). We assume an EMP traveled, almost at the speed of light, in the dielectric. It triggered dielectric break down and was amplified by stimulated dielectric break down. This may create a strong **sub-femtosecond soft x-ray pulse**.

Applications 3: Explosive work with synchronized energy release of synthetic atoms

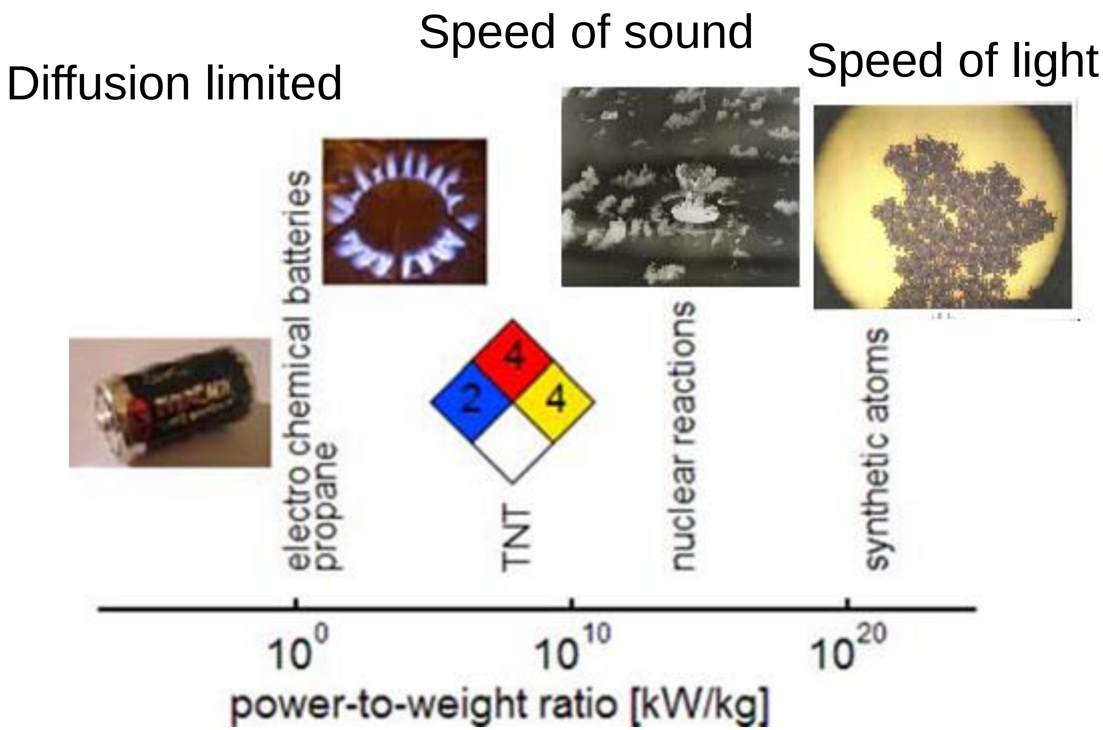
	Specific Energy [MJ/kg]	Min. Energy Release Time [s]	Power-to-Weight Ratio[kW/kg]
Typical electrostatic capacitor	0.000036	(speed of light)	
General Atomics high voltage capacitor	0.0023	(speed of light)	6.8×10^{3}
Saft VL 6Ah Li-ion battery	0.004	(diffusion limited)	2.1×10^{1}
Nesscap Electric double-layer capacitor	0.005	(diffusion limited)	5×10^{0}
10nm SiO_2 nanocapacitor (0.8V/nm, soft γ)	0.005	3×10^{-17}(speed of light)	2×10^{17}
4nm Al_2O_3 nanocapacitor (1V/nm, soft γ)	0.011	1.2×10^{-17}(speed of light)	1×10^{18}
Typical Li-ion battery	0.8	10^{4} (diffusion limited)	1×10^{-1}
10 nm synthetic atom (vac. gap., 25V/nm, soft γ)	1	3×10^{-17}(speed of light)	3×10^{20}
TNT	4.6	10^{-5} (speed of sound)	5×10^{8}
Kerosene	42	10^{4} (diffusion limited)	4×10^{0}
Weapon grade Uranium (hard γ)	144,000,000	10^{-5} ? (speed of sound?)	1×10^{16}

Large energy density can create a large amount of heat => can melt and burn solids.
Large power density can create large forces => can break and slice solids, even if the energy density is small (slicing bread).

[1] https://en.wikipedia.org/wiki/Energy_density
[2] http://en.wikipedia.org/wiki/Power-to-weight_ratio
[3] Alfred Hubler, Synthetic atoms, Complexity 18(4), 12-14 (2013)



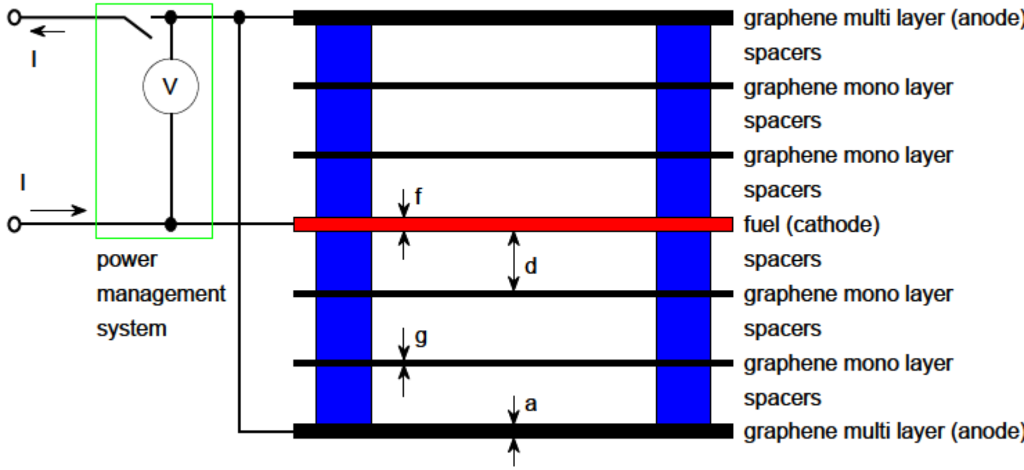
Application 3: Explosive work with synchronized energy release of synthetic atoms



Synthetic atoms have potentially a record power density, more than 20 orders of magnitude larger than Li-ion batteries and almost 1 million times larger than nuclear devices. This means 50 milligram (3 table spoon) of charged synthetic atoms can deliver the same power as a nuclear chain reaction of 50kg (100 pounds) of highly enriched nuclear material. Currently, 50 milligrams of synthetic atoms can store roughly the same as amount of energy as a digital camera battery, but can potentially store 100-1000 times more energy.

Bottom line: We may have reached the end of the 'nuclear age'.

Application 4: Harvesting nuclear energy with synthetic atoms without a heat engine



Efficiency of conventional nuclear power plants (heat engines): 35 percent.

Here: The kinetic energy of nuclear reaction products is directly converted into electric energy in a stack of charged capacitors with a gap size of 500 nm and graphene electrodes.

- Graphene is expected to be chemically and mechanically stable in high radiation environments because it's tensile strength of 130 GPa is very large, about 100 times larger than most metals.
- The dielectric strength of nanocapacitors is very large, above 1 GV/m.
- In a 1 GV/m electric field charged nuclear reaction products, such as 5.6 MeV alpha particles, come to rest in of a stack with 5000 nanocapacitors.

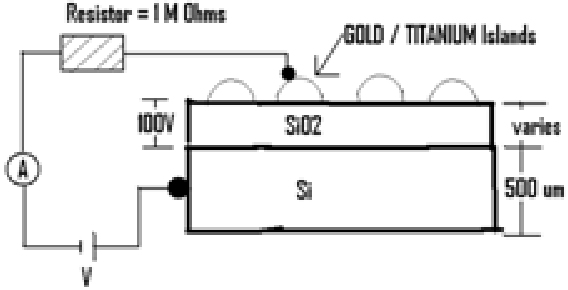
We show that during the deceleration more than 90 percent of kinetic energy of charged nuclear reaction products is stored as electric energy in the stack. Each stack is 2.5mm thick and produces a high voltage DC current. A device with a 1 Ci - ^{241}Am source generates 22 mW of electric power.

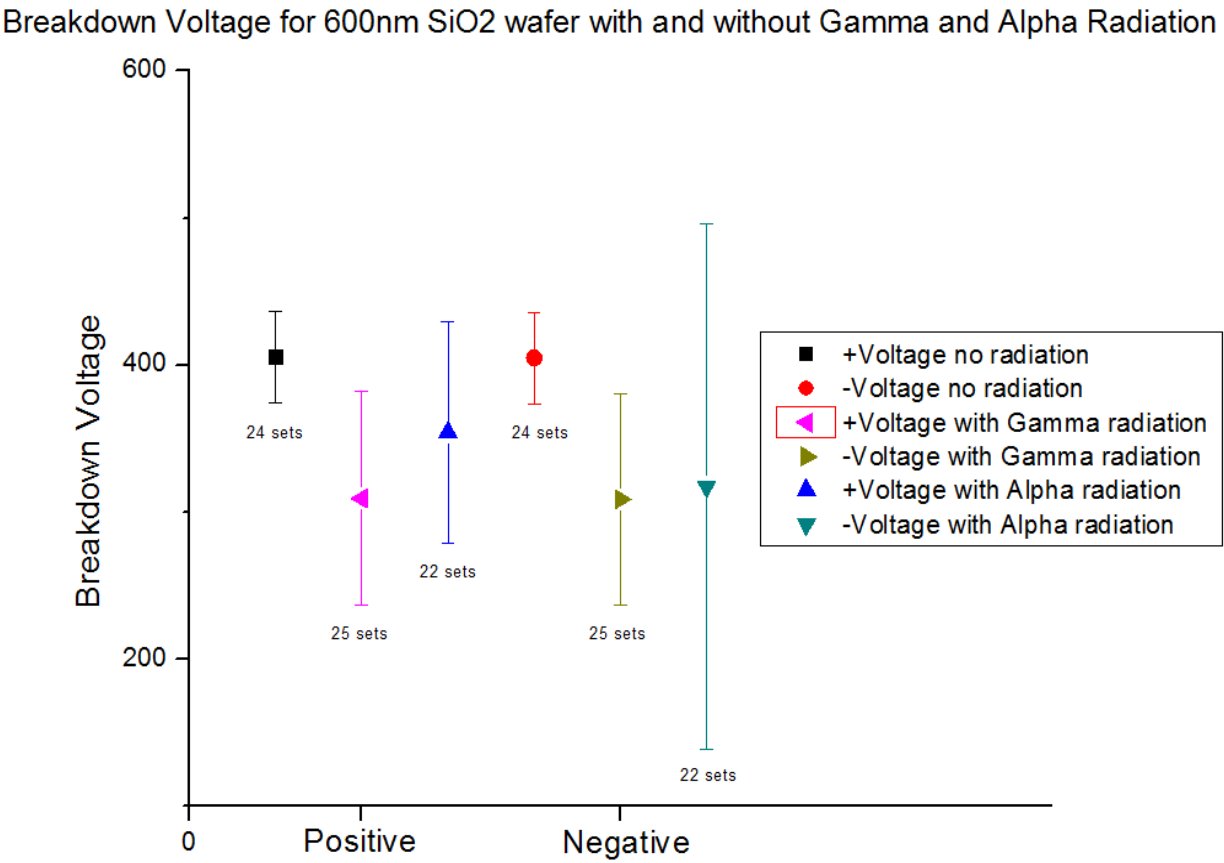
Similar reactors with a 200nm Am-242(m) foil and beryllium / beryllium oxide sheets to act as both neutron moderators and reflectors are critical [1]. 72 percent of kinetic energy of charged nuclear reaction products is stored as electric energy in a stack of 8000 sheets of graphene.

[1] Y. Ronen, A. Hatav, N. Hazenshprung, Nucl. Instr. and Meth. A 531, 639 (2004).
[2] E. Shinn, A. Hubler, D. Lyon, M. Grosse-Perdekamp, A. Bezryadin, A. Belkin, Complexity 18(3), 24–27(2013).

Application 4: Harvesting nuclear energy with synthetic atoms without a heat engine

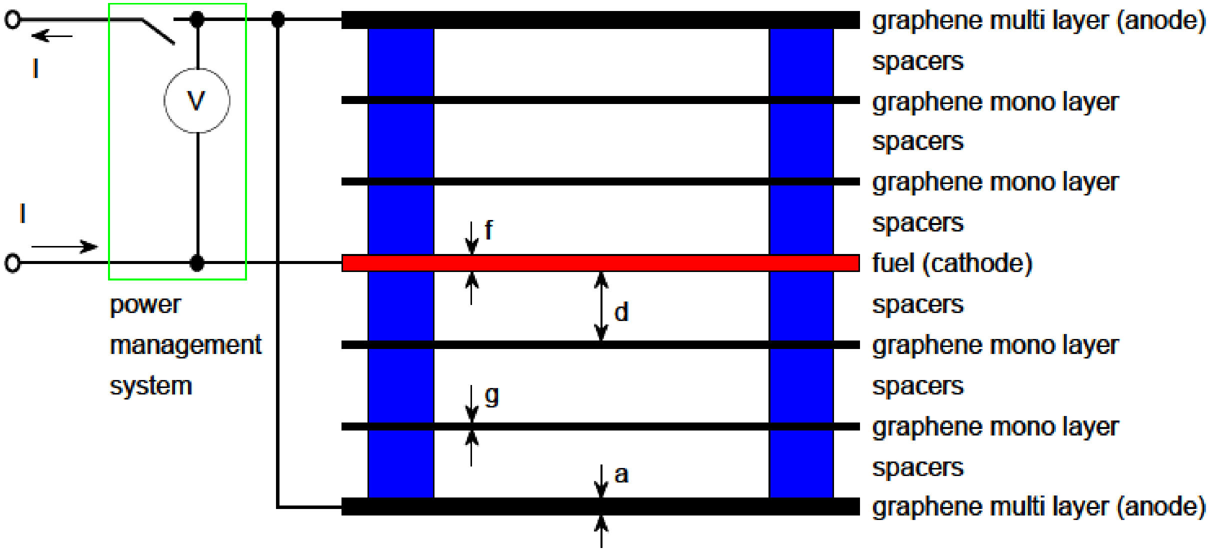
Am 241 alpha source





Conclusion: Nuclear radiation (Co-60 10.5mCi gamma source, 8.51 mCi Am 241 alpha source at a distance of 1cm from the NC) reduces the dielectric strength only by 25%.

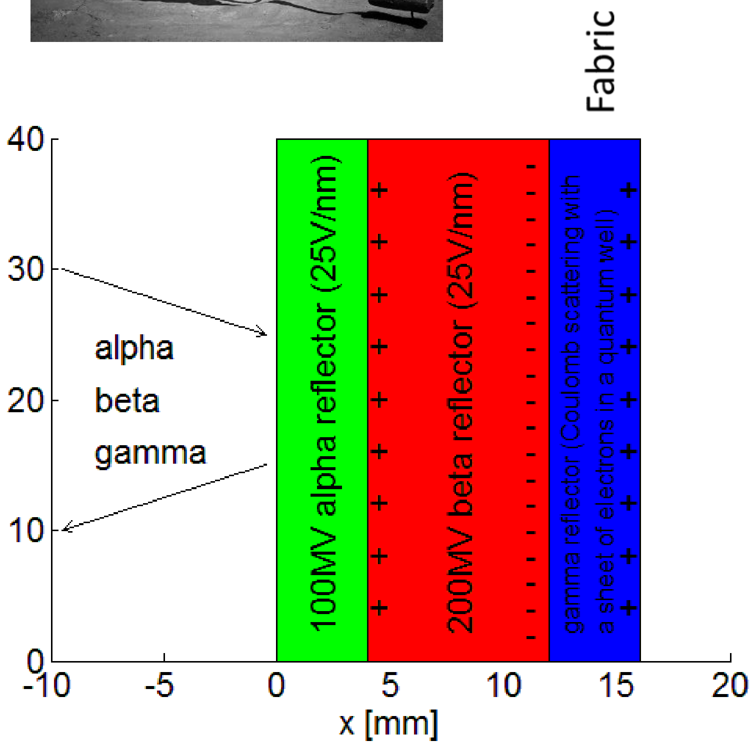
Application 5: Synthetic atoms as nanoscale particle accelerators



If the polarization is reversed this design can be used as a nano-accelerator for propulsion, a X-ray source for lithography and medical applications.

Bottom line: Smaller is better

Application 6: Nuclear protection suits made of synthetic atoms - *Fabric with 16mm thick, 1cm^2-plates which reflect nuclear radiation*



Conclusion: Nuclear radiation suits are electrically neutral and can **reflect charged particle radiation with energies up to 100MeV/charge**, and efficiently scatter gamma radiation.

Summary

Crystals of synthetic atoms:

- Can reach an energy density comparable to Li-ion batteries (currently linear dim a factor of 3 larger);
- operate with undiminished efficiency after millions of charging/discharging cycles;
- operate with undiminished efficiency in a large temperature range, compared to chemical batteries;
- have a record power density among all sources of energy;
- have a large range of operating voltages (currently 10 MV / cm dielectric)

Applications of this devices include:

- rechargeable battery for all electric cars, ships, and airplanes; utilities; advanced digital electronics; analog devices
- capacitors with a large charge density
- high voltage electrical insulation

- digital wires
- a novel type of energetic material, with a record power density, for propulsion systems
- micro-scale particle accelerator
- EMP source
- direct conversion of nuclear energy to electrical energy without a heat engine
- protective clothing for areas with high nuclear radiation
- micro-scale X-ray source

Thank you.

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Appendix: Classical Theory

Capacitance Density[8]: $$C_d = \frac{C}{v} = \frac{\varepsilon_0 \varepsilon_r}{t^2} \quad (1)$$

Specific Capacitance [8]: $$C_s = \frac{C}{M} = \frac{C_d}{d} \quad (2)$$

Resistance[10]: $$R = \frac{t}{A}\rho \quad (3)$$

Capacitance[8]: $$C = \frac{A}{t}\varepsilon_0 \varepsilon_r \quad (4)$$

Self Discharge Time[11]: $$\tau = RC = \rho \varepsilon_0 \varepsilon_r \quad (5)$$

Self Discharge Time at Breakdown : $$\tau_b = \sqrt{LC} \quad (6)$$

Inductance[17]: $$L = \mu_0 r N^2 \left[\ln\left(\frac{8r}{l}\right) - \frac{1}{2}\right] \quad (7)$$

Maximum Energy Density[9]: $$u_{max} = \frac{1}{2} E^2 \varepsilon_0 \varepsilon_r \quad (8)$$

Maximum Specific Energy[14]: $$E_s = \frac{u_{max}}{d} \quad (9)$$

Appendix: Classical Theory

Maximum Charge Density[15]: $$Q_d = \frac{q}{v} = \frac{CV}{v} = C_d E t \qquad (10)$$

Maximum Specific Charge[16]: $$Q_s = \frac{q}{M} = \frac{Q_d}{d} \qquad (11)$$

Maximum Power Density[18]: $$P_d = \frac{u_{max}}{\tau_b} \qquad (12)$$

Maximum Specific Power[19]: $$P_s = \frac{E_s}{\tau_b} \qquad (13)$$

Where v is the volume, M is the mass, q is the capacitor's charge, V is the maximum voltage determined by the dielectric strength, μ_0 is the magnetic constant $4\pi\times10^{-7}$ H/m, and ε_0 is the electric constant 8.85×10^{-12} F/m. L (see Eq. 7) represents the inductance of a system where the two plates are connected by a circular wire loop of radius r, where r could be large, for example r = 1 mm, 1 m, 100 m. The smallest value of the radius is $r = max\left\{\frac{t}{2}, \frac{\sqrt{A}}{2}\right\}$, a short-cut between the plates. For this smallest value, L approximates the inductance of a plasma-column discharge.

What is the best dielectric for energy storage?

Table 1: Comparison of Material Properties

Material	Density d [kg/m^3]	Bulk Resistivity ρ [Ω-m]	Dielectric Strength E [V/m]	Relative Permittivity ε_r	Capacitance Density C_d [F/m^3]	Specific Capacitance C_s [F/kg]
GO	1800 [13]	1.5×10^7 [3]	1.5×10^8 [1]	10^4 [6]	5.5×10^9	3.1×10^7
SiO_2 (BP)	2210 [12]	6.3×10^{14} [2]	5.6×10^8 [2]	3.9 [4]	2.2×10^6	9.8×10^2
Si_3N_4 (BP)	3180 [12]	5.2×10^{11} [2]	2.4×10^8 [2]	7.5 [4]	4.2×10^6	1.3×10^3
Al_2O_3 (UP)	3990 [12]	2.3×10^{14} [2]	6.2×10^8 [2]	9.4 [5]	5.2×10^6	1.3×10^3
Vacuum	—		6.5×10^9 [22]	1		

At small fields only?

What is the best dielectric for energy storage?

Table 3: Comparison of Nano-Gap Capacitor Properties

Dielectric Material	Self-Discharge Time τ [s]	Maximum Energy Density u_{max} [J/m^3]	Maximum Specific Energy E_s [J/kg]	Maximum Charge Density Q_d [C/m^3]	Maximum Specific Charge Q_s [C/kg]
GO	1.3	1.0×10^9	5.5×10^5	3.3×10^9	1.8×10^6
SiO_2	2.2×10^4	5.4×10^6	2.4×10^3	4.9×10^6	2.2×10^3
Si_3N_4	36	1.9×10^6	6.0×10^2	4.0×10^6	1.3×10^3
Al_2O_3	1.9×10^4	1.6×10^7	4.0×10^3	1.3×10^7	3.3×10^3
Vacuum					

Vacuum near STM tip: 3 x 10^9 J/m^3

Li-ion batteries: ~ 1 x 10^9 J/m^3

Kerosene: 50 x 10^9 J/m^3

Theoretical limit: 1600 x 10^9 J/m^3

boron nitrate

What is the best dielectric for energy storage?

Table 4: Nano-Gap Capacitor Properties with Area = 1 m^2

Dielectric Material	Resistance R [Ω]	Capacitance C [F]	Self-Discharge Time at Breakdown τ_b [s]	Maximum Power Density P_d [W/m³]	Maximum Specific Power P_s [W/kg]
GO	0.060	22	3.5×10^{-3}	2.9×10^{11}	1.6×10^{8}
SiO_2	2.5×10^{6}	0.0086	6.9×10^{-5}	7.8×10^{10}	3.5×10^{7}
Si_3N_4	2.1×10^{3}	0.017	9.7×10^{-5}	2.0×10^{10}	6.2×10^{6}
Al_2O_3	9.2×10^{5}	0.021	1.1×10^{-4}	1.5×10^{11}	3.6×10^{7}
Vacuum					

Table 5: Nano-Capacitor Properties with Area = 100 nm^2

Dielectric Material	Resistance R [Ω]	Capacitance C [F]	Self-Discharge Time at Breakdown τ_b [s]	Maximum Power Density P_d [W/m³]	Maximum Specific Power P_s [W/kg]
GO	6.0×10^{14}	2.2×10^{-15}	3.5×10^{-15}	2.9×10^{23}	1.6×10^{20}
SiO_2	2.5×10^{22}	8.6×10^{-19}	6.9×10^{-17}	7.8×10^{22}	3.5×10^{19}
Si_3N_4	2.1×10^{19}	1.7×10^{-18}	9.7×10^{-17}	2.0×10^{22}	6.2×10^{18}
Al_2O_3	9.2×10^{21}	2.1×10^{-18}	1.1×10^{-16}	1.5×10^{23}	3.6×10^{19}
Vacuum					

Single plasma column discharge

Dielectric thickness t = 4 nm