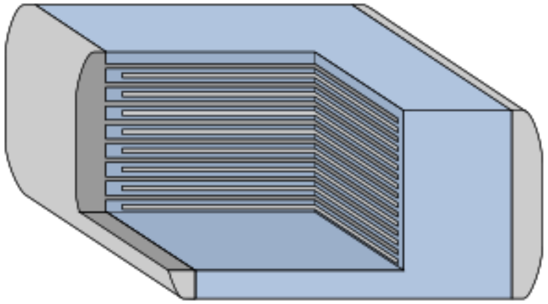
Capacitors

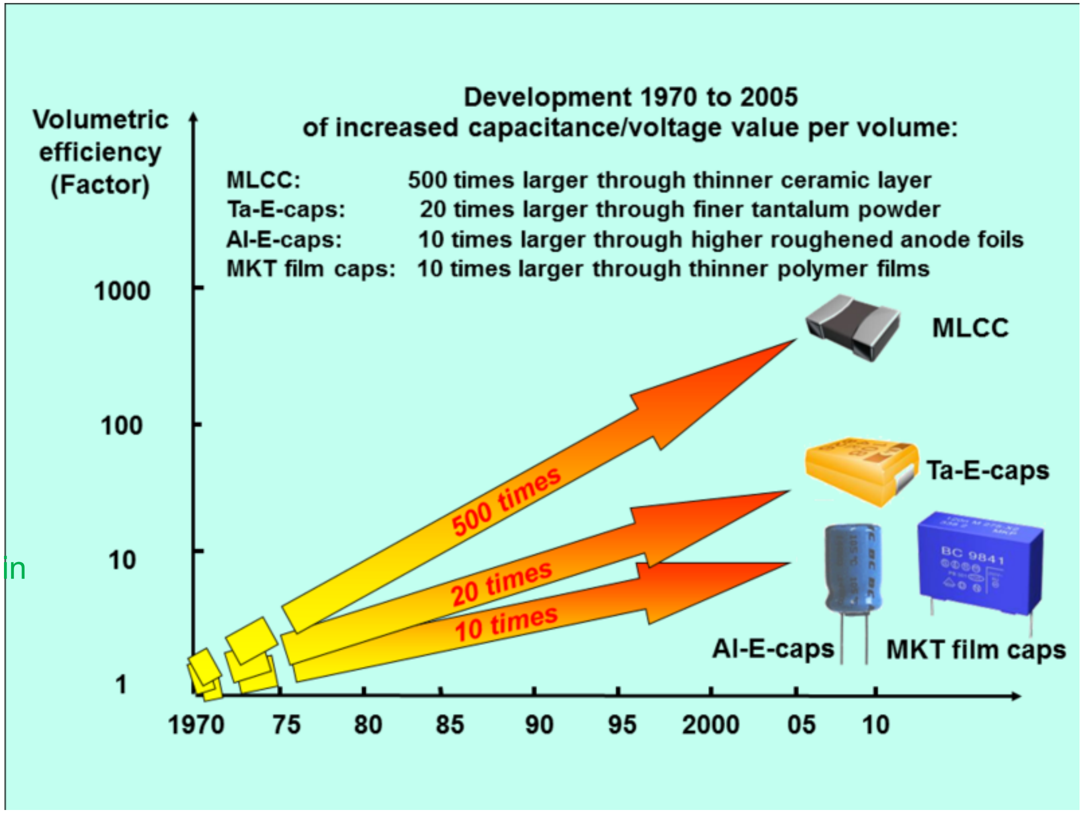
Different kinds (or families) of capacitors are available in the market, to be chosen according to the desired capacitance and to the operating conditions (remarkably, **size and operating voltage)**

Technological progress well demonstarted by the increase of the "volumetric efficiency" in terms of capacitance and maximum operating voltage for a defined size (and volume)

New materials (**dielectric permittivity** & **improved dielectric stiffness**)

New architectures, e.g., multilayered capacitors with thin dielectric layers:





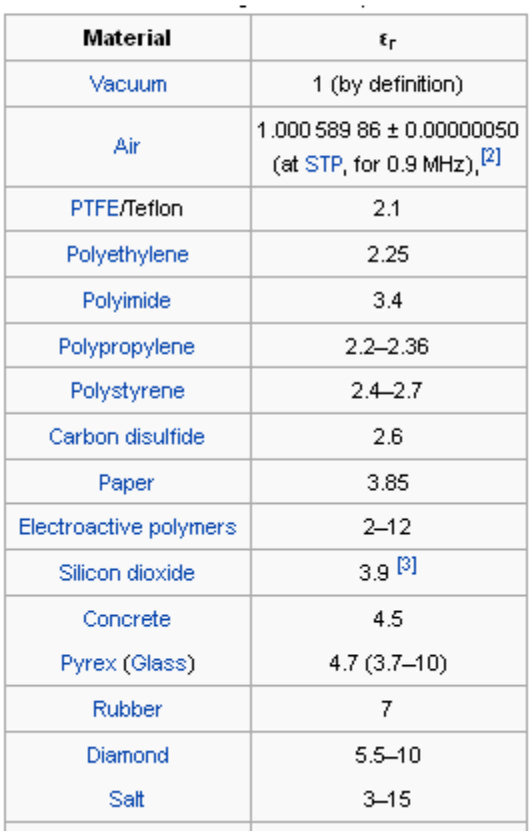
Development 1970 to 2005 of increased capacitance/voltage value per volume:

MLCC: 500 times larger through thinner ceramic layer
Ta-E-caps: 20 times larger through finer tantalum powder
Al-E-caps: 10 times larger through higher roughened anode foils
MKT film caps: 10 times larger through thinner polymer films

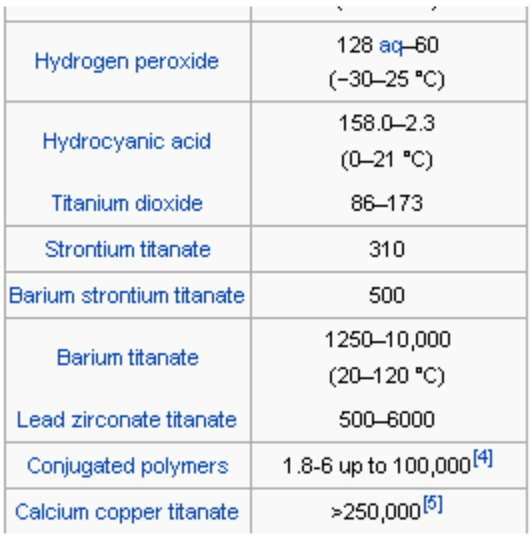
Note: capacitance of a parallel amount s to the sum of capacitances!

Dielectric permittivity

The **dielectric permettivity** , acting as a multiplier in the capacitance evaluation (independently of geometry) is a material property ruling the ability of the dielectric to get “polarized”



Material	ε_r
Vacuum	1 (by definition)
Air	1.000 589 86 ± 0.00000050 (at STP, for 0.9 MHz),[2]
PTFE/Teflon	2.1
Polyethylene	2.25
Polyimide	3.4
Polypropylene	2.2–2.36
Polystyrene	2.4–2.7
Carbon disulfide	2.6
Paper	3.85
Electroactive polymers	2–12
Silicon dioxide	3.9 [3]
Concrete	4.5
Pyrex (Glass)	4.7 (3.7–10)
Rubber	7
Diamond	5.5–10
Salt	3–15



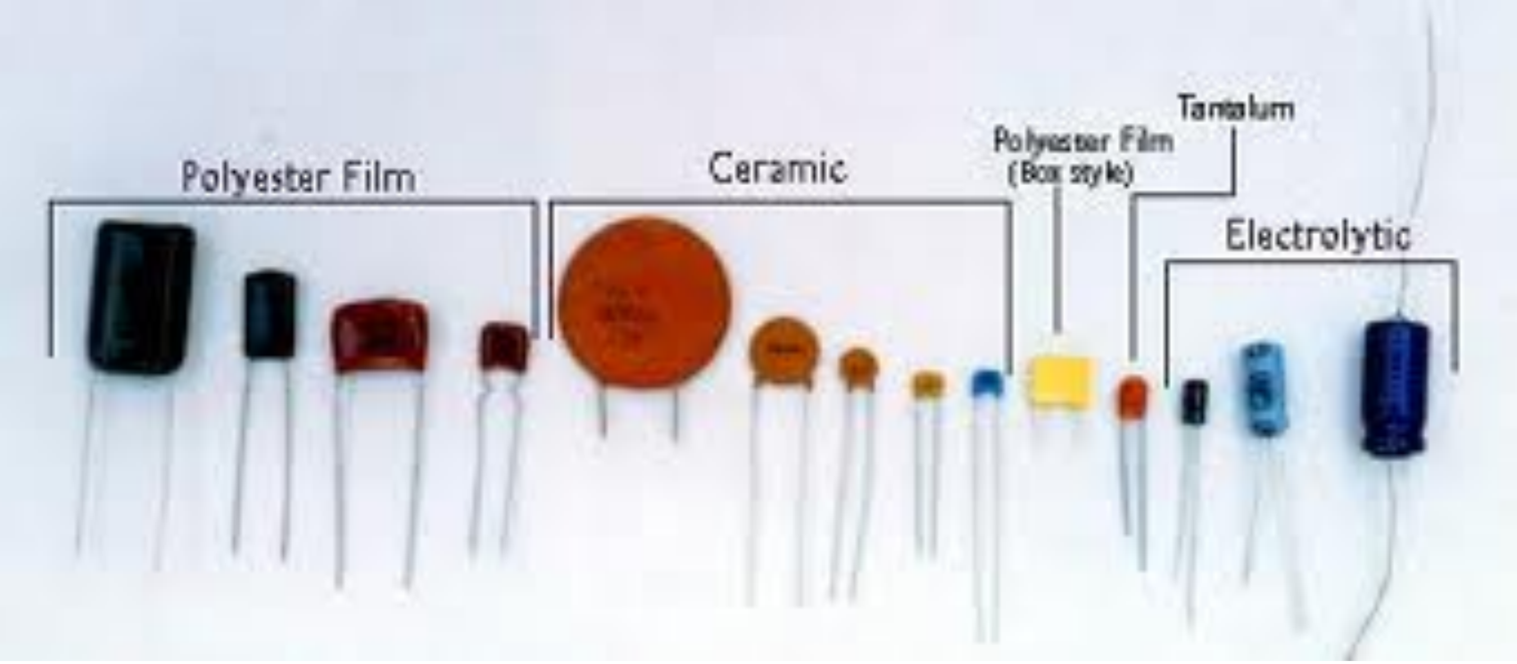
Hydrogen peroxide	128 aq–60 (−30–25 °C)
Hydrocyanic acid	158.0–2.3 (0–21 °C)
Titanium dioxide	86–173
Strontium titanate	310
Barium strontium titanate	500
Barium titanate	1250–10,000 (20–120 °C)
Lead zirconate titanate	500–6000
Conjugated polymers	1.8-6 up to 100,000[4]
Calcium copper titanate	>250,000[5]

Quite often, in materials owning very large dielectric permittivity, dielectric stiffness is a concern, especially when thin layers are considered

In fact, the inhomogeneous structure of such materials (typically, polycrystalline) promotes the occurrence of structural defects which can easily lead to avalanche conduction phenomena (unwanted)

Note: having a thin dielectric layer improves the capacitance (see the capacitance evaluation in plane parallel capacitors) but enhances the electric field strength, with deleterious consequences in terms of dielectric stiffness

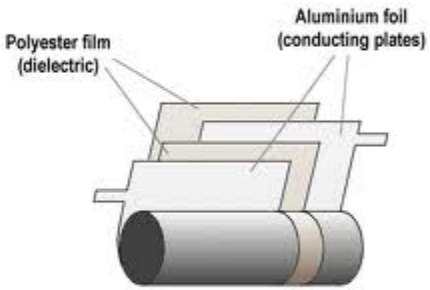
Commercial families of capacitors (components)

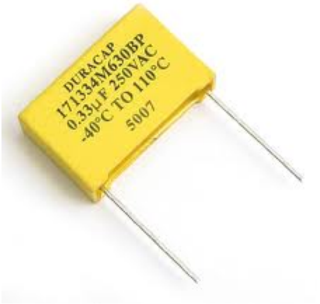


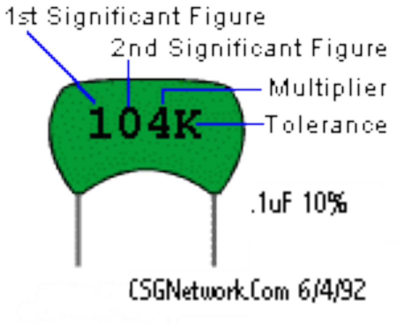
A huge variety of shapes, sizes, materials (and, obviously, capacitance)

Polyesther capacitors

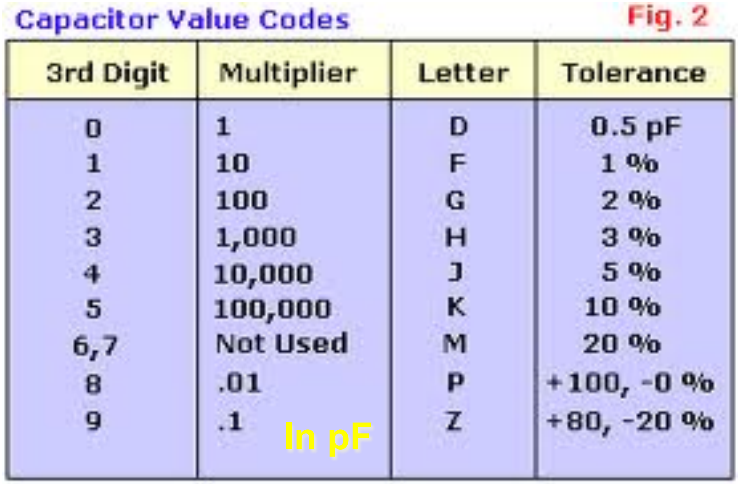
Typically made by alternating a conductive (e.g., aluminium) foil with a dielectric layer. Rolling up the foil allows achieving a large surface, hence improving the capacitance. Dielectric is frequently polyesther, but other polymers (e.g., Mylar, PTFE, polymide, etc.) or even paper are used







Capacitance value is typically encoded in an alphanumeric code



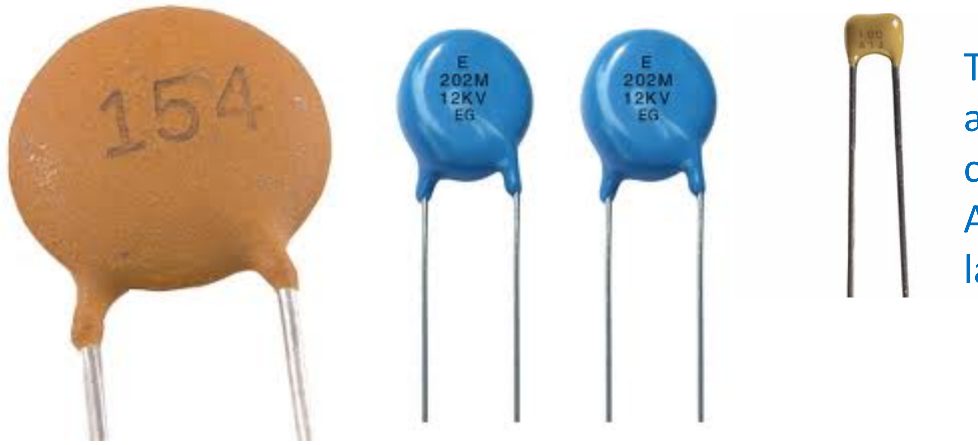
Capacitor Value Codes

Fig. 2

3rd Digit	Multiplier	Letter	Tolerance
0	1	D	0.5 pF
1	10	F	1 %
2	100	G	2 %
3	1,000	H	3 %
4	10,000	J	5 %
5	100,000	K	10 %
6,7	Not Used	M	20 %
8	.01	P	+100, -0 %
9	.1	Z	+80, -20 %

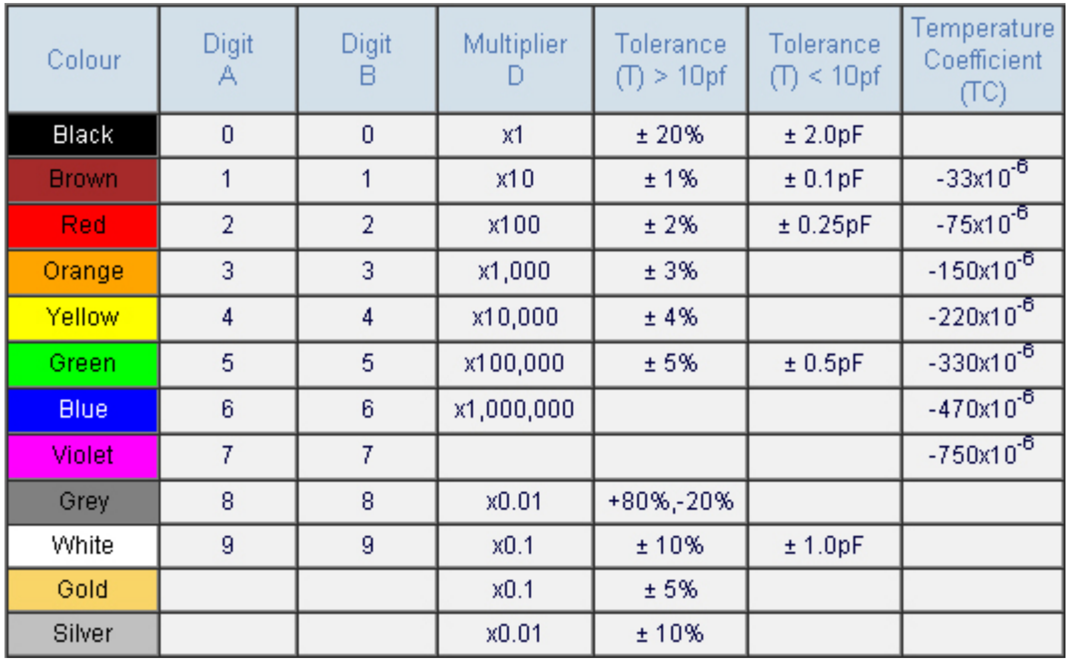
In pF

Ceramic capacitors



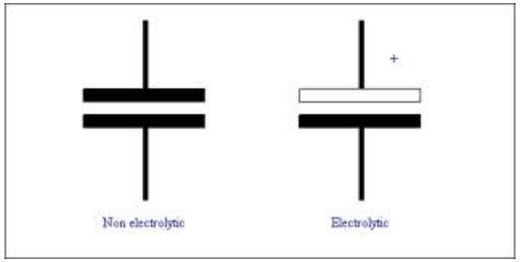
The dielectric is here a ceramics (typically, a ceramic paste, e.g., a resin embedding ceramic particles)
Advantages: large dielectric stiffness → large operating voltages (up to several kV)

Sometimes: capacitance encoded in colors (similar to resistors)



Colour	Digit A	Digit B	Multiplier D	Tolerance (T) > 10pf	Tolerance (T) < 10pf	Temperature Coefficient (TC)
Black	0	0	x1	± 20%	± 2.0pF	
Brown	1	1	x10	± 1%	± 0.1pF	$-33x10^{-6}$
Red	2	2	x100	± 2%	± 0.25pF	$-75x10^{-6}$
Orange	3	3	x1,000	± 3%		$-150x10^{-6}$
Yellow	4	4	x10,000	± 4%		$-220x10^{-6}$
Green	5	5	x100,000	± 5%	± 0.5pF	$-330x10^{-6}$
Blue	6	6	x1,000,000			$-470x10^{-6}$
Violet	7	7				$-750x10^{-6}$
Grey	8	8	x0.01	+80%,-20%		
White	9	9	x0.1	± 10%	± 1.0pF	
Gold			x0.1	± 5%		
Silver			x0.01	± 10%		

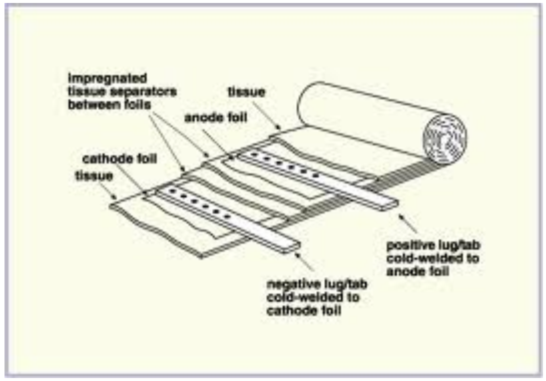
Electrolytic capacitors



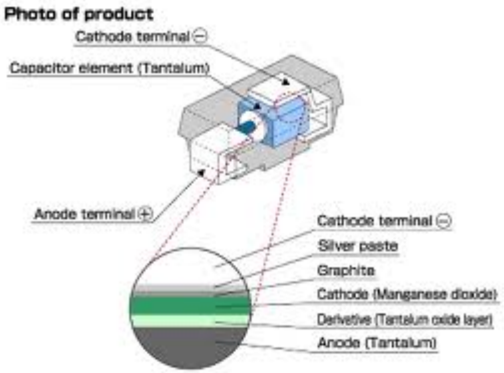
Dielectric is typically an aluminum oxide – impregnated layer

Advantages: very large capacitance (up to mF range)

Disadvantages: very low operating voltages (typically < 300V), large tolerance, fatigue and ageing, **must be used with proper polarity**

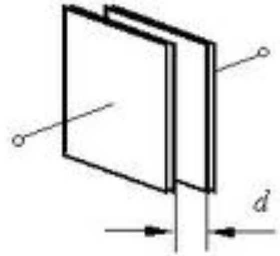


In high-end applications, electrolytic capacitors tend to be replaced by (more expensive, but smaller and more reliable) **tantalum** capacitors, which exploit tantalum oxide as the dielectric

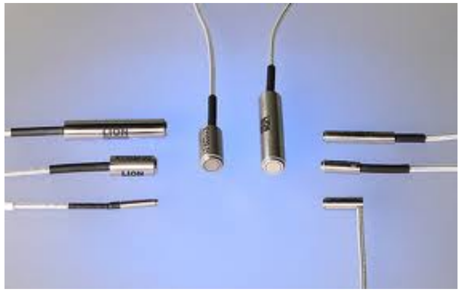


“Exotic” applications I

Highly sensitive displacement sensors



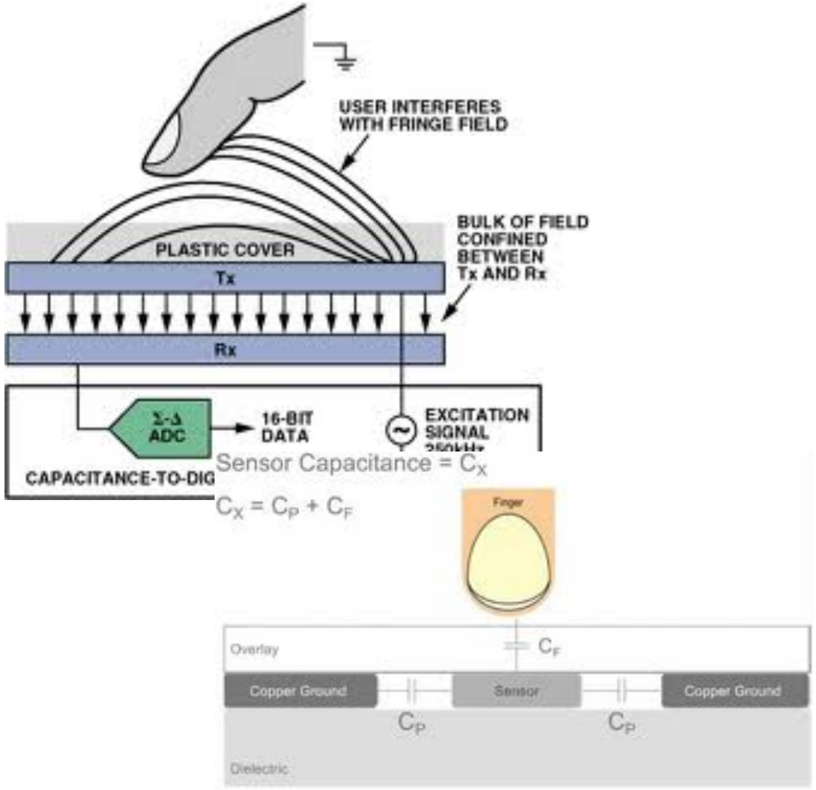
Spacing variation



Let’s consider a paralllel plane capacitor with A=1cm^2 and d=1mm → $C = \varepsilon_0 A/d \sim 1$ nF (air is assumed as the dielectric)

With appropriate methods (e.g., AC impedance or de Sauty’s bridge), capacitance variations of a few pF can be measured $\Delta C/C = \Delta d/d < 1\%$
→ Δd can be measured with an accuracy on the order of the nanometer!

Note: the operating principle is the same as for capacitive (proximity) sensors and touch screens

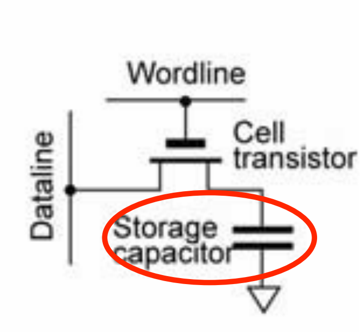


"Exotic" applications II

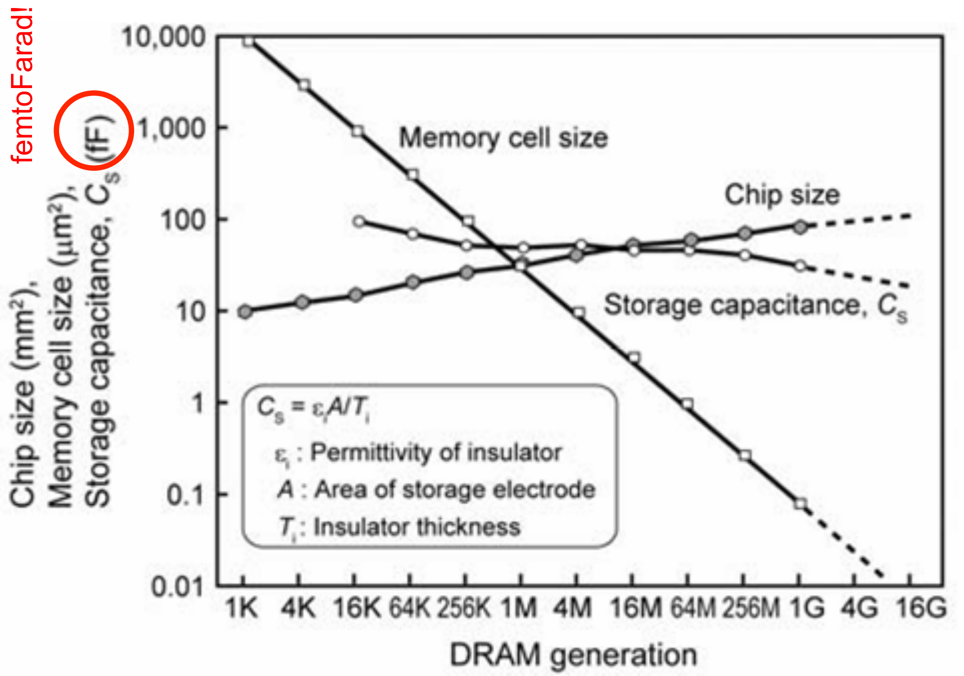
Data storage in all "on-chip" devices (e.g., Dynamic Random Access Memories – DRAMs, Flash Memories – like USB pens or SD cards) traditionally use the charge stored in a capacitor as the recorded bit

A 4 GB RAM chip may contain up to 8x4x10^9 capacitors in a few cm^2 area (not individually addressable, though)!!

Typically, the unit capacitor is part of a miniaturized transistor, called MOS-FET (Metal Oxide Semiconductor – Field Effect Transistor – you will study them next year!)



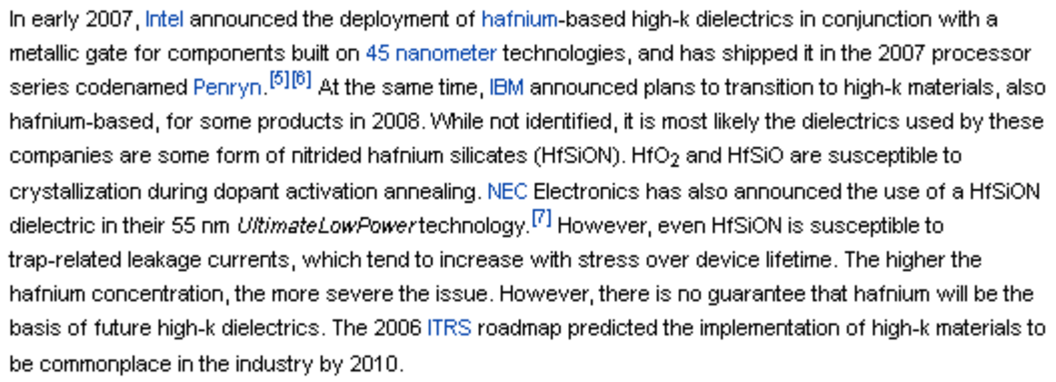
(In DRAMs readout is destructive)



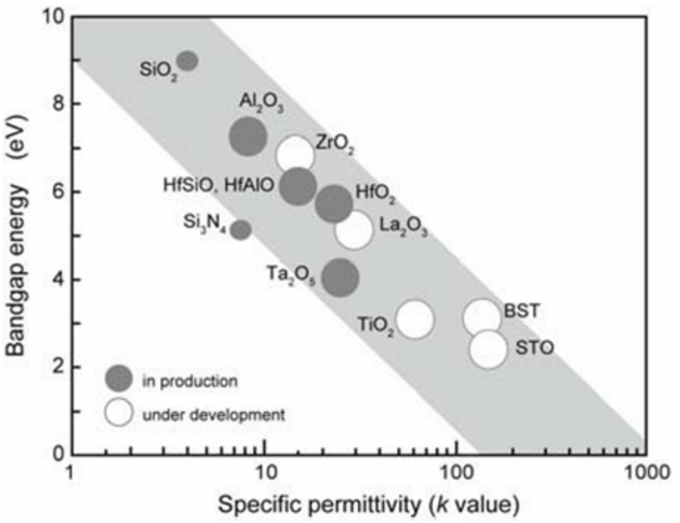
femtoFarad!

Miniaturization implies size reduction (both area *A* and dielectric thickness *T*)
→ *Need for ultra-high electric permittivity (so-called high-K materials)*

Limits ??



In early 2007, Intel announced the deployment of hafnium-based high-k dielectrics in conjunction with a metallic gate for components built on 45 nanometer technologies, and has shipped it in the 2007 processor series codenamed Penryn.[5][6] At the same time, IBM announced plans to transition to high-k materials, also hafnium-based, for some products in 2008. While not identified, it is most likely the dielectrics used by these companies are some form of nitrided hafnium silicates (HfSiON). HfO_2 and HfSiO are susceptible to crystallization during dopant activation annealing. NEC Electronics has also announced the use of a HfSiON dielectric in their 55 nm *UltimateLowPower* technology.[7] However, even HfSiON is susceptible to trap-related leakage currents, which tend to increase with stress over device lifetime. The higher the hafnium concentration, the more severe the issue. However, there is no guarantee that hafnium will be the basis of future high-k dielectrics. The 2006 ITRS roadmap predicted the implementation of high-k materials to be commonplace in the industry by 2010.



But there are at least two limiting considerations:

-The stored energy, $CV^2/2$, scales down as C and can get values comparable to the thermal energy (k_BT ~ 1/40 eV @ T = 300K) → thermal fluctuations can play a role for too small C (say, C < 1 aF, still far to be reached)

- The interplay between V, a continuous quantity, and Q, a discrete quantity, can lead to complicated phenomena (see the "Coulomb blockade" effect)