Other Electronic Materials

Supercapacitors

Introduction:

- The rapid increase in the global energy consumption and the environmental impact of traditional energy resources has led to tremendously increased research activities on clean and renewable energy sources during the last decade.
- As these new energy forms are intermittent or regionally limited, there is a pressing need to develop advanced energy storage systems, such as supercapacitors, for efficient storage.

- The efficiency of energy storage devices depends on structure and properties of the component materials.
- The recent development in nanotechnology has opened up new frontiers by creating new materials and structures for efficient energy storage.

Supercapacitors

History of supercapacitor:

Year	Inventor	Invention
1876	Fitzgerald	Invented a wax-impregnated paper dielectric capacitor with foil electrodes.
1897	Clarles Pollak	Developed Borax electrolyte aluminum electrolytic capacitor.
1957	H.Becker	Developed a low voltage electrolytic capacitor with porous carbon electrodes.
1970	Donald L. Boos	Developed electrolytic capacitor with activated carbon electrode.
1978	Nippon electric corporation	Introduced commercial product of double-later capacitor designs patented by Standard Oil company of Ohio.
1994	David A. Evans	Developed electrolytic-hybrid electrochemical capacitor using the anode of a 200 V high voltage tantalum electrolytic capacitor.
1999	Brian Evans Conway	Coined the term supercapacitor to explain the increased capacitance by surface redox reactions with faradaic charge transfer between electrodes and ions.
2002	VAG, public transport company, Germany	Tested a bus which used a diesel-electric drive system with supercapacitors.

Supercapacitors

What is a capacitor?

- Capacitor is an electronics component which is used to store charge in the form of electric potential.
- Capacitor is consists of two parallel plates, separated by a small distance in few millimeters.
- Amount of charge store in the capacitor is known as capacitance of capacitors and it depend upon dimensions of the capacitors.
- When a capacitor is attached across a battery, an electric field develops across the dielectric, causing positive charge (+Q) to collect on one plate and negative charge (−Q) to collect on the other plate.
- The capacitance increase or decrease changing dimensions of the capacitor and material used in it.

Supercapacitors

What is a supercapacitor?

- Supercapacitors (SC) are specially designed capacitor which has huge capacitance value and energy density compared to capacitors.
- The principle of energy storage in a supercapacitor can be either
  - ✓ Pure charge storage on an electrode/ electrolyte interface electrostatically by electrochemical double layer capacitance (EDLC) or
  - ✓ It can transfer a charge to the layer of redox molecules on the surface of the electrode.
- Supercapacitor cells are able to fill the gap between conventional capacitors and batteries by providing high power performance in a compact design.

Supercapacitors

Working of supercapacitor:

- A Supercapacitor consist of two porous electrodes, a membrane, which separates positive and negative plated is called separator.
- Electrodes are electrically connected with ionic liquid called electrolyte.
- When the voltage is applied to positive electrode it attracts negative ions from electrolyte.

- When the voltage is applied to negative electrode, it attracts positive ions from electrolyte.
- These ions are stored near the surface of electrode and this ions decrease distance the between the electrodes.
- Due to decrease of distance electrodes, the capacitance become very huge.

$$C \propto \frac{A}{d}$$

Supercapacitors

Types of supercapacitor:

Supercapacitors

Criteria for choosing nanomaterials for supercapacitors:

Electrode materials:

Supercapacitors

Electrolyte materials:

Supercapacitors

I. Electrical Double Layer Capacitors (EDLCs):

- EDLCs are constructed using two carbon based materials as electrodes, an electrolyte and a separator.
- EDLCs can either store charge electrostatically or via non faradic process, which involves no transfer of charge between electrode and the electrolyte.

- EDLCs utilize an electrochemical double-layer of charge to store energy. As voltage is applied, charge accumulates on the electrode surfaces and ions in the electrolyte solution diffuse across the separator into the pores of the electrode of opposite charge.
- However, the electrodes are engineered to prevent the recombination of the ions. Thus, a double-layer of charge is produced at each electrode.
- These double-layers, coupled with an increase in surface area and a decrease in the distance between electrodes, allow EDLCs to achieve higher energy densities than conventional capacitors.

Supercapacitors

i. ***Activated Carbon (AC):***

- The conventional electrode materials for EDLCs are porous AC with large specific surface areas.
- The charge accumulation capability of carbon materials at the electrode/electrolyte interface is increased with their specific surface area (SSA).
- However, specific capacitance is not always linearly increased because of the wide pore size distribution of activated carbon materials, which possess random pore connections.

- Therefore, the ion transport in pore channels may dramatically slow down, and then the energy and power density of EDLCs will be limited.
- Researchers are developing for another type of carbon material with a narrow distribution of ordered mesoporous carbons (OMCs) (2–50 nm).

Supercapacitors

ii. Carbon nanotubes (CNTs):

- Because of the inherent high electrical conductivity and chemical stability, carbon nanotubes (CNTs) have been considered as promising electrodes for supercapacitors.
- Carbon nanotubes are produced via catalytic decomposition of some hydrocarbons and by carefully manipulating different parameters.

- CNTs have mesopores that are interconnected, this allows for a continuous charge distribution that utilizes almost all of the accessible surface area.
- CNTs can be chemically activated with potassium hydroxide, in order to improve its specific capacitance.

Supercapacitors

iii. Graphene:

- With high electrical conductivity and charge transport mobility, graphene is attracting extensive attention as an electrode material for high-power EDLCs.
- Graphene nanosheets grown on a metal current collector exhibited a high power performance that is even close to that of conventional dielectric capacitors.

- Researchers are working on porous graphene oxide preparation by KOH activation as an electrode material for EDLCs.
- Different methods are being researched on synthesis of graphene for supercapacitor applications.
  i. Thermal exfoliation of graphitic oxide,
  ii. Heating nano-diamond at 1650 °C in a helium atmosphere,
  iii. Camphor decomposition over nickel nano-particles.

Supercapacitors

Advantages:

- ✓ Higher energy densities than conventional capacitors.
- ✓ No chemical or structural change during charge storage.
- ✓ Work in extreme temperatures and are very safe.
- ✓ Have high cycling stability.

Disadvantages:

- ✓ Cannot match energy densities of mid-level batteries because limited surface area and pore size distribution of conventional electrode materials.

Supercapacitors

II. Pseudocapacitors:

- Pseudocapacitors store charge faradaically through the transfer of charge between electrode and electrolyte.
- This is accomplished through underpotential deposition, reduction-oxidation reactions, and intercalation processes.
- These faradaic processes may allow pseudocapacitors to achieve greater capacitances and energy densities than EDLCs.

- It involves reduction-oxidation reaction just like in the case of batteries; hence they also suffer lack of stability during cycling and low power density.
- It's construction is similar to EDLCs, but the electrodes are made from metal-oxides or conducting polymers.

Supercapacitors

Mechanism:

- This is accomplished through underpotential deposition, reduction-oxidation reactions, and intercalation processes.
- Underpotential deposition occurs when metal ions form an adsorbed monolayer at a different metal's surface well above their redox potential. One classic example of underpotential deposition is that of lead on the surface of a gold electrode.

- Redox pseudocapacitance occurs when ions are electrochemically adsorbed onto the surface or near surface of a material with a resulting faradaic charge-transfer.
- Intercalation pseudocapacitance occurs when ions intercalate into the tunnels or layers of a redox-active material accompanied by a faradaic charge-transfer with no crystallographic phase change.

Supercapacitors

i. ***Conducting polymers:***

- Conducting polymers, including polyacetylene (PA), polypyrrole (PPy), polyaniline (PANI), and poly(3,4-ethylenedioxythiophene) (PEDOT) have been considered as promising pseudo-capacitive electrode materials for supercapacitors.
- They offer capacitive behavior through redox reactions that occurs on the surface and throughout the entire bulk.
- The redox processes are highly reversible because no structural changes, such as phase transformation, happen during the redox reactions.
- PANI and PPy are the most promising members due to their low cost, environmental stability and facile synthesis.
- Conducting polymers may swell and shrink in the process of intercalation and de-intercalation, which often results in a low cycling stability when they are used in supercapacitors.

Supercapacitors

ii. Metal Oxides:

- Metal oxides generally have much higher spatial capacitance compared with that of carbon materials for EDLCs.
- During the past years, various metal oxides (e.g. $RuO_2.H_2O$, $IrO_2.H_2O$, $MnO_2.H_2O$, V_2O_5, NiO, Co_3O_4, SnO_2, and Fe_2O_3) and some hydroxides (such as $Co(OH)_2$, $Ni(OH)_2$, or their composites) have been widely investigated as pseudocapacitive electrode materials.
- Many studies have also focused on combining RuO_2 with cheap metal oxides, such as SnO_2, MnO_2, NiO, VO_x, TiO_2, MoO_3, WO_3, and CaO, to form composite oxide electrodes.

Supercapacitors

Advantages:

- ✓ Higher energy densities than EDLCs.
- ✓ Hydrous ruthenium oxide can achieve extraordinary capacitances.

Disadvantages:

- ✓ Lower power densities than EDLCs.
- ✓ Cycle life can be limited by mechanical stress caused during reduction-oxidation reactions.
- ✓ Negatively charged conducting polymer electrodes are not very efficient.
- ✓ The best metal-oxide electrodes are very expensive and require aqueous electrolytes, which means lower voltage.

Supercapacitors

III. Hybrid capacitors:

- Hybrid supercapacitors storage principle is governed by a combination of the EDLCs and pseudocapacitor storage principles.
- The limiting property of EDLCs is not present in the pseudocapacitor and vice versa.
- The combination of EDLCs & pseudocapacitor storage together leads to overshadowing of the limitations of the combining components, with an advantage of delivering higher capacitance.

- Hybrid supercapacitors, when composed of two different electrodes made of different materials show better electrochemical behavior than the individual ones.
- Research has focused on three different types of hybrid capacitors, distinguished by their electrode configuration: composite, asymmetric, and battery-type respectively.

Supercapacitors

i. ***Composites:***

- Composite electrodes combines carbon based materials with either metal oxides or conducting polymer in a single electrode.

ii. ***Asymmetric:***

- Asymmetric hybrids combine non faradic and faradic processes by coupling and EDLC with a pseudocapacitors electrode.
- They are set up in a way that the carbon material is used as a negative electrode while either metal oxide or conducting polymer as positive electrode.

iii. ***Battery type:***

- Battery type hybrid combines two different electrodes, a supercapacitor electrode with battery electrode.
- This configuration was set up so as to utilize both properties of supercapacitors and batteries in one cell.

Supercapacitors

Advantages:

- ✓ Have the most flexible performance characteristics of any supercapacitor, it fits the widest range of application.
- ✓ Can achieve very high energy and power densities without the sacrifices in cycling stability and affordability.

Disadvantages:

- ✓ Relatively new and unproven technology.
- ✓ More research is needed to better understand the full potential of hybrid capacitors.

Supercapacitors

Electrolyte materials:

- The electrolyte, including solvent and salt, is one of the most important constituents of electrochemical supercapacitors due to its advantages of ionic conductivity and charge compensation on both electrodes of the cell.
- These electrolytes can be classified as

  i. **Organic electrolytes:** Tetraethyl ammonium tetrafluoroborate ($TEABF_4$)) dissolved in acetonitrile or propylene carbonate (PC) solvent.

  ii. **Aqueous electrolytes:** H_2SO_4, KOH, and Na_2SO_4.

  iii. **Ionic liquids:** Pyrrolidinium, imidazolium or aliphatic quaternary ammonium salts coupled with such anions as PF_6, BF_4 etc.

  iv. **Solid-state polymer electrolytes:** Dry polymer electrolyte, gel polymer electrolyte, and polyelectrolyte.

Supercapacitors

Applications:

Supercapacitor electric bus

To power the Note 9 stylus

HD Car Camcorder

To light LEDs

For IoT

Solar supercapacitors for wearable sensors

Supercapacitors, Electric Double Layer Capacitor Ultracapacitor

Supercapacitor

- High capacitance
- High energy density
- Lower Voltage
- High cycle life
- Charge and discharge much faster than batteries
- Bridges the gap between capacitors and rechargeable batteries

Supercapacitor

- Regenerative braking
- Loading and unloading activities
- Start-Stop of electric vehicles

Supercapacitor:	Electrical energy, uses ions
Battery:	Chemical energy, uses ions
Capacitor:	Electrical energy, uses electrons

Supercapacitor

Electrode
electrons
ions
Electrolyte
+
Flat surface
Two dimensional electrode surface
Three dimensional electrode interphase

24hr 1 charge & 1 discharge.
Charge-Discharge duration
Cycle Life
Hours
Thousand
Batteries
24hr Several hundred acceleration deceleration event.
Seconds to Minutes
Nearly a million
Super-capacitors
Capacitors
ms to µs
'Infinte'
10^6
10^1
10^1
10^6
Specific Energy (Wh/kg)
Specific Power (W/kg)

Materials Used:

Electrode:
Activated carbon, Graphene, Carbon nanotubes

Activated Carbon: Natural carbons and polymers heat treated in inert atmosphere
Graphene can restack
Carbon nanotubes – cylindrical surface is used

Materials Used:

Electrolyte:

Aqueous electrolytes:	Voltage restricted to 1.23 V
Organic electrolytes:	Lower conductivity (Propylene Carbonate)
Ionic liquids:	Organic salts with no solvents and melting point below 100 °C

Conclusions

1) Supercapacitors bridge the gap between capacitors and batteries
2) High surface area carbon materials used in electrodes
3) Aqueous, organic as well as ionic liquids considered as electrolytes

Supercapacitors

- https://www.youtube.com/watch?v=iFVVv23ZzGE
- https://www.youtube.com/watch?v=1n1X2fDrn7g

Carbon Nanotubes(CNT)

Carbon Nanotubes (CNT)

A rolled-up sheet of graphene

⇒ into a tube.

1991 Sumio Iijima Journal Nature

?

Classification of CNT : SWNT & MWNT

CNT

- SWNT (Single-walled Nanotube)
- MWNT (Multi-walled Nanotube)
  - Russian Doll
  - Parchment

~ 3.4 Å

~ interlayer separation of graphite.

NPTEL

ETSC, IIT DELHI

SWCNT & MWCNT

Graphene
Graphite
Multi-layered
Rolled up
Rolled up
Multi-layered
Single-walled carbon nanotube (SWCNT)
Multi-walled carbon nanotubes (MWCNT)

Physical Parameters

Parameter	SWCNTs	MWCNTs
Key parameters		
Typical diameter	1–2 nm*	7–100 nm
Typical length	Up to 1 mm**	Up to 1 mm
Aspect ratio	Up to 10 000	50–4000
Mechanical properties		
Elastic modulus	1000–3000 GPa	300–1000 GPa
Tensile strength	50–100 GPa	10–50 GPa
Electronic structure properties		
Thermal conductivity at 300K	3000–6000 W/(m·K)	2000–3000 W/(m·K)
Minimum working dosage as an anti-static additive	0.01%	0.5%

Properties

- The strongest and most flexible molecular material because of C-C covalent bonding and seamless hexagonal network architecture

- Young's modulus of over 1 TPa vs 70 GPa for Aluminum, 700 GPA for C-fiber
  - strength to weight ratio 500 time > for Al; similar improvements over steel and titanium; one order of magnitude improvement over graphite/epoxy

- Maximum strain ~10% much higher than any material

- Thermal conductivity ~ 3000 W/mK in the axial direction with small values in the radial direction

Properties

- Electrical conductivity six orders of magnitude higher than copper
- Can be metallic or semiconducting depending on chirality
  - 'tunable' bandgap
  - electronic properties can be tailored through application of external magnetic field, application of mechanical deformation…
- Very high current carrying capacity
- Excellent field emitter; high aspect ratio and small tip radius of curvature are ideal for field emission
- Can be functionalized

Synthesis of carbon nanotubes

- **plasma arc discharge**: production of carbon nanotubes in an arc discharge plasma in a helium atmosphere.

- **laser evaporation** (pulsed laser ablation): evaporation of a graphite target in a high-temperature reaction by the action of a pulsed laser.

- **chemical vapor deposition (CVD)**: catalytic (nickel, cobalt, iron or their combinations) deposition of carbon from hydrocarbons (methane, ethylene, acetylene)

CVD

Furnace 500 – 1000 °C
Hydrocarbon gas
C_2H_2
Inert gas
CNTs
Catalyst
Substrate
Gas outlet

C_xH_y
Catalyst
Substrate
C_xH_y

Steps in CVD

1st step:
evaporation of metal

2nd step:
metal vapor condensation into nanoparticles

3rd step:
calytic decomposition of hydrocarbon on metal nanoparticles and formation of nanostructures

4th step:
growth of carbon nanotubes on catalyst particle

SWCNT

Classification of Nanotubes : Chirality
CNT
Chiral
(Handed)
Mirror is absent
Achiral
(Not handed)
Mirror Present
zig-zag
Armchair

Armchair, Zigzag and Chiral

(a) armchair, (b) zigzag, (c) chiral

Zig- Zag & Armchair

Notation of CNT

Zig-Zag

(n, m) notation
4a2
(0a1 + 4a2)
(0, 4)
Chiral vector
≡ Circum ferential vector
≡ C
T
a2
a1
(0,0)
d
d
C has to be a lattice vector of graphene.
C = na1 + ma2
(n, m) tube.
NPTEL

Arm-chair

Chiral

Chiral angle

C and θ

Both diameter ~~and~~ d and the Chiral angle θ ~~can~~ of an (n, m) CNT can be expressed in terms of n and m (and C-C bond length for d.)

$(n, m) \rightarrow \vec{C} = n\vec{a}_1 + m\vec{a}_2$

$|\vec{C}|$ = circumference $= \pi d$

θ = Angle between $\vec{C}$ and $\vec{a}_1$.

PTEL

ETSC

Reference

- https://www.youtube.com/watch?v=XoBeu2LGL5E
- https://www.youtube.com/watch?v=nYZyQ7etgc8
- https://www.youtube.com/watch?v=mBxzPNwcn_4
- https://tuball.com/articles/single-walled-carbon-nanotubes

Introduction to Graphene

- Graphene is widely researched worldwide because of its unique properties such as zero bandgap, remarkable electron mobility at room temperature, high thermal conductivity and stiffness, large surface area, impermeability to gases, etc.
- Recently, graphene-based materials have gained intense awareness on energy storage systems, electronics, chemical sensors, optoelectronics, nanocomposites, and health such as osteogenic.
- Graphene has been used in many applications, which include energy storage devices like supercapacitors and lithium-ion batteries, gas detection, and conducting electrodes.

Introduction to Graphene

- Graphene is among the allotropes of carbon; its carbon atoms are arranged in a single layer.
- These carbon atoms are organized in a honeycomb lattice with a two-dimensional arrangement.
- The carbon–carbon bond distance in a single graphene sheet approximates 0.142 nm.

Structure of graphene sheet, stacked graphene, wrapped graphene, and rolled graphene

Graphene-Synthesis

- Graphene synthesis means any process of fabricating or extracting graphene from graphite.
- The method to be chosen is governed by the desired size, quantity, and purity.
- Synthesis technique contributes to the structure and properties of graphene produced.
- There are variations of graphene layers from different techniques such as a single layer, double layer, or multiple layers.

Graphene-Synthesis

Some Synthesis Techniques are

- Exfoliation technique
  - Mechanical exfoliation and
  - Chemical exfoliation.
- Chemical vapor deposition (CVD) methods
- Pyrolysis of graphene
- Unzipping CNTs
- Thermal decomposition of SiC

Applications of graphene

Graphite and its derivate recently gained science and engineering awareness due to its numerous applications. Some Fields are

- Electronics
- Energy storage
- Water purification
- Biomedical applications
- Biosensors
- Plasmonics
- Lubricants
- Radio wave absorption
- Nanoantennas
- Sound transducers

Superconductors

- As most high-purity metals are cooled down to temperatures nearing 0 K, the electrical resistivity decreases gradually, approaching some small yet finite value characteristic of the particular metal.
- There are a few materials, however, for which the resistivity abruptly plunges at a very low temperature, from a finite value to one that is virtually zero and remains there upon further cooling.
- Materials that display this behavior are called ***superconductors,*** and the temperature at which they attain **superconductivity** is called the critical temperature T_C
- The critical temperature varies from superconductor to superconductor but lies between less than 1 K and approximately 20 K for metals and metal alloys.
- Recently, it has been demonstrated that some complex oxide ceramics have critical temperatures of greater than 100 K.

Superconductors

Type of material	What happens in a wire?	Result
Conductor	Electrons flow easily (like water through a garden hose)	Collisions cause dissipation (heat)
Insulator	Electrons are tightly bound no flow (like a hose plugged with cement)	No current flow at all
Superconductor	Electrons bind into pairs and cannot collide (a frictionless hose)	No collisions No dissipation No heat No resistance

Superconductors

- At temperatures below T_C, the superconducting state ceases upon application of a sufficiently large magnetic field, termed the critical field H_C, which depends on temperature and decreases with increasing temperature. The same may be said for current density—that is, a critical applied current density J_C exists below which a material is superconductive

Classification

- On the basis of magnetic response, superconducting materials may be divided into two classifications, type I and type II.
- Type I materials, while in the superconducting state, are completely diamagnetic—that is, all of an applied magnetic field is excluded from the body of material.
- The exclusion of magnetic field phenomenon is called **Meissner effect**.

(a) While in the superconducting state, a body of material (circle) excludes a magnetic field (arrows) from its interior.
(b) The magnetic field penetrates the same body of material once it becomes normally conductive.

Classification

Levitation

Classification

- As H is increased, the material remains diamagnetic until the critical magnetic field H_C is reached. At this point, conduction becomes normal, and complete magnetic flux penetration takes place. Several metallic elements, including aluminum, lead, tin, and mercury, belong to the type I group.
- Type II superconductors are completely diamagnetic at low applied fields, and field exclusion is total.
- However, the transition from the superconducting state to the normal state is gradual and occurs between lower critical and upper critical fields, designated H_{C1} and H_{C2}, respectively.
- The magnetic flux lines begin to penetrate into the body of material at H_{C1}, and with increasing applied magnetic field, this penetration continues; at H_{C2}, field penetration is complete.
- For fields between H_{C1} and H_{C2}, the material exists in what is termed a *mixed state*—both normal and superconducting regions are present.

Classification

$H = \frac{NI}{l}$	Magnetic field strength within a coil
$B = \mu H$	Magnetic flux density in a material
$B_0 = \mu_0 H$	Magnetic flux density in a vacuum
$\mu_r = \frac{\mu}{\mu_0}$	Relative permeability
$B = \mu_0 H + \mu_0 M$	Magnetic flux density, in terms of magnetization
$M = \chi_m H$	Magnetization
$\chi_m = \mu_r - 1$	Magnetic susceptibility
$B \cong \mu_0 M$	Magnetic flux density for a ferromagnetic material
$M_s = 0.60\mu_B N$	Saturation magnetization for Ni
$M_s = N'\mu_B$	Saturation magnetization for a ferrimagnetic material

Classification

- Type II superconductors are preferred over type I for most practical applications by virtue of their higher critical temperatures and critical magnetic fields.
- The three most commonly used superconductors are niobium–zirconium (Nb–Zr) and niobium–titanium (Nb–Ti) alloys and the niobium–tin intermetallic compound Nb_3Sn.
- Recently, a family of ceramic materials that are normally electrically insulative have been found to be superconductors with inordinately high critical temperatures.
- Initial research has centered on yttrium barium copper oxide, YBa2Cu3O7, which has a critical temperature of about 92 K.

Classification

Material	*Critical Temperature* T_C *(K)*	*Critical Magnetic Flux Density* B_C *(tesla)*[a]
	Elements[b]	
Tungsten	0.02	0.0001
Titanium	0.40	0.0056
Aluminum	1.18	0.0105
Tin	3.72	0.0305
Mercury (α)	4.15	0.0411
Lead	7.19	0.0803
	Compounds and Alloys[b]	
Nb–Ti alloy	10.2	12
Nb–Zr alloy	10.8	11
$PbMo_6S_8$	14.0	45
V_3Ga	16.5	22
Nb_3Sn	18.3	22
Nb_3Al	18.9	32
Nb_3Ge	23.0	30
	Ceramic Compounds	
$YBa_2Cu_3O_7$	92	—
$Bi_2Sr_2Ca_2Cu_3O_{10}$	110	—
$Tl_2Ba_2Ca_2Cu_3O_{10}$	125	—
$HgBa_2Ca_2Cu_2O_8$	153	—

Applications

- Superconducting magnets capable of generating high fields with low power consumption are being used in scientific test and research equipment.
- Used in magnetic resonance imaging (MRI) in the medical field as a diagnostic tool.
- electrical power transmission through superconducting materials—power losses would be extremely low, and the equipment would operate at low voltage levels;
- magnets for high-energy particle accelerators;
- higher-speed switching and signal transmission for computers;
- high-speed magnetically levitated trains, for which the levitation results from magnetic field repulsion.
- The chief deterrent to the widespread application of these superconducting materials is the difficulty in attaining and maintaining extremely low temperatures.

- https://www.youtube.com/watch?v=D-9M3GWoBrw