Resistive electrodes
Decoupling surface from bulk material properties

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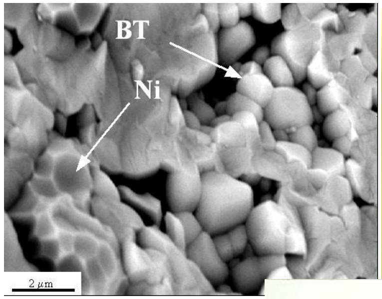
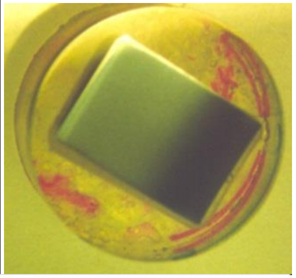
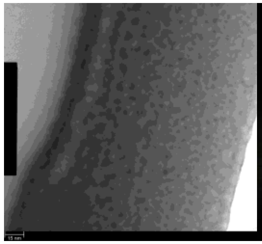
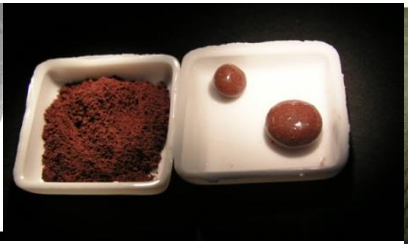
- Percolative ceramic/metal composites



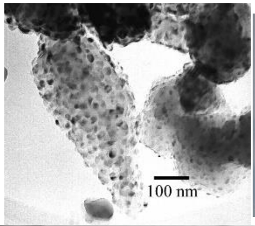


- Plasmonic and metamaterials

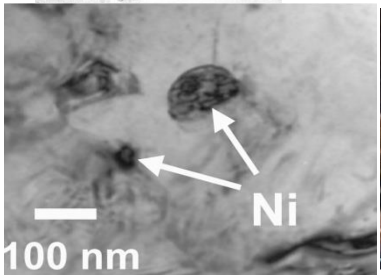


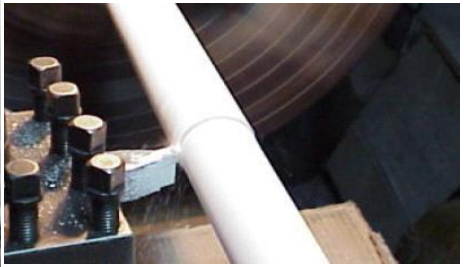


- Biomedical applications



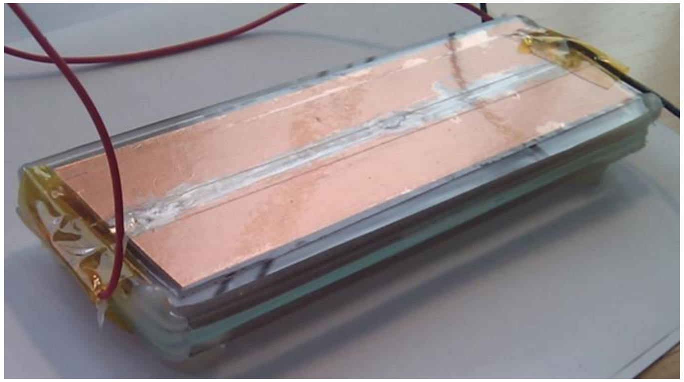
- Cutting tools



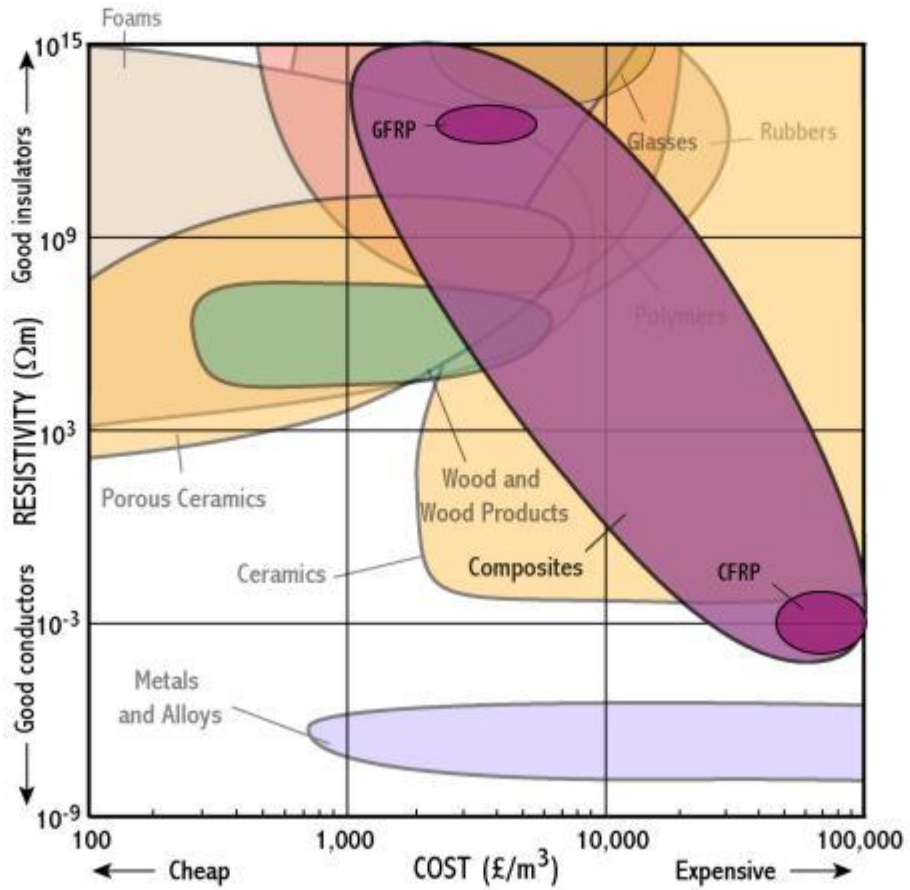


High rate resistive electrode requirements

- **Resistivity [$10^{8\text{-}9}$ -10^{11}] Ω·cm.**
- **Low ageing**
  - Electronic conductivity vs Ionic conductivity
- High voltage breakdown
- Good surface quality
- Good mechanical properties
- Not very expensive
- ….



Materials from scratch



Composites

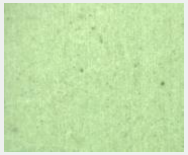
Polymers

Ceramics

Glasses

http://www-materials.eng.cam.ac.uk/mpsite/interactive_charts/resistivity-cost/basic.html

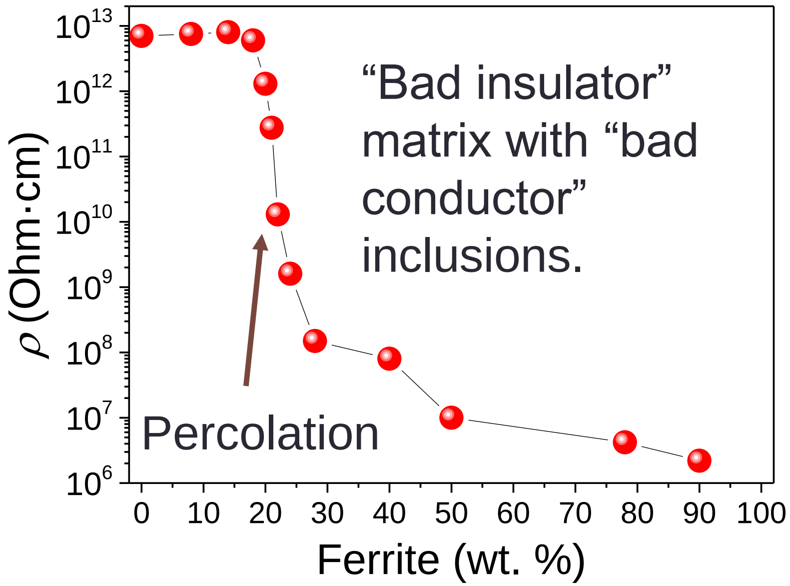
Some Resistive Electrodes

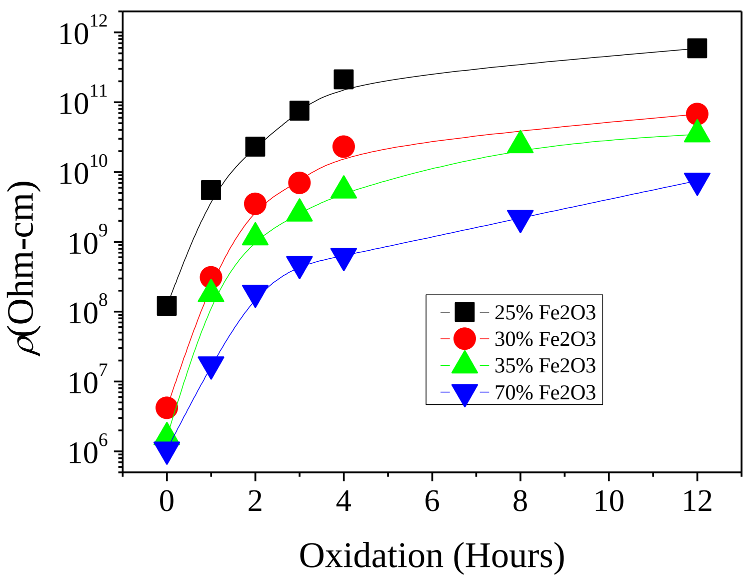
		Materials	Experiments
Glasses			
		Soda Lime Silicate Glasss (**SLS Glass**)	Hades, Belle
		Low Resistive Silicate Glass (**LRS Glass**)	CBM
Polymers			
		**Bakelite**	CMS, BaBar
Ceramics			
		**Si_3N_4/SiC**	CBM

Ferrite Ceramic Resistive Electrode

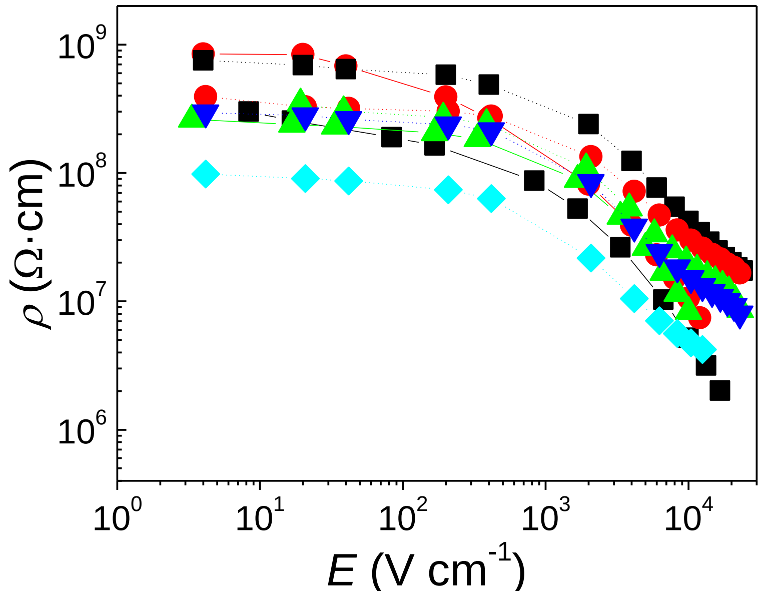
Electrical conductivity tuning

- Two conductivity tuning methods:
  - By composition
  - By thermal treatment
- Composition:
  - Resistivity goes from 10^6 to 10^{13} to Ω·cm.
- Thermal treatment:
  - Three orders of magnitude Two-ways (up/down) reversible post fabrication conductivity tuning.

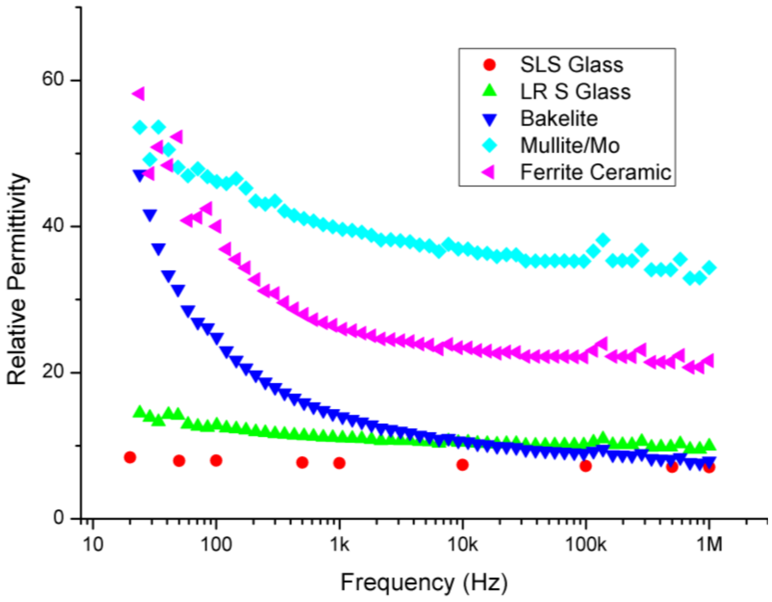


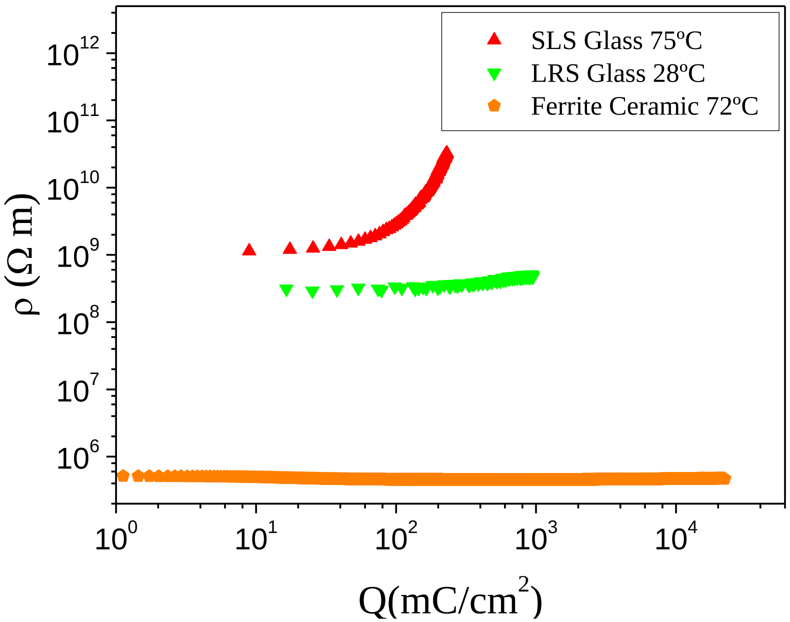


Electrical properties – Long run



- Non linear conductivity I/V
- Resistivity decrease an order of magnitude for high E fields.
- Not very high **permittivity.**
- This composites **do not present ageing** at all.

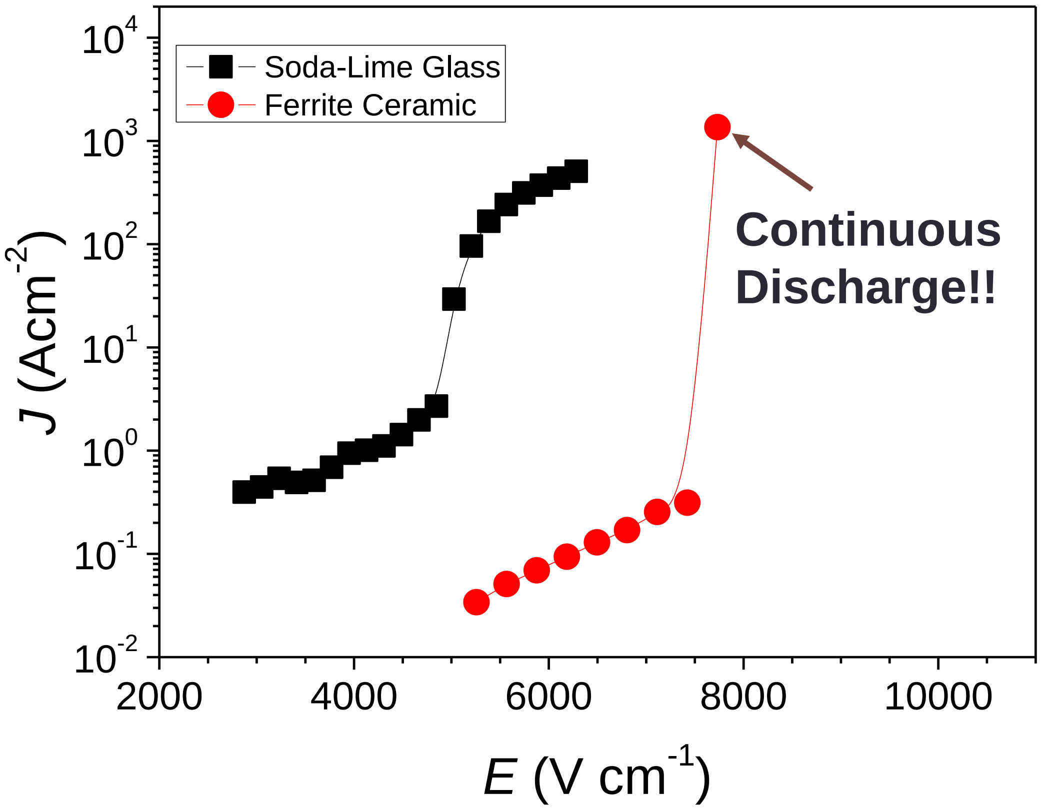


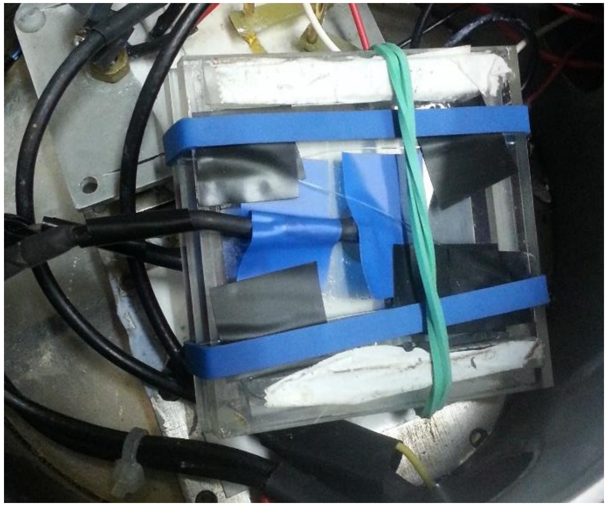


Chamber test

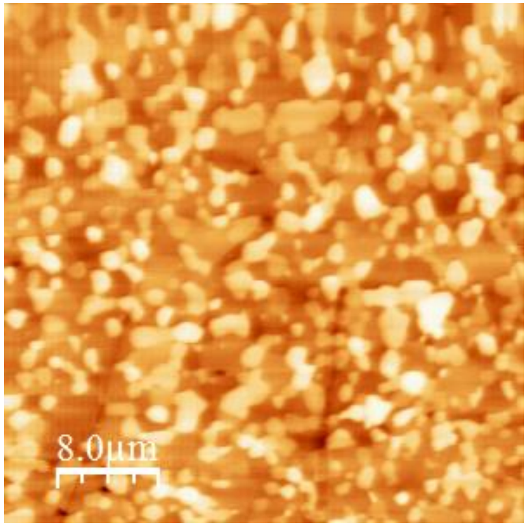
HV Test

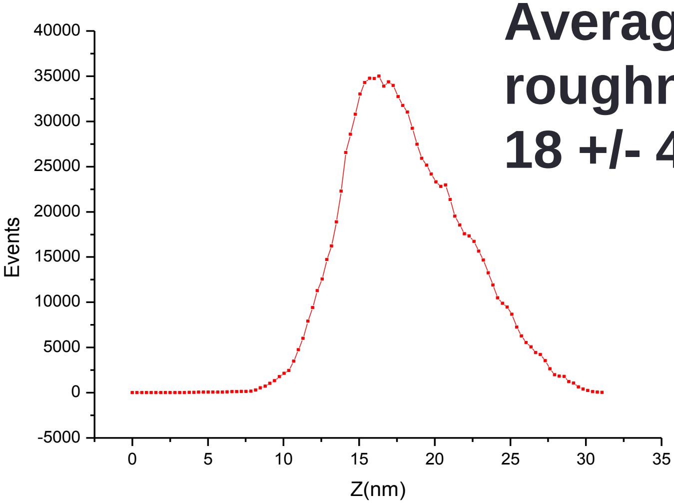
0.3mm gap $C_2H_2F_4$



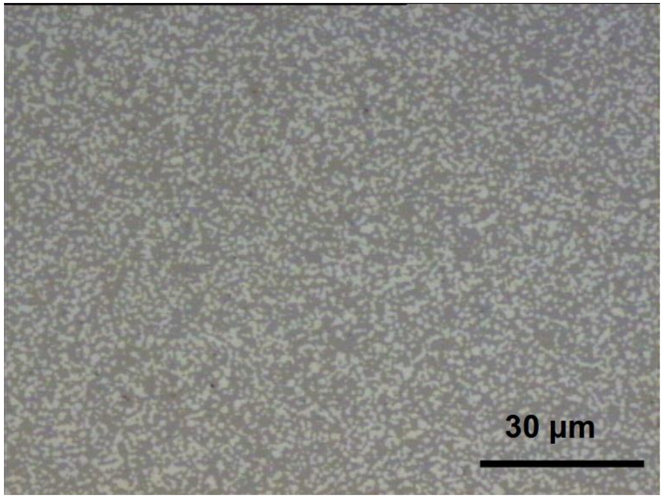


Ceramic Surface Quality

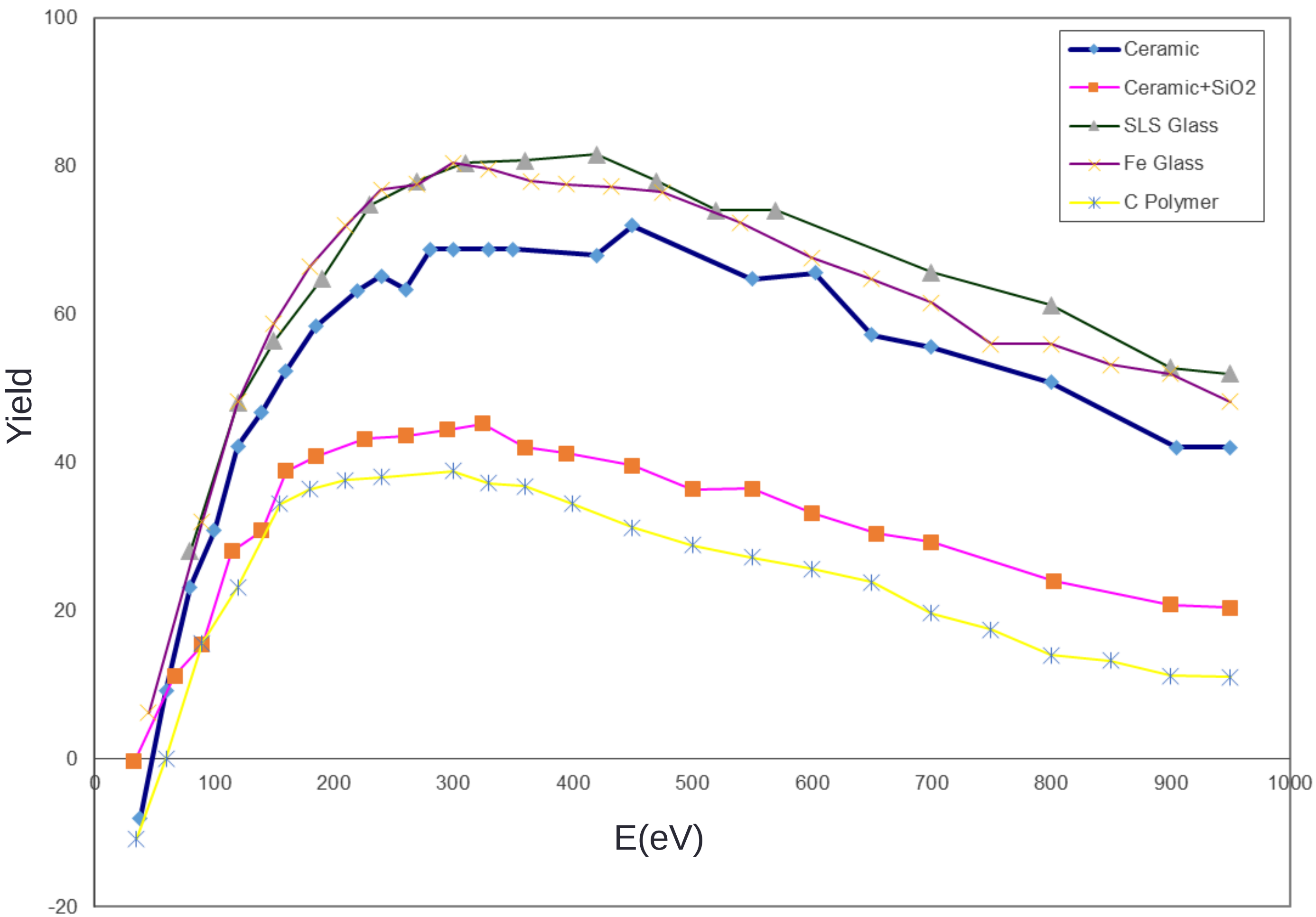


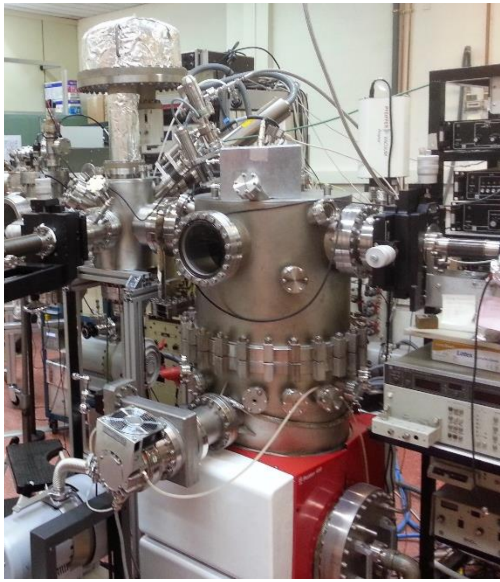


Average roughness 18 +/- 4 nm

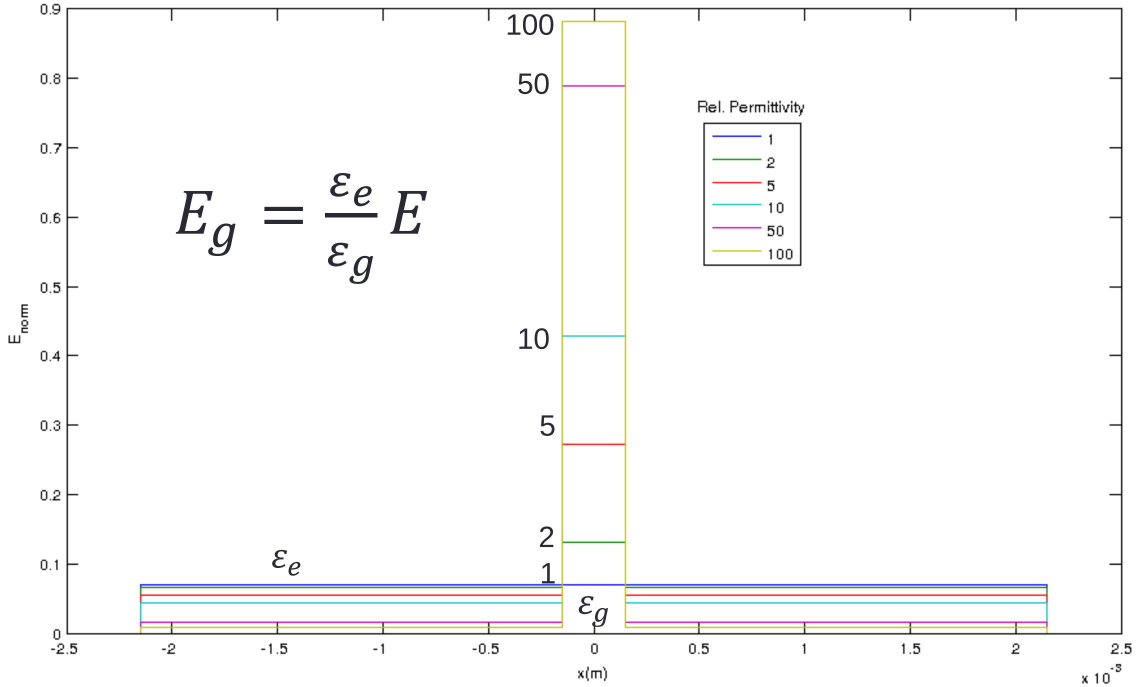


X-ray Photoelectron Spectroscopy (XPS) Secondary Yield Emission





E distribution vs Electrode permittivity



Gas – Electrode boundary

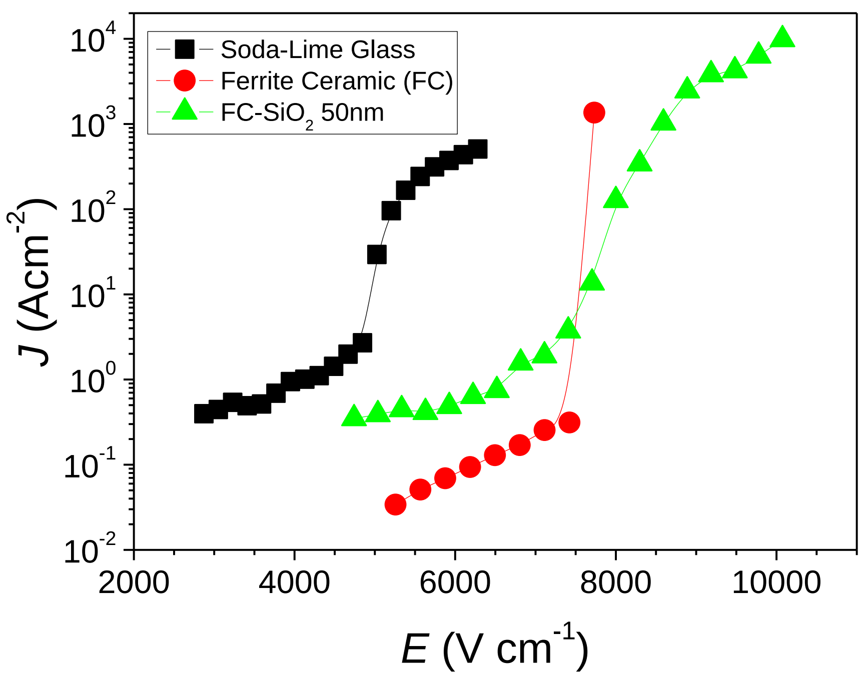
Material Maxwell Eqs.

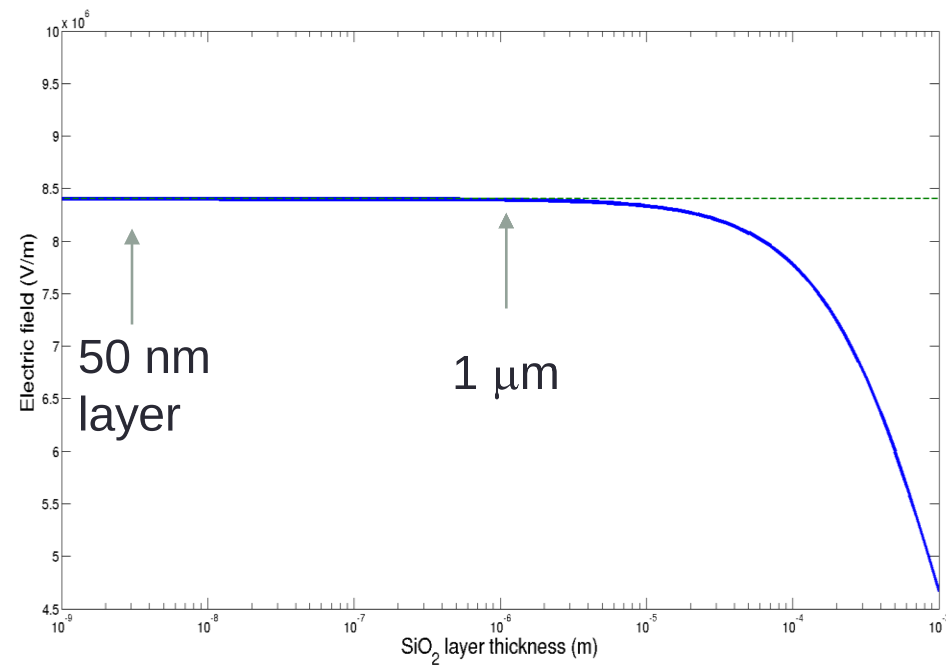
$$\nabla D = \rho_f \quad \nabla D = \rho_f$$

$$D = \varepsilon E + P$$

Displacement field continuity

Gas – Electrode interface





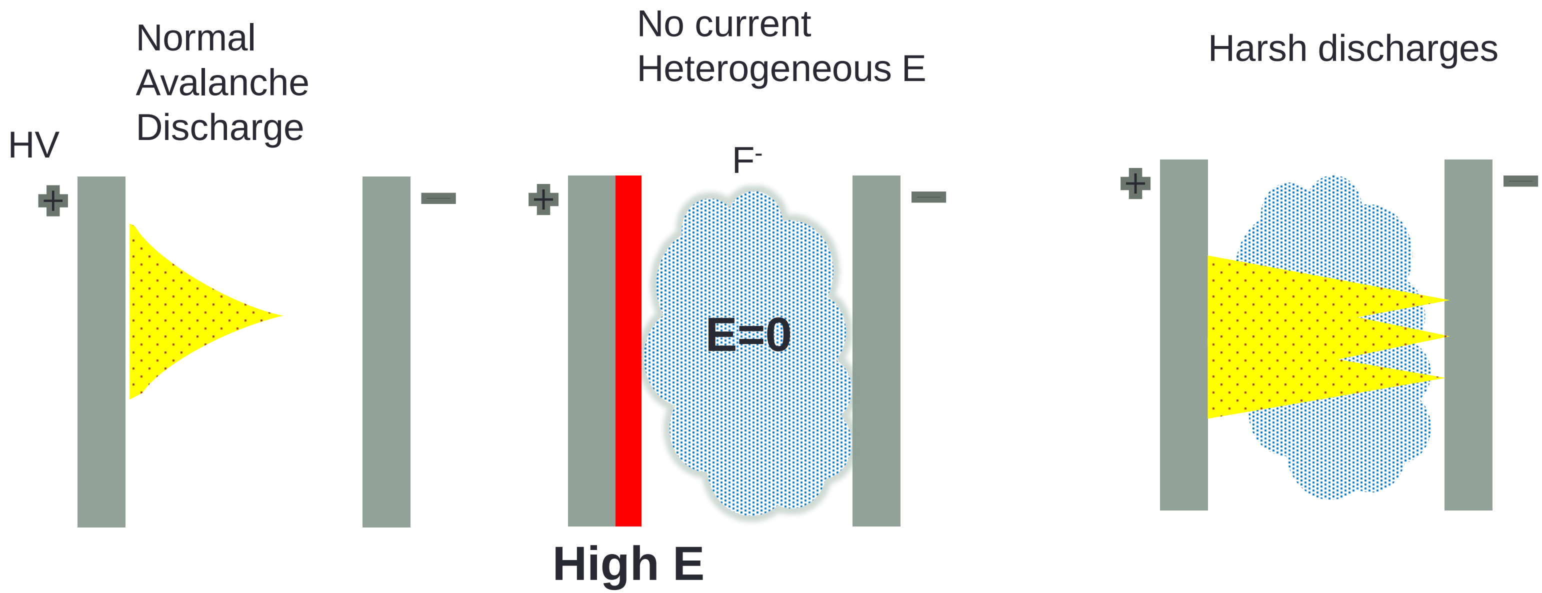
There is no effect in the E field for SiO_2 thin films under 1 μm

Proposed model

$C_2H_2F_4$	Primary Ionization (eV)	C-F Bond Energy (eV)
1st	13.6	4.5
2nd	17.4	

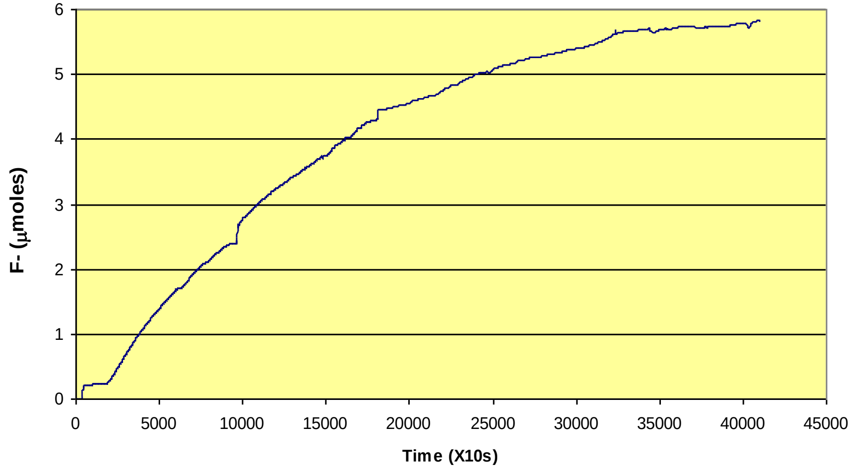
- Quenching gas forms F^- species after e^- collisions.
  - By instance, $C_2H_2F_4 + e^- = C_2H_2F_2^+ + 2F^-$, $C_2H_2F_4 + 2e^- = C_2H_2F_2 + 2F^-$

- **Surface** of the RPC electrode material **reacts with fluorine**, so the gas anions density decrease
- Ceramic affinity to F^- is very low, therefore concentration increases to produce a **cold plasma**
- Plasma produces electric field screening → Zero field inside plasma and high field around it
- The presence of a thin layer (~nm) of SiO_2 has no effect at the field distribution but capture F^-.



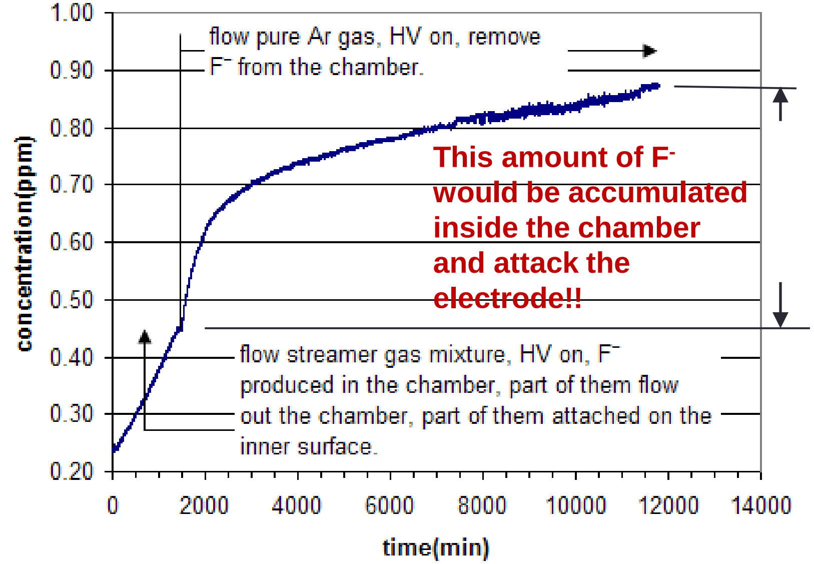
Bakelite F^- density

Bakelite



G. Aielli et al., NPB-PS, 158 (2006) 1

IHEP Bakelite



F- density	F^- exhaust (F^-/C)	F^- captured (F^-/C)
C. Lu	1.19×10^{19}	1.67×10^{19}
G. Aielli	1.3×10^{19}	1.2×10^{21}

C. Lu, NIMA, 602 (2009) 3

HF SiO_2 etching

- $SiO_2 + 6HF = 2H^+ + SiF^{-2}_6 + 2H_2O$ (Verhaverbeke,JoTECS, 141 (1994) 10)

The Free Energy Change of Reaction of Si or SiO_2 and F_2 or HF (Ref. Reaction of Cl_2 or HCl)

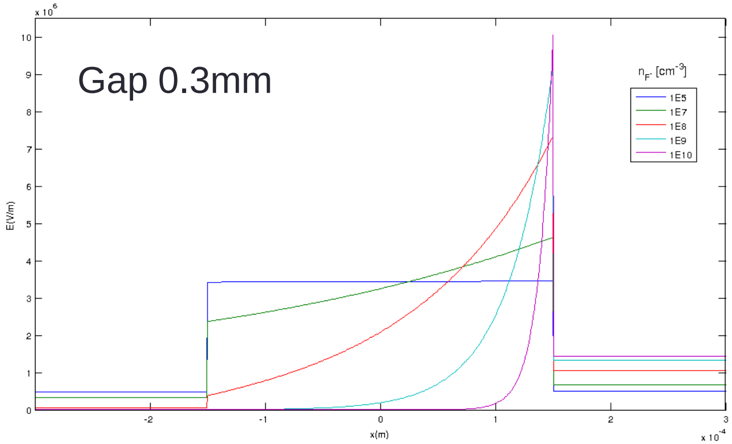
The Free Energy Change of Reaction	ΔF (eV/mol)	ΔF (kJ/mol)	Formula
Si (s)+2 F2 (g) = SiF_4 (g)	−16.2	(−157.65)	(1)
Si (s)+ 4 HF (g) = SiF_4 (g)+2 H_2 (g)	−4.94	(−479.85)	(2)
SiO_2 (s)+2 F2 (g) = SiF_4 (g) + O_2 (g)	−7.38	(−716.05)	(3)
SiO_2 (s)+4 HF (g) = SiF_4 (g)+2 H_2O (g)	−0.83	(−80.35)	(4)
Si (s)+2 Cl_2 (g) = $SiCl_4$ (g)	−6.35	(−616.98)	(5)
Si (s)+4 HCl (g) = $SiCl_4$ (g)+2 H_2 (g)	−2.43	(−235.78)	(6)
SiO_2 (s)+2 Cl_2 (g) = $SiCl_4$ (g) + O_2 (g)	+2.47	(+239.42)	(7)
SiO_2 (s)+4 HCl (g) = $SiCl_4$ (g)+2 H_2O (g)	+1.69	(+163.68)	(8)

Note: Standard Gibbs free energy [ΔG^0 (eV/mol)] at 298.15 K. HF (g): −2.81; SiF_4 (g): −16.2; SiO_2: −8.82; HCl (g): −0.98; $SiCl_4$ (g): −6.35; H_2O (g): −2.35.

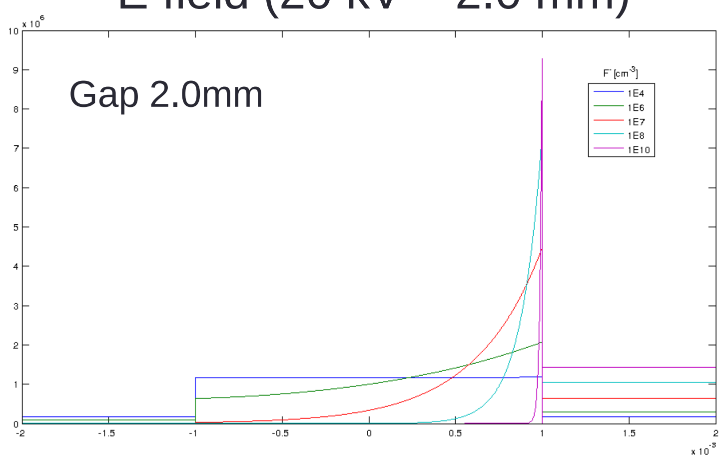
“Etching of various SiO2”, Tatsuhiro Yabune, 2005

Ionized particles density effect

E field (3kV – 0.3mm)



E field (20 kV – 2.0 mm)



Boltzman distr.
Charge density

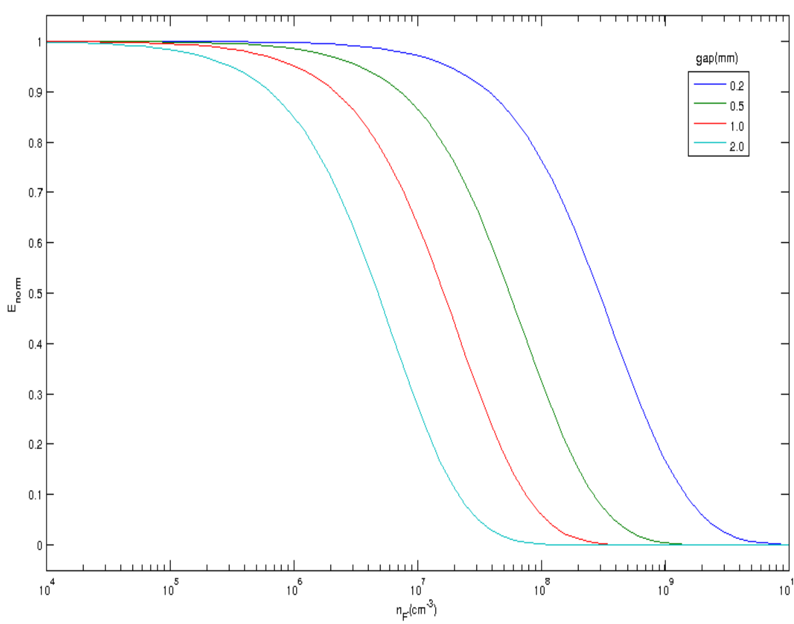
$$n_e \alpha\, e^{\frac{q\,\varphi}{k_b T}}$$

Gauss law

$$\nabla^2 \varphi = -\frac{\rho_f}{\varepsilon}$$

$$\varphi(r) = \frac{Q}{4\,\pi\,\varepsilon_r} e^{\frac{-r}{\lambda_D}}$$

Debye length $\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{n_e q_e^2}}$



Conclusions

- Electrode materials fulfilling all the known requirements could be useless if they have low **chemical affinity** with the gas ionized particles.
- **Glass, bakelite and linseed oil** have high affinity to the F^- anions.
- **F^- plasma physics** has been used to understand gas discharge instabilities.
- Epitaxial **surface treatment** allows to make “gas-compatible” materials with optimal electric properties.
- In high rate electrodes, the **total absence** of aging should be avoided.
- **ToDo:** Check compatibility between other gases and surfaces.

Thank you.

Annex:

E_{norm} Gap